S.N. Glazer

Mine Seismology: Data Analysis and Interpretation

Palabora Mine Caving Process as Revealed by Induced Seismicity

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For surely knowledge itself, in a world of illusions, can only be illusory.

Jacques Lacarriere, *The Gnostics*

I would like to dedicate this book to all my geophysics teachers from AGH University of Science and Technology, Kraków, Poland. They have given me sound basics of geophysics and above all they have taught me to think independently. My special gratitude goes to professors: S. Małoszewski, Z. Fajklewicz, J. Kowalczuk, K. Pietsch, M. Lemberger and assistant professor G. Bojdys. When in March 1968 I was arrested for the participation in student riot against the communist rulers I was expelled from the university. After getting out of prison as further punishment I got a ticket to the army. That is when Prof. S. Małoszewski helped me. He arranged with his friend K. Sojka the GM of PGGN (Geophysical Company of Oil Industry) employment which automatically excluded me from army.

....and to the authorities in the field of seismology professors: J. Niewiadomski, S. Gibowicz, A. Kijko and S. Lasocki. I had the privilege to meet them personally in my work and have been honoured by their friendship.

Foreword

Through the course of a professional career one encounters many voices and approaches. Gazing back through all I have read, this book by Dr. Stefan Glazer stands out as unique in this genre, transcending all the rules and conventions which inhibit so many academic textbooks. Mine seismicity is already a narrow branch in seismology and mine caving seismology is all the more so. This book covers the analysis and interpretation of seismicity induced by mine caving in a formidable manner. Stefan shuns the routine boredom of a book filled with equations, definitions and graphs accessible only to the few specialists with him in the ivory tower of his field. Instead he expresses his unique voice with a completely original textbook which bears little resemblance to the mundane, giving us the diary of the professional journey of an engineer whose responsibility it was to provide management with information on how to mine safely while still maximizing productivity.

Everything in Stefan's book is new. Before this book the field was limited to some sparse publications in obscure journals and conference proceedings. Based on his deep understanding of mechanisms and physics of rock fracture, Stefan has forged a consistent scientific approach based on seismological records, processing and interpretation which lead to sound recommendations on how to mine safely.

The fact that everything in Stefan's book is new comes as no surprise. I first had the pleasure of meeting minds with him in 1990 during a brief visit to South Africa. At that time Stefan was responsible for the new digital seismic network in the gold mines around Klerksdorp. Stefan's enthusiasm was palpable as he told me what kind of information he was going to extract from his new digital records, and for the first time related his idea of creating an index of apparent stress, a parameter which would simultaneously utilize both seismic moment and seismic energy. Without revealing my age, by then I already enjoyed the benefit of 20 years of experience in mine seismology and yet I had never encountered anything resembling the originality of Stefan's approach. Stefan's ideas were always new and refreshing at a time when everybody was talking about the prediction of earthquakes and most seismologists believed that it is only question of time before we would be able predict the location, timing and occurrence of strong seismic events. Stefan, with his engineering common sense and excellent understanding of physics of rock fracture, never fell into this trap.

Essentially, the book consists of three parts. The first one serves admirably as an introduction to mine seismology and outlines basic principles of the instrumental monitoring of induced seismicity by mining. It continues with an outline of its development in South Africa and introduces basic seismic hazard parameters of seismicity such as seismic moment and energy. The second part, my favourite one, describes in detail, the history and development of cave mining, associated induced seismicity as well as the history of the Phalaborwa cave mine, one of the biggest open pit mines in the world. The last part is a comprehensive survey of all the possible aspects of caving mine processes and the assessment of seismic hazard. This part of his book Stefan calls “future” and indeed it elucidates what 10 years of extensive experience gained during the mining of the mine’s Lift 1 can, and should be used in the future, particularly during the excavation of the new mine, which will be located about 400 m below the present one.

This book is written by a practitioner for practitioners. It presents the basic principles of mine seismology, the principles of cave exploitation and most efficient procedure of seismic hazard assessment in mines.

Does the book have weak points? Only one. The book is largely based on its author’s experience of seismic hazard assessment for the Palabora mine which is located in the edge of Kruger National Park. Not long ago I visited the mine and the biggest impression left on me was not the massive, massive size of the pit, but rather the elephants walking freely over the wide expanse of the mine. It would make the book significantly more exciting if in addition to the many informative illustrations already there, the author would add a picture of these amazing animals as they cross the reaches of the vast pit at sunset.

Andrzej Kijko

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Chapter 1
Introduction

To start with I was planning to document the South African copper mine Palabora Lift 1 Mine history as evidenced by the recorded seismicity. With time concept of this book changed. From being only a seismic history of a cave mine the book concept evolved into something more complex. This book has three parts. First part is about seismic source parameters, what they mean and about their limitations. This part explains what can be and what can not be done with these parameters. The second part of this book is a seismic history of a cave mine. It describes the caving process from the beginning to the end. This part describes the past. The third part is about the future. Having over 10 years of data (not only seismicity) it seems reasonable to assume that it should be used for the future mine that will be developed below the present one. The underground mine called in this book Lift 1 is located 400 m below the open pit bottom and 1200 m below the surface. A new mine will be developed about 400 m below the present Lift 1 Mine. This will be Palabora Lift 2 Mine.

What I had written is based on my over 40 years personal industry experience. This book presents my subjective opinions that are far-off the objective and neutral manner of presenting science. The form of this book is more of a professional diary than science documentation. I have joined Palabora Mine after being a seismologist for more than 10 years at deep gold mines of the Klerksdorp area. At Palabora Lift 1 mine I have spend more than 10 years. I joined the mine before the caving process was initiated and were still there when the caving process came to its end. I have had described using the recorded seismicity the complete caving process milestone after milestone as they took place. It is not possible to live a professional life with no contact with people. These people in this case would be the work equals and managers. These relations in many ways influence the professional accomplishments and often lead to failure. For example I know that my employment at Palabora Mine was against the wish of the general manager. He did not think that a seismologist can help with production, development or safety. I am not commenting this attitude or why it was there. He changed his viewpoint when analysis of the recorded ground motions permitted for continuous underground mine development

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while blasting in the open pit. For the manager this was simply money. He become an enthusiast of mine seismology and contacted me a couple years later with a problem when he was a manager at a different mine on a different continent. But the next manager that came after him was not to happy to have a seismologist at the mine. You can be the best in your profession but you still need luck. It happened to me on several occasions. One was when during February 2003 I insisted that the crown pillar has failed sometime by the end of 2002. This pillar between the cave and the open pit was at that time still 200 m thick and was there to stop the rain water getting into the mine and for the safety of the open pit miners. My analysis was based on the recorded seismic data. Mine management called in several consultants who agreed with my findings. Still reservations stayed as no one could substantiate my findings directly by looking into the rock mass of this pillar. That is were the luck struck, there was a heavy rainfall and the water was recorded underground in a couple of hours not days as it would be expected with a solid pillar. Some parts of the mine were flooded. Nature verified my interpretation results. This established my reputation as well that of the mine seismology. From then on I was permitted to try some new concepts even if some of them required capital. My aim was to improve the seismic network sensitivity by installation of four geophone probes in a 400 m deep borehole. I had put on paper all technical requirements and that the work should include geophone installation and then grouting of the borehole. This went into the system and after being signed at all required power levels moved on for tender. Next after a couple of months a contractor with a drilling rig appeared at the mine. After he started to drill it appeared that he became a famous target for safety inspections. These inspections were carried out according to the company safety policy. Every one had the right to approach the drilling site and then enquire about safety measures and then propose his improvements in this matter. It did not matter if this person had any idea about drilling. The main objective of this exercise was to fill in a special form and give it to the manager. One had to collect so many of them for every appraisal that influenced the salary increases. Because of this the driller wanted to finish the contract as soon as possible and leave the mine. When he reached this state of mine I asked him about installation of the geophones and grouting. His answer was surprising. His contract was only to drill a 400 m deep borehole. He then produced his contract. He was correct and his contract was signed by the mine administration manager. Who knows better the administrator or the technician? Administrator did not see any problem with installation of the geophones in the borehole and then he knew that it would be enough to send a man with a bucked of cement to complete the grouting. The driller did not want to hear about any additional work. So I had no alternative but again to go through the administration requirements to get the work out for the new tender. Then I was become lucky but not the driller. The drill bit got lost in the hole and it turned out impossible to recover. At this stage the hole was more than 350 m deep. The driller asked me what now so I told him that he must move the drill and start drilling the 400 m borehole as it is in the contract. At this point the driller was ready to negotiate. He installed the geophones and grouted the existing hole.

This book has three parts. First part is about seismic source parameters, what they mean and about their limitations. This part explains what can be and what can not be done with these parameters. The second part of this book is a seismic history of a cave mine. It describes the caving process from the beginning to the end. This part describes the past. The third part is about the future. Having over 10 years of data (not only seismicity) it seems reasonable to assume that it should be used for the future mine that will be developed below the present one. This is a very specific application of the past into future as it involves not some mine located somewhere in the world which is mining some other mineral using a different mining method. Here I need to explain that Palabora Mining Company (PMC) was a cave copper mine. The underground mine called in this book Lift 1 is located below the open pit. By the end of 2013 the owner of the mine changed as did the mines name. Now it is Palabora Copper (Pty) Limited. Sometime during 2015 development of a new mine will start about 400 m below the present Lift 1 Mine. This will be the Lift 2 Mine. In this book I am also using a more general name for the mine, Palabora Mine. This name brings together the open pit mine the Lift 1 and Lift 2 Mines regardless of their owners who in the end as this book is concerned are of no importance.

The book starts off with the history of mine seismology. This history is not about hardware or software development but about interpretation and practical applications of the recorded seismicity analysis. This is described in Chap. 2 and the presented facts indicate that understanding and based on scientific principles analysis of recorded seismicity resulted in practical rock engineering concepts that in consequence improved safety and mining. This is what mine seismology is about. This took place in the age of analogue technology before the digital networks were invented. Practical outcomes of that pre-digital mine seismology are valid and practiced at present. This establishes the intention of this book, which is to demonstrate that it is possible to make good use of the recorded seismicity. The scientific approach has a logical starting point. My book starts with considering what it takes to understand the input data for analysis and interpretation. It seems to me that at present the concept of understanding the input data is not considered as important. The first part of the book which starts with Chap. 3 describes the physical meaning of the seismic source parameters. This is then followed in Chap. 4 by description of these parameter ranges as they are in the mine. This chapter ends with a comparison between real earthquakes and events experienced in mines. Here I have included some estimates of the released energy by a wide seismic magnitude range. Using seismic efficiency concept I have compared the released energy with TNT explosions and electricity demands of South Africa. Depending on the earthquake size its energy when converted into electricity that would be consumed in less time as it takes to blink an aye or could fulfil the nearly 300 years demand. Having described parameters the last chapter of part one deals with interpretation methods. This chapter also describes limitations of seismic data and of the interpretation methods. This is a very important part. In my professional life I have experienced that concept of data limitation is not understood or even not considered important. The presented limitations of the seismic data should not be seen as pessimistic but as a realistic description of the problem. It is still possible to analyse and interpret data which originated in the process of an educated estimate. And what more nothing prevents these analysis and interpretations to be correct. But not all interpretation techniques can be successfully applied to this type of data. Despite the fundamental limitations of the recorded seismic data they still are a source of valid information, not only about the mining but also about the surrounding rock mass in which the mining is taking place. The strength of this data is based on two factors: that it is taking place all around the mine and that there is a lot of them. The fact that there is a lot of seismic data available allows for implementation of specific interpretation methodologies that in turn compensate for the input data limitations. Seismic data on its own can be deceptive and for this reason must be supported by other data such as geology, mining or other relevant geotechnical input. It must be understood that all of the seismic source parameters are in some way related to each other. Even the seismic energy release and the seismic moment that are often described as independent of each other are in fact related to each other. Here the general relationship is directly proportional, the larger the energy release the larger will the seismic moment. The locations of seismicity in mines are not random but are directly associated with the mining and geology. This fact should help in finding logical explanations for the observed patterns of seismicity. The best locations and more reliable source parameters are for the events located inside of the network, that is when the source is surrounded by sensors (also above and below). All events that take place outside of the seismic network by definition will be poorly located and their calculated source parameters could be far from the accuracy of the source parameters of events locating in the network. If that is the case then one might ask a question whether there is any sense bothering with interpretations of such poor data sets. The answer is that an interpretation of such data makes sense but only with the use of proper techniques. One such interpretation method for example would be looking only at data trends ignoring their absolute values. Presented interpretation methods link the recorded seismicity with ore extraction from the developing, undercutting and caving operations. While the detection and seismicity recording itself is a reasonably simple matter, the data evaluation and its interpretation is a much more complex problem, which may result in several explanations for the same observation. However it is well established that seismicity in mines is related to mining conditions and excavation methods and for this reason it is possible to link seismicity with various parameters characterising the mining and rock mass conditions.

At Palabora Mine the seismic system was separated from the Rock Mechanics Department and classified as a cave monitoring tool and consequently the seismic system became part of the Cave Management Section. In result the seismic monitoring priorities were clear, resulting in planning, testing and implementation of interpretation methods specifically for the purpose of cave monitoring and its management. Second part of this book starts with Chap. 6. In this chapter there is a description of the Palabora Mine seismic recording system as it was when I arrived at the mine. The following upgrades are discussed together with their influence on the quality of the recorded data. In the further part of this chapter I describe how in real time I have reported the caving progress. Firstly it was the stress caving process initiation followed by the central pillar failure and then its break through into the open pit. Seismic monitoring during production stoppages allowed for estimating the air gap size at the top of the cave. At the time this was very important as every manager at the mine still remembered the tragic consequences of a large in size air gap at Northparkes Lift 1 Mine. The main part of this book is the Chap. 7 titled "Palabora caving process as evidenced by induced seismicity". Here I am illustrating how the seismicity was changing with the cave progressing from one milestone to the next one. The stress caving process was initiated in April/May 2002 and the caving process ended by the end of 2012. This chapter is backed by my experience from other cave mines as El Teniente, PT Freeport DOZ Mine or Northparkes Lift 2 Mine. The main value of all presented analyzes is how the interpretation results were achieved. For this reason some of the presented analysis is elaborate and full of details. This part includes the description the open pit North Wall failure. As it was spectacular it attracted a lot of attention. I was often asked if seismicity could be used to predict this failure. That there would be a failure it was expected but its size turned out to be a complete puzzle. It took a couple of years for the modelling research in the back analysis mode to come close to what has happened in reality. Caving process is associated with seismic hazard. It is possible to monitor its changes with the recorded seismicity. How I went about it is described in the next chapter, Chap. 8 titled "Caving process and seismic hazard". In this chapter there is a discussion on the subject of predicting or about the so called instability concept. This is done in a subchapter titled "Medium and short term seismic hazard assessments—are they possible?" When as a consultant I travelled from mine to mine I experienced the fact that a lot of senior Rock Engineering management were convinced that prediction (time, place and size) is possible and that it is already practiced at some other than theirs mines. This false assumption leaded them to formulate curious demands from their seismic staff. The most common was hoping that a certain and concrete value of the energy index could be a straight forward indication of a large seismic event taking place in a very near future. This magic number would then allow for evacuation of the underground personnel. They would get back underground to a safe environment after the event took place. Nice dream, but it doesn't take into account for example the fact that after stopping the mining process the seismicity declines dramatically. It then starts once the mining starts again. This is the experience from the gold mines, when the production was stopped due to a strike action. For this reason it was assumed that the safest mining would be continuous mining. The earthquake prediction concept in seismology was rejected and then exhumed several times. I will quote Richter who in 1977 had this to say about predictions: "Since my first attachment to seismology I had a horror of predictions and of predictors. Journalists and the general public rush to any suggestions of earthquake prediction like hogs towards a full through… (Predictions) provides a happy hunting ground for amateurs, cranks and outright publicity seekers. The vaporising of such people, are from time to time seized upon by the news media, who then encroach on the time of men who are occupied in serious research" (Mulargia and Geller 2003). The prediction concept as it was easy to foresee found its way into mine seismology. Supported by numerous gadgets of the digital technology it flourished and found supporters in the mining industry mainly using this concept for their public relations. We are doing (that is financing) everything what is possible to improve the underground safety. The other aspect of prediction in mine seismology is the fact that at least at present it is destined only for the privileged. In this way those who preach this belief for me are like the ancient Egypt priests. These priests were only serving their goods and did not have any interest in people as such. Common people were there only to support their life style and were expected not to ask for anything in return. The last chapter of the second part (Chap. 9) presents a riddle that for the first time I was confronted with when I was working at the gold mines. All was in place, good quality seismic system, and quality seismic data base and professional and experienced staff employed. The last years were good as the mining management was taking advice and had confidence in our data interpretation results. Unexpectedly the seismicity character changed. In practice one would expect that at this point in time the seismic response to the mining process has changed. This usually is bad news as it means change of seismic hazard. This was not the case. The reason was astonishing as it was the new seismic processing software. There were large differences in the seismic parameter values depending on the version of the software. This illustrated how dependent of the contractor the seismic source parameter values can be and really are. This also was a direct prove that their values are not the real thing. This problem repeated itself while I was working for the Palabora Mine. Chapter describing this problem is different from the others as it is not about using seismic data to monitor the caving process or the resulting seismic hazard. Here interpretation was to find what are the differences and then decide are they acceptable or no. In the end one wants to know which software to use that is to assess which one results in data that can be explained by application of basic physical rules To be honest I enjoyed this analysis as it was different from what I was doing more or less regularly. It was a case when I could use different approaches and have some fun.

The third part of the book is about what seismic experience gained during the Lift 1 caving process should be transformed to Lift 2 mine. Here observations based on data recorded during mining Lift 1 cave are analyzed to find out which ones would be valid for Lift 2 Mine This might give an impression that there is a lot of stuff that is a repeat of what was already presented in the second part. This is the way of going about the problem when the aim is to analyze the past for its application in the future. From the beginning of 2002 until the end of 2013 about 50 % of the recorded seismicity, released seismic energy and seismic moment took place below the extraction level. This seismicity at some stage migrated down to −1200 m. This elevation will be the future Lift 2 Mine extraction level. In Chap. 10 I have compared the seismicity recorded above the mine extraction level where the caving process took place and the rock mass was successfully mined out with that recorded below the mine. The rock mass below the mine will become Lift 2 cave. The main conclusion from this analysis is that the top volume of the potential Lift 2 rock mass is already de-stressed/preconditioned and fractured so it will cave rather than form an arch that will not cave resulting in the formation of a significant air void. Chap. 11 of the book deals with designing the seismic monitoring system for Lift 2 Mine. My understanding of a seismic monitoring system goes beyond its hardware, software, size, location accuracy or network sensitivity. These elements are important but they are not enough for the monitoring system to provide reliable information. The important element often not present is the professional team that is required for operating this system. Some mistakes were done that should be avoided in the future. For example because of installations taking place in stages the early seismicity was not recorded in all details and nearly two first years of the Palabora seismic data are of low quality. It also seems that to start with there was no clear concept for the seismic monitoring system. A great failure was that the system had no sensors located below the extraction level. This happened because at some stage after the initial break through the mine management was informed by the Rock Engineer that there is no further use for the seismic network. In the end it was decided to keep the system operational but no more money was to be spent on its development. The last book Chap. 12 takes advantage of the recorded and confirmed as bona fide seismic signature of the Lift 1 caving process for monitoring the Lift 2 caving process and related seismic hazard. A detailed and concrete proposal how to monitor and report these matters is given. Here a question arises. Will experience gained with Lift 1 be used while mining Lift 2 Mine? Well I am afraid that not. Lift 2 project team did not show any interest in the actual rock mass state of the Lift 2 cave which is described in Chap. 10. What more it asked for an assessment of preconditioning this rock mass volume by hydro-fracturing and blasting and its influence on the caving process. The consultant was from overseas and he did not know about the Lift 1 caving process. One would assume that the time difference between the initiation of the stress caving process and the time when the initial pillar failed and the cave broke into the open pit is some type of useful information. It is a fine supposition that the history can be used to improve matters in the future. In other words we cumulate experience and then use it in the future only to make it easier for us. My experience indicates that this not is the case. I witnessed cases when after the person retired the whole technical data bases disappeared with no trace. It was there somewhere on the computer but no one was left with its knowledge. In the end it disappeared when the computer become a relict of the past and disappeared into the abyss. This is a typical case of lost experience. As lately the mine changed its owners then the new staff will not even know what to ask for. I am not trying to say that with no experience from Lift 1 Mine there will be no Lift 2 Mine. On contrary Lift 2 Mine will be developed and mined providing the economy and prices will be right. It will repeat the mistakes done with Lift 1 Mine add new ones and this will influence not only the costs but unfortunately the work force safety. There is no way to quantify the past experience benefits. We just know that they are at least some. Its is the classical case when we know but can not back it with a value. An example from my life illustrating this problem: I have decided to get myself a solar geyser because I wanted to save on electricity costs. This geyser is in operation but I can not estimate my savings for the reason that the electricity prices went up (substantially) so the monthly payments are more than they used to be. Additionally I have no physical access to the electric meter and the readings I receive with the bill apart of the fact that they are mixed with estimates are for ever different time periods. Still I assume (believe) that if not for the solar installation my bills would be even higher.

At the end of the book in Appendix A there is a list of literature that refers to Palabora Mine. I have traced 48 such positions. Not all of them I managed to collect and read so not all are listed in the text. Second Appendix B is a press release dated 25th February 2015. It states that Palabora Mine received R9.3bn to build Lift 2. This will extend the life of mine until 2033. As there is no literature that would deal with interpretation of recorded seismicity then I hope that my book will fill this gap. What are available are theory and some papers describing only the interpretation results. There is no discussion on the input data quality or why a certain interpretation technique was applied. Finally one must ask himself if there is or will be something as quantitative seismology. The answer is really simple and is in the input data that is in the nature of the seismic source parameters They are not a result of measurement they are estimates. Estimates can be good or bad but we never will know how well or bad they represent the real phenomenon. So better forget about quantitative seismology and try to reach excellence in what is possible that is qualitative seismology.

Reference

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Chapter 2
Applications of Seismic Monitoring in Combating Rock Burst Hazard

Abstract This chapter describes the history of mine seismology. This history is not about hardware or software development but about interpretation and practical applications of the recorded seismicity analysis. It indicates that understanding and based on scientific principles analysis of recorded seismicity resulted in practical rock engineering concepts that in consequence improved safety and mining. This is what mine seismology is about. This took place in the age of analogue technology before the digital networks were invented. Practical outcomes of that pre-digital mine seismology are still valid and practiced at present. This establishes the intention of this book, which is to demonstrate that it is possible to make good use of the recorded seismicity. For this reason this book starts from the basis that is from what it takes to understand the input data for analysis and interpretation. It seems to me that at present the concept of understanding the input data is not considered as important.

Rock bursts and rock falls have posed a serious problem in gold mines of the Witwatersrand practically since the beginnings of the industry. Data on their incidence reveal that these events are the single most important cause of accidents and fatalities in gold mines. They also result in loss of production and of revenue. It is not surprising that these events have already for many years been, and continue to be, of great concern to the gold mining industry. Evidence of this is the fact that Government Committees were appointed in 1908, 1915, 1924 and 1964 to report on earth tremors and rock bursts. Despite the considered advice of those committees and continued efforts by the gold mining industry, the problem of rock bursts and rock falls remain as serious as ever, mainly as a result of the increasing extent and depths of mining. In the decade since 1964, there has been a growth in the science and practice of rock mechanics, for example: Hill and Dennkhaus (1961), Hodgson and Joughin (1967), Hodgson and Cook (1970), McGarr (1971), Steele and Ortlepp (1972), Salamon and Wiebols (1974), Spottiswoode and McGarr (1975), McGarr (1976a), Cook (1976), McGarr and Wiebols (1977) and Ortlepp (1978). However, by 1977 it was realized that most of the information which had been accumulated is dispersed throughout a great number of scientific and technical publications and in

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the proceedings of many conferences and some of the important practical issues concerning implementation have not been published or implemented in industry. For this reason it becomes necessary to bring together the scientific, technical and managerial knowledge regarding these problems. This has been done by the High—Level Committee on Rockbursts and Rockfalls, which was formed on the recommendation of the Research Advisory Committee of the Chamber of Mines of South Africa. This committee comprised of the Research Advisory Committee, the Technical Advisory Committee, the Association of Mine Managers and representatives of the rock mechanics engineers. This committee published in "An Industry Guide to the Amelioration of the Hazards of Rockburst and Rockfalls" (COMRO 1977). In this guide it was concluded, as far as seismic monitoring is concerned, that the use of seismic networks should result in:

1. Location of seismic sources
2. Indication of trends in ground behaviour
3. Planning and control of mining operations—providing the mechanics of rock bursts will become understood
4. Indicating areas which might be more active due to geological features or inherent stress

Today those objects are as valid as they were in the past.

2.1 Early Monitoring Facilities of South Africa

Before 1908 only a couple of tremors per year were known to occur in the vicinity of Johannesburg mines (Gane 1939). In 1911, a Wiechert seismograph was installed. This instrument recorded nearly 15,000 events, from 1911 to 1937. The first significant study of mine related tremors in South Africa started in 1939, when a surface array of mechanical recorders was installed. Those studies, despite their limitations, clearly showed the direct relationship between the face advance and seismicity (Gane et al. 1946). According to Finsen (1950), for the time period 1938–1949 over 29,000 mine tremors were recorded.

The first underground seismic system was installed in the late 1950s at ERPM (East Rand Propriety Mines) by Cook (1962). Using this system he was able to show, that most of the recorded events occurred in front of and close to the stope face. He was also able to classify the events roughly by size and based on this he concluded that only the largest of events resulted in rock burst damage. Joughin (1966) installed a nine seismometer network at Harmony Mine, Free State Gold Fields, from which he was able to show that not only did the seismic events locate in the reef plane and in the hanging wall, but that some events located along the dykes. He also observed that a small portion of events occurred a couple of hundred of meters above the reef in a sill. The importance of these first seismic observations was that they not only confirmed the close relationship between the mining and the seismic activity, but that the local geology played a major role in controlling the distribution of the events. They also indicated that mine seismology, even with limited knowledge, has a potential to provide management as to where an event would occur and the like hood of rock burst damage.

The next important seismological development was during 1970–1980 with the establishment of the Klerksdorp Regional Seismic Network in 1971 and its continuous upgrading, which started the wide-spread use of mine-wide networks for management information purposes. Studies from this network (van der Heever 1982) were directed at the relationships between the extensively faulted geology and the seismicity. The development by Brink (1978) of a single-station triaxial accelerometer unit for the location of micro seismic events opened a new era of mine seismology, viz. an attempt to predict larger events. Those developments established the potential for using seismic information for rock burst control management purposes. The majority of rock bursts in this area are associated with movement on major geological discontinuities. This type of mine induced seismicity for this region was recognized before 1981 and is described by several authors, for example van der Heever (1982) and Gay et al. (1984).

The Klerksdorp Regional Seismic Network was established in 1971 as a result of the abnormally high seismic activity observed during years 1960–1970. Some of those events resulted in rock bursts that caused several deaths and damage to underground excavations. Some damage to surface structures was also observed. The main objective of this network was to obtain some understanding of hazards associated with seismicity in the Klerksdorp area in order to introduce preventive measures. This network was a joint venture between the Chamber of Mines and the four mines of the Klerksdorp Goldfield; Vaal Reefs, Hartebeestfontein, Buffelsfontein and Stilfontein and it covered about 107 km^2. At the beginning (1971/1972), the network consisted only of five geophone stations. In 1973 the network was expanded to eight stations. During 1976/1977 another eight geophone stations were added. In 1982 the network consisted of 24 stations, and in 1988 it had already 29 stations, of which eight were surface ones, and the rest was located at depths up to 2700 m below surface. By end of 1988 I have investigated this network configuration for location accuracy (Glazer 1998). At that time the need for more accurate determination of location of the sources of mine tremors in general led to an increase in the number of stations in mine seismic networks. For this reason, optimization of the network configuration became a very important factor (Kijko 1977, 1978). This resulted in the development of methods and software which could test network configurations with respect to location errors. The area that was at that time covered by the Regional Network was large and amounted to over 300 km^2. For purposes of this study it was assumed that all stations are simultaneously operational, which in reality is never the case, the maximum velocity error is 250 m/s, the maximum error in the arrival time reading is 0004s and that the co-ordinates of the seismic stations are accurate. The analysis was made for an elevation of 2500 m below datum. The expected errors of foci locations were calculated in the XY plane and in the Z direction (depth). The analysis was done for two cases, firstly, when a seismic event triggers 5 stations, and then when it triggers 8 stations. This analysis indicated that most of the Vaal Reefs, Hartebeestfontein and Buffelsfontein areas had a maximum XYZ location error between 100 and 150 m, while the error in XY plane, indicated that most of the the Vaal Reefs, Hartebeestfontein and Buffelsfontein had good cover, with location error below 100 m. For the northern part of Vaal Reefs and southern part of Hartebeestfontein, this location error was below 50 m.

In order to verify the location accuracy and measure the seismic wave velocity five calibration blasts were made before 1982 in various areas, within the Klerksdorp Goldfield (van der Heever 1982). The result was that the network could reliably locate sources of seismic events with an accuracy corresponding to about 0.8 % of the seismic path lengths, providing corrections were made for waves travelling through the Ventersdorp lava and Transvaal dolomite. Those corrections were then calculated, and applied to surface stations.

The technical description of the network, as it was at the beginning of the 1980s is given by Scheepers (1982) and van der Heever 1982. From that time the network went through several upgrades and modifications. All the monitoring stations by this time were equipped with 14 Hz geophones which were installed as triaxal units in brass boats. In the case of underground stations the geophone probe was installed in a 5 m long hole drilled into the hanging wall. The analogue signal from the geophone was passed through amplifying and modulating circuits on the site, then through telephone cables along crosscuts, haulages and up the shaft to a transmitter located at the top of the headgear. This analogue signal was transmitted continually by V.H.F radio to the seismic office that at that time was located at Margaret Shaft on Stilfontein Gold Mine. The surface sites, located at remote locations were powered by solar panels. At the central processing office, the signals from 29 stations were collected, demodulated, filtered and then held in the processors memory buffers. All channels were then simultaneously monitored by a trigger circuit. The trigger was activated by simultaneous changes in at least five geophones. When a trigger impulse was given, a four second history of each channel was written into memory. The location of the event was then calculated from the first arrival times, which were read manually channel by channel. The event magnitude was then calculated from a duration scale, which was calibrated against magnitudes as reported by the Geological Survey, Department of Mineral and Energy Affairs, RSA (Webber 1988). The duration Klerksdorp Regional Seismic Network magnitude, M_{KRSN} itself, is given by the following relation:

$$M_{KRSN} = 1.45 \log D + 0.12$$

where D is the event duration in seconds.

It was common practice to correct magnitudes of those events that were also recorded by the South African Geological Survey Network to values as reported by them in their monthly Seismological Bulletins.

The source parameters of the events recorded by the Klerksdorp Regional Seismic Network were then estimated as follows:

The approximate moment was calculated using the formula (Hanks and Kanamori 1979):

$$\log M = 1.5\, M_{KRSN} + 9.1\, [Nm]$$

The approximate seismic energy was calculated using the formula (Gutenberg and Richter 1956):

$$\log E = 1.5\, M_{KRSN} - 1.2\, [MJ]$$

2.2 Application of Seismic Data in Rock Mechanics Practice

I have already proved that there indeed was mine induced seismicity monitoring taking place long time before the digital monitoring system was invented. Recorded data was then analysed interpreted and conclusions used for practical purposes. These applications are not only impressive but still valid and in use at present. This indicates that these who made them were researches of great calibre. This proves the case that one will always end with better results having a professional team and not up to date equipment in comparison to the case of second hand experts and the state of art hardware.

2.2.1 Applications Relating to 1970–1980

The original purpose of the Klerksdorp Regional Seismic Network was twofold:

1. Rapid and accurate event locations for prompt rescue and opening up operations.
2. Identification of seismically hazardous geological structures.

The aim was also twofold, to improve safety and productivity of the mines. With time the purposes of the seismic networks become more and more complex and included the following:

1. Identification of seismically hazardous mining situations in highly faulted ground
2. Establishment of criteria likely to result in seismically hazardous situations
3. Investigation of rock burst damage and its relation to focal mechanism of the event that caused it.

As early as 1973 a rock burst research project was formed by Anglo American Corporation in conjunction with the Mining Operations Laboratory of the Chamber of Mines of South Africa. The aim was to study all aspects of the rock burst and rock fall as encountered in deep-level South African gold mines and recommend approaches for the amelioration of the problem. During the first few years considerable progress was made in developing an understanding of rock burst and rock fall problems. In the next phase the project aim was concentrated on developing an understanding of the nature of the rock burst and the rock fall problem. The effects of energy release rate, geological discontinuities such as faults, dykes and joints and blasting were investigated. It then became apparent that a distinction should also be made between rock burst control measures and rock fall control measures as these constitute two essentially different problems. The findings of the Rockburst Research Project highlighted a basic difference between the nature of the rock burst and rock fall hazards (Lawrence 1977). It was found that the most suitable criterion for expressing the relative difficulty of mining on a particular reef or in a particular area is the spatial rate of energy release (ERR) due to mining. This single scalar quantity expresses the combined effort of the mining geometry, depth of mining, stoping width and some rock characteristics. The methods of calculation of the rate of energy release were described by Cook et al. (1966). It was found that the rock burst hazard is linearly related to energy release rate, whilst the overall rock fall hazard is apparently not so strongly related to the ERR and is more likely related to a combination of quality of support, stoping width, the mining method employed and the geological structure. From this it was concluded that control of rock bursts can therefore only be effected through a reduction of the average energy release rate, while rock falls, given a particular reef and mining method, can only be reduced by improving the quality of support. Those findings, even though only of a general nature, were valuable in making strategic decisions concerning the evaluation of mining lay-outs. The following conclusions were made at the time: In general, the so defined rock burst hazard is directly proportional to the energy released by mining. This implies that installed support of any kind does little to reduce rock burst frequency or energy and only serves to minimize the damage resulting from the rock burst.

In the linear relationship, rock burst hazard = k × ERR, the k value may vary widely from reef to reef, and from area to area on a particular reef. The k value can only be established from actual mining experience in the area or on the reef concerned. Once the value has been established this relationship should prove very useful in comparing alternative mining geometries for new mining areas. The overall rock fall hazard is not strongly related to energy release rate. In a given mining situation, the only practical way of reducing the rock fall hazard, short of changing the method of mining would be to improve the quality of support in the immediate vicinity of the working faces and gullies. By end of 1979 it was known that most mining induced seismic events are associated with geological discontinuities in the surrounding rock mass. These include dykes, faults, joints and bidding planes. The discontinuities represent planes of weakness and are therefore likely to fail first before mining induced stresses reach the high levels required for the fracturing of intact rock. Similar to the relations developed in global seismology that the maximum magnitude of an earthquake originating on faults is strongly related to the displacement on the fault, the following relationship for the Klerksdorp area was established (van der Heever 1978).

$$M = 0.32 + 1.88 \log D$$

where:

D is the fault throw in meters

M is the maximum Richter magnitude

From this relation it was concluded, that at least theoretically, the Kromdraai Fault with its 800 m displacement can become a source of a magnitude 5.6–5.8 event. In general, from this type of relation it could be concluded that very large rock burst are possible only where large displacement faulting exists. An important observation concerning the intersection of dykes and faults was made (Heunis 1977). It was found that these intersections act as point stress concentrations and generate small seismic events at a distance of few hundred meters away from an advancing face. For this reason it was concluded that this phenomenon manifesting itself strongly during the early stages of mining could be used to delineate dykes and faults before mining approaches them. This additional information could result in reduction of the rock burst and rock fall hazard when used for mine planning.

As far as geological discontinuities are concerned the following was concluded:

1. Large displacement faulting (40 m +) presents special rock burst and rock fall difficulties in that the risk of very large seismic events is considerably amplified by the presence of these faults. Little is known about methods of preventing the occurrence of these very large events.
2. In planning new longwall systems, the effects of known dykes and small faults in the proposed mining area can be fairly accurately estimated in terms of the rock burst and rock fall hazard as well as production. Allowance can also be made for the presence of dykes striking perpendicular to the direction of longwall advance.
3. In the case of slight faulting, it was estimated that the contribution of these geological discontinuities to the rock burst and rock fall hazard can be reduced by ensuring that long wall shapes are more or less maintained. In deep-level mines this additional effort would therefore appear worthwhile.

Advances in seismic recording systems have resulted in the development of highly efficient location techniques. These systems if introduced on new mines at a very early stage, preferably before actual mining commences, could prove extremely valuable as a strategic planning tool by revealing the presence of major geological discontinuities long before they are exposed by mining. At the same time a lot of effort was put into the study of the relationship between blasting and seismicity, for example (O'Connor 1978; Lawrence 1975). It was found that a significant number of recorded seismic events on a mine are associated with enlargement of excavations. If it is assumed that most of the mining induced seismicity is closely coupled to the actual enlargement of the stoping excavations, then continuous mining will distribute seismicity more uniformly in time, resulting in a likely increase of seismicity during shifts. Blasting in one area of a mine was found to increase rock burst probability elsewhere, depending on the distance and amount of blasting. This is of importance where adjacent mines blast at different times and would complicate the use of scattered blasting methods for reducing ore surge capacity requirements in deep level mines. The exact sequence of blasting between various sections using a centralized blasting system does not appear to significantly affect seismicity on later shifts. For instance, synchronized blasting is neither expected to aggravate nor alleviate the rock burst safety hazard of later shifts. The important factor is to minimize the exposure of people in stopes while blasting takes place in the vicinity. Optimum re-entry periods vary from reef to reef. Development of effective rock burst control strategies should on the one hand improve the safety at the underground working places in general, but on the other hand, should lead to limiting the occurrence and effects of single very large rock bursts. Reduction in the energy released by mining can be achieved by introducing partial extraction methods, by back filling or by reducing the stoping width in extensively mined areas. Design criteria and the advantages and disadvantages of various mining methods using partial extraction have been looked into with great of detail, for example in Cook et al. (1966), Salamon (1974), Wagner (1975, 1976) and Salamon and Wagner (1979). In deep-level mines with longwall mining the introduction of reef strike pillars spaced regularly along the entire length of the long walls proved, at the time, to be the most effective method of reducing the energy released by mining.

In the late 1970s and early 1980s it was hoped that the wide introduction of seismic networks into deep gold mining will result in the following:

1. Rock burst prediction, understood as identification of sites where rock bursts are going to take place in matters of hours so that evacuation of workers will be possible (Brink 1978)
2. Understanding of the interaction between induced and geological discontinuities and its relationship to the stability of the fracture zone surrounding the underground excavations
3. Development of seismic methods for delineating dykes and faults ahead of mining excavations for long term planning.
4. Understanding of the violent failure of large faults and dykes subjected to mining induced stresses.

2.2.2 Applications Relating to 1980–1990

Several years of recording and analysis of mining induced seismic events led to the quantification of the relationship between seismicity and parameters that control them. In general there are two types of such parameters, mining and geology. There are several mining parameters which influence seismicity, and those are, depth of mining, blasting, area mined and rate of extraction. It is assumed that seismicity increases with depth of mining. This relationship is difficult to quantify probably because of the influence of geological factors. Coal mining, which in South Africa is very shallow (100–300 m) does not generate any significant induced seismicity. The relatively shallow Rustenburg platinum mining region (800–1200 m) which is situated in an area which experiences a moderate level of natural seismicity has only several mine induced events in the ranges 2.0–3.0 magnitude annually. Evander and West Rand mining areas, which are deeper (1200–1600 m) are more seismically active, but events above magnitude 3.5 are not very frequent. The deeper mines (2200–2600 m) in the Orange Free State and Klerksdorp Goldfields experience irregularly spaced events that exceed local magnitude 4.5. The ultra—deep mines of the Far West Rand (below 2500 m), region generate relatively high levels of seismicity. The events are regularly spaced in time and their magnitudes are in the range between 2.5 and 3.8.

During the time period 1971–1990 the Klerksdorp Regional Seismic Network recorded about 15,000 events. All those events occurred within the mining boundaries. This is an indication that all those events are mine induced. According to van der Heever (1978) who investigated the relationship between blasting time and occurrence of seismic events, there is a substantial increase in the number of small events directly after blasting. Large events tend to be independent of blasting and take place at any time of the day. I have studied (Glazer 1997) the time distribution of seismic event occurrence in relation to the time distribution of released seismic energy. It was found that the distinctive peak in number of recorded events starts at 14h00 and ends at about 18h00 and that it is directly connected with the blasting time. This is illustrated by Fig. 2.1. The distribution of seismic energy released per hour does not correlate with the number of events per hour. This is illustrated by Fig. 2.2.

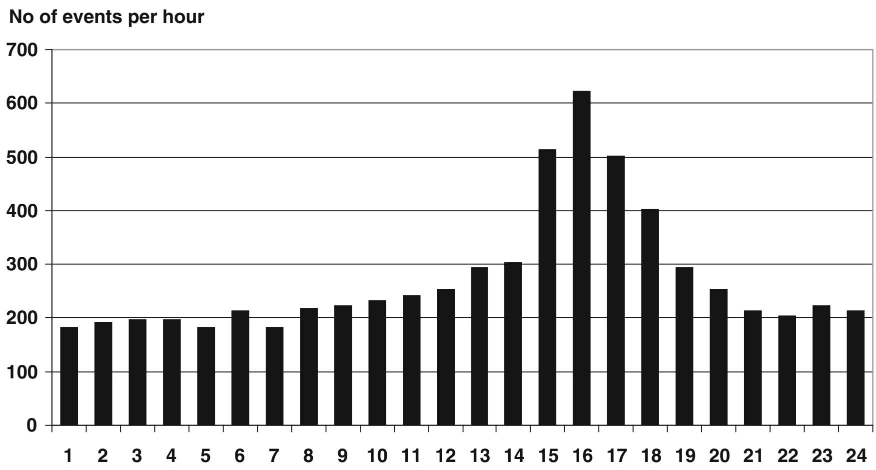

Fig. 2.1 Time distribution of recorded seismicity

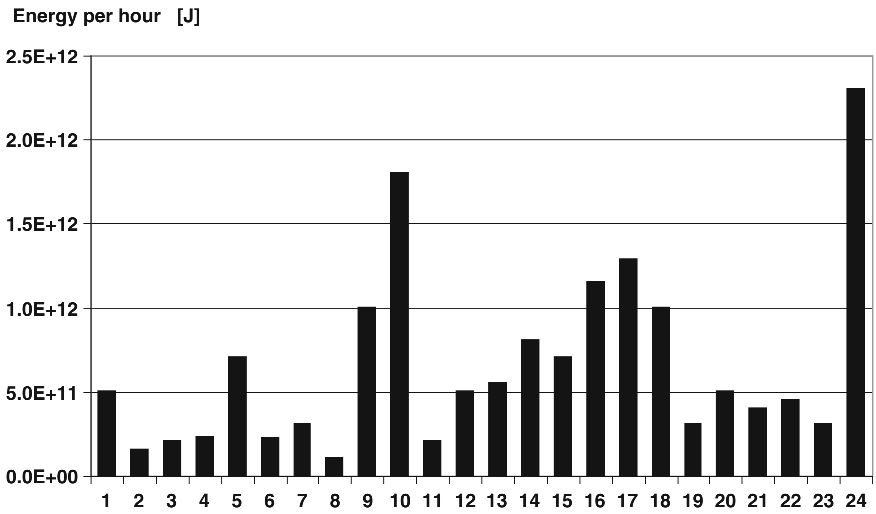

Fig. 2.2 Distribution or seismic energy release

While the peak number of events per hour correlates directly with the blasting time, the peak amount of energy released per hour comes 7 h later, between 22h00 and 23h00. There are in fact three distinct peaks in the energy distribution. The first one coincides with the peak of the number of events per hour, between 15h00–16h00, the second one between 20h00 and 21h00, which is twice as big as the first one, and the third and main one between 22h00 and 23h00 which is about 5.5 times as big as the first one. From the above analysis it was concluded that blasting on its own triggers a lot of events, but most of them are relatively small ones. While their number is high, a low amount of released energy is associated with them. It seems that there is some kind of ageing period of about 7 h, after which the high energy release events occur.

According to Gay et al. (1984), there is a good correlation between number of events and the total area mined (for data relating to 1971–1981). From the plot of cumulative energy released by seismic events against centares mined, a very interesting conclusion was made, that the occurrence of big events seems to be independent of mining activity. At that time, the relationship between rate of advance and seismicity was not defined, but it was regarded as good mining practice to keep it constant and not to advance beyond the normal stress induced fracture zone. As far as stoping width is concerned it was known that it influences mine seismicity due to the fact that the amount of seismically radiated energy is dependent on the elastic closure. The relation (McGarr 1976b)

$$Mo = G \cdot V$$

where:
Mo is seismic moment
V is volumetric closure (area x stoping width)
G is modulus of rigidity

states, that if a mined-out area would be subject to total closure, then doubling of the stoping width, would result in a two fold increase in seismically radiated energy. Regional support such as barrier pillars or backfill result in reduced elastic convergence and for this reason lower the amount of released seismic energy. Webber (1989) investigated the seismic deformation due to mining for the four mines of the Klerksdorp area. He used the following relationship,

$$\Sigma \text{Mo} = \gamma \cdot G \cdot \Delta V$$

where:
Σ Mo is cumulative seismic moment
G is modulus of rigidity
ΔV is volume change due to mining
γ is factor between 0 and 1

The value of γ was then evaluated for individual mines and for the whole district. It was found that the value of γ varied over individual shafts and production areas, but was relatively constant over the individual mines. It was then concluded that mine values of γ are dependent on the age of the mine and the ratio of the mined to un-mined area. More interesting findings resulted from the attempts to evaluate the γ values for individual production areas. In this case it was found that those values varied very much from area to area. The conclusion was that mining in one area influences the seismicity of another area.

Rock bursts in the Klerksdorp area have two main sources. The first is due to shear movement on faults, and the second are associated with highly stressed dykes, (van der Heever 1982). More than 10 years of recording seismic information allowed for the following observations in regard to faults:

1. Large events are usually associated with normal faults with throws between 10 and 200 m
2. Faults with throws of less than 10 m have events of lower magnitude
3. Fault planes with intruded dykes are more hazardous
4. Planar, regular and extensive faults planes are more hazardous than curved, splayed or composite ones
5. Dilatated fault planes with well defined contacts are more hazardous than multiple fault zones
6. Susceptibility to slip is unrelated to fault strike orientation
7. Events are biased towards the hanging wall of the reef in the up-throw block, and toward the footwall in the down-throw block.

The above observations, based on seismic monitoring, led to the development of strategies for mining near seismically active faults that can be summarized as:

1. Mine panels adjacent to the fault plane first
2. Keep adequate sidings and more intensive support near the fault
3. Gullies should be footwall lifted
4. Avoid excessive lags or leads
5. Final remnants must be remote from fault
6. Use pillars to clamp faults
7. Minimize fault exposures in service excavations

Dykes and sills have a significant influence on seismic event and rock burst distribution. Several studies have been done on the incidence of rock burst and seismic events for stopes which traversed dykes, e.g. Gay and Jager (1986) and Roberts and Brummer (1988). The results indicate that a substantial increase in the number of seismic events occurs when mining faces are within 30 m of a dyke. It was found that there are several factors that influence the seismicity levels on the dykes. The width of the dyke is an important parameter. Dykes which are up to about 5 m thick are too small to store large amounts of strain energy and usually do not become sources of large seismic events. On the other hand, very thick dykes, (above 60 m) are sufficiently large to render the strain energy in a stable pillar. It was found that the type of dyke is very important. Soft, weak and decomposed dykes are less seismically active than the strong, brittle fresh types. Well jointed blocky dykes are seismically less active than the intact massive ones. Again due to active seismic monitoring, the above observations allow for the development and implementation of the following mining strategies:

1. Avoid mining breast-on towards a dyke
2. Keep the number of dyke pillars to a minimum
3. Do not extract dykes with a lagging face configuration
4. Minimize the length of face which is within a dyke
5. Do not site vulnerable excavations in dykes
6. Leave reef pillars if stresses in the dyke exceed 60 % of UCS (uniaxial compressive strength)

Publications on the rock burst phenomena and methods of combating the rock burst hazard in deep gold mines in the 1980s are numerous, some of which are, Wagner (1984), Ortlepp (1983, 1984), Rorke (1985), Hepworth (1985), O'Ferrall (1986), Spottiswoode (1986), Roberts (1986), Gay (1986), Ryder (1986) and Gay et al. (1988). It is worth mentioning that this and other research work in regard to rock burst were used to complete "An Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts." This guide was published by the Chamber of Mines in 1988 (COMRO 1988b) and was then implemented in all gold mines of South Africa.

The network in the Klerksdorp area that was started in 1971 was established in order to understand the hazards associated with seismicity in order to introduce some preventive measures. By early 1980 it was known that all large magnitude events in this area were related to geological features. Several hazardous faults and dykes were identified that were associated with large seismic events van der Heever (1984) and the influence of geology on the seismicity is described by Potgierter and Roering (1984). This resulted in the application of several support patterns and changes in mining sequences around those faults. Additionally, some protective actions for service excavations passing through those features were taken. A comprehensive summary of the strategies for combating rock burst hazard based on seismic information gathered in the Klerksdorp area is given for example by Gay et al. (1984) and O'Ferrall (1986). Seismic information was also used for planning and mining shaft pillars, for example Emmenis and O'Ferrall (1971), Taljaard (1992) or van der Heever and O'Connor (1994). The system was capable of informing management where the event took place in matter of minutes. This information was vital in the case of a large event and was used to start the rescue action, almost immediately in the area of concern. The number of recorded events increased in years due to the increase of the number of stations and varied from 40 to over a hundred per month. By 1989 it was accepted that the Klerksdorp Regional Seismic Network suffered the basic limitations of analogue transmission. All attempts to calibrate the system have been unsuccessful. However, studies of first motions recorded after big events resulted in reliable fault plane solutions. This gave information about the focal mechanisms of those events; van der Heever (1982), McGarr et al. (1989) and Rorke and Roering (1984). By the beginning of 1990, significant progress was made not only in development of hardware for seismic networks, but also in extracting source parameters from recorded seismograms. But the most important progress was made in the use of seismic source parameters for evaluation of underground hazard.

Starting in the 1970s, significant contributions to mine seismology studies have been made by the staff of the Bernard Price Institute of Geophysics, University of the Witwatersrand, Johannesburg. The results of research work of that time can be found in McGarr (1974, 1976a, 1981, 1984), McGarr et al. (1975, 1981, 1982), McGarr and Green (1975), McGarr and Wiebols (1977, 1978), Spottiswoode and McGarr (1975) and Spottiswoode (1980). Knowledge obtained from these seismic studies was then used for the design of rock burst support. This was done by Wagner (1984) when he used the ground velocity to analyze damage patterns of a number of seismic events. From this analysis Wagner was able to recommend improvements to support systems which were used at that time in stopes and tunnels. Studies of seismic data from the Carletonville area area have been concerned with both mine-wide data, for example Spottiswoode (1984, 1990), Hagan (1990) or, Lenhardt and Hagan (1990), and micro seismic data, for example Cichowicz and Green (1989), Cichowicz et al. (1987, 1988, 1990) or Green (1984). Contributions towards a better understanding of source mechanisms of mining induced seismic events also came from other parts of the world, for example, from Poland where a number of works have been published by the members of Institute of Geophysics, Polish Academy of Sciences, Warsaw. Examples of these are Teisseyre (1980), Gibowicz (1984, 1986, 1990a, b), Gibowicz et al. (1991). Other regions that made significant contributions is the Polish coal district, for example, Dubinski and Dworak (1989). All these and other contributions were then summarized in a book by Gibowicz and Kijko (1994) "An Introduction to Mine Seismology". The accumulated experience from several mine networks, Lawrence (1984), Brink and Mountford (1984), Waldeck (1988), Mendecki et al. (1990), Flannigan and Hewlett (1988), van der Heever (1989), Patric and Kelly (1988), COMRO (1988a), Hewlett and Flannigan (1989), Brink (1990), made it clear that the time of analogue technology in this application is over.

By the end of 1988 mine management was expecting from the seismic system the following (Glazer 1998):

1. Identification of seismically hazardous structures for strategic planning, sequencing and adequate support implementation
2. Recognition of seismically hazardous areas for implementation of adequate strategies to combat risk
3. Assessment of seismic source parameters for planning guidelines, for example for situating pillars along an active fault or for support design
5. 24 h management information service, for rescue and opening-up operations
6. Data base that can be used for planning purposes. For such a data base to be of use for rock engineering purposes it must contain not only accurate information in regard to locations of big events, but also of all small events lets say of magnitudes down to 0.5 (that was the requirement at the time, as far as sensitivity of a regional network is concerned). It must also contain as accurate as possible source parameters of those events, calculated from good quality seismograms.

The above requirements could not be fulfilled any more by an analogue seismic system. The Klerksdorp Regional Seismic network had to be upgraded to a digital system (Glazer 1997). In April 1989, the Klerksdorp Mine Managers Association (KMMA) gave its approval to implement the necessary upgrading. At that time, it was also agreed to reallocate the network itself, from its present remote location at Stilfontein GM, to a more central site at Vaal Reefs. The new location of the Klerksdorp Regional Seismic Network was chosen for two reasons. First for technical reasons, if the network was to expand, its number of stations had to increase. A centrally located site is best suited for radio communication purposes. The second reason, which from today's perspective, is much more important, because recent advances in communication systems have made the first reason redundant, was to situate the networks central site as close as possible to the Rock Mechanics Department, van Wyk and Coggan (1990). 2 years after the reallocation, the network and its staff became a section of the Vaal Reefs Rock Mechanics Department. This integration was a natural process, and indicated that seismic information became a more and more important part of the rock engineering recommendations. The new site was located close in the same building as the Vaal Reefs Rock Engineering main offices.

Figure 2.3 illustrates the fact that due to the continuous network enlargement after installation of the digital system by mid 1990 the number of recorded seismic events started to increase. This increase was obviously in number of small size events below magnitude 0.0. According to data presented by this figure the monthly

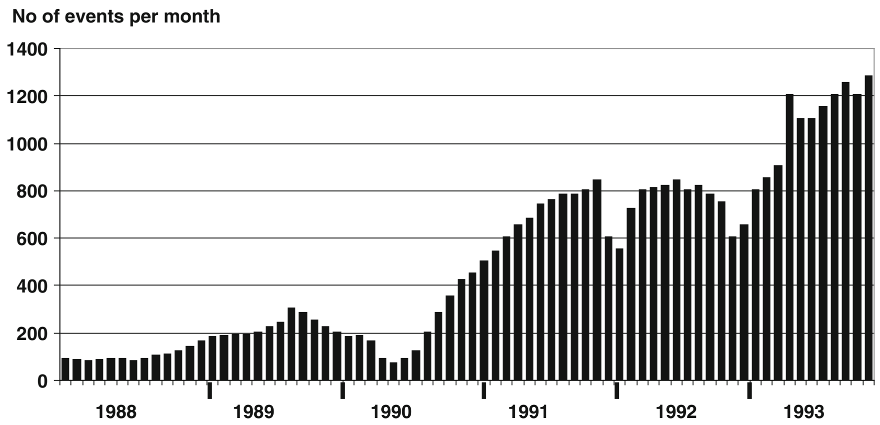

Fig. 2.3 Seismic activity rates between 1988 and 1993

activity rates increased from less than 200 events per month (1988) to nearly 1200 by mid 1993. In June 1997 there were 97 stations operational while another 33 were in different stages of installation. At that time the recorded number of events increased to about 30,000 events per month. This resulted in two problems that had to be addressed:

1. Capacity to process the recorded data
2. Data interpretation

The first problem was mainly manpower and at that time was solved quickly. As from June 1994 the seismic central site was manned 24 h a day, on a 3 shift basis. This resulted not only in improved quality of recorded seismic data, but more importantly, all events of damaging potential were immediately reported to the shafts. This allowed, when required, to send proto teams with no delay, or start the opening-up operations directly at the affected areas. The second problem was more complex as it required not only more of well qualified manpower but also development of new interpretation techniques that could cope with large amounts of seismic events (Glazer 1999).

2.3 Summary

Digital seismic recording systems started to operate in the mines during early 1990 years. Their main and undisputed contribution towards mine seismology was increased amount of recorded seismicity. Some researches claim that this recorded seismicity is of improved quality when compared to older data that was recorded with the analogue technology. In my opinion this is questionable. This becomes obvious when trying to list something new due to digital technology in the field of seismic data interpretation that wasn't done in the past. The success of seismic data interpretation should be measured in its contributions into rock engineering practical applications for combating rock bursts. Nothing really new in this matter happened during the last 25 years. All principles of mining in seismically active rock mass volumes are the same as 25 years ago and there are no new ones. It is accepted as true that the better understanding of the seismic source the more efficient anti rock burst measures can be applied. For this reason research into mechanics of the seismic source continues but with no practical results. Why is that so? The answer seems to be hard to believe as the issue is the digital technology itself. More precisely the problem is the general trust in the recorded data. It is considered not only of superior quality but deemed to be genuine in describing the seismic source. In my over 25 years practice in mine seismology I don't record any analysis of the input data and of what in reality are the seismicity parameters. This at present is considered to be of no importance. This indicates that at present the understanding of interpretation input data is generally not considered to be an important issue. It was definitely important before the digital seismic systems came to operate on the mines.

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Chapter 3
Seismic Parameters and Their Physical Meaning

Abstract This chapter describes the physical meaning of the seismic source parameters. Earthquake source parameters were derived over a long time period in order to get first of all a measure and then a better understanding of them. With time, seismology was introduced to the mines and it was found that there was a lot of similarity between the large earthquakes and the smaller size seismic events recorded in mines. Spectral analysis has become a standard technique used to estimate the source parameters of seismic events recorded by mine digital seismic networks. Simple source models of circular dislocations are used for the interpretation of seismic spectra and for the purpose of deriving source parameters. Seismic moment, corner frequency and seismic energy are inverted from the spectra that are corrected for the instrumental, distance and attenuation effects of each waveform and then averaged. Seismic source parameters are not measured, they are estimated. There is a difference between a measurement and estimation. Understanding these differences results in understanding the limitations of the source parameters. The reliability of seismic data is low. It is my experience that most or a lot of its users do not realise that the seismic source parameters they are using for interpretation purposes are only estimates. Their values are not derived from a process of a measurement. The reality is that the seismic source parameters are just an educated guess.

Earthquake source parameters were derived over a long time period in order to get first of all a measure and then a better understanding of them. “And there was trembling in the host, in the field and among all the people. The garrison and the spoilers also trembled and the earth quaked, so it was a very great trembling” (Samuel 17). There are numbers of earthquake descriptions in the Bible and this one very well describes the predicament with the problem of measuring them. This description gives the following information: that there was an earthquake and that it was not only felt by people but also has resulted to some change to the ground around them. But no one was able to compare it to the last one or use it as a measurement for the next one. To stay with the problem of earthquake origins they

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did not seem to be very complicated and ancient myths and popular believes provide a variety of reasonable origins for the earthquakes:

- Xhosas believed that there is a snake under the ground and that when it moves the earth shakes
- The western world had Atlas with the world on his shoulders, every time he moved the earth shook
- The Indians believed that an elephant carries the world on his back and that every time it went for a wee the earth shook
- The Japanese believed in a large cat fish under the ground that shook the whole earth and a small cat fish that caused the after shakes.

The Japanese earthquake theory seems to be the most advanced one as it accounts also for the aftershocks. This just proves that long time ago before modern technology and knowledge became available people were able to make scientific observations and make the right connections. The origins of seismology are probably in China. The first instrument to record an earthquake was constructed in China by Chang Heng. As this story took place before I was born I do not know if true or not but it is interesting. Chang Heng an astronomer and a man of many talents constructed the first seismograph in year 132 AM. It was in shape of a wase with eight dragon heads. These eight dragons in their jaws held balls. Below were eight frogs. Inside of the wase there was a mechanism that when put into motion by a seismic wave would hit the dragon, the dragon would loose the ball which then would be cought by the frogs open mouth. Which dragon would be waken up would indicate the direction from where the wave came from. The falling ball would make a noise and this would indicate the shock arrival time. Just think having a network of these seismograph would allow for locating the source. The story goes on that one day this device was triggered by a earthquake located far away. The day of Chang glory came when a couple of days later a messenger arrived from some remote side of the country with an information about a large earthquake. It seems that Chang Heng's seismograph was not only a measurement instrument but a work of art. It would be difficult to construct something like this today as there are no more dragons around and not every engineer has seen a frog. The early history of seismology is described by Bullen and Bolt (1987) and I refer anyone interested to their book "An Introduction to the Theory of Seismology". I will only add that seismology as a lot of other sciences benefited from the cold war. A lot of money and resources were given to monitor the nuclear explosions, nuclear submarines or movement of armored divisions on the ground. So by the end of the cold war in the late eighties it was already well developed and with a lot of professional staff. According to Gibowicz and Kijko (1994) seismology found its way into mines at the beginning of XIX century at two remote of each other mines one in Germany and the other in which in future will become South Africa.

The first seismological observatory was built in Bohum, Ruhr in Germany. It was established in 1908 and was operating until the Word War II started. During

1910 a single seismograph was installed in Witwatersrand gold field in South Africa. First seismic network was installed during 1920 at Rozbark Coal Mine located in the Upper Silesia Coal Basin. It had four stations of which one was located underground. Apparently this network was still in operation during 1994. As mentioned in the previous chapter the first seismic network with five seismographs in South Africa was installed in Witwatersrand during 1940. The KMMA Regional Seismic Network in Klerksdorp started to operate during 1970. I joined this network in 1982 and was then responsible for its management until 2000. KMMA stands for Klerksdorp Mine Managers Association.

With time, seismology was introduced to the mines and it was found that there was a lot of similarity between the large earthquakes and the smaller size seismic events recorded in mines. Spectral analysis has become a standard technique used to estimate the source parameters of seismic events recorded by mine digital seismic networks. Simple source models of circular dislocations are used for the interpretation of seismic spectra and for the purpose of deriving source parameters. Seismic moment corner frequency and seismic energy are inverted from the spectra that are corrected for the instrumental, distance and attenuation effects of each waveform and then averaged. Seismic source parameters are not measured, they are estimated. There is a difference between a measurement and estimation. Understanding these differences results in understanding the limitations of the source parameters. This is then very important for successful interpretation of seismicity. It is worth mentioning after Gibowicz and Kijko (1994) that "early attempts to apply the spectral theory of a seismic source to seismic events induced by mining (Smith et al. 1974; Spottiswoode and McGarr 1975; Gibowicz et al. 1977; Hinzen 1982) have shown that simple source models in the form of a circular dislocation (Brune 1970, 1971; Madariaga 1976) or a rectangular fault (Haskel 1964; Savage 1972) can be successfully used for the interpretation of seismic spectra and the determination of source parameters of mine tremors". This indicates that not only the theory for deriving seismic parameters from spectra but also some of the source parameters were derived from spectra before the introduction of digital seismic systems.

3.1 Seismic Parameters Derived from Spectral Analysis

The reliability of seismic data is low. It is my experience that most or a lot of its users do not realise that the seismic source parameters that they are using for interpretation purposes are only estimates. Their values are not derived from a process of a measurement. The reality is that the seismic source parameters are just an educated guess. If one would try to find a comparison in the same reliability range then there is an estimate one gets from a builder. No one really expects this estimate to be accurate and usually it is accepted as accurate enough if the final costs are within the same order of magnitude as the estimate. This seems to be generally acceptable and provisions in a form of contingences are always attached to any capital expenditure. In case of seismic data one can not attach to them any contingences but good understanding of the way they were derived will help in improving the reliability of the interpretation process. To start with one has to be aware that the seismic source parameters are approximated from an unobserved signal making use of an observed signal that contains noise. The unobserved signal is the one that originated at the source and the observed one is the one recorded by the seismic sensor. The noise is all the additions to the original signal that originated at the source. If the recording is done by a geophone then the recorded ground motion history contains the original signal and noise that originated for multiple and complex reasons. The source parameters can be reconstructed only from the original source signal. This implies that it must be possible to subtract from the recorded ground motions history the complete noise component. In practice this is done by assuming that we know how to correct for attenuation and scattering effects that took place along the travel paths of the seismic waves. To start with this process requires knowing the location of the seismic source as we need to know the distance to which these corrections should by applied. As it will be discussed later the location of the sources are usually not as good as it might be expected. When applying the corrections it is assumed that we know the rock mass properties for example its density or the seismic wave velocities. Although we have an idea about the rock mass properties we do not know their exact values at every point of the rock mass. We also know that the rock mass is not homogeneous. This by definition implies that its properties are not consistent in all directions. The matter is then further complicated by the mining process itself that continuously changes the rock mass properties in the volume around the mine. These changes are not only un-measurable but also extensive and take place in the rock mass volume that contains not only the seismic events (the source) but also the seismic sensors. This influences the reliability of the assumptions. The resulting source parameters for the same single seismic source will also be different depending on the recording system. The principles of signal processing that are applied in various seismic processing software's are generally the same but not down to the details. These details depend not only on some more or less sound theoretical assumptions but unfortunately also on individual preferences based on so called research progress that in theory is the process of closing the gap between the theory and reality. I do not intend to list all assumptions that are done in the process of estimating the source parameters. Here I want to point out that by nature the method of their deriving makes them if not dubious then uncertain and for sure different from their real values that we will never know.

3.1.1 Seismic Moment

The seismic moment (M_o) is a measure of earthquake strength. It is defined using a pure shear source model. This is not totally correct as it will be presented later with the events recorded at the mines. Seismic moment is defined as:

$$M_o = \mu\,\bar{u}\,A$$

where

- μ is the shear modulus at the source
- $\bar{u}$ is the average displacement across the fault
- A is the fault area

Such definition implies that theoretically the value of seismic moment could be calculated if there would be access to the source area. Such cases are very rare In case of the spectral analysis the seismic moment is calculated from the following relation:

$$M_o = \left(4\pi\rho_o c_o^3 R_c \Omega_c\right)/(F_c R_c S_c)$$

where

- ρ_o is the density of source material
- c_o is either P-wave velocity or the S-wave velocity at the source
- R_c is the distance between the source and the receiver
- Ω_c is the low frequency level, this is a spectral parameter
- F_c accounts for the radiation of either P or S waves
- C_c accounts for the free-surface amplification of either P or S wave amplitudes
- S_c is the site correction for either P or S waves

None of the listed above parameters is really known as we have only their estimates. On the bright side we know the value of π but there still might be some doubt as to its accuracy requirement. Figure 3.1 illustrates the way in which the spectral parameter Ω_c and the corner frequency f_c are determined. This figure is presenting the spectrum concept. In reality the spectra are complex and on top of this the source parameters are based on stacked spectra,

Seismic moment of the source is the mean of two moment values, the one derived from the P-wave and the moment derived from the S-wave. Difference of 25 % between seismic moment values based on the S-wave and P-wave are not

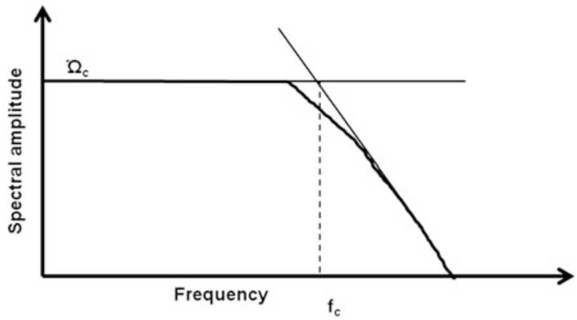

Fig. 3.1 Frequency spectrum —concept

unusual. Spectral analysis uses several filters (tapers) that very strongly influence the final results. Each seismic system, which is available on the market, uses different mutations of the above techniques with the result that estimated source parameters of the same seismic source would be different. In physics the term moment can refer to many different concepts. Roughly speaking any physical quantity multiplied by a length can be called moment. The SI unit of moment is a Newton-metre, which is also a way of expressing a Joule (the unit for energy). As moment is not energy to avoid confusion, we use the units Nm, and not J.

Reminder:

$$\mathrm{N} = \mathrm{m} \times \mathrm{kg} \times \mathrm{s}^{-2}$$

$$\mathrm{J} = \mathrm{m}^2 \times \mathrm{kg} \times \mathrm{s}^{-2} = \mathrm{Nm}$$

3.1.2 Seismic Energy

The radiated seismic energy of P and S waves is calculated from the velocity power spectrum integral

$$J = 2\int_0^\infty \mathrm{v}^2(f)df$$

where f is frequency

$$\text{Radiated energy } E = 4\pi\rho_o c_o \mathrm{J}$$

where

ρ_o is the density of source material

c_o is either P-wave velocity or the S-wave velocity at the source

In case of seismic energy the total released seismic energy is calculated as the sum of P-energy and S-energy. The ratio of S-wave energy to P-wave energy is an important indicator of the type of focal mechanism responsible for the generation of seismic waves in mines (Gibowicz and Kijko 1994).

3.1.3 Source Dimensions

The radius r_o of the circular source is inversely proportional to the corner frequency f_c of either the P or S wave

$$r_o = K_c \beta_0 / 2\pi f_c$$

where

K_c is a constant depending on the source model

β_0 is the S-wave velocity in the source area

For the simple Brune model which is represented by a circular dislocation with instantaneous stress release, the constant K_c equals 2.34. It is commonly accepted that in case of mine induced seismicity the source sizes estimated using the Brune model are overestimated. The source size as such has very limited application in interpretations of mine induced seismicity.

3.2 Stress Release Estimates

There are four different estimates of stress release in use:

Brune stress drop—when a complete stress release is assumed

When a complete stress release is assumed, the stress drop is calculated from the following relation:

$$\Delta\sigma = (7\ M_o)/\left(16\ r_o^3\right)$$

Note that this estimate depends on the source radius which is usually an over-estimated value.

Static stress drop—average difference between the initial and final stress levels over the fault plane.

Dynamic stress drop—difference between the initial stress and the kinetic friction level.

Apparent stress—quantity based on the radiated energy and seismic moment.

Apparent stress is based on the estimation of radiated seismic energy and seismic moment (Snoke et al. 1983 or Wyss and Brune 1968)

$$\bar{\sigma}a = \mu E/Mo = \eta\sigma$$

where

μ	shear modulus
E	radiated energy
η	seismic efficiency
$\bar{\sigma} = (\sigma_1 + \sigma_2)/2$	average stress acting on the fault
σ_1	stress level before the event
σ_2	stress level after the event

Snoke (1987) proved that if the P-wave contribution to the seismic energy and the azimuthal dependence of the energy are neglected, then $\sigma_B = 2\sigma a$. The Brune's stress drop σa is strongly dependent on the assumed model. On the other hand, if the contribution of the P-wave energy is taken into account in the energy release calculation, then the apparent stress becomes an independent energy release parameter (Gibowicz et al. 1990, 1991). The value of apparent stress is proportional to the shear stress acting on the fault.

3.3 Magnitude Concept

The earthquake magnitude is a relative scale (Richter 1935). It defines a standard size of earthquake and rates the others in a relative manner by their maximum amplitude under identical observation conditions. Richter scale is tricky to use as for any different place as southern California, other than shallow earthquakes and other as Wood-Anderson seismograph. These differences require corrections. The first magnitude scale was defined in 1935 for use in southern California, where there was a group of recording stations with identical seismographs. These stations permitted the locations of epicenters for earthquakes originating in this area, so that it was possible to study the decrease in recorded ground motions with increasing distance from epicenter. By plotting the amplitude read from the seismogram against distance from the source, a sort of standard attenuation curve could be set up. The observed range of amplitudes was so large that the amplitude was plotted logarithmically. On the logarithmic plot, the curves representing different earthquakes were roughly parallel, which would imply that the amplitudes recorded for two given earthquakes are in constant ratio at corresponding distances. The logarithm of this ratio was defined as the difference in magnitude between two events. It then remained to fix the zero level magnitude. This was arbitrary chosen to fit some of the smallest true earthquakes. Magnitude 3.0 was fixed as maximum trace amplitude of one millimeter on the recording sheet of a torsion seismometer, with a free pendulum period of 0.8 s, static magnification of 2,800, and damping of 0.8 critical. Later more sensitive seismographs could detect earthquakes even smaller than the ones originally chosen to define magnitude zero. Their magnitudes are accommodated on the Richter scale by the use of negative numbers. Although the scale has no theoretical upper limit, the largest earthquakes have not exceeded a scale value of 9.0. The scale was then refined by Richter and Gutenberg to remove the restrictions of distance and type of seismograph used. With time other types of magnitude scales were devised. Today with the digital seismic networks the magnitude is estimated usually after the seismic moment and energy are calculated in the process of spectral analysis. For example the Palabora local magnitude M_L is calculated from the following formulae:

$$M_L = 0.272 \log E + 0.392 \log Mo - 4.63.$$

This magnitude is already correlated with the national network run by Geological Survey of South Africa (GSSA) magnitude scale. The magnitude values of the Klerksdorp Regional Seismic Network, as from the time of its upgrade (September 1990) were calculated, as it was in other AAC mine seismic networks, from the values of energy and seismic moment.

The moment magnitude (Mm) is calculated from the following formula (Hanks and Kanamori 1979)

$$M_m = 0.666 \log_{10} M_o - 6.066$$

The energy magnitude (Me) is calculated from the following formula (Gibowicz 1963)

$$M_e = 0.526 \log_{10} E - 1.16$$

The local magnitude (M_L) is calculated as mean of M_m and M_e

$$M_L = (M_m + M_e)/2$$

$$M_L = 0.333 \log_{10} M_o + 0.263 \log_{10} E - 3.613$$

This magnitude scale was not correlated with the national network run by Geological Survey of South Africa (GSSA) magnitude scale. For this reason I have calculated the relationship between the magnitude values as reported by the Klerksdorp Regional Seismic Network (ML) and by the Geological Survey of South Africa (Mp) several times in 1991 and 1992. During 1992 for the above comparison I have used 333 events that were recorded by the Regional Seismic Network and by the national network run by Geological Survey of South Africa (GSSA).

$$Mp = \log (A) + 1.11 \, \mathrm{Log} D + 0.00189D - 2.09$$

where

A is maximum recorded amplitude on a seismogram after applying a correction for the instrument in nanometers

D is hipocentral distance in km

Reminder: one nano-meter = 10E − 09 m

It was found that the relation between these two magnitudes is as follows:

$$M_L = 0.86M_p + 0.76$$

Table 3.1 Relation between magnitudes

Mp	Mm	Me	M_L
2.0	2.2	2.8	2.5
2.5	2.5	3.3	2.9
3.0	2.9	3.8	3.3
3.5	3.2	4.3	3.8
4.0	3.6	4.9	4.2
4.5	3.9	5.4	4.6
5.0	4.2	5.9	5.1
5.2	4.4	6.1	5.2

Table 3.1 illustrates the relations between the magnitude of the Geological Survey of South Africa (Mp), the energy magnitude (Me), the moment magnitude Mm and the Klerksdorp Regional Seismic Network magnitude (M_L).

Table 3.1 indicates that:

1. The energy magnitude is always higher than the GSSA magnitude by an almost constant value of 0.8.
2. The moment magnitude is higher than the GSSA magnitude up to about 2.5, and then for greater magnitude values is lower than that of the GSSA.
3. The mean magnitude is basically greater than the GSSA magnitude, but with growing values this difference becomes less, and the two are equal at a value of 5.2.

As the mining personnel got used to the local magnitude and could in some way relate it to damage and their own personal experience, it was at the time decided not to do any changes to the method used to calculate the local magnitude. This was a very serious matter as occurrence of large size seismicity was very frequent.

The definition of most of the magnitudes can be found in Gibowicz and Kijko (1994) from where I quote the following definitions: "The most popular measure of earthquake strength for small events is local magnitude M_L introduced by Richter (1935). It is defined as:

$$M_L = \log A(\Delta) - \log A_0(\Delta)$$

where A is the maximum trace amplitude at distance Δ. This magnitude scale has also been used to quantify mine tremors in Poland (Gibowicz 1963) and in South Africa (e.g. Spottiswoode and McGarr 1975). Later, the empirical functions were extended by Gutenberg and Richter (1956) to enable independent magnitude estimates from body- and surface-wave observations. These magnitude scales, denoted by M_s and originally defined for surface waves having 20 s period and by m_b defined for body waves with 1-s period recorded at teleseismic distance, are found to be strong function of wave frequency".

3.4 Single Event Source Parameters

I have worked for the Klerksdorp Mine Managers Association Regional Seismic Network from 1988 until the end of 2000. This network covered the area of four gold mines: Vaal Reef Gold Mine, Hartebeestfontein Gold Mine, Buffelsfontein Gold Mine and Stilfontein Gold Mine. By the end of 1970 this network had 7 stations by the end of 1978 it had 20 stations. When I arrived there by the end of 1988 it had 29 recording stations. My experience with this network is describes in details in my PhD thesis (Glazer 1998). This mining area was seismically very active and there were a lot of larger size seismicity. For example from January 1972 until the end of 1999 there were 756 events of magnitude above 3.5. In this time period there were 144 events with magnitude size above 4.0. I have had presented the KMMA Klarksdorp Regional Seismic Network procedure of deriving seismic source parameters for several reasons. First of all probably no one remembers or knows how it was done in the past. The second reason is to make it clear that when the digital networks started to operate in mines there was a tendency to consider all what was done to this time as old fashion and useless and that it has to be replaced by the new. To start with the magnitude as such was considered to be a hopeless parameter that soon will be replaced by something better and much more worthy. It tuned out that this was not to be as it was preached. It is worth remembering that when I worked for these mines their owner Anglo-American explanation for seismic related accidents was always that it "was an act of God". This was due to the fact that all faults in the mining are were by their nature active ones as preached by the company. For this reason the observed seismicity (at least the large size ones) had nothing to do with mining activity.

Today each recorded at Palabora seismic event is described by the following parameters:

1. Date
2. Time
3. Number of stations that recorded the event
4. X
5. Y
6. Z
7. Location error
8. Energy magnitude
9. Moment magnitude
10. Seismic moment
11. Moment P
12. Moment S
13. Energy
14. Energy P
15. Energy S
16. Corner frequency
17. Corner frequency P

18. Corner frequency S
19. Static stress drop (Pa)
20. Dynamic stress drop (Pa)
21. Source radius (m)
22. Apparent stress (MPa)

Let's examine the largest to date seismic event recorded at Palabora. This event took place on 27 February 2004 at 23 h 15 min 55 s. This event is illustrated by Figs. 3.2 and 3.3.

The source parameters of this event are:

Date: 27/02/2004
Time: 23 h 15 min 29 s
X = 23931
Y = −12717
Z = −500
M_L = 2.0
E = 1.25E = 07 J
Mo = 7.9E+11 Nm

According to Fig. 3.3 this event located at an intersection of two faults: the Central and Mica Faults. This location was assumed to be the most probable.

Table 3.2 illustrates the fact that the location of the seismic event changes with the number of accepted seismic stations during processing of the event. This process is about picking the arrival times of the P-wave and the S-wave. That is the only thing done by the processor. After accepting stations and finding the arrival

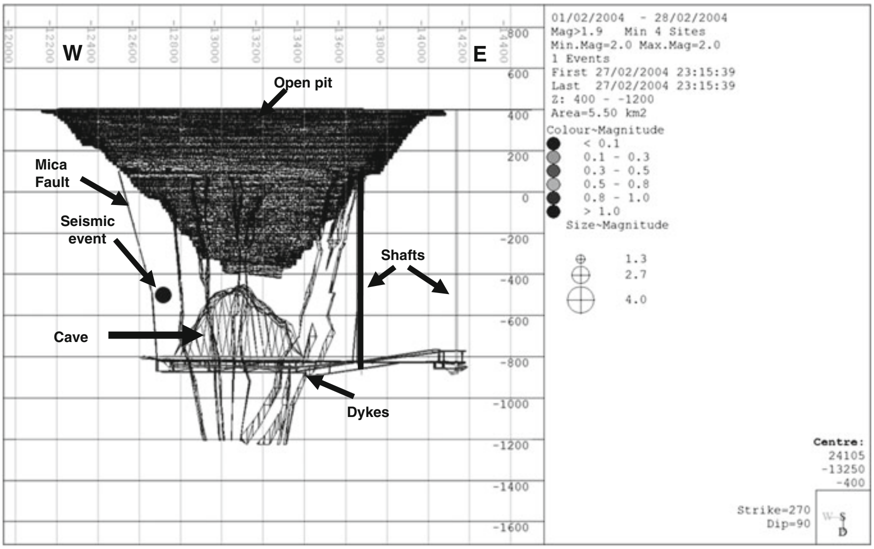

Fig. 3.2 Vertical W-E section largest event recorded at Palabora

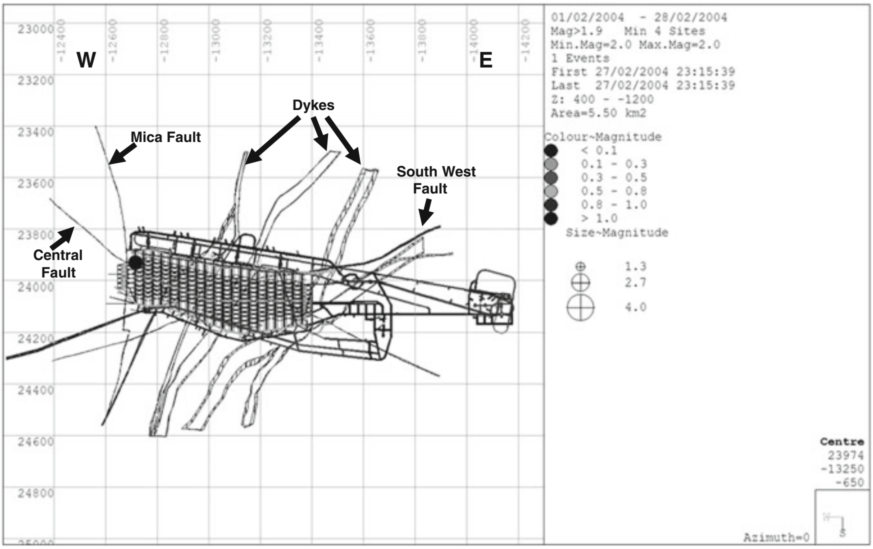

Fig. 3.3 Horizontal W-E plan largest event recorded at Palabora

Table 3.2 Posible coordinates of the largest Palabora seismic event

Date	Time	X	−Y	−Z	Mag.	E (J)	Mo (Nm)	No of stations
27/02/2004	23:15:55	23865	13014	258	2.0	1.90E+07	8.80E+11	3
		23871	12526	787	2.1	3.90E+07	1.00E+12	4
		23873	12534	788	2.0	2.10E+07	9.00E+11	5
		23882	12589	723	2.1	4.00E+07	9.40E+11	6
		23929	12632	652	2.1	4.60E+07	9.20E+11	7
		24108	12678	545	2.1	3.70E+07	1.00E+11	8
		24028	12643	581	2.1	3.00E+07	9.70E+11	9
		23997	12722	508	2.1	2.00E+07	9.80E+11	10
		23931	12717	500	2.0	1.40E+07	7.40E+11	11

time he presses a button “calculate source parameters” and then all goes in an automatic mode. Which is a correct procedure as with hundreds or thousands of events recorded each day it would not be possible to evaluate thousands of source parameters manually. Still the processor should be responsible for quality of accepted seismograms and then the accuracy of the time picks. The other factor that he has to consider is the geometry: how well is the event surrounded by the recording stations. Never the less this example indicates that the final source parameters are dependent on the number of recording stations used in the process of calculating the source parameters. The range of seismic energy or seismic moment doesn’t change a lot what is clear when considering that the magnitude size can be

2.0 or 2.1 only. At this stage one has to consider what the energy and moment will be used for. For example a possible difference in seismic moment of 10 times might be a lot when considering for example a source mechanism of this event analysis. The more serious problem is with the XYZ coordinates that can change by couple of 100 m. In this example X and Y coordinates can differ by 200 m while the estimation of depth can change by 500 m. This example leaded to more investigations as with time more and more events were taking place outside of the seismic network and for this reason the problem became more significant.

3.4.1 Recording Geometry and Seismic Source Parameters

As from the beginning of 2004 over 50 % of all recorded at Palabora seismicity located outside of the seismic network then it would be useful to establish the influence of the recording geometry on the event source parameters. By recording geometry I understand the relationship of the seismic source to the recording points. In other words the problem can be defined as: do the source parameters of the same seismic event depend on the number of accepted stations. In order to test this assumption I have randomly selected 65 events that were recorded during 2007. I have then processed them with 4, 5, 6, and so on stations. The minimum number of stations is 4 while the highest number of accepted stations was 21. Table 3.3 lists the times the accepted number of stations has occurred. According to data presented by this table all 65 events were accepted with a minimum 4 and maximum off 10 stations. Events with higher number of accepted stations then decrease rapidly. This seems to be a true representation of what takes place in reality. Table 3.4 lists the number and percentages of total seismicity recorded during 2007 processed with different numbers of stations.

Data presented in Table 3.4 indicates that with the increase of accepted number of stations the number of events decreases rapidly. Only 57 % of all recorded events were processed with 5 stations. The number of events processed with 10 stations is only 952 and this is less than 10 % of recorded events. Figure 3.4 illustrates the percentages of seismicity recorded with different number of stations.

Figure 3.5 illustrates the magnitude range of the total 2007 seismicity. The maximum size event recorded during that year was an event of magnitude size 1.4. It seems that this catalogue is complete down to magnitude −0.8.

Figure 3.6 illustrates the magnitude range of the test sample (65 events). The smallest event is of magnitude −0.4 and the largest event is of magnitude size 1.4. This range when compared with the range of all recorded magnitudes during 2007 indicates that the test sample is representative of the whole data set. According to data illustrated by Fig. 3.7 each magnitude in the test sample appears a number of times. For example there are 5 events of magnitude 0.1.

Figure 3.8 illustrates the energy and moment ranges of the test sample while Fig. 3.9 illustrates the energy and moment range of the 2007 seismicity. The test

Table 3.3 Number of accepted stations during the test

Number of stations	Occurred times
4	65
5	65
6	65
7	65
8	65
9	65
10	65
11	61
12	50
13	35
14	30
15	20
16	18
17	17
18	12
19	9
20	4
21	1

Table 3.4 Number of events with different number of accepted stations

Number of accepted stations	Number of events	Percentage
4	13062	100
5	7473	57
6	4552	35
7	2896	22
8	2034	16
9	1399	11
10	952	7
11	603	5
12	372	3
13	209	2
14	149	1
15	109	0.8
16	85	0.7
17	59	0.5
18	45	0.3
19	29	0.2
20	16	0.1
21	4	0.03

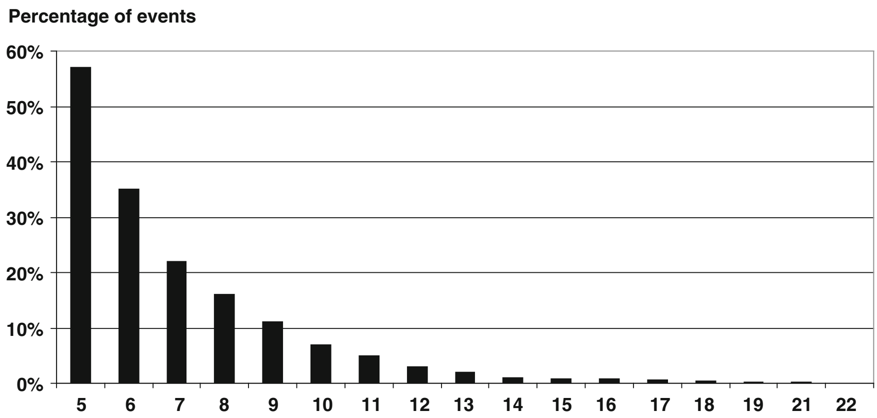

Fig. 3.4 Percentages of seismicity recorded with different number of stations

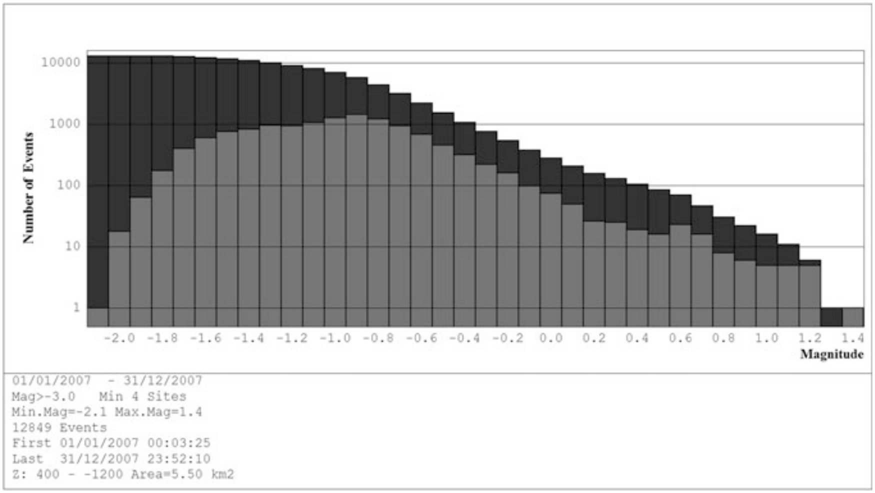

Fig. 3.5 Distribution of magnitude sizes

sample ranges adequately covers the ranges of the 2007 seismicity. The exception is the lower limit of the seismic moment.

Typical distances source to receiver (test sample) vary from about 100 m up to 180 m In case of an event recorded with 10 stations the maximum distance is about 1000 m.

It seems that the test sample of 65 events is well representative of the seismicity recorded during 2007. Table 3.5 illustrates an example of the test. This example is based on an event that was recorded on 20 March 2007 at 15:03:04. This table lists the changes of this event's seismic energy, seismic moment and magnitude size depending on the number of accepted stations.

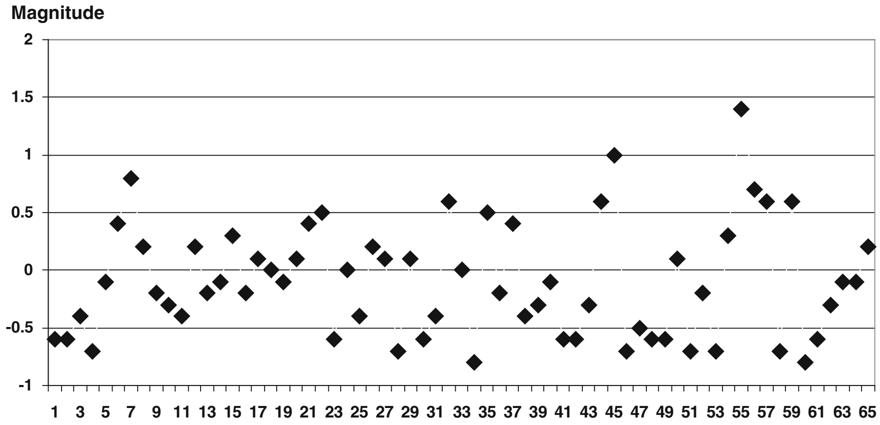

Fig. 3.6 Magnitude range of the test sample

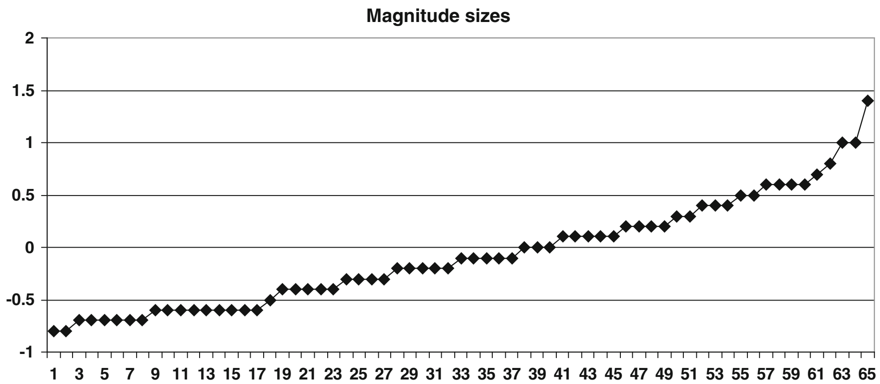

Fig. 3.7 Test sample number and magnitude range

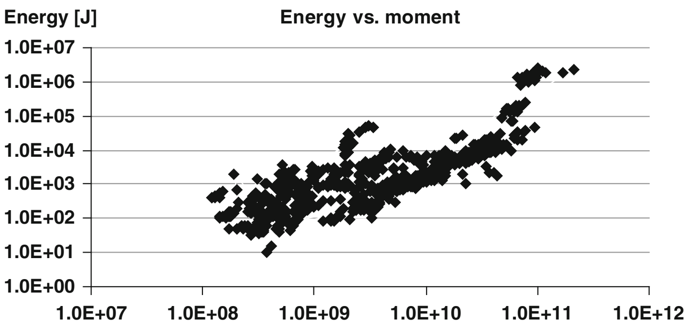

Fig. 3.8 Energy and moment range of sampled data

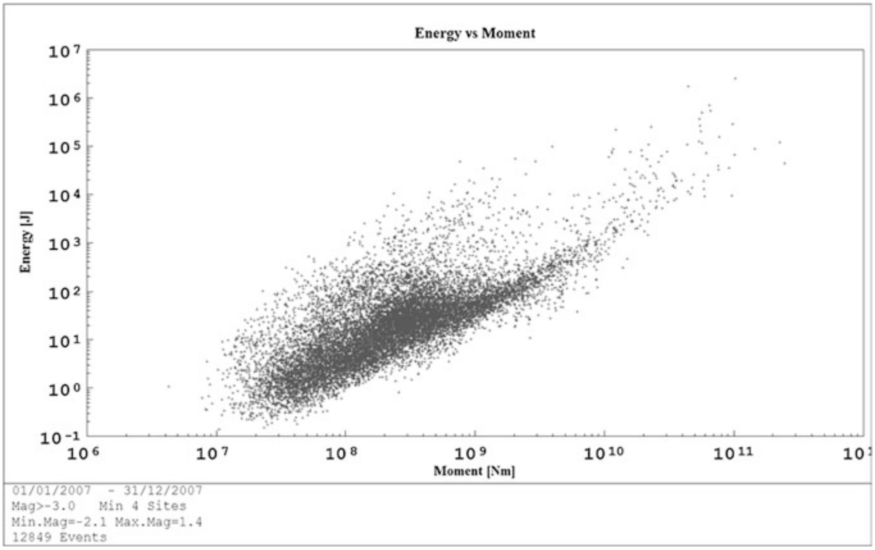

Fig. 3.9 Energy versus moment for data recorded during 2007

Table 3.5 Example of source parameter changes

No of stations	Seismic energy (J)	Moment (Nm)	Magnitude
4	9.50E+01	5.70E+08	−0.7
5	8.30E+01	5.30E+08	−0.7
6	4.00E+01	4.90E+08	−0.8
7	4.80E+01	4.60E+08	−0.8
8	4.80E+01	4.90E+08	−0.8
9	6.40E+01	4.70E+08	−0.7
10	2.10E+02	5.20E+08	−0.6
11	1.40E+02	4.70E+08	−0.6
12	1.40E+02	4.90E+08	−0.6

Figures 3.10 and 3.11 illustrate this relationship. According to Fig. 3.10 this seismic event will have the minimum seismic energy of 4.00E+01 J when processed with 6 stations. When processed with 10 stations its seismic energy will have a maximum energy value of 2.10E+02 J. The difference between the minimum and maximum energy release sizes for the same event is nearly 5 times. According to Fig. 3.11 this seismic event will have the minimum seismic moment of 4.60E +08 Nm when processed with 7 stations. When this event will be processed with 4 stations then its seismic moment will have the maximum seismic moment of 5.70E +08 Nm. In this case the difference between the minimum and maximum moment values will be low just above 1.00E+08 Nm.

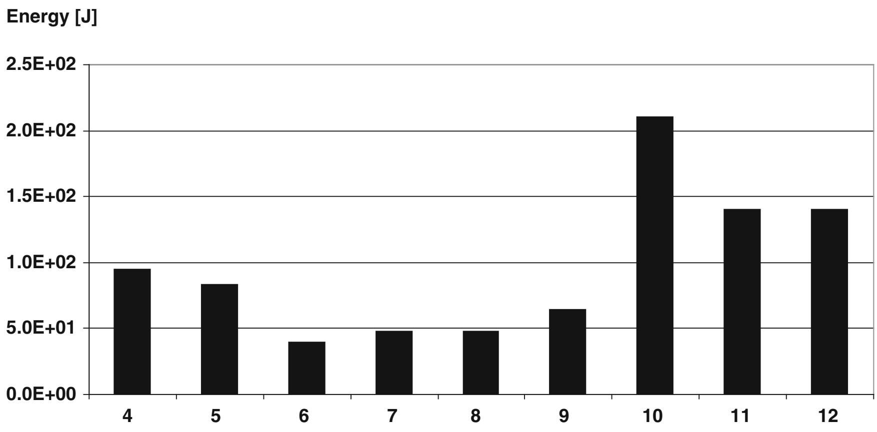

Fig. 3.10 Energy values depending on the station number

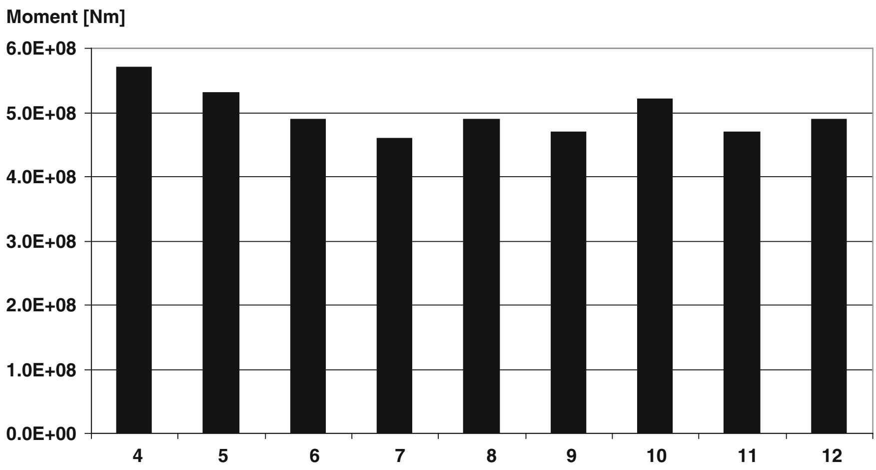

Fig. 3.11 Moment values depending on the station number

The above example indicates the manner in which the differences between the maximum and minimum values of released seismic energy and of seismic moment were calculated for all the 65 events of the test sample.

Figure 3.12 illustrate the released seismic energy differences resulting from processing each of the 65 events with a different number of accepted stations. This difference varies from just around 1.0 up to over 10 times. The average difference is about 4 times.

Figure 3.13 illustrate the seismic moment maximum differences resulting from processing each of the 65 events with a different number of accepted stations. This difference varies from just around 1.0 up to over 4 times. The average difference is about 2 times.

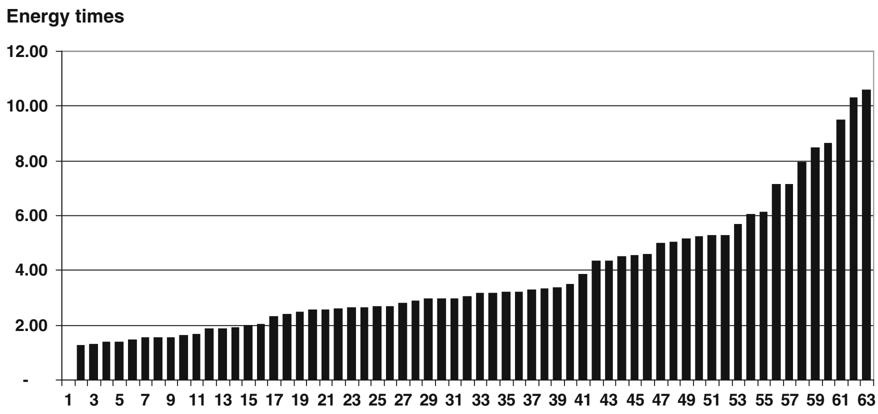

Fig. 3.12 Maximum energy changes of the test sample

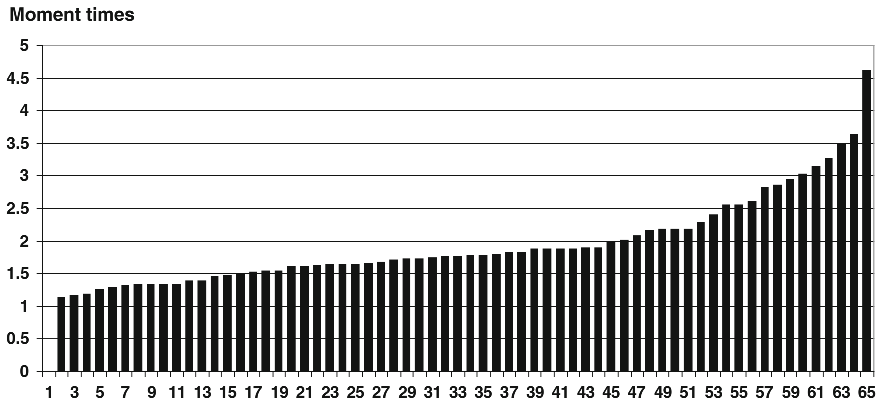

Fig. 3.13 Maximum moment changes

This test clearly indicates how unstable the seismicity parameters are for the events that locate outside of the seismic network. As indicated by Table 3.5 the change in the source parameters (moment and energy) influences the magnitude size.

Processing events with different number of stations results not only in changing the values of the seismic energy and moment but also in changing their locations. While most of the maximum differences in X and Y coordinates are below 100 m the differences in the elevation values are larger and more scattered. For the test sample the maximum difference averages are:

- Average ΔX is 97 m
- Average ΔY is 68 m
- Average ΔZ is 227 m

3.5 Seismicity Versus Single Event

Analysis of the single event seismic source indicates that their foundation is in an estimate not a measurement. Even if you name this estimate an educated guess it still will be what it is that is only an approximation. The consequence of this is that quantitative analysis of seismicity is not on the cards. Seismicity is a collection of seismic events. Figure 3.14 presents such a collection of seismicity.

Seismicity of Fig. 3.14 consists of some 23779 individual seismic events which were recorded from the beginning of 2008 until the end of 2010. The first observation is obvious that there is a lot of seismic events. The second observation is more important, these events are located all around the mine. And this observation is the strength of this data set. Despite the fundamental limitations of data based on a single seismic event when considered all of them together as a set then they are a source of valid information, not only about the mining but also about the surrounding rock mass in which this mining is taking place. The fact that seismicity is taking place all around the mine implies that it has a potential to provide information about the whole rock mass volume that is influenced by the mining process. In this sense it is very different from other methods like for example borehole measurements which can provide only point information. The fact that there is a lot of seismic events available allows for implementation of specific interpretation methodologies that in turn compensate for the input data limitations.

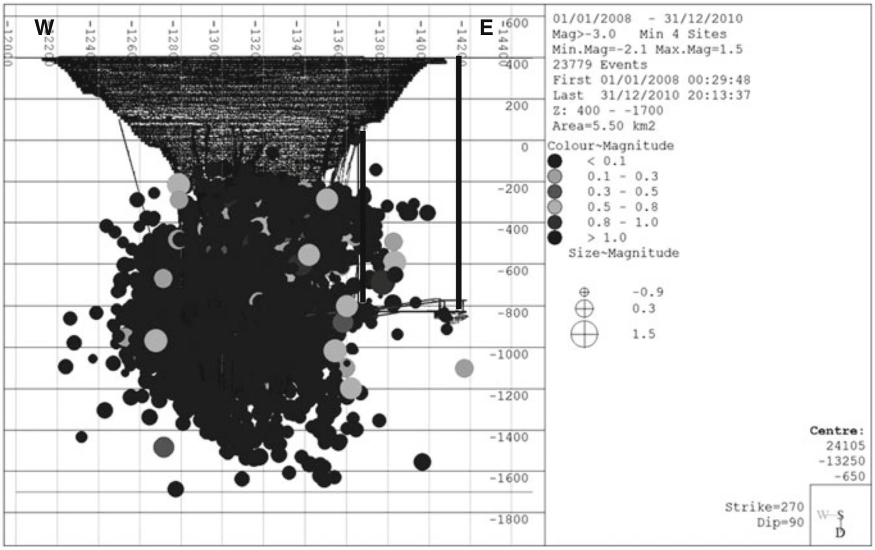

Fig. 3.14 W-E section seismicity recorded from 2009 until 2010

3.6 Summary

Understanding the seismicity parameters limitations is the basic for successful and what more important reliable interpretation results. This is a fact that can not be omitted and no shortcuts are permitted. Here I assume that seismic data interpretation is performed for fundamental reasons that are to improve and progress the mining process in a wide sense of these expressions. On the other hand if the seismicity interpretation has some other goals then it does not make the grade of science and the fundamental can be changed, rejected or chopped as required. Here I will do a seismicity parameters review in a form of their grading. This grading will depend on the number of assumptions that have to be done while estimating the parameter. The grading is done in ascending order. Grade I parameter more trustworthy than parameter of for example of Grade II. There are four grades. In my over 40 years practice as a geophysicist I made use of all parameters of Grade I, Grade II and Grade III. I have found that all parameters of Grade I and Grade II have sound physical meaning and in many cases are independent of each other. Problem starts with the parameters of Grade III. There are three of them and they repeat each other in this sense that they do not supply new information once one of them was applied in the interpretation process. The choice between them is easy to make. The energy index is the most comprehensive among them. It is also reasonably uncomplicated to use and understand. I did not use any of the parameters listed in Grade IV. I have read about them and studied some interpretation results with their applications. In general as all of them depend on cumulative seismic moment or cumulative seismic energy release or both those values at the same time they repeat the interpretation results of the energy index. They are as the cumulative apparent stress and cumulative apparent volume in the relation to the energy index: they do not contribute anything innovative.

Grade I Seismicity Parameters

Recorded seismicity is the first parameter on this list and it consists of a number of seismic events. Recorded seismic events are facts. I assume that the blasts are discarded during the processing of recorded events. There is a possibility that some of the recorded events originate from secondary to mining activities as for example flow of ore in the mine. This would include some activities around the ore passes or crushers. If required this seismicity could be rejected on basis of its clustering but usually they do not influence analysis based on seismicity recorded during longer time periods than 1 week. Other out of the ordinary seismicity would be that locating in the cave. At Palabora there were only less than hundred of them against thousands locating around the cave. Still most of the visiting consultants and most of them very experienced noticed them immediately while took no notice of bona fide ones. I could get rid of these easily but instead decided to keep them for fun. While analysing seismicity it must be understood that not all events can be recorded and that there can be some volumes where there is more of recorded seismicity only because of the distribution of the active recording stations.

Second parameter of Grade I is the **cumulative number of recorded seismicity**. This refers to some time period. This parameter of limited practical value indicates if the seismicity in the mine is stable or has periods of increased and decreased seismic activity.

Third parameter of Grade I are the **seismic activity rates** for time periods that the accurate origin times are of no consequences. Usually these activity rates are calculated for time periods ranging from 1 week or 1 month up to 1 year. Other time periods are permitted and should be used. The calendar time periods are there mainly because of the mine reporting cycle into which the reporting of seismicity must match up. For special projects like for example analysis of seismicity induced by hydro-fracturing the time periods will be lesser but not below 1 h. These activity rates should be compared with mining rates. In general it is assumed that increased mining rate should result in increase in seismic activity rates but that not always is the case especially with cave mining. The 24-h seismicity distribution is a seismicity rate associated with this parameter. The input data is seismicity recorded in a longer time period than 1 day for example during 1 month. It is used to monitor seismic activity rates induced by blasting but also to monitor the caving process. Other versions of seismic activity rate are (for example) the monthly percentages of seismicity locating above the mine or outside of the mine footprint. Here again it doest make any difference if some of the events assumed to locate above the mine in fact located below the mine. Probably there will be a close number of events that were assumed to be located below the mine and in fact located above the mine. This approach also allows for discarding the influence of the seismic network performance. In the end the time histories of the seismicity percentages are averaged when analysing the trends. It was proven that this type of parameter is very valuable while monitoring the caving process. What more it is applicable from the initiation of the caving process right to the end of the caving process.

Grade II Seismicity Parameters

There are nine parameters in this Grade. The first one is the **seismicity locations and their accuracy**. Location will be accurate only if the event locates in the volume that is surrounded by recording stations. This means stations above and below this event. It is very difficult to build seismic networks with recording stations that are around, below and above the mine. Even if it is possible to locate recording stations around the mine at some time seismicity will start to locate outside of such perimeter. This was the case of Palabora Lift1 seismic network. When the caving process was initiated the networks recording stations were located around the cave but their elevation distribution was very limited. By the time the network was completed the seismicity induced by the caving process migrated in all directions away from the mine. For this reason the quality of seismicity locations rapidly deteriorated. Practice indicates that when analysing seismic catalogues containing hundreds or thousands of seismic events their location accuracy is of no consequence.

The second parameter of this Grade is the **average** for example **monthly seismicity elevation**. The seismicity elevation is the most unreliable component of the location. Still if validated by the caving process progress it becomes a reliable value when displayed as a time history. In this case the absolute values are not as important as is the trend and its changes.

The third parameter in Grade II is the **seismically active volume**. The seismically active volume encompasses most of the recorded seismicity during a certain time period. This time period can be for example 1 or 3 months. Such seismically active volumes are estimated with progressing time and then displayed as time histories. Again the absolute values of the volumes are not important as is the trend and its changes with time. Analysis of seismically active volumes time histories were validated by the caving process.

The fourth parameter of Grade II is the **cumulative seismic moment** (ΣM_o). It is a progressing sum of individual seismic events seismic moments which are derived in the process of spectral analysis (Gibowicz and Kijko 1994). The seismic moment (and seismic energy) is approximated from an unobserved signal making use of an observed signal that contains noise. The unobserved signal is the one that originated at the source and the observed one is the one recorded by the seismic sensor. The noise is all the additions to the original signal that originated at the source. If the recording is done by a geophone then the recorded ground motion history contains the original signal and noise that originated for multiple and complex reasons. The seismic moment can be reconstructed only from the original source signal. This implies that it must be possible to subtract from the recorded ground motions history the complete noise component. In practice this is done by assuming that we know how to correct for attenuation and scattering effects that took place along the travel paths of the seismic waves. To start with this process requires knowing the location of the seismic source as we need to know the distance to which these corrections should by applied. As already stated the locations of the sources are not as good as it might be expected. When applying the corrections it is assumed that we know the rock mass properties for example its density or the seismic wave velocities. Although we have an idea about the rock mass properties we do not know their exact values at every point of the rock mass. We also know that the rock mass is not homogeneous. This implies that its properties are not consistent in all directions. The matter is then further complicated by the mining process itself that continuously changes the rock mass properties in the volume around the mine. These changes are not only un-measurable but also extensive and take place in the rock mass volume that contains not only the seismic events (the source) but also the seismic sensors. This influences the reliability of the assumptions. Seismic moment is a function of: the density of source material, the P-wave velocity or the S-wave velocity at the source, the distance between the source and the receiver, the low frequency level, which is a spectral parameter, the radiation of either P or S waves, the free-surface amplification of either P or S wave amplitudes and the site correction for either P or S waves. None of the listed parameters is really known as we have only their estimates. Seismic moment as such is based on an average of the stacked spectra (each of them originating from a different recording station that was triggered). Seismic moment of the source is the mean of two moment values, the one derived from the P-wave and the moment derived from the S-wave. In theory those two should be exactly the same but they never are. A difference of 25 %

between them is regarded as small. Cumulative moment time histories indicate if the seismicity in the mine is stable or has periods of increased and decreased activity.

The fifth parameter in Grade II is **seismic moment rate**. As with seismicity rate it indicates the change of seismic deformation with time. A version of this parameter is percentages of seismic deformation above the mine or outside of the mine footprint. The values as such are not important. The important are the trends and times when they change.

The sixth parameter in Grade II is **cumulative seismic energy** (ΣE). This parameter is a sum of consecutive seismic energy release values. The radiated seismic energy of P and S waves is calculated from the velocity power spectrum integral and is a function of several parameters for example the density of source material or the P-wave velocity or the S-wave velocity at the source. In case of seismic energy the total released seismic energy is calculated as the sum of P-energy and S-energy. Cumulative seismic energy release time histories indicate if the seismicity in the mine is stable or has periods of increased and decreased energy release amounts.

The seventh parameter of Grade II is **seismic energy release rate**. As with seismicity rate and seismic moment release rate it indicates the change of seismicity with time. Versions of this parameter are monthly percentages of seismic energy release above the mine or outside of the mine footprint. Again values as such are not important. The important are the trends and times when they change.

The eight parameter of Grade II are the **ratios of S-wave energy to P-wave energy**. These values indicate the source mechanisms Gibowicz and Kijko (1994). This parameter can be displayed for example as percentages of monthly seismicity with this ratio above 10 (15 or 20). The analysis is then of the trend and its changes in time. This parameter can be displayed also as a map (horizontal or vertical) of seismicity where different ratio values are displayed by different colours.

The ninth parameters of Grade II are the **magnitude range changes**. Today with the digital seismic networks the magnitude is estimated after the seismic moment and energy are calculated in the process of spectral analysis. This parameter can be applied in several means. The first most obvious is to monitor what are the percentage changes of a given magnitude range (for example range between −0.5 and 0.0) with time. The lowest magnitude must be above the minimum complete recorded magnitude, this is obvious. The other option is to monitor the monthly rates of one single magnitude for example −0.3 and compare its relation to the energy released by these seismicity rates. Again the values to look for are the trends and their changes in time.

Grade III Seismicity Parameters

There are only three parameters in this Grade. The first one is **energy index**. The energy index for a given event is the ratio of the events estimated value of the emitted energy to the mean value of the emitted seismic energy by events of the same seismic moment as this events estimated value. In this way the input data for interpretation and analysis consists of a full catalogue from small to large size events. The energy index parameter allows for several applications. Seismic data can be displayed as events where the colours indicate several ranges of the energy index. In this way the horizontal map or vertical plan indicates areas where stresses are higher in comparison to other places. Such stress presentation can be displayed as contour maps. Energy index can also be displayed in form of history time curve. History time graphs usually require smoothing in order to make the trend evident. The interpretation results of the energy index were validated with results based on other parameters like among others the seismicity rates, moment rates, energy release rates, average seismicity elevation or energy S-wave to energy P-wave time histories, seismically active volumes and also by the mining data. It must be well understood that the mean values will change with the various amounts of input data and the result of their assessment which usually is the line of the best fit. For this reason absolute values of the energy index as it is practiced from time to time can not be used to grade the seismic hazard level.

The second parameter of Grade III is **cumulative apparent stress** ($\Sigma\sigma_A$). This parameter is derived from seismic energy (E) and seismic moment (M_o) as is the energy index. Because of this it is not surprising that the time history graph based on apparent stress and that based on energy index are the same as trends and their changes are concerned. Because of its relation to moment it's not possible to display and compare seismicity of complete seismic catalogues. It is only possible to use from this catalogue seismicity of the one magnitude size not as in the case of the energy index. Applications of this parameter are limited and there is no use of it once an analysis and interpretation of the energy index is already available.

The third parameter of Grade III is **cumulative apparent volume** (ΣV_A). This parameter is based on seismic moment (squared) and energy index as are energy index and apparent stress. This parameter strongly depends on seismic moment. Its cumulative graph presentation is very similar to the cumulative graph of the seismic moment and as such doesn't contribute anything new to the interpretation process. The other problem with this and other parameters that are dependent directly from rock mass parameters are these values them self. We do not know them to such degree that we are able to use different shear modulus values for adjacent rock mass volumes. Probably the shear modulus is in the equations only in order to get the units correct. Apparent volumes unit is cubic meter so it should be assumed that in some way it represents the source volume. For this reason its cumulative values together with cumulative active seismic volume could be used to assess the seismicity clustering. The closer these graphs are to them self the stronger would be the seismicity clustering. I have tested this option while comparing over 10 years of seismicity that was recorded above the mine with that recorded below the mine. The amounts of that seismicity were similar. The seismically active volumes above the mine were continuously larger from those below the mine. This would indicate greater clustering of the seismicity below the mine. Introducing cumulative apparent volume into the interpretation did not result in complete confirming of this conclusion. By definition the cumulative apparent volume should be continuously lower than the seismically active volume. This was not the case indicating a major problem with using this parameter. In fact Grade III is reduced to only one parameter.

Grade IV Seismicity Parameters

There are several parameters in this grade. The following three are from Dunn (2005). All of them are based on ΣE and ΣM_o. The first one is **seismic stress** (σ_s). This parameter is calculated from the following formulae:

$$\sigma_s = 2G\Sigma E/\Sigma M_o \text{ where G is rigidity}$$

Seismic stress is a ratio between ΣE and ΣM_o multiplied by rigidity twice two. The values of ΣE and ΣM_o are for the same volume and time period. Seismic stress formula is similar to that of apparent stress. The main difference is that it is multiplied by two.

The second parameter in Grade IV is **seismic strain rate** (ξ_s). This parameter is calculated from the following formulae:

$$\xi_s = \Sigma M_o/2\mu Vt \text{ where } \mu \text{ is shear modulus}$$

Seismic strain rate is cumulative moment divided by two times shear modulus multiplied by volume and time.

The third parameter in Grade IV is the **seismic viscosity** (η_s). This parameter is based on the following formulae:

$$\eta_s = \sigma_s/\xi_s$$

Seismic viscosity is the ratio between seismic stress and seismic viscosity. "When evaluating the values of seismic viscosity … similar results as for the seismic stress analysis were obtained" (Dunn 2005).

The next parameters in Grade IV are:

Seismic viscosity $\eta_s = (4\mu^2\Delta V\Delta t\Sigma E)/(\Sigma M_o)$
Seismic diffusion $D_s = (\Sigma M_o)^2/4\mu L\Delta t\Sigma E$
Seismic Deborah Number $De_s = (4\mu\Delta V\Sigma E)/(\Sigma M_o)^2$
Seismic Schmidt Number $Sc_{sd} = (4\mu^2\Delta V\Delta t(t)\Sigma E)/(\rho(X)^2 (\Sigma M_o)^2$

These four last formulas are from Mendecki (1997). The parameter L in seismic diffusion is the length of a cube and ρ, t and X in the seismic Schmidt number formula is the rock mass density average time and average distance between consecutive events (taking into account the source size). It is evident that all four parameters are based for the most part on the ΣM_o and ΣE values. As already proven with parameters of Grade III that are also based on these two values they do not contribute anything new once one of them was used in the analysis and interpretation process. For this reason it should be recognized that these parameters are redundant and of no practical significance. In fact all parameters of Grade IV are overdone versions of the energy index. More about Grade IV parameters and especially on their applications can be found in Chap. 8.

I have commented only on bona fide seismicity parameters. I am not sure if average time between seismic events or average distance between consecutive events can be considered as valid seismicity parameters. The matter becomes more complicated as the average distance includes the source size. These two do not reflect the real seismicity as they apply not to the entire but only the part of seismicity that was recorded. The cumulative values of seismic moment and seismic energy refer to the recorded seismicity. It is reasonable to assume that the not recorded seismicity is of very small size so their absent in the values of ΣM_o and (ΣM_o) will make no difference. Not taking the not recorded seismicity into account will influence the difference between assumed and real values of average time between seismic events or the average distance between consecutive events. In any way the average time and distance constant values as such can not make a big difference when for example in formuls there are ΣE and $(\Sigma M_o)^2$ values.

Energy index was the first parameter that was developed in order to cope with the increasing number of the recorded seismicity. It was easy to use and because of the way it was derived it could be applied and presented in several forms. This parameter allowed for more detailed inside into the induced seismicity than only its space and time distributions. Combination of energy index with space and time distribution of seismicity together with mining rates, geology and geotechnical data seemed to be the logical direction for any future analysis and interpretation. Apart of the recorded seismicity and its time distributions which are solid pieces of evidence all other parameters are based on a number of assumptions. This implies that probably they are remote from the real values. How far-off they are we will newer know. Not as single source event parameters the seismicity parameters are proven to be reliable and valid. This I have experienced during more than two decades of practice in seismicity interpretation when using independent of each other input data leads to the same results. Seismicity parameters permit only for analysis of their time trends. For this reason the analysis and interpretation result of induced seismicity can be only qualitative. They will never become quantitative as for this we need to know the real values and the error of the measurement. For the last 10 years I applied the recorded seismicity parameters for monitoring the caving process and associated with it seismic hazard. Final back analysis and comparison based on over 10 years of seismic data with over 10 years of underground observations and mining rates resulted in confirmation of all interpretation results made with partial data that was available at the time when it was performed. What more practice indicated that once the energy index was used in data analysis and interpretation application of other seismicity parameters containing and based on ΣM_o and ΣE values as apparent volume or stress does not result in reaching independent results. Using them just duplicates the results. For this reason adding to the interpretation process even more of these type parameters for sure leads to nowhere.

Finally the seismicity parameters don't have to be precise and accurate. This applies to the seismicity locations. Coordinates of events describe a point in space. Seismic event is not a point as it has a size (volume). Does this point represent the place where the event started? Location accuracy depends on a number of factors: network density, geometry between the event and recording stations. Most accurate locations will be for seismicity locating in side of a seismic recording system with recording stations not only around the event but also above and below this event.

This usually is not the case. Do we really need super accurate locations and are they achievable taking into consideration that each event has a volume and most probable have an asymmetric shape? Location becomes important when analysing individual seismic events. Usually more important will be if this event is associated with some geological discontinuity. Exact locations of those are unknown. Association of event with geology is a guess even if it is an education guess. Exact locations are important only when considering small volumes with low activity rates. Such analysis by definition will be unreliable. In case of large size volumes and high activity rates (large number of seismicity counted in thousands) accurate locations are not essential. There will be some seismicity that locates outside but in reality took place in this volume and there will be seismicity that that in reality located outside but their estimated location put them inside.

Very important is the consistency of the data base which contains the recorded seismicity. Data base consistency and its quality without difficulty overcome the existing apparent disability due to low accuracy of the estimated seismic source parameters.

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Chapter 4
Seismic Source Parameter Ranges

Abstract In this chapter there is a description of the seismic parameter ranges as they are in the mine. Chapter ends with a comparison between natural earthquakes and events experienced in mines. Here I have included some estimates of the released energy in a wide seismic magnitude range. Using seismic efficiency concept I have compared the released energy and seismic energy with TNT explosions and electricity demands of South Africa. Depending on the earthquake size its energy when converted into electricity would be consumed in less time as it takes to blink an aye or could meet the nearly 300 years demand.

4.1 Seismic Energy

Presented analysis is based on seismicity recorded at Palabora. Other mine seismic networks record similar ranges of seismic energy and seismic moment when taking into account magnitude range of Palabora which is from −2.0 up to 2.0.

Figure 4.1 illustrates the relation between the magnitude values and the released seismic energy. This relation is based on 149,000 seismic events recorded from 2002 until 2013 in magnitude range from −2.0 up to 2.0. The energy range varies from less than 1 Jule (magnitude −2.0) up to over ten million Jules (magnitude 2.0). Two trends are clearly evident. The first one is that with increasing magnitude values there is a general increase in the emitted seismic energy. This trend is obvious and to be expected. The second trend is not as usual as the first one. Each magnitude value has a range in which the seismic energy can be emitted. This energy range is considerable as it is close to 100. This means that seismic events of the same magnitude size can emit different seismic energy amounts for which the minimum and maximum might vary by about 100 times. This also means that although with increase of magnitude size there is a general increase in size of released seismic energy this is not always the case. Based on data presented by Fig. 4.1 some seismic energy release range approximations are presented in Table 4.1.

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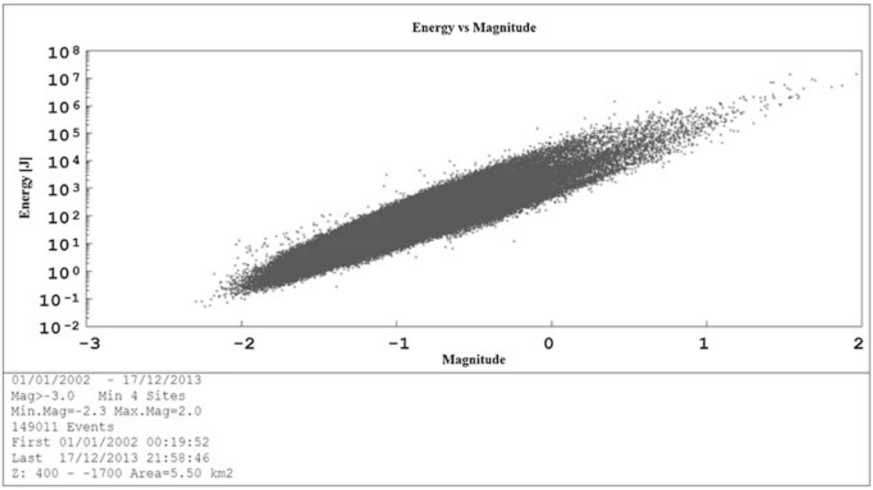

Fig. 4.1 Relation between magnitude values and released seismic energy

Table 4.1 Approximation of seismic energy release ranges

Magnitude size	Energy release	
	Minimum	Maximum
−1.0	10E+00 J	10E+02 J
0.0	10E+02 J	10E+04 J
1.0	10E+04 J	10E+06 J

This table indicates that while the seismic energy release size increase with magnitude it still is possible that a larger size magnitude event will release less or similar amounts of seismic energy than the lower magnitude size event. For example magnitude size 1.0 can release 10E+04 J of energy while event of magnitude size 0.0 can be associated with the same energy release size. In general it is expected that higher magnitude sizes will result in more underground damages but this is not totally true. Underground damage depends on the quantity of seismic energy that reaches the underground excavations. This in turn is not only dependent on the amounts of the seismic energy released but also on the distance this energy had to travel before reaching the underground workings. It is easy to realize that the balance of energy reaching the underground excavations is dependent on the rock mass and its condition.

Figure 4.2 and Table 4.2 illustrate the average energy release sizes per magnitude size. This data is based on seismicity recorded from 2001 until the end of 2010. The horizontal axis of Fig. 4.2 presents the magnitude range from −1.0 up to 2.0 in 0.2 increments. Vertical axis indicates the average energy release in Jules. Additionally Table 4.2 lists total amounts of seismicity in each magnitude range and the total energy released by that magnitude range.

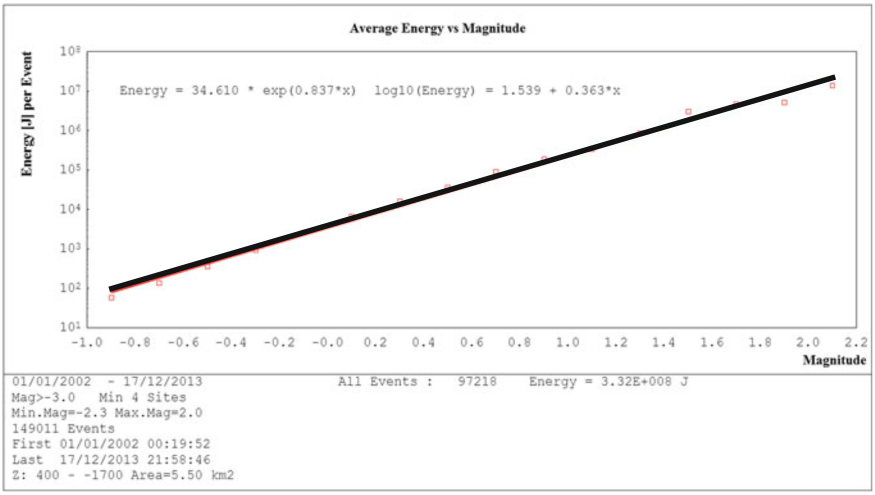

Fig. 4.2 Average energy released per magnitude size

The average seismic energy releases per each magnitude range are the same as the ones presented by Fig. 4.2. The higher the magnitude size the larger is the average seismic energy released size. More interesting piece of information is provided by the total values. Column 2 lists the total numbers of recorded events for magnitude ranges listed in column 1. There is much more of smaller size events than the larger size events. The number of smallest events is in thousands while the largest events are in tens and less. For this reason the average seismic energy release per magnitude size for the lower magnitudes are reliable while the release sizes for the larger seismic events are less reliable values. The seismic energy release ranges even if they are only approximations still provide conclusions of practical significance. Data listed in Table 4.2 clearly indicates that from magnitude 0.0 above the total seismic energy releases are of similar sizes. While the total seismic energy released by the events of magnitude 0.2 up to 0.3 is 1.02E+07 J the total energy released by larger magnitude size events are in the same size range. This indicates that although small size events release small amounts of energy but when put together this energy becomes of significant size. From this it is obvious that if it would be possible to release the strain energy from the rock mass by a large number of small size events rather than limited number of the larger size seismicity it would make the underground mine a much safer environment.

Table 4.3 lists the amounts seismic energy released by earthquakes in Richter's magnitude scale starting with magnitude −2.0 and ending with magnitude of 9.0. Each magnitude size event releases about 32 times more energy than event one magnitude lower. The energy release difference between earthquake magnitude 0.0 and earthquake magnitude 8.0 is about 1,000,000,000,000 (10.0E+12) times. This indicates that the range of energy that can be released is enormous. The smallest earthquake size that we can feel is earthquake of magnitude 1.5. Magnitude 3.0 will

Table 4.2 Energy release sizes

Magnitude range	Number of events	Energy release (J)	Average energy (J)
−1.0 ≤ M < −0.9	13175	6.04E+005	4.59E+001
−0.9 ≤ M < −0.8	14629	9.98E+005	6.82E+001
−0.8 ≤ M < −0.7	14817	1.57E+006	1.06E+002
−0.7 ≤ M < −0.6	13069	2.23E+006	1.70E+002
−0.6 ≤ M < −0.5	10555	2.93E+006	2.77E+002
−0.5 ≤ M < −0.4	8072	3.70E+006	4.59E+002
−0.4 ≤ M < −0.3	6171	4.61E+006	7.47E+002
−0.3 ≤ M < −0.2	4512	5.34E+006	1.18E+003
−0.2 ≤ M < −0.1	3090	6.33E+006	2.05E+003
−0.1 ≤ M < 0.0	2121	6.75E+006	3.18E+003
0.0 ≤ M < 0.1	1441	7.47E+006	5.19E+003
0.1 ≤ M < 0.2	1078	9.30E+006	8.63E+003
0.2 ≤ M < 0.3	754	1.02E+007	1.36E+004
0.3 ≤ M < 0.4	547	1.03E+007	1.88E+004
0.4 ≤ M < 0.5	401	1.31E+007	3.26E+004
0.5 ≤ M < 0.6	261	1.02E+007	3.91E+004
0.6 ≤ M < 0.7	241	1.81E+007	7.49E+004
0.7 ≤ M < 0.8	168	1.86E+007	1.11E+005
0.8 ≤ M < 0.9	115	2.00E+007	1.74E+005
0.9 ≤ M < 1.0	83	1.63E+007	1.97E+005
1.0 ≤ M < 1.1	49	1.33E+007	2.72E+005
1.1 ≤ M < 1.2	28	1.23E+007	4.39E+005
1.2 ≤ M < 1.3	23	1.47E+007	6.38E+005
1.3 ≤ M < 1.4	4	5.79E+006	1.45E+006
1.4 ≤ M < 1.5	13	2.98E+007	2.29E+006
1.5 ≤ M < 1.6	9	3.60E+007	4.00E+006
1.6 ≤ M < 1.7	4	1.07E+007	2.68E+006
1.7 ≤ M < 1.8	2	1.74E+007	8.71E+006
1.8 ≤ M < 1.9	1	4.75E+006	4.75E+006
1.9 ≤ M < 2.0	1	5.38E+006	5.38E+006
2.0 ≤ M < 2.1	1	1.39E+007	1.39E+007

be felt at distances up to 20 km. Events of magnitude 4.5 will result in some damage near the epicentre. Events of magnitude 6.0 are destructive over some restricted areas while events of magnitude of about 7.5 are at the lower limit of major earthquakes (Bullen and Bolt 1985). Effects of earthquakes will include damages to buildings, effects on people and in extreme cases geological effects. To accommodate this number of intensity scales were created. The most commonly used is the Mercalli scale which was modified by Wood and Neumann in 1931. This scale has twelve intensity values, starts with intensity I and ends with intensity of XII. This type of scales is used to catalogue historical earthquakes of which

Table 4.3 Seismic energy releases based on the Guttemberg-Richter formula

Magnitude	Seismic energy (J)	Notes
−2.0	6.3E+01	–
−1.0	2.0E+03	32 times more
0.0	6.3E+04	32 times more
1.0	2.0E+06	33 times more
2.0	6.3E+07	31 times more
3.0	2.0E+09	30 times more
4.0	6.3E+10	33 times more
5.0	2.0E+12	32 times more
6.0	6.3E+13	32 times more
7.0	2.0E+15	32 times more
8.0	6.3E+16	32 times more
9.0	2.0E+18	32 times more

Table 4.4 First known earthquake in South Africa

Date	H:m:s	Geog lat.	Co-ordinates long.	Region and comments	Magnitude	Intensity	Source
1620/04/07	04:00:00	34.0S	18.4E	Robben Island	±4	III–IV	Theron (1974)

descriptions can be found in church records or for example in ancient sailing boat log books. The first position in the South African catalogue of earthquakes (Fernández and Guzman 1979) must have come from a log book of a sailing ship (Table 4.4).

The intensity scale is converted into Richter magnitude scale using the following formula:

$$M = 0.661 * I + 1.0$$

where

M is the magnitude

I is the intensity of the modified Mercalli scale.

In the listed below modified Mercalli intensity scale in brackets are the corresponding Richer magnitude values.

I. Not felt except by a few under especially favourable circumstances (1.7).
II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing (2.3).

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognise it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of a truck (3.0).
IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors, disturbed, walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably (3.7).
V. Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometime noticed. Pendulum clocks may stop (4.3).
VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight (5.0).
VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-build ordinary structures; considerable in poorly build or badly designed structures; some chimneys broken. Noticed by persons driving motor cars (5.7).
VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturb persons driving motor cars (6.3).
IX. Damage considerable in especially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken (7.0).
X. Some well-build wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks (7.7).
XI. Few if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe-lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly (8.3).
XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air (8.9).

Table 4.5 compares the average energy released by the Palabora seismic events in Palabora local magnitude with these with the Richter scale magnitudes.

Table 4.5 and Fig. 4.3 both indicate that for the whole magnitude range the Palabora magnitude events constantly release on average less energy than events of the same magnitude in the Richter scale. The difference is from about 40–22 times for the lower magnitude values to about 10 times at the higher end of the scale. In case of the Palabora mine the largest event was an event of magnitude 2.1. There are mines that experience larger events but not as large as these observed for natural

Table 4.5 Palabora and Richter magnitude energy release comparison

Magnitude	Palabora average energy released	Richter scale energy release	Difference
−0.5	2.8E+02	1.1E+04	40 times
−0.4	4.6E+02	1.6E+04	35 times
−0.3	7.5E+02	2.2E+04	29 times
−0.2	1.2E+03	3.1E+04	26 times
−0.1	2.0E+03	4.4E+04	22 times
0.0	3.2E+03	6.3E+04	20 times
0.1	5.2E+03	8.9E+04	17 times
0.2	8.6E+03	1.2E+05	14 times
0.3	1.4E+04	1.8E+05	13 times
0.4	1.9E+04	2.5E+05	13 times
0.5	3.3E+04	3.5E+05	11 times
0.6	3.9E+04	5.0E+05	13 times
0.7	7.5E+04	6.3E+05	8 times
0.8	1.1E+05	1.0E+06	9 times
0.9	1.7E+05	1.4E+06	8 times
1.0	2.0E+05	2.0E+06	10 times
1.1	2.7E+05	2.8E+06	10 times
1.2	4.4E+05	4.0E+06	9 times
1.3	6.4E+05	5.6E+06	9 times
1.4	1.5E+06	7.9E+06	5 times
1.5	2.3E+06	1.1E+07	5 times
1.6	4.0E+06	1.6E+07	6 times
1.7	2.7E+06	2.2E+07	8 times
1.8	8.7E+06	3.2E+07	4 times
1.9	4.8E+06	4.5E+07	9 times
2.0	5.4E+06	6.3E+07	12 times
2.1	1.4E+07	8.0E+07	6 times

earthquakes. Figure 4.1 illustrates that each Palabora magnitude can have different values of released seismic energy and that this difference is of large extent. On the other hand the Richter magnitude has only one specific energy release size. The Palabora magnitude size is flexible as far the released seismic energy is concerned. What this means and what are the resulting consequences will be analysed in the Chap. 5 describing the interpretation methods.

The energy released by Richter scale magnitude events is a tidy graph as it is based on a specific formula that assigns one energy release size to each magnitude. The graph for the Palabora energy releases is not as neat as it is based on the mean energy release values and these mean values are based on variable in size populations. According to Table 4.2 the number of events in a given magnitude size

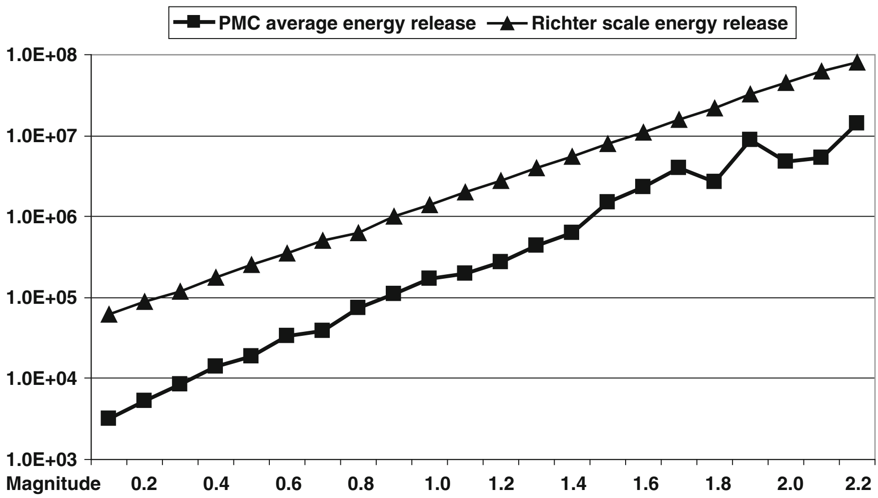

Fig. 4.3 Comparison between seismic energy releases

varies from thousands events for small seismicity, through hundreds and tens of events of medium sizes. At the end of scale in case of the largest events there are only two or one of them. This will result in a "messy" graph. The next fact about the fit of these two graphs is that the difference decreases with increasing magnitude values. The reason for that is probably because the Richter scale is defined rather for larger size events than magnitude 0.0. Also the mine magnitude scale could be calibrated with the national network magnitude scale only in magnitude range above 2.0 as smaller mine events are not recorded by the national network. From this it appears that the fit between the mine and Richter scales on the lower end of the scale might be not so good as for the top end of the scale. The other matter is the fact that the mine magnitude is a mean one. This is an interesting problem, if the mine events of the same magnitudes release different amounts of energy is this change random or is there a pattern? If there is a pattern then from what is it dependent?

Table 4.6 lists the largest size seismicity recorded in the mines. The largest events are associated with the potash mines in Germany and with goldmines in

Table 4.6 Largest mine induced seismic events (Gibowicz and Kijko 1994)

Date	Magnitude	Place
13/03/1989	M_L = 5.5	Potash Mining District, South Germany
09/03/2005	M_L = 5.3	Klerksdorp, South Africa
23/06/1975	M_L = 5.2	Potash Mining District, South Germany
07/04/1977	M_L = 5.2	Klerksdorp, South Africa
24/03/1977	M_L = 4.5	Lubin Copper Mining District, Poland

Table 4.7 Potentially damaging events—Klerksdorp area

Magnitude size	1989	1990	1991	1992	1993	1994	1995	1996
Above 4.0	2	2	3	0	5	1	2	1
3.0–4.0	57	87	121	118	102	84	70	69
2.0–3.0	351	432	814	793	625	641	554	443
Fatalities due to seismic events	6	28	11	12	18	10	5	16

South Africa. The largest recorded to date was an event of magnitude 5.5 which according to the modified Mercalli scale would be classified as of intensity VII that is as an earthquake of negligible consequences. Still one has to take into account the depths of the earthquakes. In global seismology shallow earthquakes are those that take place up to 60 km below the surface. The Mercalli intensity scale makes use of damages or no damages taking place tens of kilometres from the earthquake source. The seismicity recorded in the underground mines is much shallower and in general clusters around the mining depths. For this reason events of magnitude from 1.0 up to 5.5 that in global seismology are considered to be of no consequence to life or man-made constructions in case of them taking place in mines are of great significance.

One of the largest events in the history of the Klerksdorp Goldfields took place on 7th April 1977 at Vaal Reefs. This tremor was recorded by 40 seismological stations around the world and the US Geological Survey assigned a body wave magnitude (m_b) of 5.5 to it (Fernández and van der Heever 1984). The local Richter magnitude was determined by the South African Geological Survey to be 5.2. The main tremor was followed by an aftershock swarm (Fernández and Labuschagne 1979). All access tunnels close to the focal region were rendered inaccessible, while scattered falls occurred over an area of approximately 7.0 km^2. The main shock also resulted in appreciable damage to structures in the surrounding towns of Klerksdorp, Orkney and Stilfontein. No life was lost. Unfortunately this not always was and still is not the case. The extent of the hazard resulting from seismic events is illustrated by Table 4.7 which shows the amount of potentially damaging events in the Klerksdorp area from 1989 to end of 1996, together with the number of fatalities due to seismic events, for the same period (Glazer 1998). The results of alleviating this hazard are described in Glazer (2000). It is also important to realise that in those years during the morning shift there were over 24,000 miners underground. The magnitude sizes are in local magnitude values.

4.2 Seismic Moment

Figure 4.4 illustrates the relation between the magnitude values and the seismic moment This relation is based on nearly 145,000 seismic events in magnitude range from −2.0 up to 2.0. The moment varies from less than 10E+06 Nm for

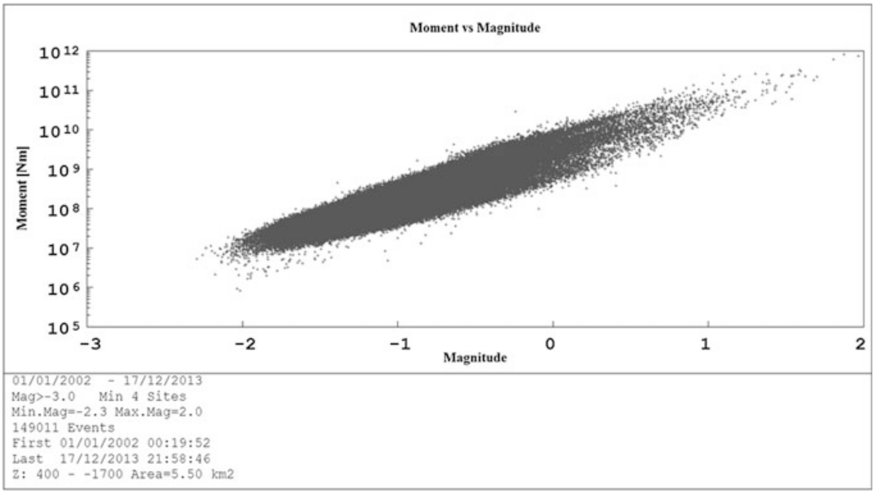

Fig. 4.4 Relation between magnitude and seismic moment

Table 4.8 Approximation of seismic moment ranges

Magnitude size	Seismic moment	
	Minimum	Maximum
−1.0	10E+07 Nm	10E+08 Nm
0.0	10E+08 Nm	10E+09 Nm
1.0	10E+10 Nm	10E+11 Nm

magnitude −2.0 up to 10E+12 Nm for magnitude 2.0. This means that the moment extend for magnitude range from −2.0 up to +2.0 is one million times. Two trends are clearly evident. The first one is that with increasing magnitude values there is a general increase of the seismic moment. The second trend is that each magnitude value has a range of moment values. This range is about 10 which is less than in case of the seismic energy (100). This means that although with increase of magnitude size there is a general increase in seismic moment but that is not totally correct. Based on data presented by Fig. 4.4 seismic moment sizes approximations are presented in Table 4.8.

Table 4.8 indicates that while the seismic moment ranges increase with magnitude sizes it still is possible that a larger size magnitude event will have a lower seismic moment than the lower magnitude size event.

Figure 4.5 and Table 4.9 illustrate the average seismic moment values per magnitude size. This data is based on seismicity recorded from 2001 until the end of

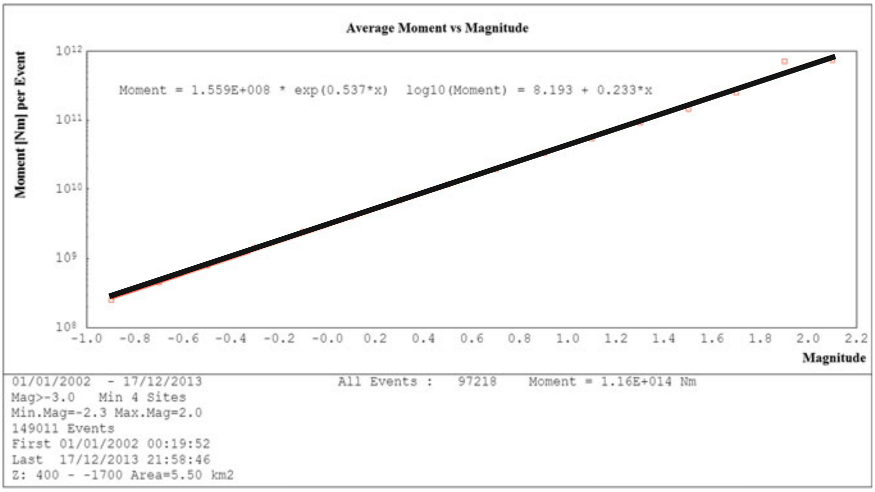

Fig. 4.5 Average seismic moment per magnitude size

2012. The horizontal axis of Fig. 4.5 presents the magnitude range from −1.0 up to 2.0 in 0.2 increments. Vertical axis indicates the average seismic moment in Nm. Additionally Table 4.9 lists total number of seismicity in each magnitude range and its total seismic moment. This table indicates that for example the total seismic moment of seismic events magnitude range from −1.0 up to −0.9 which is 2.72E+12 Nm is 3.7 times more than the seismic moment of the largest seismic event magnitude 2.1 which is 7.42E+11 Nm. This observation applies to all small and medium size events.

Kanamori (1977) estimate of radiated seismic energy (for larger size events):

$$\text{Energy} = \text{Moment}/20{,}000$$

Knowing earthquake energy release estimates values (Table 4.10) it is possible to use the Kanamori formula to estimate the seismic moment values. It seems that even as this formula was derived for larger size events it still provides reasonable values for small events of magnitude 0.0, 1.0 and 2.0 as they are well-matched with values derived from processing mine events. This correlation is especially good for magnitude 1.0 and 2.0 and not so excellent for events of magnitude 0.0. The Kanamori estimate formula is for larger size events and the Palabora seismic moments are average ones which imply that for seismic moment there is a range and not one specific value. The range of moment for magnitude 0.0 is from 10E+08

Table 4.9 Palabora seismic moment values

Magnitude range	Number of events	Cumulated seismic moment (Nm)	Average moment (Nm)
−1.0 ≤ M < −0.9	13164	2.72E+12	2.07E+08
−0.9 ≤ M < −0.8	14612	4.17E+12	2.85E+08
−0.8 ≤ M < −0.7	14811	5.73E+12	3.87E+08
−0.7 ≤ M < −0.6	13067	6.78E+12	5.19E+08
−0.6 ≤ M < −0.5	10553	7.36E+12	6.98E+08
−0.5 ≤ M < −0.4	8071	7.41E+12	9.18E+08
−0.4 ≤ M < −0.3	6170	7.67E+12	1.24E+09
−0.3 ≤ M < −0.2	4512	7.39E+12	1.64E+09
−0.2 ≤ M < −0.1	3090	6.47E+12	2.09E+09
−0.1 ≤ M < 0.0	2121	5.93E+12	2.80E+09
0.0 ≤ M < 0.1	1441	5.07E+12	3.52E+09
0.1 ≤ M < 0.2	1078	4.94E+12	4.58E+09
0.2 ≤ M < 0.3	754	4.42E+12	5.86E+09
0.3 ≤ M < 0.4	547	4.61E+12	8.43E+09
0.4 ≤ M < 0.5	401	4.27E+12	1.06E+10
0.5 ≤ M < 0.6	261	3.51E+12	1.35E+10
0.6 ≤ M < 0.7	241	4.06E+12	1.68E+10
0.7 ≤ M < 0.8	168	3.94E+12	2.35E+10
0.8 ≤ M < 0.9	115	3.27E+12	2.84E+10
0.9 ≤ M < 1.0	83	3.42E+12	4.11E+10
1.0 ≤ M < 1.1	49	2.39E+12	4.87E+10
1.1 ≤ M < 1.2	28	1.85E+12	6.59E+10
1.2 ≤ M < 1.3	23	2.30E+12	1.00E+11
1.3 ≤ M < 1.4	4	4.46E+11	1.11E+11
1.4 ≤ M < 1.5	13	1.62E+12	1.25E+11
1.5 ≤ M < 1.6	9	1.60E+12	1.77E+11
1.6 ≤ M < 1.7	4	1.11E+12	2.78E+11
1.7 ≤ M < 1.8	2	4.04E+11	2.02E+11
1.8 ≤ M < 1.9	1	6.08E+11	6.08E+11
1.9 ≤ M < 2.0	1	8.28E+11	8.28E+11
2.0 ≤ M < 2.1	1	7.42E+11	7.42E+11

Nm up to 10E+09 Nm (Table 4.8) so even for this small events size the Kanamori moment estimate is surprisingly well in line with the mine observations. The largest mine seismic events have seismic moment values in range E+18Nm. The largest known earthquake seismic moment was about 10E+22 Nm.

Table 4.10 Earthquake magnitudes and seismic moment values

Magnitude	Seismic energy (J)	Seismic moment (Nm)	Palabora seismic moment values from Table 4.8
0.0	6.3E+04	1.3E+08	2.80E+09 Nm
1.0	2.0E+06	4.0E+10	4.11E+10 Nm
2.0	6.3E+07	1.3E+12	7.42E+11 Nm
3.0	2.0E+09	4.0E+13	–
4.0	6.3E+10	1.3E+15	–
5.0	2.0E+12	4.0E+16	–
6.0	6.3E+13	1.3E+18	–
7.0	2.0E+15	4.0E+19	–
8.0	6.3E+16	1.3E+21	–
8.9	1.4E+18	3.0E+22	–

4.3 Seismic Energy Release Per Seismic Moment Ranges

Figure 4.6 illustrates the relation between seismic moment and released seismic energy. This relation is based on over 147,000 seismic events recorded between 01/01/2002 and 28/08/2013. The weighted orthogonal fit for his set of data is:

$$\mathrm{Log}\,E = 1.777 * \log Mo - 13.590$$

Figure 4.6 confirms that for Palabora the seismic energy release range is between 10E-01 and 10E+07 J and that the seismic moment range is between 10E+07 and

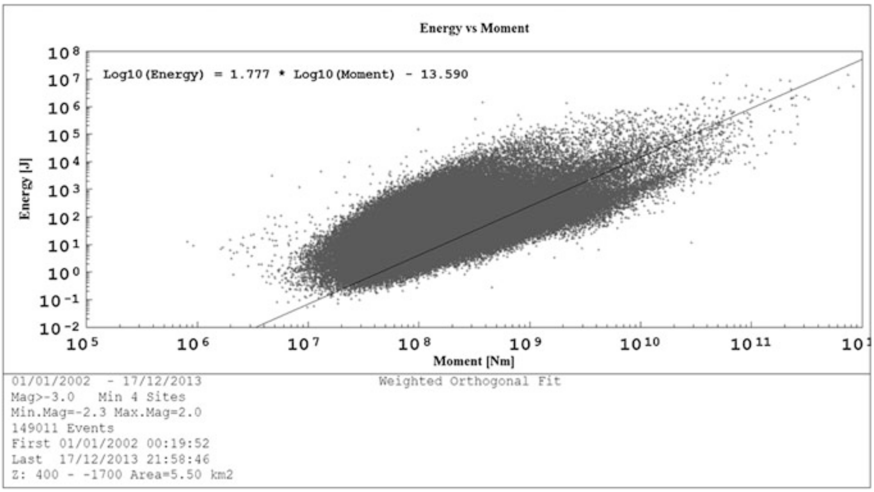

Fig. 4.6 Palabora relation between seismic moment and released seismic energy

Table 4.11 Approximation of ranges of energy per moment

Moment size	Energy size	
	Minimum	Maximum
10E+08 Nm	10E+00 J	10E+03 J
10E+09 Nm	10E+01 J	10E+04 J
10E+10 Nm	10E+02 J	10E+05 J

Table 4.12 Average seismic energy emission per moment

Value	Moment (Nm)					
	10E+07	10E+08	10E+09	10E+10	10E+11	10E+12
Seismic energy J	0.06	3.7	217	12.8E+03	7.5E+05	4.4E+07
Magnitude	Below −1.0	−1.0	−0.4	0.4	1.2	Above 2.1

10E+12 Nm. The more important fact is that for every moment value there is an energy range and that according to Table 4.11 this range is close to 1,000 times. As this energy range size per moment is large enough to be well above the estimation error then a question has to be raised: why it is there and what it indicates?

Table 4.12 lists the average seismic energy emissions per seismic moment values which are calculated by using formula as presented by Fig. 4.6. This table also lists magnitude values per each moment. These values are only approximate and are according to Table 4.9.

4.4 Apparent Stress Ranges

Figure 4.7 illustrates the relation between seismic moment and apparent stress. It is interesting to note the apparent stress range is between 10E+02 and 10E+07 Pa (Table 4.13).

In practice all of the analysed to date relations can be reduced to the relation between the released seismic energy and seismic moment.

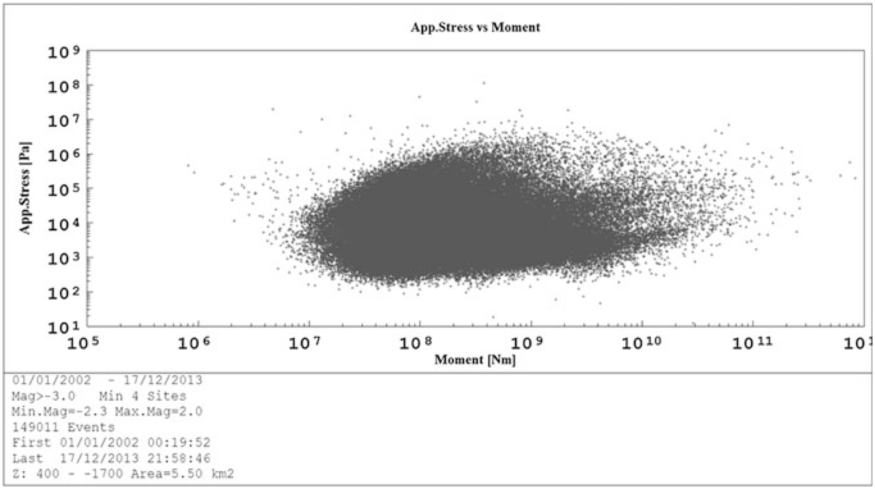

Fig. 4.7 Seismic moment versus apparent stress

Table 4.13 Apparent stress ranges per seismic moment

Moment size	Apparent stress range	
	Minimum	Maximum
10E+08 Nm	10E+03 Pa	10E+06 Pa
10E+09 Nm	10E+03 Pa	10E+06 Pa
10E+10 Nm	10E+03 Pa	10E+06 Pa

4.5 Energy S Versus Energy P

According to Gibowicz and Kijko (1994) “the ratio of the energy released by the S-wave to the P-wave is an important indicator of the type of focal mechanism responsible for the generation of seismic events in the mines. There is definite evidence from natural earthquakes that the energy radiated in P waves is a small fraction of that in S waves, with the ratio Es/Ep ranging between 10 and 30”. According to the authors for the small seismicity recorded in several mines (none of these mine was a cave mine this ratio changes from 1.5 up to 30. For about 60 % of these mines’ seismicity this ratio was lower than 10.0. The lower is the Es/Ep ratio the more energy was released by the P-waves indicating a higher tensile component in the source mechanism. On the other hand the higher this ratio is the higher is the contribution of energy released by the S-wave indicating a higher component of the double couple mechanism in the source. For this reason the high percentages of seismicity with ES/Ep ratios above 10.0 indicate that the principal caving process mechanism is shear failure (Table 4.14).

Figure 4.8 illustrates the energy released by S-wave for events magnitude range −2 up to 2.0.

Table 4.14 Es and Ep per magnitude sizes

Magnitude	Es	Ep	Es/Ep
−1.0	23.33 J	1.10 J	21.2
0.0	4.65E+03 J	2.03E+02 J	22.7
1.0	9.29E+05 J	3.70E+04 J	25.1

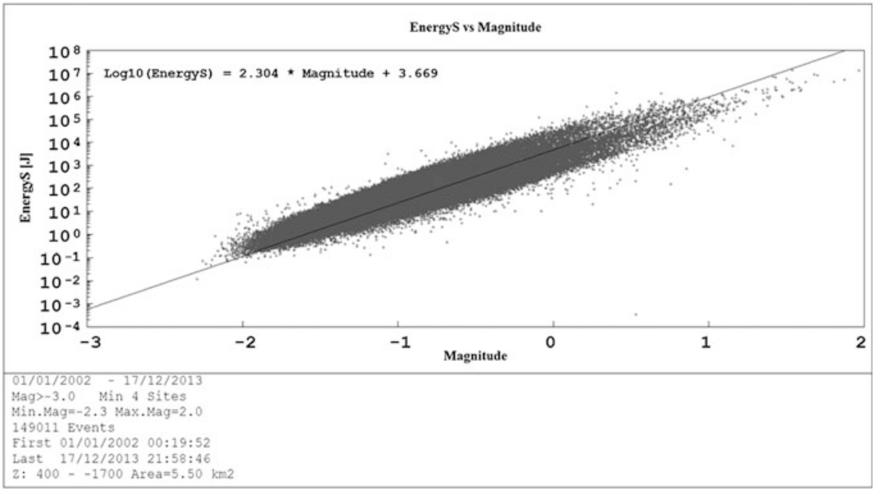

Fig. 4.8 Palabora magnitudes versus energy released by S-wave

Figure 4.9 illustrates the energy released by P-wave for events magnitude range −2 up to 2.0.

Table 4.15 illustrates the fact that the energy released by S-waves range is larger from that for energy released by P-waves. The P-wave energy range fits into the S-wave energy range.

From Fig. 4.8 log Es = 2.304 × Mo+3.669

From Fig. 4.9 log Ep = 2.271 × Mo+2.315

These two formulas were used to calculate values of Es and Ep for seismic events magnitude −1.0, 0.0 and 1.0 which are presented in Table 4.14. Last column of this table presents the Es/Ep ratios.

From Table 4.14 the average Es/Ep ratio for Palabora is 23.0. It is high and indicates the fact that most of the seismicity induced by the caving process is of double-couple mechanism. The total seismic energy released at Palabora from 01/01/2002 until 31/01/2012 was 3.33E+08 J. This means that during that time only 1.38E+07 J of the energy (about 5 % of the total) was released by P-waves and 3.19E+08 J of energy (close to 95 % of the total) was released by the S-waves.

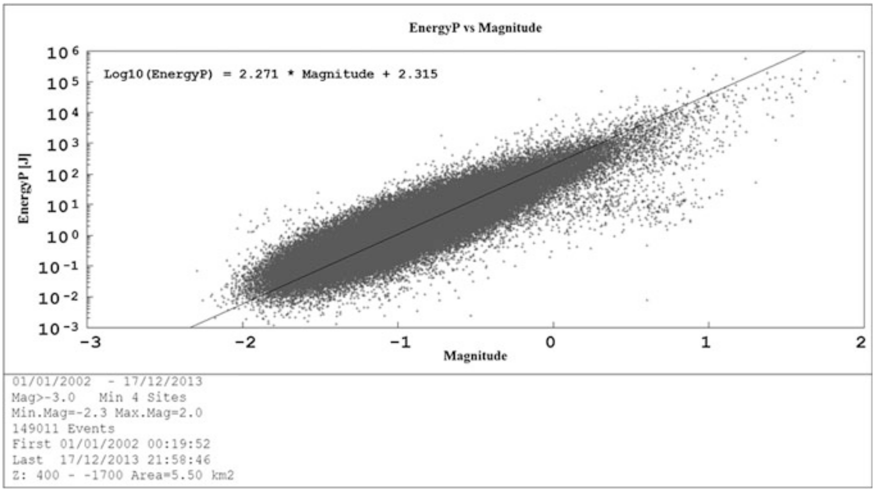

Fig. 4.9 Palabora magnitudes versus energy released by P-wave

Table 4.15 Energy release ranges

Energy	Energy range	
	Minimum	Maximum
Energy S-wave	10E-01 J	10E+07 J
Energy P-wave	10E-03 J	10E+05 J

4.6 Mine Induced Seismicity and Earthquakes

As a matter of interest I will now present data that relates the amounts of released energy by TNT explosions and then compare them with seismic events. This, should, put seismic events into right perspective. To start with I must make several assumptions

$$m = 5.4 + 0.4 * \log AY$$

This formula (Båth 1973) presents the approximate relation between the body wave magnitude (m) the yield (Y) in kilotons and the seismic coupling factor (A). Seismic coupling factor is a ratio of the seismic energy to the total energy. The coupling depends on a number of factors like for example where the explosion is taking place, underground and at what depth or in the air above the surface. For my calculations I will use the following values for the coupling factor:

$A = 1 \times 10^{-3}$ for underground explosion

$A = 1 \times 10^{-5}$ for an explosion at altitude of 1 km.

This means that the underground explosion is about 100 times more efficient than one in the air. The body wave magnitude (m) will be recalculated into a magnitude based on a surface wave (M) using the following formulae (Bullen and Bolt 1985):

$$M = 1.58m - 3.96$$

And finally the released seismic energy (E) will be calculated using formulae:

$$\text{Log}\,E = 11.8 + 1.5M\,(\text{erg})$$

Remainder: 1 erg = 10^{-7} J

According to Table 4.16 the atom bomb dropped on Hiroshima by the end of WW2 had a yield of 20kt of TNT. The largest and most powerful weapon ever exploded was the Tsar Bomb a hydrogen bomb with a yield of 57,000kt of TNT, It was exploded 30.10.1961. This hydrogen bomb in its yield was equal to 2850 atom

Table 4.16 Total energy and seismic energy released during TNT explosions

Exploded amount of TNT	Total energy (J)	Seismic energy (J)	Approximate Richter magnitude	Notes
1 kg 0.000001kt	9.2E+05	1.3E+03	−1.1	u/g explosion
10 kg 0.00001kt	8.2E+06	1.2E+04	−0.5	u/g explosion
100 kg 0.0001kt	7.3E+07	1.1E+05	0.1	u/g explosion
1 ton 0.001kt	6.5E+08	9.3E+05	0.8	u/g explosion
1kt	4.5E+11	6.5E+08	2.7	u/g explosion
20kt	7.8E+12	1.1E+10	3.5	Hiroshima atom bomb u/g explosion
20kt	7.8E+12	1.4E+08	2.3	Hiroshima atom bomb explosion in air
100kt	3.6E+13	5.1E+10	3.9	u/g explosion
500kt	1.6E+14	2.3E+11	4.4	u/g explosion
750kt	2.4E+14	3.4E+11	4.5	u/g explosion
1000kt (1Mt)	3.2E+14	4.5E+11	4.6	u/g explosion
5000kt (5Mt)	1.5E+15	2.1E+12	5.0	u/g explosion
10,000kt (10Mt)	2.8E+15	4.0E+12	5.2	u/g explosion
20,000kt (20Mt)	5.4E+15	7.8E+12	5.4	u/g explosion
30,000kt (30Mt)	8.0E+15	1.1E+13	5.5	u/g explosion Largest u/g seismic event
50,000kt (50Mt)	1.3E+16	1.8E+13	5.6	u/g explosion Larges man-made explosion

(continued)

Table 4.16 (continued)

Exploded amount of TNT	Total energy (J)	Seismic energy (J)	Approximate Richter magnitude	Notes
100,000kt (100Mt)	2.5E+16	3.4E+13	5.8	u/g explosion
1,000,000kt (1,000Mt)	2.2E+17	3.2E+14	6.5	u/g explosion
2,000Mt	4.3E+17	6.2E+14	6.7	u/g explosion
10,000Mt	1.9E+18	2.8E+15	7.1	u/g explosion
20,000Mt	3.8E+18	5.4E+15	7.3	u/g explosion
100,000Mt	1.7E+19	2.5E+16	7.7	u/g explosion
500,000Mt	8.0E+19	–	–	–
1,000,000Mt	1.5E+20	2.2E+17	8.4	u/g explosion
50,000,000Mt	6.3E+21	9.0E+18	9.4	–
75,000,000Mt	9.2E+21	1.4E+19	9.5	Largest earthquake

bombs dropped on Hiroshima. The Hiroshima bomb if exploded underground would result in an earthquake of magnitude 3.5. It was exploded in air and this detonation would result in an earthquake of magnitude 2.3. The Tsar Bomb with magnitude 5.6 seismic energy release is still remote from the seismic energy released by the largest earthquake. The difference between these two energy releases is about one million times.

Table 4.17 compares the largest seismic events recorded in the mines with their equivalent in TNT yields. The largest of these events magnitude 5.5 is comparable to energy released by 30,000kt which is 1500 times the 20kt atom bomb dropped on Hiroshima. Magnitude 3.2 and larger size seismic events at the South African gold mines are not that rare. According to Table 4.16 a magnitude 3.5 event is equal as far as energy release is concerned to an explosion of 20kt of TNT, which is the amount of energy released by the atom bomb dropped at Hiroshima. Very often these large size events do not result in much damage. The underground mine survives much larger explosions. Why? The answer as to why this is so is because the seismic efficiency is very low. The seismic efficiency is the ratio of the seismic

Table 4.17 Largest mine seismicity and TNT explosions

Exploded amount of TNT	Seismic energy	Magnitude	Place
30,000kt	1.1E+13	5.5	Potash Mining District, South Germany (13/03/1989)
Nearly 20,000kt	7.8E+12	5.3	Klerksdorp, South Africa (09/03/2005)
10,000kt	4.0E+12	5.2	Potash Mining District, South Germany (23/06/1975) Klerksdorp, South Africa (07/04/1977)
750kt	3.4E+11	4.5	Lubin Copper Mining District, Poland (24/03/1977)

energy to the total energy released during an earthquake. The strain energy released during a tremor is consumed mainly in heat and friction. It is estimated that only between 0.3 and 5 % of the total released energy is transmitted by the seismic waves. Understanding seismicity and it relation to rock mass extraction means linking seismic activity with various quantities characterizing mining works. In the studies carried out in gold mines in South Africa (Cook 1976, or McGarr and Wiebols 1977) the sum of released seismic energy per excavation area was assumed to be a criterion of rock burst hazard. High values of released energy were interpreted as an increase in the number of formed fractures leading to a rock burst. For a gold reef of approximately 1 m thickness, assuming that the change in potential energy of a system resulting from mining is equal to the product of weight of mined rocks and their depth, it was shown that no more than half of this energy can be stored as elastic energy (Cook 1976). The rest of the energy must be then released in different forms, such as heat and friction. The amount of resulting elastic energy is debatable, but the main conclusion that the seismic energy is proportional to the volume of the mined out rock is still valid at least for mining tabular deposits. Seismic efficiency is very low. McGarr (1976) has estimated the seismic efficiency in a gold mine in South Africa by comparing the total energy released by the closure of mine excavation with the observed seismic energy radiated during the same time interval and he has found the value of about 0.24 %. The strain energy released during a rupture is consumed in heat, rock mass crushing and seismic waves. A similar result concerning seismic efficiency was found in a study of the Lubin tremor of 1977 in a copper mine in Poland, where its value was estimated to be close to 0.5 % (Gibowicz et al. 1979).

I have estimated the seismic efficiency at Palabora to be 0.3 %. The relation between apparent stress (σ_a) and the average stress at the seismic source (σ) is as follows (Wyss and Brune 1968):

$$\sigma_a = \mu \sigma$$

The average stress at the seismic source is defined as half of the sum of the stress before and after the seismic event. The value of apparent stress is determined for every recorded event using the estimated values of seismic energy and seismic moment However, the seismic efficiency and the average stress cannot be determined separately. Still the seismic method can be used to establish their product. The value of apparent stress at Palabora is 0.13 MPa. This value was based on data from 19 largest events recorded with a minimum of eight stations. According to McGarr et al. (1979) from their studies of tremors in mines, they concluded that the ruptures are produced by shear stresses between 40 and 70 MPa in the source area, and that these stresses increase with depth. The seismic efficiency value of 0.3 % and apparent stress value of 0.13 MPa results in average stress of about 44 MPa. This value of seismic efficiency fits well with other observed and theoretical data.

Table 4.18 lists the total earthquake and seismic energy released by earthquakes from magnitude 0.0 in magnitude 1.0 increments up to magnitude 9.0. It is assumed that seismic efficiency is 0.5 %. From this table it appears that the largest seismic

Table 4.18 Earthquake and seismic energy releases

Magnitude	Earthquake energy (J)	Seismic energy (J)
0.0	1.3E+07	6.3E+04
1.0	4.0E+08	2.0E+06
2.0	1.3E+10	6.3E+07
3.0	4.0E+11	2.0E+09
4.0	1.3E+13	6.3E+10
5.0	4.0E+14	2.0E+12
6.0	1.3E+16	6.3E+13
7.0	4.0E+17	2.0E+15
8.0	1.3E+19	6.3E+16
9.0	4.0E+20	2.0E+18

Table 4.19 Earthquake energy releases and South Africa electricity consumption

Mag	Seismic energy		Earthquake energy	
	Energy (J)	SA consumption	Energy (J)	SA consumption
0.0	6.3E+04	2.35E-06 s	1.3E+07	4.78E-04 s
1.0	2.0E+06	7.35E-05 s	4.0E+08	0.015 s
2.0	6.3E+07	0.0023 s	1.3E+10	0.47 s
3.0	2.0E+09	0.07 s	4.0E+11	15 s
4.0	6.3E+10	2.3 s	1.3E+13	8 min (480 s)
5.0	2.0E+12	1.22 min	4.0E+14	4 h (240 min)
6.0	6.3E+13	0.64 h (39 min)	1.3E+16	5.5 days (132 h)
7.0	2.0E+15	0.85 day (20 h)	4.0E+17	170 days
8.0	6.3E+16	26 days (0.07 year)	1.3E+19	15 years
8.9	1.4E+18	1.6 years	2.8E+20	325 years

energy releases recorded in underground mines (close to E+12 J) are equivalent to small earthquakes magnitude between 3.0 and 4.0 that in global seismology are regarded to be harmless.

Finally to illustrate the earthquakes energy release ranges I will compare it with electrical energy and its consumption. South Africa produces annually around 240300 gigawatt-hours (865,000 TJ) of electricity. Some of it is exported but some electricity is also imported. For this reason it can be assumed that all produced electricity is consumed. Table 4.19 takes this yearly consumption and compares it with energy released by seismicity magnitude sizes from 0.0 up to the maximum magnitude of 8.9. This comparison includes both seismic and the total earthquake energy.

Here not only energy release values but the time they would take care of the South Africa electricity consumption demands are extreme in values. Palabora experienced u/g damage after seismicity magnitude just below 1.0. The total energy released by this size earthquake and then converted into electricity with 100 %

efficiency would be consumed in less time than it takes to blink an eye. Apparently a blink of an eye takes about 300 ms. If that is the case then the electrical energy converted from total energy released by a 1.0 earthquake would be consumed by South Africa in a time period that is about 20 times less than it takes to blink an eye. The largest mine seismic event of magnitude 5.5 would produce a bit more of electricity that would last for about 1 day (total energy) or for a couple of minutes (seismic energy). The largest earthquake size released energy would last South Africa for over 300 years. The seismic energy released by such large size earthquake if it could be converted into electrical energy would be enough for just more that the one and a half year consumption.

The earthquake energy is released in a fraction of a second. Nature has some more in its armory. A tropical hurricane can release in 24 h as much energy as a developed, medium size nation as Britain or France uses in a year.

By end of 2013 the total seismic energy released at Palabora amounted to 3.33E +08 J while the total moment was at 1.21E+14 Nm. When converting these two totals into magnitudes the following emerge:

- Energy converted to magnitude using Guttenberg–Richter relation results in magnitude 2.5

$$\text{Richter magnitude Log E} = 11.8 + 1.5\text{M (erg)}$$

- Moment converted into magnitude results in magnitude 3.4

$$\text{Moment magnitude Mm} = 0.667 \log \text{ Mo} - 6.01$$

- Moment and energy converted into Palabora magnitude results in magnitude 3.2

$$\text{Palabora magnitude Ml} = 0.272 \log \text{ E} + 0.392 \log \text{ Mo} - 4.63$$

From the mining point of view seismic events of magnitude between 2.5 and 3.4 are rather large size events that could result in risk to the operation of the mine. Earthquakes of these sizes are of no consequence and according to Table 4.21 are classified as minor.

Table 4.20 lists the seismic energy that was released from the beginning of 2002 until middle of 2013 in certain magnitude ranges (column 1). Column 2 lists the number of seismic events per magnitude range, column 3 lists the seismic energy that was released per magnitude range and column 4 provides the cumulative energy as it increases from range to range. Column 5 provides the cumulative percentages of the released energy. Seismicity in magnitude −1.0 up to −0.5 released 2.5 % of the total seismic energy. Seismicity of this magnitude range with the next magnitude range (−0.5 up to 0.0) released together 10.5 % of the total energy. When analysing these percentages it becomes evident that even the small size seismicity in case of mine induced seismicity contribute strongly towards the energy balance. Small size events up to magnitude size 0.5 that could be classified

Table 4.20 Palabora total seismic energy release in magnitude ranges

Magnitude range	Number of events	Energy (J)	Cumulative energy (J)	Cumulative percentages	Notes
−1.0 < M < −0.5	66221	8.32E+06	8.32E+06	2.5	–
−0.5 < M < 0.0	23908	2.67E+07	3.50E+07	10.5	–
0.0 < M < 0.5	4193	5.02E+07	8.52E+07	25.7	–
0.5 < M < 1.0	854	8.29E+07	1.68E+08	50.8	u/g damage
1.0 < M < 1.5	111	7.47E+07	2.43E+08	73.4	–
1.5 < M < 2.0	17	7.42E+07	3.17E+08	95.8	–
2.0 < M < 2.5	1	1.39E+07	3.31E+08	100.0	4.2 % energy released by largest event

as minor released 25 % of the total energy. On the other hand the largest size event was responsible for only 4.2 % of the released seismic energy.

Table 4.21 lists the seismic energy by earthquakes taking place during 1 year. Data listed in Table 4.21 is after the USGS National Earthquake Information Centre and it illustrates the frequency of earthquakes during 1 year for the whole globe.

Other values of average number of events per year are estimates.

The seismic energy for each magnitude range (column 4) is based on the largest for this range magnitude, for example for the range 5.0–5.9 the energy is calculated for magnitude 5.9. For magnitudes above 8.0 I used magnitude 8.5 for the calculations. Magnitude range in Table 4.21 starts where it ends in Table 4.20. The minor events (up to magnitude 3.9) release only 0.6 % of the total energy. The major and great events are responsible for the 80 % of the released energy. This is a reverse pattern of the energy released by mine induced seismicity. In practice this means that it is not possible to avoid or stop the major or great events taking place. In order to release seismic energy of earthquake magnitude above 8.0 there should be during 1 year (in an area of size close to that of Chile or Alaska):

Table 4.21 Frequency of earthquake occurrence

Magnitude range	Class	Average per year	Energy (J)	Total seismic energy (J)	Cumulative energy (J)	Cumulative percentage
2.0–2.9	Minor	1,300,000	1.4E+09	1.82E+15	1.82E+15	0.1
3.0–3.9		130,000	4.5E+10	5.85E+15	7.67E+15	0.6
4.0–4.9	Light	13,000[b]	1.4E+12	1.82E+16	2.59E+16	2
5.0–5.9	Moderate	1319[b]	4.5E+13	5.93E+16	8.52E+16	7
6.0–6.9	Strong	134[a]	1.4E+15	1.87E+17	2.72E+17	21
7.0–7.9	Major	15[a]	4.5E+16	6.75E+17	9.47E+17	73 %
Above 8.0	Great	1[a]	3.5E+17	3.54E+17	1.30E+18	100

[a]Based on observations since 1900
[b]Based on observations since 1990

Table 4.22 Largest recorded earthquakes

No	Location	Date	Moment magnitude
1	Valdivia, Chile	22 May 1960	9.5
2	Sumatra, Indonesia	26 December 2004	9.3
3	Prince William Sound, Alaska, USA	17 March 1964	9.2
4	Kamchatka, USSR	04 November 1952	9.0
5	Arica, Chile	13 August 1868	9.0
6	Cascadia subduction zone, Canada and USA	26 January 1700	9.0
7	Maule, Chile	27 February 2010	8.8
8	Ecuador and Columbia	31 January 1906	8.8
9	Sumatra, Indonesia	25 November 1833	8.8
10	Rat Islands, Alaska,USA	04 February 1965	8.7
11	Lisbon, Portugal	01 November 1755	8.7
12	Valparaiso, Chile	08 July 1730	8.7

a. 100,000,000 events of magnitude 4.0 (274,000 events per day) or
b. 1,000,000 events of magnitude 5.0 (2740 events per day) or
c. 100,000 events of magnitude 6.0 (274 events per day) or
d. 1,000 events of magnitude 7.0 (2.7 events per day).

The above is only an estimate but it proves the point that there is nothing that can stop a major or great earthquake taking place. Table 4.22 lists the largest twelve earthquakes that were experienced to date. Data listed in Table 4.22 is after the USGS National Earthquake Information Centre. The earthquake off 12 December 2004 is the first magnitude 9.3 event since the general adoption of the seismic moment magnitude scale. The Richter scale is no longer applied to such large earthquakes. The 9.5 moment magnitude earthquake in Chile of 22 May 1960 would reach magnitude 8.5 on the Richter scale.

4.7 Summary

Seismic source parameters are the result of an estimation process. Estimation or scientific guess is an approximation of the parameter value in opposition to its measurement. The important matter is the reliability and validity of these estimates. These two reliability and validity together define if what we assume in fact is a parameter and if it is consistent. When as reliability we will assume the extent to which the seismic system (hardware and software produces stable and consistent estimates of the parameters then it is evident that there is no reliability in these parameters (See Chap. 9). The parameters values depend on the input used for its estimation process. Reliability on its own is not enough as the parameter estimate still has to be valid. Validity can be assesses by comparing the same parameter estimates performed with different tools in this case different software versions from the same source or software from two or more different sources. There is no validity as with each software version the seismic system user must recalculate the data base to keep its consistency. This is because each software version results in different estimates of the seismic source parameters So seismic source parameters as such have no reliability and are not valid as estimates. If that is the case then what about the parameters describing the seismicity that are based on source parameters? Can they be reliable and also valid? Their reliability can be tested in the analysis and interpretation process. If the results are stable and consistent then the parameters should be considered as reliable. Validity of the seismicity parameters analysis and interpretation is assessed with other non-seismic data in this case the mining process, geology or other geotechnical data that is available. In many cases seismicity parameters were proven to be valid. In this way parameters describing the seismic source are not reliable and not valid while parameters describing seismicity are reliable and valid. Where then starts the reliability and validity? The answer is that it must depend from the quantity of seismicity. That this seismicity must be consistent there is no question. It also seems correct to presuppose that the more seismicity available for analysis and interpretation the more reliable and valid will be the result. This implies that the lesser is the input seismicity for analysis and interpretation the less and less reliable and less valid will be the results. Short term hazard analysis is based on limited amount of input seismicity and for this reason will be unreliable and will have no validity. On the other hand analysis and interpretation of data based on large amounts of seismicity as for example monitoring the caving process will be reliable and valid.

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Chapter 5
Interpretation Methods of Mine Induced Seismicity

Abstract Having described parameters the last chapter of part one deals with interpretation methods. This chapter also describes limitations of seismic data and of the interpretation methods. This is a very important part. The presented limitations of the seismic data should not be seen as pessimistic but as a realistic description of the problem. It is still possible to analyse and interpret data which originated in the process of an educated estimate. And what more nothing prevents these analysis and interpretations to be correct. But not all interpretation techniques can be successfully applied to this type of data. Despite the fundamental limitations of the recorded seismic data they still are a source of valid information, not only about the mining but also about the surrounding rock mass in which the mining is taking place. The strength of this data is based on two factors: that it is taking place all around the mine and that there is a lot of them. The fact that there is a lot of seismic data available allows for implementation of specific interpretation methodologies that in turn compensate for the input data limitations.

Spectral analysis has become a standard technique used to estimate the source parameters of seismic events recorded by mine digital seismic networks. Simple source models of circular dislocations are used for the interpretation of seismic spectra and for the purpose of deriving source parameters. Seismic moment, corner frequency and seismic energy are inverted from the spectra that are corrected for the instrumental, distance and attenuation effects of each waveform and then averaged. These techniques as well as the seismic source parameters are described in Gibowicz and Kijko (1994). Mine seismic networks record on a daily basis from tens to thousands of seismic events. It is not possible to analyze each event separately. As indicated by Fig. 5.1, which is a W-E horizontal plan, from January 2004 up to June 2007, the Palabora seismic network recorded 74852 events with four or more stations. The minimum magnitude included in this set of data is an event of magnitude –2.3 while the largest event is of magnitude 2.0. These events were recorded for an elevation range of 2100 m (from +400 m down to –1700 m). As indicated by Fig. 5.2 most of these events are located outside of the network, so their source parameters as well as locations are off poor quality. The only certainty

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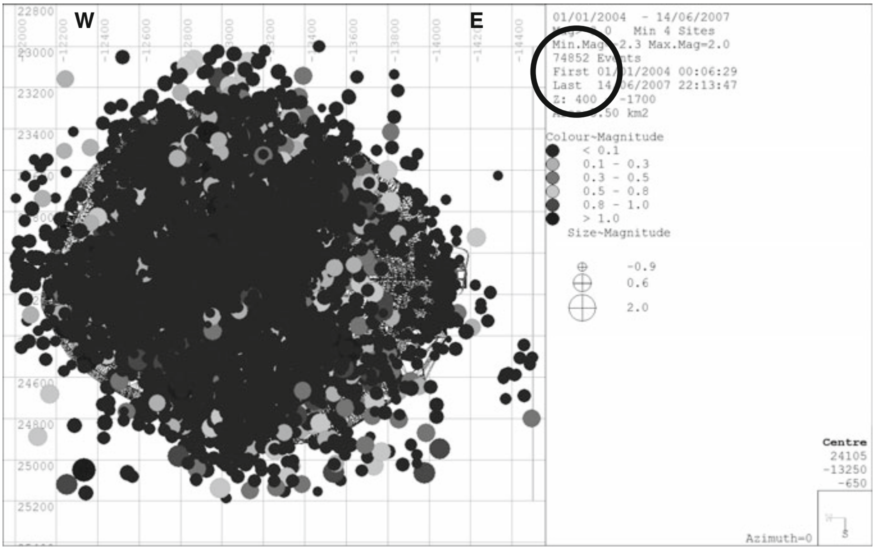

Fig. 5.1 Palabora seismicity recorded during 2004–2007 in horizontal W-E plan

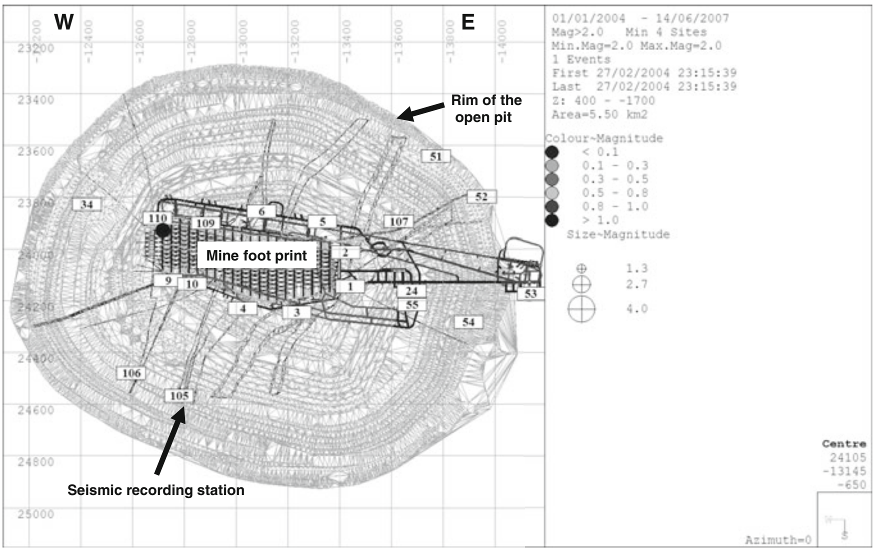

Fig. 5.2 Palabora distribution of sensors in W-E horizontal plan

about these events is that they took place and that they located somewhere south, north, east or west of the mine.

Figure 5.3 shows this seismicity in a vertical W-E section. Some of this seismicity plots above and some plots below the mine. As indicated by Fig. 5.4 the

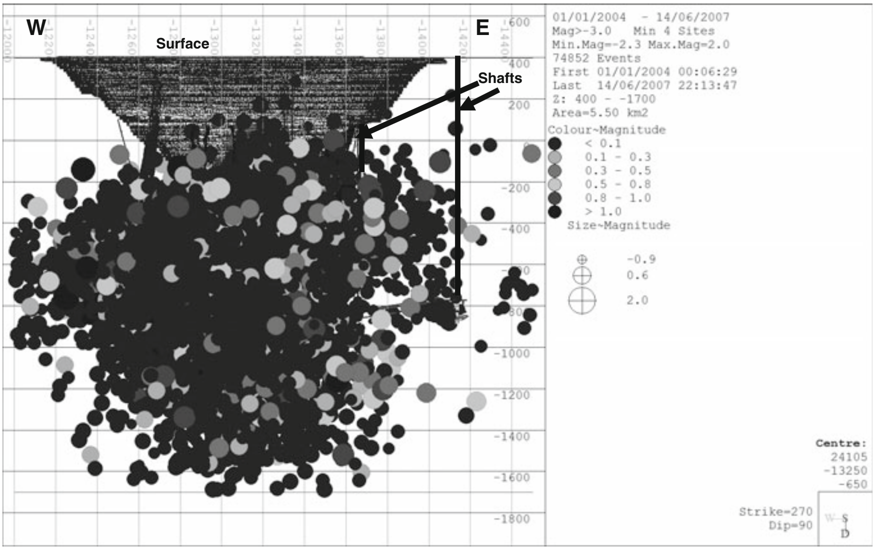

Fig. 5.3 Palabora seismicity 2004–2007, vertical W-E section

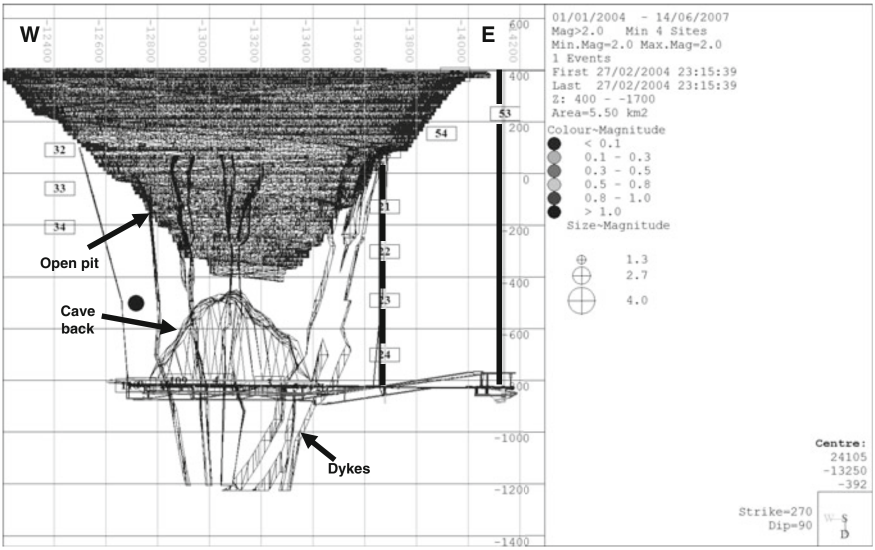

Fig. 5.4 Palabora distribution of sensors in W-E vertical section

seismic sensors are located only on and above the mine level (the cave back on this figure is dated February 2004). This means that the locations as well as the source parameters of the events that located above the mine should be of better quality than of these that located below the mine.

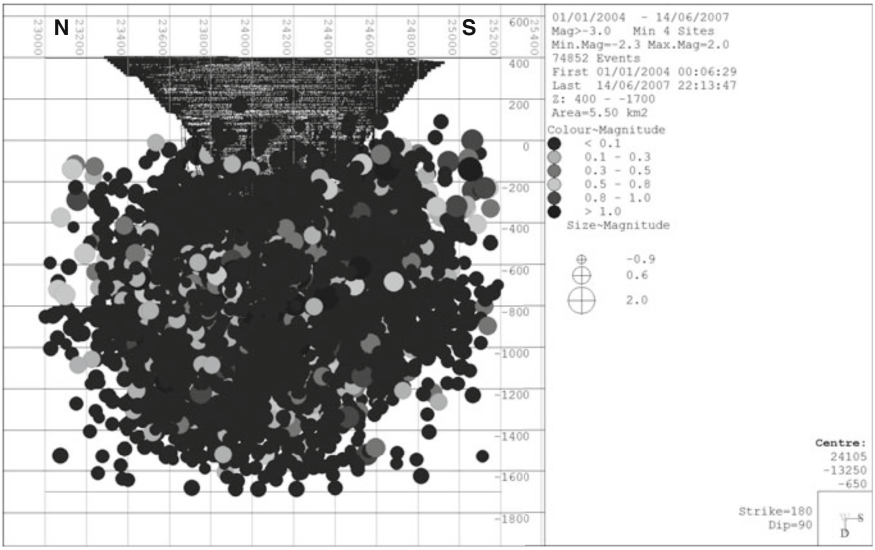

Fig. 5.5 Palabora seismicity recorded during 2004–2007 in vertical N-S section

Figure 5.5 shows this seismicity in a vertical N-S section. Again it is evident that most of the events plot outside of the network at distances up to a couple of hundred meters from the mine. There might be some seismicity at even further distances but the existing network is not able to detect them.

5.1 Space Distribution of Seismicity

Space or plan distribution of seismicity can, on its own, be used to extract important information. Figure 5.6 shows the changes over time of the Palabora seismically active area (in km^2) from the beginning of 2002 up to the end of March 2007. These areas were calculated for each quarter of the year using a moving 6 month period. The seismically active area is an area that includes at least 95 % of all recorded seismicity during this 6 month period. In May 2002 when the caving process was initiated (A) the seismically active area was close to 0.22 km^2. When the Crown Pillar failed at the end of 2002 (B) the seismically active area had increased to 0.4 km^2. By the time the cave had broken into the open pit (C) about May 2004, the seismically active area was already 1.7 km^2 in size. In March 2007 the seismically active area was 2.4 km^2. The March 2007 size of the seismically active area is very close to the area enclosed by the open pit rim (2.45 km^2). As indicated by Fig. 5.6 the seismically active area has increased continuously during this time period. There are three distinctive time periods of different increments. From the time of the cave initiation to the time of the Crown Pillar failure the quarterly increments were

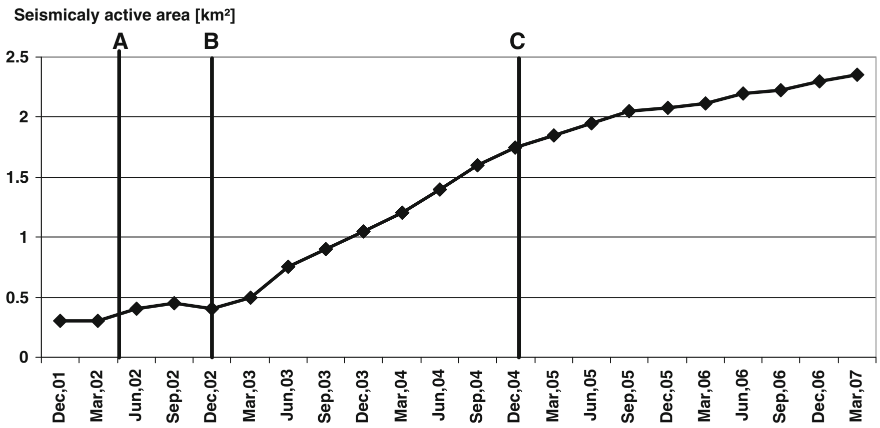

Fig. 5.6 Seismically active area changes with time

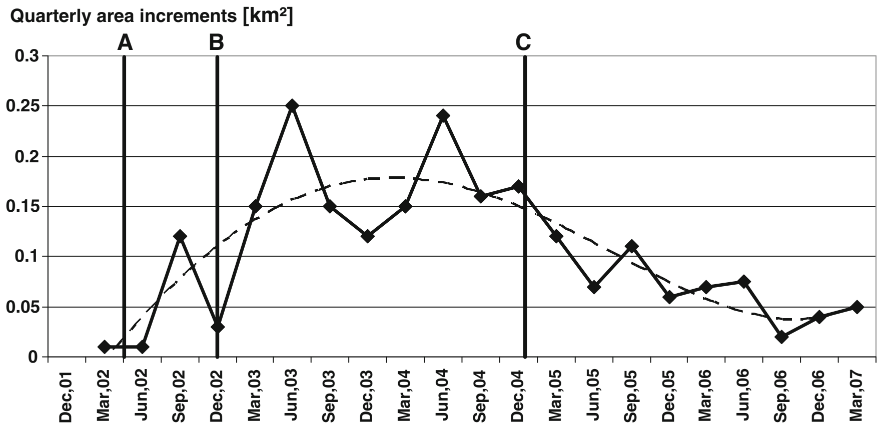

Fig. 5.7 Quarterly seismically active area increments (km^2)

low (average of 0.075 km^2/quarter)—see Fig. 5.7. After the Crown Pillar failure the quarterly area increments doubled to an average of 0.15 km^2. After the cave broke into the open pit the quarterly area increments started to decrease continuously. During the first quarter of 2007 the quarterly increments were down to 0.05 km^2 from the value of 0.15 km^2 for the first quarter of 2005. It is clear that the changes in size in the seismically active area are directly connected with the phases of the caving process.

The seismically active area expansion rates have not only changed with time but there was also a very clear change in the direction in which this area has expanded. As indicated by Fig. 5.8, initially the seismically active area expanded only to the

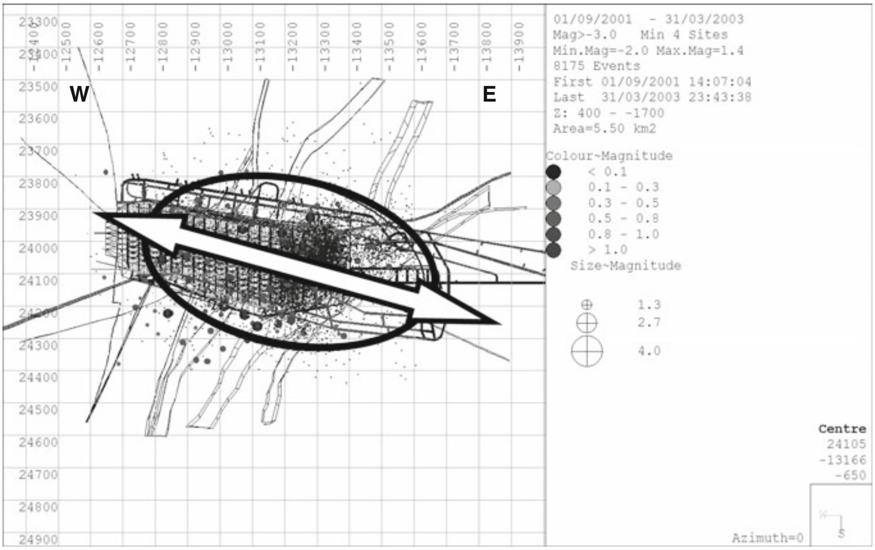

Fig. 5.8 Principal directions of the seismically active area expansion since end of 2003

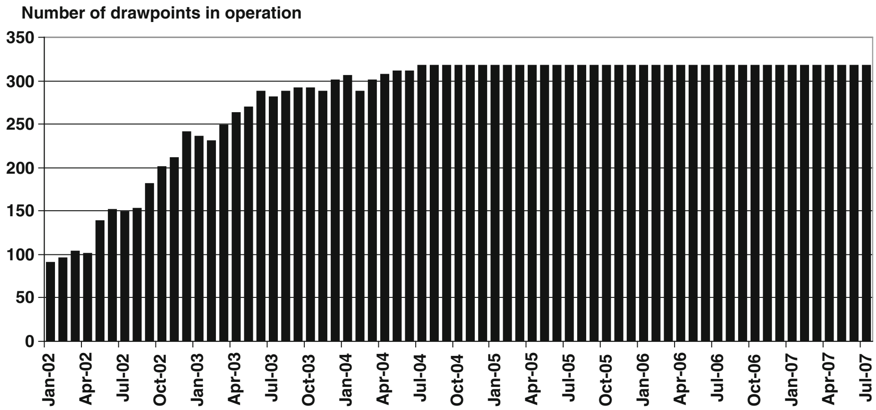

Fig. 5.9 Number of draw points in production

west and to the east. These are the directions of the development and the early cave mining at the time it was expanding.

The undercut was completed in February 2004 and the draw bells were completed during August 2004. From about the beginning of 2003, when close to 250 (out of 320) draw points were in production (Fig. 5.9), the seismically active area started to expand to the north and south. As indicated by Fig. 5.10, this is the time when the monthly production rate increased from about 3,00,000 to over 5,00,000 tonnes.

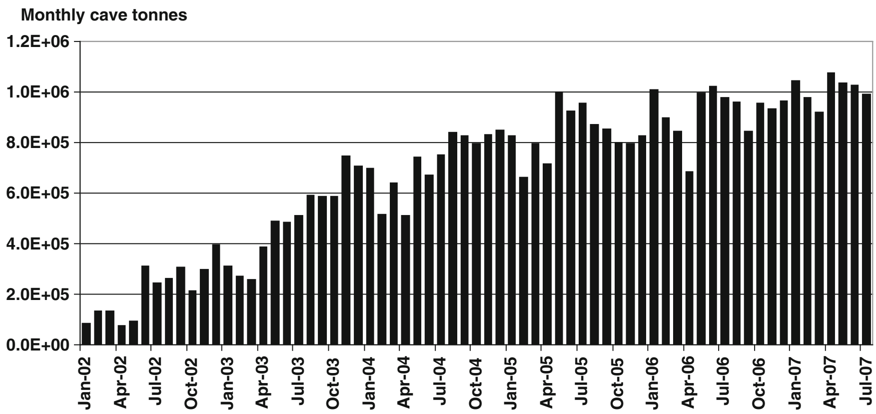

Fig. 5.10 Cave production tonnes per month

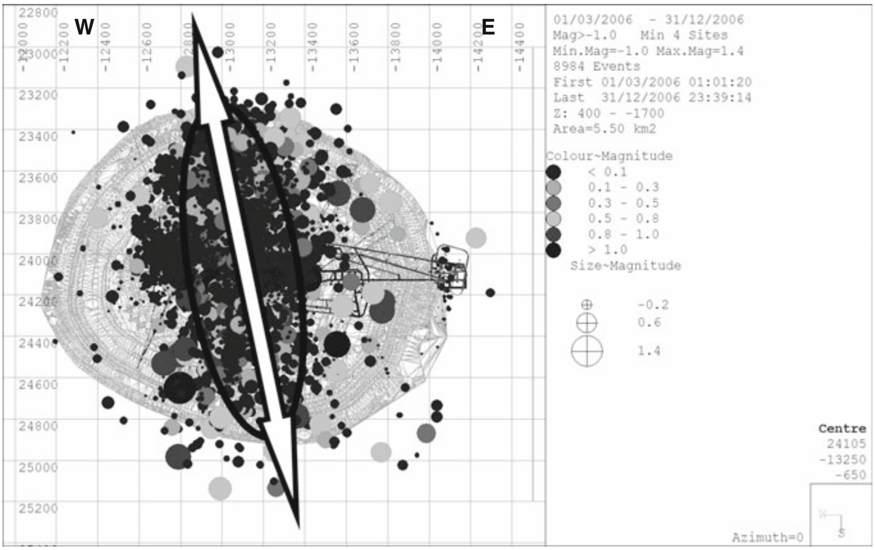

Fig. 5.11 Directions of the cave expansion since beginning of 2006

Figure 5.11 indicates that from the beginning of 2005 the main expansion direction of the seismically active area changed from west and east to northwest and southeast. Figure 5.11 shows these directions based on data recorded from surface down to –1700 m. Data presented by Fig. 5.12 was recorded only below the Production Level. In both cases the maximum expansion of the seismically active area took place in the same two directions. This prominent direction of expansion is not there by chance. This is the direction of the principal horizontal stress. Seismic

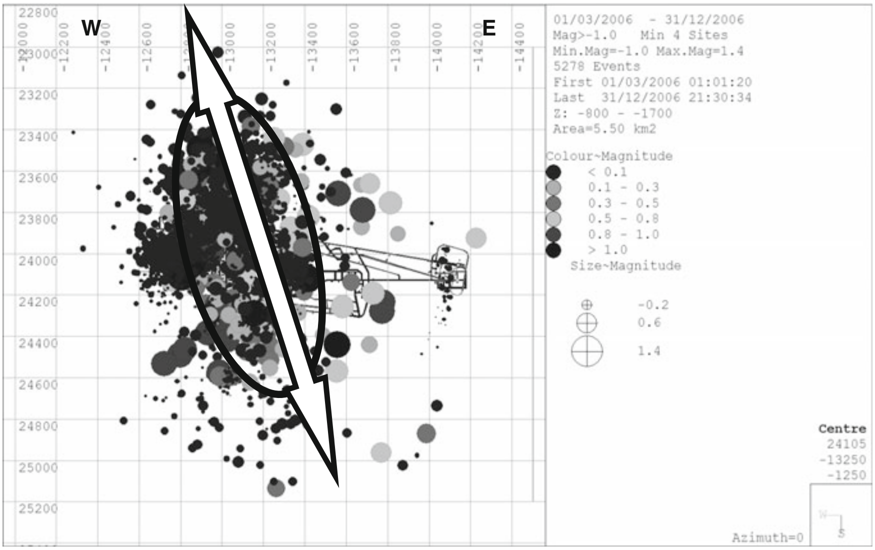

Fig. 5.12 Expansion directions below the mine level

data indicates that at the future possible Lift 2 depths, the horizontal principal stress direction will be similar to that of Lift 1.

The space distribution of seismicity is a very important factor that provides valid information but such figures as the ones above are not very helpful in understanding the seismicity. More information can be derived from the time distributions of seismicity. Here one can look for example at the daily, weekly or monthly activity rates as well as the rates of released seismic energy or seismic moment.

5.2 Activity Rates

Figure 5.13 illustrates the monthly seismic activity rates. In this example the number of recorded events per month varies from less than a hundred to about 1500 per month. There is no single trend in the activity rate. After the 2003 increase, there was less seismicity recorded during 2004, followed by an increase in seismicity during 2005. From the end of 2005 there was a decreasing trend through to mid 2007. The line represents the cave production tonnage. In general it would be expected that with increased production rates there would be more induced seismicity. This doesn't seem to hold in this case. There are times, particularly at the beginning, when more cave tonnes resulted in an increase in seismicity but from some point this relationship no longer appears to be evident. This is especially noticeable during 2006 and 2007 when the monthly production rates were higher than during the previous years but the monthly seismic activity rates are lower than

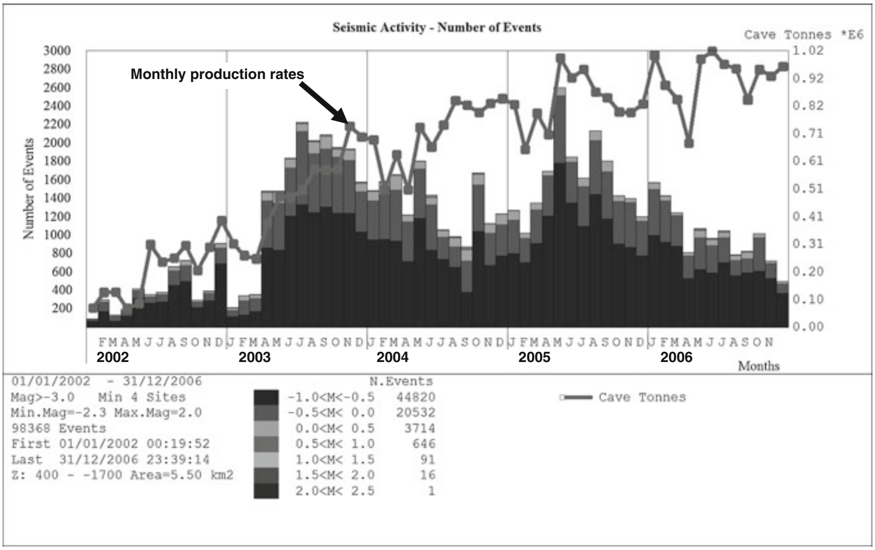

Fig. 5.13 Monthly seismic activity and cave production rates

there were previously. It seems that something has changed and that with time the amount of seismicity becomes dependent from some different factors.

Figure 5.14 illustrates the monthly seismic activity rates and the monthly average depth of seismicity. The average depth of seismicity appears to be an unsophisticated parameter but it has proven to be essential in solving a number of issues. This figure indicates that to start with the seismicity migrated upwards until the end of 2002. From then on there seems to be a continuous downward trend. Closer examination indicates that this downward trend can be further divided into several sub trends. From mid 2003 until the end of 2004 the downward trend is slow. From the beginning of 2005 until mid 2005 the seismicity migrates downward very fast. From mid 2005 the downward trend is still there but again it is slower. By the end of 2006 and the beginning of 2007, there are times when the seismicity also migrates upward but the general trend still remained downwards. This simple analysis indicates that the high seismicity rates of 2003 and 2005 might be associated with different elevations.

Figure 5.15 shows the monthly seismic activity rates and the average monthly seismicity elevations below the mine. To start with, there is practically no seismic activity below the mine up until mid 2003. The maximum amount of seismic activity below the mine was recorded during 2005. Comparison of Figs. 5.14 and 5.15 indicate that the increased seismic activity rates of 2003 are associated with the rock mass located above the mine while most of the 2005 seismicity took place below the mine.

Locations of seismicity are generally not as good as expected. This is usually due to the fact that most of the seismicity locates outside of the seismic network.

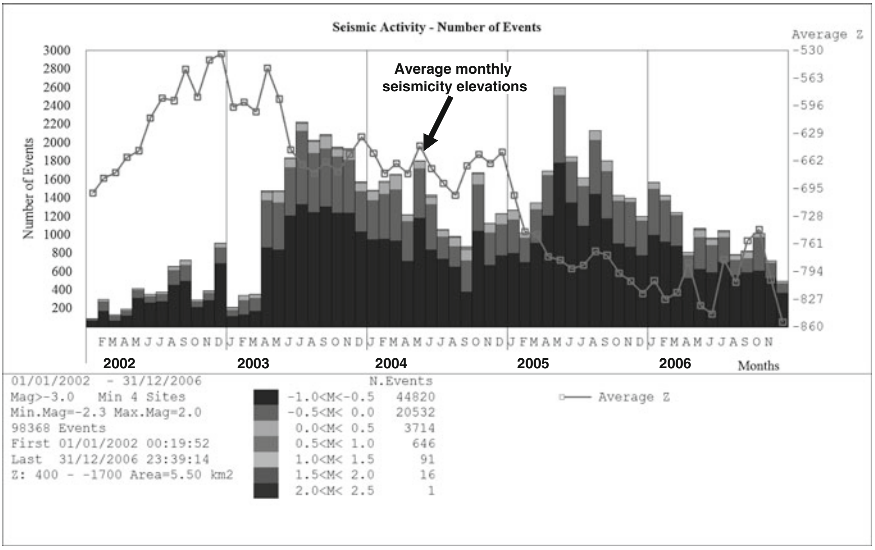

Fig. 5.14 Seismic activity rates and average monthly seismicity depths

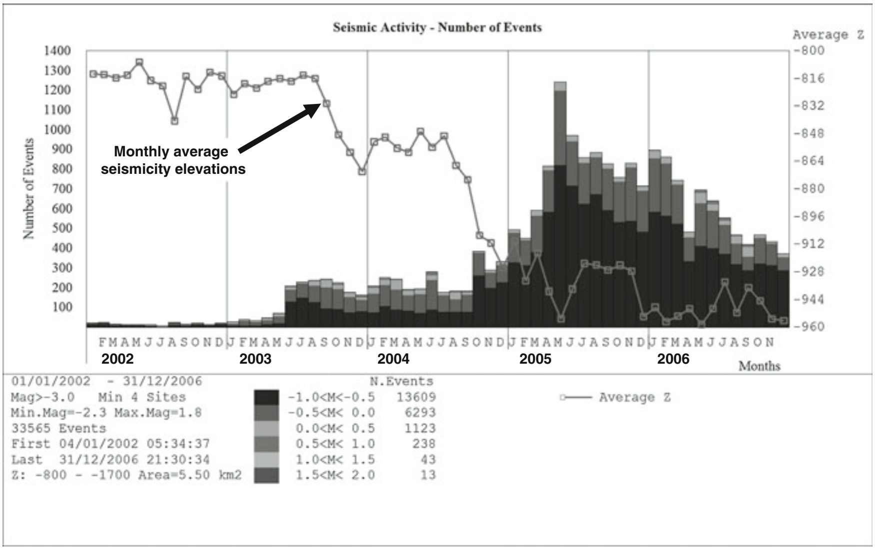

Fig. 5.15 Seismic activity rates below the mine level

All recorded events carry useful information that has to be extracted, but taking into account their location ambiguity. For this reason I usually divide the whole data set into such subsets for which accurate location is no longer critical. If the two data subsets divide the entire seismicity into that locating above and that locating below

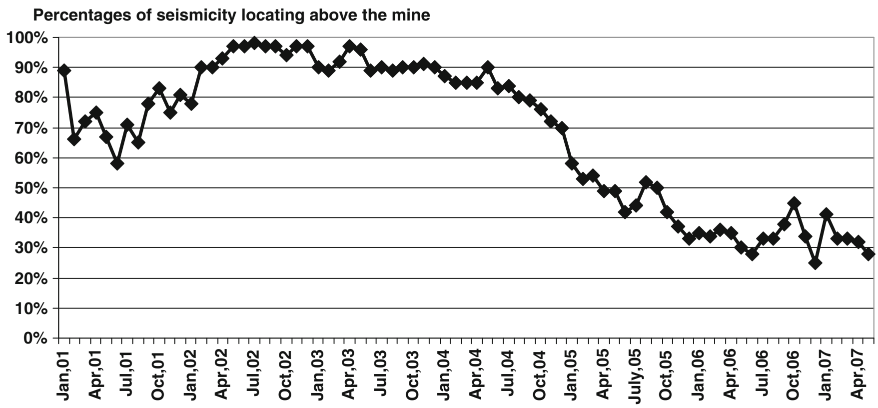

Fig. 5.16 Percentages of recorded seismicity above the mine

the extraction level, then it can be assumed that most of this data fulfils this simple requirement. If a small percentage of this data still doesn't fulfil this requirement then it doesn't really matter. Statistically it can be expected that the same number of events that took place above the mine will be included in the subset that contains seismicity from below the mine as the number of events that took place below the mine will be included in the subset above the mine. Further more, when one deals with large data sets and for interpretation purposes uses only their trends, then this final output has gone through such smoothing processes that the remaining location ambiguity is of no significance. In addition when the output is in percentages then the network performance (number of stations off line) doesn't influence the final results. If for a period the network is down or some of its stations are not operational then it influences the amounts of recorded seismicity above as well as below the mine in a similar manner.

Figure 5.16 shows the percentages of seismicity recorded above the mine level from January 2001 until the end of May 2007. 100 % seismicity is the total amount of seismicity recorded every month above and below the mine level in the depth range from +400 m down to –1700 m. Initially, during 2001, the amounts of seismicity recorded above the mine were as high as 70 %. With the initiation of the caving process in April 2002, over 90 % of seismicity was recorded above the mine level. These high levels of seismicity above the mine level continued until the cave broke into the open pit in May 2004. After the initial break through there was a slow but continuous decrease in the amounts of seismicity recorded above the mine level. From about May 2005 the amounts of seismicity above the mine level started to drop below the 50 % level. By May 2006 only about 30 % of all recorded seismicity plotted above the mine level. During September, October and November 2006, there was more seismicity recorded above the mine level (up to 40 %). From February 2007 to date when the input data ends this amount is down to about 30 %. This interpretation connects together two different types of input data, seismicity and the caving stages. The quality of the seismic input is low but the information

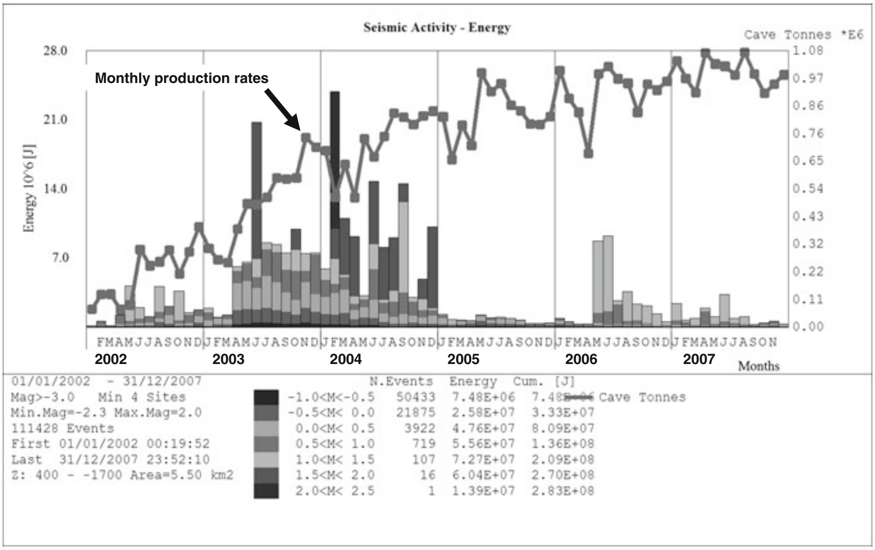

Fig. 5.17 Monthly seismic energy release and production rates

about the cave is still accurate. We know when the caving process was initiated, we know when the Crown Pillar failed and we know when the initial cave break through into the open pit took place. This example indicates that the recorded seismicity, regardless of its poor quality, contains information about the caving process. Further more, use of very basic and simple parameters such as activity rates and the average monthly seismicity depths (elevations), provide a detailed insight into the caving process.

Figure 5.17 shows the monthly seismic energy release rates. This figure indicates that to start with during 2002 there was some energy release but these amounts were low in comparison to the energy release rates during 2003 and 2004. During 2005 and the first 5 months of 2006 the energy release rates were very low. During the second half of 2006 the energy release rates increased, only to decrease again during 2007. It is generally accepted as a norm that with the increasing volumes of mined ore the amount of seismic energy must increase. Data recorded at Palabora indicates that this not always the case. Induced seismicity strongly depends on the mining method. Seismicity induced by cave mining will be different from that induced by, for example, the mining of tabular deposits.

Figure 5.18 shows the monthly seismic energy release rates below the mine level. The maximum rates were recorded about 3 months after the Crown Pillar failure. Large size energy release events did not stop when the cave broke through into the open pit in May 2004, as there are large seismic energy rates right up to the end of 2004. During the whole 2005 and the first 4 months of 2006 the monthly energy release rates remained low. There was a lot more seismic energy released from May 2006 to October 2006. The downward migration of seismicity

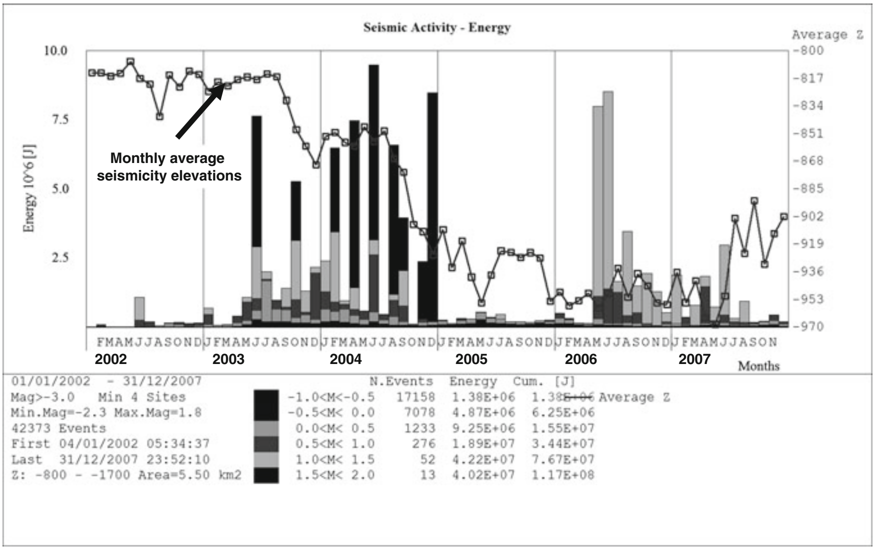

Fig. 5.18 Seismic energy release rates below the mine

(down to –900 m) started in mid 2003 and ceased in December 2004. This migration period coincides with the period of high-energy releases. Because the seismic energy release rate and the source elevation are independent of each other then the observed correlation between seismicity migration and energy release should increase confidence in the consistency of the recorded seismicity.

Figure 5.19 shows the energy release rates above the mine. The time period for the maximum energy release above and below the mine is exactly the same (From April 2002 up to December 2004), but the release processes are different. Above the mine the release process is more continuous than below the mine. Below the mine the high energy releases are divided by low energy time periods. This is easy to explain. The caving process is taking place above the mine, so this is the part of the rock mass that must be strongly fractured. The rock mass below the mine will be more solid and for this reason able to absorb more strain energy. The energy is accumulated (low energy release times) and then released in single large bursts (high energy release periods). Again this is a simple interpretation but easily explained in terms of the mining process or the state of the rock mass.

Figure 5.20 shows the percentages of seismic energy released above the mine level from January 2001 until the end of May 2007. From October 2004 more than 50 % of the seismic energy was released below the mine. It is interesting to note that the continuous decrease in the percentage of energy released above the mine level ended in March 2006. From March 2006 to the end of July 2006, the amounts of energy released above the mine footprint have increased from 15–40 %. During August up to December 2006, less than 10 % of the seismic energy was released above the mine level. During January 2007 the amount of released energy above the

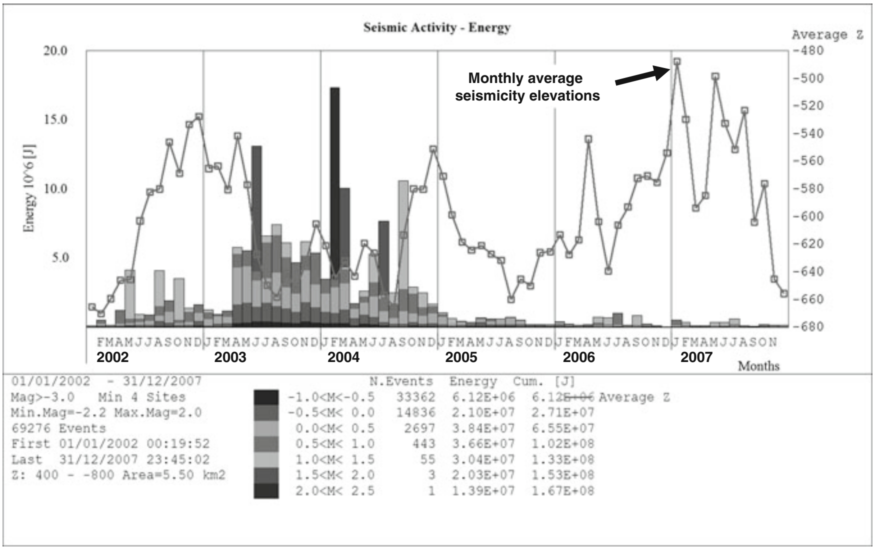

Fig. 5.19 Seismic energy release rates above the mine

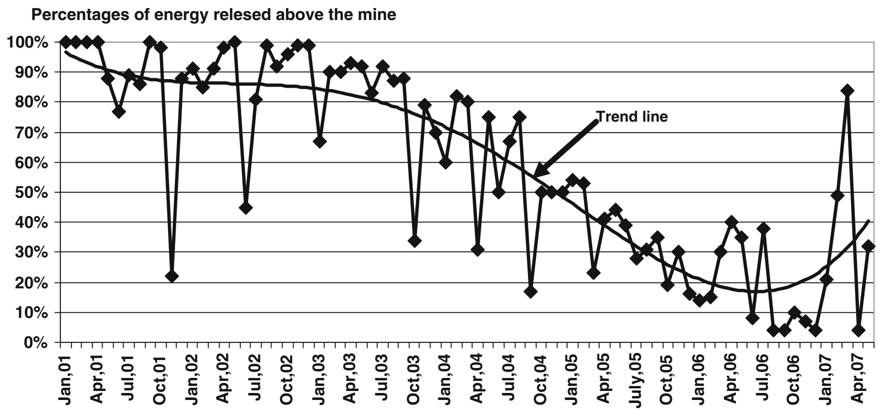

Fig. 5.20 Percentages of seismic energy released above the mine

mine increased to 21 %. In February 2007 about 49 % of seismic energy was released above the mine. In March 2007 close to 84 % of seismic energy was released above the mine. During May 2007 32 % of seismic energy was released above the mine level. This probably indicates that the cave in the east has already broken into the open pit. The seismic energy release ranges are enormous. For this reason the energy trend as shown by Fig. 5.20 would be closer to the general trend graph if all larger size seismicity would be excluded from such an analysis.

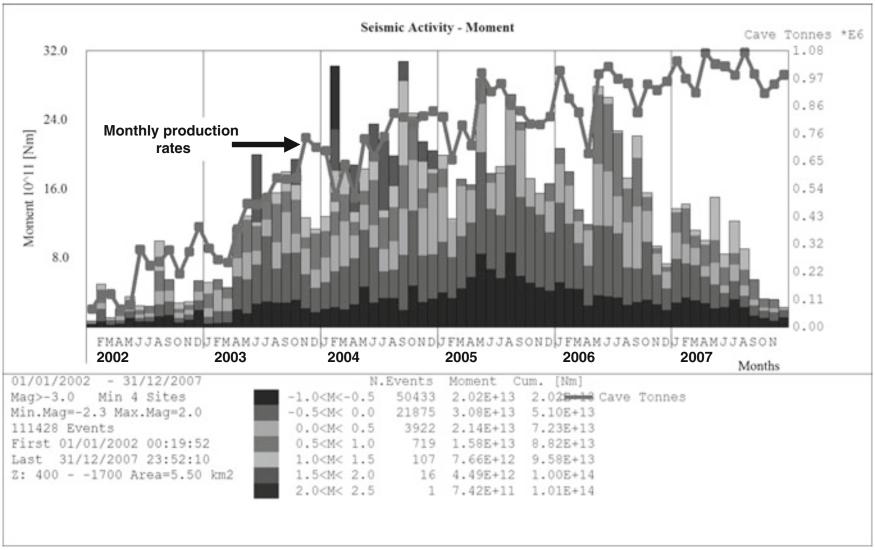

Fig. 5.21 Monthly seismic moment and production rates

Figure 5.21 shows the monthly seismic moment (deformation) rate. As with the seismic activity rate one should expect that some of this deformation took place below the mine. This indeed is the case as illustrated by Fig. 5.22. It is interesting to note that the time periods of high seismic deformation do not coincide with the high energy release periods. There was a lot of seismic deformation at the time of the larger size energy releases but there was also a lot of seismic deformation with low energy release rates. This indicates that the rock mass was deforming also during times of low energy release.

Figure 5.23 shows the percentages of the monthly seismic deformation rates above the mine. The maximum deformation rates above the mine are associated with the caving process. After the cave broke through into the open pit the percentages of seismic deformation above the mine level dropped from about 80 % (June 2004) to less than 50 % in January 2005. This decrease continued until April 2006 when only about 20 % of observed seismic deformation took place above the mine level. From May 2006 until the end of February 2007 the amount of seismic deformation taking place above the mine increased to about 50 %. In March 2007 this amount decreased slightly to 44 %. In April 2007 this amount again decreased, this time to 37 %. In May 2007 this amount increased to 54 %. It must be assumed that until the full break through into the open pit occurs, there will be additional seismic deformation associated with this process.

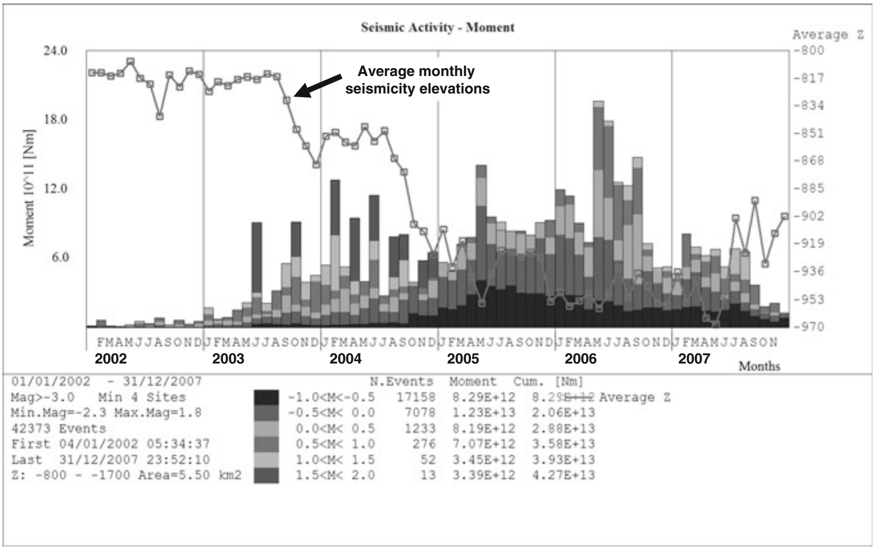

Fig. 5.22 Seismic deformation rates below the mine

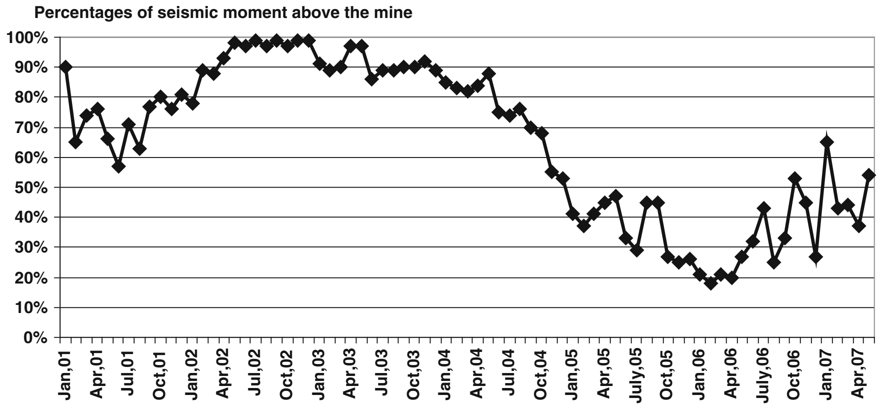

Fig. 5.23 Percentages of seismic deformation above the mine

5.3 Cumulative Values

Cumulative plots are used to monitor seismicity trends. They are usually based on large amounts of recorded seismic events. Figure 5.24 shows a cumulative plot of seismic moment. In this case there are close to 1,10,000 seismic events used to derive this plot. To start with, up to about April 2003 the cumulative moment plot increases slowly. From April 2003 to about September 2006 the cumulative plot indicates that there is more seismic moment than during the first time period.

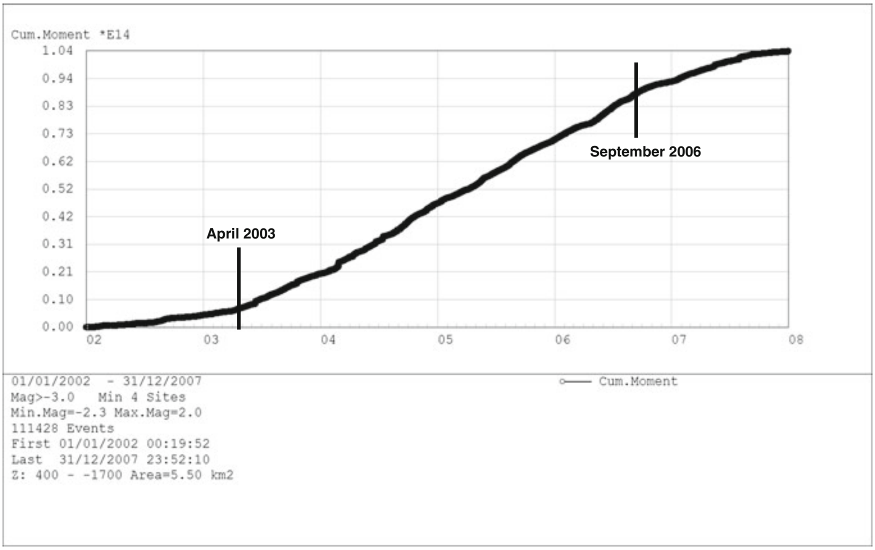

Fig. 5.24 Cumulative seismic moment

A closer examination of the trend changes in this time period will result in dividing this second period into a number of sub-periods, but in this case I want to concentrate only on the main trends. From about September 2006 there is less seismic deformation taking place. This is a drastic change after nearly 5 years of continuous increase in seismic deformation.

Figure 5.25 shows that the April 2003 increase in the amounts of seismic deformation was associated with increased seismic activity rates. The monthly seismic activity rates started to decrease from about May 2005 but this did not change the general trend of the cumulative moment graph as it still indicated a continuous increase. Figure 5.25 shows that the April 2003 increase in the amounts of seismic deformation was associated with increased seismic activity rates. The monthly seismic activity rates started to decrease from about May 2005 but this did not change the general trend of the cumulative moment graph as it still indicated a continuous increase.

Figure 5.26 indicates that from about April/May 2003 the production rates have increased.

Figure 5.27 shows the monthly cave tonnes for the period January 2002 to December 2003. There is a distinct production increase from April 2003. During March 2003, about 3,00,000 tones were lashed from the cave. This figure for May 2003 was close to 5,00,000 tones. During November 2003 over 7,00,000 tones were lashed from the cave. In summary, during a 6 month period, the production increased more than twofold. Up to March 2003 the draw rates were about 45 mm/day or less. In May 2003 the average draw rate reached 64 mm/day and in November 2003 it was already 92 mm/day. Seismic data has enabled estimating

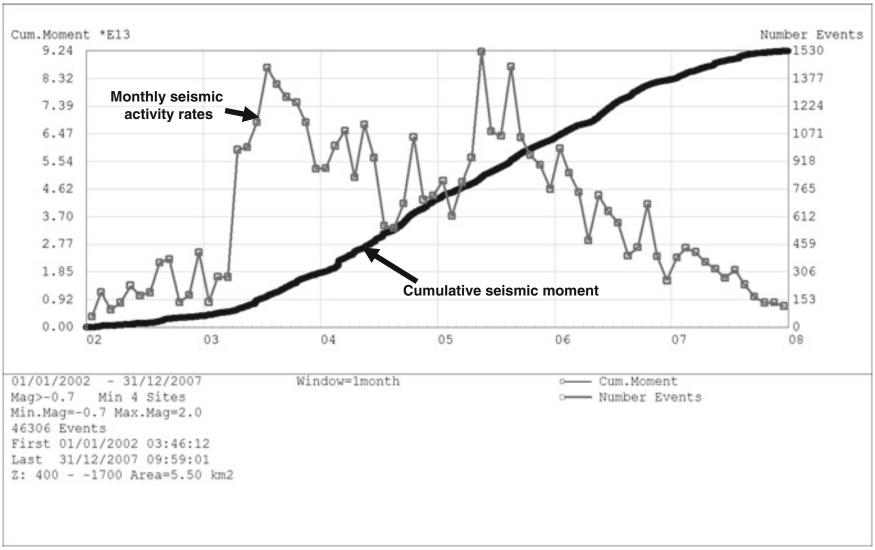

Fig. 5.25 Cumulative seismic moment and monthly seismic activity rates

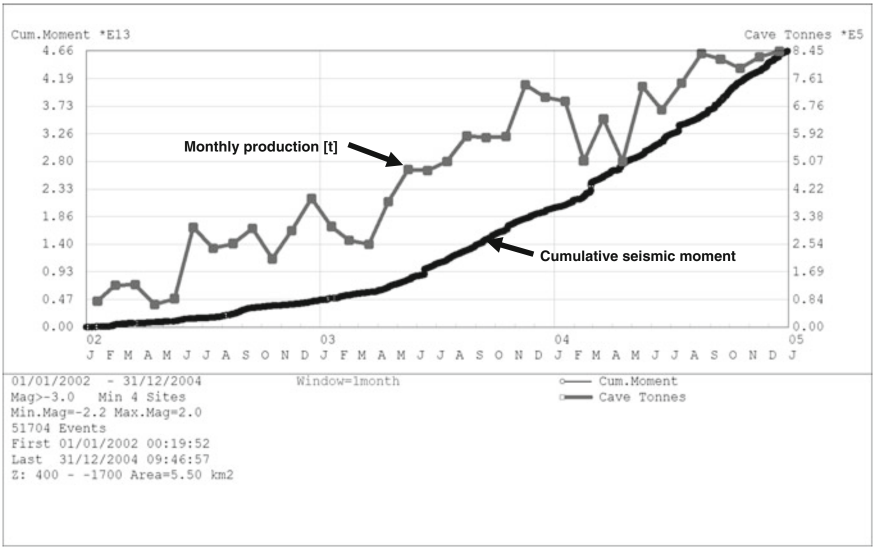

Fig. 5.26 Cumulative seismic moment and cave tonnes

that the cave natural expansion rate was about 120 mm/day. The more rapid increase in seismic deformation rates started only when the average monthly draw rates reached values greater than 50 % of the natural cave expansion rate.

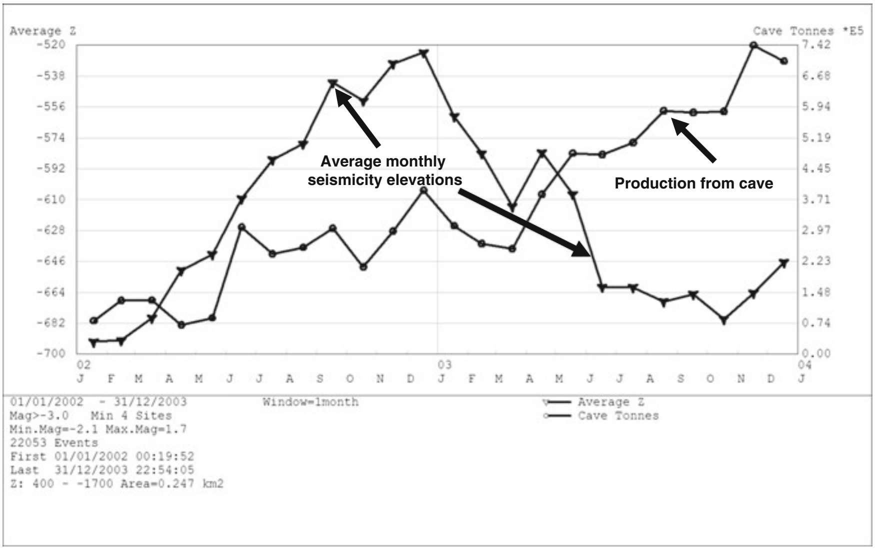

Fig. 5.27 Cave production rates

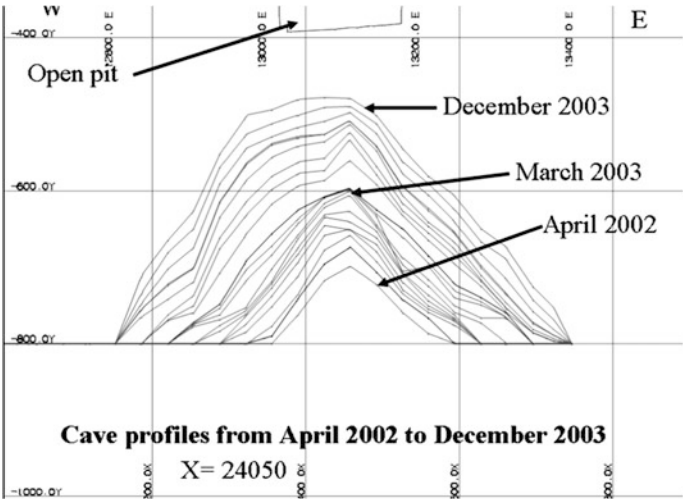

Fig. 5.28 Cave profiles April 2002–December 2003

Figure 5.28 shows the cave profiles along their maximum elevations from April 2002 to December 2003. By the end of March 2003 there were 11 cross cuts in production. In August 2003 the number had increased to 15. Probably a more representative value would be the number of draw bells in production or their percentage of the final number. This figure indicates that once the failure of the crown pillar was confirmed, there was a change in the draw strategy. At this point of time there was no reason to hold back the cave vertical expansion any longer. The 200 m exclusion zone above the cave maximum elevation (in March 2003 the cave maximum elevation was at –600 m) was already fractured and no longer able to prevent storm water from entering the underground mine. According to Fig. 5.28, from April 2003 the cave expanded vertically and horizontally. By the end of 2003 the cave maximum elevation was at about –500 m. Figure 5.9 indicates that in April 2003 there were 250 (out of a total of 314) draw points in production. In this example mining data has been used to validate observations based on seismic data. The observed increase in seismic deformation rates from April 2003 were caused by increased production rates. However, the reason for the decrease in seismic moment rates from September 2006 remains unclear. As indicated by Fig. 5.25 it is not directly associated with a decrease in the seismic activity rates as these started to decrease much earlier.

Figure 5.29 indicates that the general trends for the cumulative seismic moment and seismic energy are different. The only similarity is the more rapid increase from March/April 2003 for both trends. Other than that the graphs are different. From the beginning of 2005 there was less seismic energy released but still a fair amount of seismic deformation was taking place. Figure 5.30 shows the seismically active volume and the cumulative seismic energy release graphs. It seems that there is a relationship between these two values. The maximum seismic energy release took place only after the Crown Pillar failure (B) and then stopped with the cave breaking into the open pit (C). This is shown by the cumulative seismic energy graph when it flattens rapidly just after the break through. The high energy release

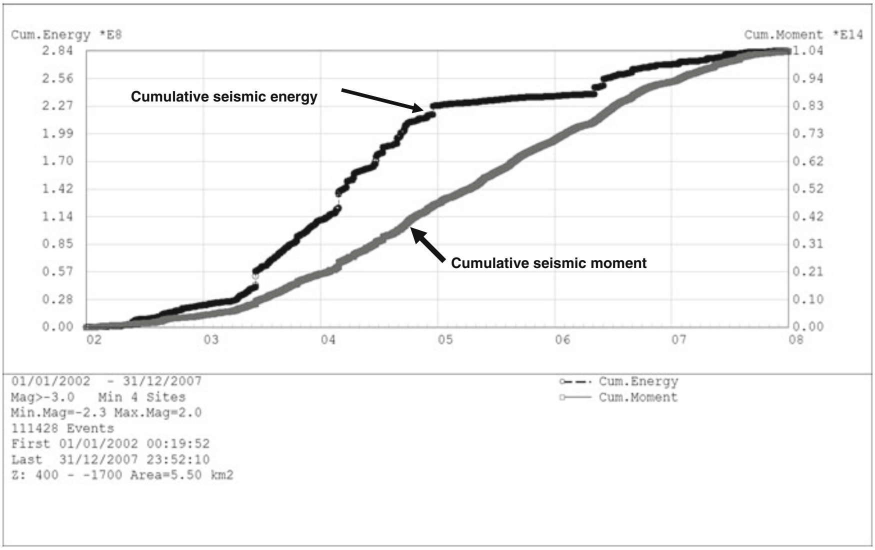

Fig. 5.29 Cumulative seismic energy and moment

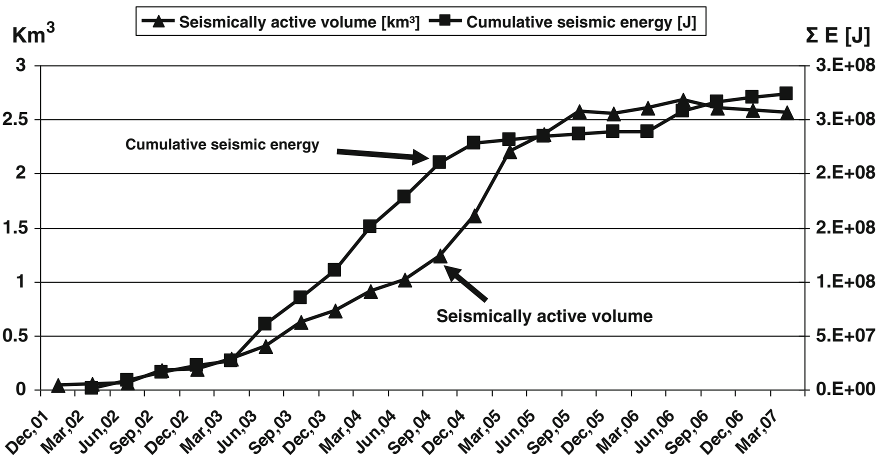

Fig. 5.30 Seismic volume and cumulative seismic energy

time period correlates well with the time of the rapid increase in the seismically active volume. The low energy release period started more or less at the same time as when the active volume stopped increasing as rapidly as it had been doing up to that time.

Figure 5.31 shows the seismically active volume changes together with the graph of the cumulative seismic moment. There is lower seismic moment from the time when the seismically active volume started to decrease. Here two independent parameters, space distribution of seismicity and seismic moment, indicate that the caving process is probably reaching its mature phase.

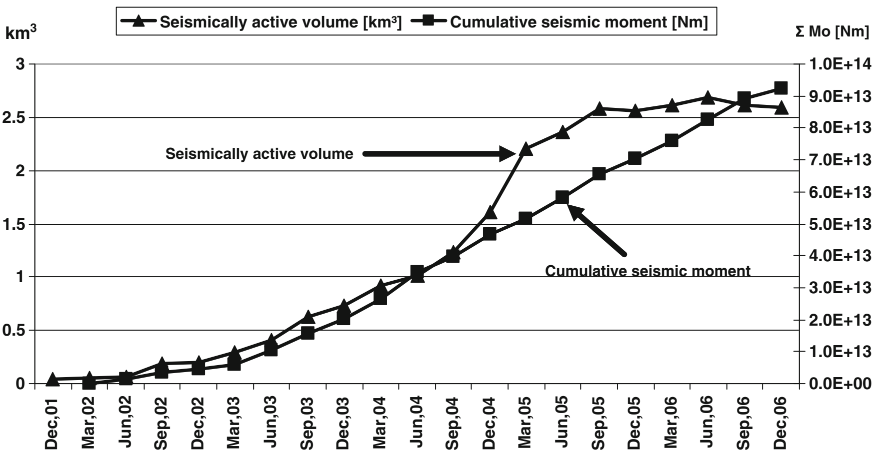

Fig. 5.31 Seismic volume and cumulative seismic moment

In most of the analyses presented to date, apart from seismic data, I have in addition used other data. Seismicity on its own is difficult to understand and interpret. For this reason it must be used with some other data. Probably the best supporting information is the actual mining itself. Let's try an analysis involving the cumulative amounts of seismic moment. This analysis will be done for two 400 m thick rock mass volumes, the first one located above the mine and the second one located below the mine. These volumes are based on the mine footprint. The first volume is the Palabora Lift 1 cave while the second rock mass volume is the potential Palabora Lift 2 cave. The area of interest as presented by Fig. 5.32 is a volume that is 800 m thick (400 m above the mine level and 400 m below the mine level). Table 5.1 presents the cumulative seismic energy release values and cumulative seismic moment values for each of the 100 m thick layers. Data used to calculate these values was recorded between 01/01/2002 and 30/11/2006.

The amounts of seismic deformation (and released seismic energy) associated with the first layer above the mine (layer 4) and the first layer below the mine (layer 5) are for all practical purposes the same. The same relation exists for the layer located 100 m above the mine (Layer 3) and the layer located 100 m below the mine (Layer 6). Figure 5.32 shows the amounts of cumulative seismic moment in each of the eight layers in a W-E vertical section.

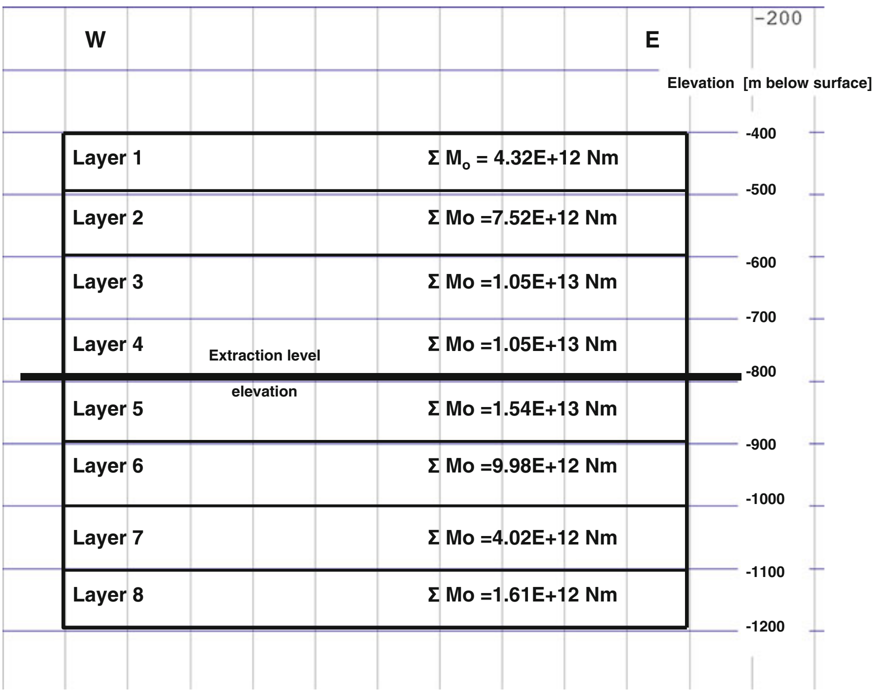

Fig. 5.32 Cumulative seismic moment in layers

Table 5.1 Distribution of seismic energy releases and seismic moment

Layer no	Depth range	Seismic energy		Seismic moment	
		J	%	Nm	%
1	–400 m/–500 m	3.11E+07	13	4.32E+12	6
2	–500 m/–600 m	4.23E+07	18	7.52E+12	11
3	–600 m/–700 m	2.52E+07	11	1.05E+13	15
4	–700 m/–800 m	4.55E+07	19	1.56E+13	23
5	–800 m/–900 m	5.26E+07	22	1.54E+13	22
6	–900 m/–1000 m	2.63E+07	11	9.98E+12	14
7	–1000 m/–1100 m	1.15E+07	6	4.02E+12	6
8	–1100 m/–1200 m	5.57E+05	Below 1	1.61E+12	3

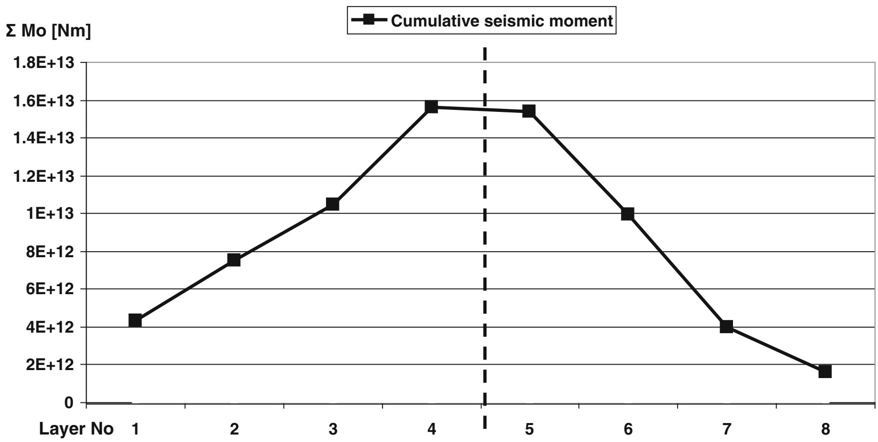

Fig. 5.33 Distribution of seismic moment in layers

Figure 5.33 shows the distribution of the cumulative seismic moments in the layers. This distribution is symmetrical for layers 3, 4, 5 and 6, which is in the rock mass volume 200 m above and below the present production level. The axis of symmetry is the production level (A). In practice this implies that for 200 m above and below the mine, the amounts of seismic deformation are the same. This does not apply to the two top and two bottom layers (layers 1, 2 and layers 7 and 8). Experience with the Palabora caving process indicates that the amounts of seismic deformations as listed in Table 5.1 were sufficient to initiate enough of the primary fragmentation for the whole rock mass volume above the mine to cave. The unknown factor is the amount of a-seismic deformation that took place above the mine. Above the mine the mechanism that triggered both the seismic and a-seismic deformation was the caving process. By the end of 2006 (nearly four and a half years after the initiation of the caving process) the amount of seismic deformation above and below the mine are very similar.

5.4 Energy Index Concept

The energy index concept was developed in South Africa during 1990 (Glazer 1998) after the introduction of digital seismic networks into the mining environment and then only after increasing the number of seismic stations.

5.4.1 Development of the Concept

Increased number of seismic stations in the KMMA Regional Seismic Network resulted (Chap. 2, Fig. 2.3) in recording an increased number of seismic events of which most were of magnitude less than 0.0. At that time, there was an urgent need to find an interpretation method that would make practical use of this small size seismicity. That is the reason behind the origin of the energy index concept. To start with this concept was based on the apparent stress values. As the value of the apparent stress is proportional to the shear stress acting on the fault it then appears that higher apparent stress might indicate higher shear stress acting on the fault, while the lower apparent stress should then indicate lower shear stress on the fault. Because of this relationship it was then assumed that the apparent stress has the potential for mapping areas of higher and lower stresses. As the value of apparent stress is calculated independently of the magnitude, then events of the same magnitude should have different values of apparent stress. Unfortunately because there is a direct proportional relationship between the event size and its apparent stress, apparent stress values cannot be used directly if one wants to make use of a wide range of magnitudes. A way around this dilemma was to find some mean value for a given magnitude size and then compare the calculated one from a new event with this mean. The result of such comparison is an index value that has no units attached. The mean value is always 1.0 (in this case the average and the seismic event apparent stress are equal). Each event of higher that the average apparent stress will have an index greater than one, and each event of apparent stress lower than the average will have an index value lower than 1.0. In this way it become possible to make use of all size events. Table 5.2 shows how the first mean values that were calculated and were based on 1990 recorded seismicity (Glazer 1998). The first column contains the magnitude values. In order to increase the amount of data used to calculate the mean value it was assumed that all events of magnitude between, for example 0.8 and 1.2, are of magnitude 1.0. According to column 2 there were 307 such events. The mean apparent stress (column 3) for magnitude 1.0 is 3.4 Pa. Table 5.2 also illustrates the fact that the apparent stress increases with the increasing magnitude values.

Figure 5.34 shows the plot of the mean apparent stress values presented by Table 5.2. The graph of these mean values divides the plot area into two sub-areas. Above the mean apparent stress values is the area where the index values are above 1.0 and below is the area of index values below 1.0. Initially during 1990 the

Table 5.2 Magnitudes and mean apparent stress values

M_L = +/–0.2	Number of events	Mean value of σ_A (Pa)
1.1	307	3.4E+04
1.3	329	6.7E+04
1.5	430	8.9E+04
1.7	413	1.3E+05
2.0	322	2.0E+05
2.3	257	3.3E+05
2.5	219	4.7E+05
2.7	160	6.6E+05

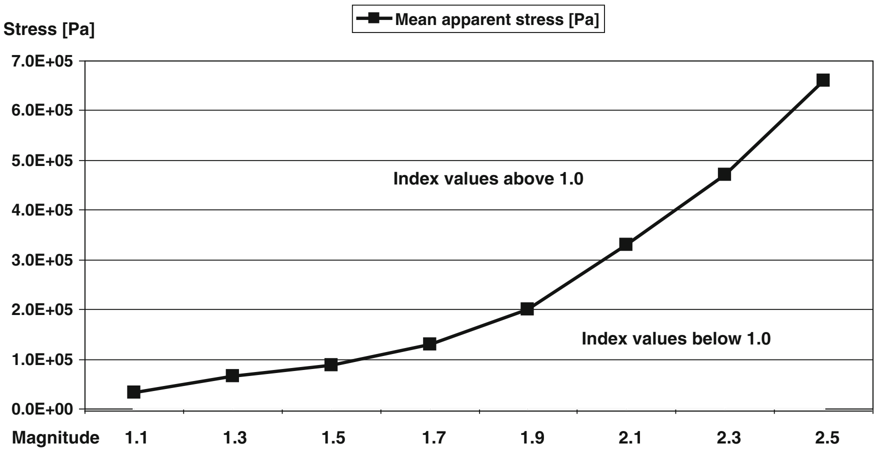

Fig. 5.34 Magnitudes and apparent stress values

amount of data recorded by the seismic network was low. First applications of the apparent stress index were very limited and far from perfect. To evaluate the index values I had to divide the whole mine into blocks of 500 m by 500 m for which I then calculated a mean from all indexes. The areas for which the index values were above the value of 1.0 covered a lot of ground on shafts that were known for their rock burst hazard (Glazer 1998). As indicated by Table 5.2 the mean apparent stress values were derived only for events up to magnitude 2.7. It was assumed that for larger size events the source parameters are totally unreliable and for this reason cannot be incorporated in the index concept. With time experimenting with this index resulted in the formulation of the following conclusions (Glazer 2000):

1. Large events are associated with areas where there are steep gradients of apparent stress index
2. Damage might be experienced in areas where this parameter is high, even when the seismic source locates outside of these areas

3. The index concept could be used as a tool for dividing the mine into areas prone to rock bursts and rock falls.

5.4.2 *Applications of the Energy Index Concept at Cave Mining Operations*

Figures 5.35, 5.36 and 5.37 show the daily seismic activity rates during December 2003 together with the daily production rates. These three figures indicate that the daily rates change from day to day and that the changes are not directly associated with the production rate. It also doesn't appear that there is a relationship between the number of events recorded per day and the daily seismic energy release and the seismic deformation. The presented data set consists of 2513 events recorded between 01/12/2003 and 31/12/2003. This example indicates that the data set is too small for analyzing the relationships between the various seismic activity rates. So what can be deducted from such data sets?

Figure 5.38 shows all these 2513 events plotted using their moment (x-axis) and seismic energy values (y-axis). The seismic moment range is from 10E+07 to 10E +11 Nm and the energy range is between one Joule and about one million Joules. The best fit line which represents the mean energy index (1.0) is far from perfect but divides the whole data set into two sub-sets. Events above this line have energy index values greater than 1.0 and the events below this line have energy index

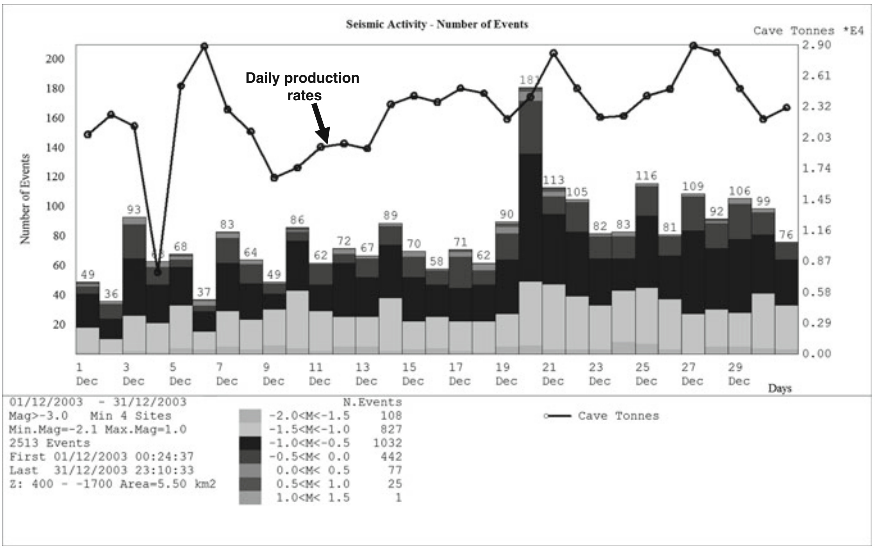

Fig. 5.35 Daily seismic activity rates

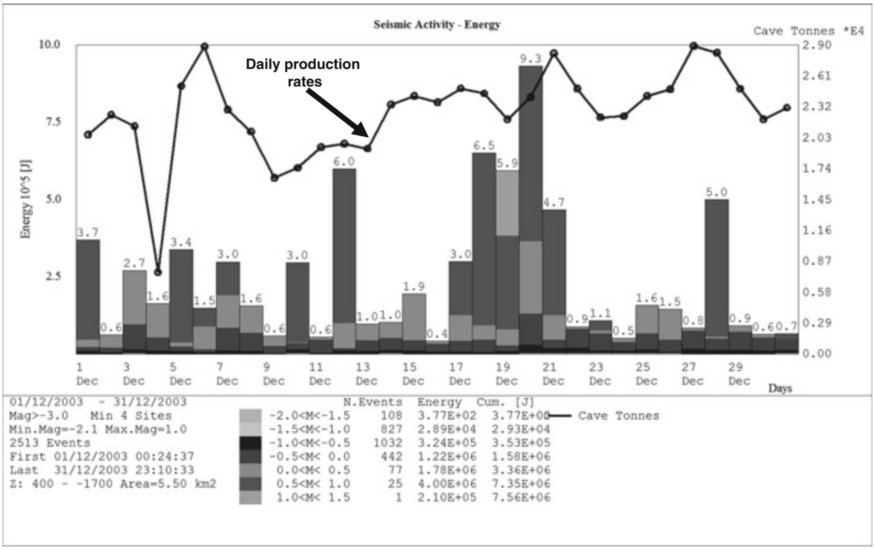

Fig. 5.36 Daily energy release rates

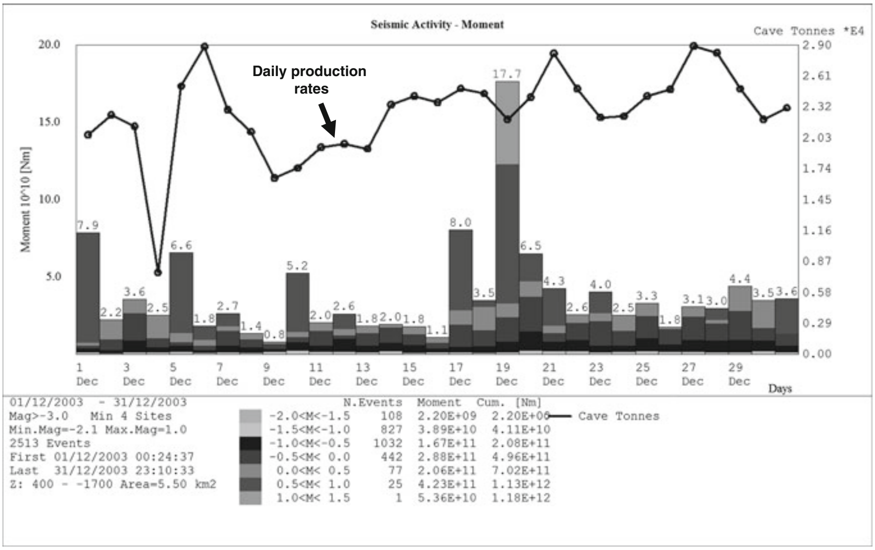

Fig. 5.37 Daily seismic deformation rates

values less than 1.0. The vertical arrow on this figure shows all events that have the same value of seismic moment. Still events of the same moment have different values of released seismic energy (as indicated by the horizontal arrows). This figure doesn't indicate from which part of the mine the events originate.

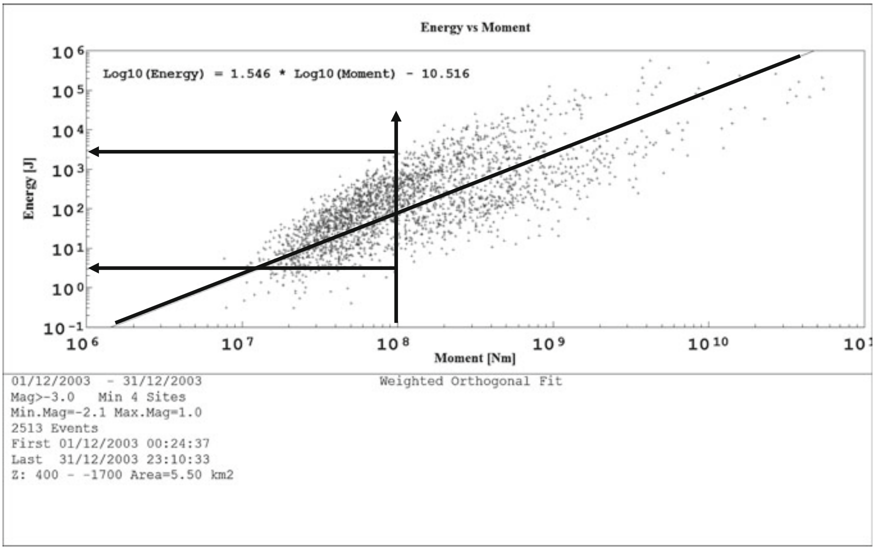

Fig. 5.38 Seismic energy versus seismic moment

When analysing the horizontal distribution of these 2513 events it is evident that the events distribution is not the same at different sections of the mine. There is more of seismicity at the east than on the west. There is also more seismicity north of the mine than south of the mine. This uneven distribution of seismicity is due to the seismic network's poor configuration of sensors. By the end of 2003 the network had more sensors at the east than at the west. Regardless of the influence of the network configuration most of the recorded seismicity plots to the west and east of the cave. The number of the larger size events (above magnitude 0.0) in the east and west is the same. There are more of smaller events (below magnitude 0.0) in the east than in the west. More information about this seismicity becomes available by displaying it with their energy index values instead of magnitude values. This display indicates that there is a very big difference between the east and the west seismicity. Practically all events plotting in the east have high energy index values, while the seismicity to the west is of low energy index values. It seems that the best fit line displayed by Fig. 5.38 is dividing the events on this basis, that is events locating in the east are above the best fit line and events in the west mainly locate below the best fit line. Interpretation of the energy index distribution in this case is straightforward: the stress level at the east is higher than at the west. This is only an example, as this type of analysis should be done on regular basis. My conclusion about the stress levels are based not only on the December 2003 seismicity but on analysis of previous seismicity as well as information relating to the mining that was taking place at that time. Another method of displaying energy index values are contour plots. Plots of this type have significance only if the data used to produce them is selected carefully. First of all there is no sense in using the whole depth range, so the plot must be done for a 100 m or a 200 m thick layer. The next important matter is the quantity of available data. If 1 month of recording fails to provide sufficient amount of data then in order to get more data one can extend the time period. This might not always be best as mining tends to change the rock mass conditions very quickly and a long time period might incorporate too many changes. Each contouring technique involves a lot of smoothing so again one has to experiment with getting the contouring parameters right. In order to compare these types of plots with each other they must be produced using these same plotting parameters in order to eliminate any misrepresentations due to the contouring itself. The other issue that has to be taken into account is the influence of the number and distribution of the various input data. There will not be two time periods in which the number of recorded events and their distributions will be the same. This makes using contouring difficult.

The energy—moment plot presented by Fig. 5.38 is based on data recorded during a single month. Depending on the time range (and the amount of data) the best fit line and the mean values of the energy index will change. The energy moment relationship presented by Fig. 5.39 is based on 17761 events recorded over 12 months (between 01/06/2006 and 30/06/2007). In this case the best fit line formulas are:

Log E = 1.546log Mo—10.516 for 1 month of data
Log E = 1.450log Mo—11.074 for 12 months of data

In this case the difference is not substantial, but it is important to remember that such plots should not be based on too little data. The other point to make note of are the ranges of energy and moment. The larger they are the better is the straight line fit. The other way to use the energy index values is to plot their time history that is

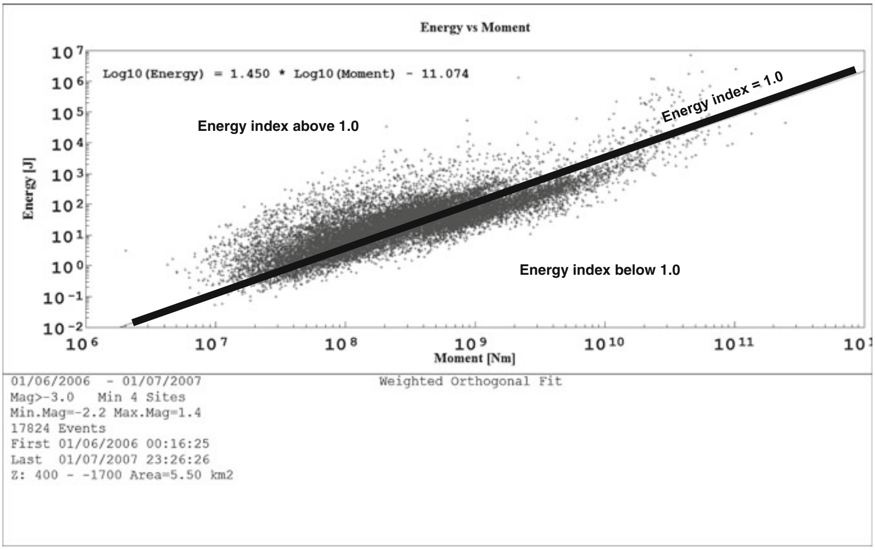

Fig. 5.39 Energy—moment plot for 12 months of data

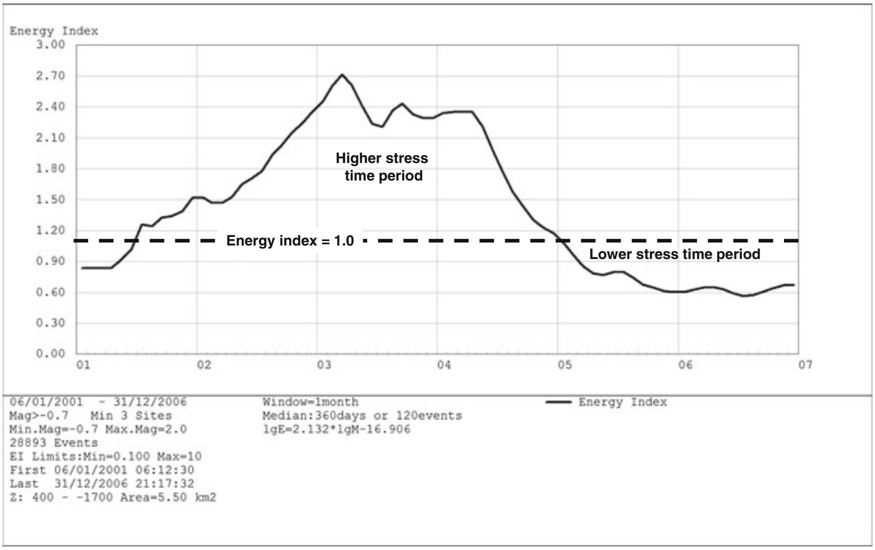

Fig. 5.40 Energy index time history

to analyze the time trends of the energy index values. Figure 5.40 shows the energy index time history from the beginning of 2001 to the end of June 2007. The energy index values at the beginning of 2001 were lower than the mean value of 1.0. From mid 2001 the energy index started to increase. This increase lasted until the beginning of 2003. From then on the energy index values changed very slightly up until about May 2004. For about 12 months there was a plateau. From May 2004 the energy index started to decrease. The mean value of 1.0 was reached at the beginning of 2005. From then on until the end of the plot (June 2007), the energy index values were lower from the mean value of 1.0. The decrease which started in May 2005 can be divided into two phases: a rapid decrease until the index reached the value of 1.0 and a slower decrease rate during the time period when the index was lower than 1.0. This plot indicates that basically there were two different stress time periods. During the first time period starting from mid 2001 until the beginning of 2005, the stresses were higher than during the second time period starting at the beginning of 2005.

Figure 5.41 indicates that the high energy index time period was associated with high seismic energy release rates. Here the monthly release energy rates are presented by the energy fragmentation index which is energy release normalised by rock mass volume. In this case the rock mass volume is a constant. In this way this index represents the energy release rate. To be honest I used this index here only because of the software presentation limits. Once the energy index reached the value of 1.0 at the beginning of 2005 the high energy seismicity ended. During 2006 and 2007 there was again some higher energy releases but these events were of different origin than the pre 2005 ones. The energy index history presented by

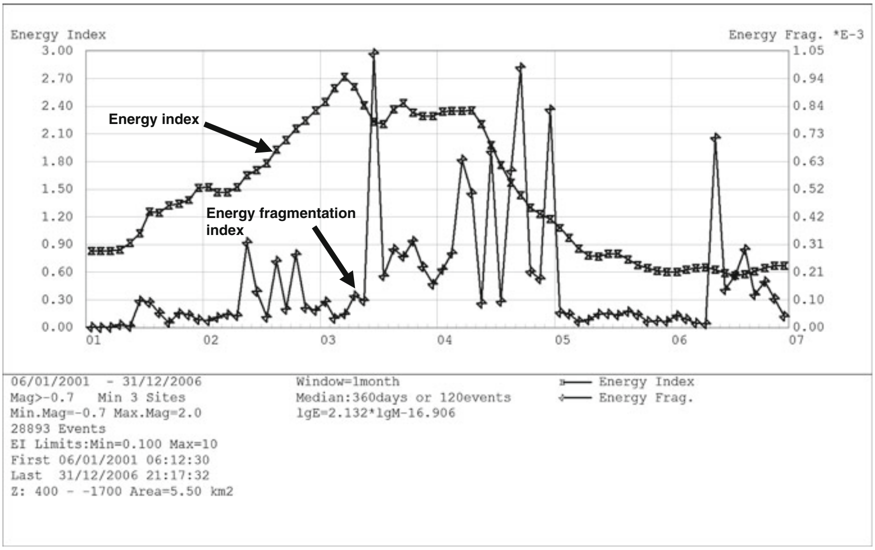

Fig. 5.41 Energy index time history and energy release rates

Figs. 5.40 and 5.41 are based on all recorded events. Here the minimum magnitude is –0.7 and the maximum magnitude is 2.0. In this data set about 90 % of all events are lower than magnitude 0.0.

The shape of the energy index presented by Fig. 5.42 is very similar to that presented by Fig. 5.41. As with other seismic data the energy index interpretation becomes much easier if some other data supports it. Figure 5.43 illustrates the energy index trend and the trend of the average monthly depth of seismicity. The stress reaches its maximum only when the seismicity depth reaches its maximu. Then during the stress plateau the seismicity remains more or less at the same level until the energy index reaches the mean value of 1.0. The other interesting fact about the graph for the average depth of seismicity is the fact that during 2006 and 2007 there was a lot of oscillations in elevation that coincided with increased seismic energy release at the same time (see Fig. 5.41). This was associated with the cave breaking into the open pit at the east side of the mine. This graph also indicates that there was a relationship between the energy index values and the average depths of seismicity but the exact nature of this relationship still remains unclear.

Interpretation of the energy index trend becomes still easier with additional data, in this case information about the caving stages. The information about the caving stages is as follows:

A—Initiation of the stress caving process
B—Failure of the crown Pillar
C—Initial cave break through into the open pit

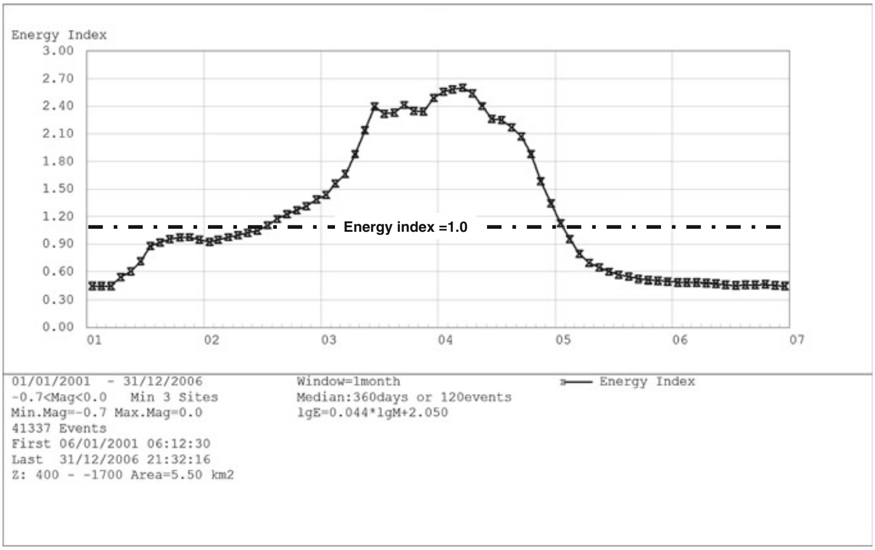

Fig. 5.42 Energy index time history based only on small size events

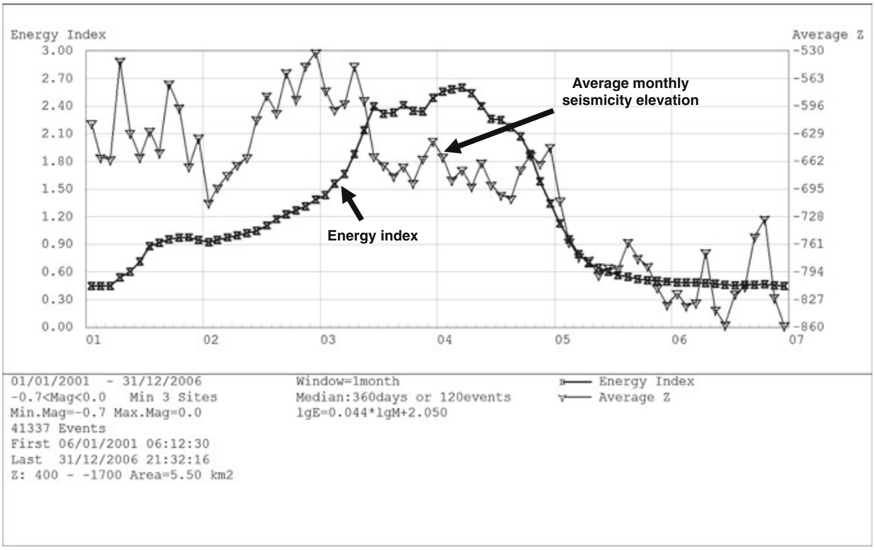

Fig. 5.43 Energy index and average seismicity monthly depths

The interpretation of data presented by Fig. 5.44 is as follows:

Figure 5.44 shows the energy index history for the whole mine, from the beginning of 2001 until end of June 2007. Data used to create this plot was recorded above and below the production level. The energy index graph represents the stress

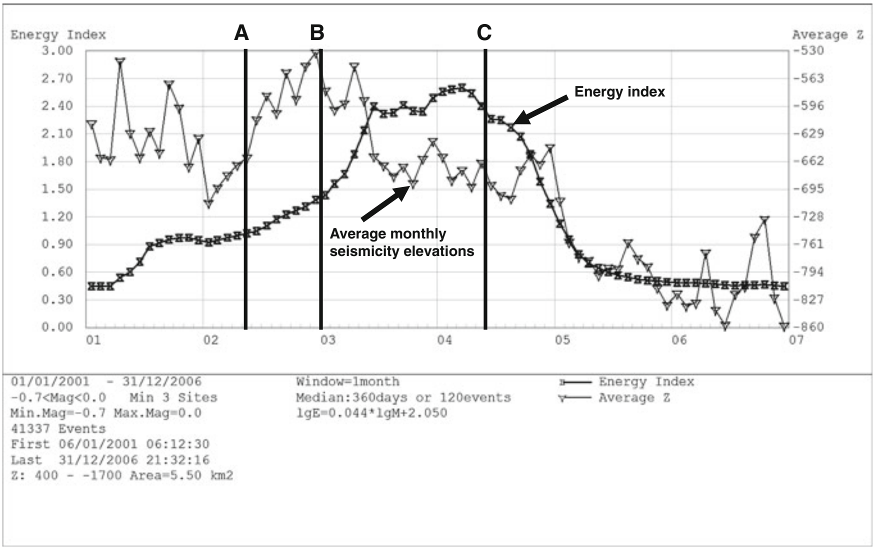

Fig. 5.44 Energy index, average seismicity depth and caving stages

regime and in this case relates its changes and values to different stages of the caving process. To start with, the stress levels during 2001 were close the average value (1.0). This stress was the result of the development mining. Start of the caving process (April 2002) was associated with a rapid stress increase that lasted until the failure of the crown pillar (end of 2002). The maximum stress time period continued until the cave broke through into the open pit in May 2004. From then on the stresses started to decrease to reach the average level at the beginning of 2005. At this stage the stress decrease rates were more rapid than the increase in rates after the caving process initiation. After reaching the average value of 1.0 the stress decrease rate slowed down. As of the beginning of 2005 the stress levels have remained below the average value. The stress increase due to the development mining phase was very low when compared to the stress increase induced by the caving process. During 2001, apart from the development mining, there was still mining taking place in the open pit. The gravity caving started in October 2001. At this stage the caving process started to induce much more seismicity than the open pit mining. For this reason the average depth of seismicity shows a downward trend. When the hydraulic radius reached 45 m, the stress caving process was initiated. Concurrent with this process the seismicity migrated upwards. By the end of 2002 the caving process resulted in the failure of the cave crown pillar and the seismicity migrated to its shallowest zone. From that point in time seismicity could only migrate further away from the cave and downwards into the still un-fractured parts of the rock mass. From the beginning of 2003 up to the end of the input data base there was a general downward trend in the depth of seismicity. It is of interest to note that the downward trend in seismicity became more evident as from the beginning of 2005, when the energy index reached the average value of 1.0.

The time related history of the energy index as presented by Fig. 5.44, was produced with the assumption that its value can change from 0.1 to a maximum of 10.0. This has reduced the amount of data used in this analysis. Figure 5.45 shows the shape of the energy index curve when this restriction on the individual energy index values is no longer present. In general this result is very similar to that presented by Fig. 5.44. The energy index reached the average value of 1.0 during 2001 and then increased slowly until March/April 2003. From then on the increase rate was very rapid. The maximum value was reached by the beginning of 2004. The subsequent decrease in the energy index values was also very rapid. The average value of 1.0 was reached by mid 2005. The rapid change in the energy index increase rate from about March/April 2003 is due to the production increase (see Figs. 5.27 and 5.28), while the rapid decrease from the beginning of 2004 was associated with the cave breaking into the open pit. Figure 5.45 also indicates that most of the high energy index seismicity was associated with the increased tonnage mucked from the cave. This is to be expected as increased production rates result in a more rapid cave expansion, which would then result in an increase in the stresses around the cave. This is the basis of the stress caving process. As with any other interpretation method the energy index analysis can be done for smaller rock mass volumes as the one for the whole mine. Dividing the mine into separate volumes is a difficult task. To start with the Palabora mine is traversed by faults and dykes. Any division of the mine will also involve taking into account only a part of a fault or a dyke. Further more the caving process cannot be divided into that taking part at the

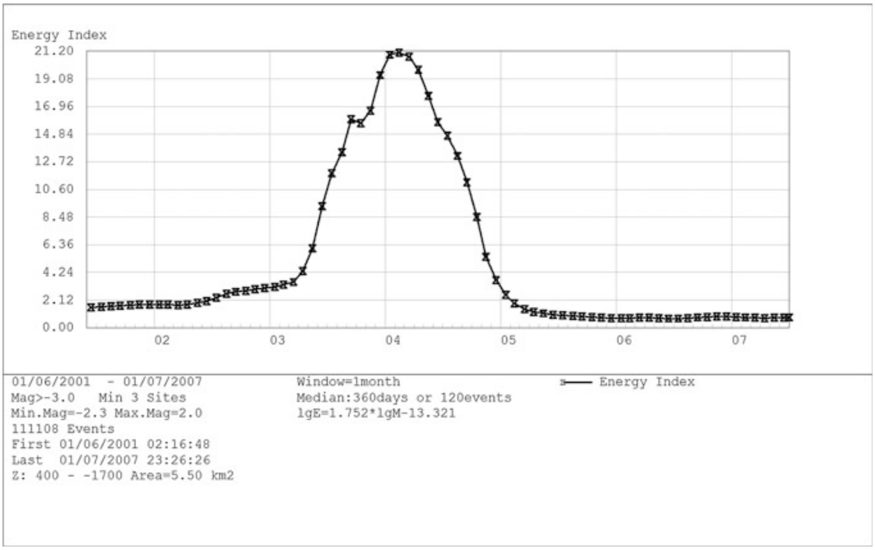

Fig. 5.45 Energy index time history—no limits to the energy index values

west or east. The only logical way of looking at smaller parts is dividing the rock mass volume into that located above the mine (where the cave is) and below the mine (where no mining is taking place). This rule doesn't apply in case of different sources of seismicity. If at the same time there is mining in the open pit, underground development and cave mining then it is important to be able to distinguish between these three different sources.

5.5 Some Problem Areas

Despite the fundamental limitations of the recorded seismic data they still are a source of valid information, not only about the mining but also about the surrounding rock mass in which the mining is taking place. The strength of this data is based on two following factors:

- Seismicity is taking place all around the mine.
- There is a lot of seismicity taking place.

The fact that seismicity is taking place all around the mine implies that it has a potential to provide information about the whole rock mass volume that is influenced by the mining process. In this sense it is very different from other methods like for example borehole measurements, which can provide only, point information or data. The fact that there is a lot of seismic data available allows for implementation of specific interpretation methodologies that in turn compensate for the input data limitations.

5.5.1 Activity Rates

Regardless of the precision dilemma with respect to seismic source parameters, a recorded seismic event is an undisputed event that took place. This applies not only to a single event but also to number of them recorded during any time period. In this sense activity rate can be regarded as an almost independent parameter of seismicity. Autonomy of this parameter is limited only by our ability to record. There is a lower size limit below which the system will not record and there is also a distance beyond which the system will not record. On the other hand all events above certain size and within certain distance will be recorded. In consequence activity rate can be treated as a reliable quantity. Seismic activity rate is the number of recorded seismic events in a certain time period. The most frequent activity rates are those based per hour, per day and monthly. Depending on the interpretation requirements one can use any time period. The longer the time span, the more smoothed will be the results. For example while analysing seismicity and production rates I have used activity rates based on time periods of 3 months. In this way the input data was smoothed, the local minima and maxima were overwritten and the long term trends become apparent. In this analysis I made use of other data than just seismic as the seismic activity rates were evaluated against production rates. This allowed for examining the relationship between these two independent quantities. Despite the fact that the seismicity was induced by the mining process, in this case cave mining, the relationship between the two rates turned out not to be straight forward. There was a time period when higher production rates result in higher seismic activity rates but then there was also a period when higher production rates resulted in lower seismic activity rates. This analysis resulted in a conclusion that there must be some other factor than mining rates influencing the seismic activity rates. The other conclusion was that this factor must be independent of the mining rates and that it starts to play a role only at some specific time. In this way I have related to each other the production and seismic activity rates with the caving process. Seismic activity rate while uncomplicated in its form is at the same time an effective parameter.

Figure 5.46 illustrates the Palabora monthly seismic activity rates and the production rates during 2008. The production rates oscillate around 10,00,000 tones/month with small percentage changes month to month. On the other hand the monthly seismic activity rates display a noticeable increase during May and June. This increase was nearly 60 %, from about 700 events during April to about 1100 events during June. This seismic activity increase was not the result of any change in production rates. At the time there was no development mining so access to a new area and a different rock mass type or some seismic activity associated with a geological discontinuity could also not be the reason for the increased seismic activity rates. The observed changes in the seismic activity rates during May and

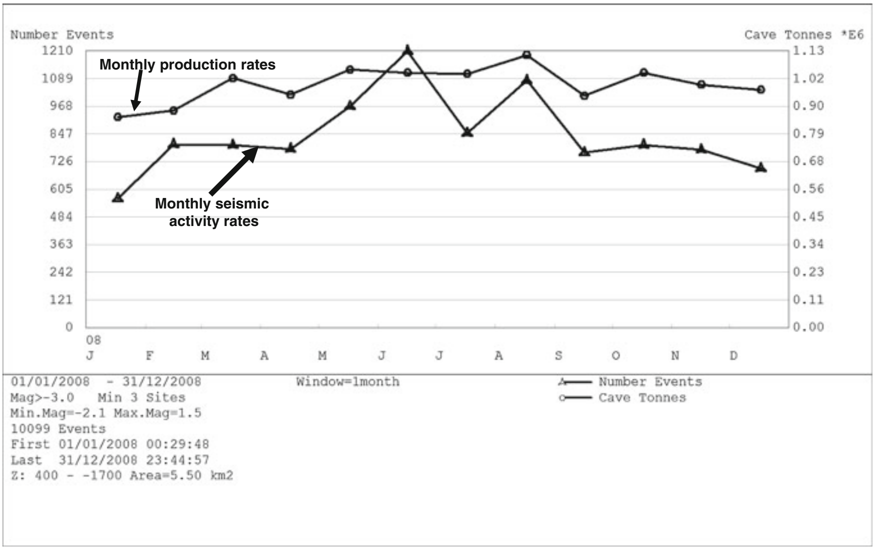

Fig. 5.46 Monthly production and seismicity rates

June 2008 were associated with the caving process as during this time period the cave was breaking through at the east side of the mine. This example, apart from the important conclusion that seismic activity rate is related to the caving milestones, indicates that seismic data interpretation must be done at the mine and not at some place remote from the mine. Increased seismic activity apart from the already listed reasons might be due to some changes to the seismic network sensor lay-out or changes to the network recording parameters. It has happened in the past that a certain research establishment has required from the mine to supply them on permanent basis with recorded seismic data. One of the researchers arrived at the mine to collect other data as geology and mine plans and then to visit the underground working places. Not much happened during the next couple of months. Then one day we have received a warning message that the mining must be approaching a seismically active geological feature as some of the recorded seismicity locates in a more or less straight and continuous line at a location that seems to be in front of the mining direction. The fact about this seismicity was correct as it was there. However the researchers did not update their mining information and their underground plans were out of date. The seismicity in question was there due to some development mining taking place and for this reason was not regarded as hazardous. But this was known at the mine and not by the remote researches. This not really out of the ordinary example illustrates the fact that any information used as input for data analysis and interpretation must be well understood and tested for bias by outside mechanisms.

5.5.2 Locations of Events

The analysis of seismic activity rates is in principle independent of the events locations. This holds true even if the analysis is restricted to especially selected rock mass volumes. There is a minimum volume size beyond which any analysis of seismicity does not make any sense. As mentioned at the beginning of the caving process there will be a time period when the locations of events will be reasonably accurate. The events will locate inside of the network as the network is usually designed around the future cave and the seismic wave velocities will still be close enough to those resulting from the calibration blasts. The seismic data recorded at the beginning of the caving process should be of very good quality and for this reason allow for very accurate information to be extracted. Locations of seismic events should be accurate to monitor not only the cave initiation process but also its progress over time. Figure 5.47 illustrates the changes in the monthly elevations of the Palabora seismicity from the beginning of 2001 to the end of 2004. During 2001 the monthly seismicity elevation changes do not form any pattern. This seismicity was induced by underground development mining and mining in the open pit. From the beginning of 2002 the seismicity elevation curve starts to show an uprising trend. The 2002 seismicity was induced by three forces: underground development, open pit mining and by the caving process. This figure illustrates the fact that the

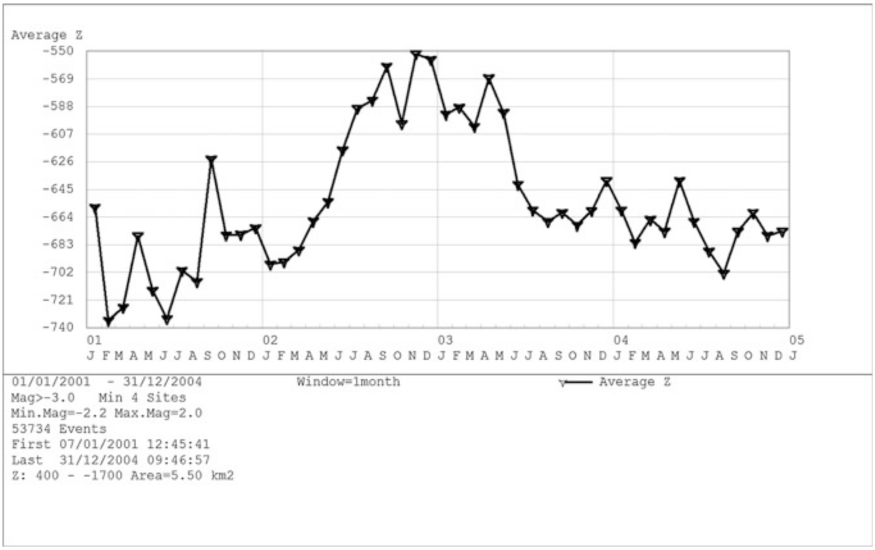

Fig. 5.47 Average monthly seismicity elevations

caving process is the main force. It is impossible to analyse individual seismic events and from them deduct the cave process initiation or progress. As caving is the process that induces the most of the recorded seismicity then analysing the monthly average elevations should provide required answers. The development and open pit mining induced seismicity will contribute only a small percentage of the recorded seismicity and for this reason during the processes of smoothing and rounding up will be eliminated. As the caving process proved to be reasonably fast then analysing longer than 1 month time periods does not make much sense. On the other hand shorter than 1 month time periods might not have enough data. The trend of the monthly seismicity elevation changes indicates that during 2002 the cave progressed upwards by nearly 250 m. This gives a growth rate of 12–13 m/month.

The recorded seismicity allowed not only monitoring the cave process but also to get an insight into the cave elements mainly to observe the a-seismic zone located above the caved material and the below the seismically active volume. The recorded data was of so good quality that it allowed estimating the size of the a-seismic zone. This is illustrated by Fig. 5.48. The tonnes extracted from the cave resulted in the cave back propagating upwards, towards the surface. This propagation is due to the rock mass fracturing above the a-seismic zone. The fracturing zone during 2002 was located about 60–80 m above the cave back.

This a-seismic zone thickness and its position were confirmed when drilling the eight open pit drain holes. These drain holes were terminated just above the lower boundary of the increased seismic activity zone. This is not unexpected. These drill holes were terminated due to loss of air pressure and water due to either open

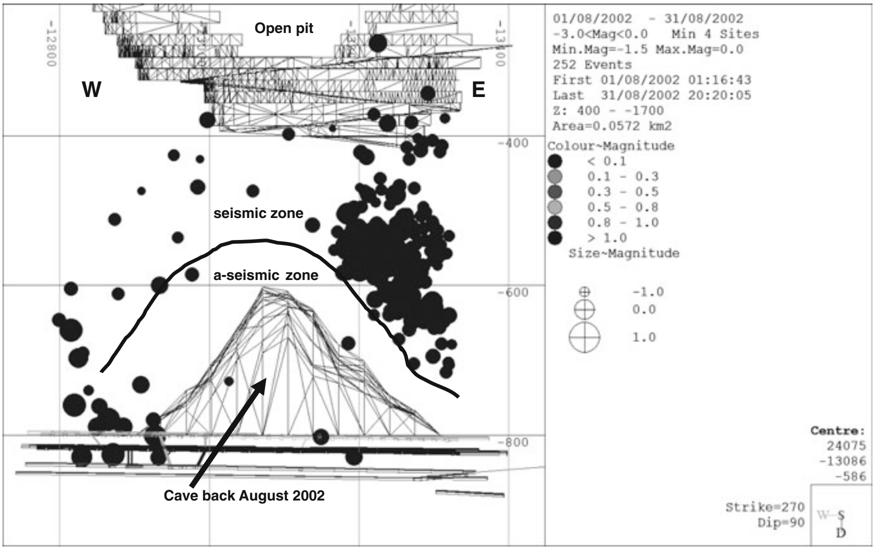

Fig. 5.48 The a-seismic zone above the cave

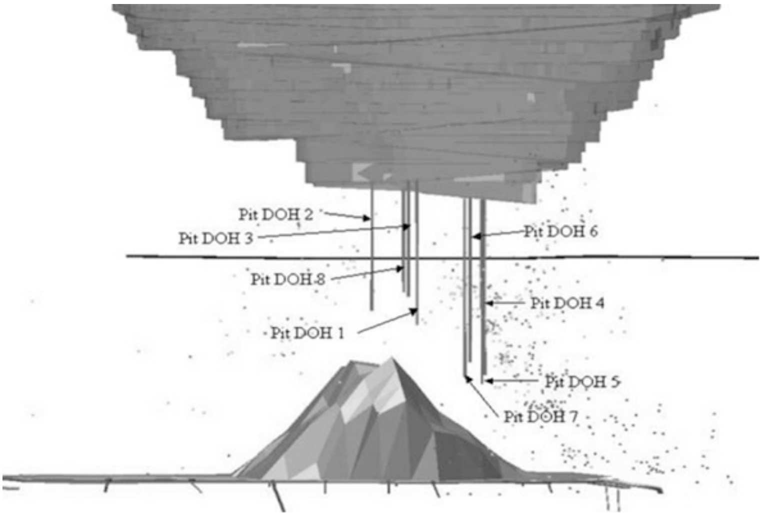

Fig. 5.49 Open pit drain holes and seismicity

geological structures or open fractures in the rock (Fig. 5.49). The position of the cave back in this figure is for September 2002.

Locations of seismicity in this initial time period were good enough to recognise seismically active and hazardous geological features. Recorded seismicity of magnitude 1.0 and above recorded during 2002 and 2003 located along faults and dykes. Over time and with the expansion of the cave and the seismically active volume the location accuracy will decline. The reason for this is obvious, the fractured rock mass will have different physical properties from the solid one. One of these properties is the seismic wave velocity. The seismic activity will also move away from the mine and the seismic network. As a result the quality and accuracy of recorded seismicity will deteriorate over time. In theory it is possible to repeat the calibration blasts in order to update the seismic velocity values. This however would require deep boreholes (for the blasts) drilled from the surface and then expanding the seismic network (to make use of the new velocity values) well beyond the underground mine. The other option would be to adopt the analysis and interpretation methods to the existing data quality. One of the techniques used with large size data recorded over considerable size volume is segregating the data into polygons on the basis of time and space.

5.5.3 Dividing the Mine into Polygons

Dividing the mine into polygons started with areas of interest. In such areas amount and size of the seismicity is of some specific importance. By mid 2011 Palabora had two such areas: the west faults and the rock mass around the ventilation shaft. As increased seismic activity associated with faults in the west might be the first warning of an impending open pit west wall failure, they were monitored together with movements along the west wall. The stability of the rock mass volume around the ventilation shaft became so important that some additional stations were installed in this volume. Seismicity recorded in these two volumes is counted but not interpreted and was then reported once a month. The areas of interest are of certain sizes and usually will have good seismic cover. With the so called polygons it is different. It happened when the seismic networks started to change from regional (mine or multi-mine cover) to shaft wide (part of the mine). In general the distances between the stations were reduced from kilometres to hundreds of meters. This resulted in recording more of the low size seismicity and then trying to associate it with mining in specific locations in relatively small rock mass volumes. In some cases this process resulted in really small polygons that did not take into account the location accuracy or the geological features. It seems logical that the polygon size can not be smaller than the location accuracy. It is impossible to artificially divide the seismically active geological discontinuities into some sections and then expect that their seismicity will be independent of other sections. Very often incorrect space filtering of seismic data will limit the reliability of the analysis and data interpretation results. Space filtering of seismicity should be based on what is possible and reasonable. For example the caving process is taking place above the extraction level. Then the seismicity above the extraction level is directly induced by the caving process while that recorded below the mine must be then induced indirectly. As already stated locations of seismicity are generally not as good as expected. This is usually due to the fact that most of the seismicity locates outside of the seismic network. All recorded events carry useful information that has to be extracted, but taking into account their location ambiguity. For this reason I usually divide the whole data set into such subsets for which accurate location is no longer as important. If the two data subsets divide the entire seismicity into that locating above and below the extraction level, then it can be assumed that most of this data fulfils this simple requirement. If a small percentage of this data still does not fulfil this requirement then it does not really matter.

Statistically it can be expected that the same number of events that took place above the mine will be included in the subset that contains seismicity from below the mine, as the number of events that took place below the mine will be included in the subset above the mine. Further more when one deals with large data sets and for interpretation purposes uses only their trends, then this final output has gone through such smoothing processes that the remaining location ambiguity is of no significance. In addition when the output is in percentages, the network performance (number of stations off line) then does not influence the final results. If for a period the network is down or some of its stations are not operational, then it influences the amounts of recorded seismicity above as well as below the mine in a similar manner. Figure 5.50 is based on nearly 1,40,000 events recorded since the beginning of 2002 until end of 2011. This type of data analysis allows not only handling large data sets but also data of changing quality. Analysis of trends and changes over time in percentages of seismicity taking place above the mine proved to be a very reliable indicator of the caving process. It is also logical to divide the seismicity into that taking place immediately around the mine and that taking place at some distance from it. With such polygons it is then possible for example to analyse the percentages of seismicity recorded above the footprint or below the footprint. It is also possible to divide the whole seismic data base into two subsets: seismicity recorded above and below the mine footprint and that which was then recorded only beyond that volume. Analyses of such subsets are first done separately and then the results are compared. It is also possible to compare seismicity

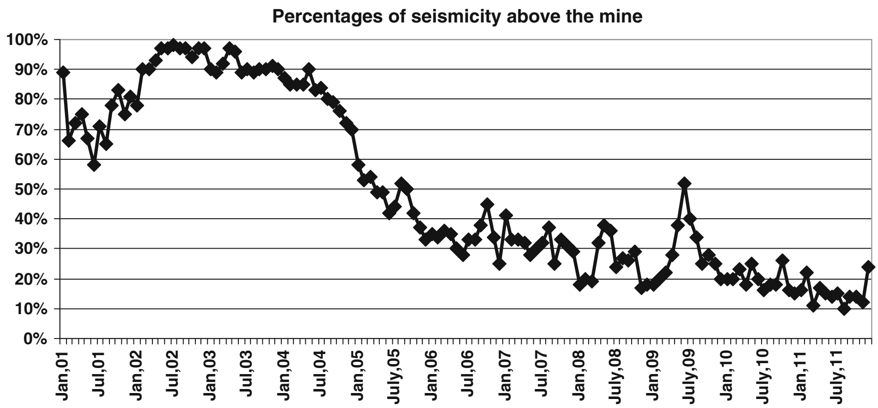

Fig. 5.50 Monthly percentages of seismicity taking place above the extraction level

recorded in two volumes, for example outside and inside of the mine footprint. These examples enabled a division of seismicity into that occurring inside and outside of a volume defined by mine boundaries. There is still a different method of dividing seismicity. In this second method the volume boudaries are defined by the seismicity itself. This method make use of the seismicity clustering.

5.5.4 *Creating Sub-Data Sets*

It is possible to create separate seismic data bases using specific volumes. For example while explaining how to divide the whole mine volume into two polygons I have created a polygon "FOOT PRINT". I have then compared its seismicity with that located outside of this polygon. This type of analysis and data interpretation can go still further. The seismic events of the whole seismic data base can be divided into two sub-sets: Sub-set with events that locate inside of the "FOOT PRINT" and sub-set only with events that locate outside of this polygon. Figure 5.51 illustrates the location of events located outside of the "FOOT PRINT".

It is then possible to study this seismicity using all the methods of analysis presented to date. Figure 5.52 illustrates the monthly seismic activity rates for this seismicity. It is interesting to note that after the failure in the open pit (October 2004) the average monthly seismicity elevations trend indicated a change. During the whole 2004 the monthly elevations were nearly constant and the downward migration started at the beginning of 2005. Analysing such sub-data sets allow for

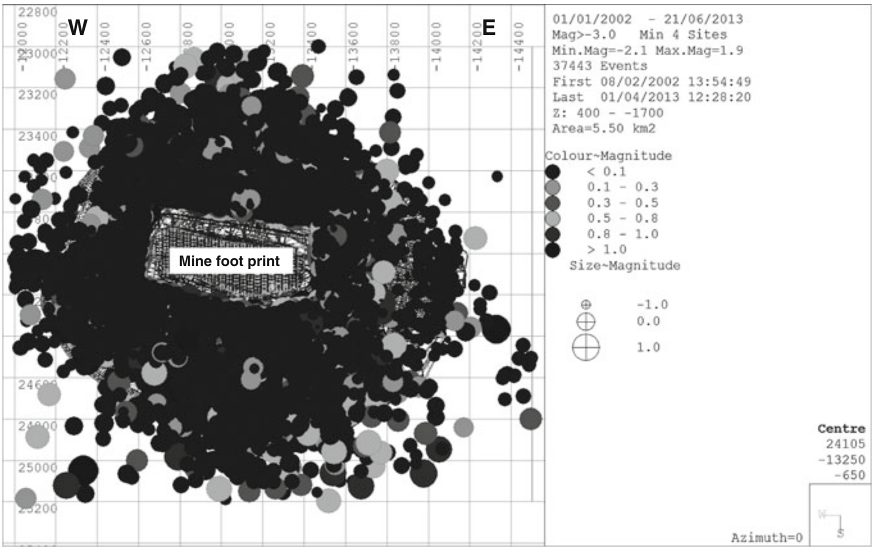

Fig. 5.51 Seismicity locating outside of the "FOOT PRINT"

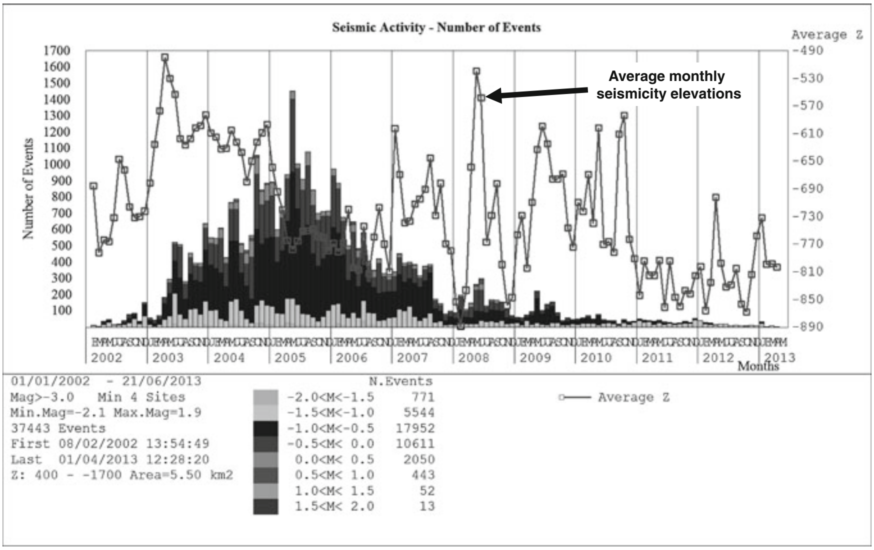

Fig. 5.52 Outside of the "FOOT PRINT"—monthly seismic activity rates

monitoring and then analysing features that are not always visible while analysing full data sets.

Figure 5.53 illustrates the monthly seismic energy release rates of seismicity recorded outside of the "FOOT PRINT". Here two features might be of interest. Larger size energy releases in this volume started during 2003 which is after the Crown Pillar failure (end of 2002). In total the outside of the "FOOT PRINT" energy release amounts to 1.89E+08 J which is over 50 % of the total seismic energy released inside and outside of the "FOOT PRINT". This comparison indicates that the caving process results in substantial seismic energy releases outside of the mine. In cases when there is a number of service excavations located outside of the mine foot print this type of information might be very important.

Figure 5.54 illustrates the monthly seismic deformation rates outside of the "FOOT PRINT". As the total seismic deformation inside and outside of the "FOOT PRINT" is 1.20E+14 Nm, then outside of the "FOOT PRINT" the seismic deformation amounts to about 60 % of the total. The possibilities of analysing such sub data sets are multiple but the main aim of the analysis should be a comparison between the sub-data sets.

Figure 5.55 illustrates the monthly energy release rates for seismicity with Ei > 10.0. About 24 % of the recorded seismicity had the energy index value above 10.0. Some of that seismicity (of 2003 and 2004) was associated with the high stress time period but the 2006 and 2008 seismicity took place in a lower stress environment. This high seismic energy index seismicity released about 46 % of the total energy released.

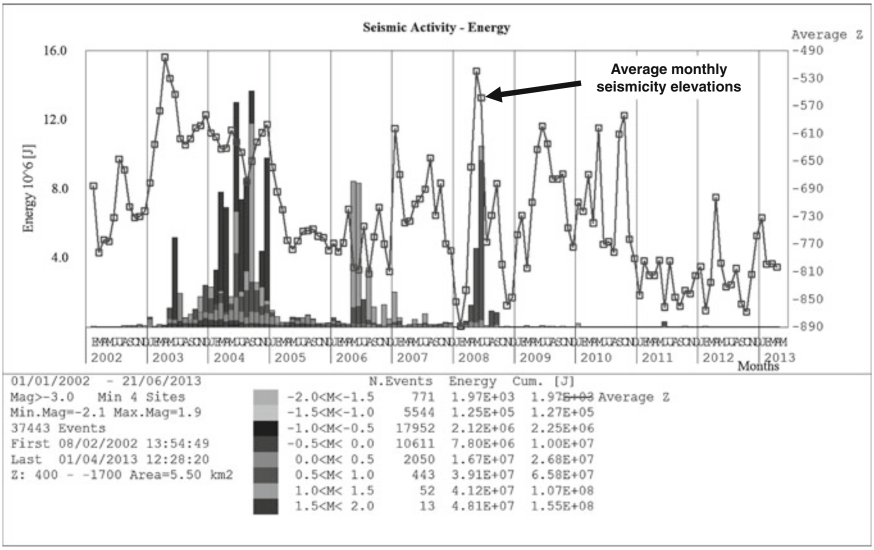

Fig. 5.53 Outside of the “FOOT PRINT”—monthly seismic energy rates

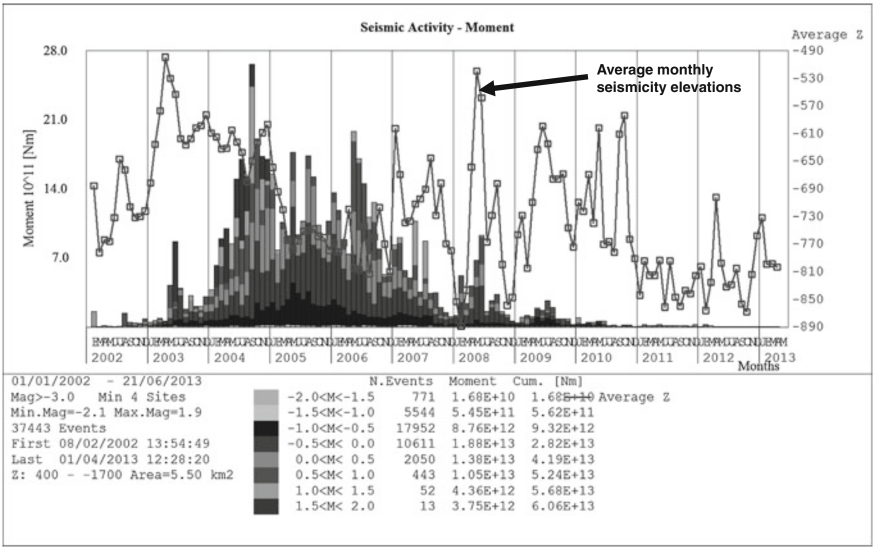

Fig. 5.54 Outside of the “FOOT PRINT”—monthly seismic deformation rates

Figure 5.56 illustrates the monthly seismic energy release rates of seismicity located inside of the “FOOT PRINT”. The vertical scale of this figure is the same as that on Fig. 5.55. In case of the “FOOT PRINT” also about 24 % of recorded seismicity had an energy index above 10.0. This 24 % of high energy index

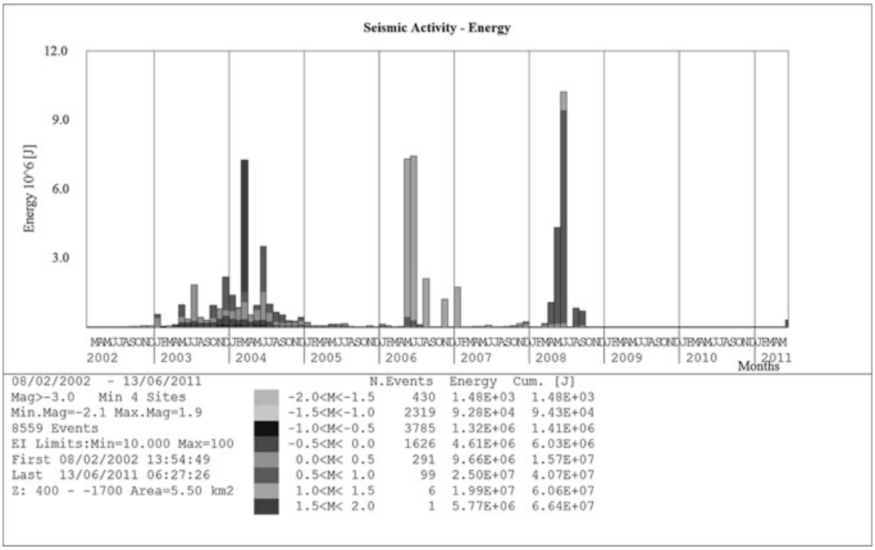

Fig. 5.55 Outside of the “FOOT PRINT”—seismicity of EI > 10.0

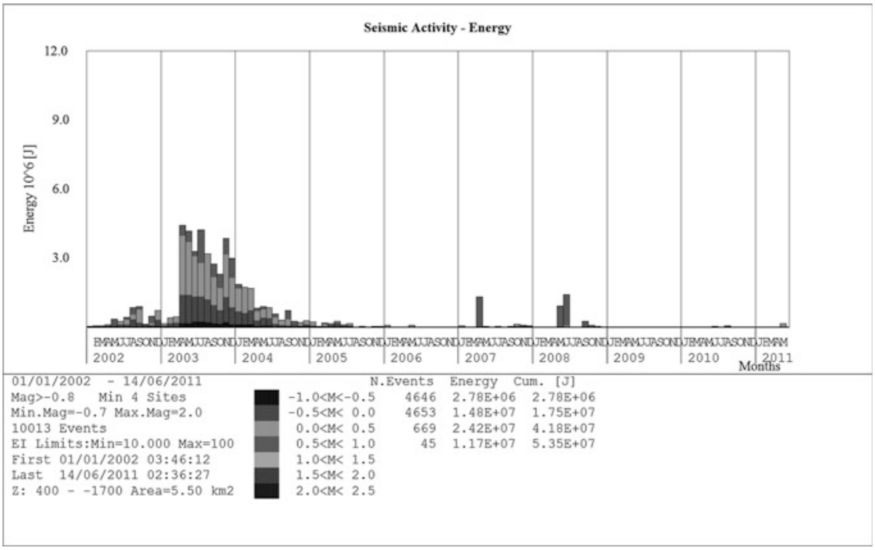

Fig. 5.56 Inside of the “FOOT PRINT”—seismicity of EI > 10.0

seismicity inside the “FOOT PRINT” accounts for 28 % of released seismic energy. This is much less than in the outside volume. The time distributions of the seismic energy releases in case of the volumes inside and outside of “FOOT PRINT” are also different. In case of the inside volume nearly 100 % of these high energy releases took place during 2003 and 2004. The high energy index seismicity different time distributions inside and outside of the "FOOT PRINT" as presented by this example might be important or not, but the observed differences contribute towards a better understanding of the caving process. This type of analysis might be used for example for comparison of seismicity induced in hydro-fractured volumes with that induced in volumes with no preconditioning taking place before mining.

5.5.5 Parameters Derived from Moment and Energy

Presentation and analysis of seismicity using its space location and different rates results in independent data for interpretations. This data is not only independent of each other but complements each other in the interpretation process. Proper use of parameters derived both from seismic moment and energy is not simple. As already indicated the seismic risk changes over time can be monitored either by the energy index time history or by the apparent stress time history or by the energy release changes of events of the same magnitude size.

Figure 5.57 illustrates the time histories of these three parameters: energy index, stress index, monthly energy releases by magnitude –0.5 size seismicity. The energy index and stress index time histories have similar trends. This implies that separate analysis of those two parameters will result in the same conclusions. The energy index time history and the apparent stress time histories must be exactly the same as both these parameters are derived from seismic energy and seismic moment. The monthly seismic energy released by events of magnitude –0.5 time history confirms what the other two time histories indicate. This duplicity in trend is especially evident up to the end of 2006. Figure 5.57 might imply that from the beginning of 2006 until the mid 2011 the energy index and apparent stress time histories are flat and so there are no changes over time.

Figure 5.58 illustrates these three time histories, but only from the beginning of 2006. This figure demonstrates that this is not the case and that these parameters do change over time. Data illustrated by this figure is based on data recorded since the beginning of 2001.

Figure 5.59 illustrates the three parameter trends that in this case are derived only from data recorded since the beginning of 2006. There are some minor differences in the trends illustrated by these two figures. The other important factor is the reliability of the average monthly energy release rates which depends on the number of events used to calculate the mean.

Figure 5.60 illustrates the monthly seismic activity rates of seismicity magnitude –0.5. These activity rates vary and are low since the beginning of 2006. This example indicates that before using any data for the interpretation and analysis it has to be tested for reliability and consistency.

It is interesting to compare Fig. 5.60 with Fig. 5.61. The first one illustrates the monthly activity rates of events magnitude –0.5. There are two time periods when these activities are higher than during other times. The first maximum was during

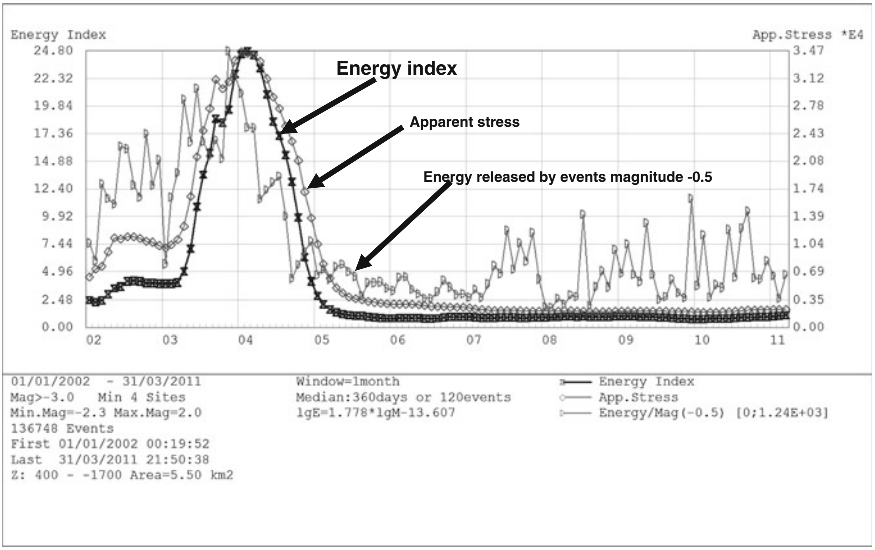

Fig. 5.57 Energy index, stress index and energy per magnitude –0.5 time histories (1)

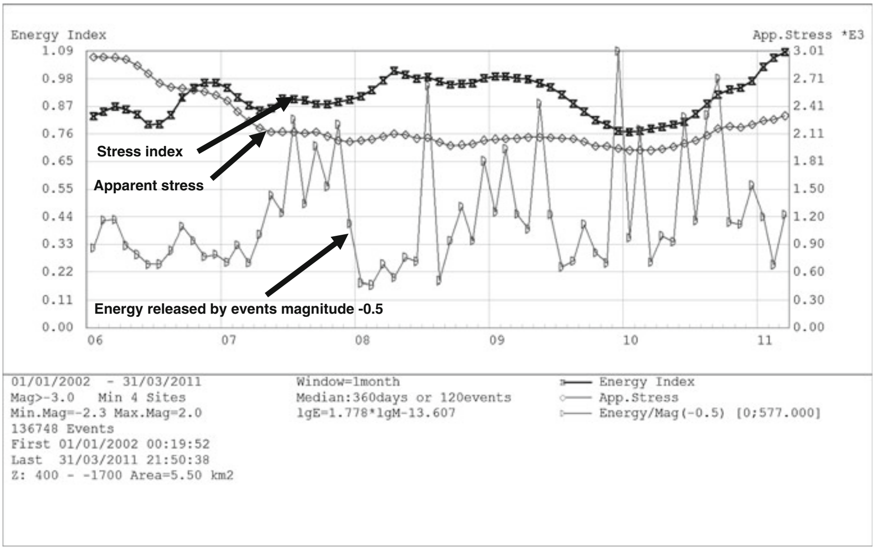

Fig. 5.58 Energy index, stress index and energy per magnitude –0.5 time histories (2)

2003 and the second one during 2005. When analysing the monthly energy released by these events it is clear that there is only one time period with high energy releases. The 2003 high energy release time period corresponds with the 2003 high activity rates. The 2004 high activity rates are not followed by the high energy

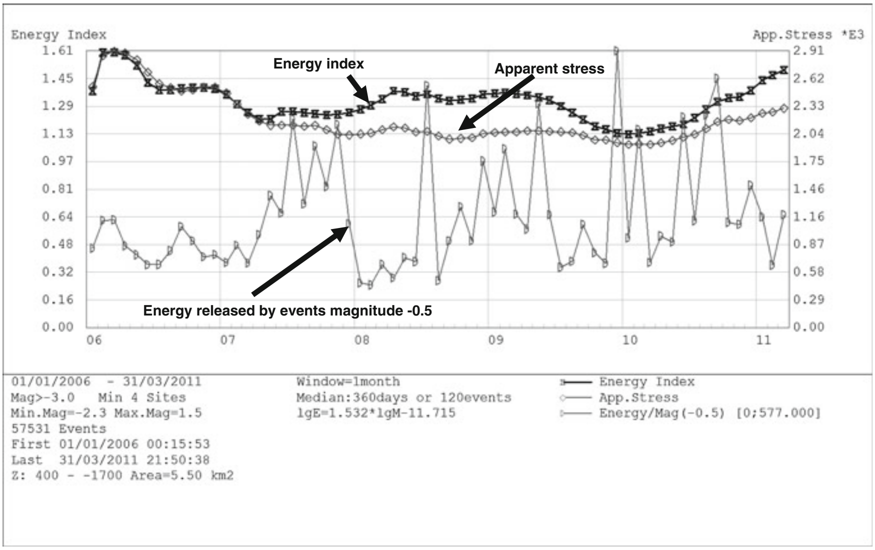

Fig. 5.59 Energy index, stress index and energy per magnitude –0.5 time histories (3)

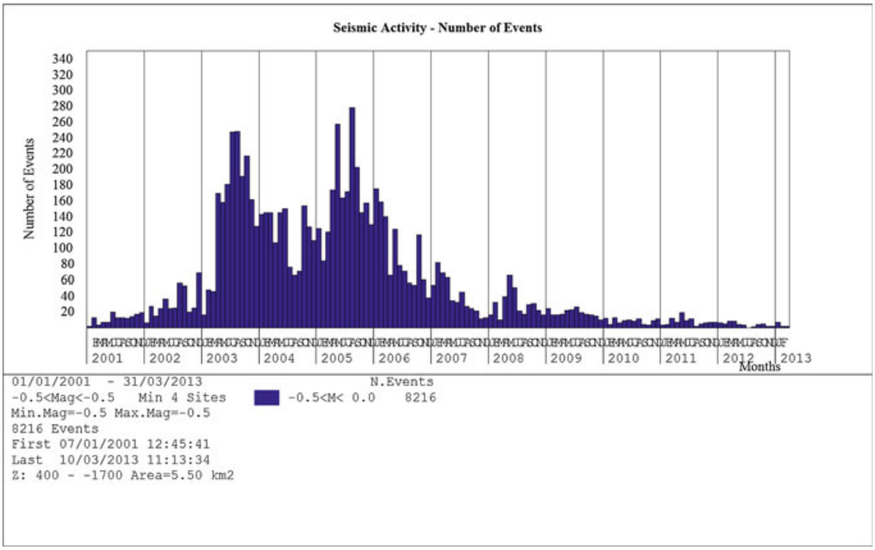

Fig. 5.60 Monthly seismic activity rates of events magnitude –0.5

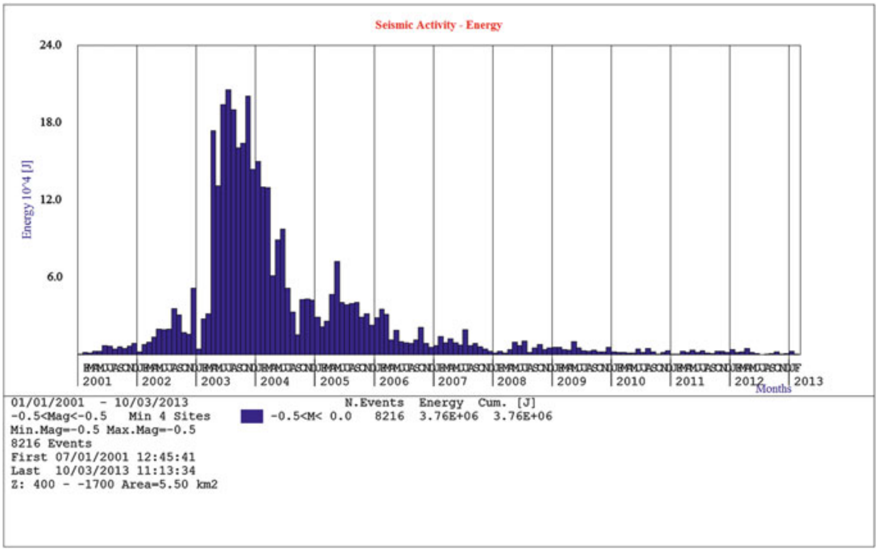

Fig. 5.61 Monthly seismic energy releases by events magnitude –0.5

release rates. This indicates that the same magnitude events can release very different amounts of seismic energy.

5.6 Limitations of Seismic Data

The reliability of seismic data is very low. It is my experience that most or a lot of its users do not realise that the seismic source parameters that they are using for interpretation purposes are only estimates and that their values are not derived from a process of a measurement. The reality is that the seismic source parameters are just an educated guess. If one would try to find a comparison in the same reliability range then there is an estimate one gets from a builder. No one really expects the estimate from the builder to be accurate and usually it is accepted as accurate enough if the final costs are within the same order of magnitude as the estimate. This seems to be generally acceptable and provisions in a form of contingences are always attached to any capital expenditure. In case of seismic data one can not attaché to them any contingences but good understanding of the way they were derived will help a lot in improving the reliability of the interpretation process. To start with one has to be aware that the seismic source parameters are approximated from an unobserved signal making use of an observed signal that contains noise. The unobserved signal is the one that originated at the source and the observed one is the one recorded by the seismic sensor. The noise is all the additions to the original signal that originated at the source. If the recording is done by a geophone then the recorded ground motion history contains the original signal and noise that originated for multiple and complex reasons. The source parameters can be reconstructed only from the original source signal. This implies that it must be possible to subtract from the recorded ground motions history the complete noise component. In practice this is done by assuming that we know how to correct for attenuation and scattering effects that took place along the travel paths of the seismic waves. To start with this process requires knowing the location of the seismic source as we need to know the distance to which these corrections should by applied. As it will be discussed later the location of the sources are usually not as good as it might be expected. Then to apply the corrections it is assumed that we know the rock mass properties for example its density or the seismic wave velocities. Although we have an idea about the rock mass properties we do not know their exact values at every point of the rock mass. We also know that the rock mass is not homogeneous. This by definition implies that to start with its properties are not consistent in all directions. The matter is then further complicated by the mining process itself that continuously changes the rock mass properties in the volume around the cave. These changes are not only un-measurable but also extensive and take place in the rock mass volume that contains not only the seismic events (the source) but also the seismic sensors. This influences the reliability of the assumptions. Up to now I have only mentioned the reliability problems that are connected with the nature and the degree to which we can try and represent it by various parameters. The software that is used to process the recorded seismic data is also a cause for distorting the reality. As I have illustrated in Chap. 9, new software versions can change the resulting source parameters by two or three orders of magnitude. Today there are several mine seismic systems available. The resulting source parameters for the same single seismic source will also be different depending on the recording system. The principles of signal processing that are applied in various seismic processing software's are generally the same but not down to the details. These details depend not only on some more or less sound theoretical assumptions but unfortunately also on individual preferences based on so called research progress that in theory is the process of closing the gap between the theory and reality. I do not intend to list all assumptions that are done in the process of estimating the source parameters. Here I want to point out that by nature the method of their deriving makes them if not dubious then uncertain and for sure different from their real values that we will never know.

Up to this point I have only mentioned some of the reasons why the estimated seismic source parameters are not the true representation of reality that are independent from the mine seismologist or the mine practitioner using the mine seismic system. For them these reasons are "deus ex machina" and there is nothing that can be done about them apart from accepting them. The mine practitioner is then the cause of further distorting the seismic source parameters. And this takes place not due to lack of knowledge or practice. Processing of recorded seismicity is a very important process that influences the quality of the seismic data base. Note that at this stage I am mentioning the seismic data base not the individual seismic events. Processing should be consistent and is the best if done for years by one and the same experienced processor. Not practically possible but that would be the optimal solution. In practice the processing is done by an ever changing number of individuals or given to contractors (located in different time zone which makes communication difficult) about whom it is assumed that they are professional. It is my experience that with no one at the mine able to control or having the time to control the processing the resulting quality is poor. The recorded data might be for example processed by using all time the same sensors or with a minimum number of them. Remote processing has further built in negative mechanisms. For example the processor does not know the mine, is not aware of the stations that are off line or has no knowledge about the blasting activities. Processing on site not always seems to be possible but it should be at least considered. In the end the capital expenditure on the network has to be substantial, as the network and its installation isn't cheap. Financial savings might not be so large but might wreck the reason for seismic monitoring. It is a fact of life that the seismic system as such is not always appreciated by miners or mine managers. It is often the task of the mine seismologist to prove the usefulness of the seismic system to the manager (not the mine). Once this is achieved then this is not the end of the process as the mine managers are rotated on rather regular basis. The other component that is necessary for good data interpretation is its understanding. I have already listed some of the reasons why this data falls into the estimate category. There are more of them. As new software version can change the parameter values by two or three magnitude orders (in both directions), accepting the recorded event depending on the number of processed stations has a similar effect. I have described this phenomenon in Sect 3.4. This trend is the result of the network configuration and the locations of the seismic events. The seismic sensors are usually located making use of the existing underground configuration. Sometimes they are also located in specially drilled boreholes but more often in the existing and the available ones. In case of cave mining the sensors will be distributed around the cave at distances from the cave that very rapidly became smaller than the distances to the seismic events. In case of Palabora less than 5 % of recorded seismicity from the beginning of 2002 to the end of 2010 located inside of the seismic network. This implies that over 95 % of recorded seismicity located outside of the network. These seismicity locations can not be accurate, as for an event to be accurately located it requires to be surrounded by sensors (also from above and below). If an event is enclosed by sensors then adding or taking one out will not influence the event coordinates or its source parameters. If the event locates outside of the seismic system then the number of accepted stations has a direct and strong influence not only on the source parameters values but also on the source location. The difference can be as large as one order of magnitude. If the number of accepted stations strongly influences the location coordinates and the values of seismic moment and the released seismic energy then what will be its influence on the moment tensor solution? One first has to understand the data and its limitations before attempting its analysis and interpretation. It is important to realise that the mine practitioner has some means that can be used to improve the matter. The process of improving the quality of recorded seismicity starts with a proper design of the mine seismic network. As mass mining is a three dimensional process so must be the seismic network configuration. It is important not only to locate the sensors above the mine but also below it. As it was reported the caving process at some stage starts to induce seismicity below the extraction level and over time the amount of this seismicity becomes compatible with the amounts induced above the mine. One should try to locate the sensors in such a pattern that will result in equal network sensitivity and location accuracy over the whole mine. This at least for some time will help with the interpretation of the recorded seismicity as there will be no need to attach to it a compensating factor for the lower sensitivity volumes. My recommendation is to make use of only one type of sensors and only use triaxal probes. There is a tendency to mix together single with triaxal probes. The reason behind this is probably to lower the installation costs. It might lower the costs but it might also result in substantial reduction of the seismic data base quality. In theory the single component seismic stations should only be used to locate the events, and the three component ones to provide input into the process of evaluating the seismic source parameters. Single component recordings should not be used in this process, as they, by definition, should be treated as rejects and not fit for this process. Still they often are used together with the three component ones with the result that source parameters become totally distorted. The other dilemma is what sensors to use: geophones or accelerometers. The general rule is the lower magnitude events one wants to record the higher frequencies have to be recorded. This is then the universal argument for the accelerometers. At this stage one has to consider not only what is the use of recording, for example, all events of magnitude –2.0 and above, but also what will be the consequences of recording such extremely low magnitude seismicity. Let's try and solve this problem making use of the Palabora experience. The Palabora seismic data base is complete down only to magnitude –0.6. Still this "limited" amount of seismicity allowed for successful monitoring of the caving process as well as for correctly evaluating the seismic risk. It allowed also recognising the seismically active geological discontinuities and then evaluating the seismic hazard. Would these tasks be simpler or results better with more input data? The answer is no. On the other hand with this sensitivity as it is the network recorded during 10 years about 1,40,000 events. With sensitivity down to –2.0 there would be over 10 million events recorded (1 million/year). One million events per year means that the system would be recording about 2700 events/day which with about 40 % of the triggers being noise would amount to about 3800 events/day (nearly 3 events every minute). Processing such large numbers of events would be a serious logistical problem and practically impossible. Instead of installing very dense seismic networks one should concentrate on full implementation of the seismic network right at the start of the mining process. The Palabora seismic network was installed in stages and was completed only 2 years after the caving process was initiated. This resulted not only in limited applications but in analysis and interpretation of incomplete data sets. Incomplete data sets restrict the possibilities of analysis in real time which are important for the mine. Back analysis results are also important but mainly for the new mines or research. After completing the installation there would be commissioning of the network during which the supplier of the equipment would set all the recording parameters. At this stage there should be some calibration blasts performed in order to calculate the seismic wave velocities. These blasts should be then repeated from time to time in order to update this information. If the network is fully operational before the cave initiation then there is a short time period when there is the chance to record real quality data. The used velocities are as close to the actual ones as is possible and the seismicity only appears inside of the network. With time these nearly perfect initial conditions deteriorate as the seismic wave velocities change and the seismicity migrates outside of the network. The next step that will improve the seismic data base quality is to familiarize with the recorded data and based on observations set some processing rules. It is then important to train the person responsible for the data processing. This person should be also responsible for running the network and making sure that all network parameters are set in a way that it is operating in an optimal way. These arrangements might seem trivial but they are extremely important. If these actions will not be implemented this will result in low quality seismic data base with irreversible consequences. Noisy events once recorded can not be repeated, accepted non-events are impossible to recognise without examining the seismograms, blasts once accepted as events will pollute the data base. With large amounts of recorded data it is then practically impossible to go back and reprocess the events.

Let’s assume that there is a properly designed and installed seismic network, that the recorded data is of good quality and that the data processing is done in the correct way. This on its own will secure that the seismic data base content will be of good quality. Seismic data on its own usually is not sufficient to solve any problem. It has to be supplemented by other data. The first data that will be required for the interpretation purposes is mining information. In the end it is mine induced seismicity that is recorded. Mining data should consist of mining rates as well as the mining plans. The mining rates should include development and production information. This information should be as detailed as possible and collected regularly on daily bases. The reality is that if one will require this information from the mine after a couple of years then it would probably be no longer available as no one would be able to locate where it was stored. Other important information supporting seismic data interpretation is geology and any available geotechnical information. What is now required is a person understanding the seismic data limitations and proper interpretation software. This last is often confused with visualisation software. If one wants to “see” the seismicity in colours and in 3D from various angles while it rotates such software is also available.

5.7 Summary

In this chapter I have described several interpretation methods that are applicable to large data sets of recorded seismicity. As illustrated each approach on its own is not sufficient to draw final conclusions. Seismic data on its own can be deceptive and for this reason must be supported by other relevant data such as geology, mining or other appropriate geotechnical input. It must be understood that all of the seismic source parameters are in some way related to each other. Even the seismic energy release and the seismic moment that are often described as independent of each other are in fact related to each other. Here the general relation is directly proportional, the larger the energy release the larger will the seismic moment. The locations of seismicity in mines are not random but are directly associated with the mining and geology. This fact should help in finding logical explanations for the observed patterns of seismicity. The best locations and more reliable source parameters are for the events located inside of the network, that is when the source is surrounded by sensors (also above and below). All events that take place outside of the seismic network by definition will be poorly located and their calculated source parameters could be far from the actual values. If that is the case then one might ask a question whether there is any sense bothering with interpretations of such poor data sets. The answer is that an interpretation of such data makes sense but only with the use of proper techniques. One such interpretation method for example would be looking only at data trends ignoring their absolute values. Interpretation methods provided in this chapter link the recorded seismicity with ore extraction from the developing, undercutting and caving operations of the cave block mining at Palabora. Seismic monitoring provides a successful tool for the detection and evaluation of seismicity occurring in the rock mass due to block cave mining operations. While the detection itself is a reasonably simple matter, the data evaluation and its interpretation is a much more complex problem, which may result in several explanations for the same observation. However it is well established that seismicity in mines is related to mining conditions and excavation methods and for this reason it is possible to link seismicity with various parameters characterising the mining and rock mass conditions.

Mine seismic networks record on a daily basis from tens to thousands of seismic events. It is not possible to analyze each event separately. I have described several methods allowing for extracting information from large seismic data catalogues. I have also described how to combine together not only different seismicity parameters but also how to bring them together with other geotechnical and mining data. I have also listed several practical applications where recorded seismicity was used to monitor the various stages of the caving process. All presented applications of seismic monitoring not only illustrate the fact that seismic data analysis can be successfully used to monitor the caving process, but also confirm how reliable it is. It is interesting to note that practically all of the illustrated analyses of recorded seismicity are independent of the location accuracy. When the data input catalogues consists of all recorded data as in the case of energy index time histories or cumulative values of released seismic energy or seismic moment or when analysing percentages of various seismic activities taking place above the mine, the locations of individual seismic events become irrelevant. When the production was stopped only the seismic activity rates changes were important, even when seismic migration trends were analysed only the monthly average seismicity elevations were taken into account. Again, in both cases accurate location of each event was not that important. Accurate locations of seismicity are very difficult to achieve. For this seismic sensors must be not only located all around the mine (or cave) but also placed at different elevations that vary from below the mine right to the surface above the mine in some instances. Such ideal sensor configurations are often not possible to implement due to technical problems but are also not viable from the expenditure required.

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Chapter 6
Palabora Seismic History

Abstract At Palabora Mine the seismic system was separated from the Rock Mechanics Department and classified as a cave monitoring tool and consequently the seismic system became part of the Cave Management Section. As a consequence of this, the seismic monitoring priorities were clear, resulting in planning, testing and implementation of interpretation methods specifically for the purpose of cave monitoring and its management. In this chapter there is a description of the Palabora Mine seismic recording system as it was when I arrived at the mine. The following upgrades are discussed together with their influence on the quality of the recorded data. In the further part of this chapter I describe how in real time I have reported the caving progress. Firstly it was the stress caving process initiation followed by the central pillar failure and then its break through into the open pit. Seismic monitoring during production stoppages allowed for estimating the air gap size at the top of the cave. At the time this was very important as every manager at the mine still remembered the tragic consequences of a large in size air gap at Northparkes Lift 1 Mine.

Palabora Mining Company (PMC) is located to the south of the town of Phalaborwa, which is situated in the in the Limpopo Province in the northern part of the Republic of South Africa. Phalaborwa is a mining town and its history and association with mines is described by Cartwright (1972). PMC is a copper mine, smelter and refinery complex. Up to 2013 the company supplies most of South Africa copper needs and exported the balance. Copper is the main business but it also mines and exports other by-products as magnetite, vermiculite, sulphure and nickel sulphate. The mine owes its origins to a unique formation in the region known as the Igneous Complex. The Igneous Complex, located in the Archean Shield of the Limpopo Province, is unique among many African alkaline complexes in that its carbonatite zone is the site of an economic deposit of copper ore. A detailed description of the Igneous Complex is given by Hammer (2000) and Vielreicher et al. (2000). The igneous intrusion is intersected by numerous faults and dolerite dykes. These have been mapped in the open pit and also showed good correlation with underground geological mapping. The discontinuities are described as follows:

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1. The Mica Fault with widths of 1–30 m dips at 70°–80° to the east.
2. The Central Fault with widths of 0.5–3 m is vertical to sub-vertical.
3. The Southwest Fault has widths of 1–20 m and has a sub-vertical dip.
4. The Tree Fault is sub-parallel to the Southwest Fault with widths of 1–20 m.
5. The dolerite dykes are sub-vertical, hard with closely jointed intrusions that strike generally north-east-south-west and are 2–60 m thick.

The underground ore body being mined by block caving method, is an extension of the pyroxenite pipe below the current open pit and is defined by the 0.55 % copper cut off. The pipe measures 1400 and 800 m along the long and short axes, respectively. The ore body is open at depth with mineralisation proven to 1800 m below surface. Copper grades of approximately 1 % are found in the central core of the ore body and decrease gradually towards the peripheries with no sharp ore/waste contact. The mine footprint is 750 m long in the east-west axis and 250 m in the north-south axis, situated at the centre of the igneous intrusion (Calder et al. 2000). The production level sits at a depth –826 m below mean sea level or 1223 m below surface. This is approximately 450 m beneath the pit bottom.

The mining method used to exploit the ore body is block caving. Block caving is a mining method that relies on natural forces to break the rock. The cave is initiated by an undercut where a large area of rock below the mining block is removed. Gravity induces stresses in the back above the undercut, causing it to fracture progressively through the entire rock mass overlying the undercut, allowing a continuous cave to be sustained by withdrawal of broken rock. To allow the cave to progress, broken material has to be removed. This is achieved by the development of draw bells between the undercut and the production level, which allow the fractured rock to gravitate from the undercut through the draw bells to the draw points on the production level. The successful initiation of the caving is described by Glazer and Hepworth (2004) or Moss et al. (2004). Secondary breaking of oversize material that either blocks the draw point or is too large to be handled by the transport system, is performed in the draw points prior to tramming to crushers and subsequent transportation to surface by conveyor and skip hoisting. The literature on the subject of mining and managing the cave is easy to find as it is my experience the management never had any problems with granting permission to publish. These papers were published mainly at the caving conferences. These papers are: Tajaard and Stephenson (2000), Gass and Wright (2007), Jaggard (2008), Ngidi and Pretorius (2010), Ngidi and Boshoff (2007), Pretorius (2007), Pretorius and Ngidi (2008). By the end of 2013 PMC was busy with a study for Lift 2 of which the extraction level will be located at elevation close to –1200 m. At current production rates this project could extend the life of the underground mine by some 10–14 years, depending on the lift height chosen (380–430 m).

Figure 6.1 illustrates the surface (open pit) and underground mines, Lift 1 and possible Lift 2. The surface elevation is close to +400 m ASL. The bottom of the open pit is at –400 m. The Lift 1 extraction level is at –800 m while the Lift 2 extraction level should be close to –1200 m (1600 m below the surface). It was planned to extend the life of Lift 1 by extending the Lift 1 footprint by additional

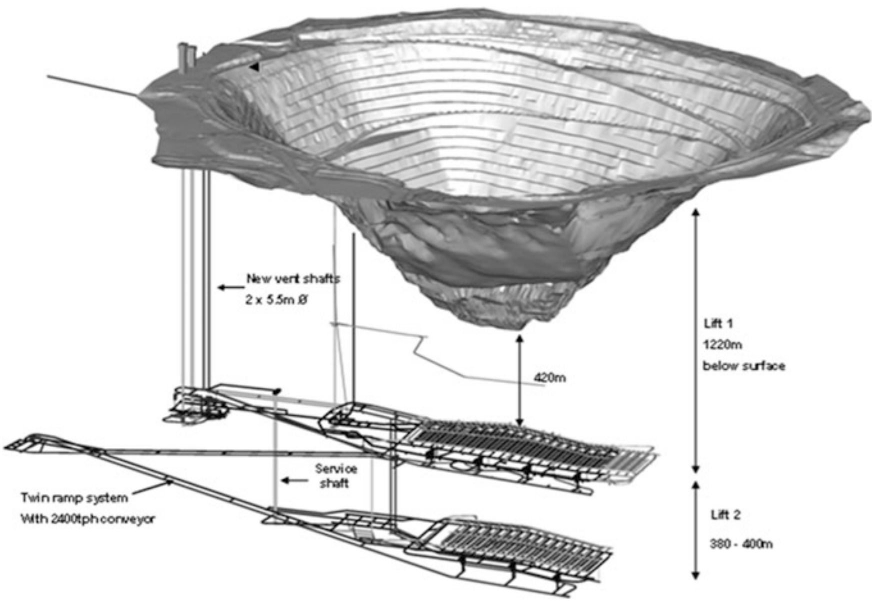

Fig. 6.1 Palabora surface and underground mines

three crosscuts located at the west (western extension). During 2008 some development work was done but in the end this project had to be abandoned. Newer the less this project resulted in some additional seismicity that forms part of the Palabora seismic data base. Figure 6.2 illustrates the monthly development and production

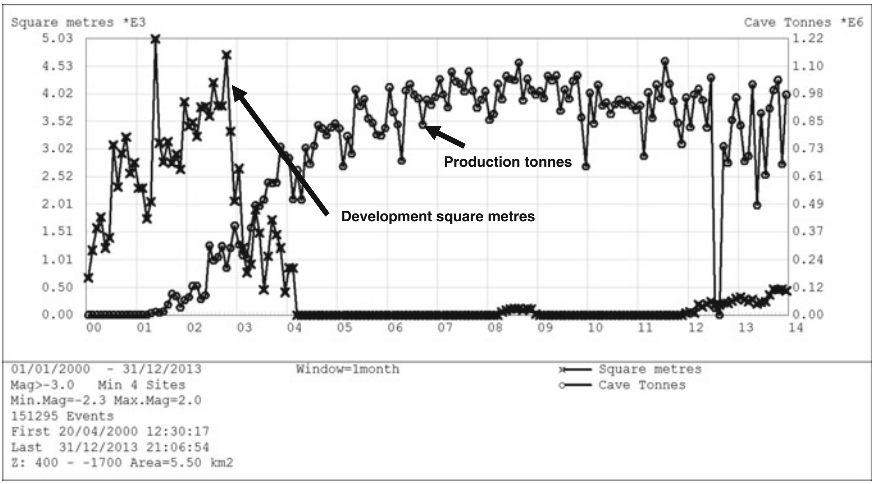

Fig. 6.2 Monthly development and production rates

rates. Up to the beginning of 2004 the development rates were associated with construction of Lift 1. The development rates during 2008 were connected with the west extension project. Development rates from the beginning of 2012 are because of the incline sinking. This is the incline that will connect Lift 1 with Lift 2 (Fig. 6.1). This incline is located north of the mine and will have two sections. The development and production rates are incorporated in the seismic data base.

The first seismic event was recorded on the 16/09/1999 and by the end of 2013 the Palabora seismic database comprises of over 1,50,000 seismic events recorded over a 13 year period. This recorded seismicity provides information about the following Palabora mining milestones

1. Development mining
   - Undercutting started November 1999
   - Undercutting completed February 2004
   - Production level started August 2000
   - Completion of draw bells—August 2004
2. Last blast in the open pit—April 2002
3. End of ramp mining in the open pit—October 2003
4. Start of gravity caving—HR 35 m October 2001
5. Initiation of the stress caving process —HR 45 m April 2002
6. Crown pillar failure —end of 2002
7. Initial breakthrough into the open pit—May 2004
8. Failure of the open pit North wall—October 2004
9. Caving process reaching mature stage—end of 2007
10. East breakthrough—May/June 2008
11. End of the caving process—end of 2012

Notes:

1. HR stands for hydraulic radius and is defined as area of an excavation divided by its perimeter.
2. Mining of open pit ramps (ramp mining) started after the end of mining in the open pit (last blast). This mining is described by Whitham et al. (2004).

At Palabora seismicity has been successfully used not only to monitor the cave development, but it has also indicated when the caving process was initiated, when the crown pillar failed and when the initial break through into the open pit took place. I have described the seismic history of the Palabora Mine in several papers. In these papers I have described the caving process using mainly the recorded seismicity as it happened. There are eleven of these papers. The first one was written in 2004 and the last one in 2012 (Glazer 2007, 2008, 2012), Glazer and Townsend (2006, 2008, 2010a, b), Glazer and Hepworth (2004, 2005, 2006) and Glazer and Lurka (2007).

6.1 Palabora Seismic Network

The first seismic event at the PMC mine was recorded by the end of 1999, but the configuration of the seismic network was subsequently expanded and changed year-to-year. The main trend was the installation of further stations in addition to the existing ones. As a result the seismic network, with a continual improved configuration of stations, increased over time in sensitivity and recorded more of the lower size (below magnitude 0.0) seismicity.

The network went through three following major upgrades:

1. 01/04 2003–4 stations located in the Exploration Shaft came on line
2. December 2003–4 stations in the western open pit deep hole came on line
3. 13/12/05–4 station extension to the network around the Ventilation Shaft

In summary these extensions resulted in:

1. Only the addition of the four stations located in the Exploration Shaft (01/04/2003 had major effect on the network sensitivity. The other two major upgrades resulted mainly in better location accuracy of the recorded events.
2. The quality of data recorded from September 1999 to the end of 2000 is poor.
3. Data recorded during 2001 is generally off poor quality
4. Quality seismic data base starts from January 2002
5. Quality of data recorded from April 2003 until the end of 2013 is high and what is more important, it is very consistent for the whole period

In October 2000 the PMC Seismic network had six sensors (two on the Production Level and four on the Development Level). By end of 2001 the PMC Seismic Network had eleven operational sensors

- Production Level—4 sensors
- Development Level 4 sensors
- Exploration Level 3 sensors (From February 2001 2 sensors, from August 2001 3 sensors)

By the end of 2002 the PMC seismic network consisted of 15 recording stations, located at three levels. Four geophone stations were located in the open pit, two accelerometer stations were located on the Exploration Level and the remainders of the sensors (accelerometers) were located on the Development and Production Levels. With all sensors operational the network's sensitivity and accuracy would be good. Due to blasting activities the open pit, stations were not always operational, and in the end had to be moved to other locations. There were also technical problems with regards to keeping the two North-West underground stations operational. By the end of 2002 it was planned to expand the network and improve the cover on the West side of the mine by installing four geophone stations in a 600 m deep borehole. All the installed prisms in the open pit were eventually lost due to blasting operations. Six new prisms were installed by the end of September 2002. Of these prisms two were damaged, one was lost, while from the other three there was no signal. In summary, at the beginning of the 2003 year there was practically just the seismic system and only one TDR left as far as cave monitoring facilities are concerned. The four geophones located in the Exploration Shaft came on line on 01/04/2003. From April 2003 the PMC Seismic Network consisted of 17 recording stations of which all were operational up to the end of the year. Of these total recording stations, 4 were located in the open pit, 4 in the Exploration Shaft and 9 were located on the underground production level. From 13 December, 2003 the number of recording stations increased by 4. These four additional stations are located in a deep borehole located at the west side of the open pit. During 2004 the PMC seismic network consisted of 21 stations which were operational for the entire year. Of this total, 4 stations were located in the open pit, 4 in the Exploration Shaft, and 4 in the western deep hole and 9 on the production level. The new stations for monitoring seismic activity close to the Ventilation and Exploration Shafts have been operational since 13 December 2005. The aim of this extension was to monitor the stability of the rock mass around the Ventilation Shaft. This extension consists of four stations. From 2005 until end of 2013 there were no changes. This was a decision taken during 2006 that the network will not develop any further but will remain operational. By the end of 2013 PMC seismic network consists of 26 recording stations, with 10 installed in the underground, 6 installed in the open pit, 4 in the Exploration Shaft, 4 in a 540 m deep borehole on bench 19 on the west side of the pit and 2 in the old in-pit conveyor incline. During 2013 it was planned to install additional for geophone probes below Lift 1. Their presence should improve the locations of events that take place below the Lift 1 extraction level. Figure 6.3 (horizontal W-E view) and Fig. 6.4 (vertical W-E view) show the final configuration of the recording stations. This configuration did not change since 2006.

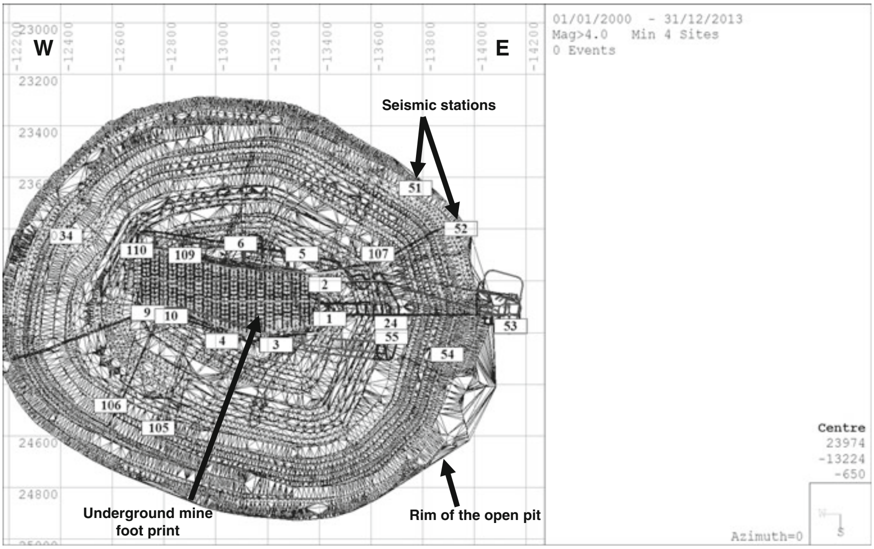

Fig. 6.3 PMC seismic network configuration from the end of 2005

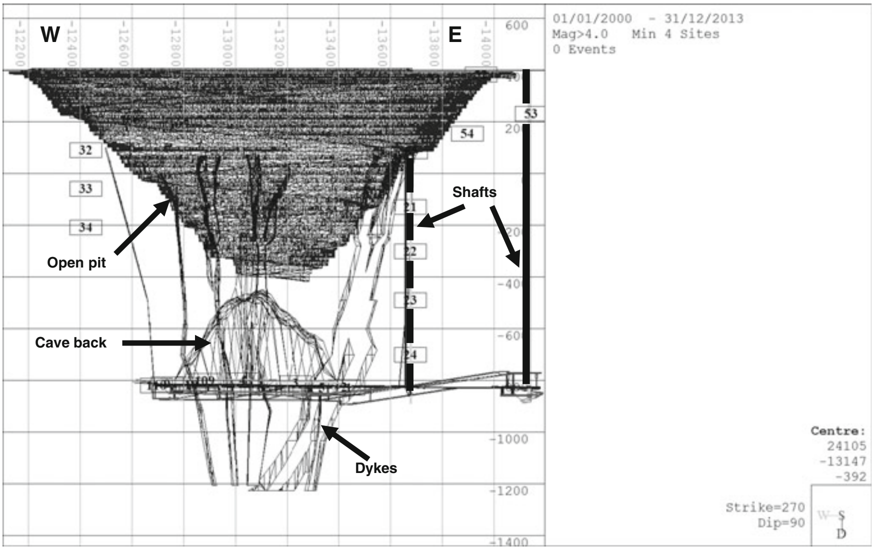

Fig. 6.4 PMC seismic network configuration from the end of 2005

6.2 Influence of the Network Upgrades on the Network Sensitivity

Figure 6.5 show the influence of the following major changes to the configuration of network sensors:

1. 01/04 2003–4 stations located in the Exploration Shaft came on line
2. December 2003–4 stations in the west deep hole came on line
3. 13/12/05–4 station extension to the network around the Ventilation Shaft on line

The network sensitivity was strongly influenced by the addition of the four stations located in the Exploration Shaft, which become operational from 01/04/2003. Further changes did not have a strong influence on the amount of recorded seismicity but they resulted in improved location accuracy. The final network sensor configuration is excellent in this sense that it covers the whole mine with the same location accuracy and sensitivity. This is very important from the seismic data interpretation point of view as there is no need to speculate about or compensate for the seismic data base completeness.

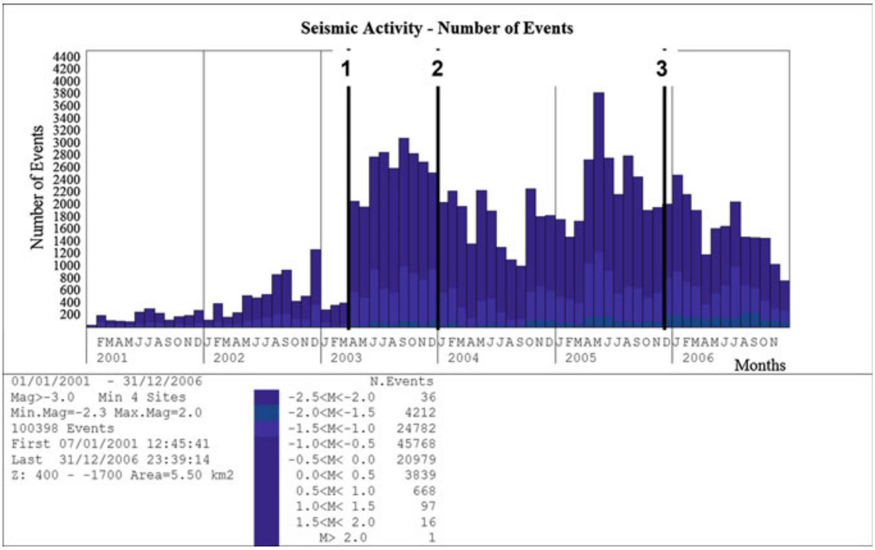

Fig. 6.5 Major changes to the network configuration

6.3 Quality of the Recorded Seismic Data

Figure 6.6 illustrates the monthly percentages of seismic events recorded with minimum five stations. In general it is assumed that five stations allow for proper location and evaluation of source parameters. Still it must be well understood that this not always is the case. There is one more important condition that these five

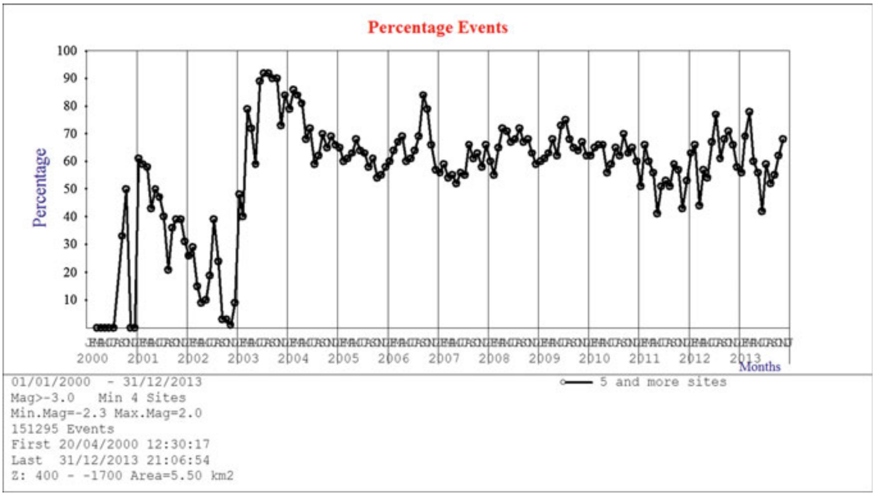

Fig. 6.6 Monthly percentages of seismicity recorded with minimum five stations

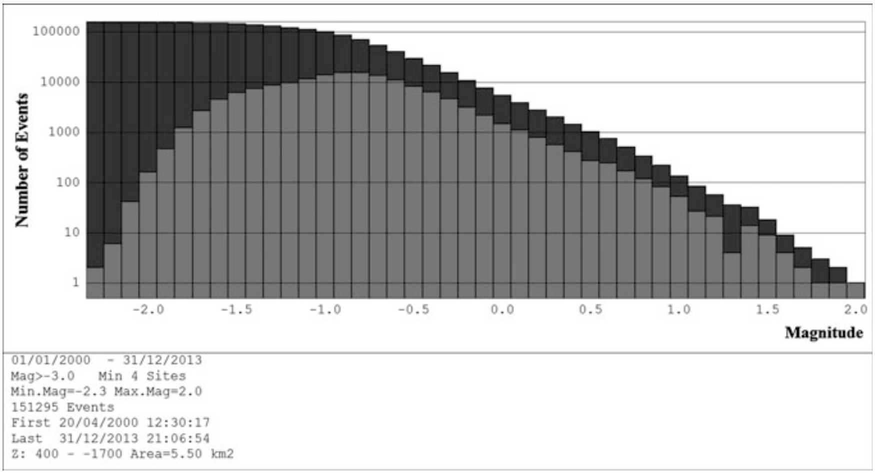

Fig. 6.7 Distribution of magnitudes

stations must be located around the source. Figure 6.6 confirms that only after installation of sensors at the east in the Exploration Shaft and at the west in the deep hole the percentages of seismicity recorded with minimum five stations increased to nearly 70 % and then stayed continuously at this level.

According to data illustrated by Fig. 6.7 the PMC seismic catalogue is complete from magnitude –0.6/–0.5. Figure 6.8 illustrates monthly percentages of recorded seismicity in magnitude range –0.6/–0.5. These types of plots are used to test the data base for quality and continuity. In this case it is clear that the percentages of

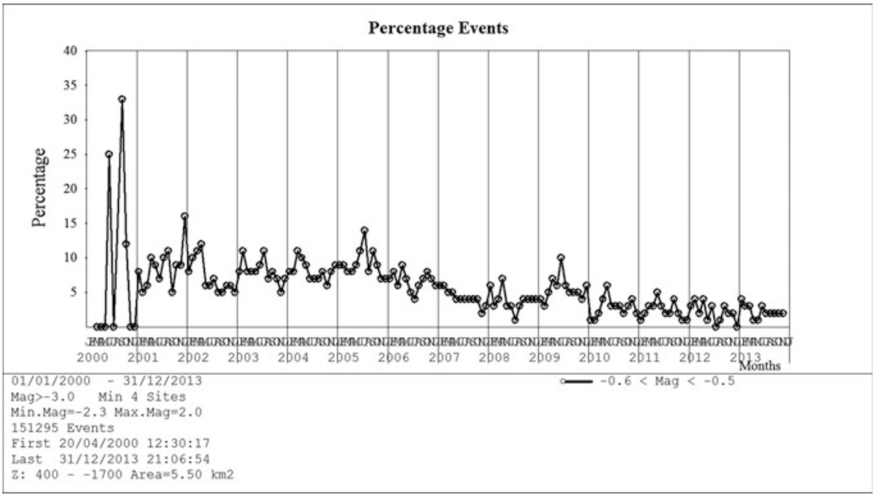

Fig. 6.8 Monthly percentages of recorded seismicity magnitude –0.6/–0.5

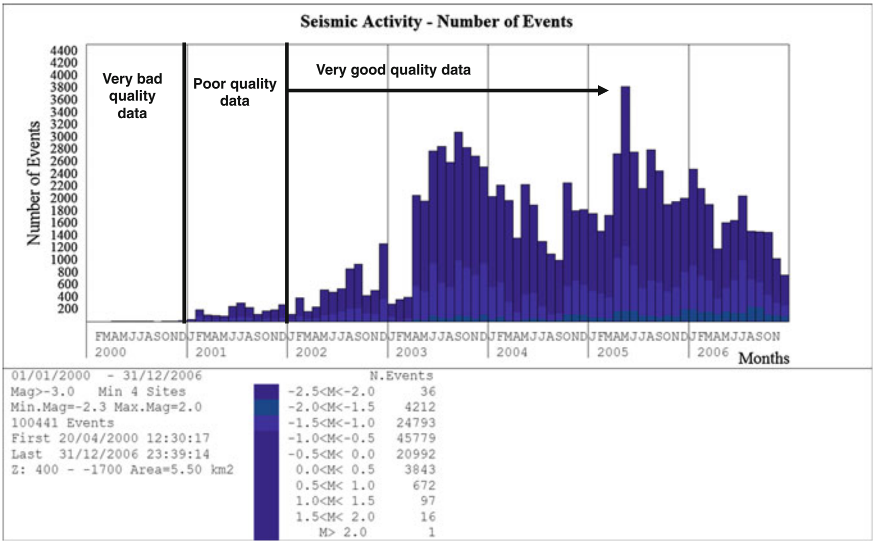

Fig. 6.9 Quality ratings to the PMC seismic data base

small size events from the beginning of 2001 are rather continuous which indicates also that the seismic network operated with no major size downtime. To test this in more detail shorter time periods should be taken into account.

Figure 6.9 summarizess the analysis of the PMC seismic data base. Figure 6.10 illustrates the recorded seismicity since the beginning of 2002 until end of

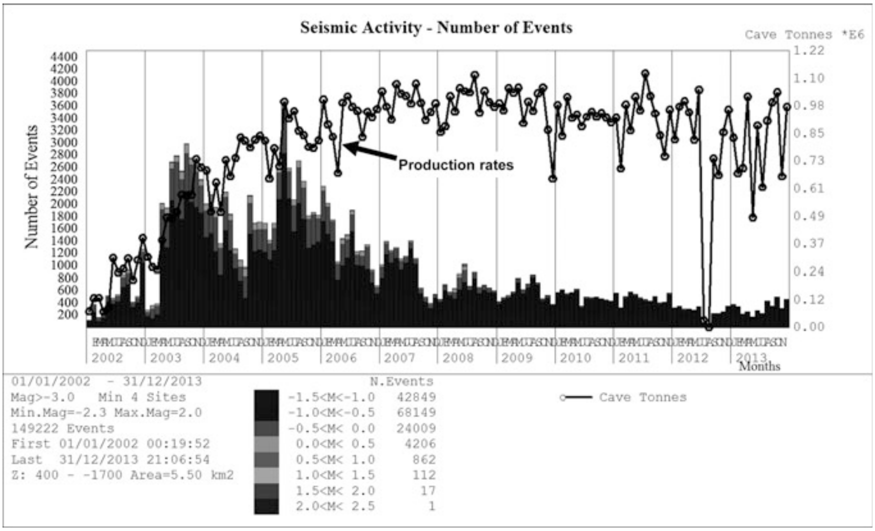

Fig. 6.10 Monthly seismic activity rates

December 2013. This figure presents monthly seismic activity rates (vertical bars) and the monthly production rates. There are 149222 events of which the smallest one is of magnitude –2.3 and the largest event is of magnitude 2.0. The production graph indicates that the production build up took nearly 4 years. From 2006 the production rates become more constant with some months indicating production problems.

6.4 Achieved Objectives of Seismic Monitoring

Seismicity is a natural process indicating that the cave is progressing and is connected with rock mass fracturing in front of the undercut and propagating cave. The space and time distributions of seismicity, as well as the changes of their source parameters with time, are directly associated with what is happening in the rock mass around the cave and underground mining infrastructure. Seismic monitoring provides a tool for the detection and evaluation of seismic events occurring in the rock mass due to the mining operations. While the detection itself is a reasonably simple matter, the data evaluation and their interpretation is usually a more complex problem, sometimes resulting in a number of solutions. It is a proven fact that seismicity in mines is related to mining conditions and the excavation methods. For this reason it must be possible to link seismic activity with various quantities that are characterizing mining and the rock conditions. This should allow for limiting the interpretation solutions. At PMC induced seismicity was primarily used to monitor the cave progress. Seismicity was also used to monitor the behaviour of the crown pillar located between the cave and the open pit, to indicate the stress distribution around the cave and to help assess the seismic hazard. This was done using the space and time distribution of seismicity as well as the various activity rates. The other parameters tested in practice are seismic energy and moment and the energy index. In this chapter I will present several objectives of seismic monitoring that were tested and implemented at PMC. Not all seismic monitoring objectives due to the nature of induced seismicity are applicable through the entire caving process. For this reason this chapter is divided into four parts:

A. Cave monitoring at the early caving stage
B. Cave monitoring at the later caving stages
C. Stress distribution around the cave and underground excavations
D. Seismic hazard monitoring

6.4.1 Cave Monitoring at the Early Caving Stage

The early caving stage in case of the PMC cave was relatively short and lasted only 8 months. This stage started with the initiation of the stress caving process about

April/May 2002 and ended with the failure of the crown pillar at the end of 2002. The height of the cave at its central part was close to 400 m. When the hydraulic radius reached 45 m, the stress caving process was initiated. Concurrent with this process the seismicity migrated upwards. By the end of 2002 the caving process resulted in the failure of the cave crown pillar and the seismicity migrated to its shallowest zone. From that point in time the nature of seismicity changed as from then it could only migrate further away from the cave and downwards into the still un-fractured parts of the rock mass. At the early caving stage the seismic monitoring should allow for (Glazer and Hepworth 2004, 2005):

1. Recording the initiation of the caving process when the critical hydraulic radius was reached.
2. Monitoring cave progress
3. Evaluation of the swell factor.
4. Estimation of the natural cave expansion rate.

Recording the initiation of the caving

The classic gravity caving would be collapse of blocks under gravity until a temporary stable arch is formed over the undercut. Then in April/May 2002 when the hydraulic radius of 45 m was reached, the stress caving process was initiated. By stress caving it is meant that there is a tangential stress component transmitted over the cave back that results in slip along and extension of pre-existing joints, forming some new fractures. This leads to additional loosening of the temporary stable arch causing the caving to migrate higher. Figure 6.11 illustrates the fact that up to April/May 2002 the energy index value was close to 1.0. With the initiation of the cave the energy index started to change values and showed an oscillation trend (Glazer and Hepworth 2004).

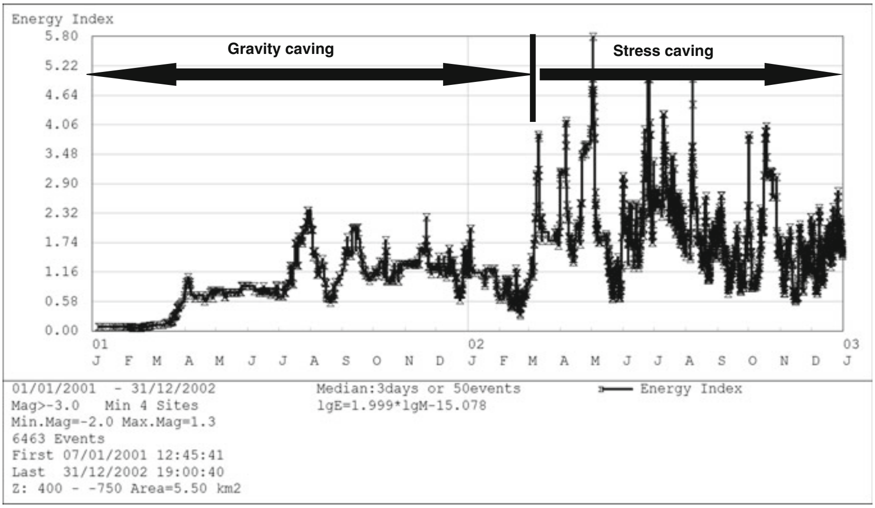

Fig. 6.11 Energy index time history

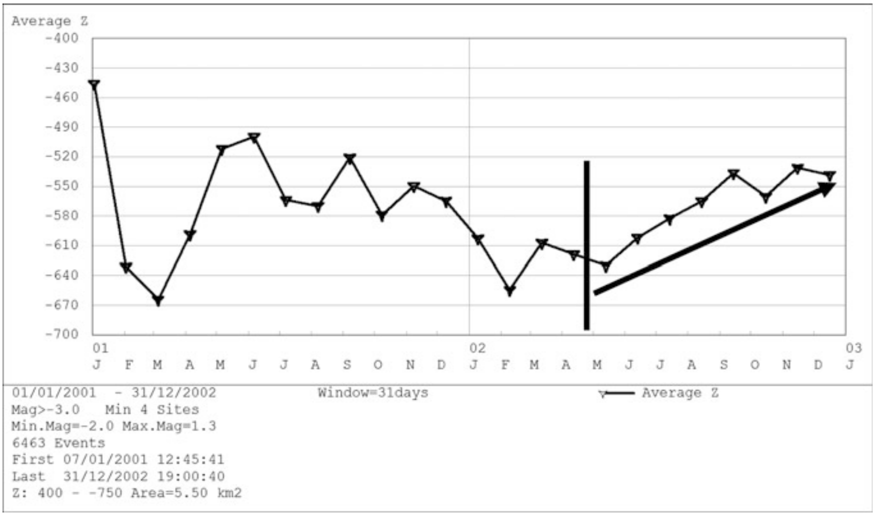

Fig. 6.12 Average monthly seismicity elevation changes

Figure 6.12 illustrates that from about April 2002 the seismicity started to migrate upward. This upward migration coincided in time with the stress caving process initiation as evidenced by the energy index time history.

Figure 6.13 illustrates the fact that from about May 2002 there was a significant increase in seismic activity rates. The stress caving process initiation during May 2002 was detected only by seismic data interpretation. Three independent of each

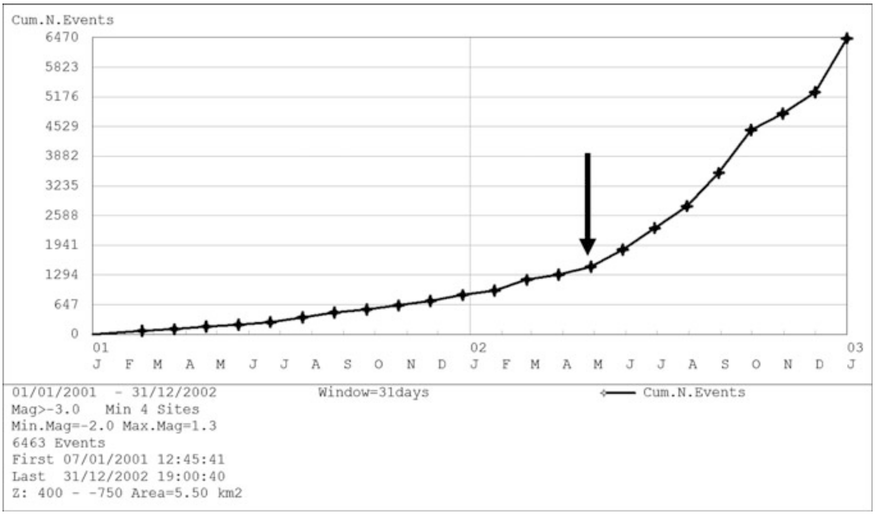

Fig. 6.13 Cumulative numbers of seismic events

other parameters were used: energy index, seismic activity rates and the average monthly seismicity elevation values.

Monitoring the caving progress

The tonnes extracted from the cave result in the cave back propagating upwards, towards the surface. This propagation is due to the rock mass fracturing above the a-seismic zone. This is the source of mode one mine induced seismicity. The fracturing zone during 2002 was located about 60–80 m above the cave back (see Fig. 5.48), so around the cave there was an a-seismic zone of already fractured rock mass (Glazer and Hepworth 2004, 2005). The thickness of this a-seismic zone from April 2002 to the end of October 2002 was constant and for this reason was used as a tool to monitor the cave back position. This a-seismic zone thickness and its position were confirmed when drilling the eight open pit drain holes. These drain holes were terminated just above the lower boundary of the increased seismic activity zone. This is not unexpected. These drill holes were terminated due to loss of air pressure due either open geological structure or open fractures in the rock (see Fig. 5.49). The position of the cave back is for September 2002.

Evaluation of the swell factor

This estimate was done by comparing the cave back profiles with different applied swell factors with the recorded space distribution of seismicity. The assumed swell factor was then confirmed by the TDR measurements.

Estimation of natural cave expansion rate

This allows control over the size of the expansion void, which is important for maintaining the correct cave profile and reducing the risks inherent with too large an expansion void. Monitoring of the extent of the a-seismic zone and of the average height increase of the recorded seismic events resulted in an estimation of the natural expansion rate of the cave. For example the increase in the average elevation of recorded events for June 2002 compared to May 2002 was 22 m. This 22 m was interpreted as a change in the height of the fracture zone above the cave. The amount of material drawn from the cave in June 2002 was equivalent to an in situ height of 3.6 m. The estimated swell factor is 20 %. Thus if we removed 3.6 m of material from the cave back and the back fell and bulked by the 20 % swell factor (multiply by 6), then the average height of the fracture zone above the cave back would also rise 22 m in June if the rate of caving was exactly equal to the rate of draw. As the 22 m is the same, this means that the natural cave expansion rate was estimated to be close to 120 mm/day of equivalent in situ draw (Glazer and Hepworth 2005). That value was then used as the maximum permitted draw rate, as it should maintain a steady expansion void. This is important for maintaining the correct cave profile and reducing the risks connected with too large an expansion void. At the end of 2002 the crown pillar was assumed to have failed in that it was no longer fracturing and emitting seismicity. Additional evidence that the crown pillar had failed was obtained at the beginning of March 2003 when a storm event indicated that there was hydraulic connection between the open pit and the underground mine.

6.4.2 *Cave Monitoring at the Later Caving Stages*

Figure 6.14 shows the energy index history for the whole mine, from the beginning of 2001 until end of December 2009. The energy index graph represents the stress regime and in this case relates its changes and values to different stages of the caving process. To start with, the stress levels during 2001 were already above the average value (1.0). This stress increase was the result of the development mining. Start of the caving process in April 2002 (A) was associated with a rapid stress increase that lasted until the failure of the crown pillar at the end of 2002 (B). The maximum stress time period continued until the cave broke through into the open pit in May 2004 (C). From then on the stresses started to decrease to reach the average level by the end of 2004. At this stage the stress decrease rates were faster than the increase rates after the caving process initiation. After reaching the average value of 1.0 the stress decrease rate slowed down. As of the beginning of 2005 the stress levels have remained below the average value. The stress increase due to the development mining was very low when compared to the stress increase induced by the caving process. The stress level during the east break through (E) was significantly lower than during the initial break through (C). Figure 6.14 also illustrates the trend of the average monthly depths of seismicity.

During 2000 and 2001, apart from the development mining, there was still mining taking place in the open pit. The gravity caving started in October 2001. At this stage the caving process started to induce much more seismicity than the open pit mining. For this reason the average depth of seismicity showed a downward trend. When the hydraulic radius reached 45 m (A), the stress caving process was initiated. Concurrent with this process the seismicity migrated upwards. By the end of 2002 the caving process resulted in the failure of the cave crown pillar (B) and

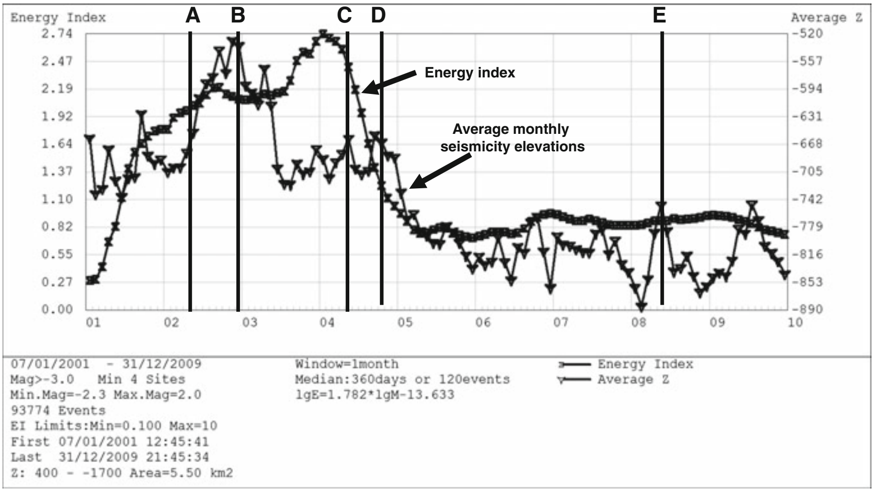

Fig. 6.14 Energy index time history

the seismicity migrated to its shallowest zone. The minimum elevation of seismicity at the time of the Crown Pillar failure was close to –520 m (Glazer and Hepworth 2006). From that point in time seismicity could only migrate further away from the cave and downwards into the still un-fractured parts of the rock mass. From the beginning of 2003 up to mid 2006 there was a general downward seismicity depth trend. It is of interest to note that the downward trend in seismicity became more evident from the beginning of 2005, when the energy index reached the average value of 1.0. Still there is some shallower seismicity associated with the failure in the open pit (D). From mid 2006 to mid 2009 the shallower seismicity was associated with the cave breaking at the east. During the east break through (E) the seismicity migrated upwards to elevations close to –740 m. Figure 6.14 illustrates the fact that that the basic seismic source parameters as the seismic energy and the moment scalar are well suitable for monitoring the caving process. The trend of the average monthly seismicity elevations indicates that that the amounts of seismicity taking place above and below the mine change with time. This fact implies that this ratio should be monitored in a continuous way, as it will not only indicate the caving progress but also provide information about the seismic hazard (Glazer and Hepworth 2006). This type of analysis is done for seismic activity rates, seismic deformation rates and for the rates of seismic energy release.

Figure 6.15 shows the percentages of monthly seismic deformation rates above the mine. The maximum deformation rates above the mine are associated with the caving process. After the cave breaks through into the open pit (C) the percentages of seismic deformation above the mine level dropped from about 80 % (June 2004) to less than 50 % in January 2005. This decrease continued until April 2006 when only about 20 % of observed seismic deformation was taking place above the mine level. From May 2006 until May 2007 the amounts of seismic deformations taking place above the mine increased to about 50 %. This value for December 2007 was back down at 35 %. This indicates that at that time the cave was still expanding on

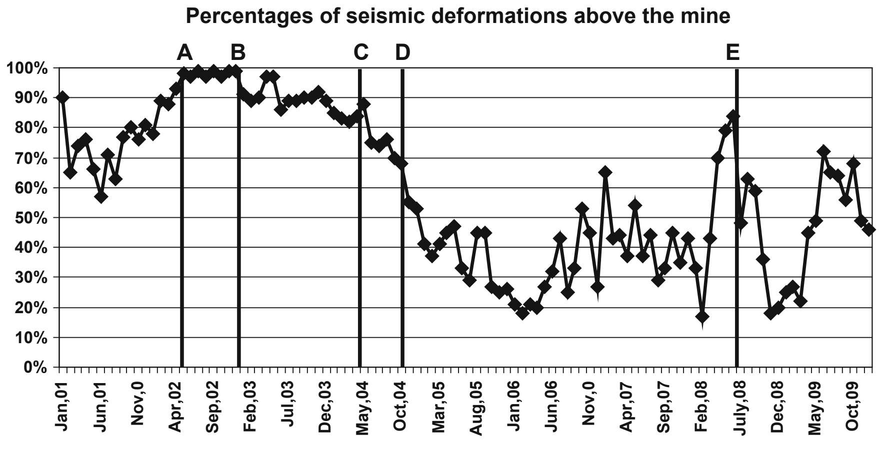

Fig. 6.15 Percentages of seismic deformations above the mine level

the east side of the footprint. During the east break through (E) the amounts of seismic deformation taking place above the mine increased up to 80 %. By the end of 2008 only 20 % of the total seismic deformation is taking place above the mine level. It must be assumed that until the full break through into the open pit occurs, there will be some additional seismic deformation associated with this process.

Production stoppages, although detrimental for mine revenue, do however also provide some very useful information about the expansion void. From the beginning of 2002 until the end of 2008 there were seven production stoppages that lasted for a few days each. In each case the daily seismic activity rates for the whole mine decreased when production from the cave stopped, even for just a couple of days. Such a rapid rock mass reaction to a relatively short production stoppage when observed for the first time was unexpected, as normally the rock mass response to any type of mining activity is delayed. The most logical explanation is that there was no expansion void on top of the cave. In this event, even for very short periods when no tons are pulled from the cave, the cave expansion will stop, as there is no place for the material to cave into (Glazer and Hepworth 2004). Once the drawing of cave material resumes, the caving process immediately commences with material caving into the void created. From this a more general relationship might be concluded. The larger the expansion void, the longer will be the delay in the rock mass response to changes in the production rate. If the production draw rate is always kept lower than the natural cave progression rate, there should be a minimal, or no expansion void. The rapid response of the seismicity to changes in the production rate suggests that the mine was always pulling at a rate lower than the natural cave expansion rate. Thus this seismic data tends to support the earlier estimation of the natural cave expansion rate. Before the initial break through there were five production stoppages and in each case the seismicity decreased virtually on the first non production day. From this it was concluded that there was no expansion void above the maximum elevation of the cave. The cave broke through the base of the open pit in April/May 2004 and as expected this took place with no immediate dramatic effects. On the contrary, this break-through was at first difficult to notice. Only by June/July 2004 the open pit started to show evidence that the break through had already taken place.

The second influence on the seismicity is directly connected with the subsequent restarting of production after a couple of days. After the period of non-production the resuming of production in all seven cases resulted in larger size seismic energy releases that were associated with restarting the caving process. It is interesting to note that most of this large size seismicity took place in the east parts of the mine. This is because from about 2003 the stresses at the east side of the mine were constantly higher than those at the west. Figure 6.16 demonstrates the relationship between the changing stress levels over time around the cave, which are illustrated by the energy index time history and the amounts of seismic energy released (vertical bars), directly after restarting the caving process. This figure is based on seismic data recorded for the whole mine. Figure 6.16 indicates that the resuming of production while the stresses around the mine are high is associated with an increased seismic hazard. The other conclusion that is to be drawn from the data illustrated by this figure is the fact that the higher the stresses around the cave, the

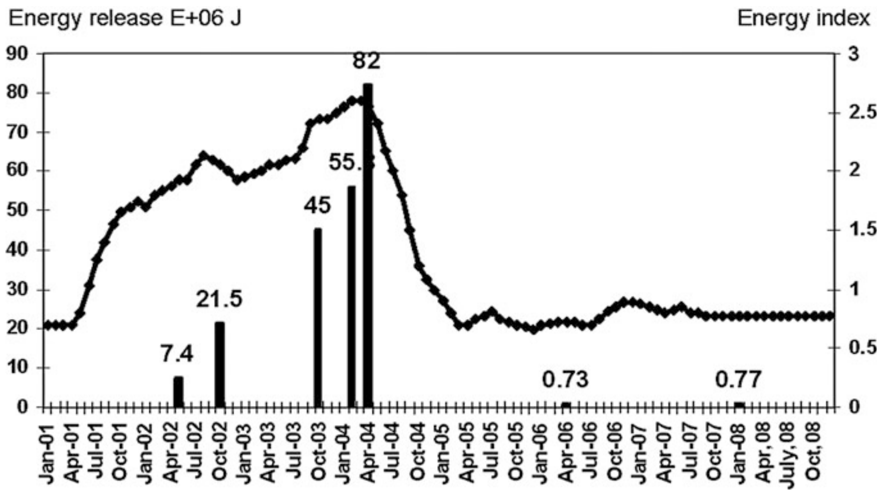

Fig. 6.16 Seismic energy releases after re-starting production

higher will be the seismic energy release associated with the restarting of the cave. After the initial break through there were two more production stoppages, the first in April 2006 and then the second in January 2008. Analysis of the general relationship between the production rates and the seismicity as well of the two production stoppages that took place after the initial break-through and their influence on seismicity indicates that at the east there was no expansion void during the period from the beginning of 2005 up to the break through during mid 2008.

Presented applications of seismic monitoring not only illustrate the fact that seismic data analysis can be successfully used to monitor the caving process, but also confirm how reliable it is. It is interesting to note that practically all of the illustrated analyses of recorded seismicity are independent of the location accuracy. When the data input catalogues consists of all recorded data like in the cases of energy index time histories or cumulative values of released seismic energy or seismic moment or when analysing percentages of various seismic activities taking place above the mine the locations of individual seismic events become irrelevant. When the production was stopped only the seismic activity rates changes were important, even when seismic migration trends were analysed only the monthly average seismicity elevations were taken into account. Again in both these two cases accurate location of each event was not that important. Accurate locations of seismicity are very difficult to achieve. For this seismic sensors must be not only located all around the mine (or cave) but also placed at different elevations that vary from below of the mine right to the surface above the mine. Such ideal sensor configurations are often not possible to implement due to technical problems but are also not viable from the expenditure required. Several applications of seismic monitoring have proved that it is a very valuable and useful tool for cave mining (Glazer and Hepworth 2004, 2005, 2006; Glazer and Townsend 2006; Glazer 2007).

6.4.3 Stress Distribution Around the Cave and Underground Excavations

The stress distribution around the cave is monitored using the energy index (or apparent stress). This can be done either by displaying the recorded seismicity with their energy index values, or using the energy index time histories and/or contouring the energy index values at selected elevation ranges. It is assumed that the energy index is related to the stress regime in the rock mass. The higher the energy index value, the higher the stress (but this relationship is not directly proportional). This type of monitoring the stress changes must be done continuously (on weekly or monthly basis) depending on the amounts of available seismicity and the risk exposure. This should allow for monitoring the stress changes with time. Examples of the energy index time history are already presented above. Figure 6.17 shows the contours for energy index values, based on seismicity recorded during December 2009. During December 2009 only 18 seismic events located between the elevations –500 and –700 m (i.e., above the Production Level). With such data it is not possible to plot a contour map. Figure 6.17 presents data for elevations between –700 and –900 m (on and around the Production Level). Contour lines can only be drawn for areas where seismic events have been recorded. Figure 6.17 indicates that for elevations between –700 and –900 m, there are areas of higher stresses around the cave.

Seismic data recorded at Palabora displays bimodal patterns typical for mine induced seismicity (Gibowicz and Kijko 1994). While for the events belonging to the first mode the maximum magnitude is in range 0.0–0.5, the events of the second mode can be of magnitude up to 2.0. The first mode of events is associated with rock mass fracturing immediately ahead of the undercut and in the propagating cave

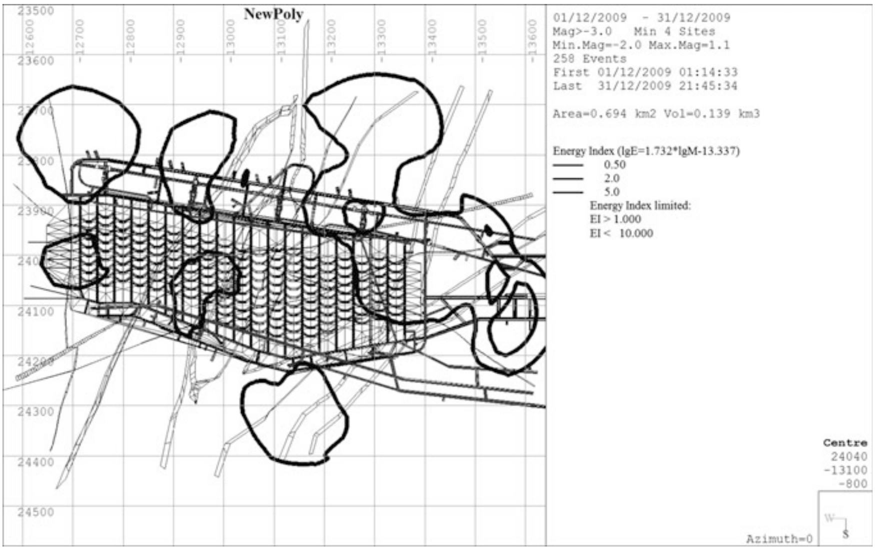

Fig. 6.17 Contours of energy index between –700 and –900 m

back. The second mode of events locates at geological discontinuities some distance from the mining. Events of this second mode are connected with stress redistribution ahead of the undercut abutment and around the cave. Due to their locations and amounts of emitted energy these events are considered a negative feature of the block caving and result in seismic hazard (Gibowicz and Lasocki 2001). On the other hand seismicity of mode one events is the principle manifestation of the cave progress and as already described is used to monitor and manage the cave and thus is considered as a positive feature.

6.4.4 Seismic Hazard Monitoring

Several seismic risk areas were recognized and actions initiated. Attached are three examples.

Monitoring the rock mass around the Ventilation Shaft

The network extension to monitor the ground condition around the Ventilation Shaft has been operational since mid December 2005.

Monitoring the Mica Fault seismic activity

As increased seismic activity associated with faults in the west might be the first warning of an impending open pit west wall failure, it is then monitored continuously together with movements along the west wall.

Monitoring the development mining at the west

Development mining associated with western extension has been in progress since the beginning of April 2008 but was then stopped during December 2008.

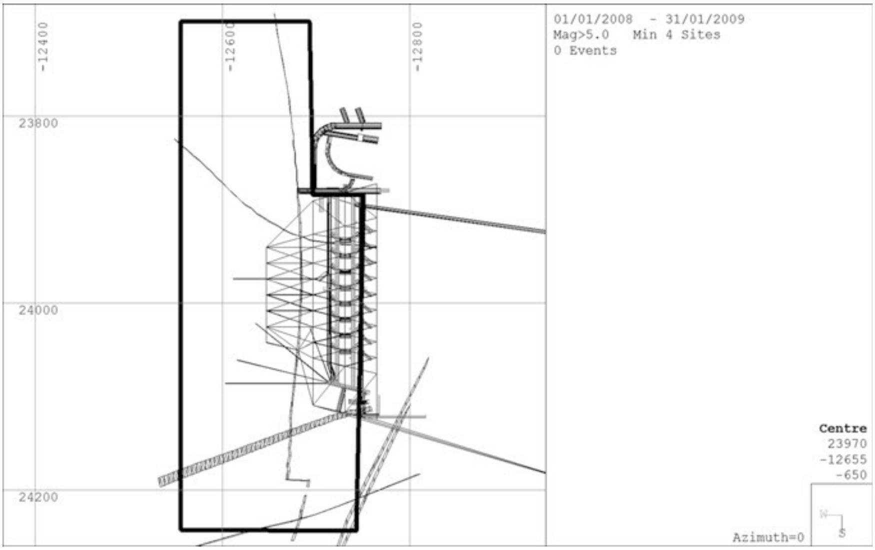

Fig. 6.18 Western Development seismic polygon

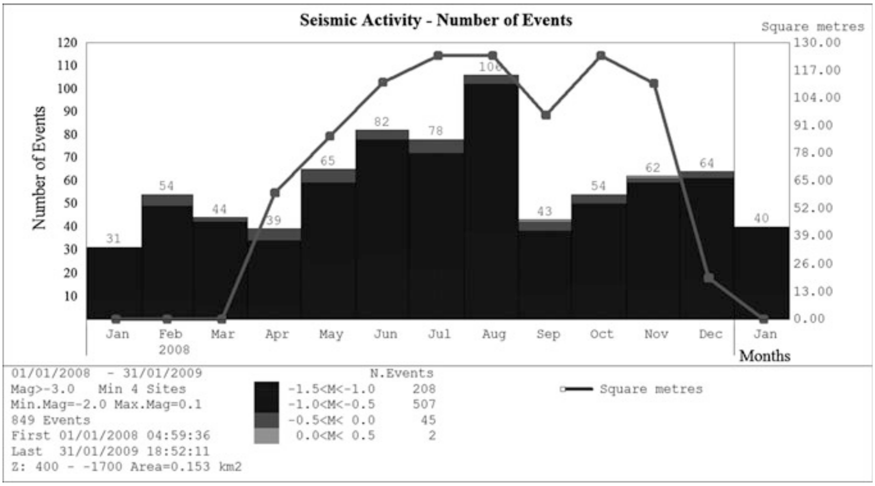

Fig. 6.19 Monthly seismic activity rates in Western Development polygon

Figure 6.18 shows the western part of the mine where the development mining was taking place. Figure 6.19 shows the monthly seismic activity rates in this polygon together with the development square meters. Since the development mining started (April 2008) the monthly seismic activity rates have increased. As indicated by this figure this increase was mainly in the very small size range of events (below magnitude –1.0). The development mining on its own did not contribute much toward seismic energy release. For example during November 2008 the total amount of released seismic energy was 1.13E+05 J while the west development induced only 2.62E+03 J of this seismic energy (2.3 % of the total seismic energy release).

6.5 General Description of Palabora Seismicity (Up to the End of 2013)

Seismic data recorded at Palabora Mining Company displays bimodal patterns typical for mine induced seismicity, but past measurements of regional seismicity also indicate a possible third mode of events larger than magnitude 2.0 related to the global effect of mining in the area from about from 1950. While for the events belonging to the first mode the maximum magnitude is in range 0.0–0.5, the events of the second mode can be of magnitude size up to 2.0. The first mode of events is connected with rock mass fracturing in front of the undercut and propagating cave. The second mode of events is events locating at geological discontinuities at distances 100–300 m around the cave. Events of this mode are connected with the stress redistribution around the undercut abutment and the progressing cave.

The first seismic event was recorded on the 16/09/1999 so by the end of 2012 the PMC seismic database comprises seismic events recorded over a 12 year period. This recorded seismicity provides information about the following PMC mining milestones (A, B, C, D, E, F and G milestones are shown on most of the following figures):

1. Development mining
   - 1.1 Undercutting started November 1999
   - 1.2 Undercutting completed February 2004
   - 1.3 Production level started August 2000
   - 1.4 Completion of draw bells—August 2004
2. Last blast in the open pit—April 2002
3. End of ramp mining in the open pit—October 2003
4. Start of gravity caving —HR 35 m October 2001
5. Initiation of the stress caving process (A)—HR 45 m April 2002
6. Crown pillar failure (B)—end of 2002
7. Initial breakthrough into the open pit (C)—May 2004
8. Failure of the open pit North Wall (D)—October 2004
9. Caving process reaching mature the mature stage (E)—end of 2007
10. East breakthrough (F)—May/June 2008
11. End of the caving process (G)—end of 2012

Figure 6.20 shows the PMC seismic database (this figure shows the monthly seismicity rates) together with development and production mining rates. By the end of 2013 the seismic database included nearly 1,50,000 seismic events. Mining data as presented by this figure consists of:

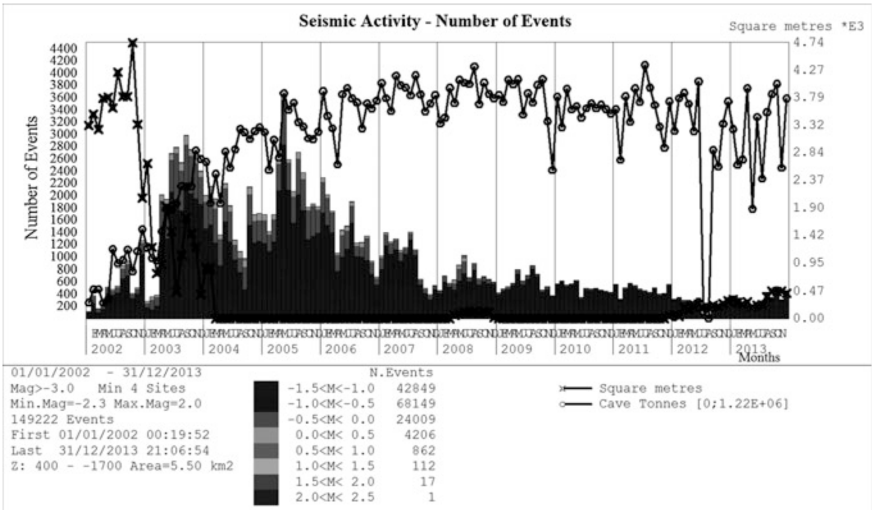

Fig. 6.20 Seismicity 2002–2013, development and production mining

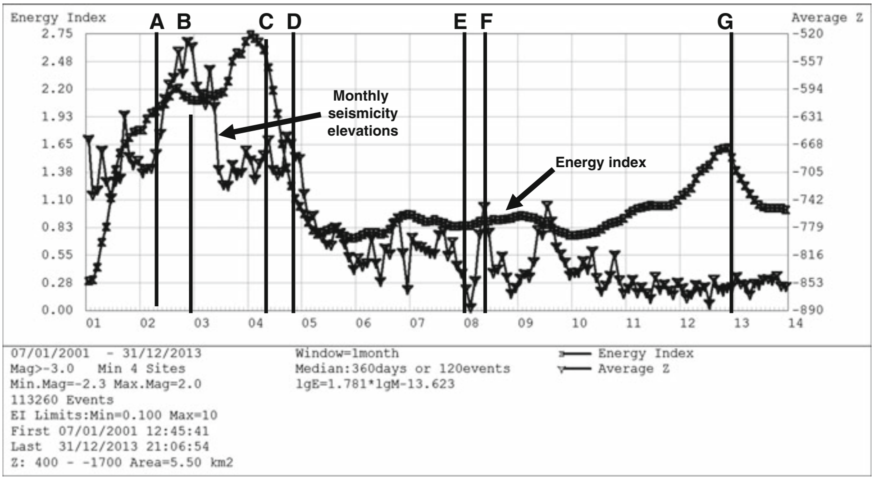

Fig. 6.21 Energy index history

a. Development square meters
b. Cave production tones

Figure 6.21 shows the energy index history for the whole mine, from the beginning of 2001 until end of December 2013. The energy index graph represents the stress regime and in this instance relates the changes and values in the energy index to different stages of the caving process. To start with, the stress levels during 2001 were already above the average value (1.0). This stress increase was the result of the development mining. Start of the caving process in April 2002 (A) was associated with a rapid stress increase that lasted until the failure of the crown pillar at the end of 2002 (B). The maximum stress time period continued until the cave broke through into the open pit in May 2004 (C). From then on the stresses started to decrease to reach the average level by the end of 2004. At this stage the stress decrease rates were faster than the increase rates after the caving process initiation. After reaching the average value of 1.0 the rate of decrease slowed down. As of the beginning of 2005 to date, the stress levels have remained below the average value. The stress increase due to the development mining phase was very low when compared to the stress increase induced by the caving process. The stress level during the east break through (E) was significantly lower than during the initial break through (C). The higher energy index during 2012 was associated with scattered and low activity rate seismicity.

The second line in Fig. 6.21 shows the trend for the average monthly seismicity elevations. During 2000 and 2001, apart from the development mining, there was still mining taking place in the open pit. The gravity caving started in October 2001. At this stage the caving process started to induce much more seismicity than the open pit mining. For this reason the average depth of seismicity showed a downward trend. When the hydraulic radius reached 45 m (A), the stress caving process was initiated. Concurrent with this process the seismicity migrated upwards. By the end of 2002 the caving process resulted in the failure of the cave crown pillar (B) and the seismicity migrated to its shallowest zone. The minimum elevation of seismicity at the time of the Crown pillar failure was close to –510 m. From that point in time seismicity could only migrate further away from the cave and downwards into the still un-fractured parts of the rock mass. From the beginning of 2003 up to mid 2006 there was a general downward trend in the depth of seismicity. It is of interest to note that the downward trend in seismicity became more evident from the beginning of 2005, when the energy index reached the average value of 1.0. There was still some shallower seismicity associated with the failure in the open pit (D). From mid 2006 to mid 2009 the shallower seismicity was associated with the cave breaking through at the east. During the east break through (E) the seismicity migrated upwards to elevations close to –715 m.

Figure 6.22 shows the monthly seismic energy release rates. Development mining resulted in very low energy release rates when compared with the amounts of energy released by the caving process. Large energy releases started immediately after the crown pillar failure and ended when the energy index reached the value of 1.0 at the end of 2004. The high energy release period is associated with a slower downward migration of seismicity. The higher seismic energy releases from mid 2006 are associated with the cave breaking through at the east. The September 2008 high seismic energy release took place below the mine. This indicated that the east break through at this stage was probably complete.

Figure 6.23 shows the seismic deformation rates. Similar to the energy release rates, the seismic deformation rates started to increase only after the crown pillar failure (end of 2002). The general increase in the trend of seismic deformation did

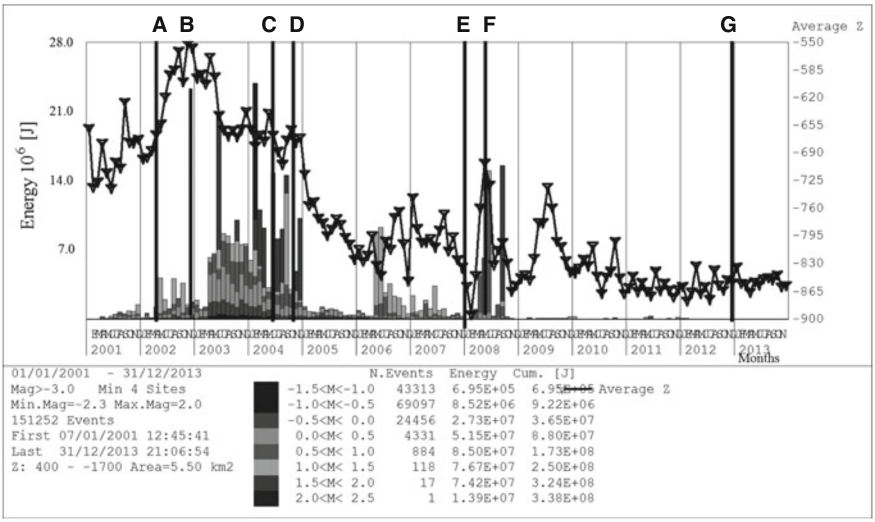

Fig. 6.22 Monthly seismic energy release rates

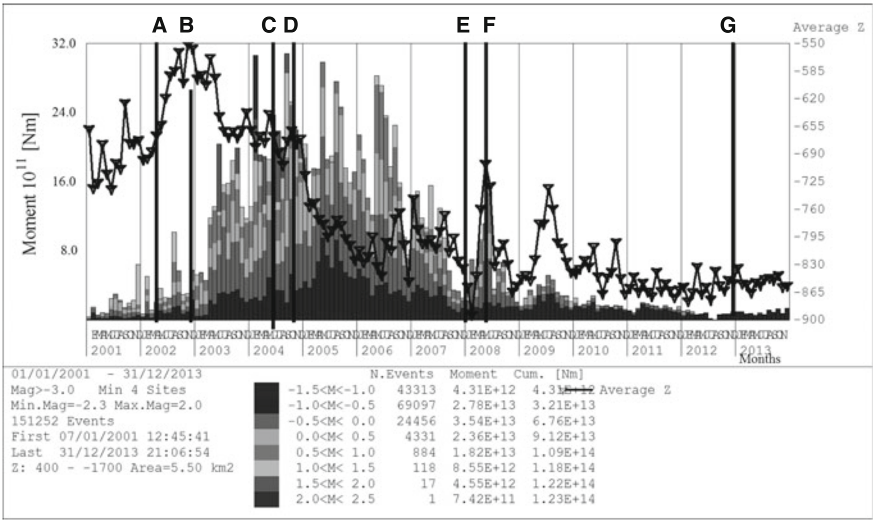

Fig. 6.23 Monthly seismic deformation rates

not stop when the energy release rates dropped (end of 2004). On contrary, they still showed an overall increasing trend until the second half of 2006. This trend was continuous and was independent of the various caving stages. The amounts of seismic deformation as indicated by Fig. 6.24 were mainly dependent on the cave production rates up to about September 2006. This figure also indicates that the amounts of seismic deformation were independent of the released amounts of

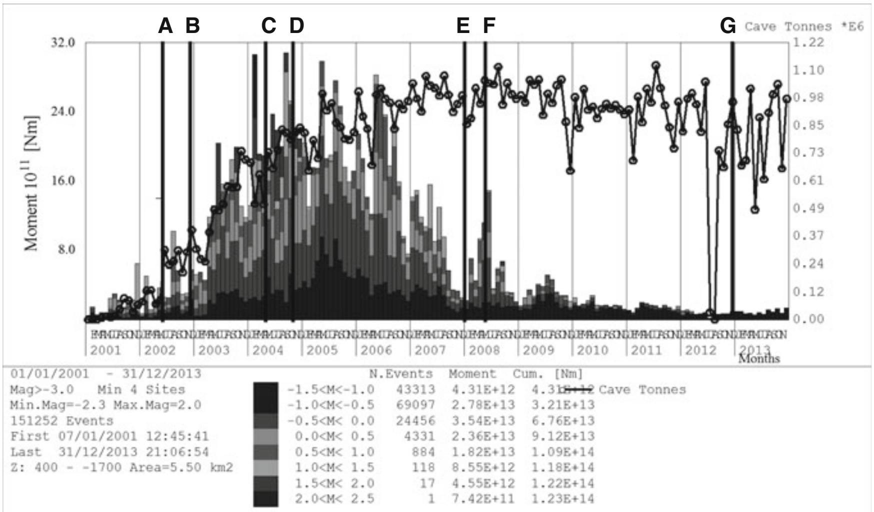

Fig. 6.24 Seismic deformation and production rates

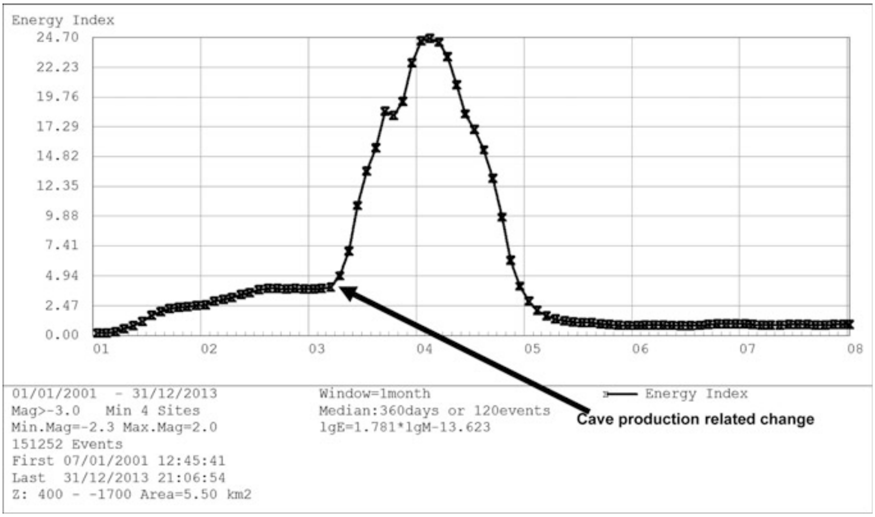

Fig. 6.25 Energy index history—version 2

seismic energy. The rock mass deforms with or without large size seismicity. From the end of 2006 the seismic deformation rates appear not follow the production trend rates any more. It seems that at this stage the deformation rates were no longer related to the production rates. The increased seismic deformation rates during the first half of 2008 were associated with the east break through.

The time related history of the energy index as presented by Fig. 6.21, was produced with the assumption that its value can change from 0.1 to a maximum of 10.0 Fig. 6.25 shows the shape of the energy index curve when this restriction on the individual energy index values is no longer present. In general this result is very similar to that presented by Fig. 6.21. The energy index reached the average value of 1.0 by mid 2001 and then increased slowly until March/April 2003. From then on the increase rate was very rapid. The maximum was reached by the beginning of 2004. The subsequent decrease in the energy index values was also very rapid. The average value of 1.0 was reached by the end of 2004.

The rapid change in the energy index increase rate from about March/April 2003 was due to the cave production increase, while the rapid decrease from the beginning of 2004 is associated with the cave breaking into the open pit. This was already discussed in Chap. 5 and illustrated by Figs. 5.27 and 5.28.

Figures 6.26, 6.27 and 6.28 illustrate the fact that from mid 2006 until mid 2008 the cave was expanding more in the east. This is indicated by an increase in the seismic activity rates, greater energy released and the higher amounts of seismic deformation above the mine. During the east break through the amounts of seismic energy and seismic deformation taking place above the mine increased considerably. Such increases in the amounts of seismicity taking place above the mine were not observed. This is probably because at the time of the east break through the

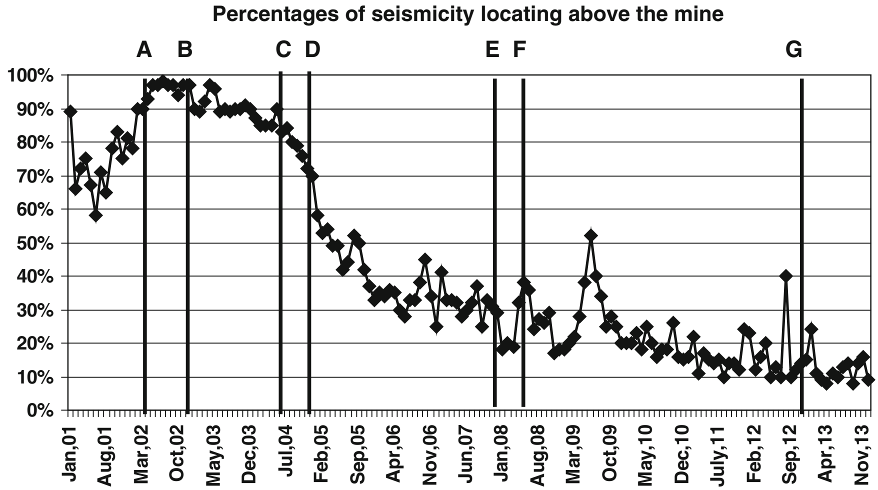

Fig. 6.26 Percentages of seismicity recorded above the mine level

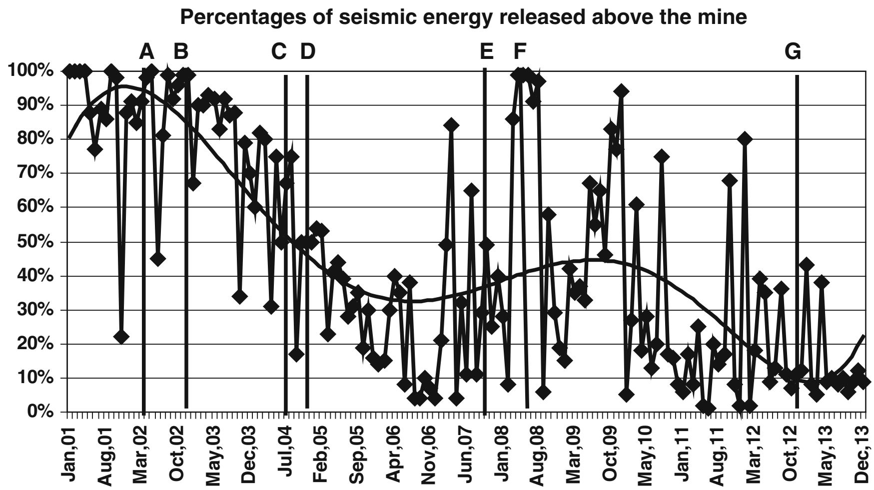

Fig. 6.27 Percentages of seismic energy released above the mine level

caving process was already at a mature stage. This mature stage as far as seismicity is concerned is characterized by a considerable decrease in all seismic activity rates since the end of 2007. Data presented by Figs. 6.26, 6.27 and 6.28 illustrate only how the percentages of seismicity, seismic energy and deformation taking place above the mine have changed over time. Although these percentage trends correlate with the caving process milestones they do not reveal the whole process behind the seismic activity rates as they do not indicate how the activity rates have changed

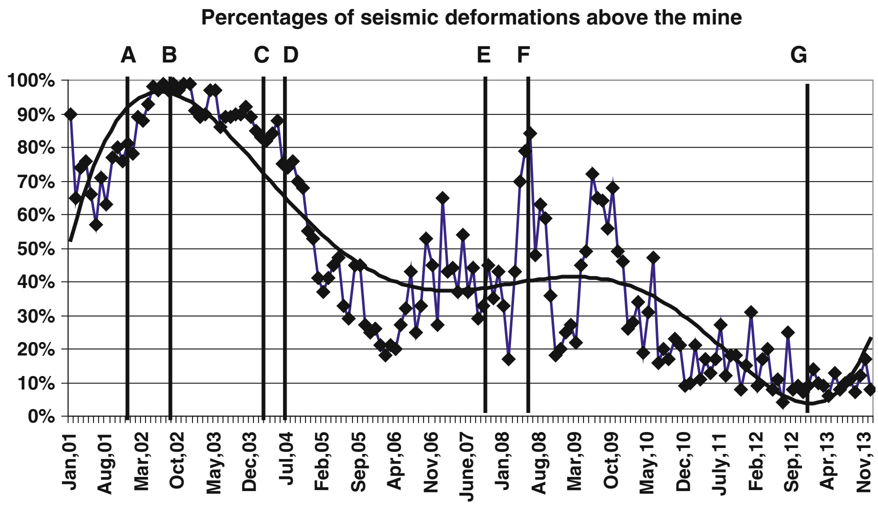

Fig. 6.28 Percentages of seismic deformations above the mine level

over time. This limitation is clearly visible with the 2009 data. All three percentage trends might indicate that after the 2008 east break-through there was some major changes in the seismicity pattern distribution during 2009. This is not the case, as in terms of percentages these changes might seem large but once evaluated using absolute values they become minor. It is important to note that the seismicity that took place below is of significant size as nearly 40 % of the recorded events emitted seismic energy and seismic deformation took place below the mine. For this reason the seismicity time and space distributions play an important role in understanding the caving process.

Figure 6.26 shows the percentages of seismicity recorded above the mine level from January 2001 until the end of December 2013. 100 % seismicity is the total amount of seismicity recorded every month above and below the mine level in the depth range from +400 m down to –1700 m. Initially, during 2001, the amounts of seismicity recorded above the mine were as high as 70 %. With the initiation of the caving process in April 2002 (A) over 90 % of seismicity was recorded above the mine level. These high levels of seismicity above the mine level continued until the cave broke into the open pit in May 2004 (C). After the initial break through there was a slow but continuous decrease in the amounts of seismicity recorded above the mine level which lasted until mid 2006. By May/June 2006 only about 30 % of all recorded seismicity plotted above the mine level. During the second half of 2006 the amounts of seismicity recorded above the mine increased to about 40 %, but then dropped back again to below 30 %. There was more seismicity recorded above the mine (up to 40 %) during the east break through (E). By the end of 2008 the amounts of seismicity recorded above the mine had decreased to 20 %, but then increased again to 50 % during July 2009. This time this shallow seismicity was associated with the cave progress both at the west and east side of the cave. By the end of 2012 the amounts of seismicity recorded above the mine had decreased to less than 20 %.

Figure 6.27 shows the percentages of seismic energy released above the mine level from January 2001 until the end of December 2013. From October 2004, which coincides with the failure of the open pit North Wall (D), more than 50 % of seismic energy was released below the mine. It is interesting to note that the continuous decrease in the percentage of energy released above the mine level ended in March 2006. From March to the end of July 2006 the amounts of energy released above the mine footprint have increased from 15 to 40 %. By the end of 2006 less than 10 % of the total energy was released above the mine level. During the whole of 2007 the percentages of energy released above the mine varied from month to month by large quantities (from 10 % up to over 50 %/month). During the east break through (E) the amounts of energy released above the mine increased to nearly 100 %. By the end of 2008 only 20 % of seismic energy was being released above the mine. The continuous increase of energy released above the mine during 2009 was associated with seismicity that located in the rock mass volume located below the open pit failure zone. These amounts of released seismicity are very low.

Figure 6.28 shows the percentages of monthly seismic deformation rates above the mine. The maximum deformation rates above the mine are associated with the caving process. After the cave broke through into the open pit (C) the percentages of seismic deformation above the mine level dropped from about 80 % (June 2004) to less than 50 % in January 2005. This decrease continued until April 2006 when only about 20 % of observed seismic deformation was taking place above the mine level. From May 2006 until May 2007 the amounts of seismic deformation taking place above the mine increased to about 50 %. This value for December 2007 was back down at 35 %. This indicates that at that time the cave was still expanding on the east side of the footprint. During the east break through (E) the amounts of seismic deformation taking place above the mine increased to 80 %. By the end of 2008 only 20 % of the total seismic deformation was taking place above the mine level. As in the case of the percentages of seismicity and seismic energy released above the mine level the observed increase in seismic deformation above the mine was taking place below the open pit failure zone. It must be assumed that until the full break through into the open pit occurs, there will be some additional seismic deformation associated with this process.

Table 6.1 gives a general indication about the amounts of recorded seismicity, seismic energy and seismic deformation that took place around the mine from 2001 until the end of 2013.

As indicated by Fig. 6.29, the increase in seismic energy released per year continued for 4 years, from 2001 to 2004. The maximum amount of seismic energy was released during 2004. The decrease in the amounts of released energy between 2004 and 2005 was considerable as the 2005 seismic energy release was 12 times lower than the 2004 energy release. The total seismic energy releases during 2006 and 2007 were also low as they were comparable with the 2005 releases. The higher energy release during 2008 was associated with the cave breaking through in the east. The amounts of seismic energy released during 2008 were less than half of the energy released during 2004 when the initial break through took place. The total

Table 6.1 Seismicity 2001–2013

Year	No recorded events	Energy released (E+07 J)	Seismic deformation (E+12 Nm)
2001	3998	0.9	3.6
2002	7250	2.4	5.3
2003	24354	8.8	15.9
2004	20973	11.9	27.0
2005	27519	1.0	23.9
2006	19560	3.3	22.1
2007	13710	1.4	11.6
2008	10099	4.5	7.5
2009	7934	0.1	4.0
2010	6677	0.08	2.2
2011	6453	0.09	1.8
2012	3472	0.03	0.9
2013	4100	0.01	1.1

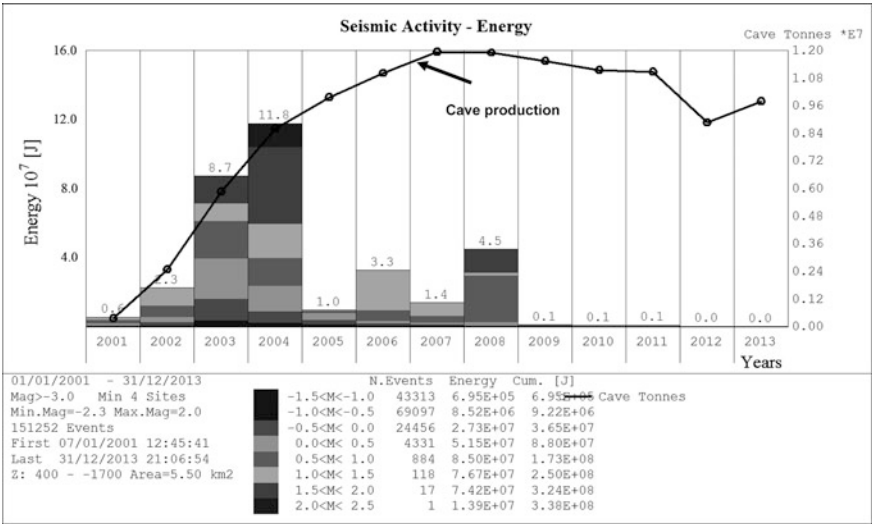

Fig. 6.29 Seismic energy releases per year

seismic energy released during 2009 was about 45 times less from the 2008 energy release. The 2010–2012 and then the 2013 energy releases are the lowest since 2001.

Figure 6.30 shows the total amounts of seismic deformation per year. As with the amounts of seismic energy release there is an increase year on year from 2001 to 2004. In both cases 2004 is the year of the maximum seismic energy release and maximum seismic deformation After 2004, the amounts of seismic deformation per year dropped but this decrease up to the end of 2006 was very gradual, not like in

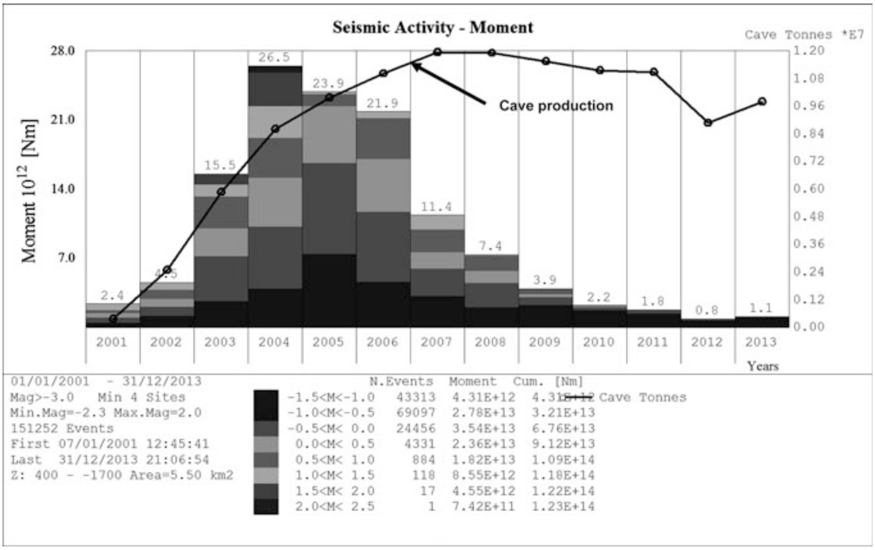

Fig. 6.30 Seismic deformation rates per year

the case of the seismic energy. For 2007 the seismic deformation rate was half of that recorded during 2007. The seismic deformation of 2008 was again lower by about 40 %, while the seismic deformation of 2009 is again 50 % lower than in 2008. The 2010 seismic deformation rate is again about 40 % lower than during 2009. The 2011 seismic deformation rate is about 20 % lower than during 2011. The 2012 seismic deformation rate is about 50 % lower than during 2011. It is interesting to note that the east break through did not change the decreasing deformation trend that has been taking place since 2005.

6.5.1 Seismic Energy Release Trends

Table 6.2 and Fig. 6.31 indicate several energy release patterns. In this figure the yearly percentages of energy released between elevations +400 and –700 m is at the top, the energy percentages released around the mine (between elevations –700 and –900 m) are in the centre. The percentages of energy released below the elevation of –900 m are at the bottom of the figure. The first trend is the 2002–2004 increase of the total amount of energy released. This was associated with the continuously increasing amounts of rock mass volume affected by the caving progression. The total energy release during 2005 was more than 10 times lower than the 2004 energy release. This indicated that the rock mass around the cave was already fractured and no longer able to accumulate larger amounts of strain energy. Increased amounts of seismic energy released during 2006–2008 indicate that the cave was at that time expanding in the east. The second and third trend is connected with the slow but

Table 6.2 Energy release trends (10E+06 J)

Year	Total energy released	Release above –800 m	Release below –800 m	Release between –700 and –900 m
2002	17.7 (100 %)	16.4 (94 %)	1.1 (6 %)	6.1 (34 %)
2003	87.3 (100 %)	54.3 (76 %)	21.2 (24 %)	38.5 (44 %)
2004	118 (100 %)	68.2 (58 %)	49.2 (42 %)	48.7 (41 %)
2005	9.6 (100 %)	6.2 (64 %)	3.4 (36 %)	3.4 (36 %)
2006	32.7 (100 %)	4.7 (14 %)	28.0 (86 %)	14.1 (43 %)
2007	13.9 (100 %)	3.0 (21 %)	10.9 (79 %)	5.4 (39 %)
2008	44.9 (100 %)	29.6 (66 %)	15.3 (34 %)	15.1 (34 %)
2009	1.13 (100 %)	0.71 (63 %)	0.42 (37 %)	0.57 (50 %)
2010	0.75 (100 %)	0.15 (20 %)	0.60 (80 %)	0.52 (69 %)
2011	0.99 (100 %)	0.09 (9 %)	0.90 (91 %)	0.76 (77 %)
2012	0.32 (100 %)	0.11 (34 %)	0.21 (66 %)	0.15 (47 %)
2013	0.15 (100 %)	0.03 (20 %)	0.14 (80 %)	0.01 (7.0 %)

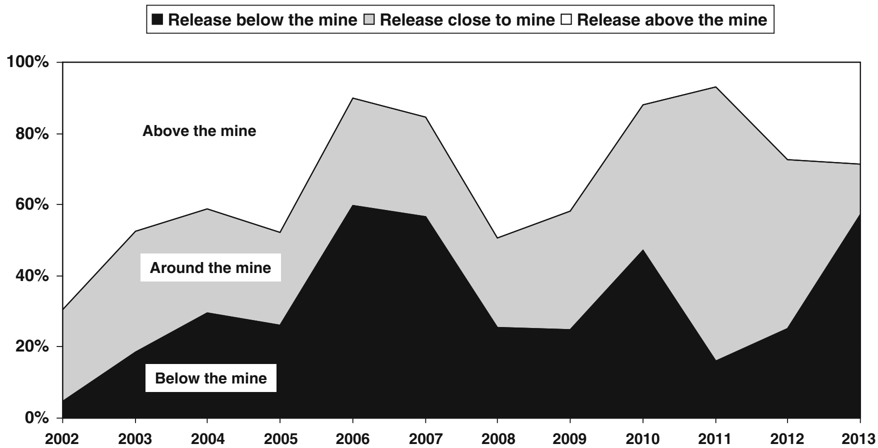

Fig. 6.31 Seismic energy release trends

continuous migration of stresses below the mine. This is demonstrated by year-to-year increased percentages of energy released below the mine. The 2009–2012 energy releases are the lowest for the 10-years period. This probably indicates that the caving process is reaching its limits. The increase in energy release above and below the mine during 2008 was associated with the east break through. The last noticeable trend is that the percentages of the total released energy around the mines depth stay more or less constant from 2002 to 2009. During 2010 and 2011 this percentage increased to over 70 %. The 2012 seismic energy release was close to 50 %. The energy release pattern for the rock mass around the production level is a combination of what happens above and below the mine.

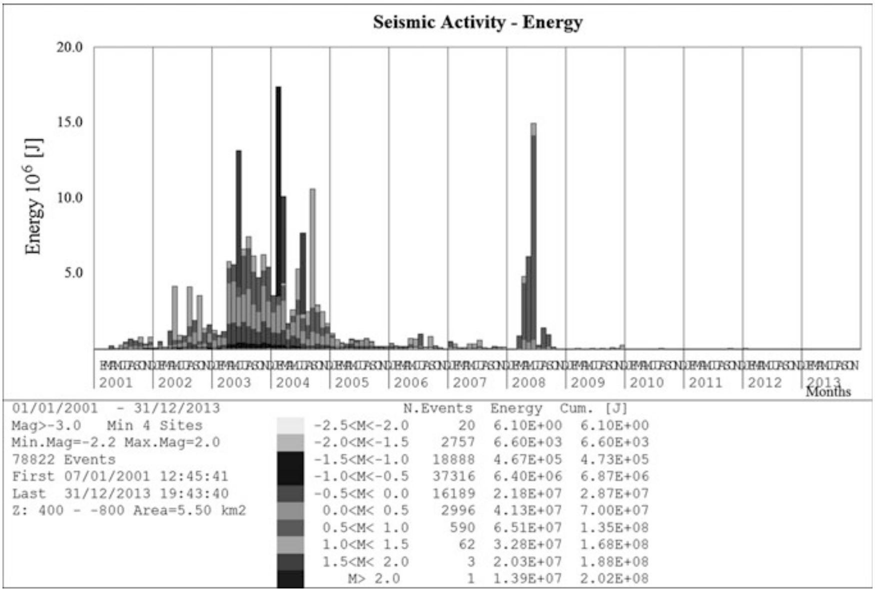

Fig. 6.32 Energy release pattern above the mine level

There is a difference in the manner in which the energy was released above and below the production level. The energy release pattern above the production level was more continuous (Fig. 6.32) and in general showed a decreasing trend. The

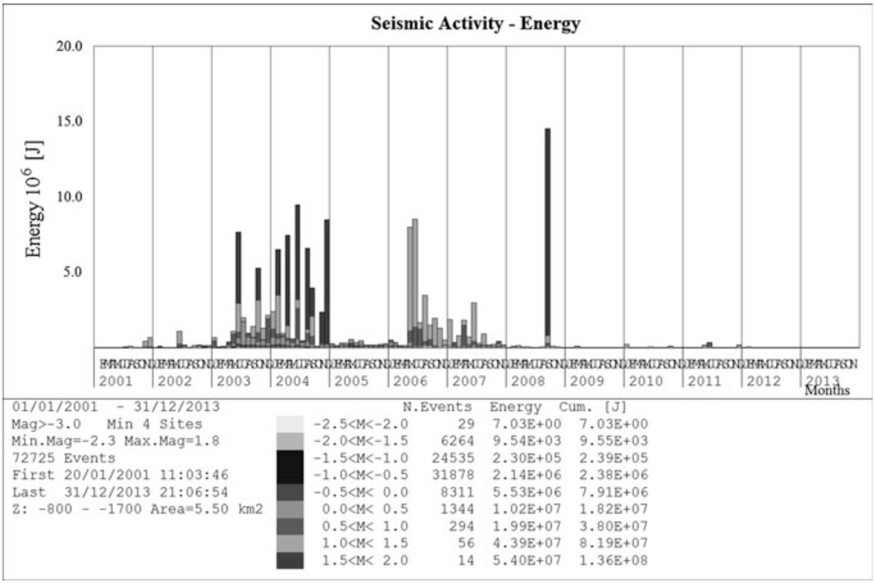

Fig. 6.33 Energy release pattern below the mine level

energy release pattern below the production level (Fig. 6.33) occurred in phases that were separated by weeks of very low energy release. This was as a result of the rock mass above the production level being weaker and more fractured than the one below the production level.

6.5.2 Occurrence and Locations of Events Above Magnitude 1.0

According to Table 6.3 the amount of large events during 2008 decreased four times in comparison to 2007 and that two out of four 2008 large size events located below the mine elevation. During 2009 and 2010 there was only one event of magnitude above 1.0 per year. The largest seismic event recorded during 2011 was an event of magnitude 0.5 while the largest event of 2012 was of magnitude 0.8. The 2002 largest events located at the east and central parts of the mine. The 2003 events located around the cave footprint. There is a concentration of these events at the intersection of the Southwest Fault with the dyke stringer (southwest part of the mine). Some of these events resulted in damage to the underground excavations. The 2004 events, with exception of only one event, located at the west and are associated with the Mica Fault and its intersections with other faults. The 2006 large size seismicity located south of the mine and all of them are associated with dykes. Most of the 2007 seismic events located north of the mine. The 2008 events located at the east side of the mine and were associated with the East Dyke. The largest event of 2009 located at a dyke on the north side of the mine. The largest event of 2010 located on the same dyke but south of the mine. As far as events of magnitude above 1.0 that located below the mine there was only one such event during 2002 and 2005.

Table 6.3 Number of events above magnitude 1.0

Year	Total no of events	Above elevation –800 m	Below elevation –800 m	Between elevation –700 and –900 m
2002	7	7 (100 %)	0	1
2003	25	10 (40 %)	15 (60 %)	18
2004	49	23 (47 %)	26 (53 %)	27
2005	3	2 (66 %)	1 (33 %)	0
2006	16	3 (18 %)	13 (82 %)	6
2007	16	7 (44 %)	9 (56 %)	11
2008	4	2 (50 %)	2 (50 %)	2
2009	1	1	0	1
2010	1	0	1	1
2011	0	0	0	0
2012	0	0	0	0
2013	0	0	0	0

Both these events located at the north part of the mine. The 2003 and 2004 events located at the east and west sides of the mine. The 2006 large size events plot north and south of the mine. As above the mine most of the 2007 events plot at the north part of the mine. The 2008 events were as the ones above the mine associated with the East Dyke. During 2009 and 2010 there were no events of this size recorded below the mine level. The largest events of 2011–2013 (above magnitude 0.0) took place north of the mine and were associated mainly with the dykes.

6.6 Summary

In block caving, the cave back progression generates fractures in the intact rock immediately ahead of the fracture zone, which alters the rock properties and reduces load carrying ability in this fractured rock. As the cave back approaches the newly fractured rock, it will yield under the increased tangential stress causing shear movement between the blocks of rock and further propagation of fractures. The cave progress will also result in breaking asperities and other locking mechanisms in the fractured rock mass creating an environment for increased shear movement and growth of the fracture zone around the cave back. Most of the recorded small size seismic events are an indication of this process. This seismicity is a natural process indicating that the cave is progressing. The space and time distributions of mode one seismic events, as well as the changes of their source parameter values over time are associated directly with what is happening in the rock mass around the cave and the mining excavations. For several years it has been an established fact that mine induced seismicity can be divided into mode one events that are directly connected with the mining operations and mode two events which are associated with movement on geological discontinuities at some distance from the mining. The mode one events are associated with the formation of cracks at stope faces or in case of block cave mining, the formation of cracks in the cave back and around the periphery of the cave. An understanding of cave induced seismicity is important for an understanding of the process of cave mining. This seismicity is a natural process indicating that the cave is progressing and should not only be monitored in a passive way to confirm the caving process, but should be also used in an active way to manage the cave development and seismic hazard. The space and time distribution of seismicity, as well as changes in the source parameters over time, are directly associated with what is happening in the rock mass around the cave and the underground mining infrastructure. Analysed seismic and mining data enabled benchmarking the seismic response to the cave mining process.

In this model the caving process consists of the following phases:

- Gravity caving
- Initiation of the stress caving process
- Cave progress
- Failure of the pillar

- Cave break through
- Cave progress after the break through
- Mature stage of the caving process
- End of the caving process

The recorded seismicity was not only induced by the caving process. Palabora went into production mode when not only the development mining is still taking place but there is still some mining taking place from the open pit or the previous lift. For this reason the recorded seismicity will be induced by all these mining activities. It might not always be possible to separate the data completely and then analyse separately. Still there are some techniques that might be helpful.

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Chapter 7
Palabora Caving Process as Evidenced by Induced Seismicity

This chapter is the main part of the book. In this chapter I am presenting how the seismicity was changing with the cave progressing from one milestone to the next one. The stress caving process was initiated in April/May 2002 and the caving process ended by the end of 2012. This chapter is backed by my experience from other cave mines as El Teniente, PT Freeport DOZ Mine or Northparkes Lift 2 Mine. The main value of all presented analyzes is how the interpretation results were achieved. For this reason some of the presented analysis is elaborate and full of details. This part includes the description the open pit North Wall failure. As it was spectacular it attracted a lot of attention. I was often asked if seismicity could be used to predict this failure. That there would be a failure it was expected but its size turned out to be a complete puzzle. It took a couple of years for the modelling research in the back analysis mode to come close to what has happened in reality.

The caving progress from a physical point of view is basically a progression of fracturing. This fracturing in case of mass mining involves large volumes of rock mass. It will continuously change the rock mass properties. With time all the rock mass properties that are used to locate and then estimate the source parameters will change from the ones that were input into the seismic system during its installation. From a practical point of view updating these parameters is not possible. In theory it is possible to repeat from time to time the calibration blasts in order to update the seismic velocity values. In reality this might be not only be technically difficult and costly but may also be disrupting to the production cycle. Over 90 % of the seismic input consists of small or very small magnitude size events of which for example their energy releases are estimated as tens or hundreds of Jules. Overestimating and/or underestimating source parameters of such small events when they are analysed together in their thousands should not result in a substantial distortion. On the other hand it is easy to recognize that over time the seismicity location accuracy will deteriorate which might result in very unreliable locations of seismic events if they are analysed as unique and single episodes. In the presented analysis this is not the case. Here the seismicity is divided into subsets for which accurate location is no longer as important. For the presented results of the seismicity analysis to have

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credibility it is fundamental that these milestones are evidenced by other means than seismicity alone. Certain consistency of seismic results is important but on its own it doesn't provide the ultimate confirmation of the events. On the other hand too much of consistency might also be questionable as two or a number of incidents of generally the similar nature (for example the cave breaks through) can not be exactly the same. The Palabora caving process consists of the following seven milestones:

A. Start of gravitycaving —October 2001
B. Start of stress caving process April 2002
C. Failure of the crown pillar in December 2003
D. Initial Break through May 2004
E. Cave reaching mature stage end of 2007
F. East break through May, June 2008
G. End of the caving process end of 2012

For further reference the above caving stages will be referred to in text and figures by capital letters as listed above. The initiation of the caving process (B) is the second milestone of the caving process. Evidence of its occurrence is in the increased production tonnages after reaching the estimated hydraulic radius at which it should take place. The main confirmation that the caving process is taking place is the progress of the cave that is usually monitored by TDR's and the measurements done in open holes. It is also evident that the further caving milestones would not take place without the initiation of the caving process. In this way the following caving milestones are also evidence of the initiation. The crown pillar failure (C) was first recognised only by analysis of seismic data and because of this was questionable but only up to the time it was confirmed by nature. Directly after a heavy storm water in excess was reported underground. This directly indicated that there is a hydraulic connection between the open pit and the underground mine through the 200 m thick (at the time rock) mass. This could only mean that this rock mass was highly fractured and that the pillar had already failed. The cave break through appears twice in the history of the PMC caving process. This is a significant advantage for the interpretation process. An event of similar nature took place twice. This should allow not only for more detailed analysis but also for deriving more general conclusions. The initial break through (D) was confirmed by TDR measurements and production data. The PMC east break through (F) was confirmed by comparing its seismic response with that of the initial break through. Additionally analysis of mining rates from the east part of the mine was used to support the seismic evidence. At some stage the caving process will reach its mature stage. This concept is based on the assumption that the caving process must end. The caving process which is kept active by the continuous process of mining must have its physical limits at some maximum distance from the mine footprint and in certain rock mass volume size it can influence. In this concept it is assumed that the caving process might come to its end before the end of the mine life time. In this case most or all of the left behind volume of the ore body rock mass volume will be fractured to such extend that it already has or will cave into the void. The end of the caving process (G) takes place when the caving as such does not induce any seismicity. All of the recorded seismicity becomes then associated only with the mining process. This is evident while analysing seismicity of long time period (for example one or couple of months) that is displayed as 24-h distribution. Here during the shift change times there is no or only minimal amount of seismicity taking place. To complete this discussion there is still one important matter that needs to be mentioned, namely the parameters I have used. As in any analysis when the final outcome depends on comparing results obtained by using several parameters the reliability of final conclusions will be influenced by the inter dependency between these parameters. If the used parameters are dependent of each other then analysis of a number of such parameters does not contribute anything innovative towards the results apart from their shared outcome. The only benefit of such analysis that I can think of is that it allows to confirm if the applied mathematical algorithms are correct or not. On the other hand when there is no dependency between the used parameters then each of then provides independent of each other results that complement each other in the process of their interpretation. In all analysis I have used two types of parameters. The first one is based on mining data and the second category is derived from seismicity. By definition the seismicity that I was analysing is mine induced seismicity. This definition implies that there is some relationship between the mining and seismicity parameters. This relationship exists but it is not continuous in its nature nor is it constant. For example an increase in production rates will not always result in an increase in the seismicity rates or in larger size seismicity taking place. The dependency between production and seismicity changes over time with the caving process progress. This observation leads to the logical conclusion that analysis of the production and seismicity relationship contributes towards independent results. The seismicity parameters that I made use of are based on seismic moment and seismic energy which are independent of each other. I have also used the locations of this seismicity as well as their rates. It is obvious that the seismicity rates, their locations and source parameters are independent of each other and for this reason provide discrete results. As mass mining is three dimensional I have used the volume of the seismically active area. The seismically active volume is derived from the seismically active area and height. The height additionally allows for monitoring the trends of the minimum (shallow) and maximum (deep) seismicity elevations. These values are not exactly dependent on the seismicity rates but on its distribution around the cave. In the analysis I have also used a parameter based on seismic energy and seismic moment, the apparent stress. Apparent stress is also regarded as an independent seismic source parameter (Gibowicz and Kijko 1994). I have also used the so called energy index which also is a function of seismic energy and seismic moment. In the presented analysis I have used these two functions in an interchangeable manner. When I used one I did not use the other one. In some cases I had no choice but to use the stress parameter (apparent stress) instead of the energy index for the convenience as it is a part of the software code ("percentages of stress"). These two functions proved to be of great importance for the simple reason. The seismic energy releases by nature are of extremely wide range and for this reason are difficult but more often impossible to present visually as graphs. This then prohibits detecting their trends. Listed below are parameters that I have used while analysing and interpreting the seismicity in order to describe the Palabora caving process

1. Seismic activity rate
   - Monthly seismic activity rate
   - Percentages of seismic activity rates
   - Increase/decrease of seismic activity rates
2. Seismic deformation rate
   - Monthly seismic deformation rates
   - Percentages of seismic deformation rates
   - Cumulative seismic deformation
   - Increase/decrease of seismic deformation rates
3. Seismic energy release rate
   - Monthly seismic deformation rates
   - Percentages of seismic deformation rates
   - Cumulative seismic deformation
   - Increase/decrease of seismic energy release rates
4. The seismicity rates
   - For the whole mine
   - Above and/or below the mine extraction level
   - Above and/or below the mine foot print
   - Inside and outside of the cave volume
5. Percentages of the seismicity rates
   - Above and below the mine extraction level
   - Above and below the mine foot print
   - Inside and outside of the cave volume
6. Monthly percentages of events with ratio of Es/Ep > 10
7. Clustering and scattering of seismicity
8. Seismically active volume
   - Seismically active area
   - Height of the seismically active volume
   - Minimum seismicity elevations
   - Maximum seismicity elevation
9. Average monthly seismicity elevations
   - For the whole mine
   - Above and/or below the mine extraction level
   - Inside and out side of the cave volume

10. Energy index time history
    - For the whole mine
    - Above and/or below the mine extraction level
    - Inside and out side of the cave volume
11. Stress (Apparent stress)
    - Percentages above and below the mine extraction level
    - Percentages above and below the mine foot print
    - Percentages in the cave volume

Finally it is obvious that each of the caving process milestones doesn't take place instantly. For this reason it is often impractical to use accurate occurrence timing. In some instances the milestone occurrence can be defined with-in a one month period. More often the milestone occurrence time can be described only by using longer time periods. For this reason in many cases I had to define the occurrence time not very precisely as for example "by the beginning of the year", "by mid of the year" or "by the end of the year".

7.1 Caving Process Time Periods

The seven caving stages divide the caving history into seven time periods. These will be referred to by using roman numbers.

I. Development mining only (I)—From 01/01/2001 to 30 September 2001 (9 months)

A. Start of gravity caving (October 2001)

II. Between gravity and initiation of stress caving 01/10/2001 to 30 April 2002 (7 months)

B. Initiation of the stress caving process (April/May 2002)

III. Time between stress caving initiation and crown pillar failure 01/05/2002-31/12/2002 (8 months)

C. Failure of the crown pillar (End of 2002)

IV. Time after crown pillar failure until initial break through 01/01/2003-31/05/2004 (17 months)

D. Initial break through May 2004

V. Time between the initial break through until the mature stage 01/06/2004 until 31/08/2007 (39 months)

VI. Time period in which the cave was in mature stage 01/09/2007-31/10/2012 (62 months)

E. Cave going into the mature stage August 2007

F. East break through May and June 2008

G. End of the caving process October 2012 (E)

VII. Time when the caving process ended from 01/11/2012 to 31/12/2013 (to the end of my data base)

The caving process was initiated before the underground development mining as well before the mining in the open pit was completed.

1. Development mining

   1.1 Undercutting started November 1999
   1.2 Undercutting completed February 2004
   1.3 Production level started August 2000
   1.4 Completion of draw bells—August 2004

2. Last blast in the open pit—April 2002
3. End of ramp mining in the open pit—October 2003

Figure 7.1 illustrates the fact that the development and open pit induced seismicity must be included in the first time period that covers the time before the gravity caving took place. This seismicity should or could be mixed with the seismicity of the second time period that is over the time when the gravity caving was taking place. The stress caving was then initiated when the production level development was still taking place. The last blast in the open pit took place at the same time the stress caving was initiated but ramp mining just commenced. During time period III from the initiation of the caving process up to the crown pillar failure the recorded seismicity was induced by three processes taking place: the caving process, the development mining and the mining in the open pit. The recorded seismicity during the time period IV which lasted to the time of the initial break through was still influenced by the development mining. Figure 7.2 illustrates the fact that the influence of development mining was not constant. Maximum development rates were recorded during 2001 and 2002 and during 2003 the rates decreased rapidly. Based on this it can be assumed that the influence of development mining on seismicity induced by the cave mining was neglect able.

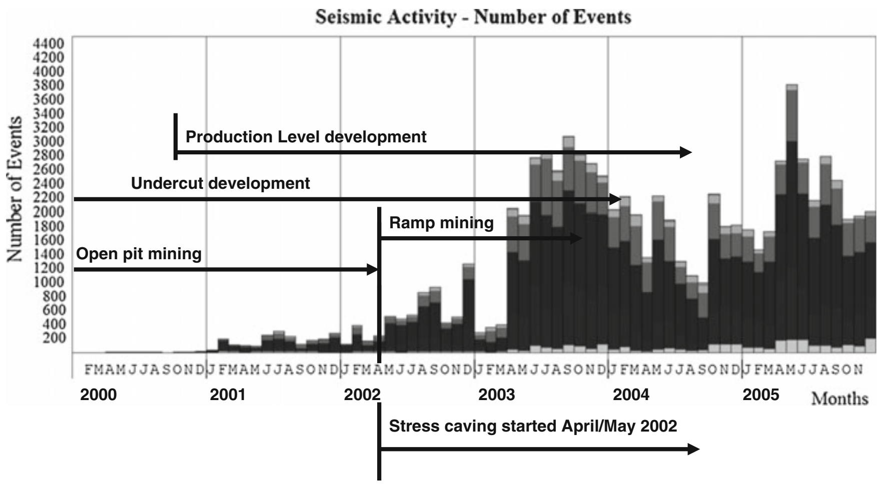

Fig. 7.1 Mining processes inducing seismicity

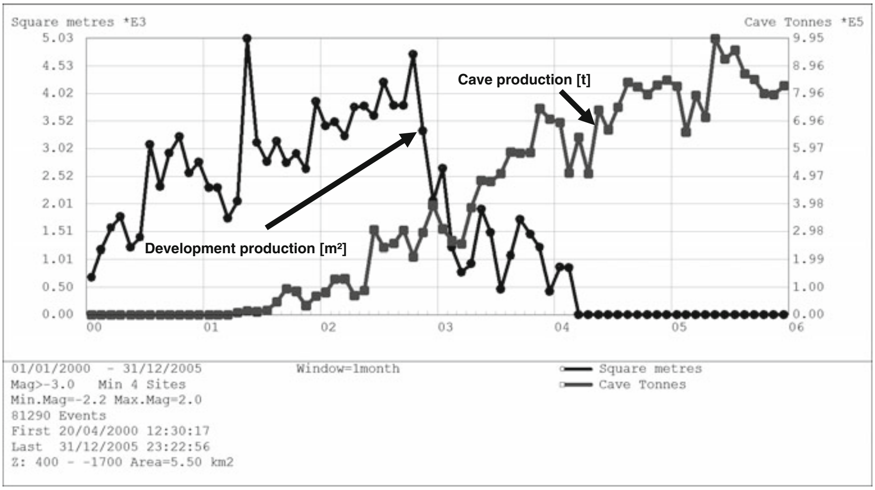

Fig. 7.2 Monthly development and production rates

Figure 7.3 illustrates the energy index time history. This figure illustrates the thirteen years mine history when the caving process milestones took place. This figure also indicates the positions of the seven time periods. It is tempting to mention that the energy index time history fits very well with the caving stages It only seems that energy index time history during time period VI especially during 2012 might not be consistent with the process of the caving in its mature stage The

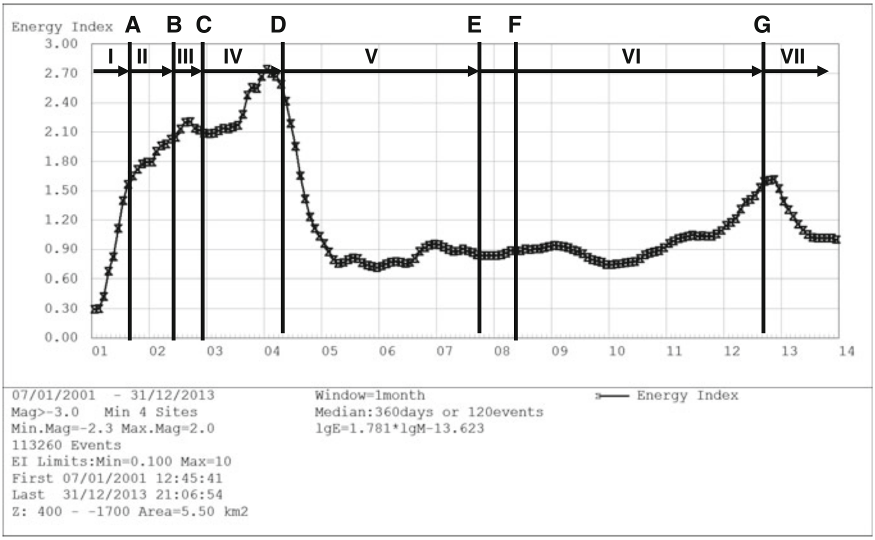

Fig. 7.3 Energy index time history and seven time caving periods

other inconsistency might be suspected at the time of the east break through (E) as the energy index during this time is very low and below its mean value of 1.0. It has to be understood that for this figure the energy index is based on the whole seismicity recorded over the whole time period (from the beginning of 2001 until end of 2013). The different energy index values and trends during the two break through times probably indicate the fact that the stress during the initial break through had to be much higher than that which was during the east break through. It seems (at least at this stage of analysis) that the high stress as indicated by the energy index time history during the mature stage of the caving process appears to be inconsistent with the whole caving history.

To start with it seems reasonable to test and confirm the time positions of the seven time periods. For this I will make use of some credible parameters. These parameters are based on recorded seismicity and also on production rates parameters. These parameters on their own or combined together are unquestionable in their quantity and quality and posses an invariable status. Even if the magnitude values would be recalculated using a different formula the percentages of the largest events would not change very much. First parameter is the occurrence of rock bursts and times of reported underground damage Those are facts that could be traced through rock engineering reports.

Mining results in changes to the stress distribution away from the mining openings or cave back as well adjacent to the openings. The stress changes tend to concentrate around geological discontinuities of different types with the geotechnical parameters of these features playing a major role in how and when accumulated energy is released. Seismic sources of the second mode tend to concentrate in certain areas forming clusters of different sizes and shapes. In general, the second mode events result in increased seismic hazard due to their sizes and associated amounts of released energy. Examination of the relationship between blasting time and occurrence of seismic events indicates that there is a sizeable increase in the number of small events directly after the blasting. Large events tend to be independent of blasting and take place at any time of the day. Recorded large seismic events that resulted in FOG (fall of ground) are typical for the PMC mine induced seismicity. Seismic data recorded at PMC displays bimodal patterns typical for mine induced seismicity, but past measurements of regional seismicity also indicate a possible third mode of events larger than magnitude 2.0 related to the global effect of mining on geological structures. While the events belonging to the first mode the maximum magnitude is in range 0.0–0.5, the events of the second mode can be of magnitude above 1.5. The first mode of events is connected with rock mass fracturing in front of the undercut and propagating cave. The second mode of event are events locating at geological discontinuities at distances 100–300 m around the cave. Events of this mode are connected with the stress redistribution ahead of the undercut abutment and around the cave. This mode appears to have increased markedly in March 2002, which may indicate the onset of sustained stress cave propagation at this time. The hydraulic radius based on operating draw bells had reached 45 m in March 2002, which is similar to the hydraulic radius predicted from the Extended Mathews Stability Graph for when caving should occur in hard rocks. The second mode events at PMC have resulted in clusters of seismic activity on three faults, the Central, the Southwest and the Tree Faults, as well as the Main Dyke. This clustering process started in September 2001, but has accelerated from May 2002. This clustering activity was concentrated on the east side. Where the clusters concentrated on the dykes, or at intersections fault-fault or fault-dyke, the energy accumulates to the point where no more can be accommodated and is then released in one big burst of magnitude 1.0 or more. Analysis of these clusters revealed certain trends. The first trend was that the analysis of the average elevation of the clusters indicated migrating upward with time, while the second trend was an increase in the amount of energy released in these clusters with time. Based on the observed seismic clustering, the Central, Southwest and Tree faults as well as the Main Dyke were considered as seismically hazardous. As such, heavier ground support was required where these structures intersected the underground infrastructure.

Table 7.1 clearly indicates that all rock bursts and underground damage was associated with time period IV that is the 17 months time after the crown pillar failure until the initial break through. The last underground damage took place just after the initial break through during the time period when the energy index values were declining as illustrated by Fig. 7.3. The next parameter that can be used to test the time periods positions in the history of the caving process are the largest recorded seismic events. Table 7.2 lists all seismic events magnitude 1.5 and above recorded in the Palabora history. There are eighteen such events. Analysis of their time occurrence indicates that they took place only during time period IV and V. This means that this large size seismicity that potentially could result in underground damage was taking place after the initial pillar failure (IV) and then after the initial break through (V).

It is interesting to note that after the pillar failure this seismicity was taking place above and below the extraction level. After the initial break through this large size seismicity practically occurred only below the extraction level. This seems to be an

Table 7.1 Occurrence of rock bursts

Date	Magnitude	Notes	Period
16 January 2003	1.1	Rock burst	IV
13 June 2003	1.7	Rock burst	IV
24 August 2003	1.2	Rock burst	IV
20 October 2003	1.6	Event induced by restarting production	IV
26 November 2003	1.2	Shake down after large size seismicity	IV
19 February 2004	1.5	Shake down after large size seismicity	IV
28 February 2004	1.4 and 1.5	Events induced by restarting production	IV
28 August 2004	1.5	Rock burst	IV
06 September 2004	1.1	Rock burst	IV
29 November 2004	1.5	Rock burst	IV
17, 19 December 2004	1.7 and 1.0	Rock burst	IV
28 July 2005	1.0	Shake down after large size seismicity	V

Table 7.2 Occurrence of the largest size seismicity

No.	Date	Magnitude	Time period	Notes
1	13/06/2003	1.7	IV	Above the mine
2	13/06/2003	1.8	IV	Below the mine
3	20/10/2003	1.6	IV	Below the mine
4	19/02/2004	1.5	IV	Below the mine
5	27/02/2004	2.0	IV	Above the mine
6	28/02/2004	1.5	IV	Below the mine
7	24/03/2004	1.5	IV	Above the mine
8	12/04/2004	1.6	IV	Below the mine
9	15/04/2004	1.6	IV	Below the mine
10	20/06/2004	1.6	V	Below the mine
11	24/06/2004	1.5	V	Below the mine
12	14/07/2004	1.9	V	Above the mine
13	28/08/2004	1.5	V	Below the mine
14	28/08/2004	1.5	V	Below the mine
15	08/09/2004	1.5	V	Below the mine
16	29/11/2004	1.5	V	Below the mine
17	17/12/2004	1.7	V	Below the mine
18	24/09/2008	1.5	VI	Below the mine, event associated with east break through

important difference between these two time periods which is logical and easy to explain. After the pillar failure and the initial break through the stress pattern around the mine changed and the seismicity migrated down below the mine. The last event in Table 7.2 is very different from the other ones. It is associated with the east break through and not the time when the cave was in its mature stage This event indicates that the break through as such is associated with increases seismic energy releases.

The third parameter that should be used for this type of test are the seismicity activity rates. Here one should consider not all recorded seismicity but only the largest size well above the limits of the minimum size events that are all recorded. Here one has to consider the history of the network. It is safe to assume that all events above magnitude 0.0 were recorded. In this test their locations are not important, as for this test only their occurrence times are essential. Table 7.3 lists the number of recorded seismicity in three magnitude ranges: from 0.0 up to 0.5, from 0.5 up to 1.0 and above magnitude 1.0. In column eight are listed the largest recorded seismic event magnitude sizes. There are two values per each magnitude range: the number of recorded events and the percentage they make out of the total number of recorded events. The results are very consistent as in all cases the larger numbers of recorded seismicity are associated with time period V and then VI.

Table 7.3 Largest seismic events per time periods

Magnitude range	0.0–0.5		0.5–1.0		Above 1.0		Max magnitude	Notes
Time	No	%	No	%	No	%		
I	93	2.3	12	1.6	1	0.8	1.0	
II	78	1.9	20	2.7	3	2.3	1.2	
III	191	4.7	58	8.2	13	10.1	1.3	
IV	1461	36.0	266	36.9	41	32.0	2.0	
V	2149	53.0	349	48.3	68	53.1	1.9	
VI	87	2.1	17	2.3	2	1.0	1.1	Excludes east break through seismicity
VII	1		0		0		0.0	
Total	4060	100 %	722	100 %	128	100 %		

Table 7.4 provides information about percentages of seismicity above magnitude 0.0 recorded during each time period. Hundred percent is the number of events recorded during all seven time periods together. It might be that the percentage values are not representative of the seismic activity rates in each time period. This is due to the fact that each time period is of different lengths. The first three are each less than ten months. Period IV has 17 months and according to Table 7.4 36 % of recorded seismicity is associated with this time period. The next time period V is 39 months long and accounts for 52 % of recorded seismicity. Time period V is longer than time period IV and because of that might have more of attached seismicity. The next time period VI is the longest one as it has 62 months. Still it accounts for only 3 % of recorded seismicity. This indicates that when the caving process goes into it mature stage the seismic activity rates decrease abruptly. During the last time period after the caving progress ends there is no larger size seismicity. This review indicates that first of all the percentages of recorded seismicity are not dependant on the lengths of the time periods. Secondly this lack of relation indicates that probably all or most of the time periods are correct not only in their lengths but also in their specific time settings. Third row of Table 7.4 lists average monthly seismic activity rates of seismicity magnitude 0.0 and above per each time period. Time period IV which starts just after the time when the crown pillar failed and ends with its break through has the highest average monthly seismic activity rate of the larger size seismicity even if it does not contain their highest percentages. Time period V after the break through has more of this size seismicity in

Table 7.4 Seismicity above magnitude 0.0

Time period	I	II	III	IV	V	VI	VII
Percentages of recorded seismicity (%)	2	2	5	36	52	3	0
No. of events per month	12	14	33	104	65	2	0

comparison with time period IV but the average monthly seismicity rate is lower. Other interesting information coming from this analysis is connected with the time between the initiation of the caving process and the crown pillar failure (time period III). Although this time period contains only 5 % of the total seismicity its activity rates are unquestionably higher from these in time periods I and II. This indicates that seismicity induced by development mining or the gravity caving process was much less from that which was associated with the stress caving process. As this analysis takes into account only seismicity of magnitude 0.0 and above then this can be taken further and related to seismic energy emission rates. Energy release rates before the initiation of the stress caving process were very low. Initiation of the stress caving process is associated with increased seismic energy release rates This can be confirmed easily by analysing a value based on ratio of average seismic energy release to the average production rate for each time period. This parameter unit will be J per tone of mined ore. The production rates include development as well as the cave tones. Those values are listed in Table 7.5.

At this stage it is difficult to assess if for example 5.0 J/t is much or no. The best solution would be to compare PMC values with other mines. Unfortunately this is not possible but some other valuation should be possible, for example evaluation of this parameter with rock bursts taking place. According to data from Table 7.1 all rock bursts and underground damage were experienced only in time period IV that is during the time after the initial pillar failure until the initial break through. This time period has the largest amounts of energy released per tone of mined out ore. The time periods II and III have this value nearly 50 % lower. In case of the time after the stress caving process initiation up to the time when the crown pillar failed (III) it would be expected that this value would be higher. Still its value would depend on the draw strategy. At the time there was a requirement to keep a 200 m safety zone between the maximum elevation of the cave and the bottom of the open pit. It was hoped that this zone will make mining in the open pit safe and that it will prevent the mine being flooded after some larger than average for the time rainfall. To keep the safety zone in place the cave development had to be limited and this could be achieved by low production rates. This strategy was abandonment then in March 2003 after the pillar failure was confirmed. When there was only mining development taking place this value was three times lower from than its maximum. It is interesting to note that the second value which is the ratio of seismic deformation per mined out tone of ore has a lower range than the energy released per tone. It is close to 2.0 E+06 Nm/t during the first five time periods. Only after the caving process went into it mature stage it decreased as did the values of Jules per tone. Table 7.6 provides values that are more informative of the seismic energy

Table 7.5 Seismicity above magnitude 0.0

Time period	I	II	III	IV	V	VI	VII
Monthly J/t	5.0	7.4	8.7	15.6	3.2	0.1	0.01
Monthly Nm/t	2.7E+06	3.0E+06	1.5E+06	2.8E+06	2.2E+06	0.3E+06	0.1E+06

Table 7.6 Production and energy release rates

Time period	I	II	III	IV	V	VI	VII
Monthly J/t	5.0	7.4	8.7	15.6	3.2	0.1	0.01
Average monthly seismic energy (J)	2.75E+05	7.72E+05	2.58E+06	8.27E+06	3.80E+06	9.50E+04	1.3E+04
Local magnitude	1.0	1.3	1.5	1.8	1.6	0.7	0.3
Maximum recorded	1.0	1.2	1.3	2.0	1.9	1.1	0

released per production.. Here the released seismic energy per month rates is based on average production rate for each time period. The average monthly seismic energy release (row 3) is used to estimate the maximum possible magnitudes which are listed in row 4. The last row lists the actual maximum magnitude events recorded during each time period. The correlation between the two magnitude values derived using different approaches is surprisingly good. This good correlation includes both the magnitude trends as well as their values in each time period. According to data listed in Table 7.1 all rock bursts took place in time period IV that is in the period for which the maximum theoretical and maximum recorded event magnitudes are of greatest values.

There is still one more value that can be used to validate the division of the caving process into seven time periods. This would be the 24-h distribution of seismicity. Again this value is based only on the times when the events took place and the location accuracy or the magnitude sizes are not influencing this distribution. Analysis of this type seismicity distributions based on three months data revealed that there are at least four different types. The differences are associated with the amounts of seismicity recorded during blasting times and later at the times of the shift changes. The relation of the induced seismicity due to blasting is well known. During blasts and directly after the blasting there will be an increase of recorded number of seismicity especially in the low magnitude range. This type of distribution is associated with time period I that is with the time when there was underground development mining taking place.

Blasting times at PMC:

1. Up to 4th January 2003 between 6.30 and 6.45 and then 22.30 and 22.45
2. From 4th January 2003 between 7.05 and 7.20 and then 19.05 and 19.20
3. From 14th January 2003 between 6.15 and 6.30 and then 22.15–22.30

Type A—Evident increase of activity during shift change (blasting times)
Type B—No prominent maximum or maxima in times of shift changes
Type C—Less of seismic activity in time of shift changes
Type D—No seismic activity during shift changes

Especially interesting are types C and D as they clearly indicate when the caving process started to end and when it really came to the end. Figure 7.3 illustrates type C of the 24-h seismicity distribution. During the shift changes there is less of recorded seismicity. This distribution indicates that there is not much of the caving process taking place when it is not stimulated by mining. This distribution is based on seismicity recorded between 01/07/2009 and 30/09/2009 that is during time period VI. Figure 7.4 illustrates the 24-h distribution of seismicity directly after the caving process reached its end. Data to present distribution type D was recorded between 01/01/2012 and 31/02/2012. The vertical scales of Figs. 7.4 and 7.5 are the same to allow for direct comparison between the two distributions. There is not only less of seismicity in the type D distribution (more than twice less) but during the times of shift changes the number of recorded seismicity is practically none.

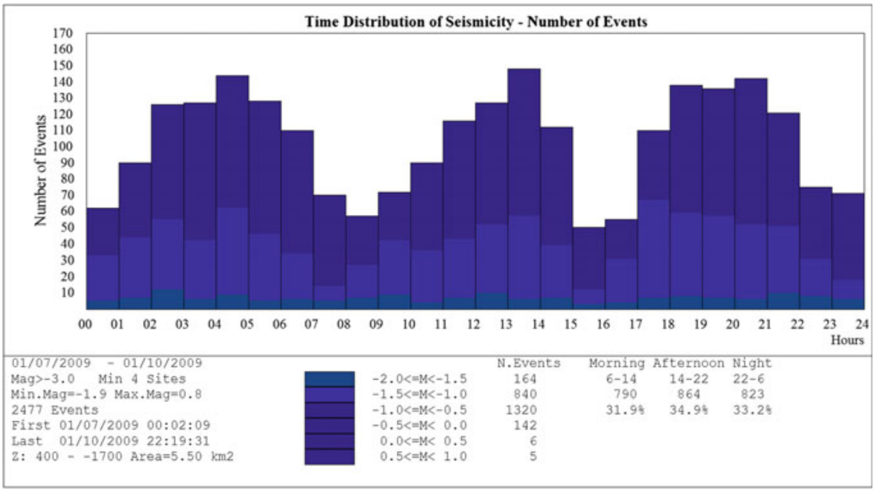

Fig. 7.4 24-h distribution of seismicity type C

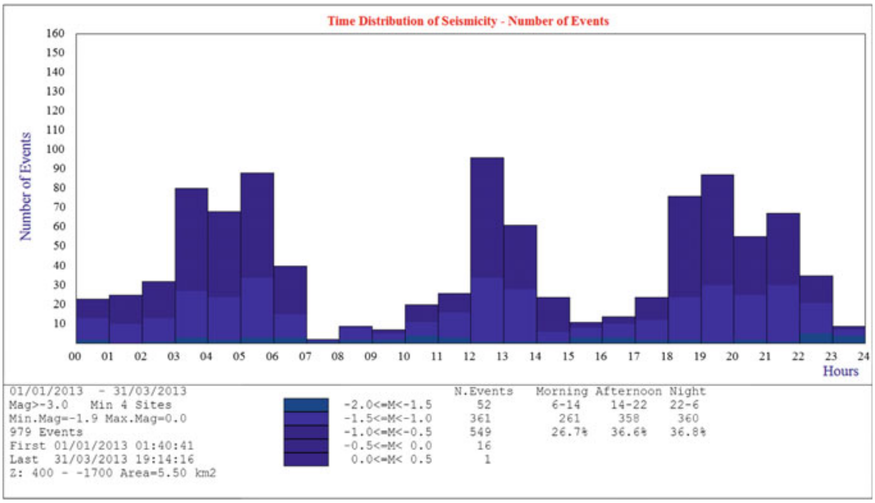

Fig. 7.5 24-h distribution of seismicity type D

Table 7.7 Time periods and the 24-h distribution of seismicity

Time period	I	II	III	IV	V	VI	VII
24-h distribution of seismicity	Type A	Type A	Type B	Type A	Type A	Type C	Type D

Table 7.8 Summary of investigated values

Value	Period I	Period II	Period III	Period IV	Period V	Period VI	Period VII
Occurrence of rock bursts				Rock bursts and FOG			
Occurrence of seismicity 1.5 and above				Mainly above the mine	Mainly below the mine		
Percentages of seismicity 0.0 and above (%)	2	2	5	36	52	3	0
Average rate of seismicity above 0.0 per month	12	14	33	104	65	2	0
Average monthly J/t	5	7.4	8.7	15.6	3.2	0.1	0.01
Average monthly Nm/t	2.7E+06	3.0E+06	1.5E+06	2.8E+06	2.2E+06	0.3E+06	0.1E+06
Type of 24-h seismicity distribution	A	A	B	A	A	C	D

This indicates that with the end of the caving process all of the recorded seismicity is induced only by the mining itself.

Table 7.7 Illustrates how with time the 24-h distributions of seismicity were taking place. Here it is worth remaining that even after the end of the development mining there still was some blasting taking place. This blasting could be associated with breaking up large hang-ups or with some changes to the underground structure.

Table 7.8 summarises the values of seismicity that were investigated up to this point. These all are uncomplicated parameters that are based on the number of recorded seismicity or its average monthly rates, or on combination of seismicity with mined out tones of ore. Important is the time distribution of the largest size seismicity and the underground damage due to seismicity. In total there were seven such parameters:

1. Occurrence of rock bursts
2. Time distribution of seismicity magnitude 1.5 and above
3. Percentage time distribution of seismicity magnitude 0.0 and above
4. Average monthly seismic activity rates of seismicity magnitude 0.0 and above
5. Average monthly seismic energy release per tone of mined out ore
6. Average monthly seismic moment rate per tone of mined out ore
7. The—24 h distributions of seismicity

At this stage it can be assumed that the caving process was divided in time periods that are indicative of what was really happening with the caving process. First conclusions are:

1. Seismicity rates associated with development mining are very low when compared with the stress caving process seismicity rates
2. The largest seismicity rates were associated with the time after the crown pillar failure up to the time of the initial break through
3. Larger size seismicity with the initiation of the caving process located mainly above the extraction level. After the initial break through they located mainly below the extraction level
4. The end of the caving process at the end of 2012 is a fact.

7.2 Caving Process Milestones

Having defined caving process time periods it is then practicable to analyse in more detail the differences between these times. It is reasonable to start with the three activities and investigate their changes over the whole caving process Figure 7.6 illustrates the time changes of the monthly seismic activity rates, the seismic energy release rates and of the seismic deformation rates. All these monthly activity rates were normalised by the average rate which is based on data recorded from the beginning of 2001 until end of 2013. This average is 100 %. This figure illustrates the fact that during different time periods the monthly rate was either lower or higher than the average rate. For example a monthly rate of 50 % indicates that it is half of the average while rate of 200 % indicates that it is twice the size of the average. Figure 7.6 illustrates the position of the seven time period as well the timing of the caving milestones:

1. Start of the gravity caving A
2. Initiation of the caving process B
3. Failure of the crown pillar C
4. Initial break through D
5. Cave going into mature stage E
6. East break through F
7. End of the caving process G

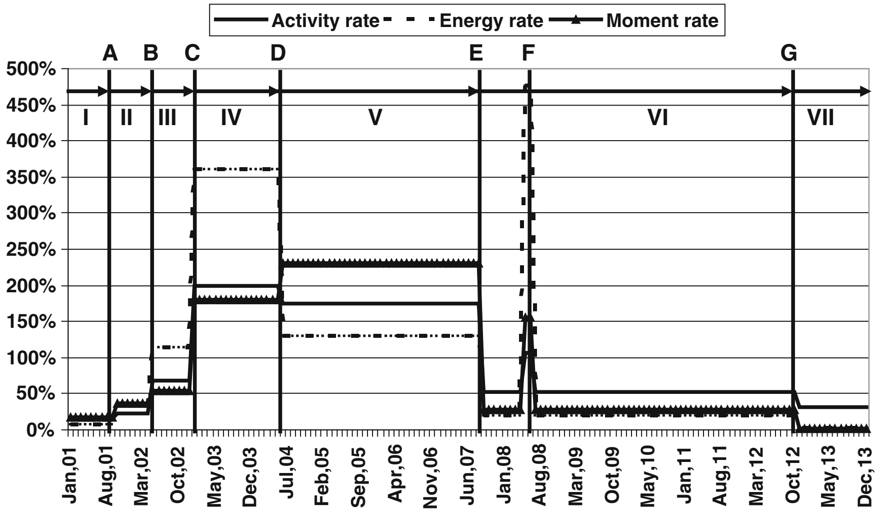

Fig. 7.6 Normalised seismic activity rates

Figure 7.6 clearly indicates that the caving milestones are characterized not only by different size rates but also by distinctive changes in their sizes. In character these changes are similar for the three rates. In size the largest changes are associated with the seismic energy release rates. During the time period (I) when only development mining was taking place the energy release rates were very low at less than 25 %. The initiation of the caving process (A) resulted in increased seismic energy release rates up to nearly 50 %. After the stress caving process initiation (B) all three rates increased but only the energy release rate increased to above the mean of 100 % (period III). The crown pillar failure (C) resulted in a further significant energy rate increase up to over 350 %. The other two rates also increased but only to about 200 %. It is worth noting that during time period (IV) during which there was only production from the cave the activity and moment rates were nearly four times higher than during the time period (I) when there was only development mining taking place. The energy release rates during time period IV were over six times higher from these during time period I. After the initial break through the energy release rates decreased to the level of 125 % (time period V). For this time period the seismic deformation rates increased while the seismic activity rates decreased but very slightly. The seismic deformation rate increase in time period V in relation the time period IV is interesting and will be further investigated. At the time when the caving process reached its mature stage (E) all three rates decreased to values below their means. During the east break through (F) there is a slight increase in activity and seismic moment rates. The seismic energy release rates increase to over four times their mean value. This is a clear indication that the east cave break through was associated with less seismicity and more of seismic energy release. This is not totally correct as the east break through took place at a location where the seismic network sensitivity was low and it could record only events magnitude above 0.0. The end of the caving process (G) starts when there is only some seismic activity taking place but the energy release and seismic moment rates are close to none.

As the seismic activity rates above and below the extraction level have different time histories it is then essential to investigate them in more details. Figure 7.7 illustrates the changes of the three rates in the rock mass volume above the extraction level. Again their changes with the caving process milestones are very similar to each other with the energy release rates displaying the largest changes. What more the whole pattern of the rate changes above the mine is very alike to that for the whole mine. Figure 7.8 illustrates the changes of the three rates in the rock mass volume below the extraction level. The most obvious difference is in time period V that is after the initial break through (D). In the two previous cases the highest rates were recorded just after the pillar failure (C) during time period IV. Below the extraction level during this period only the energy rates reach their maximum while the three rates together are then exceptionally high during time period V that is only after the initial break through (D). This difference in distribution of seismicity rates above and below the extraction level because of its major size was very crucial not only in understanding the caving process but also in recognising in time the changing nature of the seismic hazard. As the seismic hazard is directly associated with the seismic energy release rates then it becomes prudent to compare their two histories above and below the extraction level with each other.

Figure 7.9 illustrates the normalized seismic energy release rates above the extraction level and below the extraction level. This figure illustrates the fact that

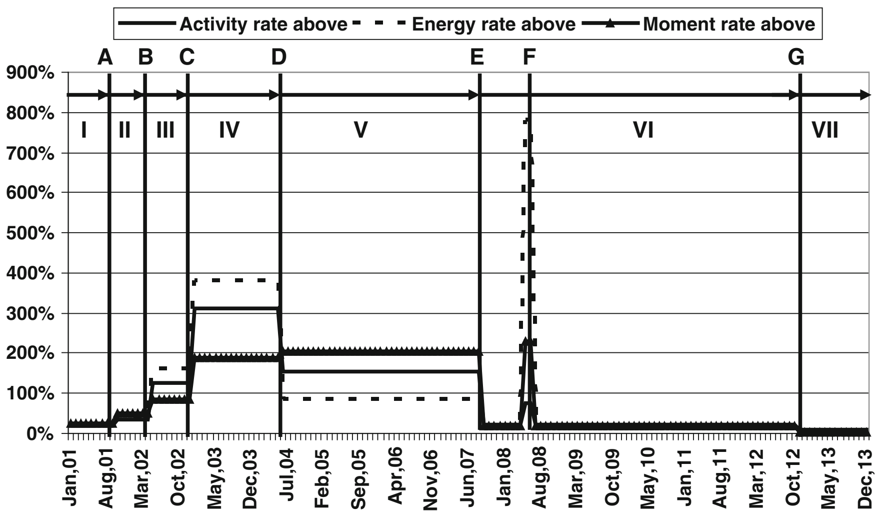

Fig. 7.7 Normalised seismic activity rates above the mine

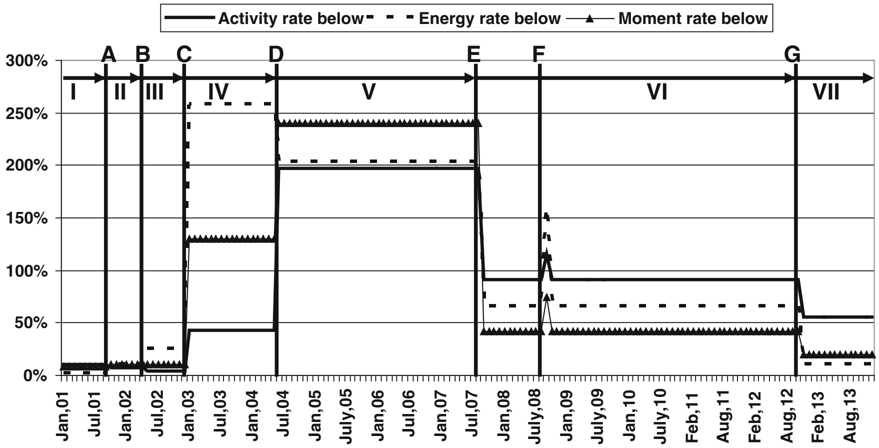

Fig. 7.8 Normalised activity rates below the mine

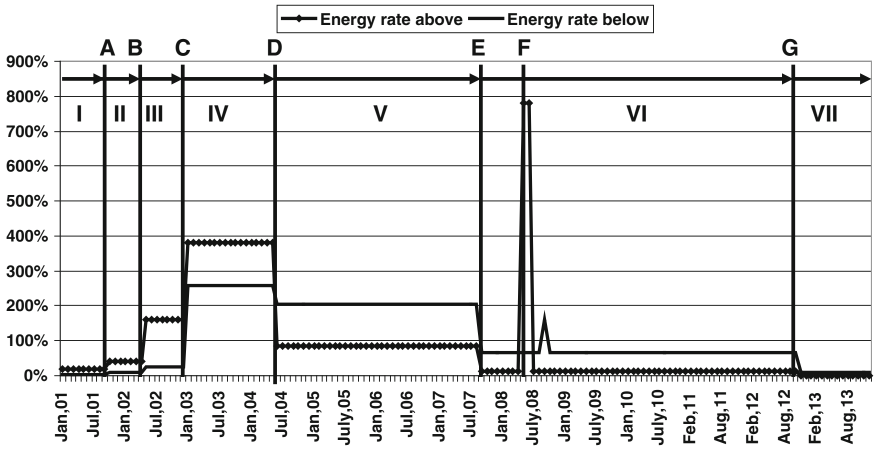

Fig. 7.9 Normalised energy release rates above and below the mine

the seismic energy release rates were changing differently above and below the mine. The initiation of the stress caving process (B) resulted in increased seismic energy release rates (up to 150 %) but only above the mine. The energy release rates below the mine increased only after the crown pillar failure (C) and this increase was then more than two times From the time the crown pillar failed until the initial break through the seismic energy release rates above the extraction level were higher than those below the extraction level. The initial break through (D) resulted in a decrease in the rates above and below the mine. The energy release rates above decreased to their mean value while these below the extraction level decreased only slightly from 250 % down to 200 %. Before the east break through took place both rates decrease significantly but the east break through resulted in increase in the energy release rates. First was a moderate increase above the mine. Only after the east break through was completed there was a substantial increase in the energy release rates below the mine. It is worth noting that this pattern of increased seismic energy release below the mine after this second break through is similar to the one experienced earlier after the initial break through.

From the presented data it emerges that with the caving process the highest seismic risk is associated with:

1. Initiation of the caving process
2. Break through

If the pillar failure and the break through are not taking place immediately then the high seismic risk is also associated with the time period after the pillar failure up to the time the break through is completed. As seismic data (together with other geotechnical measurements) can be used to monitor the cave progress then the timing of the increased seismic risk should also be known. Presented data indicates that the magnitude size values can be a misleading indicator of the actual seismic risk. As the seismic risk is directly associated with the stress levels then its estimations should result in more accurate seismic risk approximation.

Figure 7.10 illustrate the energy index time history which indicates the stress regime in the rock mass in this case around the mine and cave. During period I it increased to nearly 1.6 indicating that the stress around the mine increased due to the development mining. From the onset of the caving process the increase rate decreased. This decrease is probably there because to start with the cave volume

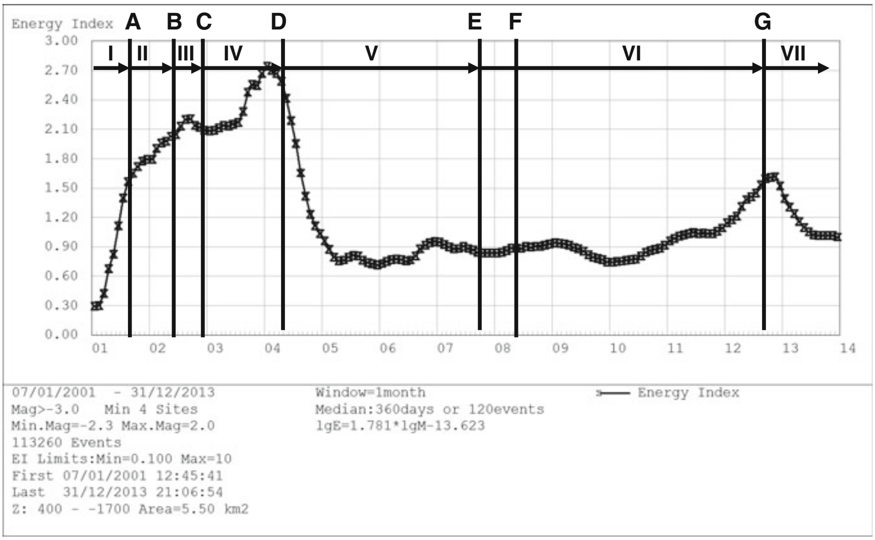

Fig. 7.10 Energy index time history and the caving time periods

was low but still it was inducing more seismicity that development and open pit mining together. The initiation of the caving process (B) is associated with ever increasing energy index values. At this stage this increase is directly proportional to the production rates. This is illustrated by Fig. 7.11. The steeper energy index curve from about April 2003 is directly connected to the increased production tonnages that took place at exactly the same time. The energy index values (Fig. 7.10) stayed in their highest values until the initial break through (D) that is during the whole time period IV. After the initial break through the energy index values started to decrease firstly very speedy and then stabilised just below the mean value of 1.0 for a long time period.

It was already noted that there is a distinction between the seismicity locating above and below the mine. In order to quantify this separation it is convenient to compare the percentages of seismicity above with those below rather that comparing the recorded rates. This way of presenting data allows getting round all problems associated with the seismic network development phases and down time periods. Figure 7.12 shows the percentages of seismicity recorded above the mine level from January 2001 until the end of 2013. 100 % of the seismicity is the total amount of seismicity recorded every month above and below the mine level in the elevation range from +400 m down to −1700 m. Initially, during 2001, the amounts of seismicity recorded above the mine were as high as 70 %. With the initiation of the caving process (B) in April 2002, over 90 % of seismicity was recorded above the mine level. These high levels of seismicity above the mine level continued until the cave broke into the open pit in May 2004 (D). After the initial break-through there was a slow but continuous decrease in the amounts of seismicity recorded above the mine level that lasted until end of 2007 (E). From that time only about 30 % or less of all recorded seismicity plotted above the mine level.

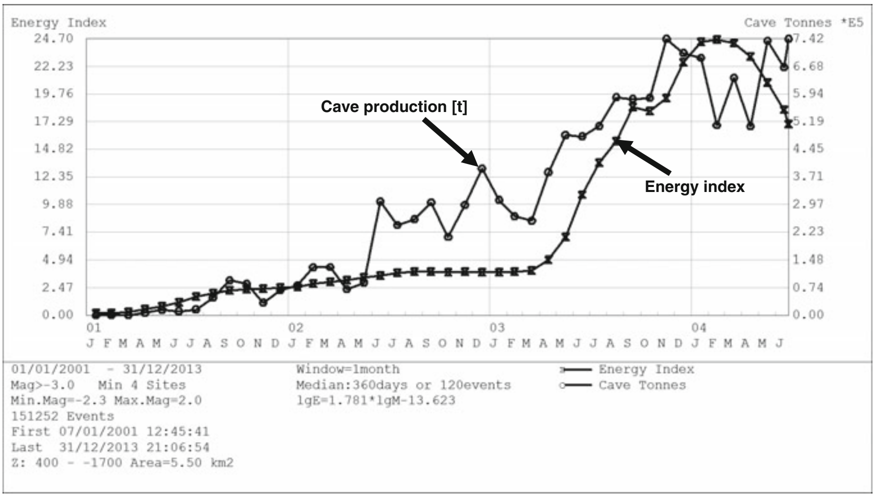

Fig. 7.11 Energy index time history and production rates

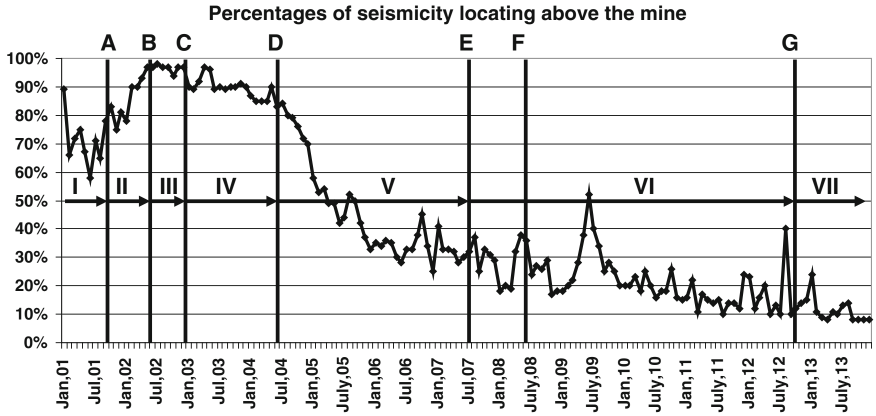

Fig. 7.12 Monthly percentages of seismicity locating above the mine

The other approach to analyse the seismicity distribution in time is to investigate how it is located in relation to the mine that is how close it is to the underground excavations. What would be expected from such distribution to be correct is a lot of seismicity during the development time locating close to the mine. With the cave expansion there should be less and less of seismicity locating close to the mine. It would be expected that with the cave expansion the seismicity would migrate away from the mine. Then this migration should stop and a reverse of seismicity migration direction would be expected. With the end of the caving process there should be more of seismicity locating closer to the mine. Figure 7.13 is illustrating such distribution. Here close to the mine means 100 m above and 100 m below the mine. For even more accurate results the horizontal distances could be also defined. At this stage it is not as important as the main interest is the trend. The presented trend is exactly as that which was expected. This means that one can be confident that the recorded data is not only of high quality but it is reflecting the caving process in a very accurate manner. Such observations are very important during the interpretation process. They not only increase the confidence in the input data but also the final results. They also keep the interpretation process in brackets of reality not allowing it to wonder into the word of fiction. Figure 7.13 illustrates that during time Periods I and VII nearly 80 % of recorded seismicity located at close distances from the mine. With the initiation of the caving seismicity started to migrate away from the mine. During the time period III that is after the stress caving process initiation (B) until the initial break through (C) 80 % of recorded seismicity was locating way from the mine. The initial break through started the slow process of more and more of seismicity locating closer to the mine. This would be the seismicity locating below and around the mine. By the time the cave reached its mature stage (E) 50 % of seismicity was already locating close to the mine. With the end of the caving process 80 % of recorded seismicity started to locate close to the mine. This seismicity is also locating below the extraction level.

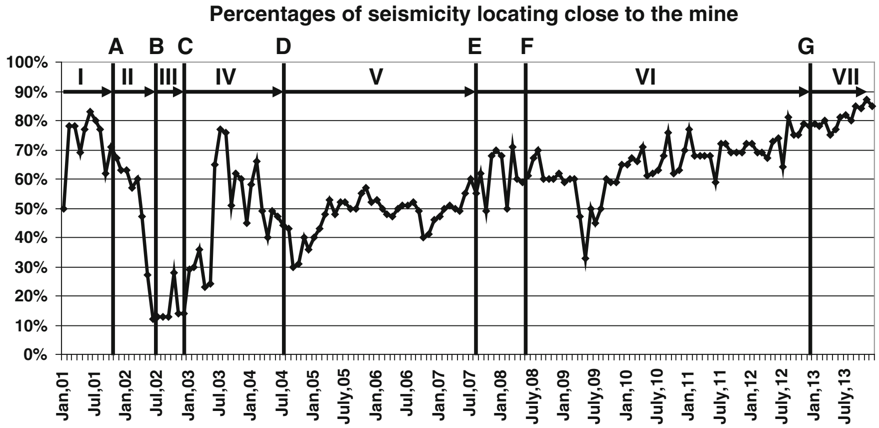

Fig. 7.13 Monthly percentages of seismicity locating close to the mine

Table 7.9 summarises the eight values that were analysed to date. These are:

1. Percentages of events based on their total mean in the seven time periods
2. Percentages of energy released based on their total mean in the seven time periods
3. Percentages of seismic deformation based on their total mean in the seven time periods
4. Percentages of seismic energy released above the mine based on their total mean
5. Percentages of seismic energy released below the mine based on their total mean
6. Energy index time history and it trends during the seven time periods
7. Percentages and trends of seismicity recorded above the mine in the seven time periods
8. Percentages and trends of seismicity locating close to the mine in the seven time periods

Figure 7.14 illustrates the time history of the seismically active volume which includes about 95 % of seismicity recorded in each quarter of the year starting in January 2001 until end of 2013. During periods I, II and III the seismically active volume was small and of the same size of 0.2 km^3. During these three time periods the seismicity located only above the mine footprint. Only after the crown pillar failure (C) the seismically active volume started to increase with more and more seismicity locating outside of the mine footprint. This increase continued after the initial break through (D) was completed. The maximum seismically active volume was reached by the end of 2005 during time period V. From then on the seismically active volume started to decrease and by the end of the caving process (G) reached the value of 0.2 km^3. At this stage practically all seismicity started to locate under the mine footprint. Figure 7.15 illustrates the changes of the maximum seismicity depths from the beginning of 2001 until March 2013. These maximum seismicity

Table 7.9 Summary of analysed parameters

Values of	Period I	Period II	Period III	Period IV	Period V	Period VI	Period VII
Percentages of events based on total average (%)	15	22	69	200	175	52	32
Percentages of energy based on total average (%)	7	33	113	360	130	20	1
Percentages of moment based on total averages (%)	17	37	55	180	230	28	1
Percentages of seismic energy above the mine (%)	10	20	150	400	100	10	0
Percentages of seismic energy below the mine (%)	0	0	20	250	200	80	0
Energy index time history and trend	Increasing from 0.3 to 1.7	Increasing from 1.7 to 1.9	Stable at 1.9/2.0	2.0/2.6 Maximum	Decreasing from 2.5 to 0.8	Increasing from 0.8 to 1.7	At 1.1
Percentages of seismicity recorded above the mine and trend	70 %	Increasing to 80 %	Maximum at 90–95 %	Maximum at 90–95 %	Decreasing to 30 %	Decreasing to 15 %	10 %
Percentages of seismicity recorded close to the mine and trend	80 %	Decreasing to 30 %	Minimum at 20 %	Increasing to 40 %	Increasing to 60 %	Increasing to 80 %	80 %

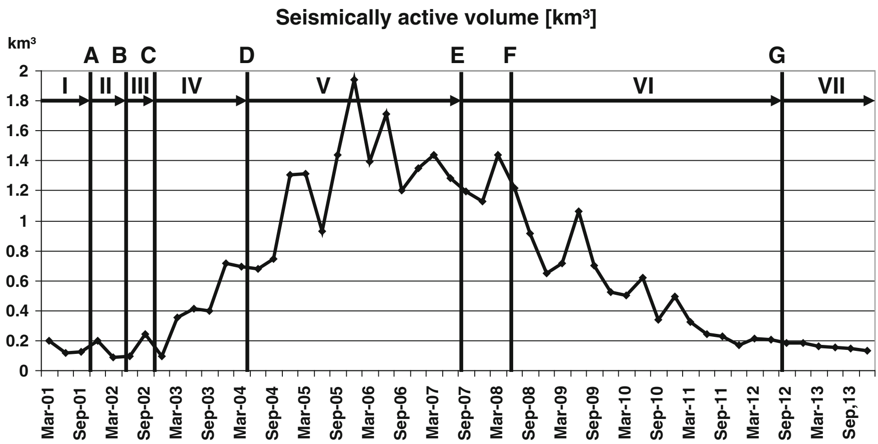

Fig. 7.14 Seismically active volumes

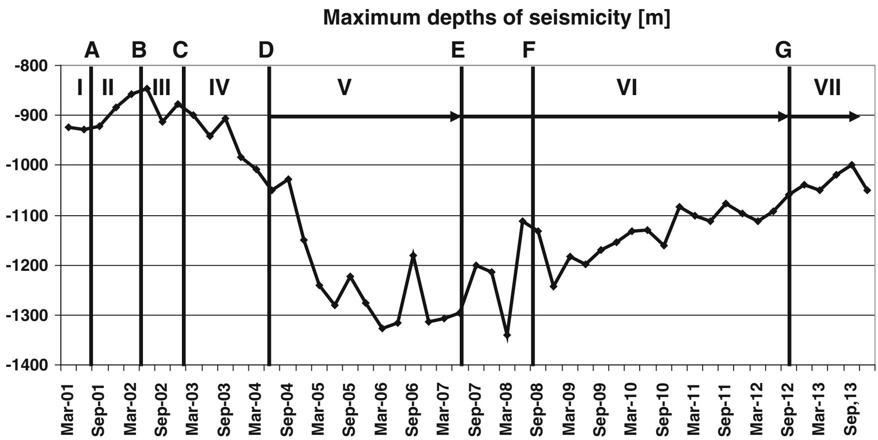

Fig. 7.15 Maximum depths of seismicity

depths were used to estimate the seismically active volumes. The maximum depths are still associated with 95 % of seismicity so there is still some seismicity below these depths. The downward trend in the seismicity depth started only after the crown pillar failure at the end of 2002 and it continued until the end of 2006 when the depth reached about −1300 m (about 500 m below the extraction level). With the caving process reaching its mature stage (E) the seismicity started to migrate up. At the end of the caving process the maximum seismicity depths are at about −1000 m.

Figure 7.16 illustrates the time history of the average monthly seismicity elevations from the beginning of 2001 until the end of December 2013. Once the stress

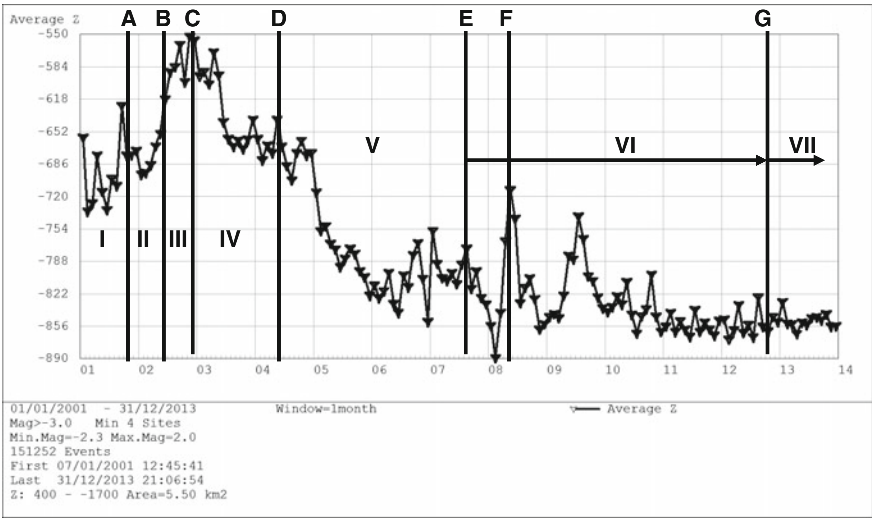

Fig. 7.16 Average monthly elevations of seismicity

caving process was initiated (B) the seismicity started to migrate upward and reached the minimum elevation at the time when the crown pillar failed (C) at the end of 2002. From that time seismicity migrated downward (and out of the mine) first slowly until the initial break through was completed. Then the downward migration becomes faster until it reaches its minimum elevation during 2006. The east break through (F) is indicated by some shallower seismicity. From then on the elevations of the monthly average seismicity become steady.

Table 7.10 lists and summarises the values and trends of the following parameters during the seven time periods:

Seismically active volume km^3
Maximum depth of seismicity
Average monthly elevations of seismicity

There are still a number of parameters that are worth analysing or comparing with each other. Up to this moment there was an analysis of seismic energy and seismic moment but as separate values. Investigation of those two values together reveals some very interesting facts about the nature of the caving process This is illustrated by Fig. 7.17. The seismic energy emission graph is the dash line and the right vertical axis represents the energy rates. The seismic moment is represented by the continuous line with the values at the left side vertical axis. During the time periods I and II the amounts of emitted seismic energy and seismic moment rates are both very low. After the initiation of the caving process (B) during time period III both the energy and moment rates increased only slightly. After the crown pillar failure (C) the energy release and seismic moment rates increase considerably. This is connected directly with the production rates that increased as from March 2003.

Table 7.10 Summary of analysed parameters

Values of	Period I	Period II	Period III	Period IV	Period V	Period VI	Period VII
Seismically active volume (km^3)	0.1	0.2	0.3	Increase from 0.3 up to 0.7	Increase from 0.7 up to maximum of 2.0 then decrease to 1.2	Decrease from 1.2 to 0.2	0.2
Maximum depth of seismicity (m)	−950 m	−850 m	−900 m	Downward from −900 m to −1000 m	Downward from −1000 m to −1300 m deepest	Upward to −1050 m	−1550 m
Average monthly seismicity elevations and trend	−700 m	−680 m	Upward migration to −550 m shallowest	Migration to –650 m	Migration to −800 m	Migration to −840 m	−840 m

The maximum energy release rates are associated with the initial break through (D). After this break through the seismic energy release rates generally decrease. While the seismic energy release rates during time period V were low the seismic moment rates while decreasing gradually were still at high values. This indicates that seismic deformation was continuing with no large size seismic energy emissions. During the east break through there is more both of seismic energy emitted and of seismic deformation rates. During the time when there caving process reached its mature stage there seismic energy release rates were very low but there was still some seismic deformation taking place.

Production stoppages as it was already explained provide very useful information about the expansion void. From the beginning of 2002 until the end of 2013 there were several production stoppages that lasted for a few days each. In each case

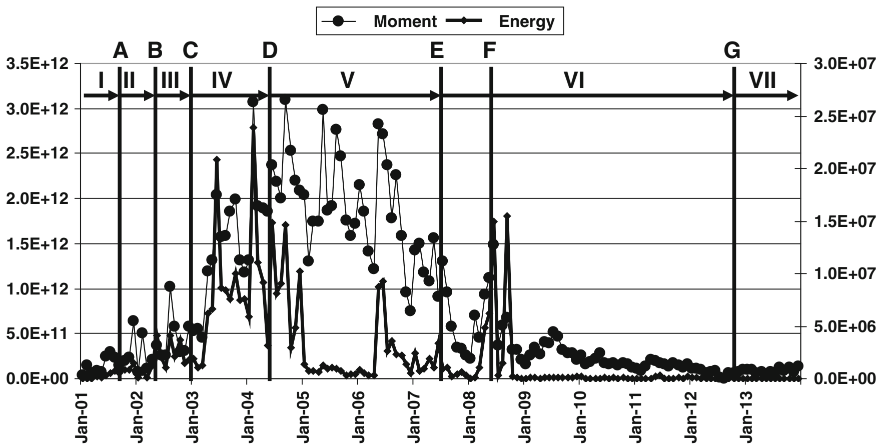

Fig. 7.17 Monthly seismic energy release and moment rates

the daily seismic activity rates for the whole mine decreased when production from the cave stopped, even for just a couple of days. If the production draw rate was always kept lower than the natural cave progression rate, there should be a minimal, or no expansion void. The rapid response of the seismicity to changes in the production rate suggests that the mine was always pulling at a rate lower than the natural cave expansion rate. Thus this seismic data tends to support the earlier estimation of the natural cave progression rate. Before the initial break through there were five production stoppages and in each case the seismicity has decreased practically on the first non production day already. From this it was concluded that there was no expansion void above the maximum elevation of the cave. The second influence on the seismicity is directly connected with the subsequent resumption of production after a couple of days. After the period of non-production the resumption of production in some cases resulted in larger size seismic energy releases that were associated with restarting the caving process Based on this seismicity characteristic it seems possible to divide the seismicity associated with the production stoppages into four types depending on:

- Response to production stoppage
- Seismicity during the stoppage time
- Response to the production restarting
- Energy release associated with restarting the caving process

There are following four types of seismic response to production stoppage and restarting

A. Gradual decrease of seismicity rates after production stoppage some low seismicity rates during the stoppage and then gradual increase of seismicity after restarting production followed by large size seismic energy release after a couple of days
B. Gradual decrease of seismicity rates after production stoppage, some low seismicity rates during the stoppage and then gradual increase of seismicity after restarting production followed by small size seismic energy release after a couple of days
C. Gradual decrease of seismicity rates after production stoppage, some low seismicity rates during the stoppage and then gradual increase of seismicity after restarting production with no seismic energy release after a couple of days
D. Immediate decrease of seismicity after production stoppage, no seismicity during the stoppage and then immediate increase of seismicity after restarting production, no seismic energy release after a couple of days

Table 7.11 indicates that there is a relation between the seven time periods of the caving process and the seismic response to the production stoppage and restarting of the production. The most violent responses to production restarting as far as seismic energy releases are concerned were during time periods III and IV. These two time periods cover the time from the stress caving process initiation (B) up to the initial break through (D). Type B that still had some seismic energy released after production restarting is associated with time period V and early stages of time

Table 7.11 Seismic response type to production stoppages

No	Stoppage date	Stoppage days	Stoppage type	Time period	Notes
1	October 2002	8	A	III	
2	October 2003	5	A	IV	
3	February 2004	5	A	IV	
4	April 2004	8	A	IV	
5	April 2006	9	B	V	
7	January 2008	5	B	VI	
8	January 2012	4	C	VI	
9	March 2012	3	C	VI	
10	June/July 2012	60	C/D	VI	Very low seismic activity during the stoppage
11	October 2012	6	D	VI	
13	March 2013	9	D	VII	
14	May 2013	9	D	VII	

period VI. This types of seismic response indicated that the production stoppage resulted in stopping the caving process and production restarting resulted in restarting the caving process. Types C and D are indicative of very limited caving process or its end. Especially type D with no seismicity what so ever during the whole production stoppage indicates that the caving process has already ended.

Figure 7.18 illustrates the relation between the energy index time history and the production stoppages This relation up to the January 2008 stoppage indicates that there is a direct relation between the stress and the seismic response to the production restarting This relation doest hold for the six stoppages taking place from January 2012. The energy index as such seems to indicate a stress increase during 2012 but the seismic response seems to be different as it was in the past. One reason is that these production stoppages took place while the caving process was at its end phase. The second reason must be in the nature of the 2012 seismic energy index increase. This will be examined in detail at the end of this paragraph.

Figure 7.19 illustrates the time history of the ratio between the energy released by the S-wave and the P-wave This time history is presented by the monthly percentages of seismicity with this parameter above 10.0. This value when above 10 indicates that the main seismic source mechanism is shearing. Figure 7.19 indicates that the caving process is about shearing. During the last months of 2002 the pillar between the cave and the open pit become de-stressed. This fact resulted in large stress changes, which influenced not only the rock mass joints, but also all the geological features. The increase in the vertical stress component resulted in loosening and allowing for much more shear movement to take place. This is exactly what the seismic data is indicating. The recorded seismic events during 2003 showed big increase in the shearing component on top of a significant increase in released energy per moment. The other very visible change was a nearly

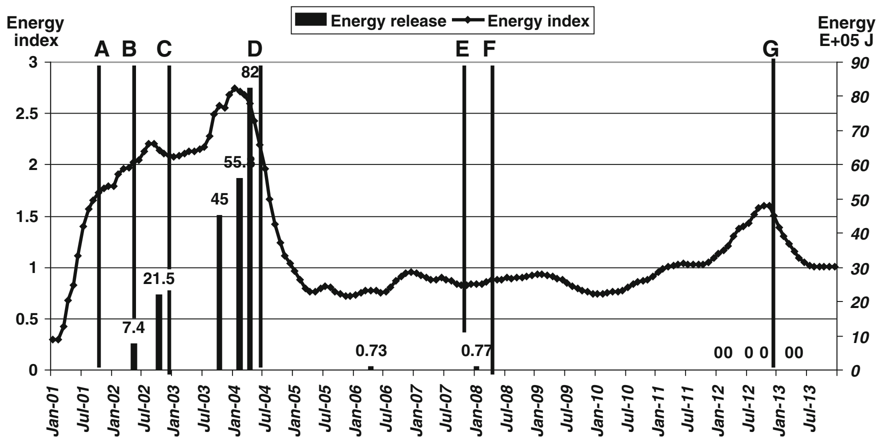

Fig. 7.18 Production stoppages and the energy index time history

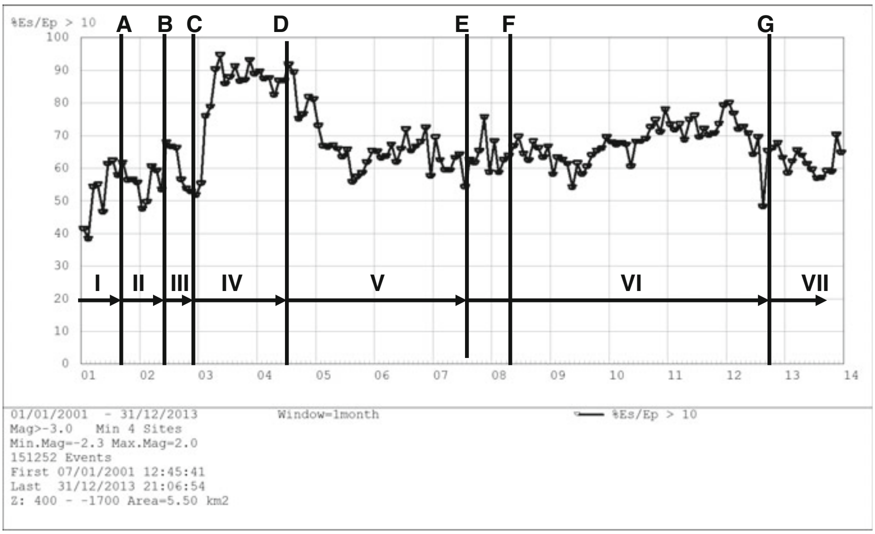

Fig. 7.19 Monthly percentages of Es/Ep ratio above 10

four-fold increase in seismic activity when taking into account magnitude size 0.0 and above. Figure 7.19 illustrates that during time period IV the percentages of seismicity with Es/Ep ratio were above 90 % of the total seismicity recorded. After the initial break through this percentage decreased but was then continually at a level of 60 %.

There is one more value that should be taken into account. The PPV (Peak Particle Velocity) analysis is based on the largest seismic events recorded from the beginning of 2002 to the end of 2007. This analysis indicates that there is a correlation between the observed PPV values and the caving process itself. This short PPV analysis also indicates that the higher PPV values were recorded only up until the time when the cave broke into the open pit. The recorded PPV values correlate not only with the stress changes around the cave as indicated by the energy index time history, but also with the caving stages From the beginning of 2002 to the end of 2007 there were 123 events of magnitude 1.0 and above. Most of these events took place during 2003 and 2004. All 17 events off magnitude size above 1.5 took place during 2003 and 2004.The largest event in the investigated catalogue, event of magnitude 2.0, was recorded in February 2004.This size seismicity stopped taking place by the end of February 2005 and then reappeared in May 2006. Nearly 80 % of all seismic deformation and seismic energy release had taken place by the end of February 2005. It is also interesting to note that these large events released about 11 % of the total seismic energy and contributed to about 50 % of total seismic moment during the six-year period between 2002 and 2007. More than four seismic stations recorded each of the 123 large events. The analysis of the PPV trends as presented below is based on 1058 observations. Figure 7.20 shows all 1058 recorded PPV values versus distances over which they were recorded. Most of the recorded PPV values fit between a maximum of 1.0E-02 m/s and a minimum of 1.0E-05 m/s. There are about 100 PPV values that are larger than 1.0E-01 m/s. Some of these larger PPV values are most likely not probable but at present their verification is impossible as this would require inspection of seismograms recorded a couple of years ago. On the other hand there are only 21 of non probable values in the whole data set of 1058 values. These non probable values amount to about 2 % of the whole data set, so they will not influence the trend analysis. PPV values presented by this figure were recorded at distances between 50 m and a maximum distance of 2300 m. Nearly 90 % of all PPV values were for distances between 100 and 1500 m. Figure 7.21 present the PPV values in sequential order as they were recorded. Here the highest PPV values (as displayed

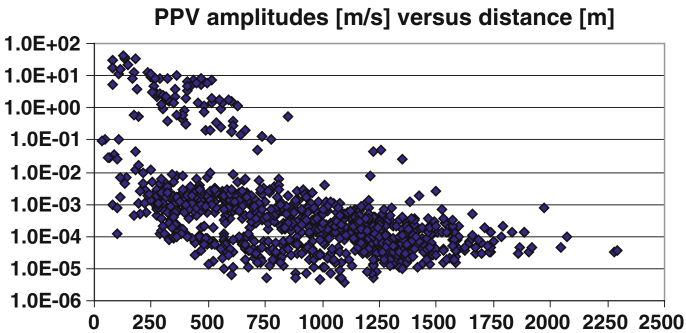

Fig. 7.20 PPV amplitudes versus distance

by Fig. 7.21) take up the positions at the left side of the graph from point 1 up to point 421 on the X-axis. There are a large number of the highest PPV values up to point 100 and then up to point 421 the high PPV values are accompanied by much lower PPV values. From point 422 to the end of the x-axis there are only 3 PPV values of outstanding size. From point 800 to the end of the graph the PPV values on average are lower than they have been up to this point. Each X-axis point can be converted to a date: point 100 relates to end of March 2003, point 421 relates to end of February 2004 while point 800 relates to January 2005. Figure 3.21 illustrates these dates. The first conclusion that can be derived from this display of data is that with time there are less and less of the higher PPV values. The rationale for such a distribution of higher PPV values is easy to trace. To start with the rock mass around the cave was solid and there were only a limited amount of fractures and cracks. Solid rock is a medium that allows transmission of larger amounts of energy with larger PPV values. The more is the rock fractured the more it attenuates the seismic energy and in this process decreases the PPV amplitudes. This is clearly illustrated by the PPV trends. Before March 2003 the PPV values were generally high. From March 2003 to the end of February 2004 the PPV values were composed of higher and lower values. After February 2004 the PPV values were only low and then after January 2005 they were still lower. The caving process was initiated about April 2002 and from then on this process resulted in a continuous increasing in the number and volume of fractures around the expanding cave. As a result the PPV values had to decrease over time. The date's changes in PPV value as presented by Fig. 7.21 correlate with the previously documented stages of the caving process using other seismic data. From March 2003 there was a substantial increase in production rates. This resulted in an increase in stresses around the cave, an increase in number of large events and associated with them, increased amounts of seismic deformation and released seismic energy. This was also the period when

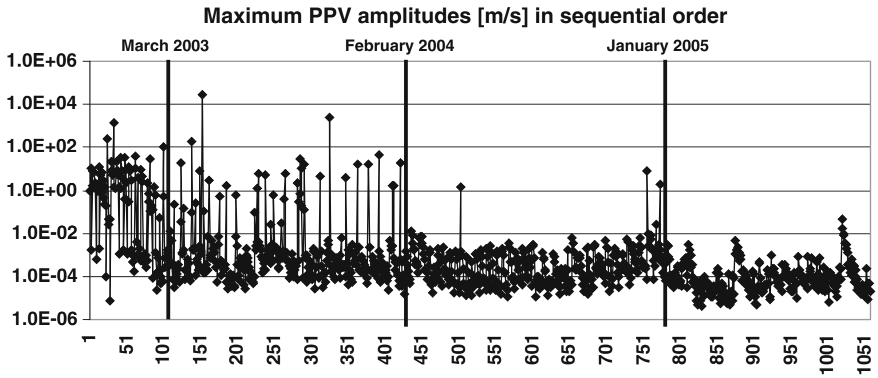

Fig. 7.21 PPV amplitudes in sequential order

the higher PPV values were recorded. The high stress around the cave lasted until the beginning of 2004 when the cave broke into the open pit. During this time the large size events were frequent and also the large size energy releases and seismic deformation rates. During this time period the high PPV values were frequent but there were also lower values appearing. After the cave broke into the open pit the stresses around the cave started to decrease very rapidly and the occurrence of larger size events came to an end. The cave physically broke through in May 2004 but this must have been a complex process taking some time. The stresses started to decrease rapidly from about February 2004 and at the same time the higher PPV values no longer appear. The PPV values remained more or less at the same lower values until beginning of 2005. This is the time period when the stresses around the cave were continuously decreasing. At the beginning of 2005 the stress reached the mean value as the energy index dropped below the value of 1.0. At the same time the recorded PPV values indicated a general decrease.

Table 7.12 lists and summarises the values and trends of the following parameters during the seven time periods:

- Seismic energy release and seismic moment rates
- Types of seismic response to the production stoppage and restart
- Production and seismic activity rates (this was not discussed)
- PPV values and the caving process

Table 7.13 provides summary of some of the observed seismicity differences in the seven time periods. This time periods indicate the point in time of the seven caving process milestones occurrence. All of them apart of the east break through (F) start or end a certain time period. The east break through took place already after the caving process reached its mature stage that is it come about during time period VI. As there are two breaks through and they took place in different stages of the caving process it will be interesting to compare them for similarities and differences. This will be done after describing the other caving steps. Table 7.13 presents general parameter trends in relation to the caving process stages and time periods

A. Start of gravitycaving —October 2001
B. Start of stress caving process April 2002
C. Failure of the crown pillar in December 2003
D. Initial Break through May 2004
E. Cave reaching the mature stage at the end of 2007
F. East break through May, June 2008
G. End of the caving process end of 2012

Table 7.12 Summary of analysed parameters (3)

Values of	Period I	Period II	Period III	Period IV	Period V	Period VI	Period VII
Seismic energy	Low	Increasing	Increasing	Maximum	Decreasing	Low	Low
Seismic moment	Low	Increasing	Increasing	Increasing	Maximum	Decreasing	Low
Seismic response to production stoppages			A	A	B	C	D
% of seismicity with Es/Ep > 10.0	Below 60 %			95 %	60/70 %	70 %	60 %
Relation between production and seismicity rate	Direct proportional				No relation		Direct proportional
PPV values			Highest	High and low	Low		

Table 7.13 Summary of the observed seismicity differences in the time periods

Stages	A	B	C	D	E	F	G
Time period	**Period I**	**Period II**	**Period III**	**Period IV**	**Period V**	**Period VI**	**Period VII**
Energy index time history	↗	↗	→	→ **maximum**	↘	↘	→
Seismically active volume	→	→	→	↗	↗ **maximum**	↘	→
Maximum depth of seismicity trend	→	→	↘	↘	↘ **Deepest seismicity**	↗	↗
Percentage seismicity recorded above the mine	70%	↗	**Maximum at 95%**		↘	↘	10%
Percentage seismicity recorded close to the mine	80%	↘	**Minimum at 20%**	↗	↗	↗	80%
Average monthly rate of seismicity magnitude 0.0 and above	12	↗	↗	**Maximum at 104**	↘	↘	0
Average monthly J/t	5	↗	↗	**Maximum 15.6**	↘	↘	0.01
Occurrence of rock bursts				**Rock bursts**			
Occurrence seismicity 1.5 and above				**Mainly above the mine**	**Mainly below the mine**		
PPV values			Highest	High & low	low		
Percentage seismicity with Es/Ep> 10.0				**Maximum up to 95%**			

7.3 Palabora Seismic Response to the Caving Process

Analysed seismicity can now be used to describe the PMC seismic response of the caving process. To start with the recorded seismicity was not induced by the caving process. PMC went into production mode when the development mining was still taking place and there still was some mining taking place in the open pit. For this reason the recorded seismicity was induced by all these mining activities. It might not always be possible to separate them completely and then analyse separately.

A. Gravity caving—October 2001

The start of the gravity caving resulted in a steady increase of seismicity locating at the caving elevation. With the mining taking place in the pit there were some seismicity elevation decreases which become evident when observing the average seismicity elevation trend. This downward seismicity migration was not real. It was the result of two separate processes. Firstly present was shallower mining process which induces a constant number of seismicity. The gravity caving over time did induce an ever increasing number of seismic events. As a result the average monthly seismicity elevation over time was continuously more and more influenced by the deeper induced seismicity. In this case the resulting monthly average seismicity elevation changes illustrated the fact that over time the gravity caving process was the main mechanism of induced seismicity. During the gravity caving the energy index time history graph remained low at the same level. The seismic energy release rates as well as the seismic moment rates increased slightly in comparison to the time before the initiation of the gravity caving process.

B. Initiation of the stress caving process—April 2002

Once the hydraulic diameter reached the size of 45 m the stress caving process was initiated. This was very strongly reflected by the induced seismicity. It seems that the initiation of the stress caving process is a very powerful physical phenomenon which is recorded by the seismic system very precisely. The initiation of the caving process took place inside of the seismic network that is it was surrounded by seismic stations. Additionally the seismic velocity values as evaluated from the calibration blasts were still close to the real values. Because of this the seismic locations and especially the elevations of seismicity were relatively accurate. The initiation of the stress caving process resulted in several changes to the recorded seismicity. First of all there was a considerable increase in the seismic activity rates This increase was mainly in the lower range of magnitude sizes. At the time of the caving process initiation there still was development mining taking place. The cave induced seismicity could be separated without difficulty. The development mining induced seismicity exhibited a very distinctive pattern as it was strongly related to the blasting times. The cave mining induced seismicity did not show this pattern. Additionally at this stage the caving induced seismicity was strongly related to the production rates. The other change in the seismicity was its continuous upwards migration. This migration was measured by the average monthly seismicity elevation changes. This upward migration as indicated by the recorded seismicity was genuine and not false as in the case of the gravity caving process. With the initiation of the caving process the energy index time history indicated an upwards trend. This increasing trend was indicating that the stresses around the cave were increasing. At the same time the percentages of seismicity with ratio of S-wave energy to the P-wave energy above 10.0 increased indicating that the cave progress was due to the rock mass fracturing (shearing). Seismicity recorded at this time, due to its location accuracy, allowed monitoring the cave progress and evaluating the thickness of the a-seismic zone. The caving process monitoring was based on the location of the seismic zone. The evaluation of the a-seismic zone thickness was then based on difference between the position of the seismic zone and the estimated cave back position The estimate of the cave back position were based on the production rates and then confirmed by other measurements (open holes and TDR's). With time the increased stresses around the cave started to influence the residual stresses of the geological discontinuities. This resulted in increased number of larger size seismic energy releases. To start with these larger energy releases took place close to the underground excavations. For this reason the process of stress caving initiation was associated with increased seismic risk Over time with the cave growth the larger size energy releases started to take place at larger distances from the extraction level. At this stage of the caving process most if not all of the recorded seismicity took place above the elevation of the mine. With time the seismic risk decreased not only because the larger size events started taking place further away of the working places. The other reason was that over time the rock mass located between these events and the underground workings became more and more fractured and more and more of the seismic energy was then absorbed before it will be able to cause any damage. The seismic energy release rates due to the stress caving process were several times higher from those induced by the development mining. The other important feature of seismicity associated with this stage of the caving process will be its clustering and continuous expansion in area and volume.

C. Crown pillar failure—end of 2002

At the time of the crown pillar failure the upwards migration of seismicity come to an end. This resulted in seismicity starting to migrate downward and also away from the mine. This resulted in further and faster increase of the seismically active volume and also in more and more of seismicity taking place outside of the mine foot print. The energy index time history at this stage reached its maximum value. The premature fracturing of the crown pillar has changed the stress distribution around the mine on a regional scale. This failed rock restricted the passage of horizontal stresses through it. This has tended to increase the vertical stress relative to the horizontal stress acting on the sub vertical structure in, and immediately adjacent to, the cave zone. In consequence PMC become a seismically active mine and during 2003 experienced several damaging seismic events, of which the first took place already in mid January 2003. Comparison of seismicity recorded during 2002 with seismicity recorded during 2003 shows very significant differences.

The stress change influenced not only the small scale jointing in the rock mass, but also the large scale sub-vertical geological features close to, and in the cave zone. The decrease in horizontal stress reduced confinement on the planes and increased shear movement, which is confirmed by the seismic data. Analysis of the source parameters of seismic events recorded in 2003 indicates a significant increase in the shearing component, in addition to a major increase of released energy per moment. Another important change was nearly a three-fold increase in relatively large seismic events. The time in between the crown pillar failure and its break through was the time when the stress levels around the cave as indicated by the energy index time history were the highest in the whole mine history. This was also the time of the highest seismic energy release rates The percentages of seismicity taking place above the mine started to decrease after the pillar failure. The percentages of seismicity with high ratio of E-wave energy to P-wave energy were close to 95 %. The seismically active volume was still increasing but this increase was slower than that observed before the pillar failure. The stress pattern change was then followed by seismicity. It did not only migrate down but at some time also appeared below the mine. By the time of the break through the rock mass above the mine was already strongly fractured and in consequence the seismic energy releases were relatively low and also located far away from the mine working places. Up to this stage of the caving process the rock mass below the mine was not influenced by the caving process. This rock mass at this stage was still solid and strong and for this reason capable of absorbing larger amounts of strain energy. Due to the stress redistribution after the pillar failure the geological discontinuities located below the mine started to be seismically active. For the first time since the initiation of the caving process there was seismic activity taking place below the mine. As below the mine there is no caving process that can fracture the rock mass then the geological features started to accumulate strain energy until it reached the critical state at which the energy release did take place. For this reason the energy releases were high and as the rock mass between the seismic source and mine was still solid then a lot of the emitted seismic energy reached the underground workings.

D. Initial break through—May 2004

The breakthrough itself was associated with increased seismic energy release and seismic deformation rates. This is well illustrated by a cumulative graph of these two rates. Up to the break through time the seismicity locating above the mine is related to the production rates. Increase in production rates resulted in increased seismicity rates. After the break through the seismicity rates become more and more related to the caving process and less and less to the cave production rates. The seismicity locating below the mine from the start is more associated with the caving process (it started to appear only after the pillar failure). Still it seems that after some time there develops some relation to the mining rates also. After the break through was completed more and more of the seismicity was taking place below the mine. Over time this seismicity did migrate deeper and just after the initial break through it has reached its maximum depth.

E. Cave reaching the mature stage at the end of 2007

At some stage the caving process must reach its maximum stage as the fracturing of the rock mass due to the cave progress can not go for ever and into infinity. Recorded seismicity indicated this process. The recorded seismicity rates not only decreased but also the volume in which they took place started to decrease. The recorded seismicity stopped clustering and become more and more scattered. The energy index time history did indicate low stresses continuously displaying a generally flat trend with values below the mean value of 1.0. This doest mean that there no longer was seismicity with high energy releases. It is true that at this stage the caving process has already well fractured the rock mass around the cave. Still it can not be assumed that this process was fully homogeneous. Around the cave there still were some parts of the rock mass (for example parts of the strong dykes or faults) capable of accumulating strain energy.

F. East break through

This break through took place already after the caving process reached its mature stage Presented up to this point data sets a limit as to which part of recorded seismicity can be contributed to this break through and which to the caving process. It seems that comparison between the initial and east break through is the correct technique to gain a better insight into the break through process. Still at this point it can be pointed out that the initial break through was an large-scale process that influenced the whole seismicity recorded at the time while the east break through was a local process that influenced only the seismicity associated with this break through.

G. End of the caving process end of 2012

As everything has to come to its end so has the caving process. At this stage all of the recorded seismicity was taking place close to the mine and below the mine elevation. This seismicity is induced only by the mining and no longer by the caving process. This was then easy to prove when analysing the 24-distribution of seismicity. During the shift changes there is no seismicity. Seismicity or rather lack of seismicity during the production stoppages is also a direct prove that the caving process no longer is there.

7.4 Comparison Between Initial and East Break Through

This back analysis of two breaks through is based primarily on seismic data. The other cave monitoring devices installed in boreholes that could provide data had been lost earlier during 2003 as a consequence of the response of the rock mass to mining. The initial break through took place in May 2004 while the east break through was completed four years later during the months of May and June 2008. There is a lot of similarity as far as stress changes (as indicated by the energy index time histories), seismicity migration, seismic energy release as well as seismic deformation patterns are concerned. There are also some differences but they seem easy to explain as the initial brake through took place 25 months after the stress caving process was initiated while in case of the east break through this time span has increased by a further four years. The continuous caving process during these four additional years undoubtedly resulted in significant changes to the condition of the rock mass around the cave that gave rise to these differences (Glazer and Townsend 2010a, b).

Figure 7.22 shows the PMC Mine in a vertical W-E plan with the estimated cave back position at the end of 2002. The maximum elevation of the cave at the end of 2002 was at −600 m which would indicate that at that time the crown pillar would be still about 200 m thick. Figure 7.22 also shows the seismicity that was recorded during December 2002 and January 2003. There is much more seismicity recorded at the east than at the west side of the cave. This is because at that time the seismic cover at the west was still very poor. This was rectified by the end of 2003. This figure illustrates the failed nature of the crown pillar illustrating that there was no seismicity recorded between the maximum cave elevation and the lowest elevations of the open pit. Figure 7.23 shows the estimated cave position in May 2004 when the cave broke into the open pit in the central section. The maximum height of the cave in the central section was 400 m. The maximum cave heights in the east and west were 500 m and 750 m respectively. The seismicity presented by this figure was recorded during May and June 2008 during the months when the cave broke into the open pit at the east part of the mine. This sample of seismicity indicates that it located in the east and at shallow elevations above the elevation of −400 m. The next interesting fact about this seismicity is that it is of rather large size magnitude (above magnitude 0.0) while at the time most of the seismicity associated with the cave expansion was of magnitude lower than 0.0.

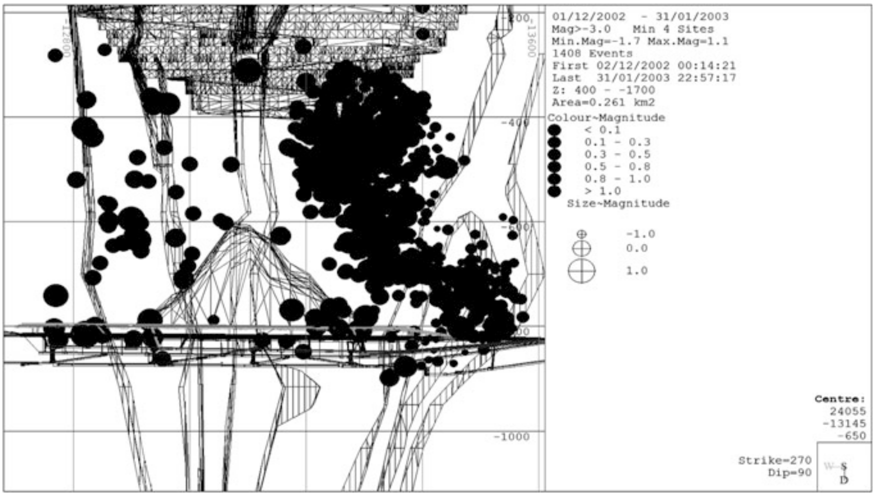

Fig. 7.22 Estimated cave back position at the end of 2002

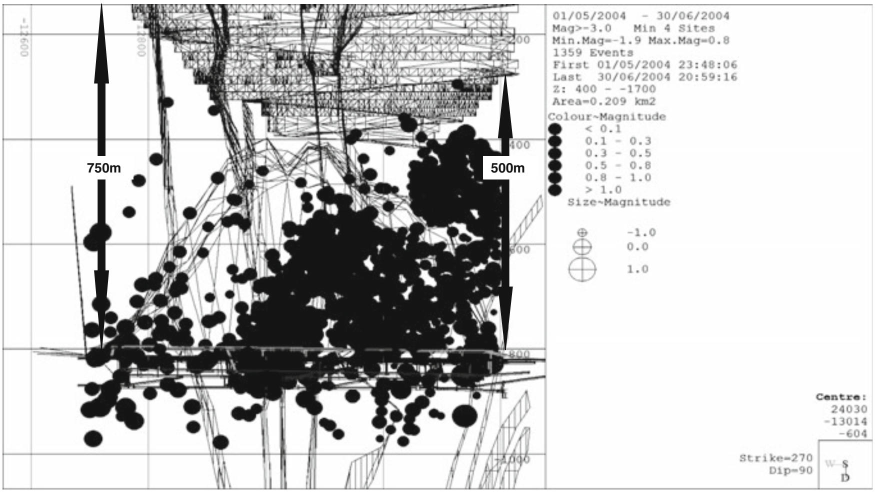

Fig. 7.23 Estimated cave back position during May 2004

Figure 7.24 compares the energy index time histories and the seismicity elevation trends in the east (top) and west (bottom) parts of the mine above the mine elevation for the time period of three years from the beginning of 2006 until the end of 2008. For direct comparison the energy index scales are the same for both the

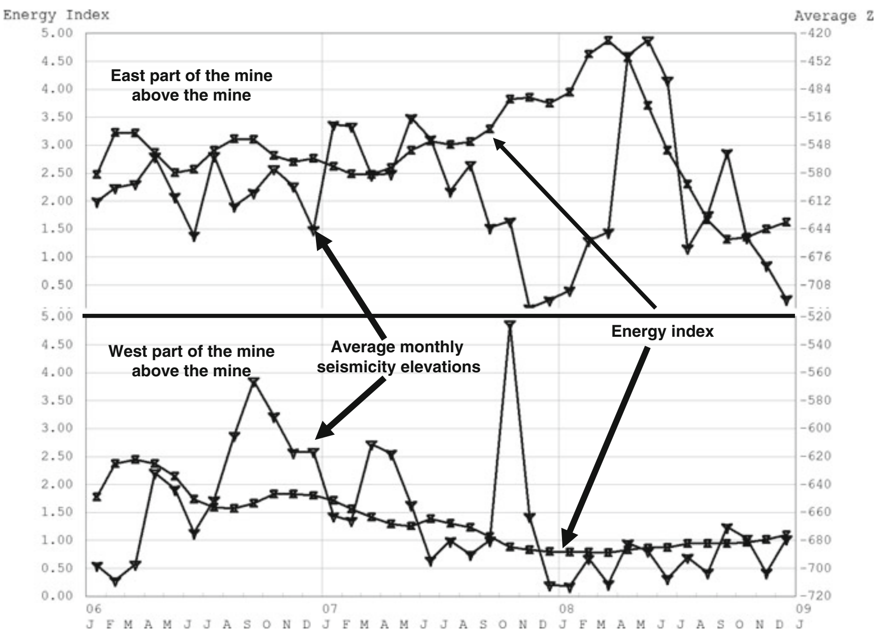

Fig. 7.24 East and west parts above, energy index histories since 2006

west and east parts of the mine. The energy index scales are from 0.00 up to 5.00. The differences are obvious and unmistakable. In comparison to the east, the west energy index and seismicity elevation changes are level and do not show any definite or obvious trends. This figure indicates that from the beginning of 2006 to the end of 2008 the seismicity characteristics and trends for the east and west were very different and that if there was a cave break through it had to have taken place in the east (Glazer and Townsend 2010a, b).

Direct comparison between seismicity associated with the central and the east breaks through will take into account:

- Energy index (stress) histories
- Seismicity elevation changes and their trends
- Seismic energy release trends in space and in time
- Seismic moment rate trends in space and in time.

All presented figures illustrating the central break through show the following caving process milestones

A—Initiation of the stress caving process April/May 2002
B—Failure of the crown pillar end of 2002
C—Initial break through May 2004
D—Failure in the open pit October 2004

All figures presenting the east break through use the following pointers:

1—Time when the stresses at the east started to increase, June 2006
2—Time when the seismicity migrated up to it shallowest elevations, April 2008
3—Time when the seismicity started to migrate down, June/July 2008

Comparisons presented in this chapter between the initial or central break through and the eastern break through are based on specific time periods. In case of the initial break through this time period started in January 2001 and ended on the last day of December 2005. In case of the east break through this time period started at the beginning of January 2005 and ended at the end of October 2008. When different time periods to these are used then they will be specified.

7.4.1 Energy Index and Seismicity Elevation Changes Associated with the Break Through

Figure 7.25 shows the energy index history and the average monthly seismicity elevation changes at the central part above the extraction level from the beginning of 2001 until the end of 2005. Figure 7.26 illustrates these two values for the east, above the extraction level from the beginning of 2005 to the end of 2008. On the left side of these two figures the vertical scales for the energy index. The right side scale is for the seismicity elevation changes.

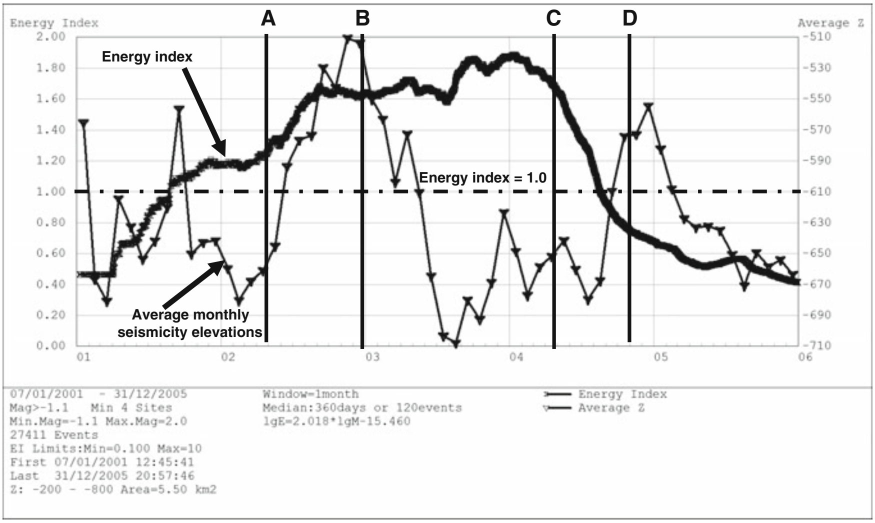

Fig. 7.25 Central break through—energy index and seismicity elevations

Above the mine level at the central part of the mine (Fig. 7.25) the energy index at the beginning of 2001 was low and increased rapidly to reach the mean value of 1.0 by the end of 2001. This stress increase lasted to about the end of 2004. The rate of stress release which started just before the initial cave break through during 2004 was higher than the rate of stress increase during 2001 and 2002. The mean energy index value of 1.0 was reached by mid 2004. This figure also illustrates the seismicity elevation trends that are based on monthly rates. It is clear that the initiation of the stress caving process (A) resulted in more seismicity taking place closer to the cave. With the cave expanding after the initiation process (A), the seismicity started to migrate upwards. The failure of the Crown Pillar by the end of 2002 (B) is also evident. At this stage the seismicity reached its shallowest elevation for this time period. After the failure the seismicity migrated downwards. This downward migration lasted only six months. From mid 2003 seismicity started to migrate upwards and then reached its next shallowest elevation at the time of the failure in the open pit (D). This second shallow period was then followed by another downward migration.

At the east above the mine (Fig. 7.26) from about June 2006 there was a continuous stress increase. From the beginning of 2007 until about March 2008 the stresses stayed at about the same level. From April 2008 there was a rapid stress release as the energy index had already reached the mean value of 1.0 by June/July 2008. From mid 2006 until mid 2007 there was a general upward migration of seismicity with the seismicity being at the shallowest elevation during the first half of 2007. During the second half of 2007 there was a rapid downward migration

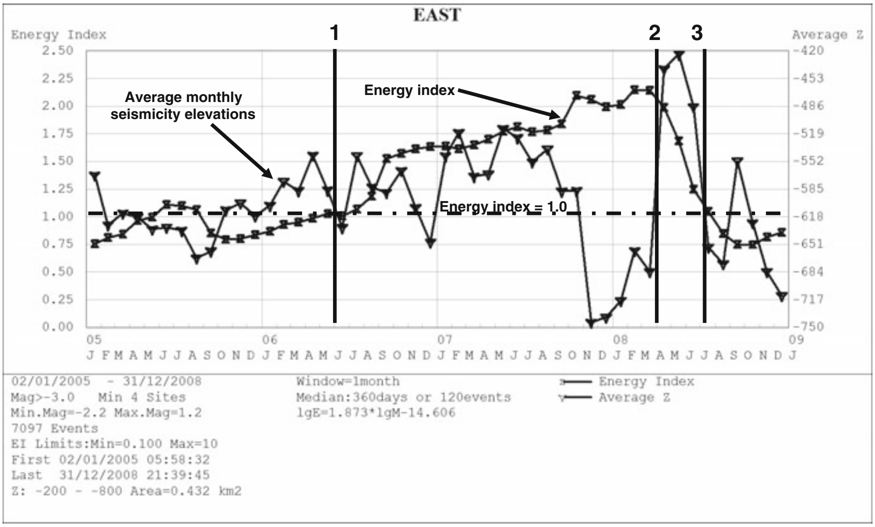

Fig. 7.26 East break through—energy index and seismicity elevations

of seismicity. At this stage the reason for this downward migration remains unknown. The seismicity elevations are based on a mean value (in this case this is a monthly seismicity elevation mean). The monthly seismicity rates in the east above the mine level during this period were lower than they were previously (the less data that is used to calculate the mean the less reliable it is). On the other hand the observed seismicity rate decrease as well as the associated downward migration of seismicity might be real and indicative of some process. This downward migration was then followed by a very rapid upward migration of seismicity with minimum elevations reached during April and May 2008. The subsequent downward seismicity migration (during June, July and August 2008) was of the same magnitude as the previous upward migration.

As far as the monthly seismicity elevations are concerned the minimum elevation at the time of the initial break through was at about −510 m and during the east break through at −520 m (mid 2007) and then at −420 m (May 2008).The seismicity elevations during the east break through during May 2008 were shallower than during the Crown Pillar failure at the end of 2003. In fact they are the shallowest for the whole history of the mine up to the end of 2008. This must be correct. The maximum height of the cave at its central part is 400 m while at the east it is 100 m higher (see Fig. 7.23). The differences between the stress levels and the maximum upward migration of seismicity during these two break through are obvious and easily derived from other information than just seismicity. The fact that seismic data, in this case two independent seismic parameters confirms this indicates how reliable it is.

7.4.2 *Seismic Energy Releases Associated with the Breaks Through*

Figure 7.27 shows the energy index and the cumulative seismic energy release time histories for the central part of the mine, while Fig. 7.28 show these two parameters for the east part of the mine. In both cases the time histories are for the rock mass located above the mine. In order to eliminate seismic energy releases due to development mining (draw bells were completed in August 2004) in case of the central part of the mine I have used an elevation range from −200 m down to −700 m. At the central part of the mine (Fig. 7.27) during the time period lasting 25 months from April 2002 (from the cave initiation time) until the cave break through there was a continuous stress build that was associated with a continuous but low seismic energy release. From the time of the central break through (May 2004) the stresses started to decrease and there was a rapid increase in released seismic energy lasting 5 months. In fact this rapid stress release period accounts for about 50 % of the total seismic energy that was released from the beginning of 2002. At the east (Fig. 7.28) there was a continuous stress increase lasting from June 2006 up to April 2007 (20 months) that was associated with a continuous but low seismic energy release (the same as for the central part of the mine). From April 2008 until June 2008 during a rapid stress decrease lasting only 3 months there was also a rapid increase in released seismic energy. During this period more than 90 % of the total seismic energy was released.

It is reasonable to expect that during the time periods when the stresses are building up there will be less seismic energy released and consequently during a

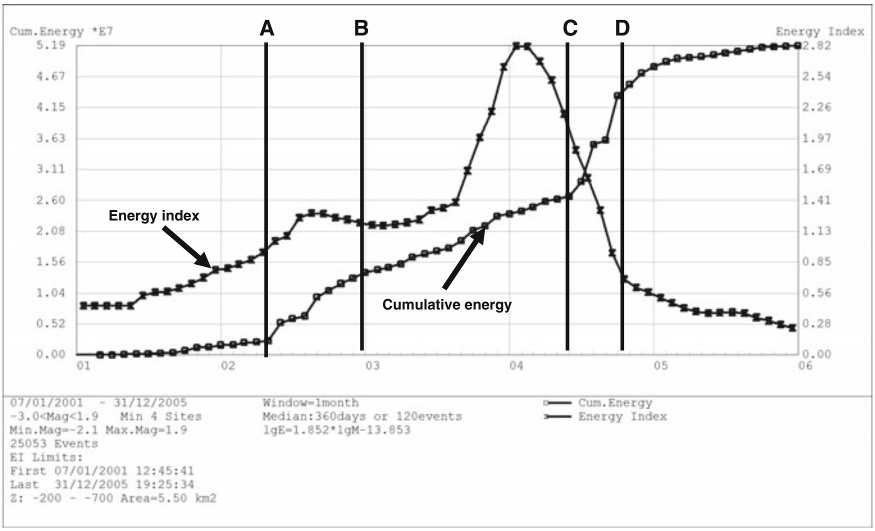

Fig. 7.27 Central break-through, energy index and cumulative energy release

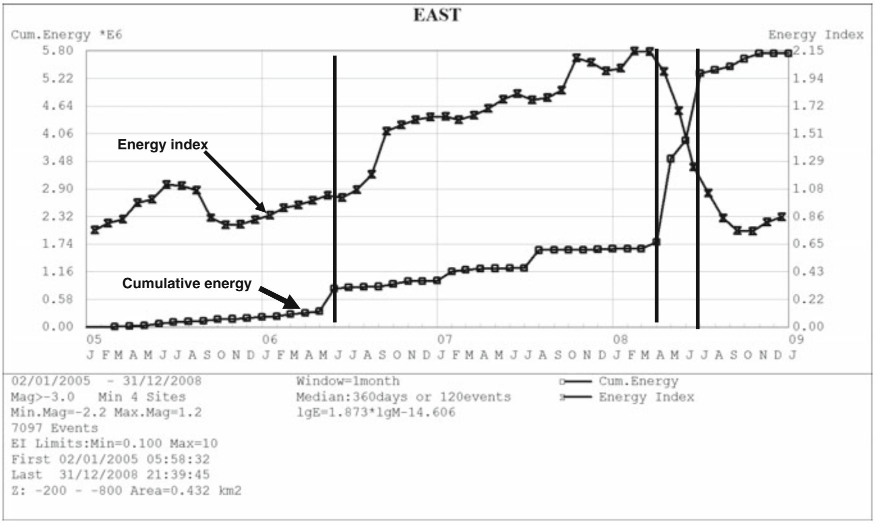

Fig. 7.28 East break-through, energy index and cumulative energy release

stress release time period there will be more seismic energy released. Further more one should expect that when the stresses are higher the energy releases will be higher than in a lower stress environment. Consequently a higher stress release should release more seismic energy than the lower stress release. In the case of the central break-through the high stress lasted for 25 months and during this period the seismic energy release amounted to 21.00E+06 J, which is an average of 0.84E +06 J per month. In case of the east break through the high stress lasted for 20 months and during this time period the seismic energy release totalled 2.40E +06 J which is an average of 0.12E+06 J per month. As indicated by the energy index values the stresses at the central part of the mine prior to the initial break through were higher than those at the east prior to the east break through. During the stress build up period prior to the central break-through the seismic energy release was nearly nine times higher than during the high stress period before the east break-through. During the stress release period after the central break through the seismic energy release totalled 21.1E+06 J (4.22E+06 J per month). After the east break through the seismic energy release amounted to 21.9 E+06 J (7.30E +06 J per month).

The following two Figs. 7.29 and 7.30, illustrate the monthly seismic energy release rates for the central and east parts of the mine. The top part of each figure shows the energy release rates above the mine and the bottom part of each of these figures illustrate the energy release rates below the mine. For the purpose of direct comparison the vertical scales relating to the energy release rates are exactly the same (from 0.0 up to 12 E+06 J for the central part and up to16E+06 J for the east part).

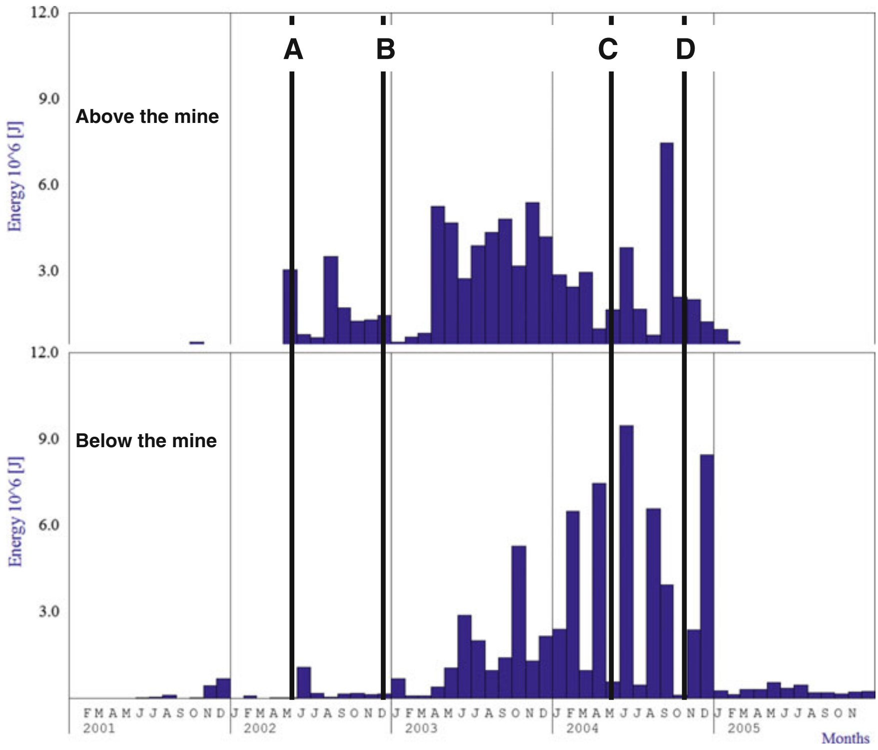

Fig. 7.29 Central part of the mine—monthly seismic energy release rates

Based on the seismic catalogues presented and the selected time periods for these two figures, the energy releases are as follows:

Cumulative seismic energy:

Central part above the mine—9.71E+07 J
Central part below the mine—7.88E+07 J
East part above the mine—3.37E+07 J
East part below the mine—3.51E+07 J

Maximum monthly rates:

Central part above the mine—7.5E+06 J (September 2004)
Central part below the mine—9.5E+06 J (June 2004)
East part above the mine—14.6E+06 J (June 2008)
East part below the mine—1.45E+06 J (September 2008)

The data presented above clearly indicates that there was much more seismic energy released at the central part of the mine (above as well as below the mine) than at the east part of the mine, but the highest monthly seismic energy releases were associated with the east part of the mine. The other differences between the energy release at the central and east parts of the mine is the timing and distribution patterns. At the central part of the mine (above the mine) the higher energy releases started after the stress caving process was initiated. The monthly seismic energy release rates then increased considerably after the crown pillar failure, but the highest monthly energy release rates were recorded only after the initial break through. Seismic energy release rates then decreased considerably just after the failure in the open pit. Below the mine the energy releases started after the failure of the crown pillar and ended after the failure in the open pit. The energy release distribution rates above and below the central part of the mine are different. While above the mine the monthly rates were more constant in size than below the mine, there were higher monthly rates below than above the mine. These higher rates are separated by months of very low monthly seismic energy release rates The reason for such different distributions of seismic energy releases is obvious. As the cave is located above the mine then the rock mass above the mine must be more fractured than below the mine. The more the rock mass is fractured the less energy it can contain, so as the rock mass below the mine is less fractured than above then it can cumulate more energy than the rock mass above the mine. During times when the energy is cumulated there are low energy release rates. Once the energy accumulation reaches its limits there is a high seismic energy release. This explains the mechanism of the energy release pattern below the central part of the mine.

At the east part of the mine the energy release pattern (Fig. 7.30) is very different from the one associated with the initial break through. Above the mine from the beginning of 2005 up to April 2008 the energy releases were extremely low. Then there were enormously high energy release rates during the next three months of April, May and June 2008. During the following months energy releases were again low. This indicates that the rock mass prior to the failure and the break through was strong and not highly fractured so it could absorb a lot of strain energy. This energy release pattern indicates that the east break through took place in highly stressed rock mass conditions. Below the mine at the east the energy releases started at the time when the stresses started to increase (Fig. 7.28). The main releases took place during 2006 and then the energy release rates decreased considerably. The energy released during September 2008 accounts for about 50 % of the total energy released below the mine. This exceptionally large energy release took place two months after the large size energy releases above the mine. This fact indicates that after the east pillar failure and the break through the stress pattern around the mine has changed similar as to what took place after the central pillar failure. By the end of June 2008 the east pillar was so fractured that it was no longer generating larger size seismicity and no longer capable of transmitting stresses. The stresses then migrated down and below the mine with the result being that large size seismicity was recorded during September 2008 below the mine level.

Analysis of vertical distribution of released energy illustrates the fact, that in case of the east break through, most of the seismic energy was released between the elevations of −300 and −400 m and that all of the energy was released above the elevation of −500 m. In case of the central break through the seismic energy releases were shallower with most of the energy being released between elevations

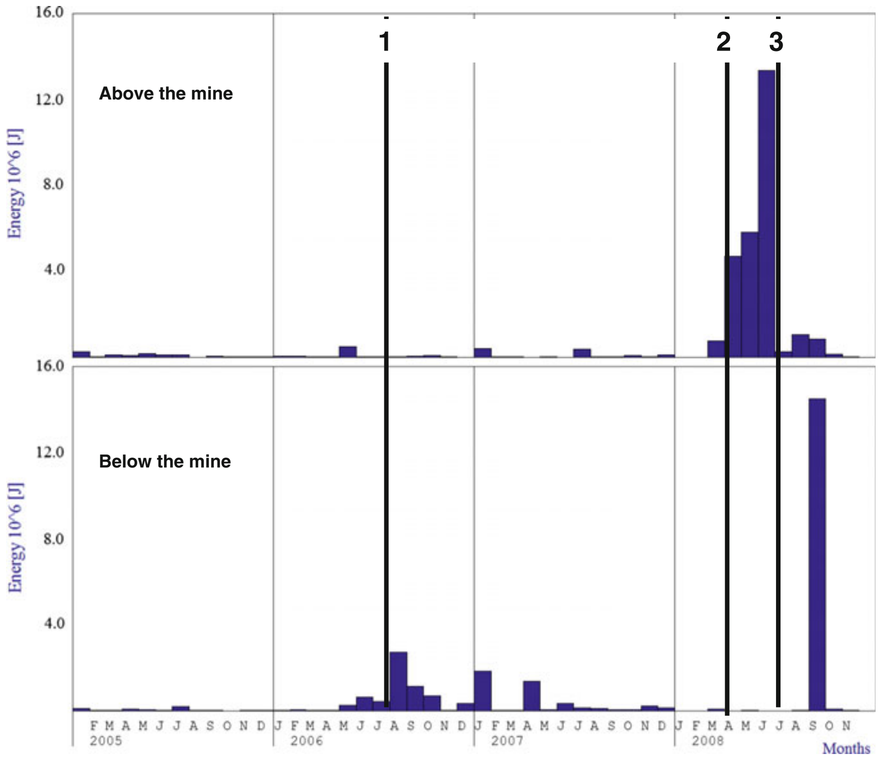

Fig. 7.30 East part of the mine—monthly seismic energy release rates

of −400 and −600 m. The highest energy release rates in layer located between elevations of −600 and −700 m took place after the central break through. In case of the east break through the energy release was limited to three months while in case of the central break through the energy releases were spread over a much longer time period. It is worth noting that although the east energy releases rates were in general higher than the central break through rates, their compositions are different. Most of the energy released that was associated with the east break through was accomplished by means of lower size magnitude events than those for the central break through. This is illustrated in Table 7.14 which compares typical monthly rates for these two breaks through. Table 7.14 provides a comparison between two typical monthly seismicity rates above the mine associated with the central and east break through during November 2003 and June 2008. The total energy release during June 2008 is over twice the November 2003 release. The November 2003 seismicity consists mainly of events of magnitude size between 0.0 and 0.5. The seismic energy released by these 86 events amounts to 37 % of the total seismic energy released during November 2003. Events of this size during June 2008 (there were 44 such size events) provided less than 4 % of that months' seismic energy release. During November 2003 there were only 7 events of

Table 7.14 Monthly seismic energy release structure comparison

Magnitude range	Central break through November 2003	East break through June 2008		
	No of events	Energy release	No of events	Energy release
0.0 up to 0.5	86	2.32E+06 J	44	5.47E+05 J
0.5 up to 1.0	7	1.05E+05 J	53	1.32E+07 J
1.0 up to 1.5	2	1.04E+06 J	1	8.24E+05 J
Maximum magnitude	1.1		1.0	
Total monthly rate		6.21E+06 J		14.60E+06 J

Table 7.15 Distributions of seismic energy released in layers

Layer		East breakthrough		Central breakthrough		
No	Elevation range	Energy J E+06	Percentage	Energy J E+06	Percentage	Percentage (5 layers)
1	−200 m/−300 m	1.86	6.02	0.54	0.49	0.77
2	−300 m/−400 m	17.7	57.30	1.74	1.58	2.47
3	−400 m/−500 m	7.20	23.31	17.0	15.41	24.09
4	−500 m/−600 m	2.41	7.80	29.3	26.57	41.51
5	−600 m/−700 m	0.94	3.04	22.0	19.95	31.16
6	−700 m/−800 m	0.78	2.53	39.7	36.00	–
	Total	30.89	100.00	110.28	100.00	100.00

magnitude size between 0.5 and 1.0, while during June 2008 there were 53 events in this size category. The November 2003 seismic energy release due to these size events amounted only to about 2 % while these size events during June 2008 released about 90 % of the total energy. The energy released by the larger size events during November 2003 and June 2008 indicate that on average the June 2003 event was of a higher energy release than the November 2003 ones.

Table 7.15 provides a direct comparison between the seismic energy release rates in the consecutive 100 m thick layers for the east and central breaks through. Data presented by this table is based on two 27 months time periods. For the east break through this 27 months time period started on the 01 July 2006 (when the stresses at the east started to increase) and ended 30 September 2008. In case of the central break through this time period started on 01 April 2002 (initiation of the caving process and ended on 30 June 2004 (just after the central break through). In both cases the energy release rates are for the rock mass volume located above the extraction level. Data for the central break through is divided into two sets, the first one taking into account all 6 layers and the second one taking into account only 5 layers (the shallowest layer 6 is in this case is excluded). This was done to make sure that inclusion of layer 6 will not change the proportions of energy released in each layer. Figures 7.31 and 7.32 illustrate data presented by this table.

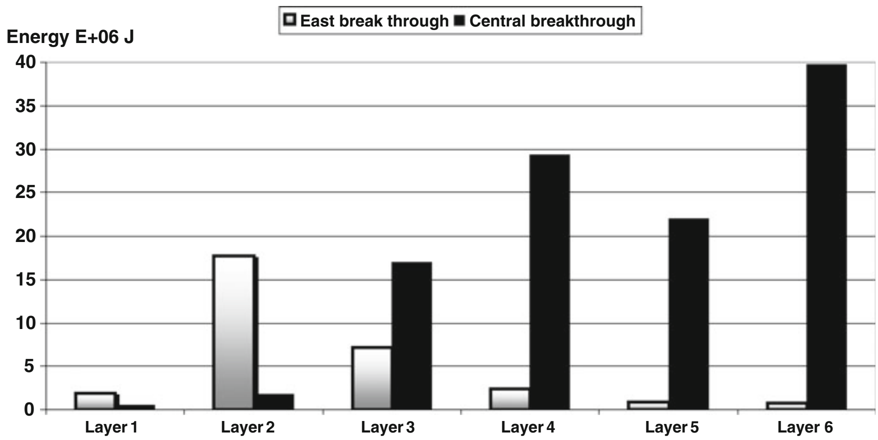

Fig. 7.31 Seismic energy released in layers

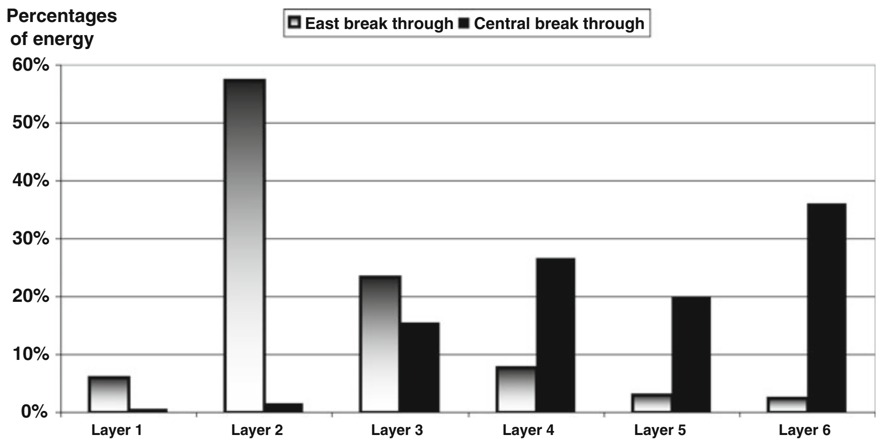

Fig. 7.32 Percentages of seismic energy released in layers

Figure 7.31 illustrates the amounts of energy released in each layer during the east and central break through. Most of the energy associated with the east break through was released in layer 2 (that is in elevation range from −300 m down to −400 m), while the maximum energy release associated with the central break through was associated with layer 4 (that is in the elevation range from −500 m down to −600 m). In case of the east break through the energy release rates were limited to the three shallowest layers (from −200 m down to −500 m) while the energy release associated with the central break through took place also in three layers but located between elevations of −400 m and −700 m). Figure 7.32 presents the percentages of energy released in each layer during these two breaks through. This figure clearly indicates that the east break through was taking place shallower than the central one.

Analysis of seismic deformations reveals the fact that not only the energy releases, but also the seismic deformation rates, that were associated with these two breaks through were different. In general there was more seismic deformation associated with the initial than with the east break through. There was also a lot of seismic deformation taking place after the initial break through while after the east break through there were only very small amounts of seismic deformation left. This is easy to explain as the initial break through took place 25 months after the stress caving process was initiated while in case of the east break through this time span increased by 48 months (4 years difference). The continuous caving process during these four additional years had to significantly change the conditions of the rock mass around the cave that resulted in these differences. Again this indicates the high reliability of the seismic data.

7.4.3 Seismic Deformations Associated with the Breaks Through

Figure 7.33 shows the energy index and the cumulative seismic moment time histories for the central part of the mine, while Fig. 7.34 shows these two parameters for the east part of the mine. In both cases the time histories are for the rock mass located above the mine. In order to eliminate amounts of seismic moment due to development mining in case of the central part of the mine I have used an

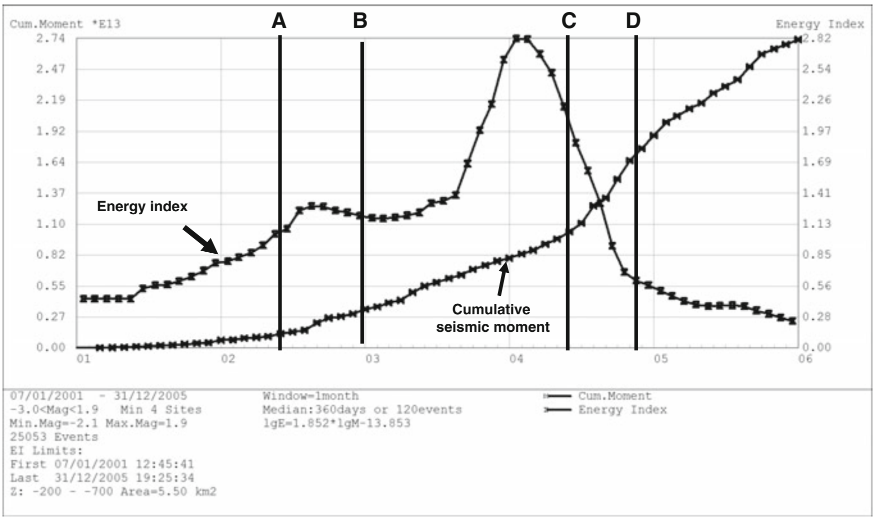

Fig. 7.33 Central break through, energy index and cumulative seismic moment

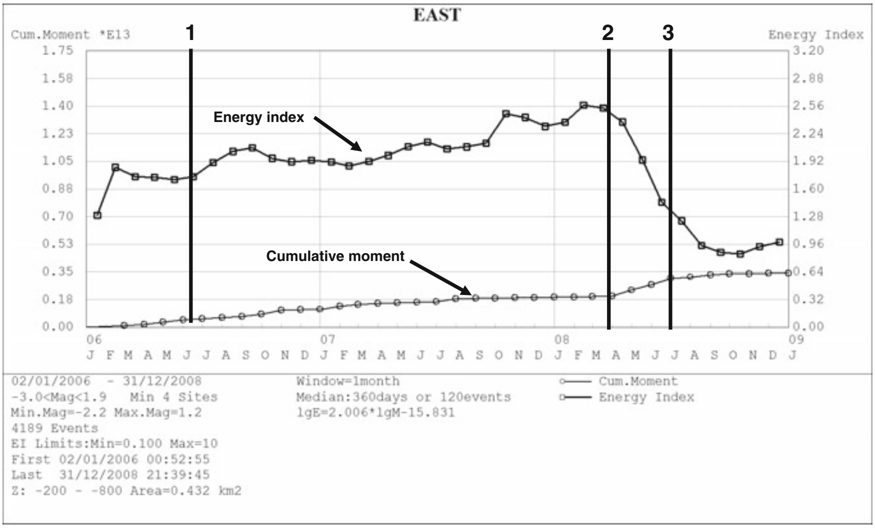

Fig. 7.34 East break through, energy index and cumulative seismic moment

elevation range from −200 m down to −700 m. At the central part of the mine (Fig. 7.33) during the time period lasting 25 months from April 2002 (from the cave initiation time) until the cave break through (C) there was a continuous stress build-up that was associated with a continuous but low seismic deformation rates. From the time of the central break through (May 2004) when the stresses started to decrease there was an increase in seismic deformation lasting 5 months. At the east (Fig. 7.34) there was a continuous stress increase lasting from June 2006 up to April 2007 (20 months) that was associated, just as at the central part of the mine, with a continuous but low seismic deformation rate. From April 2008 until June 2008 during the rapid stress decrease, which lasted only 3 months, there was also an increase in seismic deformation rates.

In case of the central break through the high stress lasted for 25 months and during this time the cumulative seismic deformation reached the value of 9.70E+12 Nm, so the average monthly deformation rate for that time period was 0.39E+12 Nm. In case of the east break through the high stress lasted for 20 months and during this time the seismic moment accumulated to 5.31E+06 Nm which gives an average of 0.27E+06 Nm per month. As indicated by the energy index values the stresses at the central part of the mine prior to the initial break through were higher than those at the east prior to the east break through. During the stress build up period prior to the central break through the seismic energy release was nearly nine times higher than during the higher stress time period before the east break through, but the seismic deformation associated with the central break through was only twice that which was associated with the east break through. During the high stress release period after the central break through the seismic moment totalled at 5.6E +12 Nm J (1.12E+12 Nm per month). During the east break through the seismic moment amounted to 2.42 E+12 Nm (0.81E+12 Nm per month), which is half of that associated with the central break through. During these two rapid stress releases the amounts of released seismic energy were similar, but there was less than half of the seismic deformations associated with the east break through than it was with the initial break through. Analysis of the monthly seismic deformation rates at the central and east parts of the mine both above and below the mine results in the following data:

Cumulative seismic deformation:

Central part above the mine—3.12E+13 Nm
Central part below the mine—2.26E+13 Nm
East part above the mine—1.51E+13 Nm
East part below the mine—1.55E+13 Nm

Maximum monthly seismic deformation rates:

Central part above the mine—1.83E+12 Nm (September 2004)
Central part below the mine—1.47E+12 Nm (May 2005)
East part above the mine—1.17E+12 Nm (June 2008)
East part below the mine—1.24E+12 Nm (September 2006)

Data presented above indicates that there was much more seismic deformation (above as well as below the mine) taking place at the time of the initial break through than during the east break through and that the highest monthly seismic deformation rates were associated with the initial break through. The other difference between the seismic deformation rates during the initial and east breaks through was the timing and distribution patterns. At the central part of the mine (above the mine) the higher deformation rates started to appear after the stress caving process was initiated. The monthly seismic deformation rates increased then considerably after the crown pillar failure, but the highest monthly deformation rates were recorded only after the initial break through. Up to this point the distributions of seismic energy and seismic moment were very similar. After the failure in the open pit the seismic energy release rates decreased considerably while the amounts of seismic deformation remained high. Below the mine the seismic deformation, similar to the energy release, started after the failure of the crown pillar but did not end after the failure in the open pit as did the seismic energy release. After the failure in the open pit there was still a lot of seismic deformation taking place below the mine. At the east part of the mine the seismic deformation pattern is different from the one associated with the initial break through. Above the mine as well as below the mine from the beginning of 2005 up to April 2008, the seismic deformation rates were low. Then there were high seismic deformation rates during April, May and June 2008 but only above the mine. During the following months up to the end of October 2008 the seismic deformation rates above and below the mine were again low. Analysis of seismic deformation distribution, not only over time, but also at varying depths both at the east and at the central parts of the mine indicates the fact that, in case of the east break through, most of the

Table 7.16 Distribution of seismic moment in layers

Layer		East breakthrough		Central breakthrough		
No	Elevation range	Moment Nm E+12	Percentage	Moment Nm E+12	Percentage	Percentage (5 layers)
1	−200 m/−300 m	0.73	8.62	0.66	3.11	5.21
2	−300 m/−400 m	2.70	31.88	1.13	5.33	8.93
3	−400 m/−500 m	1.33	15.70	2.24	10.56	17.70
4	−500 m/−600 m	1.35	15.94	3.92	18.47	30.96
5	−600 m/−700 m	1.13	13.34	4.71	22.20	37.20
6	−700 m/−800 m	1.23	14.52	8.56	40.33	–
	Total	8.47	100.00	21.22	100.00	100.00

seismic deformation took place between the elevations of −300 and −400 m. In case of the central break through the seismic deformation took place shallower, with most of it occurring between the elevations of −400 and −700 m. In case of the east break through the seismic deformation rates were limited to three months while in case of the central break through the seismic deformations were spread over much longer time period. Table 7.16 provides a direct comparison between the seismic deformation rates in the consecutive 100 m thick layers for the east and central breaks through. Data presented by this table is based on two 27 month time periods. For the east break through this 27 months time period started on the 01 July 2006 (when the stresses at the east started to increase) and ended 30 September 2008. In case of the central break through this time period started on 01 April 2002 (initiation of the caving process and ended on 30 June 2004 (just after the central break through). In both cases the energy release rates were for the rock mass volume located above the extraction level. Data for the central break through is divided into two sets, the first one taking into account all 6 layers and the second one taking into account only 5 layers (the shallowest layer 6 is in this case is excluded). Figures 7.35 and 7.36 illustrate data presented by this table.

Figure 7.35 illustrates the amounts of seismic deformation that took place in each layer during the east and central breaks through. Most of the seismic deformation associated with the east break through took place in layer 2 (that is in the elevation range from −300 m down to −400 m), while the maximum seismic deformation associated with the central break through was associated with layer 6 (that is in the elevation range from −700 m down to −800 m). In case of the east break through the amount of seismic deformation in layer two was about twice as high as in the rest of each layer while in the case of the initial break through the amounts of seismic deformation decreased with elevation. Figure 7.36 presents the percentages of seismic deformation in each layer during these two breaks through. This figure clearly indicates that the east break through was taking place at a shallower elevation than the initial one.

In case of the central break through, the shallower the layer, the less seismic energy and seismic deformation that was associated with that layer. During the east break through the maximum energy release as well as maximum seismic

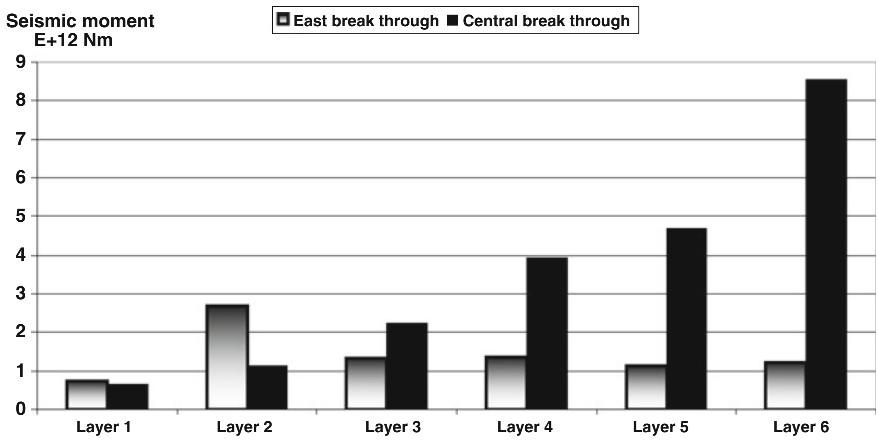

Fig. 7.35 Seismic deformations in layers

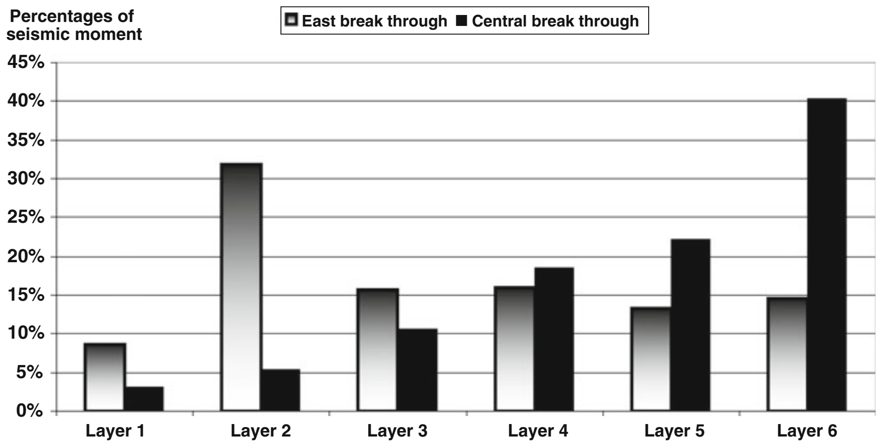

Fig. 7.36 Percentages of moment in layers

deformation was both associated with layer 2 (−300 m down to −400 m). The distribution of seismic deformation in other five the layers were equal while the amounts of released seismic energy decreased with elevation.

7.4.4 Percentages of Seismicity Taking Place Above the Mine

Figure 7.37 shows the percentages of seismicity recorded above the entire mine extraction level from January 2001 until the end of December 2013. 100 %

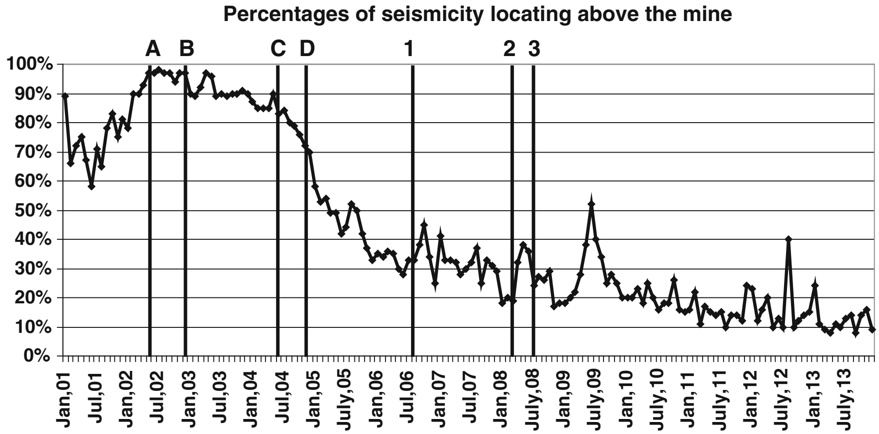

Fig. 7.37 Percentages of seismicity recorded above the whole mine

seismicity is the total amount of seismicity recorded every month above and below the mine extraction level in the elevation range from +400 m down to −1700 m. Initially, during 2001, the amounts of seismicity recorded above the mine were as high as 70 %. With the initiation of the caving process in April 2002 over 90 % of seismicity was recorded above the mine level. These high levels of seismicity above the mine level continued until the cave broke into the open pit in May 2004. After the initial break through there was a slow but continuous decrease in the amounts of seismicity recorded above the mine level. From about May 2005 the amounts of seismicity above the mine level started to drop to below the 50 % level. By May 2006 only about 30 % of all recorded seismicity plotted above the mine level. From about July 2006 the continuous downward trend ended as from then on the amounts of seismicity taking place above the mine started to fluctuate around the value of 30 %.

Figure 7.38 shows the percentages of seismic energy released above the whole mine from January 2001 until the end of December 2013. From October 2004, which coincides with the failure of the open pit North Wall, more than 50 % of seismic energy was released below the mine. It is interesting to note that the continuous decrease in the percentage of energy released above the mine level ended in March 2006. From March 2006 to the end of July 2006 the amounts of energy released above the mine footprint have increased from 15 to 40 %. This was probably related to the cave propagating more in the east. By the end of 2006 less than 10 % of the total energy was released above the mine level. During the whole 2007 the percentages of energy released above the mine varied from month to month by large quantities (from 10 % up to over 50 % per month). During February 2008, less than 10 % of the seismic energy was released above the mine level. During March 2008, 86 % of seismic energy was released above the mine. This amount increased to 99 % during April, May and June 2008. During July and August 2008 the amount of energy released above the mine decreased slightly. During September 2008 only

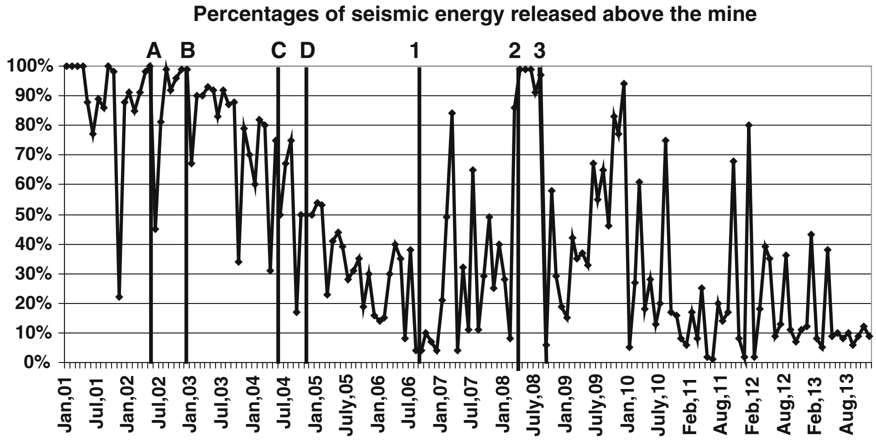

Fig. 7.38 Percentages of seismic energy released above the whole mine

6 % of the total monthly seismic energy release took place above the mine level. During October 2008 this percentage increased to 58 %. During November 2008 only 29 % of seismic energy was released above the mine level.

Figure 7.39 shows the percentages of monthly seismic deformation rates above the whole mine. The maximum deformation rates above the mine are associated with the caving process After the cave broke through into the open pit the percentages of seismic deformation above the mine level dropped from about 80 % (June 2004) to less than 50 % in January 2005. This decrease continued until April 2006 when only about 20 % of the observed seismic deformation was taking place above the mine level. From May 2006 until May 2007 the amount of seismic deformation taking place above the mine increased to about 50 %. This value for

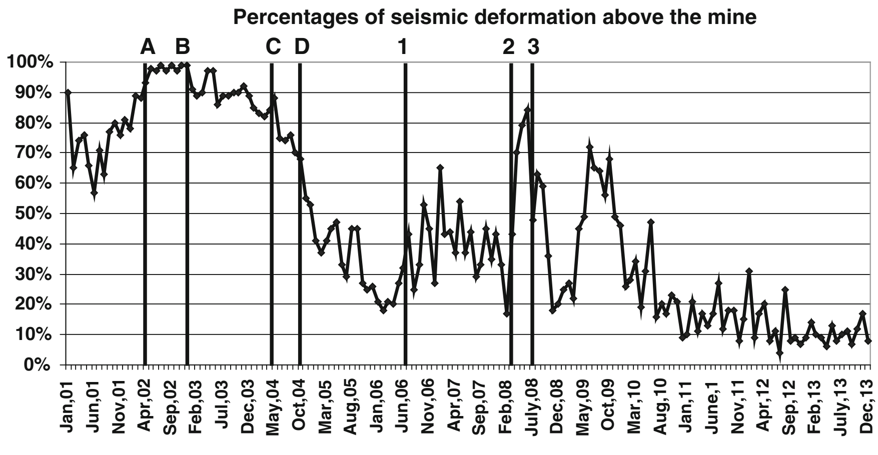

Fig. 7.39 Percentages of seismic deformation above the whole mine

December 2007 was back down at 35 %. This indicates that at that time the cave was still expanding on the east side of the footprint. During January and February 2008 the percentages of seismic deformation above the mine decreased further to 10 %. This amount increased during March 2008 to more than 40 % and then during April and May 2008 was close to 70 %. During June 2008, 84 % of the total monthly seismic deformation took place above the mine. During July August September October and November 2008, the amount of seismic deformation taking place above the mine decreased to 48 %, 53 % 54 %, 36 % and 18 % respectively. All those three figures illustrating the percentages of seismic monthly rates above the mine indicate that a new process started round about June 2006. About this time the continuous decreasing trend in the amounts of seismicity, seismic energy released as well as that of seismic deformation taking place above the mine that lasted in each case for about two years, then terminated. In all three cases from then on there was more seismicity, seismic energy release as well as seismic deformation taking place above the mine. The next three figures illustrate the percentages of seismicity (Fig. 7.40) released seismic energy (Fig. 7.41) and of seismic deformation (Fig. 7.42) above the east part of the mine from January 2006 until the end of November 2008.

These three figures indicate that as from June 2006 there was a general increase in the seismic activity above the eastern part of the mine footprint. Less evident are the increases in the amounts of seismicity, but in all three cases the percentage increases during April, May and June 2008 are evident. During this time period more than 50 % of seismicity, more than 90 % of the seismic energy release and more than 80 %of seismic deformation were taking place above the mine footprint. The subsequent decrease in the amounts of seismic activity after June/July 2008 is, in all three cases, very prominent.

Figure 7.43 shows the monthly production rates from the five eastern crosscuts and the average monthly seismicity elevations in the east. From January 2007 to

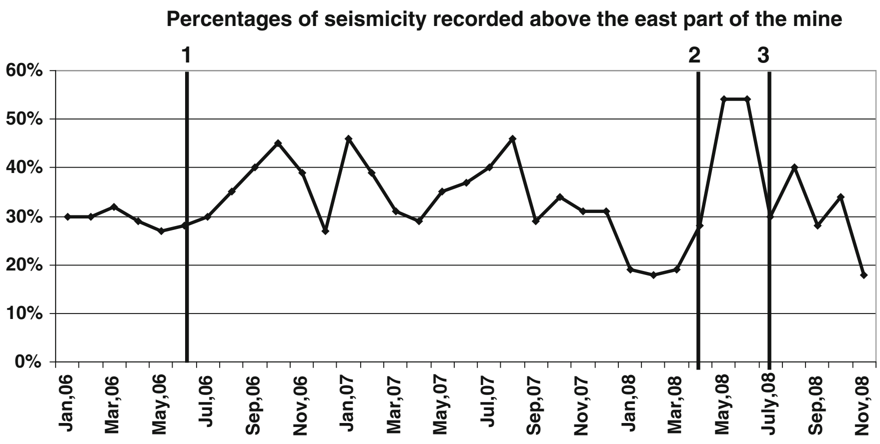

Fig. 7.40 Percentages of seismicity above the east part of the mine

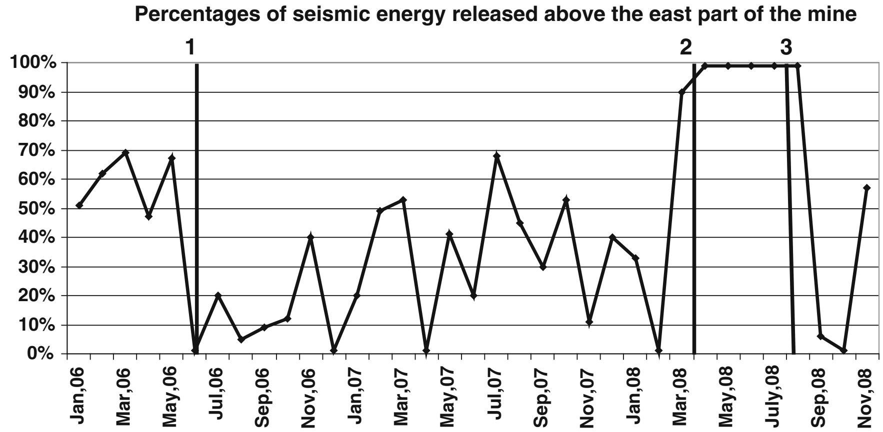

Fig. 7.41 Percentages of seismic energy above the east part of the mine

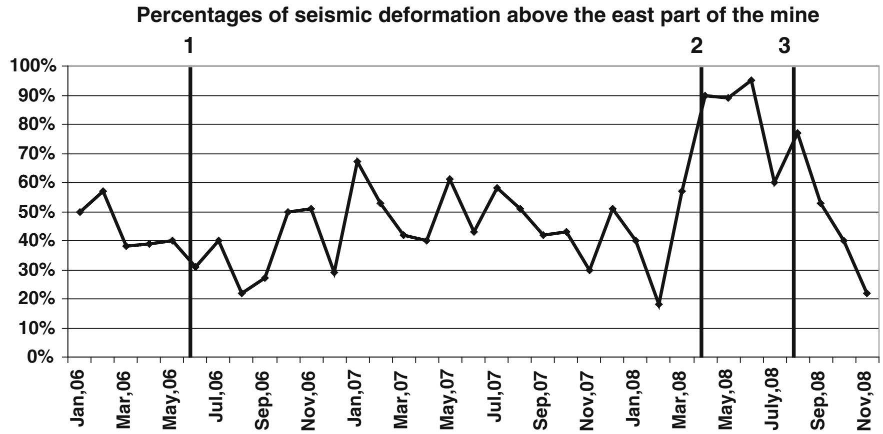

Fig. 7.42 Percentages of seismic deformation above the east part of the mine

February 2008 the production from this part of the mine decreased by nearly 40 %. This is also the same period when the amounts of seismic rates taking place above the mine did not show any specific trends as they decreased or increased from month to month. During this time the average monthly seismicity elevation decreased by nearly 200 m. During March 2008 in relation to February 2008, the production rate increased by 35 %. As a result the seismicity elevations decreased immediately by more than 250 m and according to Figs. 7.40, 7.41 and 7.43 most of the seismic activity occurred above the mine footprint. From the above data it can be concluded that the east break through might have been delayed by nearly one year due to the continuous production decrease in the east part of the mine.

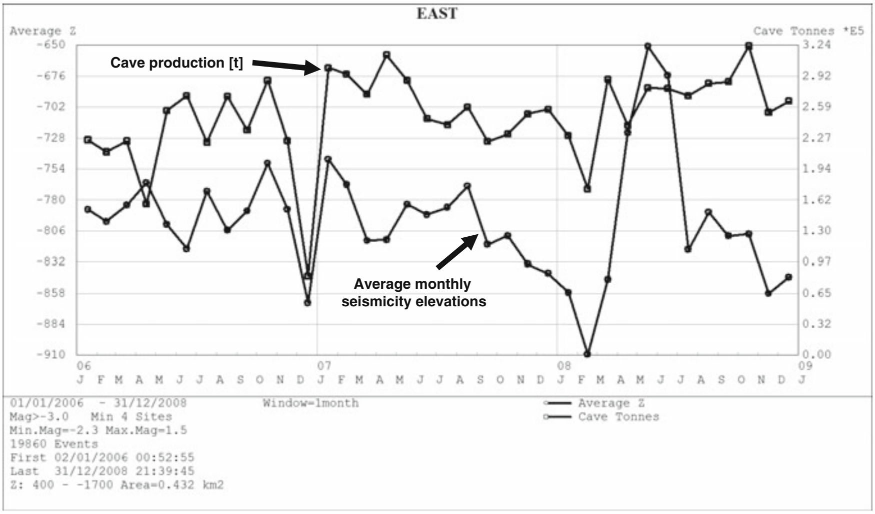

Fig. 7.43 East part of the mine—monthly production and seismicity elevations

7.4.5 Similarities and Differences Between the Initial and East Break Through

This detailed back analysis of the initial and east pillar failures are based primarily on seismic data. The other cave monitoring devices installed in boreholes that could provide data had been lost during 2003 as a consequence of the response of the rock mass to mining. The crown pillar failed at the end of 2003 and the cave finally broke through into the open pit in April 2004 with no evidence that there was any significant air gap above the caved rock mass. The east pillar broke into the open pit during May and June 2008 and there is no evidence that there was a pillar failure prior to the break through or that there was any significant air gap associated with this part of the cave. In the case of the east pillar it seems that its failure and the break through took place at the same time. The initial break through and the east break through took place 25 months and 50 months respectively, after the caving process was initiated. For this reason the rock mass conditions during these two breaks through had to be very different. Still the analysed seismic data associated with these two break troughs indicates a lot of similarities and only some minor differences.

7.4.5.1 Stress Levels

To start with the energy index time histories of the two break troughs are very similar indicating a stress increase prior to the break through with a rapid stress release after the break through. In case of the initial break through the stress increase lasted close to 24 months (from the beginning of 2002 until the end of 2003). The time period of high stresses associated with the east break through was very similar as the stresses started to increase in June 2006 and then the stress release started in April 2008. The main difference are the stress levels. Based on the energy index time histories the stress levels prior to the initial break through was higher from that prior to the east break through. This observation is confirmed by the seismic energy release sizes due to restarting of production after a couple of days of no production taking place. The two time periods of stress release are also very similar five and three months respectively. The rapid stress release period in both cases was about six times shorter from the time while the stresses were high. In both cases the pillar failure and then the break through resulted in major changes of the stress patterns around the mine. After the failure of the crown pillar larger size seismic energy releases started to appear below the extraction level. When the east pillar failed and broke through there were also some larger seismic energy releases taking place below the extraction level. In both cases the break troughs resulted in increase of the seismic hazard.

7.4.5.2 Seismicity Migration Patterns

Seismicity elevations and the seismicity source parameters are to a large degree independent of each other parameters. In both cases of the two breaks through the seismicity migration patterns were similar. Initiation of the stress caving process resulted in more seismicity taking place closer to the cave. With the cave expanding after the initiation process, the seismicity started to migrate upwards. The failure of the Crown Pillar by the end of 2002 is also evident. At this stage the seismicity reached its shallowest levels for this time period. After the failure the seismicity migrated downwards. During the east break through the seismicity at the east started to migrate upwards by mid 2006. This upward migration lasted only until mid 2007. Due to a decrease in production rates the seismicity during the end of 2007 and beginning of 2008 migrated downwards. Increase in production rates from March 2008 resulted in a rapid upward migration of seismicity. The shallowest seismicity was recorded during May 2008. The minimum elevation at the time of the initial break through was at about −515 m and during the east break through at −490 m (mid 2007) and then at −410 m (May 2008). The seismicity elevations during the east break through during May 2008 were shallower from these during the Crown Pillar failure at the end of 2003. In fact they are the shallowest for the whole history of the mine up to the end of 2008. Analysis of percentages of seismicity taking place above the mine indicate that directly before each of those two breaks through the amounts of shallow seismicity were high. Directly after the break through in both cases the amounts of shallow seismicity decreased rapidly.

7.4.5.3 Seismic Energy Release and Seismic Deformation Patterns

There was much more seismic energy released before, during and directly after the initial break through (above as well as below the mine) than that associated with the east break through, but the highest monthly seismic energy releases were associated with the east part of the mine. The other differences between the energy release at the central and east parts of the mine is the timing and distribution patterns. At the central part of the mine (above the mine) the higher energy releases started after the stress caving process was initiated. The monthly seismic energy release rates then increased considerably after the crown pillar failure, but the highest monthly energy release rates were recorded only after the initial break through. Seismic energy release rates then decreased considerably just after the failure in the open pit. Below the mine the energy releases started after the failure of the crown pillar and ended after the failure in the open pit. At the east part of the mine the energy release pattern was different from the one associated with the initial break through. Above the mine from the beginning of 2005 up to April 2008, the energy releases were extremely low. Then there were enormously high energy release rates during the next three months of April, May and June 2008. During the following months energy releases were again low. This indicates that the rock mass prior to the failure and the break through was strong and not highly fractured so it could absorb a lot of strain energy. This energy release pattern indicates that the east break through took place in highly stressed rock mass conditions. Below the mine at the east the energy releases started when the stresses started to increase. The main releases took place during 2006 and then the energy release rates decreased considerably. The energy released during September 2008 accounts for about 50 % of the total energy released below the mine. This exceptionally large energy release took place two months after the large size energy releases above the mine. This fact indicates that after the east pillar failure and the break through, the stress pattern around the mine changed similar as to what took place after the central pillar failure. By the end of June 2008 the east pillar was so fractured that it was no longer generating larger size seismicity and no longer capable of transmitting stresses. The stresses then migrated down and below the mine with the result being that large size seismicity was recorded during September 2008 below the mine level. There was far more seismic deformation (above as well as below the mine) taking place at the time of the initial break through than during the east break through and also the highest monthly seismic deformation rates were associated with the initial break through. The other difference between the seismic deformation rates during the initial and east breaks through was the timing and distribution patterns. At the central part of the mine (above the mine) the higher deformation rates started to appear after the stress caving process was initiated. The monthly seismic deformation rates then increased considerably after the crown pillar failure, but the highest monthly deformation rates were recorded only after the initial break through. Up to this point the distributions of seismic energy and seismic moment were very similar. After the failure in the open pit the seismic energy release rates decreased considerably while the amounts of seismic deformation remained high.

Below the mine the seismic deformation, similar to the energy release, started after the failure of the crown pillar but did not end after the failure in the open pit as did the seismic energy release. After the failure in the open pit there was still a lot of seismic deformation taking place below the mine. At the east part of the mine the seismic deformation pattern was different from that associated with the initial break through. Above the mine as well as below the mine from the beginning of 2005 up to April 2008, the seismic deformation rates were low. Thereafter there were high seismic deformation rates during April, May and June 2008, but only above the mine. During the following months up to the end of October 2008 the seismic deformation rates above and below the mine were again low.

Analysis of percentages of seismic energy released and seismic deformation taking place above the mine indicate that directly before each of those two breaks through the amounts of shallow energy releases and shallow seismic deformation where high. Directly before the initial break through the seismic energy releases above the mine accounted for 70–90 % of the total energy releases while directly before the east break through these amounts were close to 100 %. As far as seismic deformation is concerned in both cases, directly before the break through, nearly 90 % of seismic deformation took place above the extraction level. Directly after the break through, in both cases, the amounts of energy released as well as seismic deformation taking place above the extraction level, decreased rapidly.

7.5 Production Rates and Seismicity

It is generally assumed that the seismicity induced by mining is directly related to the mining rates. This implies that continuous increase in the volume of the mined out rock mass will always result in more seismicity, more released energy and more of seismic deformation. Presented analysis indicates that this relation for cave mining induced seismicity is different. It seems that seismicity induced by cave mining is related not only to the production rates but also to the caving process itself. For this reason at some stage of the caving process the seismicity is no longer dependent on the production rates. There is probably a short time period when the seismicity is a function of both, production and the caving process. At the end it is only the caving process that influences the induced seismicity. This scenario applies to the seismicity recorded above the mine. Analyzed to date data indicates that the seismicity recorded below the mine is more related to the caving process than to the cave production rates. There are different patterns of seismicity trends above and below the mine. This last means that with time the seismic activity rates the rates of released seismic energy and seismic deformation have different trends and also reach their maximum values at different times. Further study of these trends is important as it should result not only in better understanding of the caving process and defining it stages but also in connecting the caving process with different levels of seismic hazard and risk to underground personnel. It seems that in case of the cave mining the seismic hazard level is associated with the caving process and not with the cave production rates. Figure 7.44 illustrates the monthly seismic activity (vertical bars) and the cave production rates (curve) from the beginning of 2001 until the end of 2013. Both monthly production rates and the seismic activity rates differ month to month sometimes by quite much introducing into the analysis a lot of not so important detail. This detail sometimes might obscure the important features as well as the significant trend changes. For this reason it is practical to smooth the input data before analysing it. Figure 7.45 illustrate the same input data used for creating the image illustrated by Fig. 7.44 but in their quarterly values. Displayed by these two figures trends are the same. What changed is the left side scale. The maximum scale value of Fig. 7.44 is lower from the Fig. 7.45 maximum. Data presented by Fig. 7.45 is clear as the data trends are more obvious. The main features are the two peaks of seismic activity: first one during 2003 and the second one during 2005. In between these two peaks during 2004 the production rates increased. After the second activity peak while the activity rates decrease the production rates still are on the increase. This relation indicates that the seismic activity rates apart of some relation to production must depend also on the caving progress. Figure 7.45 illustrate the quarterly rates of the seismic activity and the production rates for the whole mine. During 2001 and 2002 there was a slow but continuous increase of the production rates that was followed by similar slow but continuous increase of the seismic activity rates. From March 2003 until about October 2003 the production rates increased very rapidly. This production increase was also followed by much more of seismic activity. The maximum of seismic activity by the end of 2003 coincides with the time when the production rates stopped to increase. The following increase of production (from March 2004) resulted in decrease of the seismic activity rates. The maximum recorded activity

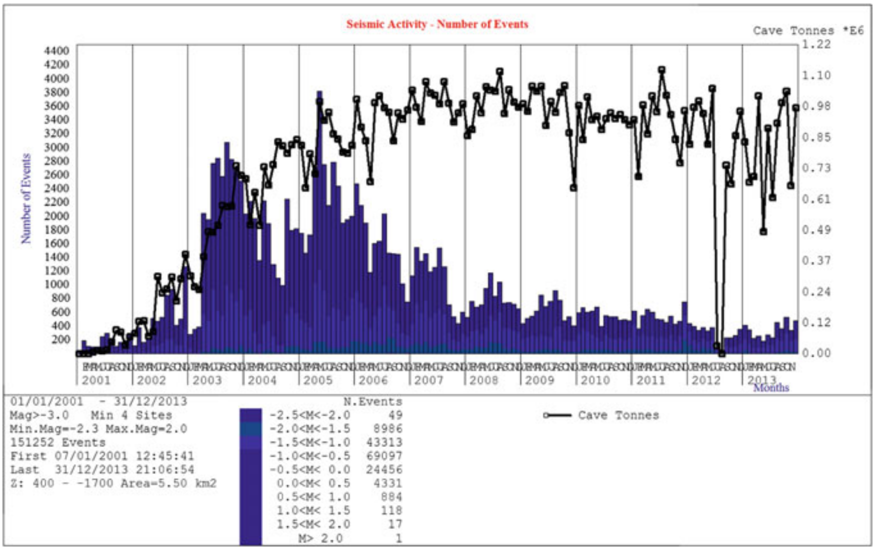

Fig. 7.44 Monthly seismic activity and cave production rates

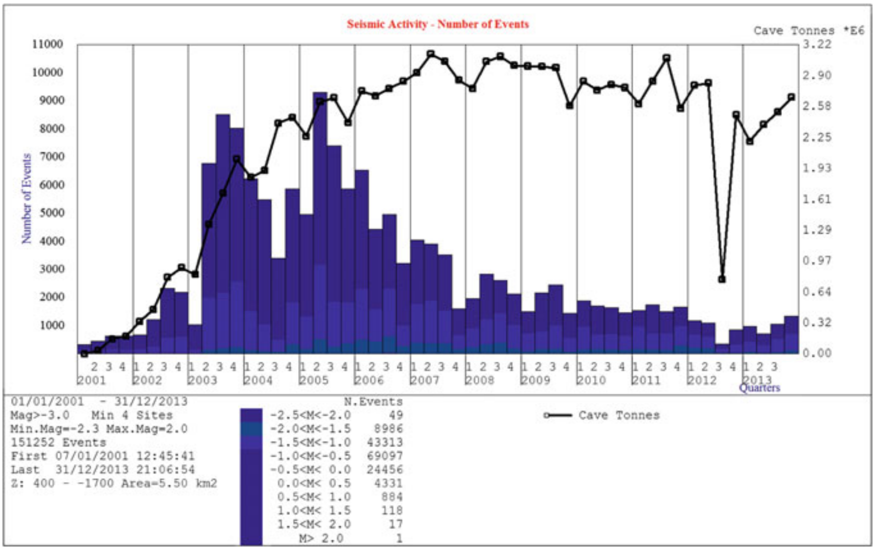

Fig. 7.45 Quarterly seismic activity and cave production rates

rate at mid 2005 coincides with an increased production rate. From then on the two graphs display two opposite trends: the production rates trend is generally increasing while the seismic activity rate displays a strong decreasing trend. This decreasing seismic activity rate trend becomes even more distinct from about mid 2007.

According to data presented by Fig. 7.45 the relation between the production rates was direct proportional only until the end of 2003. During 2004 the relation between these two rates becomes unclear. This is the year when the cave broke into the open pit and there was the failure of the open pit North Wall. It might be that these two factors in some way influenced this relation, for example there was more of seismicity in the shallowest parts of the cave that the seismic system did not record. From about mid 2005 the relation between the two rates becomes inversely proportional. The seismic activity rate graph displays two distinctive peaks. The first seismic activity peak during 2003 takes place after the failure of the crown pillar but before the cave broke into the open pit. The second seismic activity peak of 2005 took place after the failure of the open pit north wall (October 2004).

Next three figures will illustrate this relation for the activity rates, energy release rates and the seismic deformation rates. Each figure will display the activity rate and the production rate for the rock mass volume above the mine (top of each figure) and for the rock mass volume below the mine (bottom part of the figure). For direct comparison each figures top and bottom part has the same scale of the vertical axis. The caving process milestones displayed by these figures are:

A Start of gravity caving (October 2001)
B Start of the stress caving process (April/May 2002)

C Failure of the Crown Pillar (end of 2002)
D Initial break through (May 2004)
E Cave reaching mature stage (August 2007)
F East break through (May/June 2008)
G End of the caving process (October 2012)

Figure 7.46 displays the quarterly seismic activity rates above and below the mine. There is a distinctive difference between these two graphs. Above the mine the seismic activity rates were related to the production rate as from 2002 (this includes development as well as cave mining but only up to the end of 2003, which is the time just before the cave broke into the open pit (D). After the time when the cave broke into the open pit the seismic activity rates above the mine decreased rapidly despite the fact that the production rates were still increasing. Below the mine there was very low seismic activity until the failure of the Crown Pillar (D). Just before the failure in the open pit the seismic activity rate increased very rapidly and reached its maximum by mid 2005. The subsequent decrease in seismic activity rates was also very rapid. There are two activity rate peaks. The first peak of 2003 was associated with the seismicity recorded above the mine. The second peak of 2005 was related to the seismicity recorded below the mine. The first seismic

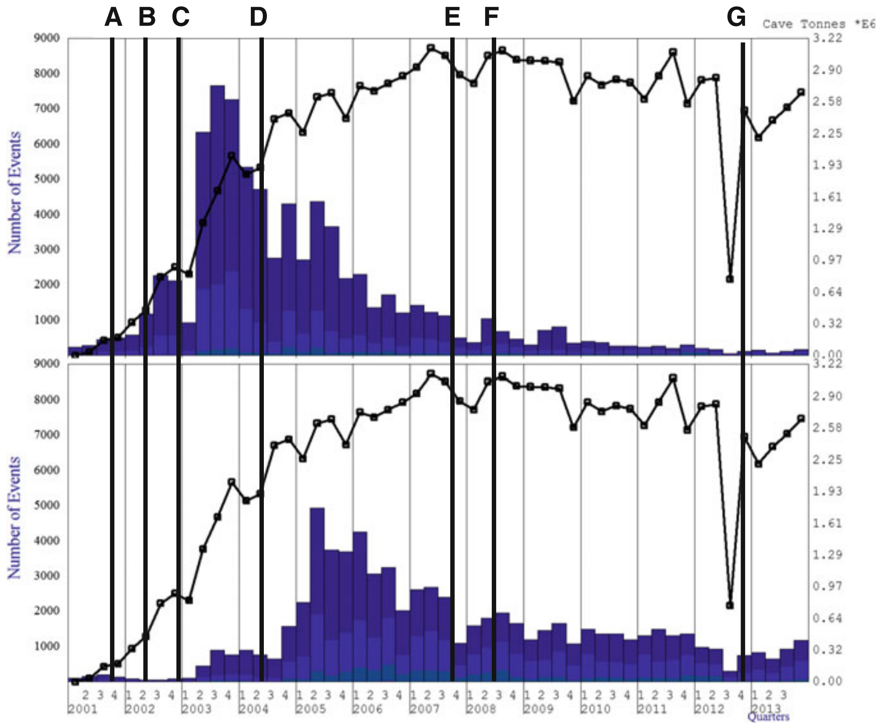

Fig. 7.46 Quarterly seismic activity rates above and below the mine

activity peak during 2003 takes place after the failure of the crown pillar but before the cave broke into the open pit. The second seismic activity peak of 2005 took place after the failure of the open pit north wall (October 2004).

Figure 7.47 shows the quarterly rates for the seismic energy release and the production rates. During 2002 there was a slow but continuous increase in the production rates that was followed by a similar slow, but continuous increase in the seismic energy release rates From March 2003 until about October 2003 the production rates increased very rapidly. This resulted in increased seismic energy rates. From mid 2003 until mid 2004 the energy release rates were the highest for the entire time period. The energy release rates decreased rapidly by the end of 2004 and the beginning of 2005. The 2008 increase in seismic energy release rates was connected with the cave breaking into the open pit on the east side of the cave. As with the seismic activity rates the relationship between the seismic energy release and the production rate changed over time. Up to about end of 2003 and the beginning of 2004 this relationship was directly proportional. During 2004 this relationship was unclear. From the beginning of 2005 to the end of 2007 increased production rates did not result in increased amounts of released energy. During this period the energy release rates appeared to be low and almost constant. There were

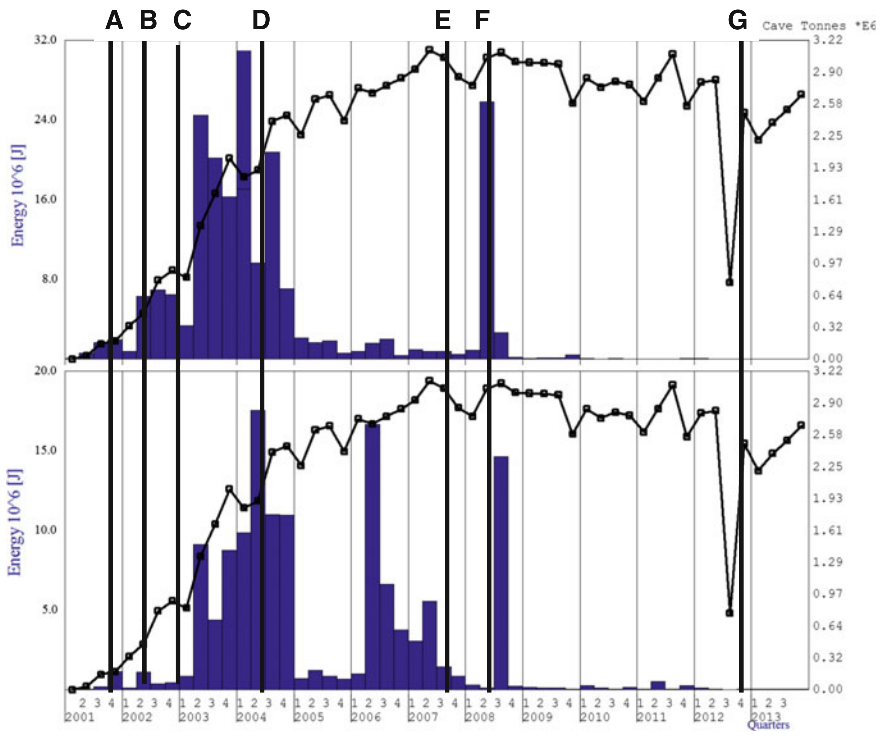

Fig. 7.47 Quarterly seismic energy release rates above and below the mine

three energy emission peaks. Two of these took place after the failure of the crown pillar and before the cave had broken into the open pit. The third peak took place after the initial break through but before the failure in the open pit. Above the mine the energy release rates increased gradually until the failure of the crown pillar. After the crown pillar failure the seismic energy release rates increased rapidly. The subsequent decrease in the released energy was associated both with the initial break through and the failure in the open pit. Failure in the open pit practically resulted in the end of the seismic energy releases above the mine for the following years. The 2008 energy release peak was associated with the cave breaking through at the east during 2008. Below the mine, up to the time when the crown pillar failed, there was practically no seismic energy releases. Seismic energy release rates increased rapidly only after the failure of the crown pillar and then reached their maximum after the initial break through. The subsequent decrease was rapid. During 2006, after a year of very low seismic energy release, there was significantly more seismic energy released. This increased energy release during 2006 took place deeper than the energy releases that occurred during 2003 and 2004. The other difference between the earlier and the later energy peak releases was the absence of seismicity above magnitude size 1.5 during 2006. Seismicity of this size below the mine occurred again during 2008 after the east break-through.

Figure 7.48 illustrates the quarterly seismic deformation rates. Above the mine the seismic deformation rates increased continuously until the failure in the open pit. During this time the relationship between production rate and deformation rate was obviously directly proportional. The direct proportional relationship then changed into an inverse relationship. Below the mine the seismic deformation rates started to increase after the failure of the crown pillar. This general increasing trend lasted until mid 2006. There appeared to be a slight change in this pattern during the second half of 2004, which was when the cave broke into the open pit, and the failure in the open pit took place. From mid 2006 there was a rapid decrease in the seismic deformation rates. The first peak during 2004 relates to seismicity taking place above the mine while the second one that took place during 2006 was associated with the seismicity below the mine. Just as in the cases for the seismic activity rates and seismic energy releases, the seismic deformation trends above and below the mine display differences. It seems that seismicity induced by cave mining is related not only to the production rate but also to the caving process itself. For this reason it becomes apparent that at some stage of the caving process the seismicity is no longer dependent on the production rate. There probably is a short period when the seismicity is a function of both production and the caving process. At the end it is only the caving process that influences the induced seismicity. This scenario applies to the seismicity recorded above the mine. The analysed data indicates that the seismicity recorded below the mine is related more to the caving process than to the cave production rate. There are different patterns of seismicity trends above and below the mine. The implication of this is that over time the seismic activity rates, the rates of released seismic energy and seismic deformation show different trends and also reach their maximum values at different stages. A study of these trends is important, as it should result not only in a better

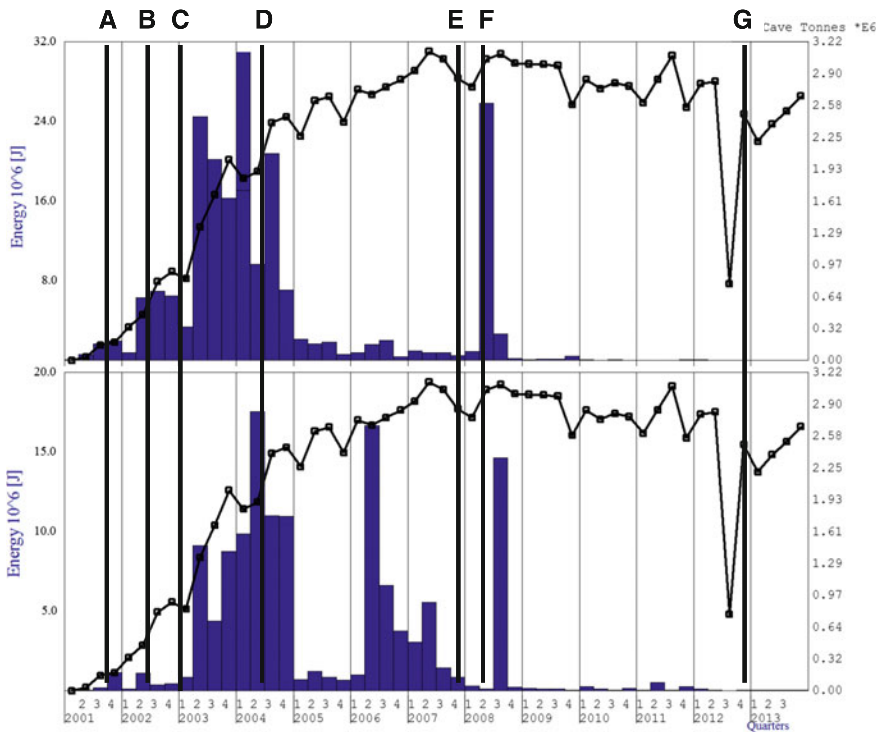

Fig. 7.48 Quarterly seismic deformation rates above and below the mine

understanding of the caving process and assist in defining its stages but will relate the caving process with different levels of seismic hazard and risk to underground personnel. It appears that in the case of cave mining the seismic hazard level is mainly associated with the caving process and not with the cave production rates.

Table 7.17 shows the timing of the various maximum seismicity activity rates above and below the mine. In general the maximum activity rates above the mine are taking place earlier than the maximums recorded below the mine. Above and below the mine all maximum rates take place at different times. Above the mine the maximum seismic activity is first. It is then followed by seismic energy release maximum rate. The last is the maximum seismic deformation rate. The order of the maximum rates below the mine is different. First is seismic deformation rate, then seismic activity rate which is then followed by the maximum seismic deformation rate.

Table 7.17 Timing of the maximum seismicity rates

Rate of	Above the mine	Below the mine
Seismic activity	End of 2003	Mid 2005
Seismic energy	2003	Mid 2004
Seismic deformation	End of 2004	Mid 2006

Figure 7.49 illustrates the fact that after the caving process initiation which had to be by definition associated with increased production rate the seismicity rates increased year after year until 2005. After 2005 the production rates were still increasing but the induced seismicity rates were continuously decreasing. Still the 2012 production decrease clearly resulted in decreased seismicity rates. These rates then increased during the next year with increased production rates.

As indicated by Fig. 7.50, the increase in seismic energy released per year continued for four years, from 2001 to 2004. The maximum of seismic energy was released during 2004. The decrease in the amounts of released energy between 2004 and 2005 is considerable. The total seismic energy releases during 2005, 2006,

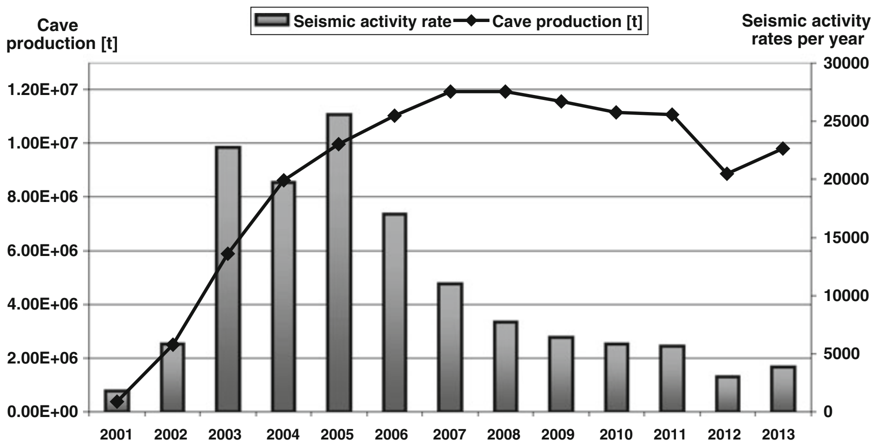

Fig. 7.49 Yearly seismic activity and production rates

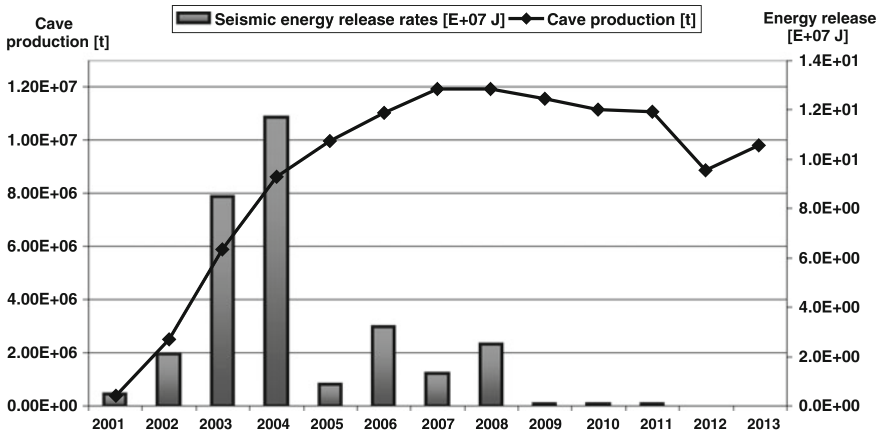

Fig. 7.50 Yearly seismic energy emission and production rates

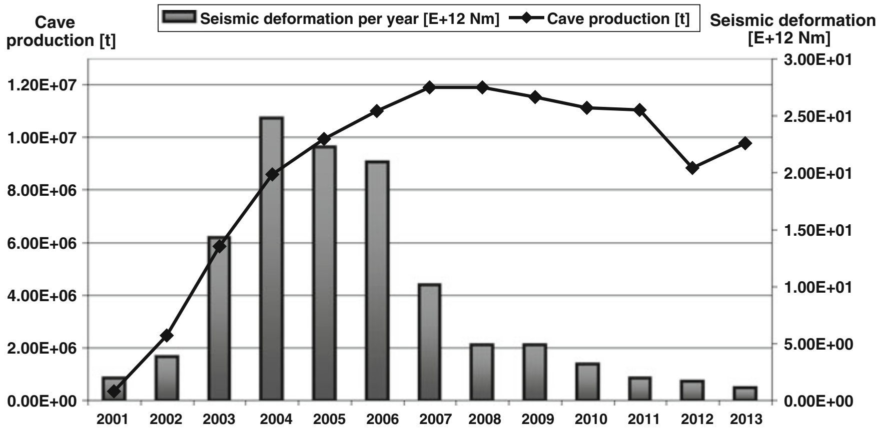

Fig. 7.51 Yearly seismic deformation and production rates

2007 and 2008 were very low. From 2009 for all practical reasons no more of energy was induced by the production rates.

Figure 7.51 shows the total amounts of seismic deformation rates per year As with the amounts of seismic energy released there is an increase year on year from 2001 to 2004. In both cases 2004 is the year of the maximum seismic energy release and maximum seismic deformation rates. After 2004, the amounts of seismic deformation rates per year started to drop but this decrease up to the end of 2007 was very gradual, not like in the case of the seismic energy.

There are different patterns of seismicity trends above and below the mine. Observed seismicity patterns are associated both with production rates and the caving process stages. To start with seismicity above the mine is associated with production rates. This relation then ends some time after the initial cave break through from when this relation doest hold any longer. From this stage this seismicity depends more from the caving process rather than from the production rates. Seismicity below the mine is more related to the caving process stages than the seismicity that is recorded above the mine. Presented analysis indicates that observed to date seismicity induced by the caving process differs from the one induced by the tabular mining. In case of tabular mining it is assumed that increased volumes of mined out rock mass result in more seismicity and more released seismic energy or seismic moment. In case of cave mining increased volumes of mined out rock mass result in more seismicity, released seismic energy and seismic deformation only to a certain point from which all seismicity activities decrease as if mining rates would decrease or stop when in reality the opposite is taking place. Results of this analysis are very important because it indicates that the caving process induces a lot of seismicity also below the mine. This fact will be taken up in Chap. 10 titled "Seismic preconditioning below Lift 1 mine and its influence on the cavability of Lift 2 cave".

7.6 Notes Relating to the Energy Index Time History Shape

The energy index graph lustrated by Fig. 7.52 has two prominent time periods during which the energy index values are above their mean value of 1.0. The first time period starts at the beginning of 2002 and then ends about June 2004. This time period is directly associated with the caving process. The maximum values of the energy index start with the stress caving process initiation and end directly after the initial break through. The second time period which starts at the end of 2011 and ends at the end of 2012, seems not to be associated with the caving process, at least in a direct way.

The energy index time history as presented by Fig. 7.52 was a matter for some deliberations. The main problem was why when the initial break through was associated with very dramatic and undisputed changes in the shape of the energy index there is no such similar energy index changes associated with the east break through. Figure 7.52 doesn't indicate anything of this sort during May/June 2008. So for sure the east break through had to take place only during 2012. This was voiced beyond doubt by some geotechnical engineers and was based only the energy index time history. No one asked me why I placed the east break through in May/June 2008. Apart of being very unprofessional these specialists did not take into account the amount of smoothing and averaging that went into creating this image of the energy index time history. Figure 7.53 illustrates the time setting of the second energy index time periods with values above the mean. This plot is done using different smoothing parameters than those used with Fig. 7.52. This is

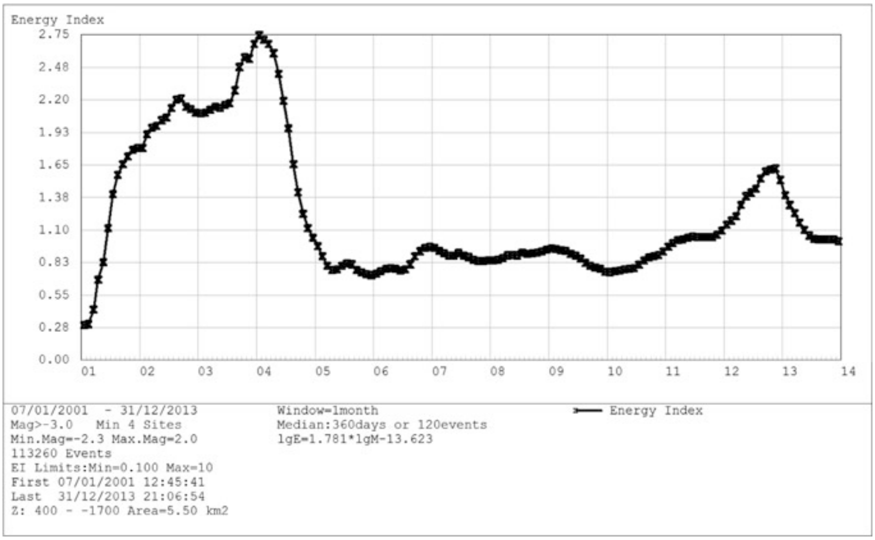

Fig. 7.52 Energy index time history

done in order to place the second energy index anomaly in a more accurate time bracket.

Figure 7.54 illustrates the monthly percentages of seismicity with energy index values above 1.1 from the beginning of 2001 until the end of December 2013. For this time period the average monthly percentage is 55 %. According to this figure there are two time periods during which these percentages were above this mean value:

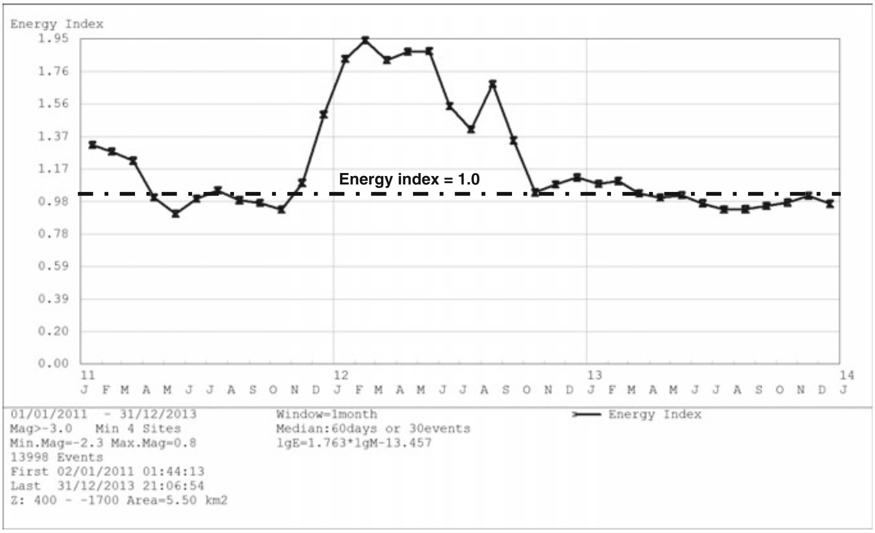

Fig. 7.53 Energy index time history from 01/01/2011 to end of May 2013

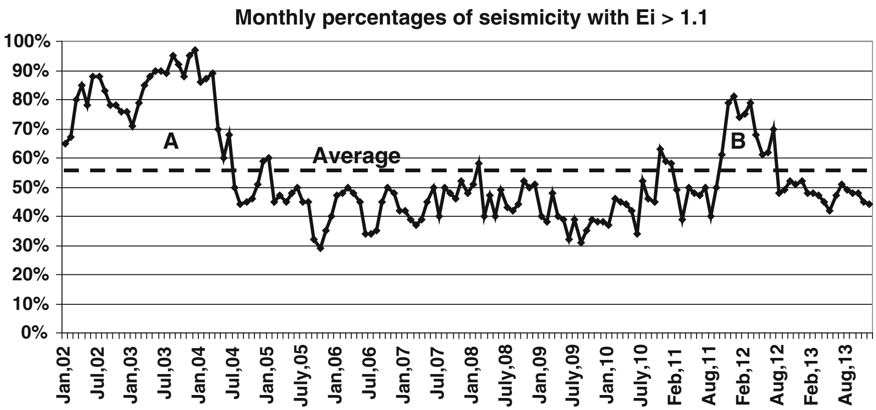

Fig. 7.54 Monthly percentages of seismicity with energy index above 1.1

- Time period A; (30 months) from January 2002 until end of June 2004
- Time period B; (10 months) from November 2011 until end of August 2012

Table 7.18 lists some of the differences in seismicity recorded during these two time periods. As time period "A" has 30 months and time period "B" has only 10 months direct comparisons of the seismicity rates might not be that informative. In both cases there is a considerable percentage of seismicity with energy index values above 1.1. This percentage is based on the totals for the two time periods. When comparing the percentages of seismicity with energy index above 3.0 they are about the same and still significant in size. More important is the fact that here the first difference becomes obvious. The average depth of this seismicity in time period "A" is −600 m while that in time period "B" is −850 m. This indicates that during time period "A" most of the recorded seismicity took place above the extraction level in the rock mass volume where the caving process was taking place. Seismicity for time period "B" was associated with the rock mass volume located below the mine. This indicates that this seismicity located at some distance from the cave. The fourth row indicates the percentages of seismicity taking place above the mine. Again these percentages are based on the number of events listed in row two. During time period "A" 90 % of all recorded seismicity located above the mine. During time period "B" only 17 % of recorded seismicity located above the extraction level. What is more, only 35 % of seismicity associated with time period "A" located close to the mine. This value for time period "B" is unquestionably higher at 70 %. This indicates that the origins of seismicity in these two time periods are certainly different. And this is not the only difference that can be very easily observed. During time period "A" there were 434 seismic events of magnitude 0.5 and above while during time period "B" there was only one event of this size. This means that the amounts of released seismic energy in these two time periods must be very different. The average seismic energy released during each month of time period "A" was 5.93E+06 J while this average value for time period "B" was at 5.16E+04 J. During each month of period "A" the seismic energy release rate was about 100 times higher than during time period "B".As a matter of

Table 7.18 Differences between seismicity of time periods A and B

Values of	Time periods	
	A	B
Number of events	42461	3608
Number of events with Ei > 1.1	27211 (64 %)	4716 (53 %)
Number of events with Ei > 3.0	21345 (50 %)	1640 (45 %)
Average depth of seismicity	−600 m	−850 m
Percentages of events above the mine	90 %	17 %
Percentages of events close to the mine	35 %	70 %
No of events above 0.5	434	1
Total energy released	1.78E+08 J	5.16E+05 J
Average energy release per month	5.93E+06 J	5.16E+04 J

interest the monthly average of 5.93E+06 J for time "A" is an equivalent of seismic energy released by a seismic event of magnitude 1.5. The monthly average of 5.16E+04 is an equivalent of seismic energy released by a seismic event of magnitude 0.5. During this analysis it become evident that although in the two time periods there were high and similar amounts of high energy index seismicity, there is a major difference between the two time periods. This difference is in the origin of seismicity and its strength. Seismicity recorded just after the stress caving initiation process until the initial break through originated from above the extraction level and from around the progressing cave. The seismicity recorded from the end of 2011 until mid 2012 originated from below the extraction level and is not associated directly with the caving process. The seismicity associated with the caving process was of high seismic energy releases. In comparison the seismicity originating from below the extraction level was of low energy release rates. The maim conclusion is that while the seismicity for the time period from January 2002 until end of June 2004 was directly associated with the caving process the seismicity for the time period from November 2011 until end of August 2012 was associated with stress readjustment at the end of the caving process.

7.7 Failure of the Open Pit North Wall

The failure of the north wall of the open pit (October 2004) took place just after the initial break through of the cave into the open pit (May 2004). This failure as such is not a milestone of the caving process. It happened only because of the cave process taking place below and proves the fact that the initial break through took place. After this failure there were a lot of speculations if this event could be predicted with the data recorded by the seismic system. First of all the Palabora seismic system was not design to monitor the open pit walls stability. It was designed only to monitor the caving process. It is true that it has recorded a lot of seismicity that located outside of the mine footprint but this seismicity also located outside of the seismic system. For this reason any analysis of such poor input data can only be used to hypothesize that if there would be a proper seismic network in place would it be then possible to predict the failure. The Palabora case is specific because the mine is located under the open pit and parts of the underground mine are located under the north wall For this reason this failure was expected but it's extend was a surprise. Figure 7.55 illustrates the north wall failure as it was in November 2004.

At PMC the network extension to monitor the ground condition around the Ventilation Shaft has been operational since mid December 2005. This shaft is located in the open pit on the east wall. Figure 7.56 plainly indicates why after the North Wall failure there was concern about the Ventilation Shaft. This extension of the seismic system still has to record something. For a number of years each monthly seismic report contains information that no seismicity was recorded in the vicinity of the Ventilation Shaft. That is why this extension is there. As it is

Fig. 7.55 North wall November 2004

Fig. 7.56 Position of the Ventilation Shaft

illustrated by Fig. 7.57 the failure in the open pit was slow and the wall deterioration was observed for some time before the failure took place.

With slow deterioration of the wall it is difficult to expect some increased seismic activity that would be associated with this type of rock mass relaxation process. There is evident change in the seismicity rates before the failure in the open pit. Figure 7.58 illustrates this fact. This figure presents the monthly percentages of seismicity locating outside of the mine foot print. All events recorded during each month are the 100 % base for these calculations. This figure clearly indicates that from April 2004 there was an increase in seismic activity outside of the mine footprint. The maximum of this activity increase took place in October 2004. By February 2005 this seismic activity increase vanishes. This is a classic case where a precursor could be defined only because it took place before the event. Still for some it might seem to be the real thing.

I have analysed seismicity that might be associated with each open pit wall and its activity rates in relation to each other. Results for the North Wall are illustrated by Fig. 7.59. During the whole 2004 when the initial break through (May 2004) and the failure of the North Wall (October 2004) took place only 20 % of the total recorded seismicity was associated with the North Wall. Only after when the failure was completed during 2005 the monthly percentages of seismicity associated with this wall increased to 80 %.

In conclusion it must be stated that the reason for the observed increase of seismic activity outside of the mine foot print is not because it foretells something. On contrary it is a result of something that already took place. Explanation is simple

Fig. 7.57 Start of the North Wall failure—September 2004

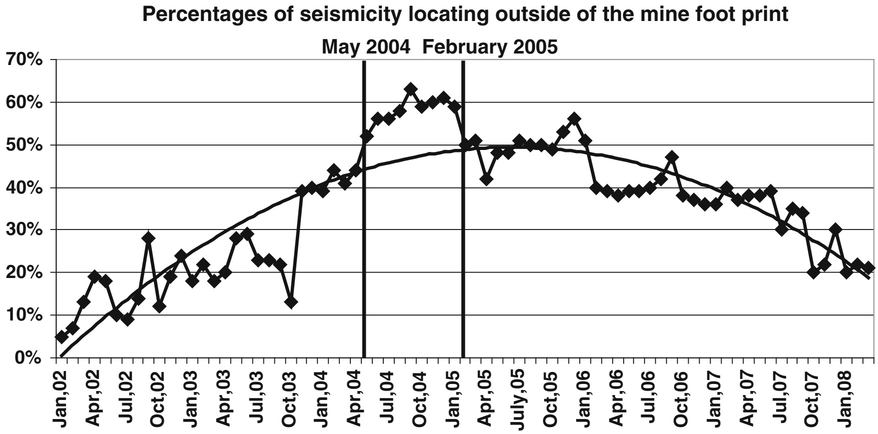

Fig. 7.58 Was the failure predictable?

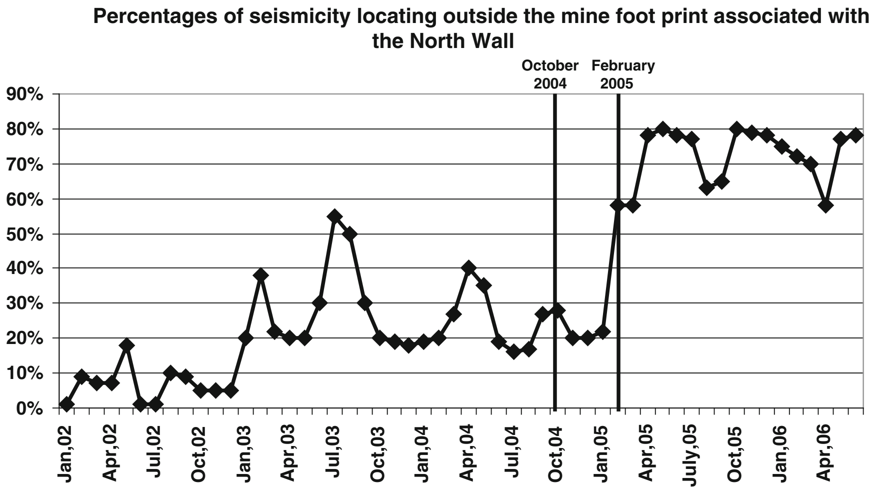

Fig. 7.59 North Wall—percentages of seismic activity rates

and straight forward. During April and May 2004 the initial break through that took place above and inside of the mine footprint. For this reason there had to be an increase of seismic activity outside of the mine footprint. It took a couple of years for the modelling research in the back analysis mode to understand and then come close to what has happened in reality. This is described by Brummer et al. (2006), Sainsbury et al. (2008), Reyes-Montes et al. (2010), Severin et al. (2010) and Woo et al. (2010).

7.8 Summary

Seismicity parameters of Grade I, II and III were used in practice for the purpose of monitoring the Palabora Lift1 caving process and associated with it seismic hazard. The time table is from the beginning of 2002 until the end of 2013. The milestones of the caving progress were reported in real time as they took place. With time the seismic data increased to over 150,000 recorded seismic events that were processed with the same software version. This processing during the whole period was done by one and the same person. For this reason the Palabora seismic data is unique in its consistency. From 2002 the mining rates become an important part of the seismic data. They were updated daily and because of that are extremely accurate not like in cases when they have to be re-created from historical data that usually is not complete. The caving process was monitored mainly using the following seismicity parameters:

- Energy index time history
- Monthly percentages of seismicity locating above the mine
- Seismically active volume
- Average monthly seismicity elevation time history
- Monthly percentages of seismicity with ratio of energy S-wave to energy P-wave
- 24-h distribution of seismicity based on seismicity recorded monthly
- Cumulative seismic moment and cumulative seismic energy release rates

It is evident that there is no direct relation or inter-relation between these seven seismicity parameters. The seismically active volume does not depend on for example the energy index time history or the 24-h distribution of seismicity and so on. It is difficult to state that the monthly percentages of seismicity locating above the mine are related to the seismic energy or seismic moment cumulative trends or the average monthly elevation time history. Analysis and interpretation results of these and other seismicity parameters were published mainly at the caving conferences. Analysis of seismic recorded data resulted in defining seven caving process milestone. I have presented listed below Palabora caving process and its milestones at several conferences.

A. Start of gravity caving October 2001
B. Initiation of the stress caving process, May 2002: Glazer and Hepworth (2004)
C. Failure of the crown pillar at end of 2003: Glazer and Hepworth (2006)
D. Initial break through during May 2004: Glazer (2007)
E. Caving process reaching the mature stage end of 2007: Glazer and Townsend (2010a, b), Glazer (2008)
F. East break through June/July 2008: Glazer and Townsend (2010a, b)
G. End of the caving process at the end of 2012

These seven caving milestones divide the caving history into seven time periods. As the east break through took place only when the caving process reached its mature stage there are only seven time periods:

I. Development mining only: up to 30 September 2001
II. Time between gravity and initiation of the stress caving (7 months)
III. Time between stress caving initiation and crown pillar failure (8 months)
IV. Time after crown pillar failure until initial break through (17 months)
V. Time between the initial break through until the caving process reached the mature stage which lasted 39 months
VI. Time period in which the cave was in mature stage (62 months)
VII. Time period after the caving process ended (13 months to the end of data, 2013)

Data that I have used to verify the seismicity analysis and interpretation results was based on underground observations, occurrence of larger size events and mining rates combined with seismic energy release and with seismic moment. These are the data:

- Occurrence of rock bursts
- Occurrence of seismicity magnitude 1.5 and above
- Percentages of seismicity magnitude 0.0 and above
- Average monthly (for the time period) rate of seismicity magnitude 0.0 and above
- Average monthly seismic energy release per tone of mined out ore
- Average monthly seismic moment per tone of mined out ore

This verification indicates that seismic hazard increases directly after the initiation of the caving process (B). During the time period IV and V that is until the caving process reaches it mature stage (E) the seismic hazard is the highest. This high hazard is indicated by occurrence of high seismic energy release seismicity of which some resulted in rock bursts. There were no rock bursts after the initial break through took place (D). Before the initial break through most of the larger size seismicity occurred above the mine. After this break through most of the large size seismicity took place below the mine level. This fact has its sound reasons in physics and while confirmed by recorded seismicity confirms its reliability and validity. The average monthly seismic energy released per ton of mined ore varies from time period to time period. Its values indicate that start of the caving process resulted in increased seismic energy emission in comparison to that which was released during the development mining. The highest energy releases per tone of ore were recorded during time period IV that is after the pillar failure and before the initial break through. It is interesting to note the large decrease of this parameter values after the caving process reached its mature stage The average monthly seismic deformation per tone of mined ore values are not changing as much with the caving process as the previous parameter. This parameter indicates that the rock mass is caving continuously even when there is no larger size seismicity taking place. This verification of the seismicity analysis and interpretation describes the relation between the caving process and the Lift 1 Mine seismic hazard and it applies to Lift 2 Mine Glazer (2012). This is due to the fact that the sources of Lift 2 seismic hazard are already known because of Lift 1 experience. As always with nature there will be some unknown factors that will influence the Lift 2 seismic hazard. In nature nothing happens twice in exactly the same way. For this reason it must be expected that the seismic hazard history of Lift 2 might not be exactly as it was in case of Lift 1. There will be differences due to the increased depth of Lift 2 extraction level, which will be located 1600 m below the surface. This should result in higher energy release rates and consequently in increased seismic risk This is not certain as in the early stage of the caving process the induced seismicity is strongly related to the production rates. In case of Lift 2 it is easy to figure out that the initial production rates and their increase with time might be different to these of Lift 1. On the other hand half of the recorded to date seismicity took place in the rock mass volume that will be Lift 2 cave. This seismicity has preconditioned this rock mass volume. Preconditioning decreases the seismic risk. In case of Lift 2 increased depth will increase the seismic risk while preconditioning will decrease this risk. The question remains in what proportions? Other applications of seismic monitoring applicable to Palabora Lift2 are described in Glazer and Townsend (2008).

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Chapter 8
Caving Process and Seismic Hazard

Palabora experience indicates that seismic hazard and seismic risk change with the caving process but these changes are not always corresponding (Glazer 2012). In this chapter I have used the recorded seismic data to describe the methodology for monitoring the seismic risk. It is interesting to note that presented results based on the analysis of independent of each other parameters (for example energy release of small events, time histories and the Peak Particle Velocity of larger size seismicity) resulted in good agreement. It is important to recognize that some of the parameters are derived from the same seismic source values. In such case the analysis results do not complement each other but simply repeat each other. In this paragraph I do not propose an absolute scale for the seismic risk description. All results are relative and describe the changes in seismic risk over time. From presented in this paragraph analysis it emerges that with the caving process the highest seismic hazard is associated with initiation of the caving progress and then with the cave breaking through. This paragraph describes the methodology that allows for monitoring the changes in the seismic risk. As the seismic risk is directly associated with the stress levels then its estimations should result in more accurate seismic risk approximation.

8.1 Seismic Risk Indicators

It is accepted that seismic hazard is expressed by the expected maximum magnitude that can take place. It is also accepted that the higher this expected magnitude the higher is the seismic hazard. The other factor that plays a role in seismic hazard estimation is the possibility of the maximum magnitude event taking place in a specific time frame. Those are the general rules that are applied to seismic hazard estimation and they follow what is practiced in global seismology. However, the underground damage due to a seismic event taking place is a function of many variables. The event magnitude in the seismic hazard estimation is important but does not totally influence the possible extent of the damage. It is a fact that events of

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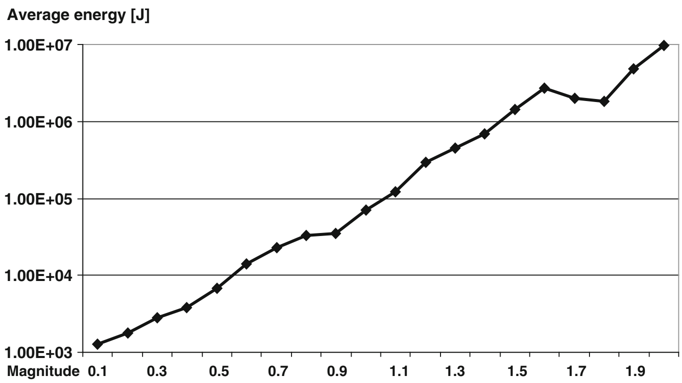

Fig. 8.1 Average seismic energy releases by events of magnitude range 0.0–2.0

the same magnitude size result in extensive damage or no damage what so ever. Apart from geometry, which in this case defines the relationship between the source and the underground excavation positions, the geotechnical characteristics of the geological discontinuities, there is one more important factor that must be taken into account. Here I am thinking about the stress regime that in mining environment is not constant and changes continuously with the caving process. Figure 8.1 illustrates the average seismic energy released by seismicity of magnitudes in range starting from 0.0 and ending with magnitude 2.0. Table 8.1 lists the total energy released by these magnitudes (for the time period 01/01/2001–31/12/2010) and then the average energy release. The energy release range is large and taking into account that the number of events is based on 10 years of data, the following is of specific interest:

1. In general with increasing magnitude size there are less events
2. This relationship doesn't hold for some of the largest size events indicating that there is more that one mechanism triggering these size events (Fig. 8.2)
3. Taking into account the total energy released by a single magnitude size it is interesting to note that the lower size events released substantial amounts of energy that are comparable with the larger size events energy releases (Table 8.1)

Figure 8.2 illustrates the fact that the number of the larger size events doesn't fit to the pattern of seismicity originated from only one source of seismicity. The numbers on the horizontal axis are indicative of the magnitude sizes as listed in Table 8.1.

Figure 8.3 illustrates the fact that the lower magnitude ranges released more seismic energy than the larger ones. The horizontal axis numbers refer to magnitude ranges as listed in Table 8.2. If one assumes that the damage magnitude includes magnitudes 0.5 and above, then all seismic events up to magnitude 0.5 released 75 % of the total released seismic energy. This leaves only 25 % of total energy that was released by events of magnitude above 0.5.

Table 8.1 Magnitude size and seismic energy release sizes

No	Magnitude range	Number of events	Energy release (J)	Average energy (J)
1	0.0 ≤ M < 0.1	7826	9.93E+06	1.27E+03
2	0.1 ≤ M < 0.2	5679	1.00E+07	1.77E+03
3	0.2 ≤ M < 0.3	3996	1.11E+07	2.78E+03
4	0.3 ≤ M < 0.4	2799	1.06E+07	3.77E+03
5	0.4 ≤ M < 0.5	1775	1.21E+07	6.82E+03
6	0.5 ≤ M < 0.6	1149	1.63E+07	1.42E+04
7	0.6 ≤ M < 0.7	763	1.74E+07	2.29E+04
8	0.7 ≤ M < 0.8	484	1.60E+07	3.30E+04
9	0.8 ≤ M < 0.9	330	1.14E+07	3.46E+04
10	0.9 ≤ M < 1.0	217	1.53E+07	7.05E+04
11	1.0 ≤ M < 1.1	143	1.76E+07	1.23E+05
12	1.1 ≤ M < 1.2	92	2.70E+07	2.93E+05
13	1.2 ≤ M < 1.3	53	2.41E+07	4.54E+05
14	1.3 ≤ M < 1.4	29	1.98E+07	6.84E+05
15	1.4 ≤ M < 1.5	10	1.45E+07	1.45E+06
16	1.5 ≤ M < 1.6	4	1.07E+07	2.68E+06
17	1.6 ≤ M < 1.7	13	2.62E+07	2.02E+06
18	1.7 ≤ M < 1.8	1	1.85E+06	1.85E+06
19	1.8 ≤ M < 1.9	1	4.75E+06	4.75E+06
20	1.9 ≤ M < 2.0	2	1.93E+07	9.64E+06

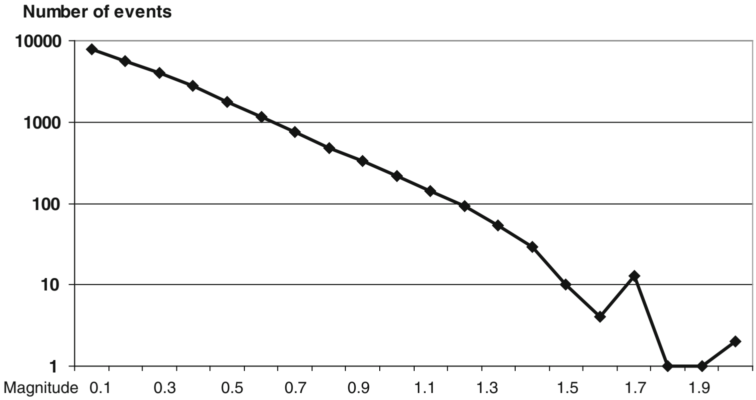

Fig. 8.2 Number of seismic events

More interesting is the time distribution of the seismic energy release and its relation to the caving process This was already presented in Chap. 7 where Fig. 7.6 illustrated the time changes of the monthly seismic activity rates, the seismic energy release rates and of the seismic deformation rates. All these monthly activity rates

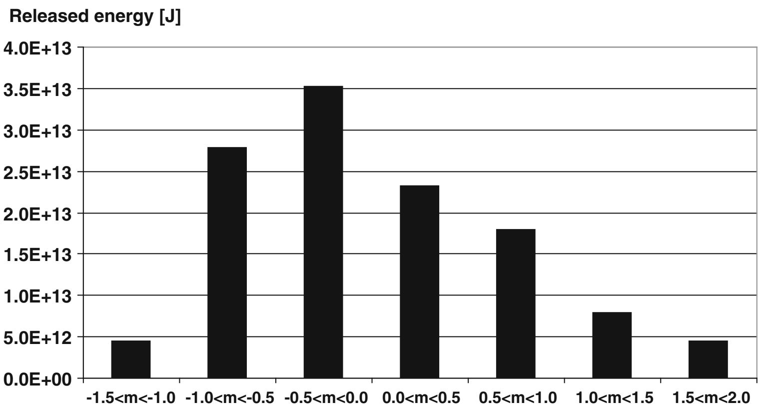

Fig. 8.3 Energy release rates per magnitude ranges

Table 8.2 Magnitude ranges and energy release sizes

No	Magnitude range	No of events	Released energy (J)
1	$-1.5 < M < -1.0$	44637	4.45E+12
2	$-1.0 < M < -0.5$	69209	2.79E+13
3	$-0.5 < M < 0.0$	24235	3.53E+13
4	$0.0 < M < 0.5$	4231	2.33E+13
5	$0.5 < M < 1.0$	866	1.80E+13
6	$1.0 < M < 1.5$	113	7.90E+12
7	$1.5 < M < 2.0$	17	4.45E+12

were normalised by the average rate which is based on data recorded from the beginning of 2001 until the end of 2013. This average is 100 %. This figure illustrates the fact that during different time periods the monthly rate was either lower or higher than the average rate. For example a monthly rate of 50 % indicates that it is half of the average while rate of 200 % indicates that it is twice the size of the average. Figure 7.6 clearly indicates that the caving milestones are characterized not only by different size rates but also by distinctive changes in their sizes. In character these changes are similar for the three rates. In size the largest changes are associated with the seismic energy release rates. During the time period (I) when only development mining was taking place the energy release rates were very low at less than 25 %. The initiation of the caving process (A) resulted in increased seismic energy release rates up to 100 %. This first significant increase during time period (II) lasted until the failure of the crown pillar (B). The crown pillar failure resulted in still a further and significant energy rate increase up to nearly 300 %. The energy release rates then remained at this level to the end of time period (III) which ended with the initial break through (C). After the initial break through the energy release rates decreased to the level of 100 %. It is worth noting that during time period (III) during which there was only production from the cave these rates were nearly four times higher than during the time period (I) when there was only development mining taking place. The east break through (E) resulted in a short time period increase in the energy release rates. The time increase was short but it size was large as during the east break through the increase was from 100 % up to nearly 400 %. After the east break through the seismic energy release rates decreased rapidly down to about 25 % and remained at this level to the end of 2010 (during time period (V)). Figure 7.9 (Chap. 7) illustrates the normalized seismic energy release rates above the extraction level and below the extraction level. This figure illustrates the fact that the seismic energy release rates were changing differently above and below the mine. The initiation of the caving process resulted in increased seismic energy release rates (up to 200 %) but only above the mine. The energy release rates below the mine increased only after the crown pillar failure and this increase was then up to 100 %. From the time the crown pillar failed until the initial break through the seismic energy release rates above the extraction level were twice as high as those below the extraction level. The initial break through resulted in a decrease in the rates above and in increased rates below the mine. After the initial break through was completed the energy release rates above and below the extraction level stayed at about the same level (50 %). From about mid 2007 the two rates decreased indicating that the caving process reached its mature stage Still the east break through resulted in significant increase in the energy release rates above the extraction level. This time this increase was from 50 % to nearly 400 %. Only after the east break through was completed there was a substantial increase in the energy release rates below the mine. It is worth noting that this pattern of increased seismic energy release below the mine after this second break through is similar to the one experienced earlier after the initial break through. From the presented data it emerges that with the caving process the highest seismic risk is associated with:

- Initiation of the caving process
- Break through

If the pillar failure and the break through are not taking place immediately then the high seismic risk is also associated with the time period after the pillar failure up to the time the break through is completed. As seismic data (together with other geotechnical measurements) can be used to monitor the cave progress then the timing of the increased seismic risk should also be known. Presented data indicates that the magnitude size values can be a misleading indicator of the actual seismic risk. As the seismic risk is directly associated with the stress levels then its estimations should result in more accurate seismic risk approximation. There are several seismic parameters that can be used for this purpose. These parameters are:

- Apparent stress
- Energy index
- Seismic energy release by small size events

It must be understood that these three parameters are derived from seismic energy and seismic moment. For this reason it should not be expected that they can provide independent from each other information. Use of one of these parameters depends mainly on the individual preferences and the quality of the graphical display.

8.1.1 Apparent Stress

According to Gibowicz and Kijko (1994) the apparent stress is defined as follows:

The apparent stress is (Wyss and Brune 1968):

$$\sigma_a = \mu\, E/M_o = \eta\, \sigma$$

where μ is the shear modulus of the source material, E is the radiated energy, η is the seismic efficiency, and $\sigma = (\sigma_1 + \sigma_2)/2$ is the average shear stress acting on the fault, in which σ_1 is the stress level before and σ_2 is the stress level after the occurrence of an earthquake. Madariaga (1976) has demonstrated that the apparent stress is proportional to the dynamic stress drop, but does not represent an actual stress difference. "If the P-wave contribution to the seismic energy and the azimuthal dependence of the energy flux are neglected, then Brune stress drop is a constant multiple of the apparent stress (Snoke 1987). For some mines tremors the energy of P-waves cannot be neglected and the apparent stress becomes an independent parameter" (Gibowicz et al. 1990, 1991). Figure 8.4 illustrates the relation between moment magnitude and the apparent stress. This figure indicates that every

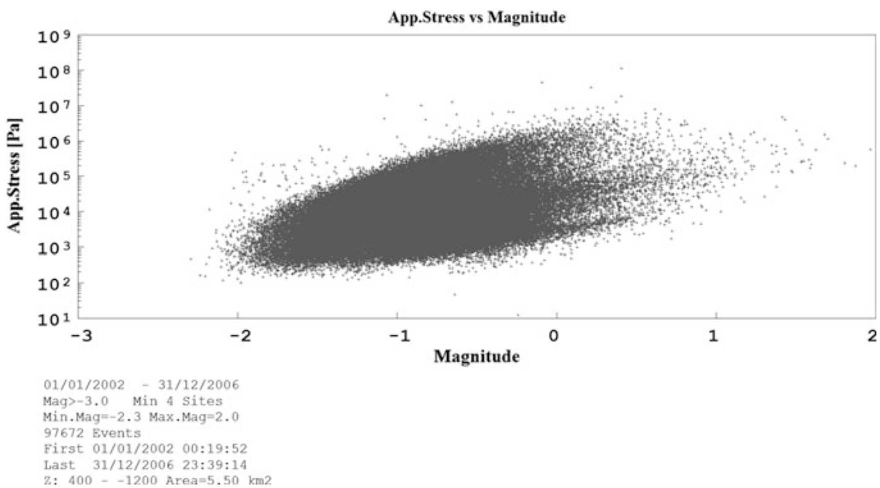

Fig. 8.4 Apparent stress versus magnitude

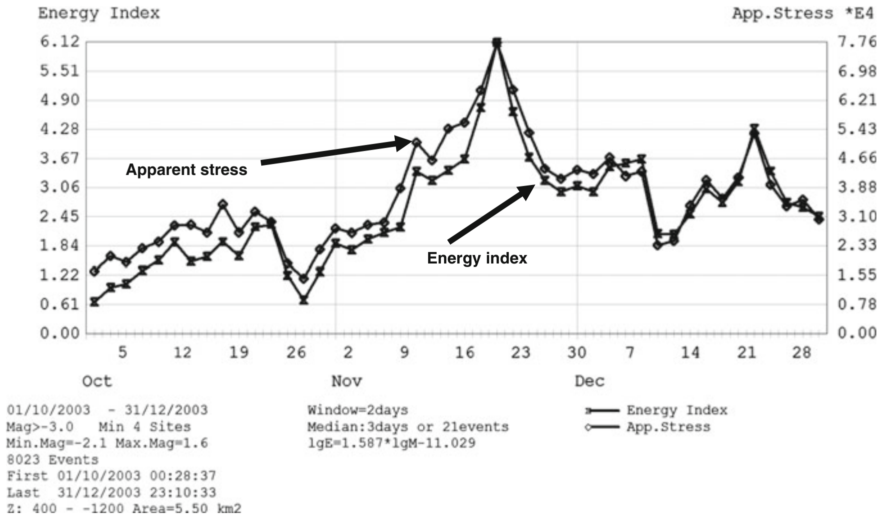

Fig. 8.5 Apparent stress and energy index time histories

magnitude size has a very wide range of apparent stress values. The other fact is that there is a general relationship between the apparent stress and the magnitude size. The higher the magnitude the higher is the stress range related to the magnitude. This proportional relationship between the magnitude size and the apparent stress restricts the direct application of this parameter for stress monitoring. In order to use the apparent stress to monitor the underground stress distribution one has to make use of one size magnitude events. This on its own is a problem as in general there are not to many events of the same magnitude size recorded in a reasonably short time period to make the analysis consistent.

There is still another way to make use of the apparent stress to monitor the stress. This is illustrated by Fig. 8.5 where the apparent stress time history indicates the stress changes during the last 3 months of 2003. This graph is based on all recorded during this time period seismic events. The other graph is the energy index time history. As both the energy index and the apparent stress are derived from seismic moment and seismic energy then their time history graphs are similar in regard to their trend. As their vertical axis's are different then their absolute values at any given time are also different. None of these two time histories can be used to provide any additional information that can be deducted from only one of them.

8.1.2 Energy Index

Energy index is derived from seismic energy and seismic moment. Figure 8.6 illustrates the energy index concept. It displays the relationship between seismic

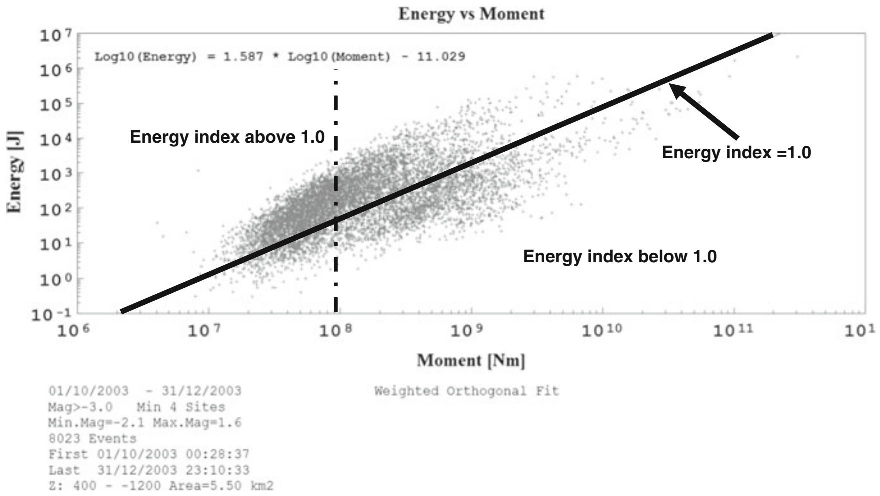

Fig. 8.6 Energy index concept

moment (horizontal axis) and energy (vertical axis). The black skew line is the fit into this data in this case it is a weighted orthogonal fit. This fit represents the mean value of the energy index. The energy index for a given seismic moment is calculated as a ratio between the measured energy release and the mean value for this moment value (on the best fit line). As for each moment value there is a wide range of seismic energy values then the energy index above the best fit line will be greater than one, and lower than one below this best fit line. When the measured value and the value on the best fit line are the same the energy index will be equal to 1.0. This is the mean value and is the same for the whole moment range. In this way the energy index concept allows for comparing with each other all events from a given catalogue regardless of their magnitude size, seismic moment and released seismic energy. This makes the energy index very flexible and applicable to a number of interpretation techniques. The theory behind the energy index concept is simple. As the same seismic moment seismic event can emit different amounts of energy then this energy size must be related to the stress regime. The higher this stress the higher will be the size of the released energy for every given moment value. With this in mind the energy index concept can be used to monitor the stress. It cannot be used to measure the stress but can be used to compare the stress regimes in space and time. The interpretation of the energy index in space will result only in defining the part of rock mass volume in which the stress is higher or lower relative to the other parts of this volume. The interpretation with regard to the time domain will allow establishing time periods in which the stresses increased or decreased and also compare the stress levels for different time spans to each other. It must be understood that the best fit (or the position of the mean value) will depend on the amount of input data that was used for its calculation. In this way the mean will be always associated with the time span during which the input data was recorded.

Lets assume that there are two subsets of data one consisting of events recorded during a short time period (lets say 3 months) and a second longer time period subset (for example 3 years) and that this specific 3 month time period is included in the 3 year period. In this way all events of the first subset will be included in the second subset. In this case the same events depending on to which subset they belong will have different energy index values. Because of this the interpretation of the energy index absolute values makes no sense. Further more calibration of energy index with underground stress measurements also makes no sense.

As already indicated there are several ways of making use of the energy index to display the stress distribution. These are:

- plotting maps with events displayed in various ranges of energy index
- contour maps of energy index values
- time history of energy index

There is still one more way in which the energy index can be used. One can investigate the appearance in time and space of only the high energy index seismic events. High is a relative description for a parameter. Still it is possible to decide what is high taking for example what percentage of events in a given data set is above 5.0 or 8.0. Based on such technique I will analyse the seismic risk separately above and below the extraction level. The input data consisted of about 145,000 events and the limit between low and high energy index values will be 8.0. From the beginning of 2001 until the end of 2013 there were nearly 22,000 such events that located above the extraction level. Figure 8.7 illustrates the monthly rates of

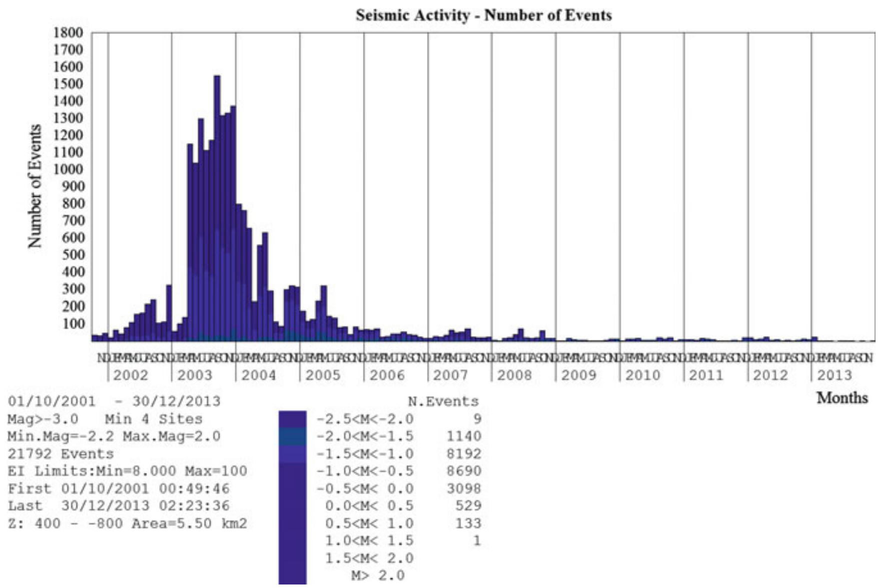

Fig. 8.7 Monthly high energy index events activity rates above the extraction level

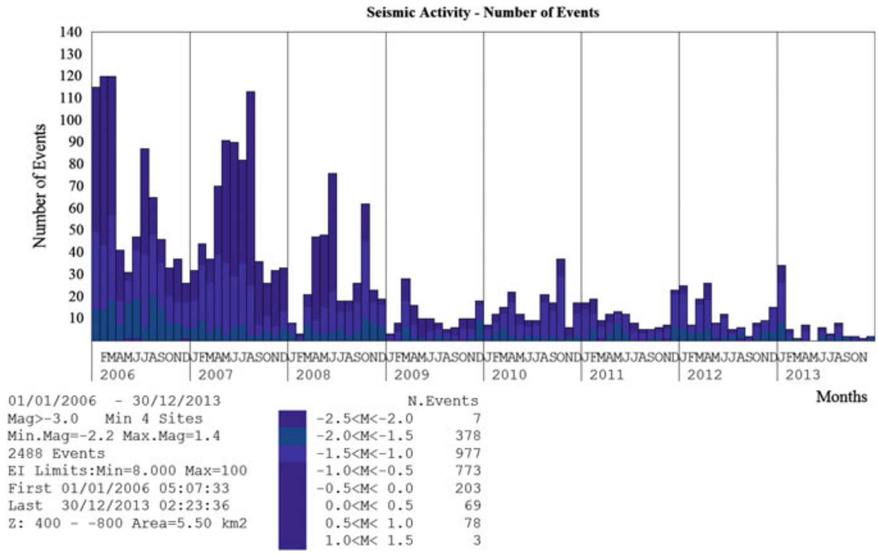

Fig. 8.8 Monthly high energy activity rates above the extraction level after 2006

these high energy index events. Most of these events took place in the time period after the initiation of the caving process (April 2002), lasting until the initial break through was completed May 2004).

After the initial break through was completed the amounts of high energy index seismicity taking place above the mine decreased. Figure 8.8 illustrates this fact. Figure 8.9 illustrates the monthly activity rates of seismicity with energy index above

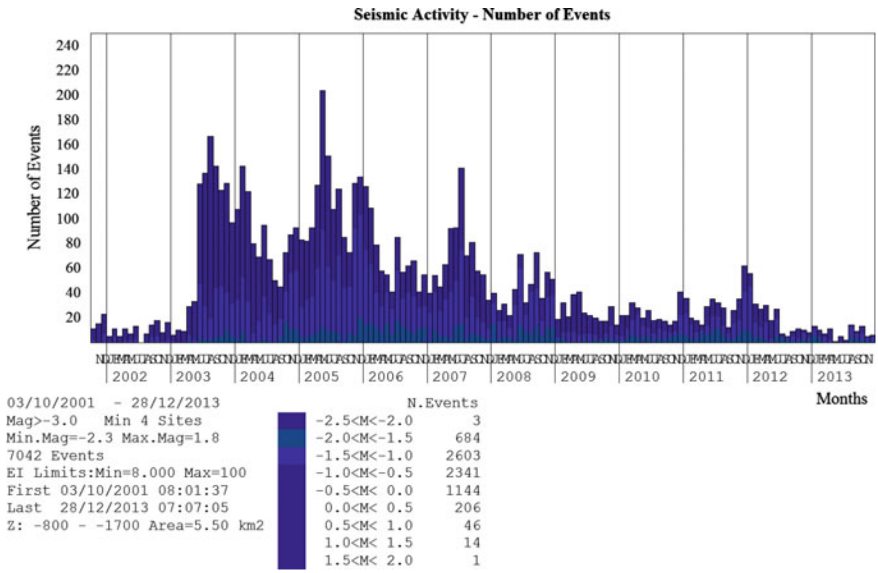

Fig. 8.9 Monthly high energy index rates below the extraction level

8.0 below the extraction level. There are less of these events below the extraction level than above it. Above the mine there were 21,700 events while below the mine only 7,000 events. These events below the mine started to appear only after the crown pillar failure and they are more evenly spread in time from these above.

8.1.3 Energy Release by Small Size Events

Figure 8.10 illustrates the monthly seismic energy release rates The horizontal doted line indicates the mean monthly energy release. This mean is based on total energy that was released from the beginning of 2001 to the end of 2010. Up to April 2002 the monthly seismic energy releases are very low. Initiation of the caving process (A) resulted in increase of the monthly rates. The rates from this time until the initial break through was completed (C) were high and constantly higher than the mean value. After the initial break through was completed the energy release rates decreased. The east break through again was associated with increased seismic energy release rates. The 2006 higher energy release rates were associated with seismicity taking place below the extraction level. Seismic energy release rates only initially depended on the production rates. After the caving process was initiated the amounts of released seismic energy started to depend on the caving process itself.

Figure 8.11 illustrates the average seismic energy release by events of magnitude range −1.0 up to 0.0

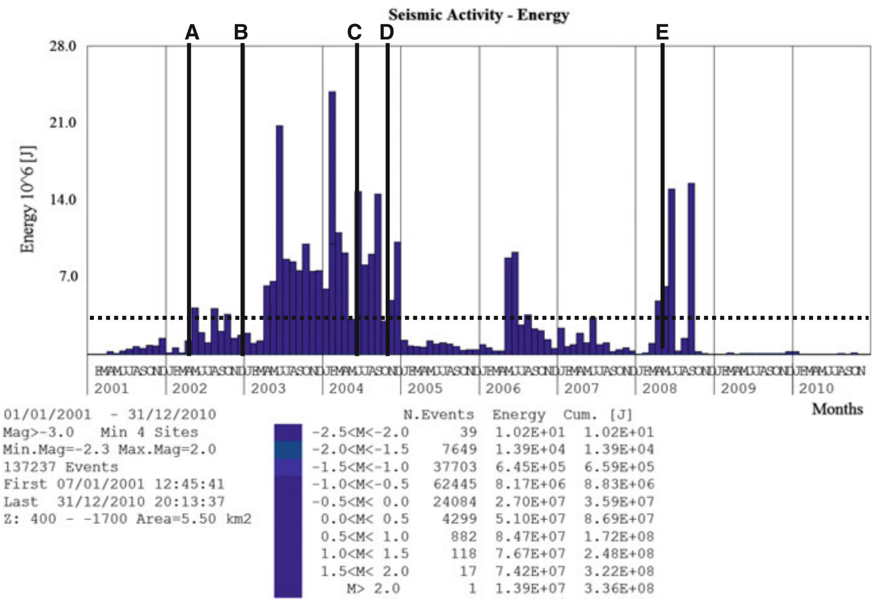

Fig. 8.10 Monthly seismic energy release rates

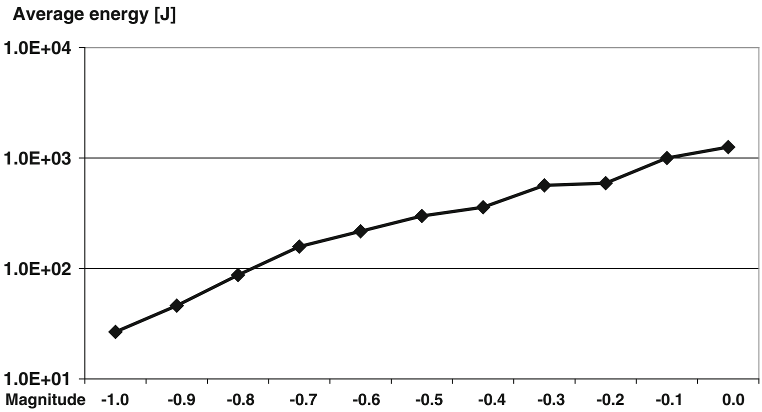

Fig. 8.11 Average seismic energy release by events of magnitude range −1.0 up to 0.0

Figure 8.12 illustrates the average energy released by events size −0.5 as well as their activity rates. The number of events, total energy release and the average energy released by events size from −1.0 up to 0.0 are listed in Table 8.3. The amounts of energy released by these small events are comparable with the energy released by the larger size events (see Table 8.1). For obvious reasons there are much more of these small size events than of the largest ones. The small size events can be used to monitor the seismic risk and its changes with time. According to Table 8.3 there were 11,597 events of magnitude in range from −0.5 to −0.4.

Figure 8.12 illustrates the bi-monthly energy release rates by events of magnitude −0.5 as well as their bi monthly activity rates. According to data presented the maximum energy rates were recorded during 2003 and 2004. After mid 2004 the

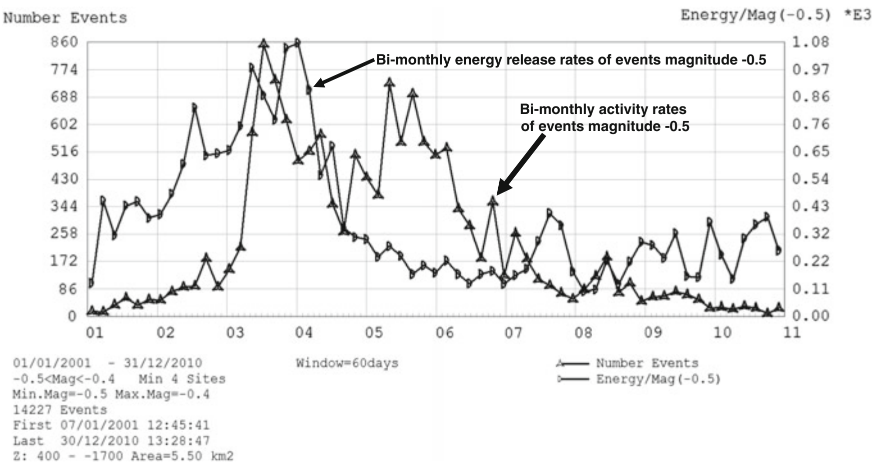

Fig. 8.12 Monthly seismic energy release rates of events magnitude –0.5

Table 8.3 Magnitude size and seismic energy release sizes (small events)

Magnitude range	Number of events	Energy release (J)	Average energy (J)
−1.0 ≤ M < −0.9	5897	1.56E+05	2.64E+01
−0.9 ≤ M < −0.8	8381	3.83E+05	4.57E+01
−0.8 ≤ M < −0.7	9730	8.48E+05	8.72E+01
−0.7 ≤ M < −0.6	10213	1.59E+06	1.56E+02
−0.6 ≤ M < −0.5	10575	2.31E+06	2.18E+02
−0.5 ≤ M < −0.4	11597	3.43E+06	2.96E+02
−0.4 ≤ M < −0.3	13204	4.78E+06	3.62E+02
−0.3 ≤ M < −0.2	13587	7.66E+06	5.64E+02
−0.2 ≤ M < −0.1	12684	7.46E+06	5.88E+02
−0.1 ≤ M < 0.0	10332	1.03E+07	9.96E+02
0.0 ≤ M < 0.1	7826	9.93E+06	1.27E+03

energy rates decreased and up to the end of 2010 were very low. The activity rates do not correspond to the energy release rates. For example, the relatively high activity rates of 2002 did not result in high energy release rated during this year. High activity rates recorded during 2003 and then in the first half of 2004 resulted in more seismic energy being released. Then higher activity rates recorded during 2005 did not result in increase of the energy released. From 2006 until the end of 2010 the activity rates become more continuous while the amounts of released seismic energy decreased. This indicates that the amounts of seismic energy released by these size magnitude events had to change over time. As indicated by Fig. 8.13 the higher energy release rates of events magnitude −0.5 are associated with the time period during which the stress levels, as indicated by the seismic energy index time history, were high.

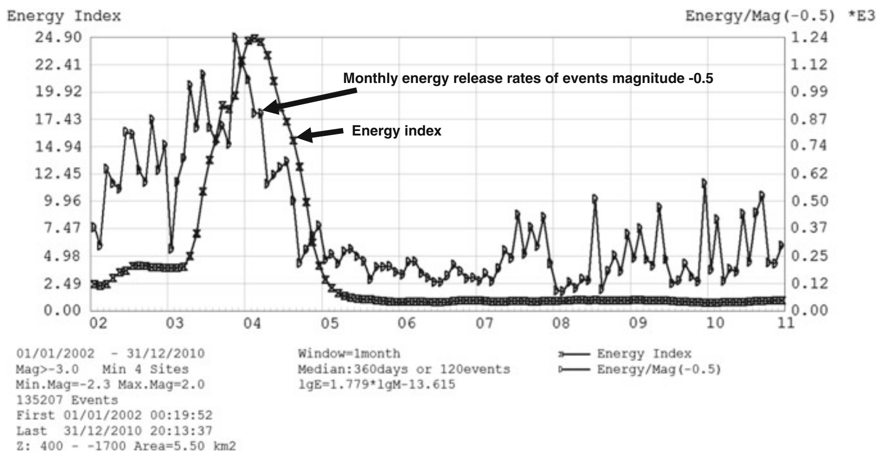

Fig. 8.13 Energy index and average monthly energy release rates events −0.5

Table 8.4 Energy release ranges for low size magnitude events

Magnitude size	Minimum energy (J)	Maximum energy (J)	Energy range (times)
−1.0	1.58E+00	2.54E+02	160
−0.9	1.78E+00	2.08E+02	116
−0.8	3.16E+00	2.96E+02	93
−0.7	4.06E+00	5.32E+02	131
−0.6	4.53E+00	8.61E+02	190
−0.5	7.38E+00	1.59E+03	215
−0.4	2.02E+01	2.54E+03	125
−0.3	2.41E+01	4.18E+03	173
−0.2	3.39E+01	6.35E+03	187
−0.1	2.88E+01	7.08E+03	245
0.0	3.36E+01	8.97E+03	266

Table 8.4 lists the minimum and maximum energy release rates of events from magnitude size −1.0 up to magnitude size 0.0. These rates were calculated with some iteration in order to exclude the extreme values. In case of magnitude 0.0 the energy release changes from 7.38E+00 J up to 1.59E+03 J. The size of the highest energy release is nearly 200 times higher than the lowest energy release rate. This energy release range is rather large. According to data presented by Table 8.4 the average range for all data is about 170. Figure 8.14 illustrates the differences between the maximum energy release rate (top line) and the minimum energy release rate (bottom line) for the magnitude range from −1.0 up to 0.0.

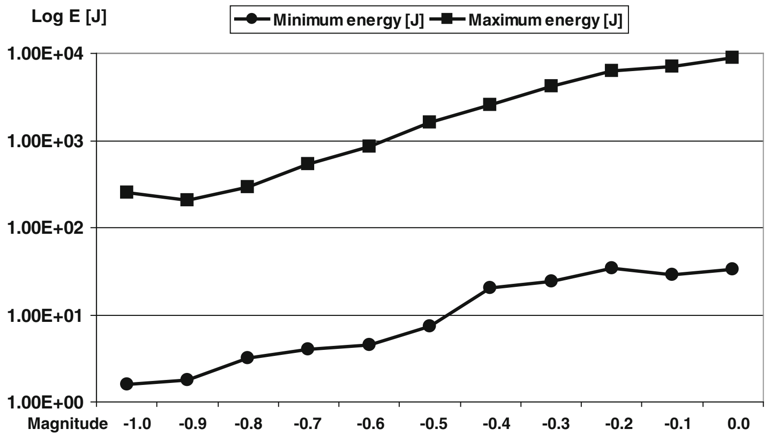

Fig. 8.14 Energy release ranges (for data presented by Table 8.4)

8.2 Seismic Hazard Estimation

Statistical methods of seismic hazard evaluation use the past seismic history to estimate the future seismic hazard. The statistical methods of seismic hazard evaluation should be used for the whole mine only. It is also possible to use the actual recorded seismicity to monitor the change in the seismic hazard level over time. This second method makes use of the various seismic parameters It should be used with caution as this method, in certain situations, can be applied to selected parts of the mine. Here the main problem is selection of this part.

8.2.1 Statistical Method

Although the occurrence of mining tremors is not strictly a random process, a statistical approach to the analysis of seismic events in mines provides a reasonable basis for seismic hazard assessment Many observations indicate that seismic events induced by mining follow the same rules (at least to some degree) as those obeyed by natural earthquakes. The best known and the simplest rule between number of seismic events and magnitude is described by the Gutenberg-Richter relationship:

$$\log_{10} N = \mathrm{a} - \mathrm{b}m$$

where:

N—is the number of events with magnitude m and a, b are parameters.

The parameter b corresponds to the ratio of numbers of small to large events. The above formula was later modified by introducing the upper limit for magnitudes (so called truncated Gutenberg-Richter relation). Detailed description of the Gutenberg-Richter relationship and of the methods used for estimation of seismic hazard can be found in Gibowicz and Kijko (1994). The following parameters of the seismic hazard are calculated:

- Probability of the occurrence of a seismic event with a certain magnitude within a given time,
- Mean return time for a given magnitude
- Maximum expected magnitude in a given time interval

Having dealt with a bit of theory let's estimate the seismic hazard using as the input seismic data recorded at Palabora. At the end of every year I used the Gutenberg- Richter method to estimate the seismic hazard for the next year. I have found that this method provided a very good estimate of the Palabora seismic hazard. Statistical methods of seismic hazard evaluation have shown to be applicable for seismicity induced by cave mining. When using them it is important to select the correct input data. The following two examples illustrate how to select the input data.

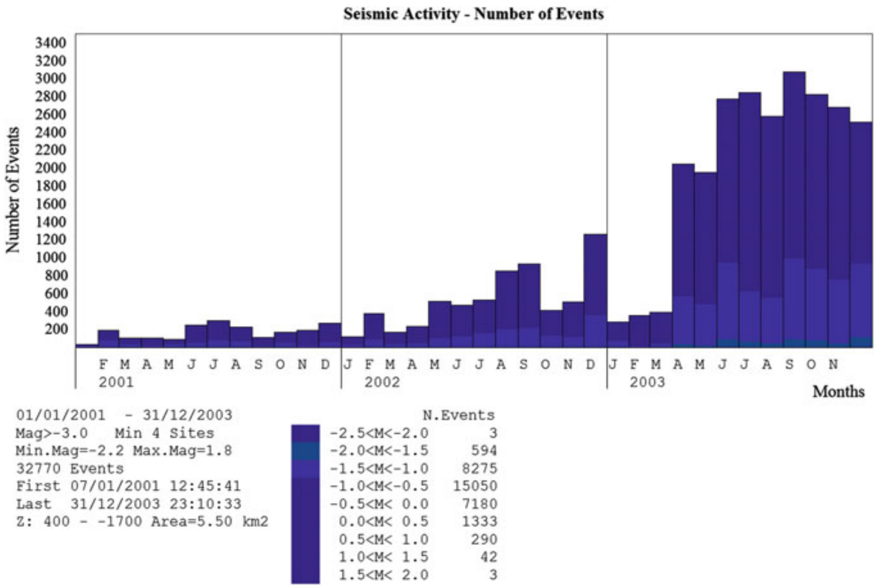

Fig. 8.15 Input data for seismic hazard estimation

8.2.1.1 Estimation of Seismic Hazard Based on Data Recorded up to the End of 2003

Figure 8.15 indicates that during the 3 years of 2001, 2002 and 2003 the seismic system recorded 32,770 events of which the largest event was of magnitude 1.8.

Summary of the seismic hazard estimation:

Based on the truncated Gutenberg- Richter distribution of the events the largest possible event that can be expected during the next 12 months is an event of magnitude size 2.0 ± 0.18. The return period of an event of magnitude above 1.5 is 7.12 months.

The probabilities of given size seismic events taking place are listed in Table 8.5.

Figure 8.16 shows all events above magnitude 1.0 and above that took place during 2004. The largest event recorded during 2004 was an event of magnitude 2.0. This event took place on the 27 February. The next large event was an event of magnitude 1.9. This event took place on the 14 July 2007.

Table 8.5 Probabilities of seismic events taking place

Magnitude above	In 1 month (%)	In 3 months (%)	In 6 months (%)	In 12 months (%)
0.0	100.0	100.0	100.0	100.0
0.5	100.0	100.0	100.0	100.0
1.0	99.9	100.0	100.0	100.0
1.5	13.1	34.4	56.9	81.5

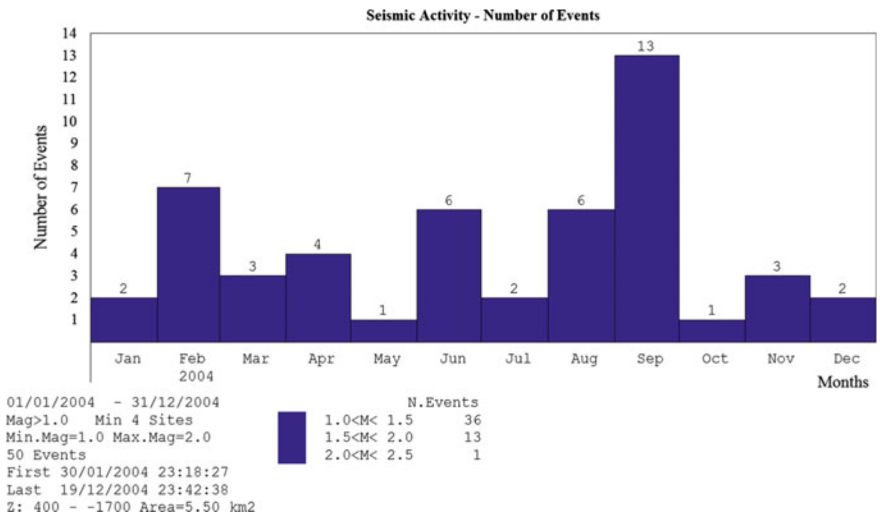

Fig. 8.16 Larger size seismicity recorded during 2004

8.2.1.2 Estimation of Seismic Hazard for 2006

The 2005 was a year of low energy releases (Fig. 8.17) when compared with the previous 2 years. The largest size event recorded during 2005 was an event of magnitude 1.2 (13/01/2005). Apart from this event there were only two other larger

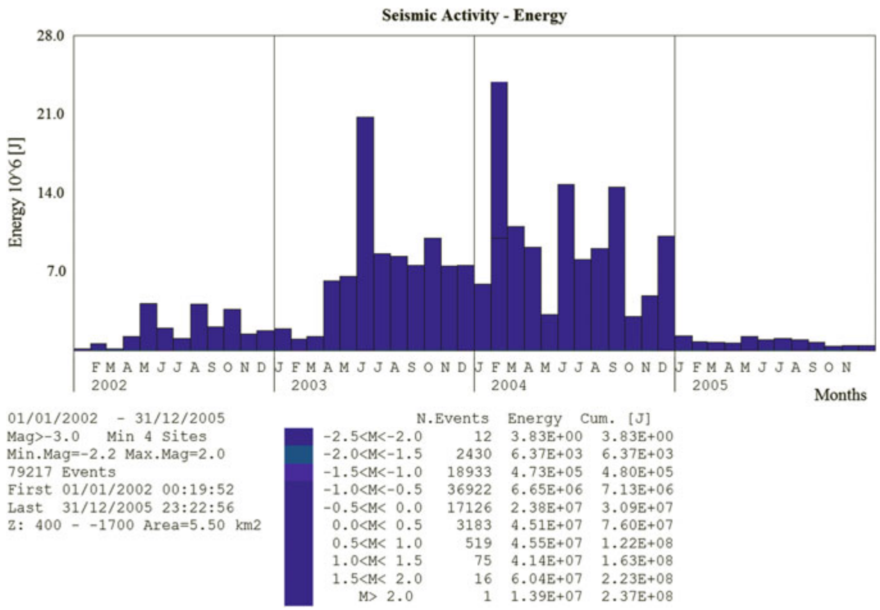

Fig. 8.17 Monthly seismic energy releases from 2002 to the end of 2005

size events, both of magnitude 1.0. I have decided that for the estimation of the seismic hazard for 2006 I will use only data recorded during 2005 and that this input will include the largest event of 2005.

Summary of the seismic hazard estimation:

Based on the truncated Gutenberg- Richter distribution of the events the largest possible event that can be expected during the next 12 months is an event of magnitude size 1.19. The return period of an event of magnitude above 1.0 is 3.38 months.

The probabilities of given size seismic events taking place are listed in Table 8.6.

Figure 8.18 illustrates that after 1 year of low energy release during 2005 there was increased energy release during 2006. The largest events recorded during 2006 were three events of magnitude 1.4.

Table 8.6 Probabilities of seismic events taking place

Magnitude above	In 1 month (%)	In 3 months (%)	In 6 months (%)	In 12 months (%)
0.0	100.0	100.0	100.0	100.0
0.5	98.4	100.0	100.0	100.0
1.0	25.6	58.8	83.1	97.1

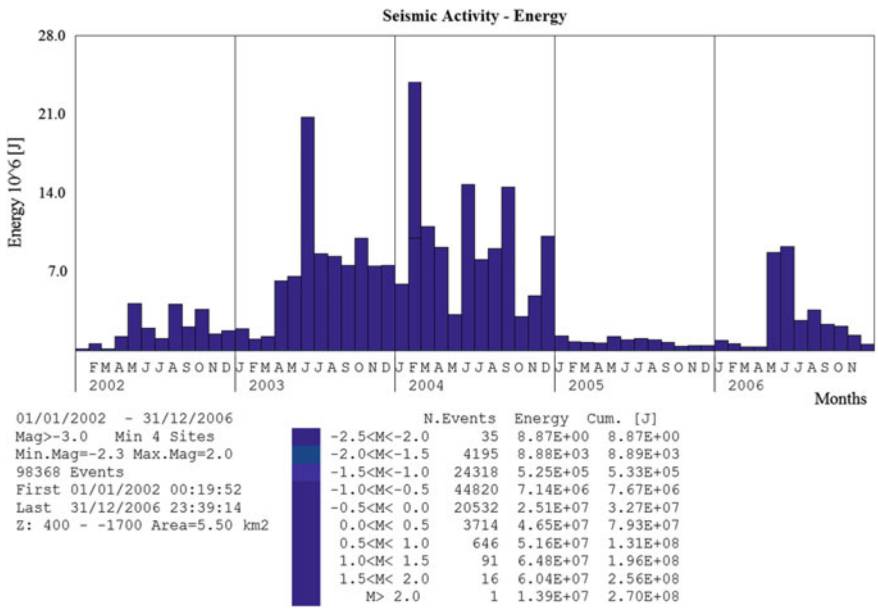

Fig. 8.18 Monthly seismic energy releases from 2002 to the end of 2006

8.2.2 Non-statistical Methods of Seismic Hazard Evaluation

Statistical methods apply to the whole mine and should not be applied to selected parts of the mine. The reason for this is that there is not a procedure that allows dividing the whole mine into smaller volumes in which the seismicity would be independent of each other. Still practice indicates that sometimes there is a need to limit the hazard estimation to a selected part of a mine. In such cases it is not possible to estimate the hazard as such but to monitor its changes over time. This approach towards seismic hazard estimation is based on monitoring changes of several seismic source parameters and then arbitrarily deciding when the seismic hazard level reaches a dangerous threshold.

8.2.2.1 Seismic Hazard Evaluation During Plugging of the Exploration Level

During 2002 it was decided to plug the Exploration Level. This was done for safety reasons. At that time it was not clear when or if crown pillar would cave in. There was a possibility that it might not and then with continuous mucking of ore from the cave a void would develop. If then at some later stage the hanging rock mass would collapse it would result in an air blast. This plugging operation was done to prevent the air blast wave getting to the underground mine. At that time the maximum cave back was at elevation of –600 m. The elevation of the Exploration Level was close to –500 m. The Exploration Level is not directly located above the cave but to the north of it. Still at this time there was a lot of large size seismicity all around the cave so such an event had the potential of putting the plug construction crew in a direct danger. For the purpose of monitoring the seismic hazard in the vicinity of the location where the plugging operation was taking place I selected a rock mass volume located around this location. At that time the decision made about the size and location of this volume was purely arbitrary. With data available today I would have first analysed the ground motions, and then decided on a safe level for the underground operations. In this way the volume that was to be monitored would be based on a more scientific basis. At that time I had decided to monitor the following parameters:

- Energy index
- Seismic activity rates

At the time these two parameters were monitored on a daily basis. When the energy reached the value close to 2.0 and the seismic activity rates were still constantly increasing, I decided that the seismic hazard level had reached a dangerous level and consequently decided to stop the plugging operation. The crew was then not allowed to continue with plugging for about 3 weeks. At some stage the energy index started to decrease but the seismic activity rates were still increasing. A magnitude 1.3 event took place on 24 August 2002 and it located inside of the monitored volume. (We do not know if it damaged the Exploration

Level, as at that time there was no access to this area). After this event took place the crew was allowed to go back and complete the operation. This example indicates how subjective this type of seismic hazard level evaluation is. Taking into account that the method wasn't really based on any sound scientific principles I would advise caution when considering this type of action. My private stress increase was there more due to the human actions than the nature taking its toll. There was pressure on the mine manager to carry on with the plugging operation which then was passed on to me. But we had a protocol in place that stated that only I could make this decision. I could be overruled but in practice this required from this task committee to decide that I am nuts.

8.2.2.2 Seismic Warning for the West Part of the Mine

From the beginning of 2003 after the failure of the Crown Pillar the underground became a rock burst prone mine. A number of rock bursts resulted in damage to the development excavations. At this time the development mining at the west was progressing in a situation similar to remnant mining. The development was moving west towards the Mica Fault, while to the east of the development mining the cave was progressing. The development area was getting smaller with time and the stresses from the progressing cave were concentrating on this ever-smaller area. By mid 2003 the Mica Fault was a barrier preventing the stress migration west and away from the mining. The high stress at the east was of less concern as it located above the mine, and not, as at the west, where it was at the elevation of the Development Level. At the West part of the mine from the beginning of 2003 until the mid 2004 I was monitoring seismic hazard with the following parameters:

- Energy index time history
- Average depth of seismicity
- Cumulative seismic energy

The energy index reached its mean value of 1.0 at the beginning of March 2003 which was less than 3 months after the Crown Pillar failure. After the pillar failure the seismicity started to migrate downward at a rate of about 20–40 m per month and as from June 2003 was close to the Development Level. A seismic hazard warning for the west side of the mine was issued at the end of June 2003 when the energy index increased rapidly indicating a rapid stress increase. The development crew had to put in place additional safety measures and additional support was installed. The seismic hazard levels at this part of the mine later dropped considerably due to forces of nature not due to any human actions. The seismicity itself broke through the Mica Fault, which then allowed for the migration of the stresses in a westerly direction away from the mine. From March 2003 there was a lot of seismicity west of the Mica Fault and also below the mine. This example indicates that in some specific situations it is possible to monitor the changing levels of the seismic hazard using the recorded seismicity. In this case the hazard area was easy to pinpoint as it included the whole development area. It is also interesting to note that the source of the seismic hazard was not the seismicity induced by the development itself but by the caving process. Because of this there was not a need to differentiate between these two different seismicity sources and all recorded seismicity at the time could be used as input data for the hazard monitoring process.

8.2.3 Seismic Protocol

Seismic monitoring at Palabora forms parts of monitoring rock mass response to mining. Seismic networks are installed underground to record the ground velocity and acceleration. This document describes the procedure to be followed in case of a seismic event taking place underground.

1. Context of Protocol.

This protocol lists known up to date seismic indicators of increased seismic hazard as well as procedures to follow in case they will occur. This list as well as the procedures will be revised every time new information becomes available or every 12 months.

2. General.

   2.1. Seismic technician will be on standby to process seismic data as required by the control room supervisor.
   2.2 The seismic system will be monitored 24 h a day by use of control room supervisors.
   2.3 Magnitude range 0.5–0.9 seismic event shall be control room alarm trigger.
   2.4 Minimum damage magnitude, based on up to date observations is 1.0
   2.5 Seismic data shall be analysed and then reported by the seismic consultant on monthly basis for trends and clusters that might indicate change of seismic hazard.
   2.6 Seismic hazard parameters (maximum possible magnitude, probability and recurrence times) will be re-assessed every 12 months or as required.
   2.7 Seismic technician, as required by this procedure will notify the Rock Engineer on occurrence of seismic events and related damage as reported from underground.
   2.8 Seismic consultant must be informed as soon as possible about occurrence of seismic hazard indicators of increased seismic hazard as listed in point 3 of this procedure.

3 Seismic indicators of increased seismic hazard, are based on anomalous seismicity rate changes as general decrease of the seismicity or increased occurrence of large events size above the damage magnitude as defined in point 2.4

3.1 General decrease in number of recorded events per day down to 3 events
3.2 More than 3 events greater than 1.0 magnitude events in a 24-h period.
3.3 Magnitude greater than 1.0 locating at depth range –750 to –850 m
3.4 Seismic event of magnitude above magnitude 2.0.

In case of one of the above indicators taking place the control room supervisor will call out the seismic technician.

4 Magnitude range 0.5–0.9 events, the control room trigger.

4.1 This control room trigger is based on the "fast location and fast magnitude" that is available on the seismic monitor (event monitor) and through a printout.
4.2 When an alarm is sound the supervisor will get the event data (magnitude and location)
4.3 Control room supervisor will phone the operations supervisor, who after receiving information will check for any underground damage
4.4 Underground supervisor will inform the control room supervisor about his check

4.4.1 If no damage recorded then no further action required
4.4.2 If damage recorded:

- The underground supervisor to assess the extend of damage
- If possible make the place safe by barring
- If not possible the underground supervisor to evacuate all personnel from the damaged area,
- The underground supervisor to barricade-off the damaged area.
- The underground supervisor to report to the control room the extend and location of damage
- The control room supervisor to call out the seismic technician, who will process all seismic data.
- Having accurate processed data (final locations and magnitudes) and information about damage extend the control room supervisor will inform the rock engineer on duty who will then visit the place and report the required corrective measures.

5. Seismic hazard indicator—less than 3 events during a day

5.1 Seismicity is expected to decrease with drop off production. When there is no production for a number of days the seismicity will decrease substantially and this must be regarded as normal. No action required.
5.2 Seismicity is expected to decrease in the final stage of the caving process which is not the present status of the caving process
5.3 At this stage the rock mass response to the decline development remains un-known. This response will be monitored and reported monthly

5.4 Seismic technician during working shift to check the seismic system for malfunction. If the seismic system is fully operational, the matter to be reported to the rock mechanic supervisor.

6. Seismic hazard indicator—more than 3 events greater than 1.0 magnitude events in a 24-h period.

   6.1 For every such event the control room will call out the seismic technician
   6.2 After each such event the control room supervisor and the underground supervisor will follow procedures as in point 4.
   6.3 If one of the recorded events magnitude 1.0 and above elevation is in the depth range of –750 to –850 m the control room supervisor to follow procedure as in point 7.

7. Seismic hazard indicator- magnitude greater than 1.0 locating at depth range –750 to –850 m.

   7.1 Control room supervisor to follow procedure listed in point 4
   7.2 Control Room Supervisor to inform the Rock Engineer regardless of the fact if there is or there is no underground damage.

8. Seismic hazard indicator—Seismic event of magnitude close to or above 2.0.

   8.1 Control room supervisor to call the seismic technician and also to follow procedure as in point 4.
   8.2 Seismic technician to analyse the seismograms to make sure if it is not an event taking place outside the mine.
   8.3 If this was an event outside the mine the control room supervisor to inform about it the underground supervisor. If no damage recorded then no further action required apart that the Rock Engineer to organize an underground inspection of the mine during the next 24 h
   8.4 If the event took place at the mine:

      8.4.1 The underground supervisor to evacuate the whole mine
      8.4.2 No underground visit to take place during the next 24 h.
      8.4.3 The control room supervisor to inform all people listed in point 9.

9. When one of the listed seismic indicators of increased seismic hazard has occurred depending on the situation and information from underground the control room supervisor or the Rock Engineer will inform the following as required:

   – Mine Manager Underground
   – Technical Manager Underground
   – Rock Mechanics Superintendent
   – Cave Management Superintendent
   – Seismic Technician
   – Seismic Consultant

10 Geotechnical review

If indicators of increased seismic hazard persist or reoccur a geotechnical review must be undertaken. As a minimum the geotechnical review team must consist of the following personnel:

- Mine Manager Underground
- Technical Manager Underground
- Rock Mechanics Superintendent
- Cave Management Superintendent
- Seismic Technician
- Seismic Consultant
- External consultant if available or deemed necessary

The Geotechnical review should include but not be limited to:

10.1 Review of draw bell draw rates and draw patterns
10.2 Review of cave profile and possible stress implications
10.3 Review of current mine plans
10.4 Review of current blasting patterns
10.5 Analysis and interpretation of seismic and other geotechnical data
10.6 Analysis of underground visit: general ground conditions, seismic activity, underground damage, and performance of support.

11. Revision of protocol.

11.1 Seismic indicators of increased seismic hazard should be reviewed as more information regarding the hazard become available or every 12 months.
11.2 Revision to be done by seismic Consultant.

8.3 Medium and Short Term Seismic Hazard Assessments—Are They Possible?

"The popular belief that earthquakes are predictable is at odds with correct research. At the RAS –JAG (Royal Astronomy Society—Joint Association for Geophysics) discussion meeting, "Assessment of schemes for earthquake prediction" (London 7–8 November 1996), the clear consensus was that individual earthquakes are inherently unpredictable because of chaotic, highly nonlinear nature of the source"

In the Mining World (May 1996) one will find the following:

"The ISS system provides three levels of warning to the mine safety officer:

- The Alert: This follows indications that rock mass movements are causing unacceptable levels of stress in the rock strata. The mine safety officer is warned to initiate change to the design of the mine, through for example, a change in the direction of stope channelling.

- The alarm: This is a 3-day advance warning of a rock burst. Mine workers should be removed from the area under surveillance
- The scram (scramble): This warning is usually given automatically by system monitoring a stope or active mining area, covering approximately 200 × 200 m. It is a one-minute advance notification of so-called "face-burst" which is a potentially lethal explosion of rock from the mine face"

This for any reader is a description of an already existing system and not a conceptual idea. Problems with this type of publicity were described by the end of 1997 by one of the AngloGold managers: "… we seem to have got ourselves into a lot of mess with public statements about the predictability of rock bursts by various people over the last few years. Normally issues of fundamental research would only be made public through the correct professional protocol, after having been verified by outside agency and then published. Certain euphoria over developments in the seismic research area have bypassed this, and can lead to some of the paranoia that now exists". What is the situation today nearly 20 years later? According to some of the papers I will discuss one might get an idea that the short-term rock burst hazard evaluation techniques are successful only because at certain mines they are performed routinely.

"It has been possible to set standards for some areas of mine seismology practice such as network design and emergency response. In other areas of practice, such as data processing, it has only been possible to provide guidelines. In yet other areas of practice, such as seismic hazard assessment and risk management, most methods currently in use have not been rigorously evaluated and validated. Many methods rely, to a greater or lesser extent, on local experience and subjective judgement. Tacit knowledge still has to be translated into explicit guidelines and procedures. It is thus deemed premature to set standards or even firm guidelines" (Durrheim et al. 2007a, b). In this chapter I intend to present some of the medium and short term seismic hazard assessments methods that are used as well as some that are no longer in use. The main reason for some of these methods not being used any more is simple. People who were supporting them left the industry and the methods vanished with them. In many South African mines (gold and platinum) not only the running and maintenance of the seismic networks but seismic data interpretation is outsourced to outside contractors who perform medium and short term seismic hazard assessments. There is no literature that would describe the seismic hazard estimation methods with enough detail that would allow for its implementation by a third party. By 2005 there were two parties that were performing this type of analysis, the ISSI on a grand scale and on a much smaller scale GeoHydroSeis. In the first part of this chapter I will concentrate on the methods used by ISSI.

To start with I will present an analysis prepared by Mr M.J. Dunn from Anglogold Ashanti Limited, South Africa (Dunn 2005). For this analysis the author has chosen seven different polygons all located in the same mine area. Each of these polygons was representing a different mining situation. Some of these polygons were adjacent to one another while two of them were standing on their own. Seismic data was collected over a 6 month period. In the authors' words "A rock engineering interpretation of the seismic observations was attempted in terms of anticipated stress levels, deformation and relative seismic hazard". This analysis was done by calculating for each of the seven polygons among other the following parameters (M_o is seismic moment and E seismic energy):

- Seismic stress

$$\sigma_s = 2G\Sigma E / \Sigma M_o \text{where G is rigidity}$$

- Seismic strain

$$\xi_s = \Sigma M_o/2\mu V \text{ where } \mu \text{ shear modulus}$$

- Seismic strain rate

$$\xi_s = \Sigma M_o/2\mu V t$$

- Seismic viscosity

$$\eta_s = \sigma_s/\xi_s$$

- Average and median apparent stress

$$\sigma_A = G \times E/ M_o$$

(Above formulas are as they were presented in this paper).

In this paper there is no indication that the author used different values for G and μ for the different polygons so one has to assume that they were constant for this analysis. The above parameters were then used to evaluate seismic hazard and then rank it for each polygon. Final seismic ranking was then based on statistical and seismicity parameters. Then the relative hazard was given to each polygon: high (H), medium (M) and low (L).There are two polygons with "H", two polygons with "M" and three polygons with "L" ratings.

Based on the seismic data for each polygon as provided in this paper, the same result cold be achieved without any of the presented analyses. All that needs to be done is to rate the polygons according to their cumulative seismic energy and cumulative seismic moment values. The two polygons with the highest cumulative seismic energy as well the highest cumulative seismic moment were rated as "H". Then there were two polygons with cumulative seismic energy values one magnitude lower from the previous two, so they got the ranking "M". Finally there are three polygons with cumulative energy still one magnitude lower so they fit into category "L". Additional available information is that the two polygons with ranking "H" already had seismic events of magnitude 1.0 and for this reason, according to the author, "are more likely to experience a $M_l > 1$ seismic event"

"There are several other parameters proposed by Mendecki and his group, such as seismic viscosity and relaxation time, seismic softening and seismic diffusion and seismic Schmidt and Deborach numbers to monitor the instability of the rock mass. These parameters however are strongly redundant since they are mostly related to only two independent quantities: the sums of seismic energy and seismic moment" (Gibowicz and Lasocki 2001).

$$\text{Seismic viscosity } \eta_s = \left(4\mu^2 \Delta V \Delta t \Sigma E\right)/(\Sigma M)$$

$$\text{Seismic diffusion } D_s = (\Sigma M)^2/4\mu L \Delta t \Sigma E$$

$$\text{Seismic Deborah number } De_s = (4\mu \Delta V \Sigma E)/(\Sigma M)^2$$

$$\text{Seismic Schmidt Number } Sc_{sd} = \left(4\mu^2 \Delta V \Delta t(t) \Sigma E\right)/(\rho(X)^2(\Sigma M)^2$$

Above formulas and a number of other ones can be found in Chap. 11 "Quantitative Seismology and Rockmass Stability" of the book "Seismic Monitoring in Mines (Mendecki 1997). The parameter L in seismic diffusion is the length of a cube and ρ in the seismic Schmidt number formula is the rock mass density.

What is interesting in the same chapter the following is found:

$$De_s(\Delta v, \Delta t) = \eta_s/\mu\,\Delta t$$

(from formula 10.31 and 10.33 Chap. 10 of "Seismic Monitoring in Mines (Mendecki 1997). This means that seismic Deborah number is equal to seismic viscosity which is divided by shear modulus which is multiplied by time Δt. So in fact the seismic Deborah number is seismic viscosity divided by a constant.

Further more according to formula 10.37 of the same chapter:

$$D_s(\Delta v, \Delta t) = L^2\mu/\eta_s$$

This simply indicates that seismic diffusion is equal to a constant divided by seismic viscosity. From the last two formulas it is easy to prove that there is a direct relation between the seismic Deborah number and seismic diffusion.

$$De_s(\Delta v, \Delta t) = L^2/\,D_s \Delta t$$

There is also a direct relation between seismic Schmidt number and seismic viscosity which is:

$$\eta_s = Sc_{sd}/\,\rho(X)^2 \Sigma\, M_o$$

In Chap. 11 of "Seismic Monitoring in Mines (Mendecki 1997) on page 235 there are three figures illustrating time histories of seismicity recorded along the Postma dyke from 09 May to 27 June 1994. The first of these figures illustrates a plot of Log (Ei) (energy index) and cumulative apparent volume, second is a plot of seismic viscosity and cumulative apparent volume while the third illustrates the time history of log (Schmidt number) and cumulative apparent volume In all these plots time span ends on the 27 June 1994, which is on the day when a local magnitude 3.7 event associated with the Posma dyke took place. Apart from minor differences all three plots (Log (Ei), seismic viscosity, log (Schmidt number)) exhibit exactly the same trend patterns with a third drop starting about mid June about 2 weeks before the large seismic event took place. This is obvious as all these parameters are interrelated with each other. Further more there is no information as to how many events were in the input catalogue or what smoothing parameters were used to produce these time histories. These three time histories are supplemented by two contour plots: iso-surface of Deborah number 10 (6 months of data prior to the large event) and contours of log (Ei) (6 weeks of data prior to the large event).

According to data presented below Table 11.2 (Mendecki 1997) titled 'Summary of trends in log(Ei); log (seismic Schmidt number) and ΣV_A precursory to significant events in the Postma dyke study area" there is some information for those who might want to use these parameters for the short term seismic hazard estimations. The scoring for the precursory behaviour rating is as follows:

+1 clear steepening of ΣV_A slope
−1 flat ΣV_A slope
+1 clear drop in Ei
−1 clear rise in Ei
+1 strong drop in Ei and recovery during final stage
+1 clear drop in seismic Schmidt number
−1 clear rise in seismic Schmidt number
+½ very strong positive trend

In a paper titled "Routine Seismic Hazard Assessment in Some South African Mines" (van Aswegen 2005) one can find the information that at the time there were about 100 polygons ("areas of interest") for which the short-term hazard assessment was performed on a regular basis (twice a day). These assessments were based on cumulative apparent volume, seismic Schmidt number, energy index and activity rate. From the above listed precursory behaviour it appears that prior to an occurrence of a large event one should expect a clear drop in energy index and a clear drop in the seismic Schmidt number. Whatever one thinks about the above methods for short term seismic hazard estimation it is clear that their practical application must be extremely time consuming and secondly that they can be performed only by some chosen individuals that not only accept as true all that what is written in "Seismic Monitoring in Mines" (Mendecki 1997) but must have a comprehensive and focussed knowledge about this specific aspect of seismology. It is a fact that in general the seismology community refrains from commenting on the contents of this book. I am in agreement with Dr A McGarr's (1998) review of this book. The essence of this review is the following: "The value of this book depends strongly on one's attitude toward the parameters of Chap. 10 and the virtues of monitoring them. Thus, Seismic Monitoring in Mines is not a general textbook on how to record and analyse seismicity in mines. Rather, it is a focused description of a very specific methodology for assessing in real time the seismic hazard associated with mining". The fact remains that up to date there is no published information about the success rate of this methodology. This fact is also reflected in (Gibowicz and Lasocki 2001): "Unfortunately, the proposed parameters have not been objectively validated so far and their actual prediction efficiency is not known". A list of parameters including some of those already mentioned in this chapter can be found in "Seismic monitoring in mines: selected terms and definitions" (Menecki and van Aswegen 2005). Here the terms are divided into three groups:

- Seismic event parameters (one page and 12 positions)
- Seismicity parameters (four pages and 24 positions)
- Terms related to the theory of non-linear and fractal geometry (21 positions)

The second source of information about the techniques used for medium and short term seismic hazard estimations is based on papers published by other group. Their approach towards the problem of seismic hazard assessment is described by Ebrahim-Trollope and Jooste (2005). This group made use of a number of techniques but made a strong point that "routinely quantifying seismic hazard using more complex parameters discussed (in this paper) requires accurate measurements and expert input". This paper describes a number of seismic hazard estimation methods that were used or were tested at the Harmony group of mines.

1. Stability analysis based on the energy index concept in combination with such parameters as cumulative apparent volume, Schmidt number, activity rate
2. $E - M_o$ relationship
3. Seismic stiffness ("inconclusive results")
4. Seismic index which is "regarded as a richer parameter in quantifying the seismic hazard between areas as well as variations in time"
5. Seismic Response Parameter (SRP)

$$SRP = Ne(\Sigma Va/\Sigma Vm)$$

where:

Ne is a number of seismic events greater than a pre-determined cut-off magnitude

Va is the apparent volume of each event

Vm is volume mined

"This parameter was not particularly successful at a scattered mining environment with complex geology".

6. Volume of Ground Motion (VGM) and hazard magnitude

VGM is a combination of magnitude-frequency, b value, activity rates, maximum magnitude, peak ground velocity and minimum magnitude of damage.

7. Quantification based on magnitude

This method makes use of mean return periods of events of certain magnitude ranges, the probability of them occurring within a given time period and the maximum expected magnitude during the life of mine and "operational basis magnitude". Appendix attached to this paper shows an example of a monthly seismic risk evaluation. There are six criteria and the final seismic risk evaluation parameter is a mean. The criteria are:

A. Major geology which include:
   - Regional seismic polygon
   - Maximum recorded magnitude
   - PPV at nearest working place
   - Probable occurrence
B. Local failures which includes:
   - Actual 2-year M_{max}
   - Statistical 2-year M_{max}
   - Combination of these two
C. Statistical number of events per month for $M_L > 1.0$ which includes:
   - Actual number of events per month for $M_L > 1.0$ during last 6 months
   - Results combined
   - Last event $M_L > 1.0$
D. Statistical number of events per month for $M_L > 2.0$ which include:
   - Actual number of events per month for $M_L > 2.0$ during last 12 month
   - Results combined
   - Last event $M_L > 1.2$
E. Probable occurrence of $M_L > 2.0$ in following months and this is combined with PPV at the nearest working place
F. Morning shift distribution of $M_L > 1.0$ during the last 2 years
   Morning shift distribution of $M_L > 1.0$ during the last 6 months

This example clearly indicates not only the complexity of the method but also the fact that by definition it is site specific. Any one intending to make use of this method must first accumulate all the required inputs that would be applicable to the specific area involved. Finally the author proposed a new parameter V_{EM}—potential violence parameter. This parameter "would need to incorporate the following term: $V_{EM} = E/M_o$" where E is the released energy in Joules and M_o is the seismic moment (Nm $\times$ 10^6).

8.4 Estimation of Maximum Possible Magnitude for Seismic Events of Mode Two and Three

One set of Palabora data, and two sets of seismic events recorded by the National Seismic Network were tested, in order to estimate the maximum possible magnitude for mode two mine induced seismic events and to see if mine related seismicity of mode three could be differentiated from that resulting from natural seismicity of the Phalaborwa area. This analysis was done by the end of 2002.

8.4.1 Introduction

Seismic hazard analysis is a standard tool used in mines to determine probabilities of occurrence of seismic events that have a damaging impact on production and are dangerous to the underground staff. Such an analysis is usually based on methods used in natural earthquake seismology (Kijko et al. 2001). Demands for an increased accuracy resulted in changes to the standard approaches in order to account for the characteristics of mine induced seismicity. The main difference between the natural and mine induced seismicity is the non-stationarity generation process of the latter. In consequence, the mine related hazard exhibits time variability. Adaptation of stationary hazard analysis to time-variability in mines has led to techniques that assess seismic hazard, locally in time and space, in order to monitor present and to foresee future states of rock fracturing (Gibowicz and Kijko 1994). The model of magnitude distribution most widely used in seismic hazard analysis in mines is based on the Gutenberg-Richter relation, combined with an assumption of the existence of a physical upper limit to the magnitude range. There are however, an increasing number of reported cases in which the observed earthquake frequency patterns differ significantly from the Gutenberg-Richter relationship. The multi-modal nature of seismic events is far more important in mine induced than in natural seismicity. For this reason the nonlinearity of the empirical Gutenberg-Richter magnitude distribution will result in an unacceptable bias in the estimation of the hazard parameters. A model free approach was used to evaluate the seismic hazard, which is based on a nonparametric estimator of magnitude distribution. The methodology applied is described by Kijko and Graham (1998). This approach provides hazard parameters with tolerable and limited errors regardless whether the magnitude sampling distribution follows the

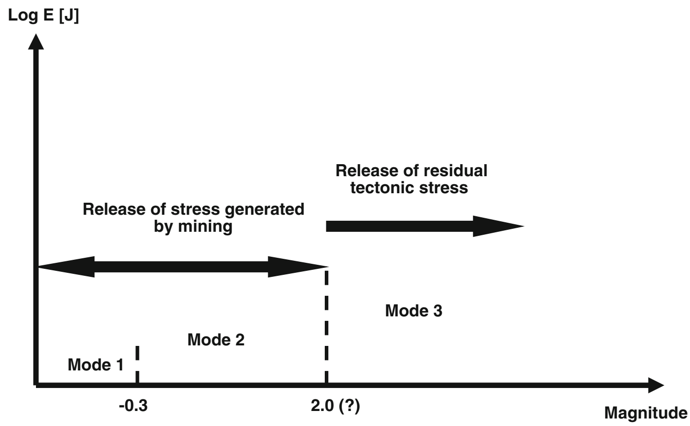

Fig. 8.19 Triple mode distribution of seismic events at Palabora

Gutenberg-Richter relation or is of multi-modal nature (Kijko et al. 2001). Prof A Kijko helped me with the calculations of the maximum expected magnitude.

This method was applied for estimation of the maximum possible magnitude of seismic events belonging to the second and third modes (Fig. 8.19). In the case of the Phalaborwa area it is expected that events of mode three are probably mixed with natural seismicity that is form one catalog.

8.4.2 Discussion of Results

Seismicity induced by surface mining is still a very much-unknown phenomenon. Up to date such seismicity was observed only in four areas around the world (Gibowicz and Kijko 1994). The open pit operations in Phalaborwa may have already generated measurable seismicity according to McGarr (unpublished comments on the nature of Witwatersrand mine tremors, 1987). In the earthquake catalogue of South Africa there are a number of events recorded for this area of which the sizes vary from 2.3 to 3.8. This might be seismicity induced by surface mining that is not being recognised as such as no special studies in this matter are undertaken. On the 7th June 1974 an earthquake of magnitude 3.3 occurred at Wappingers Falls, New York, followed by over 100 aftershocks during a period of six days. The aftershocks occurred within or beneath a block of dolomitic limestone, which was quarried extensively since 1900s. In 1974 the total depth of the quarry was in order of 50 m. One of the largest deposits of brown coal in Poland is situated in the Belchatow trench, over 40 km long, 1.5–2 km wide and 0.5 km deep. The mining started in 1976. By mid 1980 the pit was about 100 m deep, 1 km long and 2 km wide. The first tremor in the open pit was recorded in August 1979, and the first tremor was felt in 1980. Then further tremors with local magnitude ranging from 2.8 to 3.6 were recorded during the year of 1980. On 29th November 1980 a magnitude 4.6 seismic event occurred in the area. So far this is the strongest known to date manifestation of seismicity induced by surface mining. Some seismicity was observed in the Cerro de Pasco in Peru. Here the tremors were very small and the magnitudes ranged from –2.0 to 0.0. Information about this open pit seismicity is after Gibowicz and Kijko (1994).

8.4.2.1 Mode 2 Maximum Possible Magnitude Determination

All three faults, the Central, Southwest and the Tree as well as the Main Dyke by end of 2002 were seismically active. The first event of magnitude size 1.0 was recorded in June 2001. The largest to date magnitude size 1.3 was recorded in August 2002. The estimation of the maximum possible magnitude for seismic event of mode 2 gives a result of 1.4 with a standard deviation of 0.1. The input catalogue was very short. The cave mining really started only in August 2001 and it is a very dynamic process in this sense that it very quickly activates new volumes of the rock mass. For this reason the estimated value of the maximum possible magnitude might be still to low.

8.4.2.2 Mode 3 Maximum Possible Magnitude Determination

According to Fernández and Plessis (1992) Phalaborwa area is covered by seismic intensity VI of the Modified Mercalli Scale, with a 10 % probability of being exceeded at least once in a period of 50 years. This scale can be converted into the Richter magnitude by the following formulae:

$$\mathrm{Mp} = 0.66\mathrm{I} + 1.0$$

where: Mp—magnitude size as reported by Pretoria

I—intensity according to Modified Mercalli Scale (MMS)

Converting the intensity of VI (MMS) into the Richter magnitude scale using this formulae gives a magnitude value of 5.0. This magnitude size is exactly the mean of the two maximum possible magnitudes calculated for the radiuses of 50 and 100 km (4.4 and 5.6).

The same source puts Phalaborwa in the region that can experience peak ground acceleration of 50–100 cm/s^2 (up to about 0.1 g) with a 10 % probability of being exceeded at least once in a period of 50 years. In terms of global seismology value of 0.1 g (g = 980 cm/s^2) is the approximate maximum acceleration on hard ground for an event of magnitude 5.0 and a maximum intensity of VI to VII. Events of this size would require a fault of an approximate length of 4 km to take place. A magnitude size 5.5 is equal to intensity VII and is expected to course approximate maximum acceleration on hard ground of 0.15 g. Event of this size to take place need a fault of approximate length of 5–10 km. A magnitude size 6.0 is equal to intensity VII-VIII and is expected to course approximate maximum acceleration on hard ground of 0.2 g. Event of this size to take place need a fault of approximate length of 10–15 km. The Geological Survey of South Africa prepared three reports concerning seismic hazard in the Phalaborwa area.

The first report (No 0178) was completed in 1987 and is titled “Estimation of seismic hazard for Phalaborwa” (Fernández 1987). The conclusion of this report is that in the Phalaborwa area in a period of 50 years there is a 5 % probability of an event of MMS intensity VI.

The second report (No 0193) was completed in 1993 and is titled “Estimation of the earthquake hazard for Phalaborwa area, Transvaal” (Fernández and Graham 1993). In conclusion this report states: “The probabilistic analysis of the data indicates that the Phalaborwa area should be subject to an intensity V tremor at least once in a period of 10 years with probability of 5 % (±1 %). A maximum credible event of intensity VIII with associated peak horizontal ground acceleration 166.67 cm/s^2 was chosen. The extreme values distribution indicates a 10 year mean return period for MMS intensity between III and IV (less than 17 cm/s^2).”

The third report (No 0174) was completed in 1995 and is titled “An assessment of seismic hazard at Phalaborwa in terms of ground acceleration and probable damage” (Fernández and Graham 1995). In conclusions of this report the following is stated:

“There is a 10 % probability that in a period of 50 years, a peak horizontal ground acceleration exceeding the value of 0.06 g will be exceeded at least once. This value refers to hard rock, and vibrations generated by natural earthquakes”.

“In terms of seismic intensity according to the Modified Mercalli Scale there is a 10 % probability that intensity VI will be exceeded at least once in 50 years”.

“The maximum credible acceleration for the area is 0.071 g, corresponding to seismic intensities between VI and VII…..”

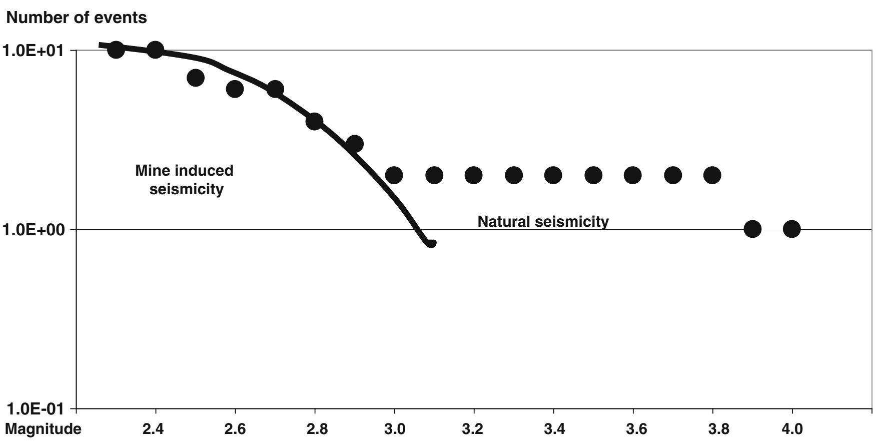

Fig. 8.20 Bimodal distribution of seismic events recorded in a radius of 50 km around Palabora

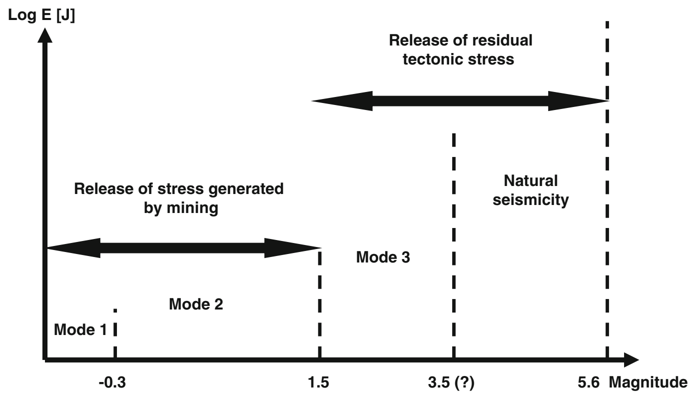

Fig. 8.21 Multimodal distribution of mine induced and natural seismicity at Palabora

In summary the above listed sources of seismic hazard for Phalaborwa area state that this area can expect an maximum earthquake of VII on the MMS scale which is a event of magnitude size 5.5. This is exactly the result of the nonparametric fit to the catalogue containing all events in radius of 100 km around Palabora. This type of analysis can be valid only for the natural and not mine induced seismicity. It is difficult to imagine that localised mining activity on an area of about 2 km^2 will result in seismic events taking place at a distance of hundred kilometres. Figure 8.20, which is based on earthquakes recorded in the radius of 50 km from Palabora, clearly indicates a bimodal distribution. The mine induced seismicity mode 3 events clearly follow a specific fit, while the natural seismicity doesn't follow this fit curve. Following the input data fitting the mode 3 events as on Fig. 8.21 this would reduce the mining influence to about 15–20 km. This influence area in reality is probably still less, when one will take into account that the National Networks location accuracy is about 10 km. Still such filtering of data would take out the two largest events of magnitude 4.0 and 3.8, leaving event of magnitude 2.9 as the maximum magnitude size to be used to estimate the hazard parameters. With such reduced input catalogue, the resulting M_{max} would be then, well below the 4.4 value, which is based on data recorded in the radius of 50 km around Palabora. The M_{max} for the mode 3 seismic events at present is an unknown value. It should be estimated, together with other hazard parameters, by recalculating the data used to produce Fig. 8.20 Such data recalculation should take into account events that took place after 1982 (for example there was an event of magnitude above 2.0 that was felt on the mine which plotted on the Tree Fault).

It is recommended to get hold of these hazard parameters, as mode 3 events very often take place below the mining levels and can be shallow (a couple of hundred meters below the production level) and course a lot of damage to the excavations. This is the experience of gold mining. Taking into account available information from the Geological Survey reports about the natural seismicity in the Phalaborwa area, it is possible to estimate the probability of magnitude size 5.0 to be exceeded

Table 8.8 Probability of magnitude 5.0 to be exceeded at least once in 50 years

Distance from Palabora (km)	Probability (%)
5.0	0.002
10	0.008
15	0.018
20	0.032
25	0.051
30	0.073
50	0.204
100	0.816

at least once in a period of 50 years for various distances from Palabora—Table 8.8.

Table 8.8 indicates that natural seismicity is not a hazard for the mining operations at Palabora. Finally, with all available information Fig. 8.19 can be supplemented with the following information (Fig. 8.21):

Maximum magnitude mode 2 event (calculated plus standard deviation) 1.5
Maximum magnitude mode 3 event (still unknown- estimate) 3.5?
Maximum magnitude for natural earthquakes 5.6

8.5 Conclusions

1. The maximum possible magnitude for events belonging to mode two at the time was estimated to be of magnitude 1.5 size
2. There is convincing evidence that in the Phalaborwa area there is enough data to differentiate between the third mode and the natural seismicity events
3. Available information indicates that seismic events of mode 3 started to take place at Phalaborwa from the end of 1967, which is about 13 years after mining has started in the open pit
4. The maximum possible magnitude for mode 3 seismic events in the Phalaborwa area still remains unknown, as the other seismic hazard parameters. At this stage it can be assumed that it is lower than magnitude 4.4
5. Mode 3 seismic events of mine induced seismicity have to be regarded as hazardous for the underground operations, due to the fact that they may occur close to the mining excavations. Experience from the gold mining industry indicates that this type of seismic events often locates only a couple of hundred meters from the production levels and results in severe damage to the excavations.
6. Up to date the largest reported by the National Seismic Network mode 3 event is of magnitude size 2.9 (equivalent to magnitude 3.3 as recorded by the Palabora seismic network).

7. Seismicity induced by surface mining is still a very much-unknown phenomenon. Up to date it was reported in only a few places around the world. The largest seismic event to date known to be related to open pit mining is of magnitude 4.6. In comparison the largest seismic event to date associated with underground mining is of magnitude 5.2.
8. According to available data, natural seismicity is not a hazard for the Palabora mining operations, as the probability of magnitude 5.0 being exceeded at least once in 50 years, at a distance of 50 km from the mine is 0.2 %.
9. Seismicity at Palabora is composite. It consists of four modes. Mode one are small events that indicate the cave progress. Their maximum size is about –0.3. Mode two are events connected with local discontinuities. Their maximum size is around magnitude 1.5. Both these mode mechanism is release of stress generated by mining. The third mode is connected with release of residual tectonic stresses, as a result of the mining history of the whole area. The fourth mode is natural seismicity.

8.6 Summary

Presented analysis indicates that the recorded seismicity can be used not only to monitor the caving process but also to analyse the seismic risk associated with this process. In this chapter I have described the methodology to asses the seismic risk. This methodology description is based on the seismic response to the cave mining process. It is accepted that seismic hazard is expressed in the expected maximum magnitude that can take place. It is also accepted that the higher this expected magnitude the higher is the seismic hazard. The other factor that plays a role in seismic hazard estimation is the possibility of the maximum magnitude event taking place in a specific time frame. Those are the general rules that are applied to seismic hazard estimation and they follow what is practiced in global seismology. However, the underground damage due to a seismic event taking place is a function of many variables. The event magnitude in the seismic hazard estimation is important but does not totally influence the possible extent of the damage. It is a fact that events of the same magnitude size result in extensive damage or no damage what so ever. Apart from geometry, which in this case defines the relationship between the source and the underground excavation position, the geotechnical characteristics of the geological discontinuities, there is one more important factor that must be taken into account. Here I am thinking about the stress regime that in mining environment is not constant and changes continuously with the caving process. Palabora experience indicates that seismic hazard and seismic risk changes with the caving process but these changes are not always corresponding. I have used seismic data recorded at Palabora to describe the methodology for monitoring the seismic risk It is interesting to note that presented results based on the analysis of independent parameters (for example energy release of small events, time histories and the Peak

Particle Velocity of larger size seismicity) resulted in very good agreement of risk assessment. It is important to recognize that some of the parameters are derived from the same seismic source values. For this reason the analysis results do not complement each other but simply repeat the result. In this project I do not propose an absolute scale for the seismic risk description. All results are relative and describe the changes in seismic risk over time. Palabora seismicity was used to create a seismic risk model depending on the caving progress. This model is based on the time changes of the monthly seismic activity rates, the seismic energy release rates and on the seismic deformation rates. All these monthly activity rates were normalised by the average rate which is based on data recorded from the beginning of 2001 until the end of 2013. This average is 100 %. This model illustrates the fact that during different time periods the monthly rate was either lower or higher than the average rate. For example a monthly rate of 50 % indicates that it is half of the average while rate of 200 % indicates that it is twice the size of the average. This model clearly indicates that the caving milestones are characterized not only by different size rates but also by distinctive changes in their sizes. In character these changes are similar for the three rates. In size the largest changes are associated with the seismic energy release rates. During the time period when only development mining was taking place the energy release rates were very low at less than 25 %. The initiation of the caving process resulted in increased seismic energy release rates up to 100 %. This first significant increase lasted until the failure of the crown pillar. The crown pillar failure resulted in still a further significant energy rate increase up to nearly 300 %. The energy release rates then remained at this level until the initial break through. After the initial break through the energy release rates decreased to the level of 100 %. It is worth noting that during the time period during which there was only production from the cave these rates were nearly four times higher than during the time period when there was only development mining taking place. The east break through resulted in a short time period increase in the energy release rates. The time period was short but the increase was large as during the east break through it was up to nearly 400 %. After the east break through the seismic energy release rates decreased rapidly down to about 25 % and remained at this level until the end of the mature stage of the caving process. Analysis of normalized seismic energy release rates above the extraction level and below the extraction level illustrated the fact that the seismic energy release rates were changing differently above and below the mine. The initiation of the caving process resulted in increased seismic energy release rates (up to 200 %) but only above the mine. The energy release rates below the mine increased only after the crown pillar failure and this increase was then up to 100 %. From the time the crown pillar failed until the initial break through the seismic energy release rates above the extraction level were twice as high as those below the extraction level. The initial break through resulted in a decrease in the rates above and in increased rates below the mine. After the initial break through was completed the energy release rates above and below the extraction level stayed at about the same level (50 %). From about mid 2007 the two rates decreased indicating that the caving process reached its mature stage Still the east break through resulted in significant increase in the energy release rates above the extraction level. This time this increase was from 50 % to nearly 400 %. Only after the east break through was completed there was a substantial increase in the energy release rates below the mine. It is worth noting that this pattern of increased seismic energy release below the mine after this second break through is similar to the one experienced earlier after the initial break through. From the presented data it emerges that with the caving process the highest seismic risk starts with the initiation of the caving process and ends directly after the cave break through.

Finally in this chapter I have put together some thoughts about the “instability concept” which was at the time supported by ISSI. Here I did not describe this concept as its description can be found elsewhere but collected together some published data on application of this concept. Today there is only a handful of professional seismologist employed directly at the South African mines. Most of the South African mines use ISSI as contractors for all their seismology requirements. This includes planning the network layouts, purchasing equipment, its maintenance, processing of recorded data and then reporting on the recorded seismicity. On the other hand from the time I started to work as an independent seismic consultant and to travel around the world I have met a lot of very confused rock engineering practitioners. Also I did not make acquaintance with any professional seismologist making use of this concept. It is used practically only by seismologists employed by ISSI. As far as South Africa is concerned ISSI had a monopoly not only in regard to seismological hardware and software but also seismological concepts. It would be easy to make this paragraph very short just stating that the instability concept is not applicable to cave mining operations but such statement would result in more confusion. Based on all application examples listed in this paragraph one has to make their own mind about this concept which is about predicting major damaging mine seismic events. Personally I do not believe in this concept but “We have learned that, no matter how fantastic or absurd a theory is, you can always find somebody eager to embrace it.” This quotation is from a book titled “Citadels of Mystery” by L. Spraque de Camp and Catherine C. de Camp (1972) published by Fontana Books. This book has nothing to do with seismology as it describes some of the unsolved puzzles of archaeology and is a guide to the twelve of the famous myths, romantic sites of the word and legends including Atlantis. This quote seems to be universal as it is also applicable to mine seismology.

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Chapter 9
Problems Related to Software Versions

Abstract This chapter presents a riddle that for the first time I was confronted with when I was working at the gold mines. All was in place, good quality seismic system, and quality seismic data base and professional and experienced staff employed. The last years were good as the mining management was taking advice and had confidence in our data interpretation results. Unexpectedly the seismicity character changed. In practice one would expect that at this point in time the seismic response to the mining process has changed. This usually is bad news as it means change of seismic hazard. This was not the case. The reason was astonishing as it was the new seismic processing software. There were large differences in the seismic parameter values depending on the version of the software. This illustrated how dependent of the contractor the seismic source parameter values can be and really are. This was a direct prove that their values are not the real thing. This problem repeated itself while I was working for the Palabora Mine. Chapter describing this problem is different from the others as it is not about using seismic data to monitor the caving process or the resulting seismic hazard. Here interpretation was to find what are the differences and then decide are they acceptable or no. In the end one wants to know which software to use that is to assess which one results in data that can be explained by application of basic physical rules. To be honest I enjoyed this analysis as it was different from what I was doing. It was a case when I could use different approaches and have some fun.

In this chapter I am comparing seismic source parameter values processed using version 9.1.2 with those based on version 10.1.3 and the latest version 10.1.4 of ISS software. Additionally this comparison includes the latest seismological processing software Jmts (version as available on 25 March 2010), which has two options allowing for Microsoft Windows or Linux environments. For this analysis I have used 2 months of Palabora data (April and May, 2008) recorded and processed with software version 9.2.1. The recalculation of the seismic source parameters for this data set using versions 10.1.3, 10.1.4 and Jmts was done by ISSI. This analysis is based on 1662 seismic events while the whole Palabora seismic data base consists of over 10 years of continuous seismic monitoring data during which over 130,000

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events were recorded. Large differences in seismic moment and released seismic energy suggest that something is very wrong with either software version 9.2.1 or with software versions 10.1.3, 10.1.4 or the March 2010 version of Jmts. Additionally it is very disturbing that there are such substantial differences between the two latest versions that both are on the market, namely software version 10.1.4 and the Jmts. At the conclusion of this chapter I have presented a short analysis of seismic energy release using the whole Palabora seismic data base which was processed with software version 9.2.1. The results presented give reason to be confident in data processed with this software version. As shown this data correlates well with the caving process.

9.1 Conclusions

The presented analysis leads to the following conclusions:

1. The latest available software versions from ISSI are: version 10.1.4 and version Jmts.
2. There are considerable differences between the source parameters calculated with the different software versions.
3. There is a significant difference between source parameters according to version 9.2.1 and the other three versions
   a. In comparison to version 9.2.1, seismicity for the other three versions has more seismic moment (in the order of 100)
   b. In comparison to version 9.2.1, seismicity for the other three versions has less seismic energy (in the order of 10)
4. Source parameters according to version 10.1.3 are closer to source parameters according to version Jmts than to those according to version 10.1.4
5. Analysed differences not only influence the seismicity visualization but also influence the interpretation of seismicity
6. Based on the analysis of the different input data sets, the interpretation of seismicity changes as follows:
   a. According to software version 9.2.1 there are two different source mechanisms, one above the mine and another below the mine
   b. According to the other three software versions there is only one source mechanism, both above and below the mine
   c. According to version 9.2.1 the main source mechanism around the cave is slip along the pre-existing discontinuities (double couple type of mechanism) while according to the other three software versions the main mechanism controlling the cave propagation is a non-double couple mechanism.
   d. According to version 9.2.1 the main source mechanism below the mine is non-double-couple mechanism (more tensile than above the mine)

7. To date the energy index time history based on version 9.2.1 has correlated very well with the history of the caving process For the analysed data sets according to versions 10.1.3, 10.1.4 and Jmts there is no such correlation.
8. It appears that the energy release per moment for larger size events (above moment magnitude 1.0) in software versions 10.1.3, 10.1.4 and Jmts are strongly underestimated (in the order of 100).

9.2 Analysis

If one would plan to upgrade the seismic system during the beginning of the second quarter of 2010 he would have to install software version 10.1.4 and additionally could make use of the Jmts. These two software versions were offered at the same time. In this chapter all magnitudes are moment magnitudes. Table 9.1 provides a very simple comparison of the source parameters as calculated by all four versions of the ISSI software. This table lists the cumulative values of seismic energy and moment of seismicity recorded from 01/04/2008 until 31/05/2008. Additionally column 5 lists the number of events that are of moment magnitude size above 1.0.

Data presented in Table 9.1 indicates that not only each software version source parameters are different but also that there is a difference between the source parameters in the two versions that are presently on the market. The main trend is that in each version later than 9.2.1 there is less seismic energy but more of seismic moment. If for the 2 months cumulative seismic energy value based on version 9.2.1 we assume a 100 % value then the version 10.1.3 cumulative value accounts for 7 %, version 10.1.4 accounts for 3 % and the Jmts accounts for 6 % compared to version 9.2.1 energy. If the 2 months cumulative seismic moment value based on version 9.2.1 we assume to be 100 % value then version 10.1.3 cumulative moment accounts for 1287 %, version 10.1.4 accounts for 331 % and the Jmts accounts for 1307 % of version 9.2.1 seismic moment. These percentage differences on their own illustrate the enormous differences between the software versions. Figure 9.1 illustrates the cumulative values for seismic moment and seismic energy for the four software versions. The vertical scales are the same allowing for direct comparison. The vertical scale for the cumulative energy is based on the energy according to

Table 9.1 Cumulative energy and cumulative moment

Software version	No of events	Cumulative energy (J)	Cumulative moment (Nm)	No of events above 1.0
9.2.1	1662	1.10E+07 (100 %)	2.05E+12 (100 %)	5
10.1.3	1662	7.39E+05 (7 %)	2.64E+13 (1287 %)	135
10.1.4	1662	2.95E+05 (3 %)	6.80E+12 (331 %)	67
Latest Jmts	1662	6.70E+05 (6 %)	2.68E+13 (1307 %)	138

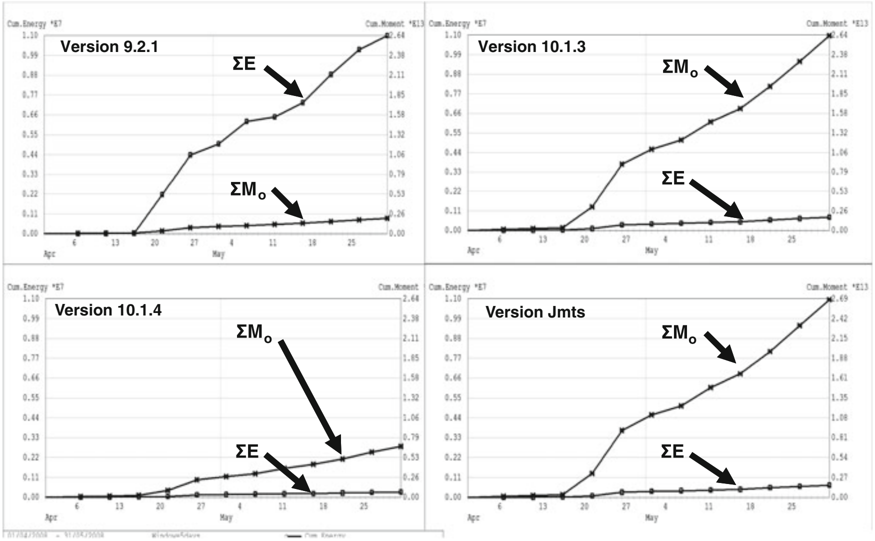

Fig. 9.1 Cumulative energy and moment

software version 9.2.1 while the seismic moment vertical scale is based on seismic moment resulting from the Jmts software.

Data presented by Fig. 9.1 is based on the same seismicity that was recorded in April and May 2008 but it demonstrates three different seismic histories. Seismic histories according to versions 10.1.3 and Jmts are quite similar. As each post version 9.2.1 has more seismic moment, and then consequently they will result in more seismicity with higher magnitude values. Table 9.2 illustrates the differences in the number of moment magnitude events per magnitude range depending on the software version.

Table 9.2 indicate that there are differences in the number of events depending on the magnitude range. It appears that the main differences in the software versions

Table 9.2 Number of moment magnitude events depending on software version

Magnitude range	Software version			
	9.2.1	10.1.3	10.1.4	Jmts
$-2.0 < M < -1.5$	1	4	3	3
$-1.5 < M < -1.0$	46	37	38	39
$-1.0 < M < -0.5$	515	373	371	371
$-0.5 < M < 0.0$	620	611	609	607
$0.0 < M < 0.5$	377	345	368	353
$0.5 < M < 1.0$	98	157	206	151
$1.0 < M < 1.5$	5	79	66	80
$1.0 < M < 2.0$		55	1	57
$2.0 < M < 2.5$		1		1

are in magnitude range −1.0 up to −0.5. Here in version 9.2.1 there are about 140 more events than in the other three versions. In magnitude range from −0.5 up to 0.5 the number of events in each software version is more or less the same. In higher magnitude ranges the number of events in version 9.2.1 is less than in the other three versions. Figure 9.2 and Table 9.3 illustrate the distribution of magnitude sizes for the four software versions. There is some similarity between the two shapes of distributions according to version 9.2.1 and 10.1.4. Still the higher the magnitude the larger are the differences—see Table 9.3 On the other hand the magnitude distributions curves both in shape and the number of events per size for versions 10.1.3 and Jmts are similar.

Data listed in Table 9.3 illustrates the magnitude size distributions according to the four versions. The total number of events in each software version is the same. The version 9.2.1 distribution is different from the three other ones while the distributions by version 10.1.3 and Jmts are similar.

Figure 9.3 illustrates the seismic energy distribution. The seismic energy distributions for version 10.1.3, version 10.1.4 and Jmts while are all in some way similar are also different from the distribution resulting from software version 9.2.1. In software version 9.2.1 there are about 100 seismic events with log energy above 4.0 while in software versions 10.1.3 and Jmts distributions there are only about 10 events in this energy range. In version 10.1.4 there are only two events above this energy range. Figure 9.4 illustrates the seismic moment distribution for the four software versions.

There is similarity between the moment distribution according to version 10.1.3 and version 10.1.4 and Jmts. According to version 9.2.1 there are about 50 events with log moment above 10.0 while in the other three versions there are about 200 such seismic events. The magnitude scale is a convention but should be reasonably consistent within the different software versions. The shallow seismicity at the east

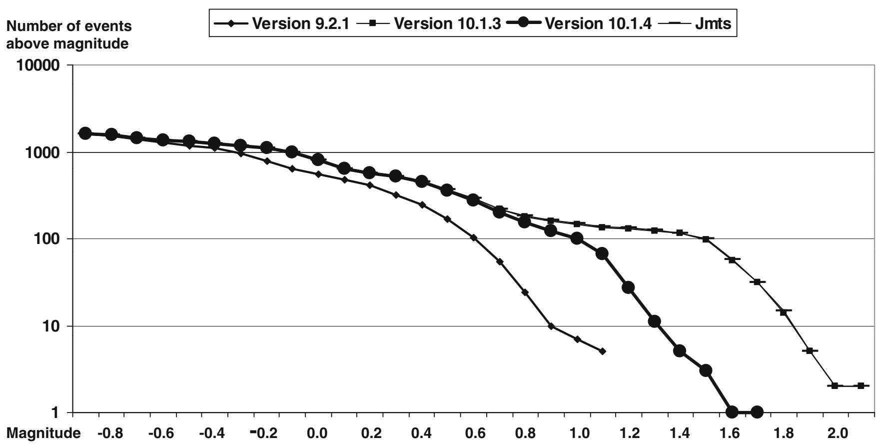

Fig. 9.2 Distribution of magnitude sizes

Table 9.3 Distribution of magnitude sizes

Magnitude	Number of events above magnitude			
	Version 9.2.1	Version 10.1.3	Version 10.1.4	Jmts
−1.0	1615	1621	1621	1620
−0.9	1524	1565	1560	1561
−0.8	1381	1458	1453	1452
−0.7	1278	1374	1374	1375
−0.6	1177	1314	1312	1313
−0.5	1100	1248	1250	1249
−0.4	955	1178	1178	1178
−0.3	784	1092	1092	1092
−0.2	639	981	987	987
−0.1	560	795	798	798
0.0	480	637	641	642
0.1	409	564	566	567
0.2	316	512	515	516
0.3	244	451	450	450
0.4	168	362	361	369
0.5	103	292	273	289
0.6	55	216	198	220
0.7	24	177	155	182
0.8	10	159	123	163
0.9	7	146	101	151
1.0	5	135	67	138
1.1		130	27	132
1.2		124	11	127
1.3		115	5	116
1.4		96	3	99
1.5		56	1	58
1.6		31	1	31
1.7		14		15
1.8		5		5
1.9		2		2
2.0		2		2
2.1		1		1
Max magnitude	1.1	2.2	1.7	2.2

is associated with the East break through. With software version 9.2.1 this seismicity was of magnitudes between 0.0 and 0.5. All three higher versions display this break through with seismicity of magnitudes 1.0 and higher suggesting that this break through was very violent, but it was not. Drastic changes in the magnitude sizes suggest that there is something wrong with the moment estimation in version 9

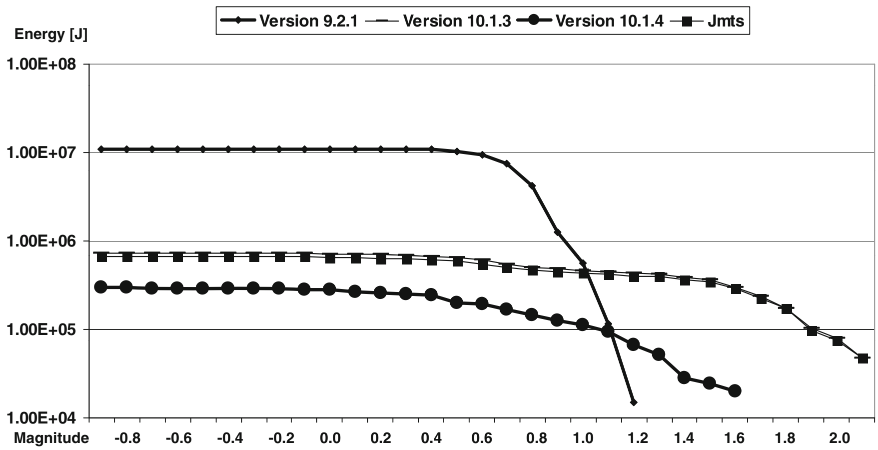

Fig. 9.3 Distribution of seismic energy for the four versions

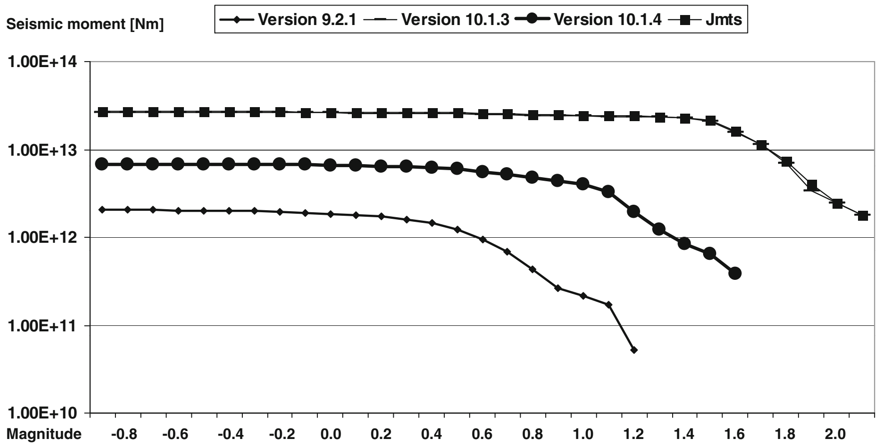

Fig. 9.4 Distribution of seismic moment

or versions 10 of the software. However, as indicated by Table 9.1 the latest software versions differ not only in the seismic moment estimations as there are also substantial differences in the seismic energy release estimates. These combined changes might affect not only the visualization of seismicity but also influence and change its interpretation. As I often make use of the energy index time histories I will start the comparison with this parameter especially as the Palabora experience indicates that it correlates very well with the caving progress. Figure 9.5 illustrates the energy index time history according to different software versions. For version 9.2.1 for the whole 2 months the energy index values are constantly above their mean value of 1.0. This would be expected as during these 2 months a lot of the

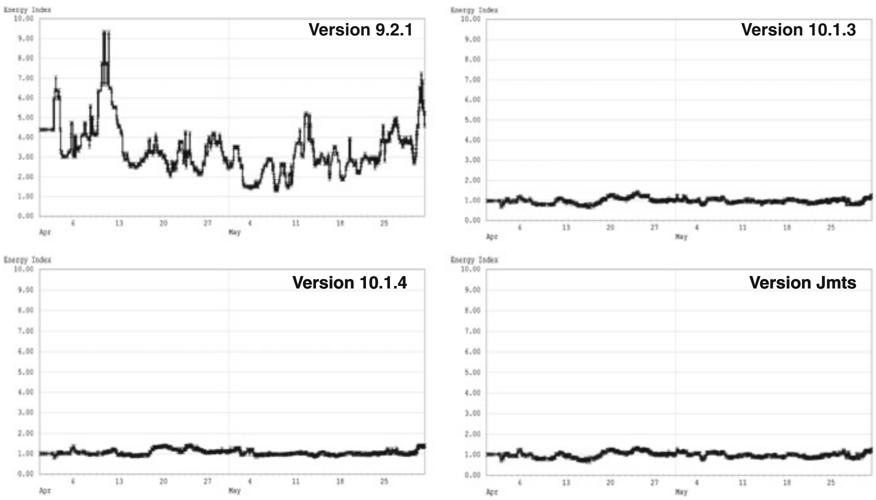

Fig. 9.5 Energy index time histories for the four software versions

seismicity was associated with the east break through and as such should be of high energy index values. In versions 10.1.3, 10.1.4 and Jmts the energy index values are practically constant and close to the mean of 1.0.

Analysis of the energy moment relation for the four software versions indicates that this relation for software version 9.2.1 is different from the other three versions. The main difference is in the higher moment values. In version 9.2.1 the larger seismicity releases higher amounts of energy than the lower size seismicity. According to the other three versions the larger size seismicity releases less energy than the lower size events. The other difference is that in version 9.2.1 the scatter is larger indicating, as would be expected, more variation in the energy release per moment. Analysis of the magnitude versus apparent stress relationship for the four software versions indicates that this relationship for software version 9.2.1 is different from the other three versions. The main difference is in the higher magnitude values. In version 9.2.1 the larger seismicity has higher apparent stress values. According to the other three versions the larger size seismicity has lower apparent stress values than the lower size events. The other difference is that in version 9.2.1 the scatter is larger indicating more variation in the apparent stress values per magnitude (or seismic moment). Table 9.4 presents distribution of Es/Ep ratios for the four software versions. According to presented distributions only processing with software version 9.2.1 resulted with over 50 % of seismicity with this ratio above 10.0. In case of other versions over 50 % of seismicity has this ratio less than 10.0.

As indicated by Table 9.5 most of the seismic events in software version 10.1.4 that do not have Es or Ep are in the lower magnitude ranges.

Figure 9.6 illustrates the energy P to energy S relationship for the four software versions. This relationship for software version 9.2.1 is different from the other

Table 9.4 Es/Ep ratios in different software versions

Es/Ep ratio	Software version			
	9.2.1	10.1.3	10.1.4	Jmts
Es/Ep > 20	632 (38 %)	176 (10 %)	117 (7 %)	161 (10 %)
10 < Es/Ep < 20	455 (27 %)	286 (17 %)	291 (17 %)	257 (15 %)
Es/Ep < 10	554 (33 %)	983 (59 %)	1037 (62 %)	1027 (61 %)
Es or Ep = 0	21 (1.0 %)	217 (13 %)	217 (13 %)	217 (13 %)
Total number	1662	1662	1662	1662

Table 9.5 Version 10.1.4 distribution of events with no Ep or Es with magnitude

Magnitude range	No of events	No P or S energy	Percentage
Up to −0.5	484	152	31
−0.5 < M < 0.0	684	82	12
0.0 < M < 0.5	443	5	1
0.5 < M < 1.0	246	0	
Above 1.0	67	0	

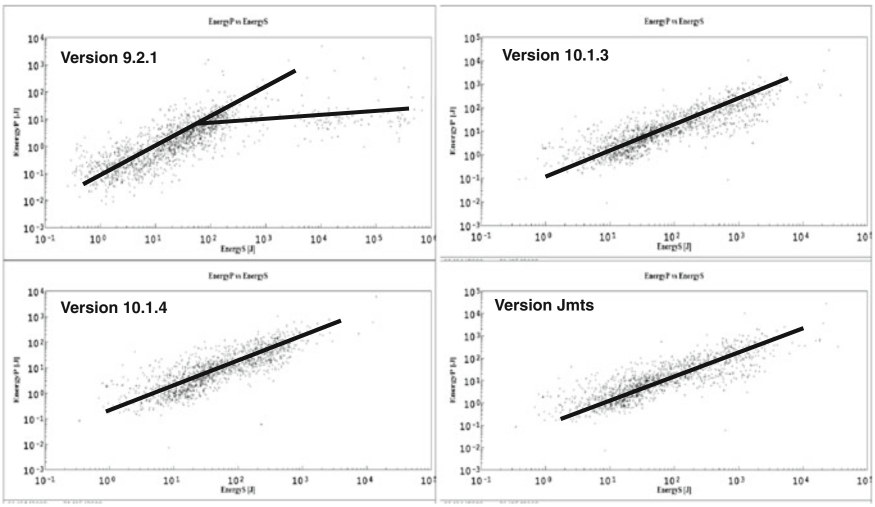

Fig. 9.6 Energy S versus energy P relationship

three versions. In this version up to S-wave energy of about 500 J the relationship between the Es and Ep is directly proportional while for larger values of Es this relation is more of a linear character. This would indicate two different source mechanisms. According to the other three versions the larger the size of Es the larger is the Ep size. This implies one seismic source mechanism. During April and

May 2008 there were two processes taking place, the caving process and the east break through.

Figure 9.7 illustrates the energy index time history for the whole mine, from the beginning of 2001 until end of March 2010. This plot uses data processed with software version 9.2.1. The energy index graph represents the stress regime and in this case relates its changes and values to the different stages of the caving process. To start with, the stress levels during the latter part of 2001 were already above the average value (1.0). This stress increase was the result of the development mining. Start of the caving process in April 2002 (A) was associated with a rapid stress increase that lasted until the failure of the crown pillar at the end of 2002 (B). This time period of maximum stress continued until the cave broke through into the open pit in May 2004 (C). From then on the stresses started to decrease to reach the average level by the end of 2004. At this stage the stress decrease rates were faster than the increase rates after the caving process initiation. After reaching the average value of 1.0 the stress decrease rate slowed down. From the beginning of 2005 to date, the stress levels have remained below the average value. The stress increase due to the development mining phase was very low when compared to the stress increase induced by the caving process. The stress level during the east break through (E) was significantly lower than during the initial (central) break through (C). This figure illustrates the fact that during April and May, 2008 there were two processes taking place: the caving process and the east break through. At the

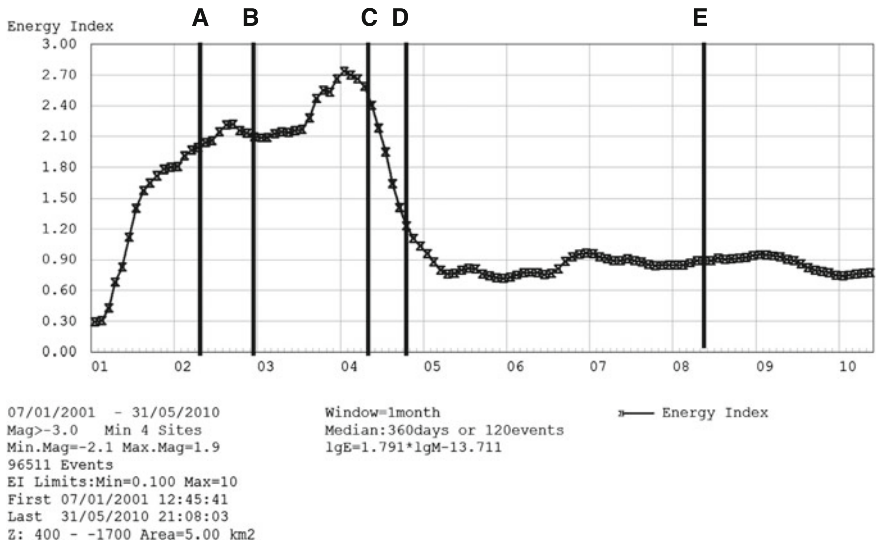

Fig. 9.7 Energy index time history

beginning of 2006 there was only one process taking place that is the caving process. Figure 9.8 illustrates the energy P versus energy S relationship based on data recorded during January 2006 (software version 9.1.2). Here the Ep versus Es relationship is not only very similar to that presented by Fig. 9.6 for version 10.1.3, version 10.1.4 and version Jmts but also as expected indicates that only one seismic source mechanism is present.

Analysis of the vertical distribution of seismicity according to their Es/Ep ratios for data processed with software version 9.2.1 and software version 10.1.4 results in two different results. According to software version 9.1.2 there is 51 % of seismicity with the Es/Ep ratio above 15 while according to version 10.1.4 there is only 15 % of such seismicity. Most of these events in version 9.2.1 are shallow which means that they are associated with the caving process and the east break through. In this version most of low Es/Ep ratio seismicity locates below the mine elevation. This implies different source mechanism above and below the mine. According to version 10.1.4 the source mechanisms above and below the mine are the same. The ratio of Es/Ep is an important indicator of the type of focal mechanisms responsible for the generation of seismic events in mines (Gibowicz and Kijko 1994). Higher Es/Ep ratios indicate double couple events, while lower ratios of Es/Ep would indicate events with more tensile type of failure. In case of the caving process one would expect the seismic events taking place around the cave to be due to fracturing (Duplancic and Brady 2001) and the events taking place below the mine more of tensile type.

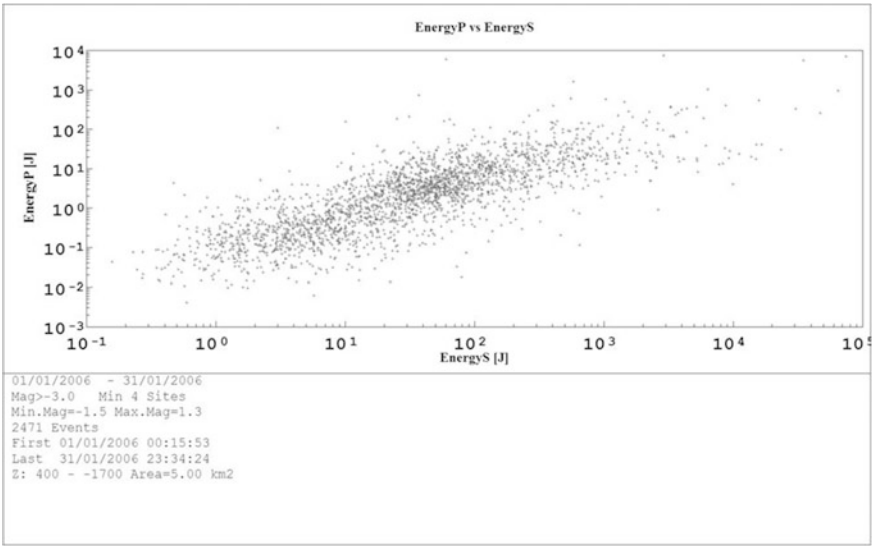

Fig. 9.8 Energy S versus energy P relationship version 9.2.1—data recorded in January 2006

Table 9.6 Cumulative seismic energy per magnitude size (J)

Magnitude	V 9.2.1		V 10.1.3		V 10.1.4		Jmts	
	No	E (J)	No	E (J)	No	E (J)	No	E (J)
−1.0	91	4.02E+02	56	5.57E+02	61	5.41E+02	59	5.22E+02
−0.9	143	1.41E+03	107	1.47E+03	107	1.27E+03	109	1.29E+03
−0.8	103	2.04E+03	84	1.14E+03	79	8.52E+02	77	8.29E+02
−0.7	101	1.73E+03	60	8.59E+02	62	7.15E+02	62	7.15E+02
−0.6	77	2.68E+03	66	8.26E+02	62	6.23E+02	64	6.49E+02
−0.5	145	6.77E+03	70	1.40E+03	72	1.15E+03	71	1.15E+03
−0.4	171	7.21E+03	86	1.98E+03	86	1.68E+03	86	1.68E+03
−0.3	145	8.31E+03	111	4.08E+03	105	3.25E+03	105	3.26E+03
−0.2	79	6.46E+03	186	8.57E+03	189	7.34E+03	189	7.32E+03
−0.1	80	6.04E+03	158	1.26E+04	157	9.92E+03	156	9.75E+03
0.0	71	7.22E+03	73	6.98E+03	75	5.75E+03	75	5.75E+03
0.1	93	9.09E+03	52	9.88E+03	51	8.24E+03	51	9.38E+03
0.2	72	3.37E+04	61	1.61E+04	65	1.15E+04	66	1.30E+04
0.3	76	4.91E+05	89	2.65E+04	89	1.85E+04	81	2.14E+04
0.4	65	8.97E+05	70	4.06E+04	88	2.81E+04	80	4.20E+04
0.5	48	2.03E+06	76	5.79E+04	75	3.00E+04	69	4.40E+04
0.6	31	3.25E+06	39	4.40E+04	43	2.07E+04	38	3.70E+04
0.7	14	2.96E+06	18	2.28E+04	32	1.92E+04	19	1.93E+04
0.8	3	7.11E+05	13	1.92E+04	22	1.38E+04	12	1.39E+04
0.9	2	4.49E+05	11	1.75E+04	34	1.88E+04	13	1.86E+04
1.0	4	9.90E+04	5	8.47E+03	40	2.71E+04	6	1.90E+04
1.1	1	1.52E+04	6	1.89E+04	16	1.38E+04	5	4.62E+03
1.2			9	2.57E+04	6	2.45E+04	11	3.47E+04
1.3			19	2.88E+04	2	3.58E+03	17	1.69E+04
1.4			40	6.37E+04	2	4.21E+03	41	5.20E+04
1.5			25	6.08E+04	0		27	6.64E+04
1.6			17	6.50E+04	0		16	5.45E+04
1.7			9	7.01E+04	1	2.00E+04	10	7.25E+04
1.8			3	2.43E+04			3	2.39E+04
1.9			1	2.50E+04			1	2.43E+04

Table 9.6 lists the cumulative seismic energy per magnitude size for the four software versions while Table 9.7 lists the average energy release per magnitude.

Table 9.6 indicates that in case of data processed with software version 9.2.1 only about 1.0 % of the total emitted seismic energy was due to events of magnitude 1.0 and above. In case of software version 10.1.3 this energy amount increased to over 60 %. In case of version 10.1.4 this percentage is at 32 % and for Jmts at 44 %. Only data according to version 9.2.1 would make it possible to try

Table 9.7 Average seismic energy per magnitude size (J)

Magnitude	V 9.2.1	V 10.1.3	V 10.1.4	Jmts
−1.0	4.42E+00	9.95E+00	8.86E+00	8.84E+00
−0.9	9.85E+00	1.37E+01	1.18E+01	1.18E+01
−0.8	1.98E+01	1.36E+01	1.08E+01	1.08E+01
−0.7	1.71E+01	1.43E+01	1.15E+01	1.15E+01
−0.6	3.48E+01	1.25E+01	1.00E+01	1.01E+01
−0.5	4.67E+01	2.00E+01	1.59E+01	1.61E+01
−0.4	4.22E+01	2.30E+01	1.95E+01	1.95E+01
−0.3	5.73E+01	3.68E+01	3.09E+01	3.10E+01
−0.2	8.17E+01	4.61E+01	3.88E+01	3.87E+01
−0.1	7.55E+01	7.95E+01	6.32E+01	6.25E+01
0.0	1.02E+02	9.56E+01	7.67E+01	7.67E+01
0.1	9.77E+01	1.90E+02	1.62E+02	1.84E+02
0.2	4.69E+02	2.64E+02	1.77E+02	1.97E+02
0.3	6.46E+03	2.97E+02	2.08E+02	2.64E+02
0.4	1.38E+04	5.80E+02	3.19E+02	5.25E+02
0.5	4.22E+04	7.61E+02	4.00E+02	6.38E+02
0.6	1.05E+05	1.13E+03	4.82E+02	9.74E+02
0.7	2.11E+05	1.27E+03	6.01E+02	1.01E+03
0.8	2.37E+05	1.48E+03	6.29E+02	1.16E+03
0.9	2.24E+05	1.59E+03	5.52E+02	1.43E+03
1.0	2.48E+04	1.69E+03	6.78E+02	3.17E+03
1.1	1.52E+04	3.15E+03	8.60E+02	9.25E+02
1.2		2.86E+03	4.09E+03	3.15E+03
1.3		1.51E+03	1.79E+03	9.95E+03
1.4		1.59E+03	2.11E+03	1.27E+03
1.5		2.43E+03		2.46E+03
1.6		3.82E+03		3.41E+03
1.7		7.79E+03	2.00E+04	7.25E+03
1.8		8.10E+03		7.98E+03
1.9		2.50E+04		2.43E+04

and release stress by preconditioning. Other three software versions suggest that mine seismicity energy release rates are similar to these of earthquakes (see Table 4.2) and no distressing will work. According to data listed in Table 9.7 the average releases of seismic energy per magnitude size in general are higher for data processed with version 9.2.1 than with any of the other versions. For magnitude size 0.7 the difference in seismic energy release between version 9.1.2 and the average based on the other three versions is greater than 200 times. While in version 9.2.1 the average seismic energy release of magnitude 0.7 is 2.11E+05 J and for the other versions the average is only at 9.61E+02 J.

Figures 9.9 and 9.10 illustrates the data presented by Table 9.7.

It is difficult to say exactly how much energy should be radiated by a given magnitude size as it strongly depends on the rock mass conditions. Still there are ways to get an estimate of this value that will at least give an idea of the energy release size.

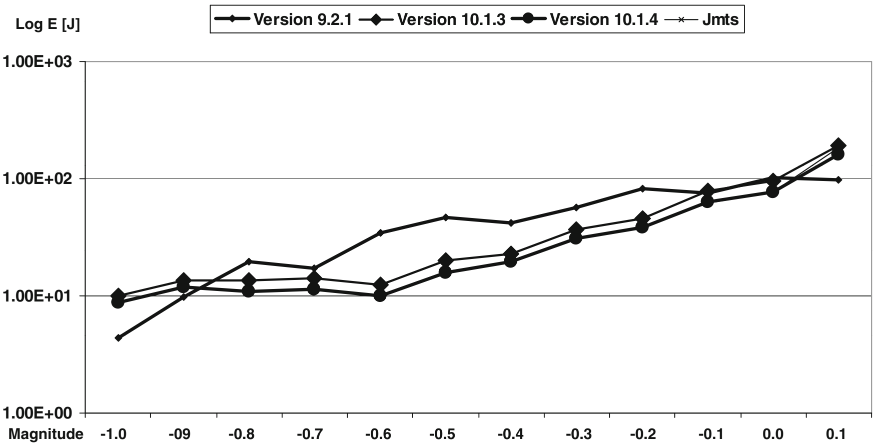

Fig. 9.9 Energy release per magnitude (magnitude range −1.0; 0.1)

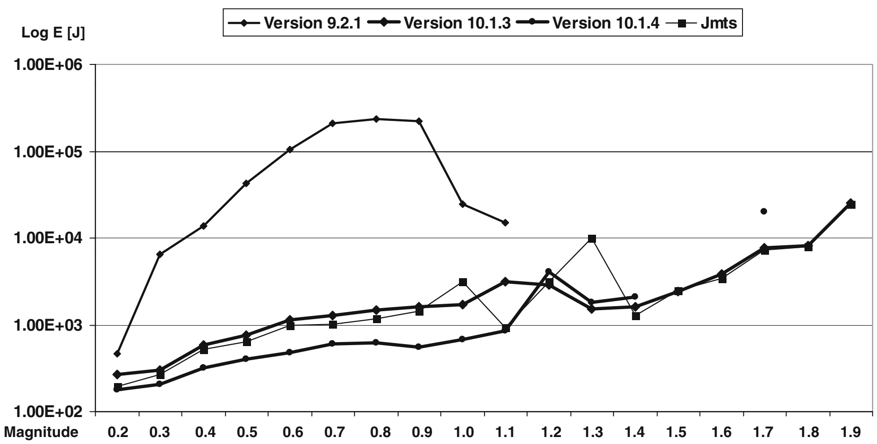

Fig. 9.10 Energy release per magnitude (magnitude range 0.2; 1.9)

Table 9.8 Moment energy relation according to Kanamori estimate

Moment (Nm)	Energy (J)	Moment magnitude
10E+07	5.0E+02	−1.3
10E+08	5.0E+03	−0.7
10E+09	5.0E+04	0.0
10E+10	5.0E+05	0.7
10E+11	5.0E+06	1.3
10E+12	5.0E+07	2.0

Kanamori (1977) estimate of radiated seismic energy (for larger size events):

$$\text{Energy} = \text{Moment}/20000$$

Table 9.8 lists the estimates of energy release for seismic moment range from 10E+07 up to 10E+12 Nm

Gutenberg and Richter (1956) estimate of seismic energy:

Log E = 1.5 M −1.2 where the energy is in MJ. From this relation the following is derived:

$$\text{For magnitude 0.7 the energy release is } 7.1\text{E}+05\,\text{J}$$
$$\text{For magnitude 1.0 the energy release is } 2.0\text{E}+06\,\text{J}$$
$$\text{For magnitude 1.3 the energy release is } 5.6\text{E}+06\,\text{J}$$
$$\text{For magnitude 2.0 the energy release is } 6.3\text{E}+07\,\text{J}$$

The two estimates give more or less the same results.

The Guttenberg-Richter estimate worked well for the KMMA Regional Seismic Network before it was upgraded with the ISSI seismic system. The magnitude used at the time was calibrated with the magnitudes as reported by the Geology Survey, Department of Mineral and Energy Affairs RSA (Webber 1988). The relationship between the Geology Survey department and the ISSI magnitude was (Glazer 1998):

$$\text{M (ISSI)} = 0.86\,\text{Mp} + 0.76$$

where Mp is the Geology Survey magnitude and M(ISSI) is the magnitude according to the ISSI system (at the time).

According to this formula the ISS magnitude 1.0 would be equal to magnitude 0.3 on the Geology Survey scale. Using the Guttemberg Richter estimate of energy this magnitude size would release about 1.8E+05 J of energy. As a matter of interest the underground damage at the Kleksdorp gold mines was usually reported for events by Geology Survey above magnitude 2.5. This size event would be then

Table 9.9 Energy release estimate for magnitude 0.7

According to	Energy (J)
Version 9.2.1	2.1E+05
Version 10.1.3	1.4E+03
Version 10.1.4	6.3E+02
Jmts	1.1E+03
Kanamori estimate	5.0E+05
Guttenberg and Richter estimate	7.1E+05

close to magnitude 2.9 on the ISSI system scale. This size event would release according to the Guttenberg Richter about 3.55E+08 J of energy. This short analysis indicates that the energy releases according to software version 9.1.2 are much closer to what should be expected than the other three versions. The energy release according to versions 10.1.3, 10.1.4 and Jmts are below the estimate in order of 1.0E+04 (see for example magnitude 1.3). Table 9.9 lists the energy release for magnitude 0.7. Only version 9.2.1 is close to the estimated values while the other three version values appear to be highly underestimated.

9.3 Comments Regarding the Seismic Energy Release Rates Based on Palabora Experience with Software Version 9.2.1

Table 9.10 lists the average seismic energy release per year of moment magnitude events from 1.0 to 1.3 during the time period from 2002 to the end of 2009. These events were recorded above and below the mine. All energy releases are close to 0.1 MJ and they change over time. The general trend is that over time these events

Table 9.10 Average energy released per magnitude size (v 9.2.1)

Year	Magnitude 1.0	Magnitude 1.1	Magnitude 1.2	Magnitude 1.3
2002	5.6E+05 J	5.3 E+05 J	–	5.3 E+05 J
2003	1.8E+05 J	1.6 E+05 J	1.4 E+05 J	7.7 E+05 J
2004	1.0E+05 J	2.1 E+05 J	2.9 E+05 J	11.0 E+05 J
2005	0.6E+05 J	0.2 E+05 J	0.6 E+05 J	–
2006	1.0E+05 J	5.8 E+05 J	2.1 E+05 J	0.3E+05 J
2007	0.2E+05 J	2.2 E+05 J	1.9 E+05 J	5.2 E+05 J
2008	0.5E+05 J	0.2 E+05 J	2.9 E+05 J	0.2E+05 J
2009	0.2E+05 J	0.2 E+05 J	1.2 E+05 J	–

emit less energy. This is to be expected as with time the rock mass around the mine becomes more and more fractured and over time it will be able to accumulate less and less strain energy. During 2003, just after the initiation of the caving process when the rock mass around the mine was still strong and un-fractured, the average energy release for events magnitude 1.0 was about 1.8E+05 J while 6 years later during 2009 this average decreased to 0.2E+05 J.

According to data presented by Fig. 9.11, from the beginning of 2008 to the end of March 2010 there were five seismic events in the magnitude range 1.0 up to 1.1. Three of these events took place during 2008. The April 2008 and June 2008 seismic events (both of magnitude 1.0) were associated with the cave breaking through at the east side. According to data presented in Table 9.11 both these

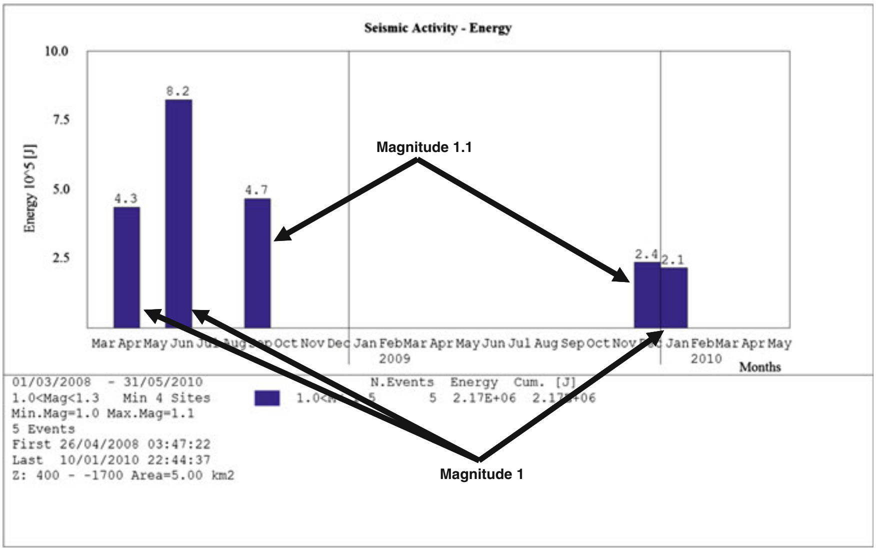

Fig. 9.11 2008, 2009 and 2010 seismicity of magnitude 1.0 and 1.1

Table 9.11 Larger size seismicity recorded during 2008, 2009 and 2010

No	Date	X	Y	Z	Mag.	Energy release (J)
1	26/04/2008	24068	−13398	−355	1.0	4.3E+05
2	07/06/2008	24550	−13367	−398	1.0	8.2E+05
3	24/09/2008	24263	−13142	−869	1.1	4.7E+05
4	04/12/2009	23915	−12964	−789	1.1	2.4E+05
5	10/01/2010	24410	−12841	−842	1.0	2.1E+05

events were shallow. The September 2008 and December 2009 events of magnitude 1.1 as well as the magnitude 1.0 event of January 2010 were deeper as all three occurred at an elevation of about −800 m. These three events are the result of redistribution of stresses around the cave after the east break-through. The September 2008 event was associated with a dyke and took place south of the mine. The December 2009 seismic event located north of the cave footprint while the January 2010 event located at a dyke south of the mine. Table 9.11 lists the seismic energy rates of these five seismic events. The December 2009 as well as the January 2010 events released very low amounts of energy in comparison to the events recorded during 2008.

Figure 9.12 illustrate the average energy release per magnitude size at Palabora. This graph is based on 123372 seismic events recorded from January 2001 until the end of March 2010.

According to the data listed in Table 9.12 the energy release for magnitude range from 1.3 up to magnitude size 1.9 is practically in the range of estimates using the Kanamori and Guttenberg and Richter estimate methods. As already mentioned it was observed that the energy release per magnitude changes over time with the caving process influencing ever larger volumes of the rock mass. Figure 9.13 illustrates how over time the average energy released by magnitude −0.3 seismicity has changed. During 2002 and 2003, when the stress around the cave was at its highest levels as indicated by the energy index, the average energy released per month was above 100 J. When the stresses decreased the average monthly energy releases decreased to about 50 J.

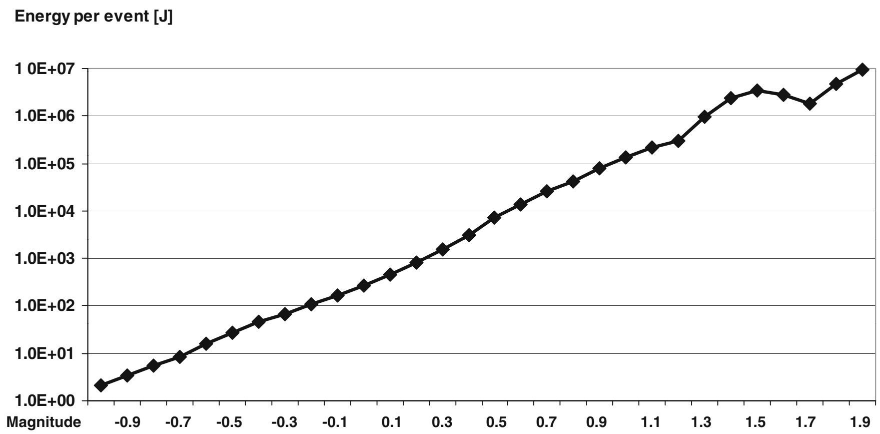

Fig. 9.12 Average energy release per magnitude—Palabora whole data base

Table 9.12 Average energy release per magnitude—Palabora whole data base

Magnitude	No of events	Cumulative energy (J)	Energy per event (J)
−1.0	2464	5.29E+03	2.15E+00
−0.9	3945	1.33E+04	3.38E+00
−0.8	4987	2.73E+04	5.47E+00
−0.7	5924	5.11E+04	8.62E+00
−0.6	6750	1.06E+05	1.57E+01
−0.5	8143	2.20E+05	2.70E+01
−0.4	10043	4.54E+05	4.52E+01
−0.3	11159	7.63E+05	6.84E+01
−0.2	10809	1.17E+06	1.08E+02
−0.1	9076	1.46E+06	1.61E+02
0.0	6951	1.87E+06	2.70E+02
0.1	4909	2.21E+06	4.50E+02
0.2	3246	2.71E+06	8.35E+02
0.3	1990	3.11E+06	1.56E+03
0.4	1177	3.54E+06	3.01E+03
0.5	694	4.94E+06	7.11E+03
0.6	439	5.83E+06	1.33E+04
0.7	292	7.73E+06	2.65E+04
0.8	184	7.85E+06	4.27E+04
0.9	132	1.07E+07	8.10E+04
1.0	97	1.32E+07	1.36E+05
1.1	57	1.26E+07	2.20E+05
1.2	34	9.96E+06	2.93E+05
1.3	20	1.95E+07	9.76E+05
1.4	6	1.43E+07	2.39E+06
1.5	3	1.06E+07	3.53E+06
1.6	9	2.54E+07	2.82E+06
1.7	1	1.85E+06	1.85E+06
1.8	1	4.75E+06	4.75E+06
1.9	2	1.93E+07	9.64E+06

Figure 9.14 illustrates how over time the average energy release by magnitude 0.5 seismicity has changed. During 2002 and 2003 when the stress around the cave was at its highest levels as indicated by the energy index the average energy released per month was above 1.00E+04 J. When the stresses decreased the average monthly energy releases decreased to about 0.20E+04 J.

The presented data gives confidence in data processed with version 9.2.1 as it correlates well with the caving process.

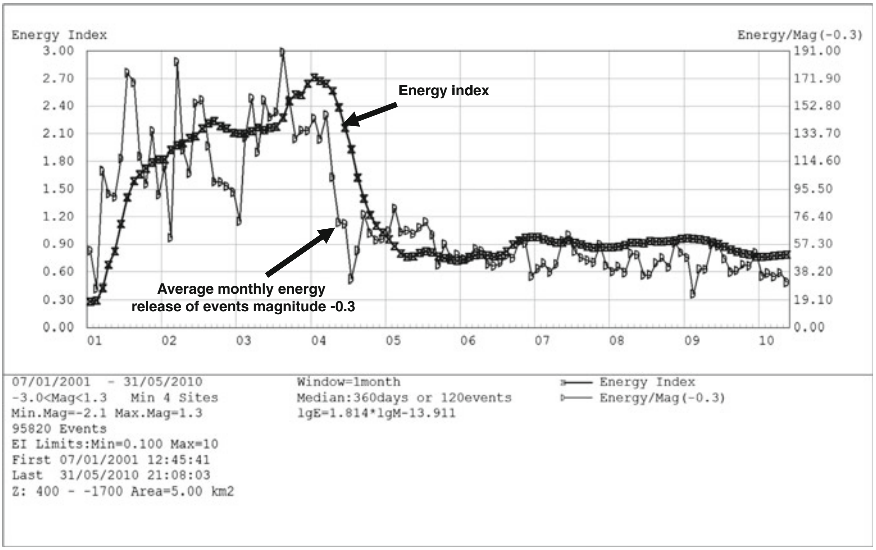

Fig. 9.13 Average monthly seismic energy releases—magnitude –0.3

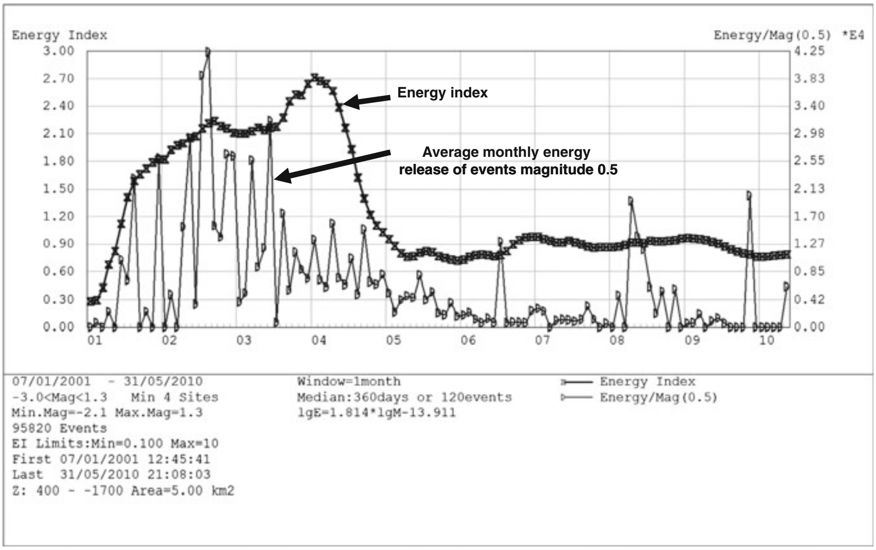

Fig. 9.14 Average monthly seismic energy releases—magnitude 0.5

9.4 Summary

Presented analysis is based on 2 months of data (1662 seismic events) while the whole Palabora seismic data base consists of over 10 years of continuous seismic monitoring data during which over 150,000 events were recorded. Before starting the comparisons between the four software versions I have made sure that the data base is sufficient and accurately represents the whole seismic data base. This involved some techniques usually not used for analysis and interpretation of recorded seismicity. This made a change from the other work. Discovered large differences in seismic moment and released seismic energy suggest that something was very wrong with either software version 9.2.1 or with software versions 10.1.3, 10.1.4 as well as the March 2010 version of Jmts. Additionally it was very disturbing that there are such substantial differences between the two latest versions that both are on the market, namely software version 10.1.4 and the Jmts. At the end of this chapter I have presented a short analysis of seismic energy release using the whole Palabora seismic data base which was processed with software version 9.2.1. The results presented give reason to be confident in data processed with this software version. All results as shown correlate very well with the caving process.

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Chapter 10
Seismic Preconditioning Below Lift 1 and Its Influence on the Cavability of Lift 2 Cave

Abstract There is no reason to question the fact that pulling from the cave resulted in fracturing the rock mass around the mine. Above the mine this process is validated by the fact that there was and still by the end of 2015 is production from the cave. If above the mine the rock mass would form one or a limited number of blocks then it would not be possible to mine out such rock mass. This is obvious. The rock mass above the mine was fractured and this fracturing process was recorded in form of seismicity. Seismicity was recorded not only from above the mine but also from below the mine. What more the amounts of recorded seismicity above and below the mine are not random in size and distribution but follow a specific consistent pattern. This pattern is controlled by the caving process and its milestones. From the beginning of 2002 until the end of 2013 about 50 % of the recorded seismicity, released seismic energy and seismic moment took place below the extraction level. This seismicity at some stage migrated down to −1200 m. This elevation will be the future Lift 2 Mine extraction level. In this chapter I have compared the seismicity recorded above the mine extraction level where the caving process took place and the rock mass was successfully mined out with that recorded below the mine. The rock mass below the mine will become Lift 2 cave. The main conclusion from this analysis is that the top volume of the potential Lift 2 rock mass is already de-stressed/preconditioned and fractured so it will cave rather than form an arch that will not cave resulting in the formation of a significant air void.

10.1 Introduction

The concept of seismic preconditioning below the mine was for the first time introduced by Glazer and Hepworth (2006). This idea was developed while analysing the mechanisms of the Palabora crown pillar failure. The detailed back analysis of crown pillar failure at Palabora was based primarily on seismic data. The other cave monitoring devices installed in boreholes that could provide data had been lost as a consequence of the response of the rock mass to mining. Analysis of the seismicity emanating from the crown pillar between the caving rock mass and the

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base of the open pit revealed the existence of a de-stressed zone of fractured rock mass below the base of the open pit when the crown pillar was reduced to 200 m thickness. At this stage the crown pillar was considered to have failed. The intensity and orientation of fracturing and jointing in this failed rock mass volume directly below the open pit did not allow the creation of a stable arch and hence an air gap over the caved rock mass. The cave finally broke through into the open pit in April 2004 with no evidence that there was any significant air gap above the caved rock mass. The existence of the failed zone below the open pit became apparent during reconstruction of the mainly a-seismic crown pillar failure mechanism. At the time this zone was created there was only a very limited amount of seismic data and only the analysis of the later seismicity provided sufficient conclusive evidence of its existence and extent. It was then concluded that by 2006 a similar process to the crown pillar failure mechanism is taking place in the rock mass below the underground production level. The existence and extension of the fractured or failed rock mass volume below the open pit became apparent only after the analysis of later seismicity, however, the process taking place below the underground production level has been monitored by the seismic network right from its initiation and data referring to this process continues to be collected on a daily basis. It was suggested that analysis of this new data from below the production level could be used to supplement the reconstruction process of the crown pillar failure mechanism. It was then noted that by the end of May 2005 the de-stressed or failed rock mass thickness below the production level was already about 100 m thick. Seismic data analysis indicated that the present fracturing process taking place below the production level is very similar to the process of the crown pillar fracturing and failure. The increased depth below surface and increased vertical and horizontal extent of the cave with the open pit above means that the in situ horizontal stresses as well as the mining induced stresses are higher from what existed initially below the open pit. For this reason it would be logical to expect that the final de-stressed zone below the production level would be thicker than the one below the open pit. The fracturing of the crown pillar has changed the stress distribution around the mine on a regional scale. This failed rock restricted the passage of the horizontal stresses through it and increased the vertical stress relative to the horizontal stress immediately adjacent to the cave zone. Comparison of seismicity recorded during 2002 with seismicity recorded during 2003 shows very significant differences. The redistribution of stress influenced not only the small scale jointing in the rock mass, but also the large scale sub-vertical geological features close to the cave zone. The decrease in horizontal stress reduced confinement and increased shear movement on these planes. This was confirmed by the seismic data where analysis of the source parameters of seismic events recorded in 2003 indicated a significant increase in the shearing component, in addition to a major increase of released energy per moment (Glazer and Hepworth 2005). In consequence Palabora became a seismically active mine and during 2003 experienced nearly a three-fold increase in relatively large seismic events, of which the first took place in mid January 2003. Concept of seismic preconditioning was then further developed and presented during MassMin2008 Conference (Glazer and Townsend 2008). Here it was noted that the seismic system has provided important information with respect to the rock mass beneath the present production footprint. This information could give valuable insights into the possible behaviour of this rock mass and implications for the potential Lift 2 Project with respect to fragmentation, cave propagation, failure of the Lift 2 crown pillar and associated seismic hazard. The wording “seismic preconditioning” was probably used for the first time in this part of the paper: “Palabora Lift 1 block cave has probably had to contend with the coarsest fragmentation ever experienced by any block cave with the most amount of secondary breaking being required on a daily basis. To a large extent the rate of production build-up for Lift 2 will be governed by the degree of primary fragmentation experienced. The build up to full production for Lift 2 is expected to be significantly quicker than was the case for Lift 1, due in part to the experience and learning’s from Lift 1, technology developed and the anticipated finer fragmentation. This is as a result of the extensive seismic activity and deformation observed below the Lift 1 extraction level since the beginning of 2005 leading to “**seismic preconditioning**” of the underlying rock mass. Although the fragmentation in the early stages of caving is still expected to be reasonably coarse, the expectations are that it will be considerably finer than that experienced for Lift 1 due to the seismic deformations that are being observed up to 200 m below the current extraction level and still extending in depth.” At that time it was considered that when the seismic cumulative moments are calculated for specific volumes then this procedure allows for comparisons between those volumes. A volume with higher amounts of seismic deformation will be more preconditioned or de-stressed than a volume with a lower cumulative moment. The distributions of the amounts of seismic deformation in a given rock mass volume will indicate how homogeneous this rock mass are as far as de-stressing is concerned. Apart from seismic deformation, the rock mass is also deforming a-seismically. This second process is slow fracturing that releases either low or no energy and for this reason cannot be recorded by a seismic system. Experience with the failure of the Crown Pillar indicates that with the caving process, a lot of the rock mass fracturing that takes place around the cave is of the a-seismic type.

10.2 Comparison of Seismicity Recorded Below with that Recorded Above the Mine

The idea of using explosives for rock burst control (preconditioning) is to stop the mechanisms that increase the horizontal clamping forces and to promote the occurrence of shear movements along fracture planes and parting planes. Both preconditioning the rock mass with explosives and the growth of the cave stimulated by drawing rock from the cave draw points, work essentially the same way and have the same effect on the rock mass. In block caving, the cave back progression generates fractures in the intact rock immediately ahead of the fracture zone, which alters the rock properties and reduces load carrying ability in this fractured rock. As the cave back approaches the newly fractured rock, it will yield under the increased tangential stress causing shear movement between the blocks of rock and further propagation of fractures. The cave progress will also result in breaking asperities and other locking mechanisms in the fractured rock mass creating an environment for increased shear movement and growth of the fracture zone around the cave back.

There is no reason to question the fact that pulling from the cave resulted in fracturing the rock mass around the mine. Above the mine this process is validated by the fact that there was and is production from the cave. If above the mine the rock mass would form one or a limited number of blocks then it would not be possible to mine out such rock mass. This is obvious. The rock mass above the mine was fractured and this fracturing process was recorded in form of seismicity. Seismicity was recorded not only from above the mine but also from below the mine. What more the amounts of recorded seismicity above and below the mine are not random in size and distribution but follow a specific consistent pattern. This pattern is controlled by the caving process and its milestones (Glazer and Townsend 2010). Figure 10.1 illustrates the percentages of seismicity recorded below the mine level from January 2001 until the end of December 2013. 100 % of the seismicity is the total amount of seismicity recorded every month above and below the mine level in the elevation range from +400 m down to −1700 m. Initially, during 2001, the amounts of seismicity recorded below the mine were at 30–40 %. This was at the time when only development mining was taking place. With the initiation of the caving process in April 2002 (A), less than 10 % of seismicity was recorded below the mine level. These low levels of seismicity below the mine level continued until the failure of the crown pillar (B) at the end of 2002. From then on the percentages of the recorded seismicity below the mine started to increase gradually. By the time of the cave breaking into the open pit (C) in May

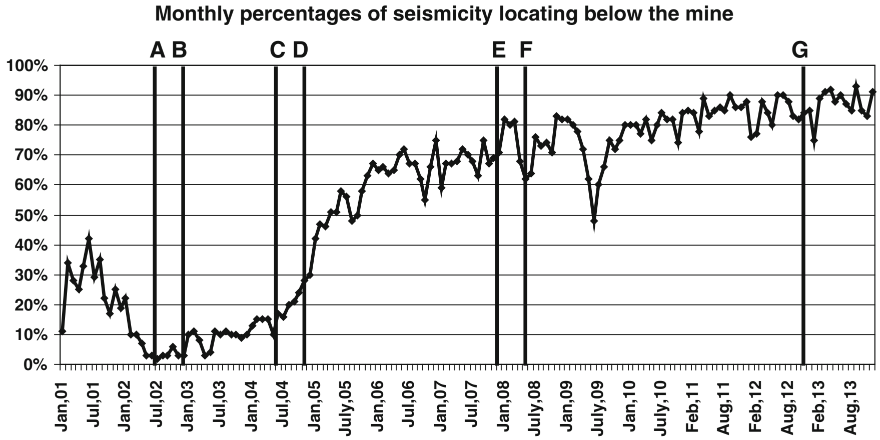


Fig. 10.1 Percentages of seismicity recorded below the mine level

Table 10.1 Seismicity recorded above and below the mine

Volume	No of events	Seismic energy (J)	Seismic moment (Nm)
Total	149222 (100 %)	3.38E+08 (100 %)	1.21 E+14 (100 %)
Above the mine	77362 (52 %)	1.99E+08 (56 %)	6.83 E+13 (56 %)
Below the mine	71860 (48 %)	1.39E+08 (44 %)	5.27E+13 (44 %)

2004 the percentages of seismicity recorded below the mine increased to about 15 %. After the initial break-through there was a continuous increase in the amounts of seismicity recorded below the mine level. From the middle of 2005 over 50 % of recorded seismicity started to originate from below the mine. From middle of 2008 this percentage increased to 80 % with some months with up to 90 % of events originating from below the mine.

Table 10.1 lists the amounts of seismicity that was recorded from January 2002 until the end of December 2013. This seismicity has then been divided into that recorded above and below the mine. The amounts of seismicity recorded below the mine cannot be ignored as it amounts to 48 % of the total recorded seismicity. The energy released below the mine is considerable as it amounts to about 44 % of the total similarly the seismic deformation that took place below the mine (also 44 % of the total).

Figure 10.2 illustrates the time history of the quarterly deepest elevations of seismicity. This figure illustrates three important facts. First until about beginning of 2005 the maximum seismicity elevations changes indicated that seismicity was migrating down and each year quarter was deeper. This seismicity migration started after the crown pillar failure and then intensified after the initial break through. The second fact is that once the seismicity depth reached about −1200 m (which is about 400 m below the mine) it stayed at this depth until the beginning of 2008. This means that for 3 years the maximum depth of seismicity was below elevation of −1200 m which is the estimated depth of the Lift 2 extraction level. This had to influence the rock mass down

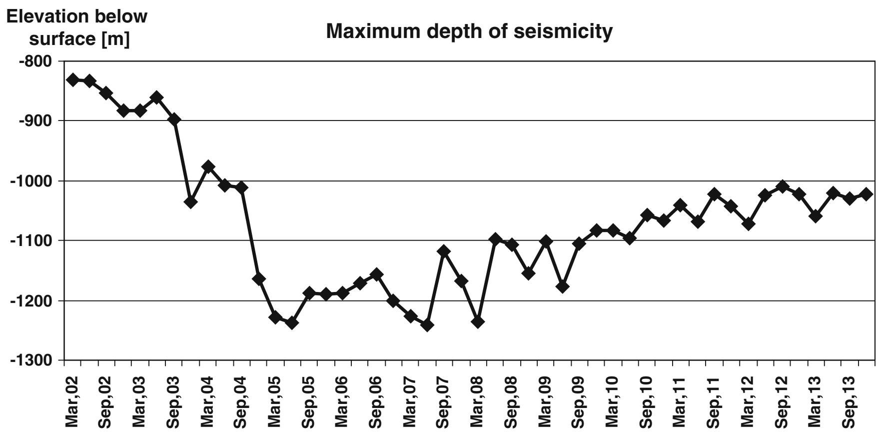


Fig. 10.2 Elevations of seismicity below the mine—time history

to this elevation as it was a long process. The third observation is that from the beginning of 2008 the seismicity migrated upwards. At end of 2013 the maximum seismicity elevation was at −1000 m. Taking into account the fact that the caving progress is about rock mass fracturing and that it is obvious that this fracturing took place above the mine then the question arises; what has happed below the mine? If nearly half of the recorded seismicity took place below the mine then it had to have an effect on and consequently it had to change the rock mass parameters. The process of changing rock mass parameters is known as preconditioning. Because in this case it is a side-effect of the caving process this process is referred to as seismic preconditioning. Verification methodology that seismic preconditioning below the mine is a genuine process is not difficult. It took place above the mine so comparison of seismicity recorded above with that recorded below the mine should provide validation or negation to the existence of seismic preconditioning below the mine. Table 10.1 gives only an indication of the amounts of recorded seismicity above and below the mine. These amounts are significant for the simple matter that they are in the same range. This is sufficient reason to attempt such analysis but on its own is not an ultimate condition that provides evidence that the rock mass below the mine is at present preconditioned by seismicity. The crucial problem is this seismicity distribution in time and space and its relation to the distribution of seismicity above the mine.

10.3 Seismically Active Volume

In this chapter I have evaluated the sizes of the seismically active volumes around the mine for every quarter starting at the beginning of 2002 and ending in December 2013. To validate the results the seismically active volumes were calculated using two procedures. In the first approach the input data consisted of 6 months of seismicity. The calculated volume was then attributed to the last month of this period. Then next 3 months were added and last 3 months were deleted. This resulted in a new 6 months period for which the seismically active volume was calculated. This procedure was then repeated until the calculated seismically active volume could be attributed to the end of December 2013. The second procedure used consecutive 3 months periods. The first one stared in January 2002 and ended in March 2002 and the last one started in October 2013 and ended in December 2013. The first way of calculation on some of the figures is indicated by "6 months" while the second one by "3 months" (Glazer 2008).

10.3.1 Seismically Active Volumes Based on Six Months Seismic Data for the Whole Mine

Figure 10.3 shows the seismically active volumes (in km^3) from the beginning of 2002 to the end of 2013. These volumes are a function of the seismically active

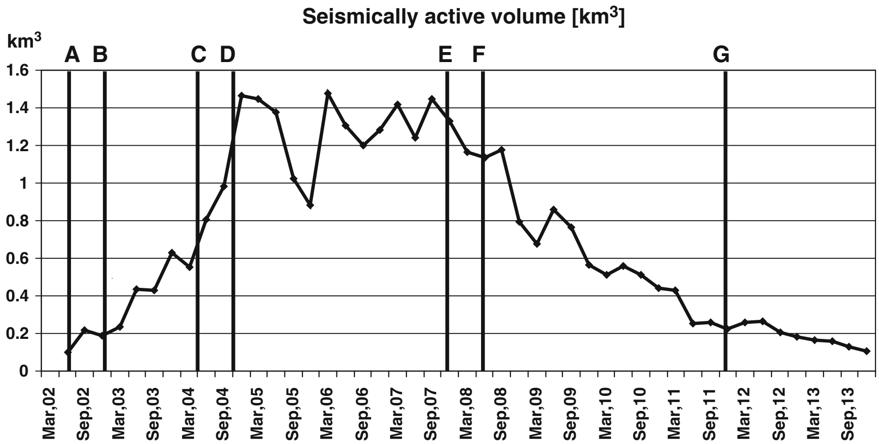


Fig. 10.3 Seismically active volume time history

areas and the seismicity vertical extension. This figure indicates that initially the volume increase was low, and then during 2003 the volume started to expand much faster. The maximum size of the seismically volume was reached at the beginning of 2005 and then it stayed at the same volume size until 2008. By 2013 this volume was low and still decreasing. This figure shows the changes of the seismically active volumes and relates them to the cave progress. The initial volume increases from the time of the cave process initiation (A) were small, but only until mid 2003. Once the failure of the Crown Pillar (B) was confirmed, there was a change in the draw strategy. At this point of time there was no reason to hold back the cave expansion any longer. The 200 m exclusion zone above the cave maximum elevation (in March 2003 the cave maximum elevation was at −600 m) was already fractured and no longer able to stop the rainwater from entering the underground mine. The maximum of seismically active volume appeared after the initial break through (C) with the failure in the open pit (D) and ended about the time when the caving process reached its mature stage by the end of 2007 (E) just before the he east break through (F). From then on the seismically active volume decreases. This volume decrease is slower from its increase rates from 2002 until the end of 2004.

Figure 10.4 shows the changes in the minimum and the maximum depths of seismicity over time. The vertical axis indicates the depths from −200 m down to −1400 m (BMSL). The two seismic migration patterns are different. After the cave initiation process took place (A) the seismicity migrated upwards to reach the elevation of about −200 m, just after the failure of the Crown Pillar (B). The cave break through into the open pit (C) had no influence on the shallower limit of seismicity. The maximum depth of seismicity remained at the same level much longer than did the minimum elevation. Only after the Crown Pillar failure (B) did the seismicity start to migrate downward, slowly and continuously. This would be expected as the Crown Pillar failure changed the stress distribution pattern. The pillar failure resulted

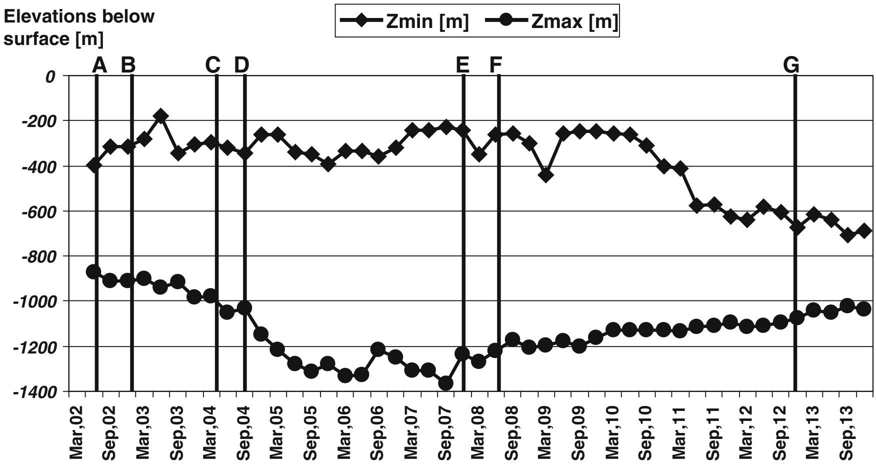


Fig. 10.4 Maximum and minimum elevations of the seismically active volume

in increased vertical stresses and this change was then reflected by the seismicity migration pattern. The breaking of the cave into the open pit during 2004 resulted in the acceleration of the downward migration of seismicity. The maximum depths were reached during the third quarter of 2005. Then the maximum seismicity depth stayed at the same elevation until the caving process reached its mature stage (E) by the end of 2007. From then on there was a slow but continuous upward migration trend of the maximum seismicity depth elevation. The minimum depth of seismicity started to indicate a downwards trend from about end of 2010.

Figure 10.5 shows the changes in the seismically active volume thicknesses (in meters). From the beginning of 2002 these heights gradually increased from about 400–1000 m by the third quarter of 2005.

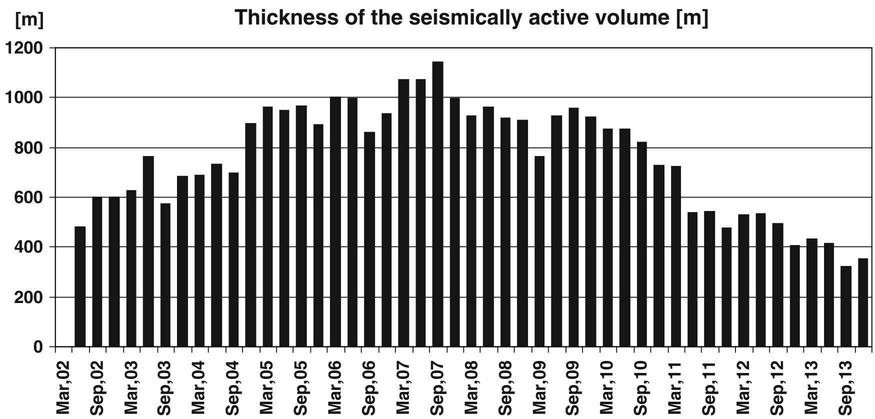


Fig. 10.5 Thickness of the seismically active volume

10.3.2 Seismically Active Volume Based on Three Months Seismic Data for the Whole Mine

The next three figures illustrate the seismically active volume time history (Fig. 10.6), the maximum and minimum elevation of seismicity changes with time and the cave progress (Fig. 10.7) and the seismically active volume thicknesses (Fig. 10.8).

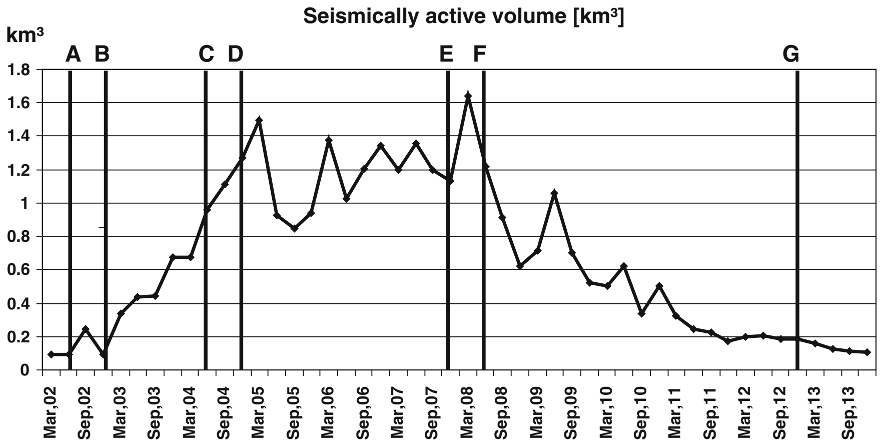


Fig. 10.6 Seismically active volume time history

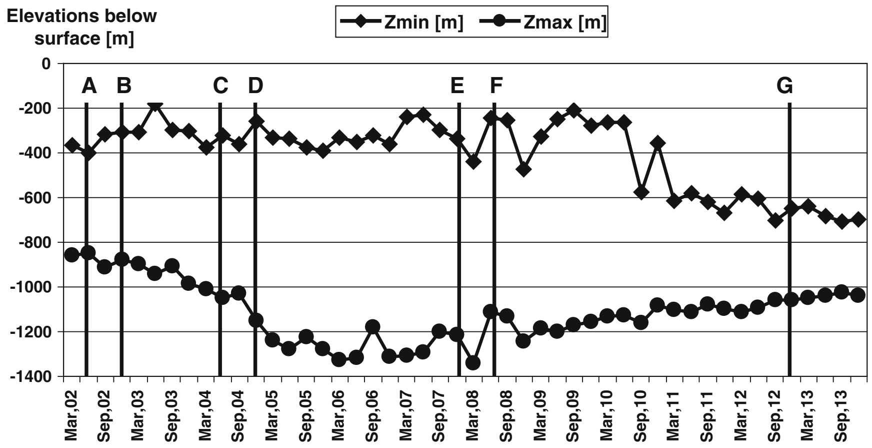


Fig. 10.7 Maximum and minimum elevations of the seismically active volume

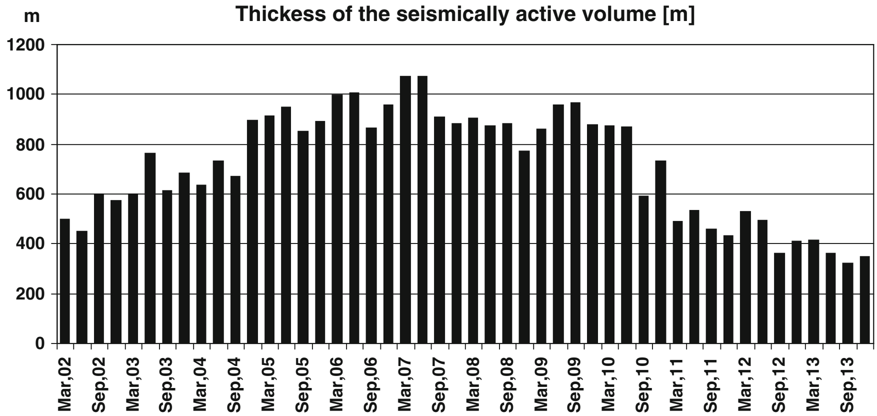


Fig. 10.8 Thickness of the seismically active volume

10.3.3 Comparison of Results Based on Six and Three Months Time Periods

Figure 10.9 illustrates the time histories for two seismically active areas. The trends as well as absolute values of these two curves are very similar. As it would be expected the curve based on 6 months of data is smoother than the one which is based on 3 months of data.

Figure 10.10 illustrates the two seismically active volume time histories. The trends as well as absolute values of these two curves are very similar. As it would be expected the curve based on 6 months of data is smoother than the one which is

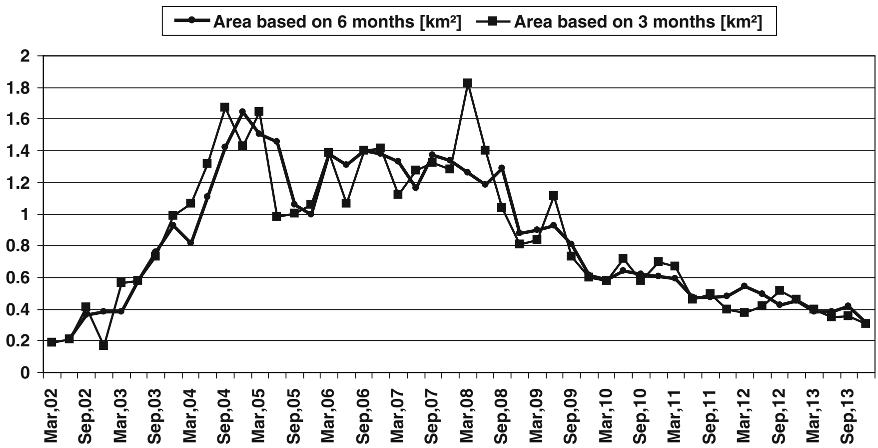


Fig. 10.9 Seismically active areas

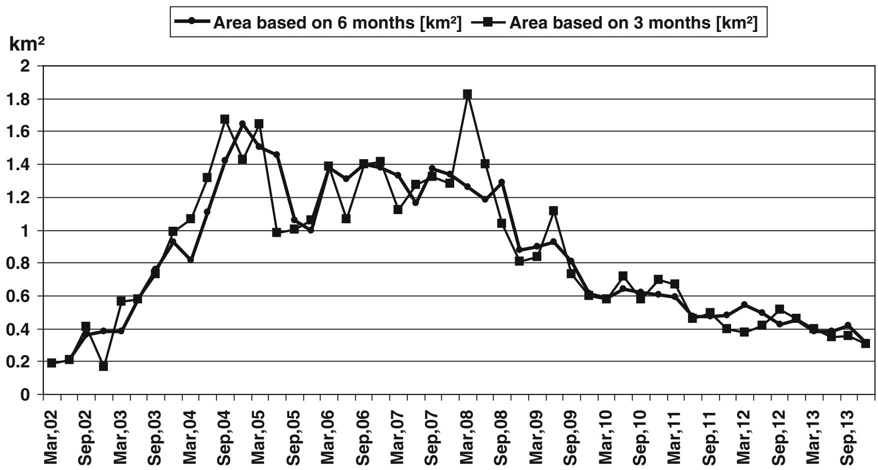


Fig. 10.10 Seismically active volumes

based on 3 months of data. This comparison indicates that for further analysis it is not important which procedure will be used as both provide similar results. As the 3 months procedure is more convenient and easy to use I will make use of this option from now on.

10.4 Apparent Volume and Seismically Active Volume

Definition of apparent volume (V_A) can be found in Mendecki (1997) and it reads: "The apparent volume for a given seismic event measures the volume of rock with co-seismic inelastic strain with accuracy in the order of magnitude of apparent stress divided by rigidity". Some additional information about this parameter can be found in Gibowicz and Lasocki (2001): "Apparent volume is supposed to be a measure of the rock volume with inelastic strain, associated with the seismic event". The apparent volume unit is m^3 and so in some way it represents the seismic source volume. To my knowledge up to date it was and still is used in support of the instability concept and then only in its cumulative form.

10.4.1 Apparent Volume and Seismically Active Volume for the Whole Mine

Figure 10.11 illustrates the apparent volume and the seismically active volume values as calculated based on the recorded seismicity in the subsequent 3 month periods from March 2002 to the end of December 2013. These two volumes are

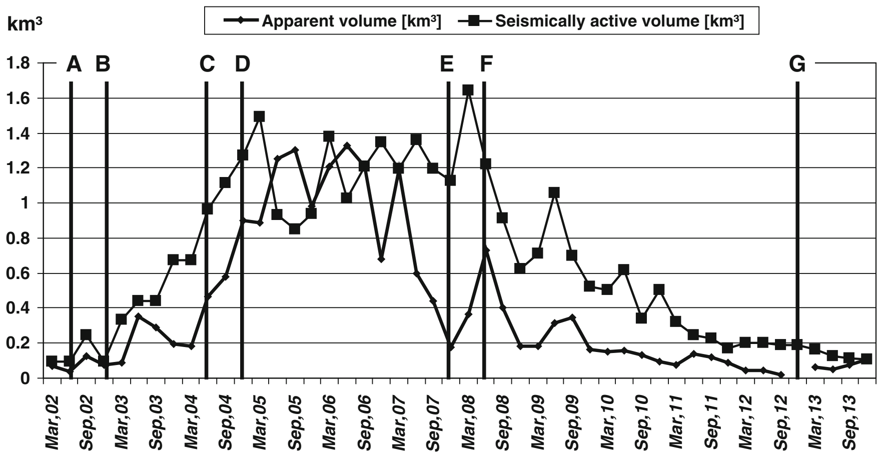
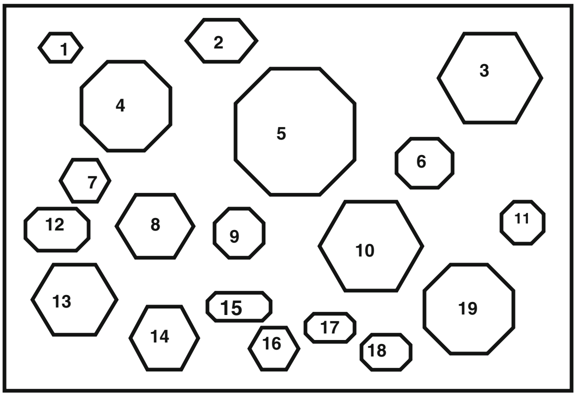


Fig. 10.11 Apparent and seismically active volumes

calculated with two totally different techniques. The apparent volume for each event is a function of moment and energy of those events—is calculated separately for each recorded event. Seismically active volume is an estimate of the volume which contains at least 95 % of events for a given time period. In other words this volume is calculated in one go for all seismic events. Taking this into account it is remarkable to note that these two volumes are very close to each other in size as they can be presented using one vertical scale. If that is the case then their proximity changes could be used to classify the seismicity clustering. This figure indicates that these two volumes were reasonably close to each other until about middle of 2007 from which time the distance between the two curves had increased.

Figure 10.12 explains the difference between the apparent volume and seismically active volume. When the seismically active volume and cumulative apparent

Fig. 10.12 Difference between apparent volume and seismically active volume



volume are calculated for the same input seismic data set then cumulative apparent volume is a sum of individual events apparent volumes:

$$\Sigma\,\text{Apparent volume} = \text{Volume}\,(1) + \text{Volume}\,(2) + \text{Volume}\,(3) + \cdots\cdots + \text{Volume}\,(19)$$

Seismically active volume is a volume of these 19 events apparent volumes plus the volumes between these 19 events. From this it can be concluded that:

- The seismically active volume in general should be larger than the cumulative apparent volume
- The closer these two volumes are to each other the closer to each other are the seismic events
- Their ratio should be a measurement of seismic clustering: if this ratio is closer to 1.0 the clustering is dense, the lower the ratio value the larger will be events scattering

Figure 10.13 illustrates that over time, the ratio between the apparent volume and the seismically active volume was changing. To start with there seems to be no obvious trend until the initial cave broke through (C). From then on this ratio first decreased and then increased but was constantly below the mean value of 2.3. From about end of 2007 the ratio increased above its mean value and then continuously stayed high. As this ratio indicates the seismicity clustering condition then this change indicates that by end of 2007 the recorded seismicity stopped clustering and became more scattered. This is the observation I made some time ago but up to date I had no concrete proof other than subjective observation. Now analysis of this ratio substantiates the theory that from end of 2007 the caving process reached its mature stage. This confirms the conclusion that the seismic apparent volume as well as

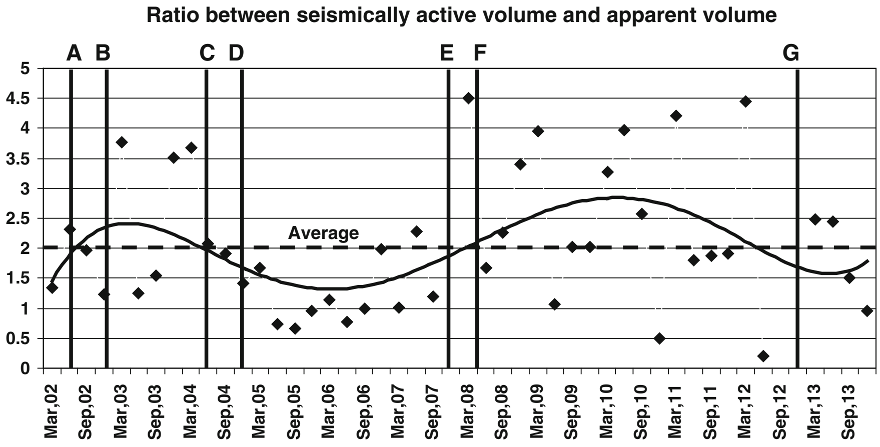


Fig. 10.13 Ratio apparent volume/seismically active volume

seismically active volume analysis have merit and should be used to monitor the caving process. From the beginning of 2013 seismicity started again to cluster more. This indicates that the caving process has ended and this seismicity is no longer induced by the caving process but by the mining itself.

10.4.2 Seismicity Recorded Above and Below the Mine

Table 10.2 lists amounts of seismicity recorded above the mine level for every quarter from the beginning of 2002 until the end of December 2013. This table lists activity rates, cumulative apparent volume, cumulative seismic energy release rates and seismic deformation rates.

Table 10.3 lists amounts of seismicity recorded below the mine level for every quarter from the beginning of 2002 until the end of December 2013. This table lists activity rates, cumulative apparent volume, cumulative seismic energy release rates and seismic deformation rates.

The next three figures illustrate data listed in Tables 10.2 and 10.3. Each of these figures consists of two parts. The top part illustrates seismicity above the mine and the bottom part represents the seismicity recorded below the mine. Both the top and bottom horizontal and vertical scales are the same. This allows for direct comparison.

Figure 10.14 displays the quarterly seismic activity rates above and below the mine. There is a distinctive difference between these two graphs. Above the mine the seismic activity rates were related to the production rate as from 2002 (this includes development as well as cave mining) but only up to the end of 2003, which is the time just before the cave broke into the open pit. During the time when the cave broke into the open pit the seismic activity rates above the mine decreased rapidly despite the fact that the production rates were still increasing. Below the mine there was very low seismic activity until after the failure of the crown pillar. The seismic activity remained at low level up until the time the cave broke into the open pit. Just before the failure in the open pit the seismic activity rate increased very rapidly and reached its maximum by mid 2005. The subsequent decrease in seismic activity rates was also very rapid. There are two activity rate peaks. The first peak of 2003 was associated with the seismicity recorded above the mine. The second peak of 2005 was related to the seismicity recorded below the mine.

Figure 10.15 shows the quarterly rates for the seismic energy release and the production rates. During 2002 there was a slow but continuous increase in the production rates that was followed by a similar slow, but continuous increase in the seismic energy release rates. From March 2003 until about October 2003 the production rates increased very rapidly. This resulted in increased seismic energy rates. From mid 2003 until mid 2004 the energy release rates were the highest for the entire time period. The energy release rates decreased rapidly by the end of 2004 and the beginning of 2005. The 2008 increase in seismic energy release rates was connected with the cave breaking into the open pit on the east side of the cave.

Table 10.2 Seismicity recorded above the mine

Date	No of events	Apparent volume (m^3)	Energy (J)	Moment (Nm)
Mar-02	585	6.51E+07	9.47E+05	7.95E+11
Jun-02	1174	3.79E+07	6.29E+06	7.50E+11
Sep-02	2267	1.18E+08	6.93E+06	1.71E+12
Dec-02	2116	7.37E+07	6.50E+06	1.03E+12
Mar-03	934	8.13E+07	3.34E+06	1.21E+12
Jun-03	6346	3.35E+08	2.45E+07	3.40E+12
Sep-03	7658	2.61E+08	2.04E+07	4.09E+12
Dec-03	7270	1.55E+08	1.64E+07	2.81E+12
Mar-04	5346	1.48E+08	3.10E+07	4.03E+12
Jun-04	4726	3.89E+08	9.64E+06	3.65E+12
Sep-04	2765	See note 1.67E+09 Corrected 4.69E+08	2.12E+07	5.69E+12
Dec-04	4301	6.25E+08	7.27E+06	5.38E+12
Mar-05	2720	5.20E+08	2.13E+06	3.27E+12
Jun-05	4374	6.23E+08	1.62E+06	3.29E+12
Sep-05	3661	7.88E+08	1.82E+06	4.46E+12
Dec-05	2192	4.63E+08	5.76E+05	2.35E+12
Mar-06	2300	4.53E+08	7.87E+05	2.06E+12
Jun-06	1366	4.71E+08	1.58E+06	2.19E+12
Sep-06	1720	4.60E+08	2.01E+06	2.31E+12
Dec-06	1205	2.86E+08	3.38E+05	1.50E+12
Mar-07	1425	6.81E+08	9.62E+05	2.03E+12
Jun-07	1227	2.52E+08	8.07E+05	1.61E+12
Sep-07	1133	1.55E+08	7.77E+05	1.03E+12
Dec-07	496	8.37E+07	4.94E+05	3.86E+11
Mar-08	376	1.16E+08	9.06E+05	3.92E+11
Jun-08	1044	5.47E+08	2.59E+07	2.81E+12
Sep-08	671	2.38E+08	2.69E+06	9.50E+11
Dec-08	457	5.02E+07	1.91E+05	2.18E+11
Mar-09	304	4.43E+07	7.56E+04	1.81E+11
Jun-09	710	1.84E+08	1.03E+05	5.37E+11
Sep-09	811	2.24E+08	1.31E+05	8.18E+11
Dec-09	351	7.34E+07	3.99E+05	4.29E+11
Mar-10	397	4.89E+07	4.12E+04	1.79E+11
Jun-10	360	5.49E+07	2.69E+04	2.09E+11
Sep-10	276	2.22E+07	6.84E+04	8.55E+10
Dec-10	276	2.15E+07	1.76E+04	8.27E+10
Mar-11	240	1.16E+07	5.89E+03	4.47E+10
Jun-11	267	2.58E+07	1.47E+04	8.93E+10
Sep-11	204	2.67E+07	1.13E+04	9.22E+10

(continued)

Table 10.2 (continued)

Date	No of events	Apparent volume (m^3)	Energy (J)	Moment (Nm)
Dec-11	295	1.57E+07	5.74E+04	5.83E+10
Mar-12	204	6.34E+06	8.09E+04	6.00E+10
Jun-12	163	5.74E+06	2.11E+04	2.78E+10
Sep-12	43	1.98E+06	1.93E+03	6.71E+09
Dec-12	117	5.90E+06	3.78E+03	1.96E+10
Mar-12	158	7.47E+06	9.74E+03	2.90E+10
Jun-13	72	5.69E+06	1.06E+04	1.82E+10
Sep-13	119	8.22E+06	2.30E+03	2.50E+10
Dec-13	172	1.20E+07	3.79E+03	4.13E+10

Note largest event ever recorded, 14/07/2004 magnitude 1.9, has an apparent radius of 80 m. There is a badly recorded/processed event of magnitude −0.2 (30/07/2004 at 08:07:2004 with apparent radius over 600 m. After rejecting this event the cumulative apparent volume decreases from 1.67 E+09 m^3 down to 4.69E+08 m^3

As with the seismic activity rates, the relationship between the seismic energy release and the production rate changed over time. Up to about end of 2003 and the beginning of 2004 this relationship was directly proportional. During 2004 this relationship was unclear. From the beginning of 2005 to the end of 2007 increased production rates did not result in increased amounts of released energy. During this period the energy release rates appeared to be low and almost constant. There were three energy emission peaks. Two of these took place after the failure of the crown pillar and before the cave had broken into the open pit. The third peak took place after the initial break through but before the failure in the open pit. Above the mine the energy release rates increased gradually until the failure of the crown pillar. After the crown pillar failure the seismic energy release rates increased rapidly. The subsequent decrease in the released energy was associated both with the initial break through and the failure in the open pit. Failure in the open pit practically resulted in the end of the seismic energy releases above the mine for the following years. The 2008 energy release peak was associated with the cave breaking through at the east during 2008. Below the mine, up to the time when the crown pillar failed, there was practically no seismic energy releases. Seismic energy release rates increased rapidly only after the failure of the crown pillar and then reached their maximum after the initial break through. The subsequent decrease was rapid. During 2006, after a year of very low seismic energy release, there was significantly more seismic energy released. This increased energy release during 2006 took place deeper than the energy releases that occurred during 2003 and 2004. The other difference between the earlier and the later energy peak releases was the absence of seismicity above magnitude size 1.5 during 2006. Seismicity of this size below the mine occurred again during 2008 after the east break-through.

Figure 10.16 illustrates the quarterly seismic deformation rates. Above the mine the seismic deformation rates increased continuously until the failure in the open pit. During this time the relationship between production rate and deformation rate

Table 10.3 Seismicity recorded below the mine

Date	No of events	Apparent volume (m^3)	Energy (J)	Moment (Nm)
Mar-02	83	4.90E+06	1.13E+05	8.96E+10
Jun-02	52	2.10E+06	1.12E+06	8.33E+10
Sep-02	58	6.25E+06	3.85E+05	1.39E+11
Dec-02	78	3.46E+06	4.58E+05	1.44E+11
Mar-03	100	8.21E+06	8.64E+05	3.33E+11
Jun-03	451	1.92E+07	9.12E+06	1.28E+12
Sep-03	893	2.69E+07	4.39E+06	1.10E+12
Dec-03	773	3.79E+07	8.75E+06	1.76E+12
Mar-04	894	3.54E+07	9.87E+06	2.34E+12
Jun-04	768	7.47E+07	1.76E+07	2.49E+12
Sep-04	643	1.13E+08	1.10E+07	1.87E+12
Dec-04	1576	2.73E+08	1.10E+07	1.66E+12
Mar-05	2247	3.71E+08	7.19E+05	1.85E+12
Jun-05	4942	6.29E+08	1.22E+06	3.33E+12
Sep-05	3747	5.10E+08	8.56E+05	2.69E+12
Dec-05	3683	5.17E+08	6.52E+05	2.74E+12
Mar-06	4256	7.56E+08	1.00E+06	3.38E+12
Jun-06	3072	8.64E+08	1.67E+07	4.59E+12
Sep-06	3245	7.47E+08	6.63E+06	4.11E+12
Dec-06	2018	3.93E+08	3.74E+06	1.81E+12
Mar-07	2621	5.13E+08	3.05E+06	2.08E+12
Jun-07	2689	3.44E+08	5.57E+06	1.96E+12
Sep-07	2396	2.84E+08	1.43E+06	1.80E+12
Dec-07	1102	9.37E+07	8.66E+05	5.52E+11
Mar-08	1598	2.48E+08	2.98E+05	9.91E+11
Jun-08	1799	1.86E+08	1.35E+05	7.38E+11
Sep-08	1950	1.67E+08	1.47E+07	6.84E+11
Dec-08	1664	1.33E+08	2.17E+05	6.32E+11
Mar-09	1200	1.37E+08	1.42E+05	5.76E+11
Jun-09	1457	1.31E+08	1.12E+05	5.37E+11
Sep-09	1648	1.22E+08	1.06E+05	4.86E+11
Dec-09	1084	8.79E+07	5.33E+04	3.51E+11
Mar-10	1485	1.05E+08	2.67E+05	4.27E+11
Jun-10	1351	1.01E+08	1.11E+05	4.61E+11
Sep-10	1355	1.09E+08	5.98E+04	3.98E+11
Dec-10	1194	7.02E+07	1.55E+05	3.71E+11
Mar-11	1302	6.52E+07	5.78E+04	2.94E+11
Jun-11	1487	1.11E+08	5.30E+05	4.80E+11
Sep-11	1305	9.32E+07	5.90E+04	3.77E+11
Dec-11	1360	7.36E+07	2.57E+05	3.59E+11

(continued)

Table 10.3 (continued)

Date	No of events	Apparent volume (m^3)	Energy (J)	Moment (Nm)
Mar-12	981	3.88E+07	1.25E+05	2.58E+11
Jun-12	936	4.15E+07	4.40E+04	1.94E+11
Sep-12	299	1.97E+07	1.28E+04	7.75E+10
Dec-12	739	4.67E+07	3.42E+04	2.23E+11
Mar-13	823	5.84E+07	3.27E+04	2.30E+11
Jun-13	644	4.55E+07	2.28E+04	1.90E++11
Sep-13	932	6.68E+07	2.71E+04	2.45E+11
Dec-13	1176	9.82E+07	3.55E+04	3.03E+11

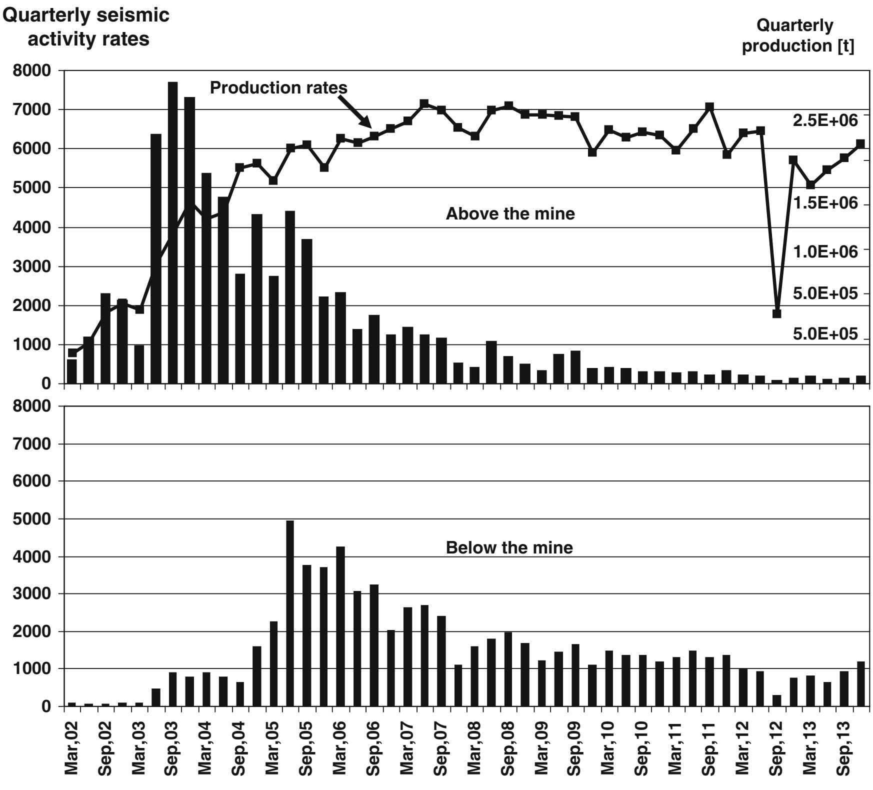


Fig. 10.14 Quarterly seismic activity rates above and below the mine

was obviously directly proportional. The direct proportional relationship then changed into an inverse relationship. Below the mine the seismic deformation rates started to increase after the failure of the crown pillar. This general increasing trend lasted until mid 2006. There appeared to be a slight change in this pattern during the second half of 2004, which was when the cave broke into the open pit, and the

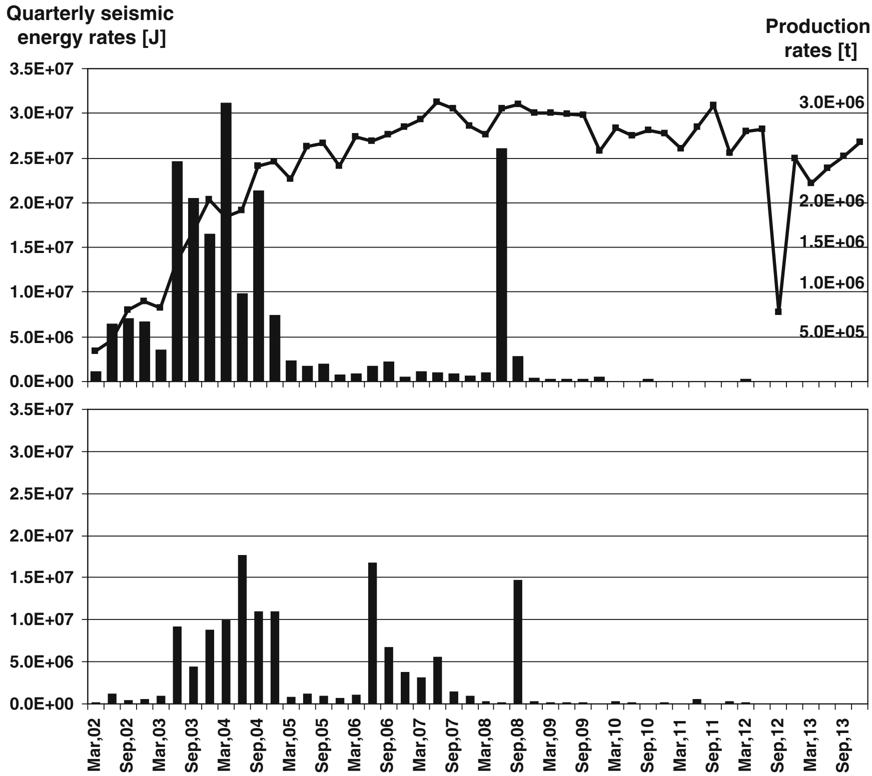


Fig. 10.15 Quarterly seismic energy release rates above and below the mine

failure in the open pit took place. From mid 2006 there was a rapid decrease in the seismic deformation rates. The first peak during 2004 relates to seismicity taking place above the mine while the second one that took place during 2006 was associated with the seismicity below the mine. As in the cases with seismic activity rates and seismic energy releases, the seismic deformation trends above and below the mine display differences. It seems that seismicity induced by cave mining is related not only to the production rate but also to the caving process itself. For this reason it becomes apparent that at some stage of the caving process the seismicity is no longer dependent on the production rate. There probably is a short period when the seismicity is a function of both production and the caving process. At the end it is only the caving process that influences the induced seismicity. This scenario applies to the seismicity recorded above the mine. The analysed data indicates that the seismicity recorded below the mine is related more to the caving process than to the cave production rate. There are different patterns of seismicity trends above and below the mine. The implication of this is that over time the seismic activity rates, the rates of released seismic energy and seismic deformation show different trends and also reach their maximum values at different stages. A study of these trends is important, as it should result not only in a better understanding of the caving

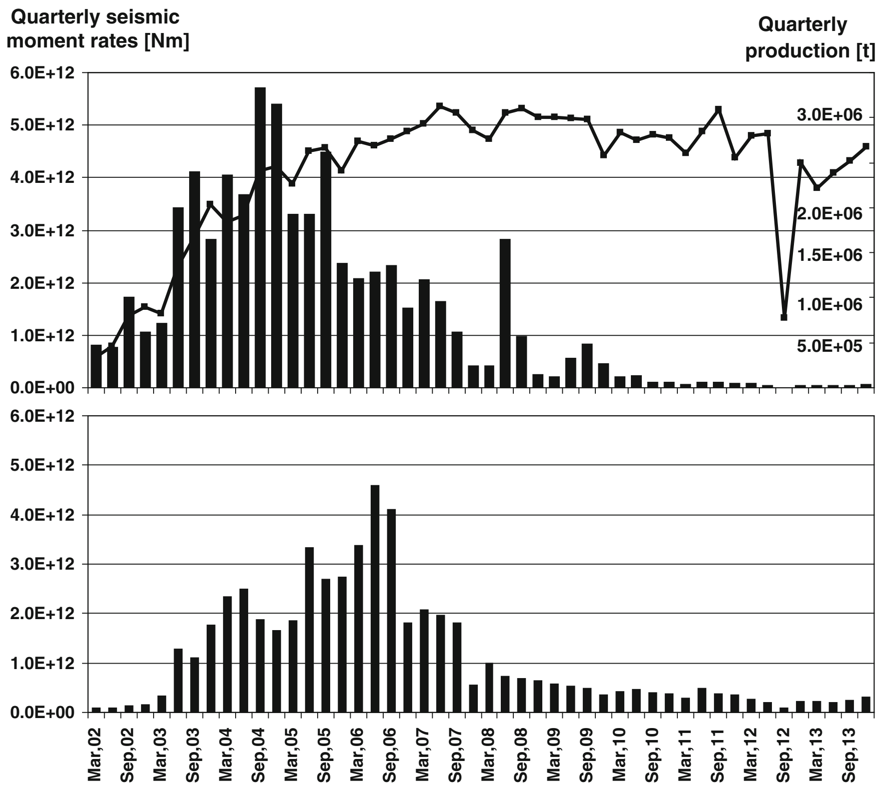


Fig. 10.16 Quarterly seismic deformation rates above and below the mine

process and assist in defining its stages but will relate the caving process with different levels of seismic hazard and risk to underground personnel. It appears that in the case of cave mining the seismic hazard level is mainly associated with the caving process and not with the cave production rates.

10.4.3 Seismically Active Volume Above the Mine

Table 10.4 lists seismically active areas and volumes above the mine. Their values are based on 3 months data inputs. Additionally this table lists the apparent volumes for each quarter. These values are taken from Table 10.2. The last column lists the ratio values. These ratios are simply the relations between the seismically active volumes and the apparent volumes for each quarter. Their plots will be used to compare the seismicity clustering above and below the mine.

Figure 10.17 illustrates the time histories of seismically active volume and apparent volume. Both volumes are in km^3. As expected the seismically active

Table 10.4 Seismically active areas and volumes above the mine

Date	No of events	Area (km^2)	Volume (km^3)	Apparent volume (km^3)	Ratio
Mar-02	575	0.196	0.087	0.065	1.33
Jun-02	1175	0.232	0.094	0.038	1.18
Sep-02	2267	0.333	0.17	0.118	1.44
Dec-02	2058	0.188	0.092	0.074	1.24
Mar-03	859	0.626	0.31	0.081	3.83
Jun-03	6345	0.679	0.38	0.33	1.15
Sep-03	7658	0.774	0.339	0.26	1.30
Dec-03	7206	0.979	0.441	0.15	2.94
Mar-04	5302	1.002	0.457	0.15	3.00
Jun-04	4726	1	0.573	0.39	1.47
Sep-04	2753	1.359	0.61	0.47	1.29
Dec-04	4287	1.605	0.794	0.62	1.28
Mar-05	2711	1.775	0.914	0.52	1.75
Jun-05	4374	1.013	0.512	0.62	0.82
Sep-05	3661	1.214	0.549	0.78	0.70
Dec-05	2157	1.314	0.69	0.46	1.50
Mar-06	2283	1.701	0.851	0.45	1.89
Jun-06	1366	1.344	0.676	0.47	1.44
Sep-06	2720	1.184	0.582	0.46	1.26
Dec-06	1197	1.486	0.76	0.28	2.71
Mar-07	1404	1.754	1.072	0.68	1.57
Jun-07	1226	1.552	0.922	0.25	3.68
Sep-07	1133	1.247	0.712	0.15	4.74
Dec-07	493	1.43	0.761	0.083	9.16
Mar-08	373	1.757	0.881	0.12	7.34
Jun-08	1044	0.998	0.58	0.55	1.05
Sep-08	671	1.156	0.667	0.24	2.77
Dec-08	454	1.118	0.562	0.05	11.24
Mar-09	297	1.405	0.757	0.04	18.92
Jun-09	710	1.362	0.791	0.18	4.39
Sep-09	811	0.996	0.568	0.22	2.58
Dec-09	350	0.998	0.559	0.07	7.98
Mar-10	390	0.897	0.49	0.04	12.25
Jun-10	360	0.841	0.493	0.05	9.86
Sep-10	276	0.834	0.398	0.02	19.90
Dec-10	275	0.797	0.424	0.02	21.20
Mar-11	239	0.94	0.403	0.01	40.30
Jun-11	267	0.95	0.441	0.02	22.50
Sep-11	204	0.628	0.327	0.03	10.90

(continued)

Table 10.4 (continued)

Date	No of events	Area (km^2)	Volume (km^3)	Apparent volume (km^3)	Ratio
Dec-11	288	0.676	0.196	0.02	9.80
Mar-12	199	0.748	0.229	0.006	36.66
Jun-12	163	0.463	0.167	0.005	33.40
Sep-12	43	0.463	0.114	0.002	57.00
Dec-12	117	0.559	0.137	0.006	22.80
Mar-13	158	0.482	0.115	0.007	16.40
Jun-13	72	0.411	0.083	0.006	13.80
Sep-13	119	0.463	0.068	0.008	8.51
Dec-13	172	0.373	0.064	0.01	6.42

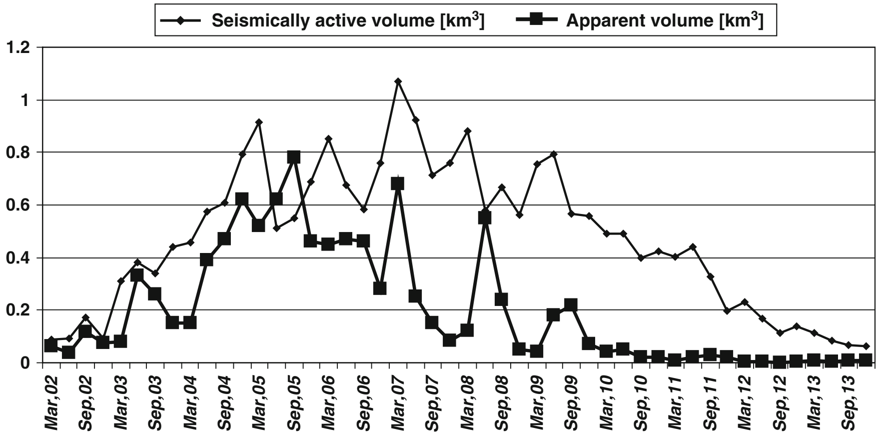


Fig. 10.17 Seismically active volume and apparent volume above the mine

volume is larger from the apparent volume. It is worth noticing that during 2002 the difference between these two values was very minor and then over time it generally increases. This difference varies between 0.1 and 0.6 km^3. The other noticeable characteristics are that the two curve trends seem to be similar. As these curves are based on data independent of each other, then these two observations validate the result as reflecting reality.

10.4.4 Seismically Active Volume Below the Mine

Table 10.5 lists the elements of the seismically active volume below the mine. Their values are based on 3 months data inputs. Additionally this table lists the apparent volumes for each quarter. These values are taken from Table 10.3. The last

Table 10.5 Seismically active volumes below the mine

Date	No of events	Area (km^2)	Volume (km^3)	Apparent volume (km^3)	Ratio
Mar-02	83	0.171	0.006	0.005	1.20
Jun-02	52	0.281	0.01	0.002	5.00
Sep-02	58	0.627	0.171	0.006	28.50
Dec-02	78	0.405	0.034	0.003	11.33
Mar-03	100	0.583	0.049	0.008	0.1
Jun-03	451	0.76	0.047	0.019	6.12
Sep-03	893	0.962	0.094	0.027	3.48
Dec-03	773	0.678	0.16	0.038	4.20
Mar-04	894	0.586	0.104	0.035	2.97
Jun-04	768	0.777	0.162	0.075	2.16
Sep-04	643	1.209	0.258	0.113	2.28
Dec-04	1576	1.089	0.398	0.273	1.45
Mar-05	2247	1.487	0.638	0.371	1.72
Jun-05	4942	1.004	0.441	0.629	0.70
Sep-05	3747	0.793	0.308	0.510	0.60
Dec-05	3683	0.825	0.322	0.517	0.62
Mar-06	4256	0.985	0.383	0.756	0.50
Jun-06	3072	0.98	0.364	0.864	0.42
Sep-06	3245	1.304	0.465	0.747	0.62
Dec-06	2018	1.588	0.639	0.398	1.60
Mar-07	2621	1.042	0.445	0.513	0.86
Jun-07	2689	1.184	0.524	0.344	1.52
Sep-07	2396	1.094	0.348	0.284	1.22
Dec-07	1102	0.744	0.273	0.093	2,93
Mar-08	1598	1.274	0.557	0.248	2.25
Jun-08	1799	1.118	0.333	0.186	1.79
Sep-08	1950	0.58	0.179	0.167	1.07
Dec-08	1664	0.667	0.237	0.133	1.78
Mar-09	1200	0.577	0.175	0.137	1.27
Jun-09	1457	0.663	0.249	0.131	1.90
Sep-09	1648	0.503	0.154	0.122	1.26
Dec-09	1084	0.507	0.145	0.088	1.64
Mar-10	1485	0.41	0.117	0.105	1.11
Jun-10	1351	0.477	0.141	0.101	1.39
Sep-10	1355	0.423	0.109	0.109	1.00
Dec-10	1194	0.36	0.096	0.070	1.37
Mar-11	1302	0.617	0.149	0.065	2.29
Jun-11	1487	0.381	0.103	0.111	0.98
Sep-11	1305	0.384	0.086	0.093	0.92

(continued)

Table 10.5 (continued)

Date	No of events	Area (km^2)	Volume (km^3)	Apparent volume (km^3)	Ratio
Dec-11	1360	0.397	0.087	0.074	1.17
Mar-12	981	0.32	0.088	0.039	2.25
Jun-12	936	0.391	0.088	0.041	2.14
Sep-12	299	0.493	0.102	0.019	5.36
Dec-12	727	0.310	0.065	0.047	1.38
Mar-13	820	0.321	0.067	0.058	1.15
Jun-13	644	0.320	0.063	0.045	1.40
Sep-13	932	0.329	0.062	0.067	0.92
Dec-13	1161	0.301	0.058	0.098	0.59

column lists the ratio values. These ratios are calculated in the same way as those listed in Table 10.4.

Figure 10.18 illustrates the time histories of seismically active volume and apparent volume below the mine. Both volumes are in km^3. Not every data is perfect as according to this figure the apparent volume at some point is larger from the seismically active volume. Otherwise the seismically active volumes are larger than the apparent volume values. It appears that both apparent volumes and seismically active volumes below the mine are smaller from these volumes above the mine. It also appears that the differences between them are lower than those observed above the mine. Below the mine these differences are between 0.1 and 0.2 km^3.

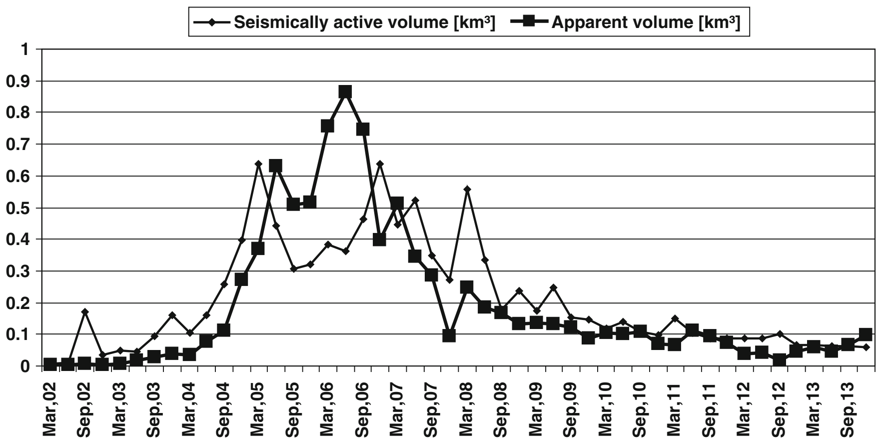


Fig. 10.18 Seismically active volume and apparent volume below the mine

10.4.5 Comparison Between Apparent and Seismically Active Volumes Above and Below the Mine

Figure 10.19 illustrates the time histories of two seismically active volumes above and below the mine. The first observation is that the seismically active volume above the mine is always larger than the seismically active volume below the mine. The other observation is that the trends of these two volumes are similar but their larger values are present at different times. The seismically active volumes above the mine larger values start from the middle of 2004 which is just after the initial break through and then continue until the end of 2009. The larger size of the seismically active volume below the mine is evident only from 2005 until end of 2007. The larger seismically active volume sizes above the mine last for 5 years which is about three times longer than below the mine. Figure 10.20 illustrates the time histories of the two apparent volumes. The two curves have similar trends and the apparent volumes above the mine are not all the time larger than the apparent volumes below the mine. To start with the apparent volumes above the mine are larger from March 2002 until middle of 2005. From then on until 2010 these two volumes are about similar in size. From then the apparent volumes below the mine are slightly larger than those above the mine. What is characteristic for the two trends are their faster increases before they reach the maximum values and then much slower decreases after attaining the maximum volume.

Figure 10.21 illustrates how the two ratios of seismically active volume/apparent volume above and below the mine have changed over time. The continuous and dotted lines are the trend lines (both polynomial order 5). In fact these two trend lines are more important than the graphs of the ratios. The trend graphs indicate than only until the initial break through (May 2004) the ratio below the mine was larger than the ratio above the mine. This indicates that during this time period the

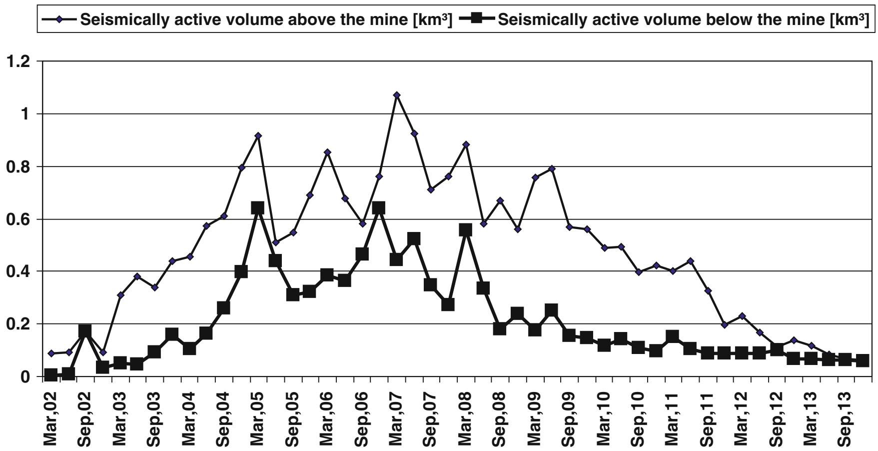


Fig. 10.19 Time histories of seismically active volumes

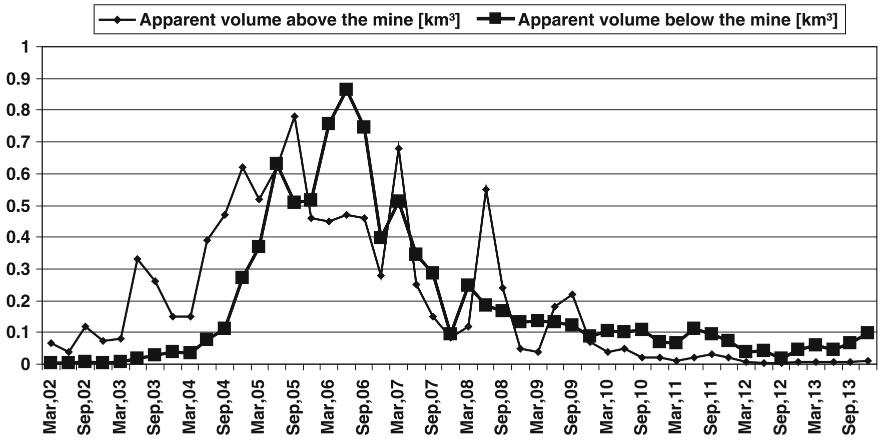


Fig. 10.20 Time histories of apparent volumes

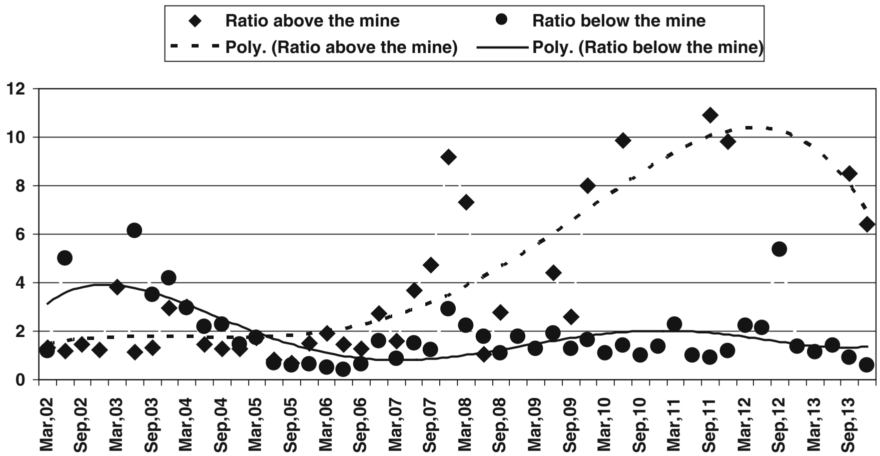


Fig. 10.21 Ratio time histories

seismicity above the mine was more clustered from that below. This is confirmed by the recorded at that time seismicity. From then on the ratio above the mine has been consistently larger than the ratio below the mine. Firstly up to the time the caving process reached its mature stage (end of 2007) this difference was low. Then the difference between these ratios started to increase rapidly until the caving process reached its end (end of 2012). The average ratio above the mine is 7.7 while the average ratio below the mine is 1.7. This graph indicates that in general the seismicity recorded below the mine is more clustered from that recorded above the mine. This observation is of significance as below the mine there was slightly less off recorded seismicity than above the mine. Taking into account that the

Table 10.6 Seismicity recorded above and below the mine

Volume	Energy per km^3 (J/km^3)	Moment per km^3 (N/km^3)	Σ seismically active volume (km^3)
Above the mine	8.7E+06	3.02E+12	22.9
Below the mine	1.4E+06	5.20E+12	10.2

seismically active volumes are always centred at the mine foot print then this higher clustering of seismicity below the mine should compensate for the lower seismic activity rates. Less seismicity below the mine but in smaller volumes implies that the process of seismic preconditioning had to be as least as intensive as that which took place above the mine. Table 10.6 confirms this statement. Values for seismic energy release and seismic moment above and below the mine are listed in Table 10.1.

The cumulative seismically active volumes above and below the mine were used to estimate the seismic energy and seismic moment per rock mass volume of one cubic kilometre above and below the mine. The cumulative seismically active volume above the mine is nearly twice larger from this volume below the mine. The amount of seismic energy released per cubic kilometre above the mine is nearly four times larger than below the mine. In spite of this there is more of seismic deformation per cubic kilometre below the mine than above the mine. This indicates that the seismic preconditioning below the Lift 1 extraction level has fractured and distressed this rock mass volume.

10.5 Distributions of Seismic Energy and Moment Above and Below the Mine Foot Print

When the seismic cumulative moments are calculated for specific volumes then this procedure allows for comparisons between these volumes. A volume with higher amounts of seismic deformation will be more preconditioned or de-stressed than a volume with a lower cumulative moment. The distributions of the amounts of seismic deformation in a given rock mass volume will then indicate how homogeneous this rock mass are as far as de-stressing is concerned. Apart from seismic deformation, the rock mass is also deforming a-seismically. This second process is slow fracturing that releases either low or no energy and for this reason cannot be recorded by a seismic system. Experience with the failure of the Crown Pillar indicates that with the caving process, a lot of the rock mass fracturing that takes place around the cave is of the a-seismic type. In this part of the chapter cumulative seismic deformation values are calculated for the rock mass volume located four hundred meters above and below the existing mine. This volume of interest covers the rock mass volume of Lift 1 and the possible future Lift 2 block cave mine. At

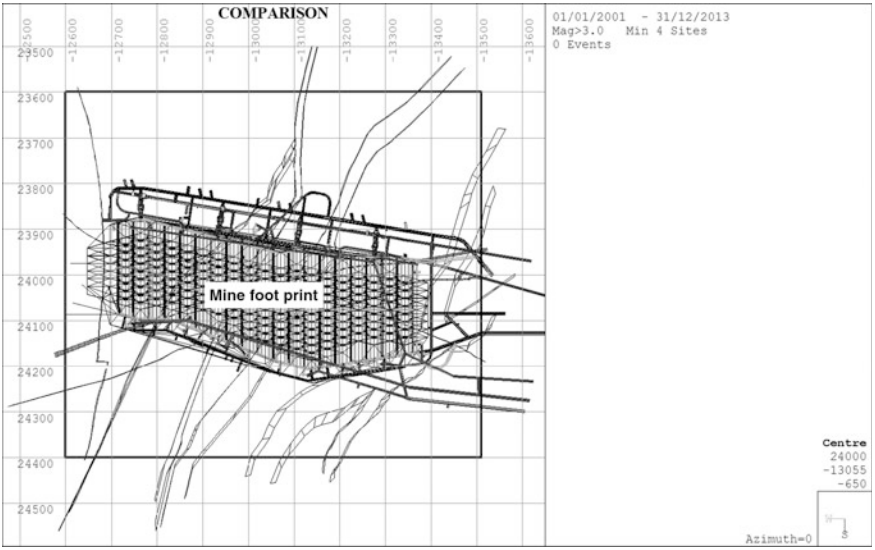


Fig. 10.22 W-E horizontal layout of volume “COMPARISON”

the end of his chapter there is a comparison of the recorded amounts of seismic deformation above and below the existing mine at the time of the crown pillar failure and at the time the cave broke through. This comparison reveals some interesting facts regarding the vertical distribution of seismic deformation that facilitates making some assumptions about the possible Lift 2 primary fragmentation conditions. Figure 10.22 shows horizontal layout of volume COMPARISON (800 m thick) for which the distribution of seismic energy and deformation will be assessed. The limits of this volume (800 m × 900 m × 800 m) are:

$$\text{North } 23600 \;\; \text{East } -13500 \;\; \text{Upper } -400\,\text{m}$$
$$\text{South } 24400 \;\; \text{West } -12600 \;\; \text{Lower } -1200\,\text{m}$$

Figure 10.23 illustrates the location of the layers in comparison to Lift 1 and Lift 2 mines. Layers 1 and 2 are located above Lift 1 mine while layers 3 and 4 are located below Lift 1 mine. In this comparison the input data is seismicity recorded from 01/01/2002 until 31/12/2013.

Table 10.7 lists the minimum and maximum elevations of the four layers. Each layer is 200 m thick. Each of these layers has specific importance for the present and future cave mining. The Lift 1 stress caving process was initiated in the volume of layer 2 while the Lift 1 cave broke into the open pit in volume of layer 1. In both cases these milestones of the caving process took place with no problems and with any negative consequences. Layers 3 and 4 or their properties will be crucial for Lift 2 caving process. This process will be initiated in layer 4 and the break through will take place in layer 3.

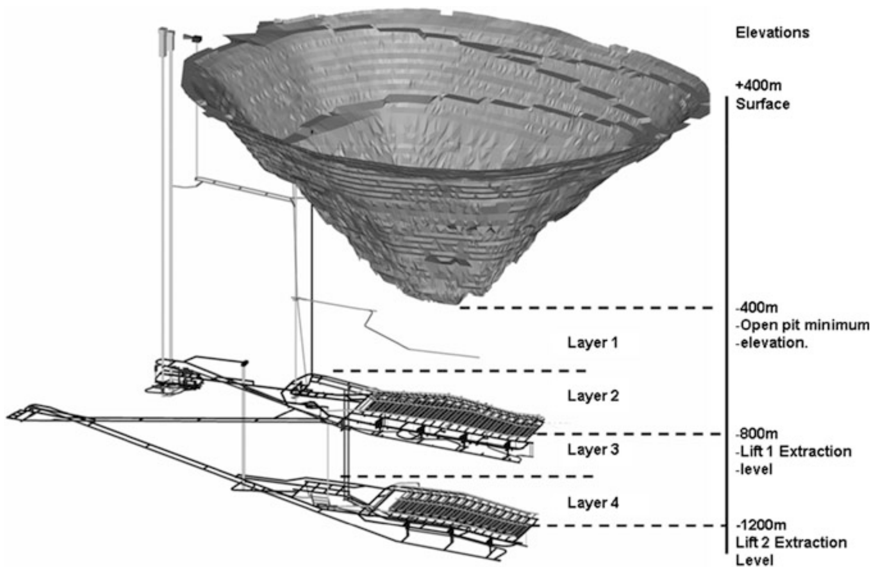


Fig. 10.23 Position of layers

Table 10.7 Definition of layers

Layer	Zmin (m)	Zmax (m)	Significance of layer
Layer 1	−400	−600	In this layer Lift 1 cave broke into the open pit
Layer 2	−600	−800	In this layer Lift 1 stress caving process was initiated
Layer 3	−800	−1000	In this layer Lift 2 cave will brake into Lift 1 mine
Layer 4	−1000	−1200	In this layer Lift 2 stress caving process will be initiated

Table 10.8 lists the total number of events, total energy released and total seismic deformations recorded for the whole mine and in a smaller COMPARISON volume which is based on the mine foot print. This seismicity was recorded from the beginning of 2002 until middle of September 2012. In the "Comparison" volume there is 87 % of all recorded events, 70 % of released seismic energy and about 68 % of recorded seismic deformation. Volume COMPARISON above the mine is short of 0.73E+08 J of energy and 2.83E+13 Nm of seismic deformation in comparison to the total mine. Below the mine these values are lower and are 0.28E+08 J and 1.06E+13 Nm. This confirms the findings that the seismicity below the mine is less scattered than that above the mine.

Table 10.9 lists the seismicity recorded in the four layers (number, cumulative energy and cumulative moment). The last two columns list the released seismic energy and the recorded seismic deformation per cubic meter. This table also lists

Table 10.8 Seismicity of the whole mine and in volume in the volume of “Comparison”)

	Total events	Total energy (J)	Total moment (Nm)
Whole mine	149222 (100 %)	3.33E+08 (100 %)	1.21E+14 (100 %)
Total COMPARISON	130835 (87 %)	2.33E+08 (70 %)	8.35E+13 (69 %)

Table 10.9 Seismicity of the four layers

Layer	No of events	Energy (J)	Moment (Nm)	J/m^3	Nm/m^3
1	20419 (16 %)	6.28E+07 (27 %)	1.20E+13 (14 %)	0.42	8.35E+04
2	43453 (33 %)	6.37E+07 (27 %)	2.82E+13 (34 %)	0.44	19.58E+04
3	61231 (46 %)	9.39E+07 (41 %)	3.55E+13 (42 %)	0.70	24.65E+04
4	6296 (5.0 %)	1.27E+07 (5.0 %)	8.04E+12 (10 %)	0.09	5.58E+04

the percentages distribution of seismicity, seismic energy and seismic moment. 100 % is the total for the four layers.

Figure 10.24 illustrates the distribution of J/m^3 values per layer. The largest value is recorded for layer 3 that is the layer between elevations of −800 and −1000 m. The two layers above the Lift 1 extraction level have about the same values of energy per cubic meter. This value for layer 4 is the lowest one among all the four layers. Figure 10.25 illustrates the distribution of seismic deformation per cubic meter in the four layers. This distribution is different from the energy per cubic meter distribution. Here again the largest value is associated with the third layer. In general the values of seismic deformation per cubic meter increase from layer 1 to layer 3. The amount of seismic deformation per cubic meter in layer 4 is the lowest but is comparable with the value in layer 1.

Figure 10.26 illustrates the percentage distribution of the number of recorded events, the emitted seismic energy and seismic deformation in the four layers. These distributions are similar to the distribution of energy and seismic deformation per

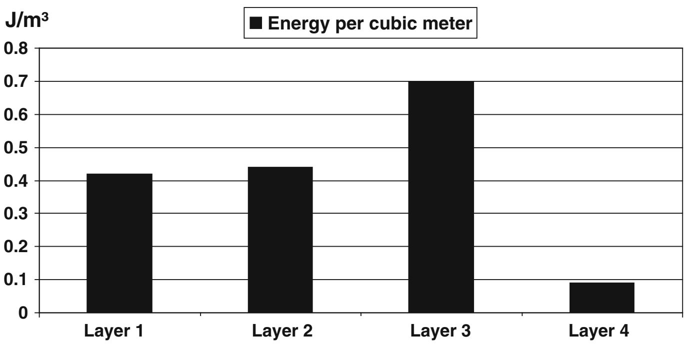


Fig. 10.24 Distribution of energy per cubic meter

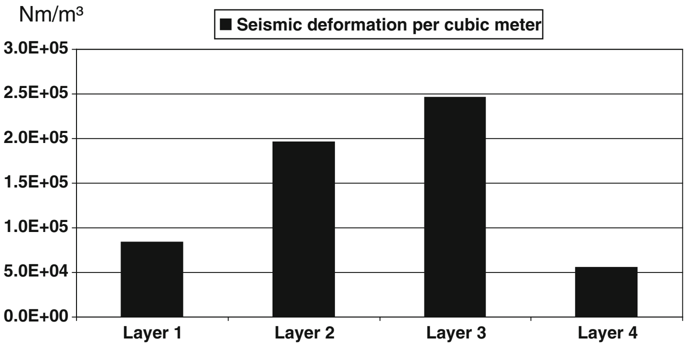


Fig. 10.25 Distribution of seismic deformation per cubic meter

cubic meter. Presented distributions were based on equal time ranges above and below. Above and below the mine the time span was from the beginning of 2002 until end of 2013. Above the mine the crown pillar failed at the end of 2002 (only 6 months after the stress caving process initiation) and the cave broke through into the open pit during middle of 2004. This means that at that time the Lift 1 caving process resulted in sufficient rock mass preconditioning for these two milestones of the caving process to take place. In this part I will analyse the seismic energy release rates and seismic deformation amounts in layer 1 and 2 as they were during these two milestones with amounts of seismic deformation and energy released in the two layers located below the mine at the end of 2013. This comparison should allow for predicting the Lift 2 caving process performance. This will be done by comparing the seismicity that was recorded in Lift 1 by the time of the two milestones with the seismicity already recorded in Lift 2 even before the mining commenced. Data for this comparison is listed in Tables 10.10 and 10.11.

Table 10.10 lists the seismic energy and moment values for layer 1 and 2 are as they were at the time of the crown pillar failure that is at the end of 2002. The

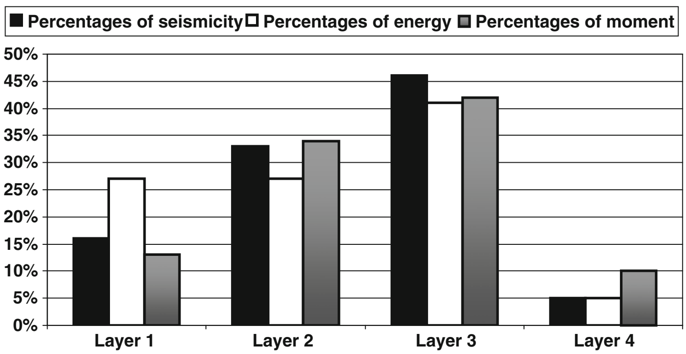


Fig. 10.26 Percentage distributions of events number, energy and deformation

Table 10.10 Layer 1−2 values by the end of 2002 (pillar failure) layers 3−4 at end 2013

Layer	Energy (J)	Moment (Nm)
1	1.16E+07	1.76E+12
2	7.76E+06	1.66E+12
3	9.39E+07	3.53E+13
4	1.27E+07	8.04E+12

Table 10.11 Layer 1−2 values by May 2004 (break through) layers 3−4 as at end of 2013

Layer	Energy (J)	Moment (Nm)
1	5.39E+07	5.89E+12
2	5.17E+07	1.19E+13
3	9.39E+07	3.53E+13
4	1.27E+07	8.04E+12

seismic energy and moment values for layers 3 and 4 are as they were at the end of 2013.

Figure 10.27 illustrates the amounts of released seismic energy in the two layers above the mine at the time when the crown pillar failed (end of 2002) and in the two layers below the mine by the end of 2013. This figure illustrates the fact that there were no large size seismic energy releases induced by the caving process and the pillar failed. As below the mine where the Lift 2 caving will take place there already is much more seismic energy released even before the caving process has started.

Figure 10.28 illustrates the amounts of seismic deformation in the two layers above the mine at the time when the crown pillar failed (end of 2002) and in the two layers below the mine by end of 2013. This figure illustrates the fact that there was not much seismic deformation and still the pillar failed. As below the mine where the Lift 2 caving will take place there already is much more seismic deformation even before the caving process has started.

Table 10.11 lists the seismic energy and moment values for layer 1 and 2 as they were at the time of the crown pillar break through that is at the end May 2004. The

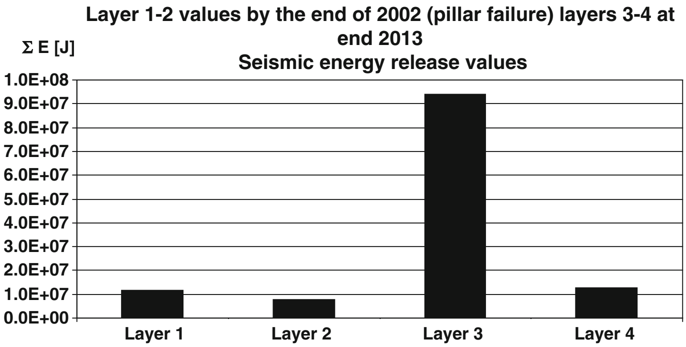


Fig. 10.27 Seismic energy released at the time of crown pillar failure in layers 1 and 2

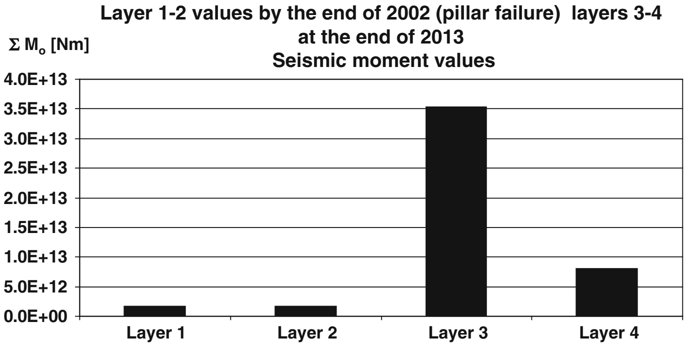


Fig. 10.28 Seismic deformations at the time of the crown pillar failure in layers 1, 2

seismic energy and moment values for layers 3 and 4 are as they are as they were by the end of 2013.

Figure 10.29 illustrates the amounts of released seismic energy in the two layers above the mine at the time when the initial break through was completed (May 2004) and in the two layers below the mine by the end of 2013. This figure illustrates the fact that by the end of 2013 there is more seismic energy released below the mine in comparison to the energy released above the mine at the time of the initial break through. The exception is layer 4. One has to take into account that this is the layer in which the mine development will take place and the future caving process will be initiated. These two processes will result in more of seismic energy being released in this layer.

Figure 10.30 illustrates the amounts of seismic deformation in the two layers above the mine at the time when the crown pillar broke through (May 2004) and in the two layers below the mine by the end of 2013. This figure illustrates the fact that there was not much seismic deformation in layer 2 and still the cave broke through.

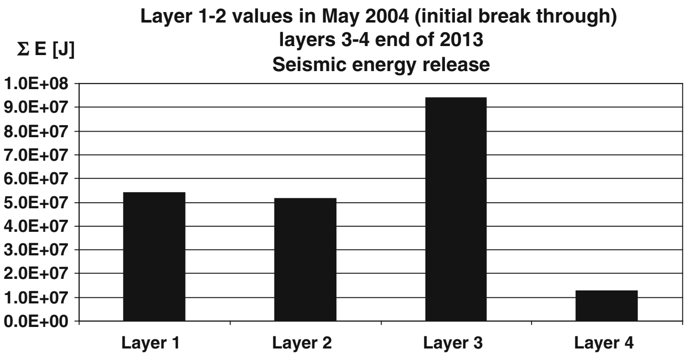


Fig. 10.29 Seismic energy released at the time of crown pillar break through

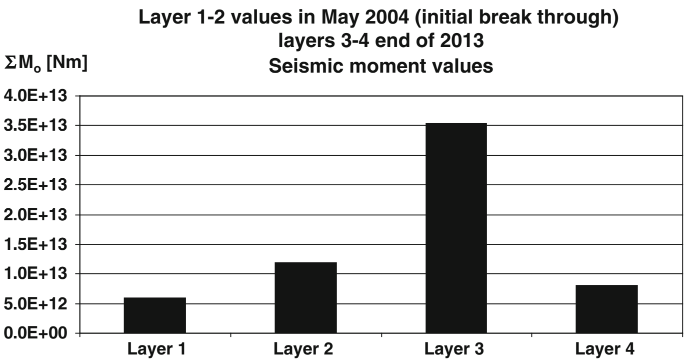


Fig. 10.30 Seismic deformations at the time of the crown pillar break through in layers 1 and 2

As below the mine where the Lift 2 caving will take place there already is much more of seismic deformation even before the caving process has started.

10.6 Conclusions

Experience with the Palabora Lift 1 caving process indicates that the amounts of seismic deformations as listed in Tables 10.10 and 10.11 were sufficient to initiate enough of the primary fragmentation for the whole rock mass volume above the mine to cave and for the crown pillar failure. The unknown factor is the amount of a-seismic deformations that took place above the mine. Above the mine the mechanism that triggered both the seismic and a-seismic deformations was the caving process. By the 2013 (nearly 11 years after the initiation of the caving process) the amounts of seismic deformations above and below the mine are very similar. Comparison between the amounts of seismic deformation above and below the current caving operation lead to important deductions with respect to the cavability and the primary fragmentation for a possible Lift 2 block cave located below the present mine. Due to the observation that after 11 years of caving at Palabora, the amounts and distribution of seismic deformation above and below the present mine are practically the same, the following can be concluded:

1. The initiation of the Lift 2 caving process will result in more seismic deformation taking place than in the case of Lift 1, as the new caving process will result in adding more seismic deformation to that which was the result of Lift 1
2. The anticipated increased seismic deformation associated with Lift 2 (compared to Lift 1) will result in a finer degree of primary fragmentation, which might in consequence improve the secondary fragmentation (as experienced with Lift 1).
3. The top volume of the potential Lift 2 rock mass is already at this stage de-stressed/preconditioned and fractured so it will cave rather than form a crown pillar (arch) that will not cave resulting in the formation of a significant air void

10.7 Summary

Block cave operations require the investment of large amounts of capital upfront and therefore the ability of strong and competent rock masses to cave and the ensuing fragmentation is absolutely crucial to the success of the new generation of hard rock block cave mines. Even though block caving has been in use for around 100 years, the basic mechanics of caving are not that well understood, particularly the complex interaction between induced stresses and structure of the rock mass that occur during the progression of the cave. To this end the industry is continually striving to develop more reliable and predictive tools to reduce the inherent risks involved in block caving. The major risk factors in block cave mining are well documented (Brown 2003). The rock being caved at Palabora represents some of the most competent ground in which caving has been carried out. Evidence of the overall rock mass strength is evident in the open pit which represents one of the deepest and steeply sloping excavations in the world. Consequently the caving process relies very much on the generation of stresses of sufficient magnitude to induce fracturing of the competent rock mass (Moss et al. 2004). As expected, the strong competent rock mass initially resulted in coarse fragmentation with secondary breaking being a major challenge. No cave operation has undertaken the amount of secondary breaking that has been required at Palabora, where some 50 % of the initial tonnage has had to be blasted to clear draw point hang-ups and blockages. Although coarse fragmentation was anticipated the ore has actually broken finer than anticipated, the process of safe and efficient clearing the hang-ups has required substantial organisational effort (Moss et al. 2006).The fragmentation was getting finer with increasing height of draw (HOD) . This resulted in increased draw rates and higher production. The ability to safely and effectively handle coarse fragmentation in the draw points (hang-ups and boulders) is critical to achieving the high production targets normally required of block cave operations and ultimately the overall viability and success of the operation.

Palabora has used a number of systems (TDRs, open holes and seismic system) to attempt to track the cave propagation. Of these, only the mine-wide seismic system has provided an ongoing and consistent broader view of the cave progression and related events. By analysis of the seismic data from the system it has been possible to identify the onset of stress caving, failure of the crown pillar and to track stress migration and the rates of changes in stress, the energy index and deformation as caving progresses as well as plots of energy index and deformation contours at various elevations (Glazer and Hepworth 2004). The system has also provided information with respect to the rock mass beneath the present production footprint. It is this information that could give valuable insights into the possible behaviour of this rock mass and implications for the potential Lift 2 Project with respect to fragmentation, cave propagation, failure of the Lift 2 crown pillar and associated seismic hazard. It is known that the Palabora ore body continues below the level of the current underground block cave operation. At current production rates this project could extend the life of the underground mine by some 10–

14 years, depending on the lift height chosen (400–500 m). Palabora has subsequently embarked on an exploration programme to get a better understanding of the structure, rock mass and ore grades going deeper. One of the major risk factors pertaining to block cave mines is the **caveability** of the rock mass. At this stage Palabora Lift 1 is caving well and this is not considered to be a major risk with respect to a Lift 2. In addition the in situ stresses are anticipated to be significantly higher giving rise to higher induced stresses to drive the caving process.

Subsidence risk: Some of the major risks pertaining to a second lift are the extent of any further subsidence on surface and in particular the possible detrimental effects on the major Production and Service Shaft systems. The viability of a second lift is very much dependent on these structures remaining serviceable for the duration of the Lift 2 life of mine. The Palabora pit failure has been extensively modelled (Brummer et al. 2006). A second important consideration is the effect on the current Lift 1 operations and the ability to maintain production while Lift 2 is being developed. Experience at Palabora has shown that once stress caving has been initiated, the observed seismicity migrates rapidly upwards. The Lift 1 crown pillar was estimated to have failed only some 10 months after the initiation of stress caving with a column height of 400 m. A similar rapid upward migration of seismicity was also experienced with the Lift 2 caving at the Northparkes Mine. The seismicity reached the base of the Lift 1 only some 6 months after caving commenced, with a 350 m lift height. This poses the risk that operations on the Palabora Lift 1 extraction level may have to be abandoned relatively soon after the caving of Lift 2 commences, long before the required production target has been attained.

Fragmentation: Palabora Lift 1 block cave has probably had to contend with the coarsest fragmentation ever experienced by any block cave with the most amount of secondary breaking being required on a daily basis. To a large extent the rate of production build-up for Lift 2 will be governed by the degree of primary fragmentation experienced. The build up to full production for Lift 2 is expected to be significantly quicker than was the case for lift 1, due in part to the experience and learning's from Lift 1, technology developed and the anticipated finer fragmentation. This is as a result of the extensive seismic activity and deformation observed below the Lift 1 extraction level since the beginning of 2005 leading to "seismic preconditioning" of the underlying rock mass. Although the fragmentation in the early stages of caving is still expected to be reasonably coarse, the expectations are that it will be considerably finer than that experienced for Lift 1 due to the seismic deformations that are being observed up to 200 m below the current extraction level and still extending in depth.

A similar process to the Lift 1 block cave crown pillar failure mechanism is taking place in the rock mass below the underground extraction level. The existence and extension of the fractured or failed rock mass volume below the open pit became apparent only after the post analysis of seismicity, however, the process taking place below the underground production level has been monitored by the seismic network since the initiation of the network and data continues to be collected on a daily basis. By the end of 2006 the de-stressed rock mass thickness below the extraction level was approximately 100 m thick. Analysis of seismic data indicates that the fracturing process taking place below the extraction level is very similar to the process relating to the crown pillar fracturing and failure. Apart from seismic deformation, the rock mass is also deforming a-seismically. This second process is slow fracturing that releases either low or no energy and for this reason cannot be recorded by a seismic system. Experience with the failure of the Crown Pillar indicates that with the caving process, a lot of the rock mass fracturing that takes place around the cave is of the a-seismic type.

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Chapter 11
Palabora Lift 2 Mine Seismic System

Abstract This chapter deals with designing the seismic monitoring system for Lift 2 Mine. Seismic network consists of specialised hardware and software. An important part is the communication system which allows transferring recorded data to the central computer. This is the widespread understanding of what is the "system". Sometimes this understanding goes a bit further and accepts the fact that an additional part of this structure is means of recorded data visualisation. Still the differentiation between visualisation and interpretation of recorded data is not clear and often not regarded as something of importance. The same applies to the network managing. Professional management of the seismic network and expert analysis of the recorded data are important parts of the "system". These parts of the seismic network are there to make sure the system records as it should, the recorded data is processed properly so the seismic data base is of high quality. This is critical for analysis and data interpretation to be reliable. When comparing hardware and software with human skills and know-how this second element is more important. It is easy to imagine that old technology combined with professional knowledge will result in more reliable results than the combination of the best technology with lack of skills. This is common sense but difficult to apply in practice.

Several Palabora applications of seismic monitoring have shown that it is a valuable and useful tool for monitoring several aspects of the caving process Analyzed data sets indicate that the seismic signature of the caving process is a fact. This in turn implies that seismic networks will be always associated with cave mining It must be made clear that the seismic network on its own, as unfortunately it is very often assumed, will never be able to provide valuable information. Seismic network is only a tool and for this reason how it will be used will depend on its user. I am familiar with seismic data recorded at Palabora since 2002. As from 2004 I have been working for Palabora as a seismic consultant. From 2005 I have been working as a seismic consultant for PT Freeport Indonesia. During 2005 I have done some work for RT based on seismic data recorded at Northparkes Mine Lift 2. From the beginning of 2009 I have been involved in analysis of seismic data recorded at the Diablo Regimento Sector at the El Teniente Mine. This experience includes both

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recording and analysis of recorded data. Understanding of what can be done with recorded seismic data is important while designing a new seismic network.

Lift 2 seismic network monitoring objectives:

1. Monitoring the caving process
2. Monitoring the stress distribution around the cave and the mine
3. Seismic hazard evaluation
4. Monitoring the rock mass located between the cave and the shafts
5. Evaluation of the rock mass condition below the Lift 2 cave

Successes of Palabora Lift 1 seismic monitoring should be transferred to Lift 2 seismic monitoring system. In the same way the known failures with the Lift 1 seismic monitoring should not be repeated with the Lift 2 seismic monitoring system. Palabora Lift 2 seismic system should be a new one. Present system with additions and extensions is operational since 1999 and at present is “old technology”.

11.1 Introduction

Designing a seismic system for Lift 2 is unique as there is already experience and knowledge from Lift 1. Further more the Lift 1 seismic system was not the only one system monitoring the seismicity induced by cave mining A lot can be learned by comparing with different seismic networks. This applies to anything from the sensor configurations up to different management conceptions. Results of such comparisons should not only help in finding the best technical solution but also in reducing the costs. If all what is expected from the system can be achieved with less seismic sensors then this reduces not only the costs of hardware but what more reduces the costs of drilling and also off cabling that is required for the communication module. This is where the savings are, in the hardware and software part of the system. Saving on skills and know-how will result in spending the capital for nothing. In some cases the damage might be irreversible for example when the seismicity was recorded with incorrect parameters. Not all mines employ professional seismologists and some of the seismic networks are run by inexperienced young engineers. Not all of them are interested in mine seismology as such so when the opportunity arises they move to other sections or mines. In this way even the basic knowledge of the nature of seismicity is lost and the new engineer starts from scratch. In some instances all or portion of the seismic tasks (data processing and/or reporting) are given to outside consultants. This solution has its good and not so good aspects. The job is done by professionals but the mine staff has no control over the seismic data quality or over the applications as required or desired by the mine. Several applications of seismic monitoring at Palabora have already proven that seismic monitoring is a very valuable and useful tool not only for managing the cave mining but also for managing the transition phase from open pit to underground mining. As cave mining is a three dimensional process not as mining of the tabular gold reefs, it thus requires seismic interpretation methods other than the standard ones developed for and used on gold mines. I have observed that from some point in time there has been a tendency for the installation of super seismic networks on the assumption that the more data recorded and the more accurate are the locations of seismicity, the more reliable will the interpretation of results. This might be correct from the academic point of view but not always from the mines' point of view. Those large seismic networks are not only expensive to install but have high running costs as proper maintenance, data gathering and then interpretation and reporting will require a large number of qualified staff. This from a practical point of view is not always possible.

Design of Lift 2 seismic recording system should starts with comparison of Palabora Lift 1 seismic network with other seismic networks that operate in other cave mines. This comparison is about the recorded seismic catalogue completeness and its relation to the seismic sensors density. Palabora seismic network is not the most sensitive network when comparing with the other ones. This brings up a question: If other networks are more sensitive and record more seismic events than Palabora network is this data then used for something that was not possible to be done at Palabora. In other words is it that more of seismic data inevitably results in a larger variety of practical from the mine point of view results. Review of literature plus my personal experience clearly indicates that no. Recorded seismicity at Palabora was used to describe the whole caving process from the beginning to its end. This was done not in back analysis mode but in real time as the mining was progressing. Other centres used Palabora results as examples and tried to get similar results in back analysis exercises.

It is important to know that up to date nearly 50 % of recorded Palabora Lift 1 seismicity located below the mine. This process was already described in many details in Chap. 10. This seismicity took place in the rock mass volume that in future will become Lift 2 cave. Comparison of seismicity recorded above the mine with that recorded below the mine confirms that seismic preconditioning is a genuine process. Recognition of this fact has practical implications. Lift 2 needs no preconditioning by blasting or hydro-fracturing. As in the Lift 1 in the non preconditioned rock mass the crown pillar failed only about 8 months after the initiation of the caving process it is reasonable to expect that with preconditioned Lift 2 rock mass this process could take less time. This conclusion is both of operational and safety importance. Initiation of the Lift 2 cave will result in even more seismicity and more rock mass fracturing that was associated with Lift 1 caving process.

11.2 Seismic Catalogue Completeness and Seismic Sensor Configurations

There is data that allows for comparisons between the Palabora Lift 1 seismic network with those that are in operation at PT Freeport Indonesia DOZ Mine, the Diablo Regimento Sector at the El Teniente Mine and Lift 2 of Northparkes Mine. Obviously each of theses mines seismic catalogues are different in size and time

Table 11.1 Seismic catalogue completeness

Mine	Catalogue complete from moment magnitude size
DR sector	−0.3
Northparkes Lift 2	−1.2
Palabora	−0.2
PT Freeport DOZ Mine	−0.3

Table 11.2 Sizes of rock mass volumes covered by the networks

Mine	Area (km^2)	Height (km)	Volume (km^3)
DR sector	0.246	0.500	0.123
Northparkes Lift 2	0.180	0.450	0.081
Palabora	0.507	0.600	0.300
PT Freeport DOZ Mine	1.320	0.500	0.660

span. The common factor is the seismic system type which was used in these mines. For presented comparison the magnitude is the same. It is the moment magnitude (Hanks and Kanamori 1979). Table 11.1 indicates completeness of each seismic catalogue. The Northparkes Mines Lift 2 seismic catalogue is complete from magnitude −1.2. Both Diablo Regimento Sector and PT Freeport DOZ seismic catalogues are complete from magnitude −0.3. The Palabora seismic catalogue is complete from magnitude −0.2. Listed completeness of the seismic catalogues implies that the most sensitive seismic network was the Northparkes one while the seismic system with the lowest sensitivity was that operating at Palabora.

Table 11.2 lists the volumes of the rock mass covered by the four seismic networks. This volume is in each case is located inside of the seismic stations. The Northparkes Lift 2 volume is by all means the smallest of the four. The system heights that is the vertical distances between the deepest and shallowest seismic stations are not so different. The area sizes are the values responsible for the volume differences. The range of volume sizes is from 0.180 km^2 up to 1.320 km^2. The area of the Northparkes Lift 2 is over seven times smaller from the one at PT Freeport DOZ Mine.

In order to compare the network sensitivities one needs to compare the concentration of the seismic stations that is to evaluate the single seismic station rock mass volume (km^3 per station) for each network. This data is presented in Table 11.3. The lowest station rock mass volume is for Northparkes Lift 2 seismic

Table 11.3 Seismic station volumes

Mine	Volume (km^3)	No of stations	km^3 per station
DR sector	0.123	6	0.0205
Northparkes Lift 2	0.081	25	0.0032
Palabora	0.300	26	0.0115
PT Freeport DOZ Mine	0.660	36	0.0183

Table 11.4 Verification of calculations

Mine	km^3 per station	Catalogue complete from moment magnitude size
Northparkes Lift 2	0.0032	−1.2
PT Freeport DOZ Mine	0.0183	−0.3
DR sector	0.0205	−0.3
Palabora	0.0115	−0.2

system. The other three seismic systems have very close to each other station volume sizes. The station volumes for the other three seismic systems on average are nearly five times lager from the station volume of Northparkes Lift 2.

Table 11.4 provides data that confirms the assumption that the network sensitivity depends on seismic station volume. This assumption intellectually is very easy to comprehend but it is convincing when there is prove based on numbers.

The station volume and the completeness of the seismic catalogue for data recorded at Northparkes Lift 2 are both the lowest. These values for PT Freeport DOZ Mine and EL Teniente DR Sector are for all practical purposes the same. The Palabora both values are the higher ones. Palabora seismic network in order to be as good as the Northparkes Lift 2 network should have 3.6 times more seismic stations. In such case the Palabora seismic system would have 93 seismic stations instead of the 26. These 93 stations should then result in the recorded seismic catalogue being complete down to moment magnitude −1.2. This might be desirable but is it really practical? In order to achieve such sensitivity the present Palabora seismic system should record about 100 times more of seismic events. Until the end of 2013 the Palabora seismic system recorded over 150 000 seismic events. This makes an average of 32 events per day. With about 40 % of noise it increases to about 45 triggers per day which is easily manageable. Hundred times more triggers would then be 4500 triggers per day which is one trigger every 20 s. Managing such amounts of triggers would require continuous processing.

11.3 Experience Based on Palabora Lift 1 Seismic System

Palabora Lift 1 seismic system is the one with the highest magnitude from which the seismic catalogue is complete. To record more data one would have to design a more dense seismic sensors configuration. Is it required? Partial answer to this question will be found by analysing what was the Palabora recorded seismicity used for. Full answer will become available after examining other network results. The other seismic networks had more recording stations. Is it because of that they provided some information which wasn't available at Palabora? The first seismic event at the Palabora mine was recorded on the 16/09/1999, but the configuration of the seismic network was subsequently expanded and changed year-to-year. The main trend was the installation of further stations in addition to the existing ones. As a result the seismic network, with better configuration of stations, improved over time in sensitivity recorded more of the lower size (below magnitude 0.0) seismicity. The final network sensor configuration is excellent in this sense that it covers the whole mine with the same location accuracy and sensitivity. This is very important from the seismic data interpretation point of view as there is no need to speculate about or compensate for the seismic data base varying completeness. At Palabora seismicity has been successfully used not only to monitor the cave development, but it has also indicated when the caving process was initiated, when the crown pillar failed and when the initial break through into the open pit took place. This is documented in several papers which I have presented at various conferences. These papers are: Glazer (2007, 2008, 2012), Glazer and Townsend (2006, 2008, 2010a, b), Glazer and Hepworth (2004, 2005, 2006) and Glazer and Lurka (2007). In summary the Palabora Lift 1 objectives of seismic monitoring can be split up into four categories:

1. Monitoring the caving process
   - 1.1 Recording the initiation of the stress caving process
   - 1.2 Evaluation of the swell factor
   - 1.3 Estimation of the cave expansion rate
   - 1.4 Monitoring the crown pillar
   - 1.5 Estimation of the air gap size above the crown pillar
   - 1.6 Recording the break through
2. Monitoring the stress distribution around the cave and the mine
3. Seismic hazard monitoring
   3.1 Monitoring seismicity at selected locations as Ventilation Shaft and faults at the west
4. Evaluation of the rock mass condition below the Lift 1 Mine.

Each of the listed above objectives of seismic monitoring are valid in case of the Lift 2 mine. Experience of monitoring the Lift 1 caving process should be directly transferred to Lift 2.

11.3.1 Lift 1 Seismic Network Successes and Failures

Successes of Lift 1 seismic monitoring should be transferred to Lift 2 seismic monitoring system. In the same way the identified failures with the Lift 1 seismic monitoring should not be repeated with Lift 2 seismic monitoring system. The successes associated with the Lift 1 seismic network are:

1. Final configuration of seismic stations is such that the network sensitivity and location accuracy are both uniform over the whole area of mine

2. The density of the network sensors was sufficient to achieve all objectives of seismic monitoring
3. All seismic stations are of the same type: three dimensional geophone probes

Point 1 of the successes is easy to understand. It makes data analysis much easier. Point 2 indicates that there is no need to plan a denser network of sensors for Lift 2. More stations would result in more of recorded events which could result in problems with its management and processing quality. Point 3 is a very important. The usual reason to mix single geophones with geophone probes with three geophones is to reduce the cost and at the same time improve the location accuracy. In theory it is possible. The failure is that the single geophone stations triggers should be used only for locations and never to calculate the source parameters. This is not generally understood and in practice all triggers are used to calculate the source parameters of the event. This results in some very strange and artificial seismicity trends. The other trend is to add into the sensor configuration some low frequency geophones. This in theory should result in more accurate evaluation of the larger size events seismic parameters Again this is not the case because of the way these parameters are evaluated.

4. From its beginning (1999) this seismic system was run and maintained by the same technician. Because of this the processing is of high quality and the seismic data base is exceptionally consistent
5. The mine during 2002 recruited a seismologist. Because of this the seismic system was maintained and run efficiently and the recorded data was interpreted expertly.
6. Potential of the seismic system to become a tool for monitoring the caving process was recognised early and the system together with the technician and seismologist was transferred from Rock Mechanic Section to the Cave Management Section.
7. From 2002 to 2013 I have developed several new techniques for using recorded seismicity for monitoring the caving process. These techniques were tested and successfully applied not only with Palabora data but with data from other caving mines.

Points from 4 to 7 are connected directly with the management system. All what was connected with running the seismic system was done at the mine and by experts. Point 6 might not be straightforwardly considered as a success. In most cases the seismic network management is in the hands of a Rock Mechanic Manager. It is my over 20 years experience at the South African mines that the rock mechanics understanding and knowledge of mine seismology is limited to tabular mining where seismicity is associated only with risk and has no benefits. With the Cave Management Section personnel I had extremely good working relations as we had common interest the caving process. Point 7 indicates that there are tools (software) available to analyse and then interpret cave mining induced seismicity. These tools were tested at other mines as DOZ Mine of PT Freeport Indonesia, El

Teniente Chile and at Lift 2 of Norhtparkes Mine. Apart of successes there were some failures connected with Lift 1 seismic system. These are:

1. Implementation in stages (final upgrade April 2003)
2. No sensors located below the extraction level
3. Implementation of seismic expertise and experience gained during monitoring Lift 1–Lift 2 not secured and not considered as important

Because of installations taking place in stages the early seismicity is not recorded in all details and nearly two first years of the Palabora seismic data are of low quality. It also seems that to start with there was no clear concept for the seismic system. A great failure was that the system has no sensors located below the extraction level (point 2) and this in spite of the fact that by the end of 2013 nearly 50 % of the total recorded seismicity located below the mine. This happened because at some stage after the initial break through the mine management was informed by the Rock Engineer that there is no further use for the seismic network. In the end it was decided to keep the system operational but no more money was to be spent on its development.

11.4 Experience from Other Networks Monitoring the Caving Process

According to Brown (2003) micro seismic monitoring has been carried out in caving mines primarily to assist in resolving the problem of rock bursts that have occurred in high stress environments (Dunlop and Gaete 1997) although a trial of a micro seismic system for monitoring the cave growth was undertaken at the Henderson mine in the 1970s (Leighton 1978). The results obtained from more recent micro seismic monitoring for rock burst management and developments in hardware and software, suggested that micro seismic monitoring could be used to study the development and mechanics of caving (Chen 1998; Dunlop and Gaete 1997). Micro seismic events result from rock fracture or from slip on pre-existing discontinuities. Since these mechanisms are likely to be involved in cave initiation and propagation it follows that micro seismic systems should be able to monitor their development (Duplancic and Brady 1999; Trifu et al. 2002), Chitombo (2010) clams that some “novel seismology and micro seismic analysis techniques have been developed. These developments provide means of tracking the rate of caving, the fracturing modes and geometry, and potentially the height of the yield zone as well as the position of the cave back. “Improved knowledge of seismicity during caving is becoming even more important given the caving taking place in strong rock masses.” Still the main progress is in using recorded seismicity to control and reduce rock bursts. According to Oraneda and Sougarret (2007) between 1994 and 1996 advance in the knowledge of rock bursts was obtained. This included practical ways to minimize the risk through the control of mining (draw and undercutting rates) the development of seismic monitoring and procedures to minimise the exposure of workers. Experience of the last 10 years has shown that geotechnical problems like collapses and rock bursts can be controlled and reduced. However they will occur. The induced seismicity control through the control of the mine process and seismic monitoring has been very successful at El Teniente. The number of rock bursts has reduced dramatically in the last 10 years. Rock burst of 30 August 2005 in Reservas Norte indicated that monitoring and control of mining were not enough to minimise that kind of risk. The answer to this was to modify the rock, using hydraulic fracturing, in order to allow it to have more controlled dissipation of energy. The experience in Diablo Regimento with preconditioning showed that the maximum size of seismic event can be reduced significantly. The cave process monitoring in real time was done at Palabora Lift 1. There is a detailed back analysis of seismicity recorded at Northparkes Lift 2. This back analysis was presented by Hudyma et al. (2007a, b). This is a comprehensive description of the seismic response to block caving at Northparkes. A range of seismic source parameters and mine seismology techniques were used to investigate and characterise the seismic response to block caving in Northparkes Lift 2. There is also a detailed discussion of crown pillar failure and a comparison of Lift 1 to Palabora: "caving mechanics models are proposed to explain the principal steps involved in the evolution of caving and map/quantify the following information: the development of a stress front at the leading edge of the seismogenic zone, the progressive upward migration of stress front and seismogenic zone, the presence of a distressed crown pillar, the break through of the stress front into the upper lift, the regional stress redistribution and its associated high seismic hazard and the a-seismic cave connection. Periods of high and low seismic hazards have been identified and their associated mechanisms have been explained or proposed. The model appears to corroborate similar experiences at Palabora as documented by Glazer and Hepworth (2005, 2006)". Interesting work was done with seismicity recorded at Telfer Mine. The combined application of monitoring data enabled the interpretation of cave initiation, caving front location and advance rate with reasonable confidence (Di Giovinazzo and Sigh 2010). Those are only some of the publications relating to seismicity induced by the caving process.

From the above it appears that in general there is a good understanding of what can be done with the recorded seismic data. The problem is that not all of the listed objectives were done in real time and by the staff employed by the mine. A lot of seismic data analysis and interpretation especially the caving process monitoring were done outside of the mine at research centres. This while it increases the knowledge about the caving process does not mean that it will be applied in industry. The reason for this is simple. All achievements are described in numerous papers that are then presented at seminars and conferences. These papers are then published in proceedings from these conferences. In my over 20 years of being a mine seismologist I have never come upon these at the mines. This problem is then made more complicated as the attendance at these conferences of mine personnel is usually limited to management which is not directly involved with the presented matters. Further more these proceedings are usually of no use to the mine seismic staff as understanding them requires more than only basic knowledge of the subject.

11.5 Seismic System Management Systems

From my experience I know that the ways the mine will manage the seismic system are few and many. Often because of vague reasons for seismic monitoring a person with no seismic knowledge will be put in charge. To make the matter worse running the seismic system will be one of the many other tasks this person will perform. I this way the seismic system will turn out to have no practical applications and so the managements will see no reason for this tool. The seismic system has two management focuses: maintenance with recorded data processing and then data analysis and its interpretation. Table 11.5 lists four seismic management systems I have came upon during visiting mines with operational seismic systems.

In Table 11.5 I assume that the contractor is providing expert services. This table indicates that as far as recorded data processing is concerned the processing is done by experts. This is because it is reasonably easy to train in processing and the then experience makes an expert. The problem with processing might occur when it is done by a contractor located outside of the mine and in a different time zone. This contractor is paid per event so he will process as much events per hour as possible. This will result in events processed with a minimum number of stations or with the same sets of recording stations. Because the processing is done outside of the mine the mine has no control over its quality. Further more different time zones result in communication problems. Outside data analysis and interpretation has positive and negative consequences. To find an expert is often difficult and is considered expensive. The normal way out is to outsource this task. The result is that the mines data is the often analysed by virtual seismologists with no experience in mining. In result the reports main part is the network performance statistics plus information about the number of recorded events presented on some plans and sections. Proper seismic data analysis and interpretation can be achieved only with knowledge of the local conditions as mining, geology and other geotechnical measurements. It is not true that seismicity on its own provides more than 80 % of information required for reliable data interpretation. There is nothing wrong with System 2. Here all is done at the mine and by experts. Professional at the mine means an expert and that his responsibility is only with the seismic system. In System 3 the data analysis and

Table 11.5 Seismic system management systems

Management type	Processing	Interpretation
System 1	Contractor away from mine	Contractor away from mine
System 2	Contractor at the mine	Professional at the mine
System 3	Contractor away from mine	At the mine
System 4	Professional at the mine	Professional at the mine

interpretation are done at the mine by a person with some limited knowledge of mine seismology and who has a number of other responsibilities to cope with. In this way he will never become an expert and will be pushed around by management with some expectations of what can be done with the recorded seismic data. This situation usually results in "expert systems" for predicting larger seismic events. This never works so the mining management attitude towards seismology can be easy to predict and this prediction is with high probability. The best system is the last one that is System 4. To start with it is difficult to justify and then to maintain. Still this system will pay back in this or in other way. The problem is that it has to be in place from the very beginning but it might provide benefits only some time later with already different management being in charge.

11.6 Palabora Lift 2 Seismic Network

Lift 2 seismic system is designed taking into account not only the experience gained with Lift 1 seismic monitoring but also taking into account experience from other caving mines.

11.6.1 Lift 2 Seismic System Objectives of Monitoring

There are five monitoring objectives for Lift 2 seismic system

1. Monitoring the caving process
2. Monitoring the stress distribution around the cave and the mine
3. Seismic hazard monitoring
4. Monitoring rock mass volume located east of the Lift 1 and Lift 2 caves towards the Shafts and around the present Ventilation Shaft
5. Evaluation of the rock mass condition below Lift 2 cave

The first three objectives are the same as there were for Lift 1 seismic system. These objectives were achieved and results available in real time. The methodology and required knowledge is there so here there is no need for further research. These objectives are basic for the safe mining. Objective 4 complies with the requirement of monitoring the rock mass volume that is located east of the caves and west of the shafts. The present Ventilation Shaft is already monitored for any unusual seismic activity and will be monitored as long as it is required for Lift 2 mine. The last objective that is monitoring of the rock mass located below Lift 2 is important for two reasons: for monitoring the Lift 2 cave progress and for evaluating the ever changing seismic hazard.

11.6.2 Recording Station Configuration for Lift 2 Seismic Network

To fulfil the listed seismic monitoring objectives it is obvious that some of the present Lift 1 seismic stations will be handy. The current Palabora Copper Mine Lift 1 seismic network consists of 26 recording stations, with 10 installed underground, 5 installed in the open pit, 4 in the Exploration Shaft, 4 in a 380 m deep borehole on bench 19 and 3 in the open pit conveyor decline. The 10 stations located underground will be lost once the Lift 2 caving process will be initiated. The other sixteen stations which are the ones located in the open pit, in the Exploration Shaft, in the west deep borehole and in the open pit conveyor belt decline will become new stations of Lift 2 seismic system. It will be impossible to replace the existing geophone probes that are installed in the west deep borehole or in the old Exploration Shaft. Access to all other ones is available so if they are faulty they can be replaced with new probes. These probes should be then located in new boreholes drilled in the vicinity of the old ones. These recording stations will be complemented with underground recording stations.

11.6.3 Palabora Lift 2 Expected Seismic Catalogue Completeness

Table 11.6 compares single Palabora Lift 2 station rock mass volume with other caving mines including Palabora Lift 1 Mine. The Lift 2 seismic system station volume is similar to Lift 1 seismic system station volume. For this reason it is logical to assume that Palabora Lift 2 seismic system will record all seismicity above the moment magnitude −0.2. As this size of catalogue completeness in case of Palabora Lift 1 mine was sufficient to complete all objectives of seismic monitoring then it must be assumed that this will be the case of Palabora Lift 2 mine.

Table 11.6 Sensor densities of the seismic networks and resulting catalogue completes

Mine	Volume (km^3)	No of stations	km^3 per station	Catalogue completes
DR sector	0.123	6	0.020	−0.3
Northparkes Lift 2	0.081	25	0.003	−1.2
Palabora Lift 1	0.300	26	0.012	−0.2
Palabora Lift 2	0.500	36	0.014	−0.2
PT Freeport DOZ Mine	0.660	36	0.018	−0.3

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Chapter 12
Lift 2 Palabora—Seismic Hazard Monitoring

Abstract This chapter takes advantage of the recorded and confirmed as bona fide seismic signature of the Lift 1 caving process for monitoring the Lift 2 caving process and related seismic hazard. A detailed and specific proposal how to monitor and report these matters is given. Methods for Lift 2 seismic hazard estimation are easy to list. What more the probability that they will be successful is high. This is due to the fact that the sources of Lift 2 seismic hazard are known because of Lift 1 experience. As always with nature there will be some unknown factors that will influence the Lift 2 seismic hazard. In nature nothing happens twice in exactly the same way. For this reason it must be expected that the seismic hazard history of Lift 2 might not be exactly as it was in case of Lift 1. There will be differences due to the increased depth of Lift 2 extraction level, which will be located 1600 m below the surface. This should result in higher energy release rates and consequently in increased seismic risk. This is not certain as in the early stage of the caving process the induced seismicity is strongly related to the production rates. In case of Lift 2 it is easy to figure out that the initial production rates and their increase with time will be different to these of Lift 1. On the other hand half of the recorded to date seismicity took place in the rock mass volume that will be Lift 2 cave. This seismicity has preconditioned this rock mass volume. Preconditioning decreases the seismic risk. In case of Lift 2 increased depth will increase the seismic risk while preconditioning will decrease this risk. The question remains in what proportions?

This paragraph has two parts. Part one contains description of the seismic hazard sources. This is then followed by some notes on the statistical method of seismic hazard estimation. There is a comparison between the estimated possible maximum magnitudes and these that were recorded. In general the agreement is good considering that the caving process which changes with time is the main contributor towards the seismic hazard. At the end of this part there is a list of parameters that should be monitored in order to estimate the seismic hazard. Part two presents an example how to estimate and then report the seismic hazard. This example report is done for January 2014 and is based on data recorded since the beginning of 2013. This date was selected because the caving process ended by the end of 2012. This

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January 2014 summary is followed by description of how the listed parameters were estimated or calculated. Not all steps could be displayed as most of the parameters have to be tested for different time periods or with different smoothing parameters or presentation options. It is evident that this type of analysis is complex. For this reason it can not be described in simple terms of what has to be done and in what order as it is done in cases of the so called expert systems (Glazer 2012).

12.1 Lift 1 Seismic Hazard Sources

In nature nothing happens twice in exactly the same way. For this reason it must be expected that the seismic hazard history of Lift 2 might not be exactly as it was in case of Lift 1. There will be differences due to the increased depth of Lift 2 extraction level, which will be located 1600 m below the surface. This should result in higher energy release rates and consequently in increased seismic risk This is not certain as in the early stage of the caving process the induced seismicity is strongly related to the production rates. In case of Lift 2 it is easy to figure out that the initial production rates and their increase with time might be different to these of Lift 1. On the other hand half of the recorded to date seismicity took place in the rock mass volume that will be Lift 2 cave. This seismicity has preconditioned this rock mass volume. Preconditioning decreases the seismic risk. In case of Lift 2 increased depth will increase the seismic risk while preconditioning will decrease this risk. Regardless of the differences it is reasonable to expect that the major seismic hazard mechanisms for Lift 2 will be the same as they were in case of Lift 1. The Lift 1 sources of seismic hazard were as follows:

1. Caving process
2. Remnant development mining at the west towards the Mica Fault
3. Restarting mining after non-production periods
4. Movements along the wedge formed by the main faults (Mica, Southwest and Central Fault)

The caving process together with the remnant mining was responsible for about 85% of the total released energy. Restarting mining after production stoppages resulted in release of about 9 % of the total released energy. Movements along the wedge formed by faults released about 6 % of the total energy. This includes the energy released by the largest to date seismic event in the Palabora mining history. Lift 2 seismic hazard monitoring should be based on all of the identified Lift 1 sources of seismicity. The methodology would be based on monitoring the recorded seismicity and production rate trends and then searching for changes and deviations from expected behavior. This approach should be then extended by continuous monitoring for still unrecognized sources of seismic hazard. This additional element of the seismic hazard monitoring will depend up to some degree on the performance of the new seismic system but mainly on the experience and skills of its users.

12.1.1 Caving Process

The seven caving stages divide the caving history into seven time periods. As the east break through took place only when the caving process reached its mature stage there are only seven time periods. These time periods will be referred to by using roman numbers.

I. Development mining only: up to 30 September 2001
   A. Start of gravity caving (October 2001)
II. Time between gravity and initiation of the stress caving (7 months)
   B. Initiation of the stress caving process (May 2002)
III. Time between stress caving initiation and crown pillar failure (8 months)
   C. Failure of the crown pillar (end of 2003)
IV. Time after crown pillar failure until initial break through (17 months)
   D. Initial break through (May 2004)
V. Time between the initial break through until the caving process reached the mature stage (39 months)
VI. Time period in which the cave was in mature stage (62 months)
   E. Caving process reaching the mature stage (end of 2007)
   F. East break through (May/June 2008)
   G. End of the caving process (end of 2012)
VII. Time period after the caving process ended to date (in this case end of 2013)

Figure 12.1 illustrates the relation between the energy index time history and the caving process Relation between the caving process and seismic hazard is described in Chap. 7 titled "Palabora caving process as evidenced by induced seismicity".

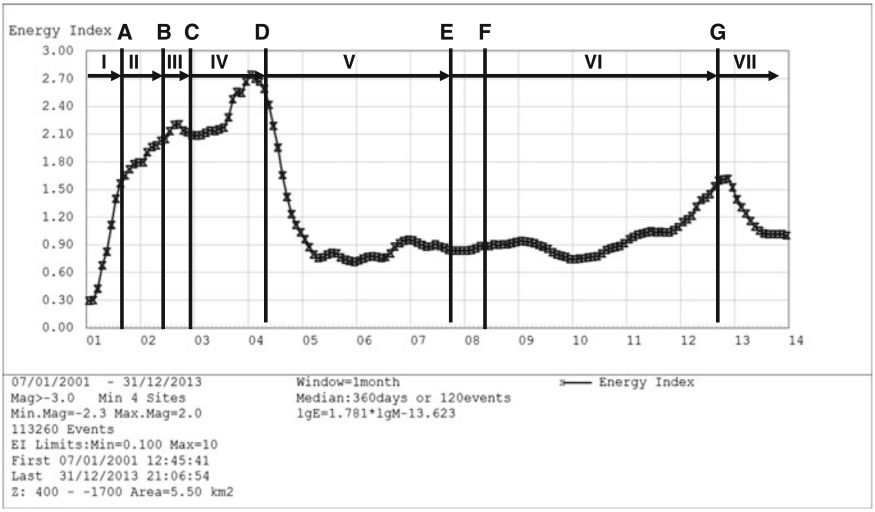

Fig. 12.1 Energy index time history and the caving process milestone

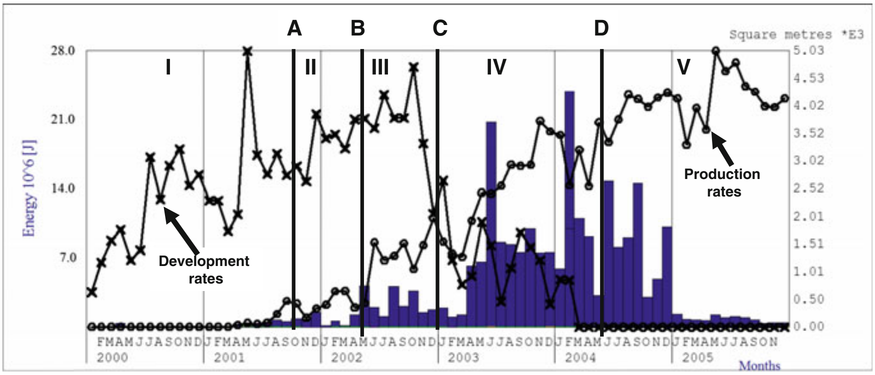

Fig. 12.2 Monthly seismic energy release rates

Figure 12.2 illustrates the monthly seismic energy release rates from the beginning of 2000 until the end of 2005. This figure indicates that:

1. Seismicity rates associated with development mining were very low (time period I and II) when compared with the rates that appeared after the stress caving initiation in May 2002 (B).
2. The largest seismic energy release rates were associated with the time after the crown pillar failure (C) up to the time of the initial break through (D) that is during time period IV
3. Larger size seismicity with the initiation of the caving process (B) located mainly above the extraction level. After the initial break through (D) they located mainly below the extraction level. See Fig. 12.3 (Here the vertical scales for above and below the mine are the same).

Table 12.1 lists the seismic risk indicators that are directly associated with the caving process.

The 24-h distribution of seismicity has four types:

Type A—Evident increase of activity during shift change (blasting times)
Type B—No prominent maximum or maxima in times of shift changes
Type C—Less of seismic activity in time of shift changes
Type D—No seismic activity during shift changes.

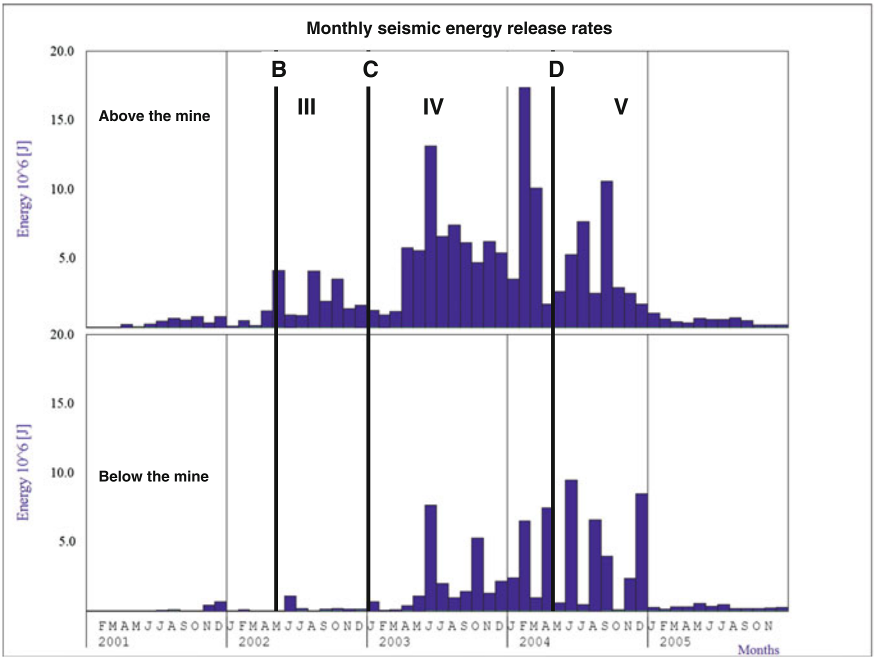

Fig. 12.3 Monthly seismic energy release rate above and below the mine

Table 12.1 Summary seismic risk indicators associated with the caving process

Value	Period I	Period II	Period III	Period IV	Period V	Period VI	Period VII
Occurrence of rock bursts				Rock bursts and FOG			
Occurrence of seismicity 1.5 and above				Mainly above the mine	Mainly below the mine		
Percentages of seismicity 0.0 and above (%)	2	2	5	36	52	3	0
Average rate of seismicity above 0.0 per month	12	14	33	104	65	2	0
Average monthly J/t	5	7.4	8.7	15.6	3.2	0.1	0.01
Average monthly Nm/t	2.7E+06	3.0E+06	1.5E+06	2.8E+06	2.2E+06	0.3E+06	0.1E+06
Type of 24-h seismicity distribution	A	A	B	A	A	C	D

12.1.2 Remnant Mining at the West Towards the Mica Fault

The premature fracturing of the crown pillar has changed the stress distribution around the mine on a regional scale. This failed rock restricted the passage of horizontal stresses through it. As indicated by Fig. 12.4 this has tended to increase the vertical stress relative to the horizontal stress acting on the sub-vertical structure in, and immediately adjacent to, the cave zone. In consequence the mine become a strongly seismically active and during 2003 experienced several damaging seismic events, of which the first took place already in mid January 2003. Comparison of seismicity recorded during 2002 with seismicity recorded during 2003 shows very significant differences. The stress change influenced not only the small scale jointing in the rock mass, but also the large scale sub-vertical geological features close to, and in the cave zone. The decrease in horizontal stress reduced confinement on the planes and increased shear movement, which is confirmed by the seismic data. Analysis of the

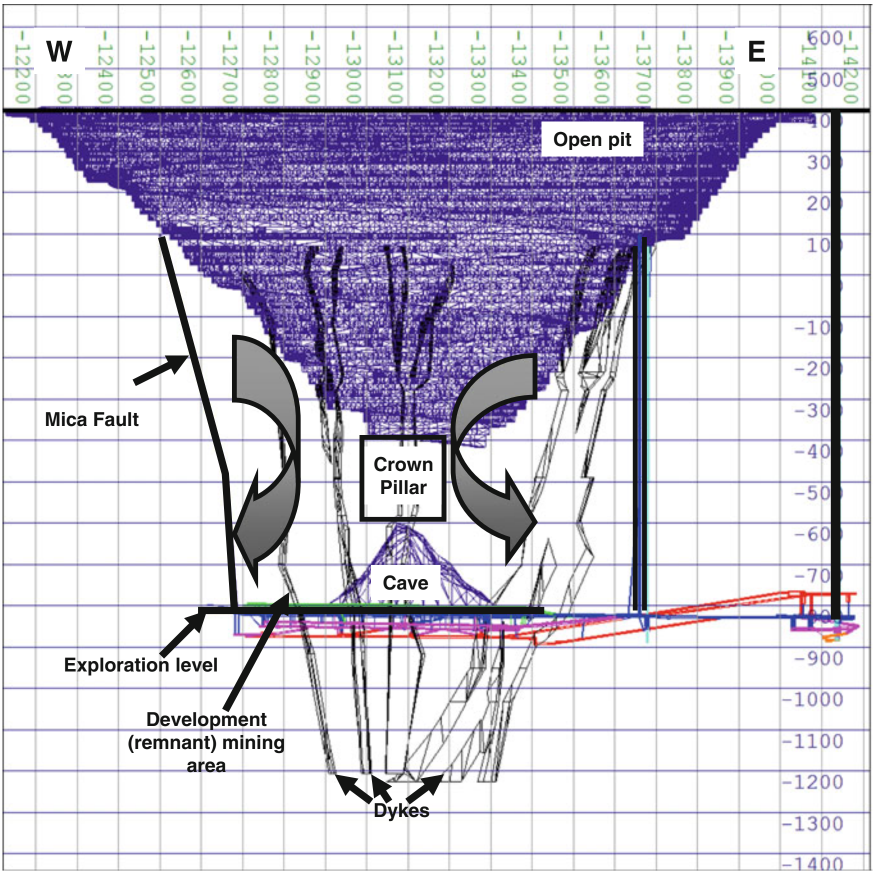

Fig. 12.4 Redistribution of stress after the crown pillar failure

source parameters of seismic events recorded in 2003 indicates a significant increase in the shearing component, in addition to a major increase of released energy per moment. Another important change was nearly a three-fold increase in relatively large seismic events. At this time the development mining was taking place at the west towards the Mica Fault. After the crown pillar failure by the end of 2002 both west and east showed high energy index seismicity which is indicative of high stress. At the time at the west there was still a lot of development in progress. At the west during 2003 a lot of high energy index seismicity located at the development level while the east high energy index seismicity located well above the production level. At this time the Mica Fault was still strong and prevented the stress migration in the west direction. By March 2004 the Mica Fault was already broken allowing the stress to migrate west away from the mine. From the beginning of 2003 until May 2004 which is the time period after the crown pillar failure and before the initial break through there were 42 seismic events of magnitude 1.0 and above. Twenty nine of these large events located at the west part of the mine located. These events released over 80 % of the total energy released by all 42 large size events. The development mining was completed by March 2004.

12.1.3 Restarting of Mining After Non-production Periods

Production stoppages provide some very useful information about the expansion void. From the beginning of 2002 until the end of 2013 there were thirteen production stoppages that lasted for a few days each. The stoppage that started in June 2012 lasted 60 days (see Table 12.2). In each case the daily seismic activity rates for the whole mine decreased when production from the cave stopped, even for just a couple of days. The first seven production stoppages resulted in increased seismic energy releases after restarting of production. Figure 12.5 illustrates the correlation between the energy index time history and the seismic energy releases after production restarting This figure indicates that the resuming of production while the stresses around the mine were high was associated with an increased seismic hazard.

Based on seismicity characteristic during and after the production stoppage it is possible to divide it into four types depending on:

- Response to production stoppage
- Seismicity during the stoppage time
- Response to the production restarting
- Energy release associated with restarting the caving process

There are four types of seismic response to production stoppage and restarting:

A. Gradual decrease of seismicity rates after production stoppage some low seismicity rates during the stoppage and then gradual increase of seismicity after restarting production followed by large size seismic energy release after a couple of days

Table 12.2 Seismic response type to production stoppages

No	Stoppage date	Stoppage days	Seismic type	Time period	Energy release after restarting production
1	October 2002	8	A	III	High energy release
2	October 2003	5	A	IV	High energy release
3	February 2004	5	A	IV	High energy release
4	April 2004	8	A	IV	High energy release
5	April 2006	9	B	V	Low energy release
6	January 2008	5	B	VI	Low energy release
7	March 2012	3	C	VI	No energy release
8	June/July 2012	60	C/D	VI	No energy release
9	October 2012	6	D	VI	No energy release
10	March 2013	9	D	VII	No energy release
11	May 2013	9	D	VII	No energy release
12	July 2013	6	D	VII	No energy release
13	November 2013	5	D	VII	No energy release

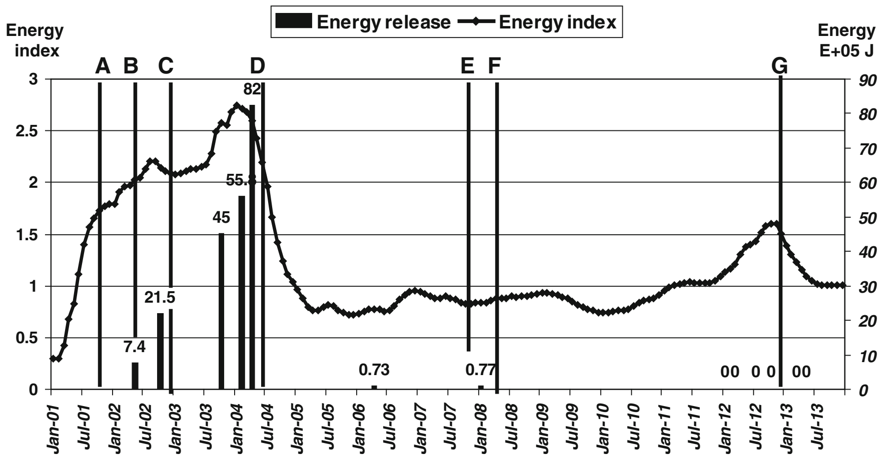

Fig. 12.5 Production stoppages and the energy index time history

B. Gradual decrease of seismicity rates after production stoppage some low seismicity rates during the stoppage and then gradual increase of seismicity after restarting production followed by small size seismic energy release after a couple of days
C. Gradual decrease of seismicity rates after production stoppage, some low seismicity rates during the stoppage and then gradual increase of seismicity after

restarting production with no additional seismic energy release after a couple of days

D. Immediate decrease of seismicity after production stoppage, no seismicity during the stoppage and then immediate increase of seismicity after restarting production, no additional seismic energy release after a couple of days

Table 12.2 indicates that there is a relation between the seven time periods of the caving process and the seismic response to the production stoppage and restarting of the production. The most violent responses to production restarting as far as seismic energy releases are concerned were during time periods III and IV. These two time periods cover the time from the stress caving process initiation (B) up to the initial break through (D). Type B that still had some seismic energy released after production restarting is associated with time period V and early stages of time period VI. This types of seismic response indicated that the production stoppage resulted in stopping the caving process and production restarting resulted in restarting the caving process. Types C and D are indicative of very limited caving process or its end. Especially type D with no seismicity what so ever during the whole production stoppage indicates that the caving process has already ended.

12.1.4 Movements Along the Wedge Formed by the Main Faults

With the stress caving process initiation all faults became seismically active. The largest event was an event of magnitude 1.9 and it occurred on the 27 February 2004. It located at the east side of the mine at an intersection of two faults: the Mica and the Central Fault. This event released the largest amount of seismic energy of the recorded to date events. What is interesting about this event is that it did not result in any underground damage and also was not felt by any one working underground at the time it took place. At the time underground damage was being reported after much lower magnitude size events. Figure 12.6 illustrates the energy index time history for the east part of the mine from July 2003 until the end of March 2004. The maximum values of the energy index were observed during August and September 2003. From then on the energy index values started to decrease indicating a stress decrease. At the time this event took place the stress level was already low as during February 2004 the energy index values were very close to their mean value of 1.0. This indicates that at the time this event took place the rock mass between its location and the underground excavations was highly fractured. Because of this the energy was absorbed before it reached the mine.

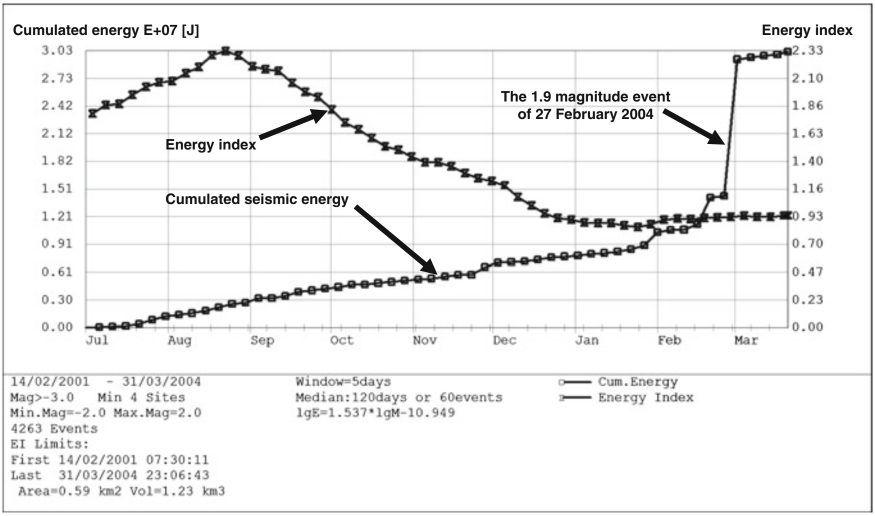

Fig. 12.6 Energy index and cumulative energy release histories

12.2 Statistical Hazard Estimation

Table 12.3 presents the M_{max} values estimated using the statistical method based on truncated Gutenberg-Richter relation. Each time the M_{max} is based on 2 years of input data. This table indicates the number of recorded seismic events during this 2 years period. Table 12.4 compares the expected maximum magnitude (in 1 year) with the maximum magnitude recorded during this year.

In Chap. 8 titled "Caving process and seismic hazard" the maximum expected magnitude for 2006 was estimated to be 1.19. This magnitude is lower from the one

Table 12.3 Maximum expected magnitude

For year	Based on time period	No of events	M_{max}	Maximum expected in		
				1 year	3 years	5 years
2004	2002–2003	30740	2.00 ± 0.18	1.66	1.78	1.89
2005	2003–2004	45308	2.20 ± 0.18	1.93	2.03	2.12
2006	2004–2005	48477	2.20 ± 0.18	1.89	2.00	2.11
2007	2005–2006	46664	1.60 ± 0.18	1.43	1.50	1.55
2008	2006–2007	32211	1.55 ± 0.14	1.47	1.51	1.53
2009	2007–2008	22607	1.67 ± 0.16	1.47	1.55	1.62
2010	2008–2009	17100	1.70 ± 0.18	1.35	1.47	1.58
2011	2009–2010	14232	1.30 ± 0.18	1.03	1.14	1.22
2012	2010–2011	13132	1.20 ± 0.14	0.80	0.94	1.07
2013	2011–2012	9925	1.00 ± 0.14	0.60	0.72	0.85
2014	2012–2013	7562	1.00 ± 0.14	0.49	0.64	0.80

Table 12.4 Expected versus actual magnitude

Year	Maximum expected	Actual maximum	Based on 1 year period
2004	1.66	2.0	
2005	1.93	1.2	
2006	1.89	1.4	1.19
2007	1.43	1.4	
2008	1.47	1.5	
2009	1.47	1.1	
2010	1.35	1.0	
2011	1.03	0.5	
2012	0.80	0.8	
2013	0.60	0.0	
2014	0.49		

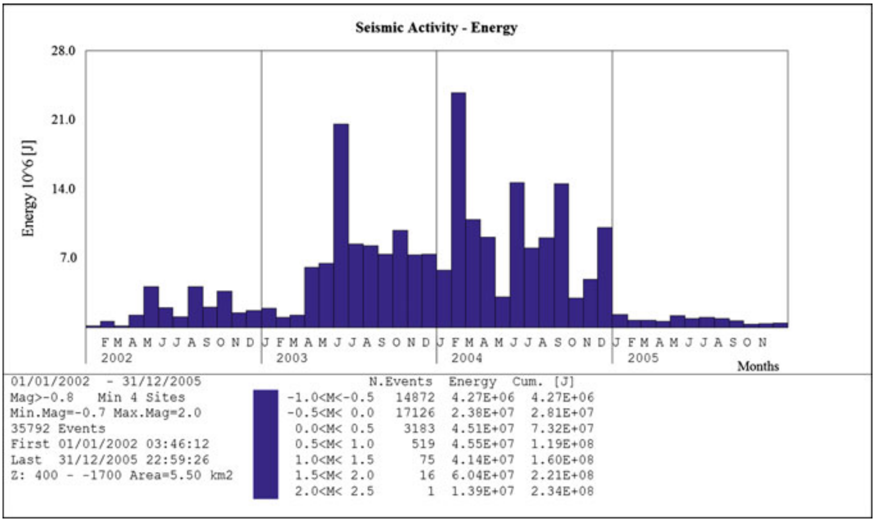

Fig. 12.7 Monthly seismic energy releases from 2002 to the end of 2005

which was estimated for year 2006 in this chapter. It is also closer to the maximum recorded during 2006 (Table 12.4). In Chap. 8 the input data was only 1 year. The 2005 was a year of low energy releases (Fig. 12.7) when compared with the previous 2 years. The largest size event recorded during 2005 was an event of magnitude 1.2 (13/01/2005). Apart from this event there were only two other larger size events, both of magnitude 1.0. I have decided that for the estimation of the seismic hazard for 2006 I will use only data recorded during 2005 and that this input will include the largest event of 2005. During mid 2004 the cave broke into the open pit. This is well documented by the energy index time history. This example illustrates

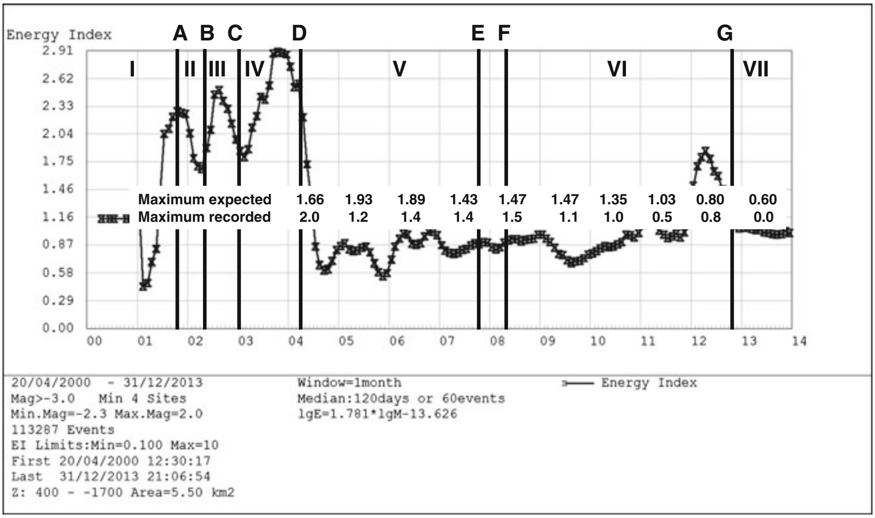

Fig. 12.8 Expected versus recorded magnitudes and the caving process

the fact that the statistical method of estimating the seismic hazard will provide better results if its user will take into account all available information including the caving process progress.

There is relation between these estimated and recorded maximum magnitudes This relation is illustrated by Fig. 12.8. It seems that the statistical approach towards seismic hazard estimation can not quite take into account all changes associated with the caving process and with the influences resulting from other mechanisms of seismicity. This method provides realistic results during the time periods of large seismic energy releases which are characteristic for the earliest caving process time periods. For this reason this method has to be used and studied in detail.

12.3 Parameters Used for Estimating the Seismic Hazard

Listed below are parameters that should be used to monitor the nature of the recorded seismicity.

1. Seismic activity rate
   - Monthly seismic activity rate
   - Percentages of seismic activity rates
   - Increase/decrease of seismic activity rates
2. Seismic deformation rate
   - Monthly seismic deformation rates

- Percentages of seismic deformation rates
- Cumulative seismic deformation
- Increase/decrease of seismic deformation rates

3. Seismic energy release rate
   - Monthly seismic deformation rates
   - Percentages of seismic deformation rates
   - Cumulative seismic deformation
   - Increase/decrease of seismic energy release rates
4. The seismicity rates
   - For the whole mine
   - Above and/or below the mine extraction level
   - Above and/or below the mine foot print
   - Inside and outside of the cave volume
5. Percentages of the seismicity rates
   - Above and below the mine extraction level
   - Above and below the mine foot print
   - Inside and outside of the cave volume
6. Monthly percentages of events with ratio of Es/Ep > 10.0
7. Clustering and scattering of seismicity
8. Seismically active volume
   - Seismically active area
   - Height of the seismically active volume
   - Minimum seismicity elevations
   - Maximum seismicity elevation
9. Average monthly seismicity elevations
   - For the whole mine
   - Above and/or below the mine extraction level
   - Inside and out side of the cave volume
10. Energy index time history
    - For the whole mine
    - Above and/or below the mine extraction level
    - Inside and out side of the cave volume
11. Stress (Apparent stress)
    - Percentages above and below the mine extraction level
    - Percentages above and below the mine foot print
    - Percentages in the cave volume.

12.4 Seismic Hazard Monitoring Report—Example

Below is an example of a seismic monitoring report for Lift 2. It presents a number of seismicity trends. This example report is for January 2014 and is making use of data recorded since January 2013.

Summary of the report:

The caving process ended by the end of 2012. Seismic hazard for January 2014 is the same as it was from the beginning of 2013 and the resulting seismic risk is estimated as low. Most of the tested parameters are of low values and/or their 13 months trends remain constant. The recorded seismicity is of low magnitude sizes (below magnitude 0.0). It concentrates below the mine foot print. The monthly activity rates of seismicity that locates below the extraction level are related to the mining rates. From the beginning of 2013 to the end of January 1014 there was no seismicity recorded in the rock mass volume around the Ventilation Shaft.

Table 12.5 lists parameters that should be constantly monitored.

Table 12.5 Observations for January 2014

Parameter	Finding	Notes
Max recorded magnitude	0.0	All results typical for time period after the caving process ended. No change during the last 13 months
Monthly J/t	0.001	
Monthly Nm/t	0.11E+06	
24-h distribution	Type D	
Seismicity rates versus cave production	Good relation for seismic moment for data from January 2013	
Monthly % of seismicity below the mine	90 %	No change during the last 13 months
Monthly % of seismicity below the foot print	90 %	No change during the last 13 months
Seismicity clustering	Two main areas (east and west). Some events clustering around crushers	No change during the last 13 months
Mining and seismicity rates	Direct proportional with seismicity recorded below the mine	No change during the last 13 months
Energy index time history	Flat and close to 1.0	No change during the last 13 months
Monthly seismicity elevation	Narrow range around −850 m from the beginning of 2013	No change during the last 13 months
Percentages of monthly seismicity with Ei > 3.0	Around 15 %	No change during the last 13 months
Seismically active volume	Area 0.3–0.4 km^2 Volume around 0.1 km^3 Thickness about 300 m	No change during the last 13 months
Es/Ep monthly ratio	60–70 % events with ratio above 10.0	No change during the last 13 months

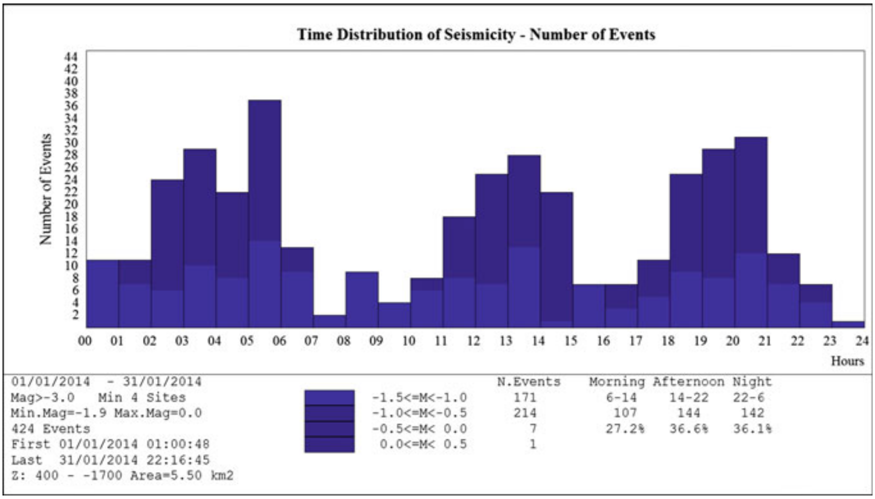

Fig. 12.9 24 h distribution of January 2014 seismicity

Below are examples of parameters, values and relations that should be regularly analysed:

A. Seismicity rates versus production rates
It should become a routine to test these relations also for other time periods than 1 month (for example days, weeks, 10 days, quarters etc.). Further more there should be additional investigations relating to the larger size events (where they locate, their mechanism etc.) and the 24 h distribution of seismicity. Figure 12.9 illustrates this distribution for seismicity recorded during January 2014.

B. Percentages of seismicity rates below the and close to the extraction level
This should include analysing percentage trends of the energy and moment rates. Figure 12.10 illustrates that from January 2013 until the end of January 2014 nearly 90 % of the total recorded seismicity located below the extraction level (−800 m below the surface. Figure 12.11 illustrates the fact that nearly 90 % of the total recorded seismicity every month located around the extraction level in elevation range from −750 m down to −850 m. These two graphs clearly indicate that the caving process is no longer there.

C. Energy index and seismicity monthly elevation time histories
Figure 12.12 illustrates the energy index and average monthly seismicity elevation time histories for the time period from January 2013 until the end of January 2014. It is important to test energy index time history using several smoothing parameters (Table 12.6).

D. Percentages of monthly seismicity rates with Ei > 3.0
Figure 12.13 illustrates the monthly seismic activity rates from January 2013 until the end of January 2014. This figure is based on all seismicity recorded during this time period. Figure 20.14 illustrates the monthly seismic activity rates of the

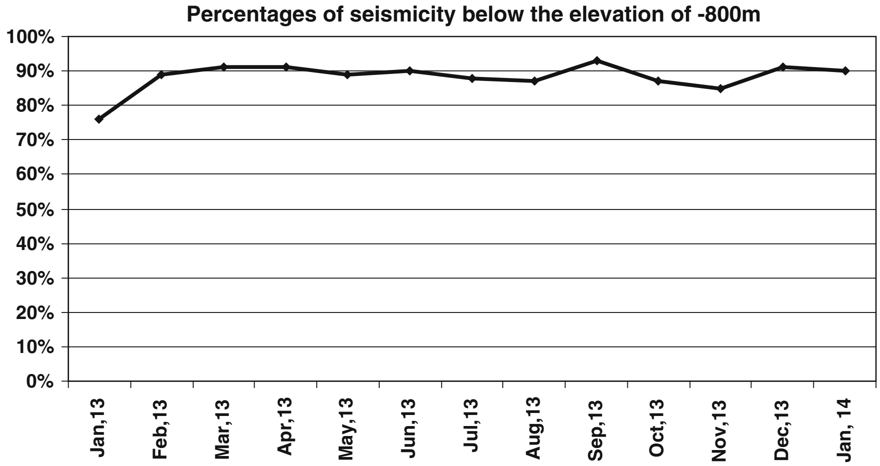

Fig. 12.10 Monthly percentages of seismicity below the mine

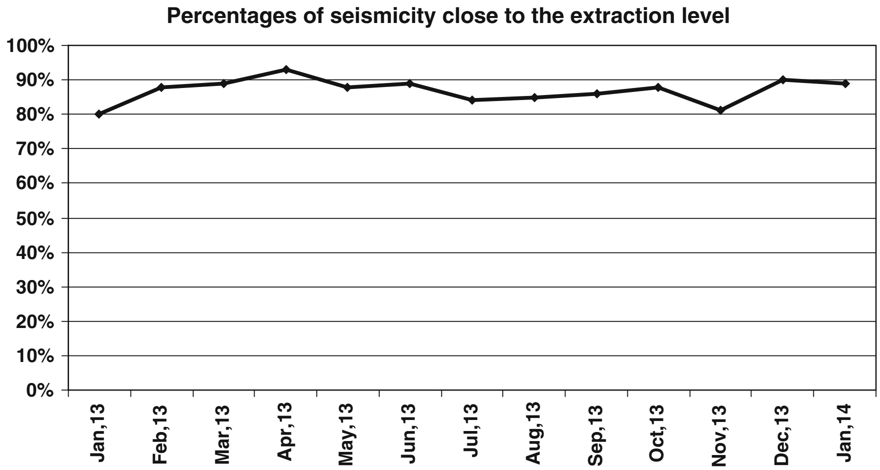

Fig. 12.11 Monthly percentages of seismicity above and below the footprint

seismicity recorded during this same time period but only that of which the ratio Es/Ep is greater than 10. Table 12.7 lists these rates and indicates that the percentages of seismicity with the ratio above 10 are in range between 10 and 20 %.

It might be beneficial to compare the seismicity with high Es/Ep rate with mining activities. Import is to establish and monitor the horizontal and vertical distributions of this seismicity.

E. Seismically active area and volume

Table 12.8 and Figs. 12.15 and 12.16 indicate that the seismically active areas and volumes remain nearly the same every month and there is no visible trend

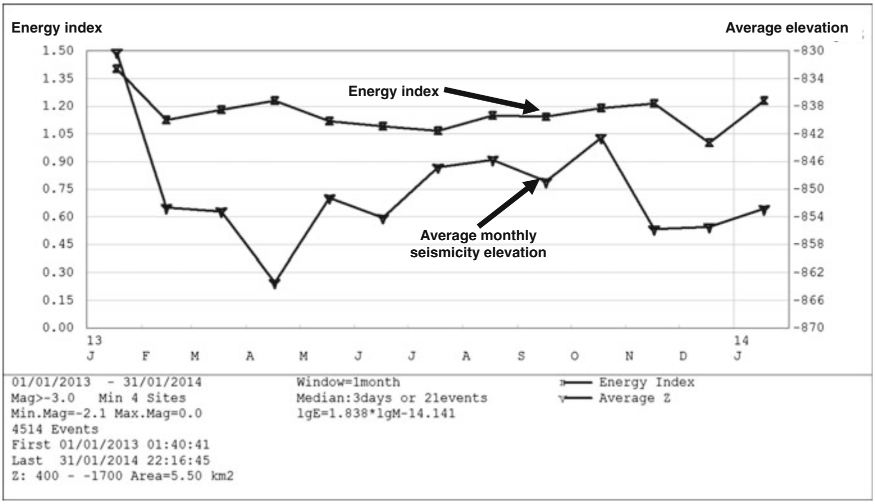

Fig. 12.12 Energy index time history and average monthly seismicity elevation

Table 12.6 Seismicity and production parameters

Month	Maximum magnitude	Monthly J/t	Monthly Nm/t	Type of 24 h seismicity distribution
January 2013	−0.3	0.02	0.10E+06	D
February 2013	−0.3	0.02	0.10E+06	D
March 2013	0.0	0.01	0.09E+06	D
April 2013	−0.2	0.02	0.07E+06	D
May 2013	−0.2	0.01	0.11E+06	D
June 2013	−0.3	0.01	0.08E+06	D
July 2013	−0.5	0.01	0.09E+06	D
August 2013	−0.3	0.01	0.12E+06	D
September 2013	−0.4	0.01	0.09E+06	D
October 2013	−0.1	0.02	0.12E+06	D
November 2013	−0.4	0.001	0.11E+06	D
December 2013	−0.3	0.01	0.14E+06	D
January 2014	0.0	0.001	0.11E+06	D

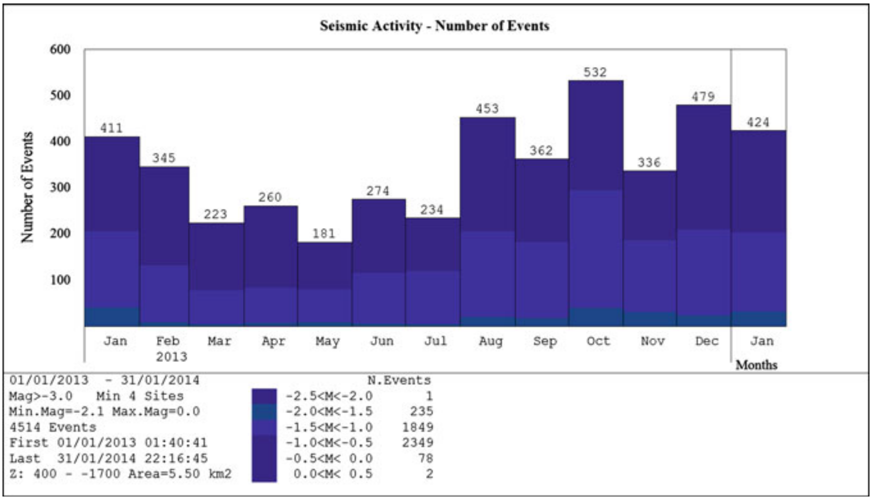

Fig. 12.13 Monthly seismic activity rates

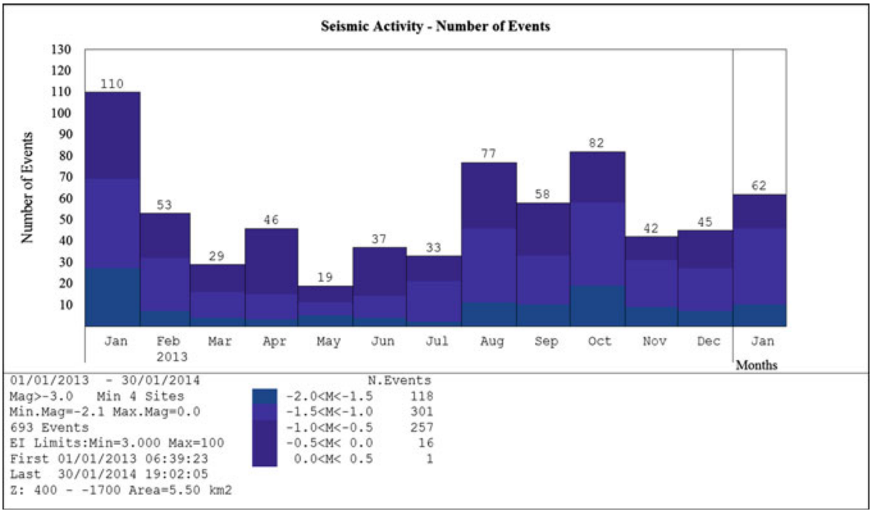

Fig. 12.14 Monthly seismic activity of seismicity with Ei > 3.0

Table 12.7 Percentages of monthly seismicity with Ei > 3.0

Month	Monthly activity rate	Number of events with Ei > 3.0	Percentage of events Ei > 3.0
January 2013	411	110	27
February 2013	345	53	15
March 2013	223	29	13
April 2013	259	46	17
May 2013	191	19	9
June 2013	274	37	13
July 2013	234	33	14
August 2013	453	77	17
September 2013	362	59	16
October 2013	532	92	17
November 2013	336	42	12
December 2013	479	45	9
January 2014	424	62	14

Table 12.8 Seismically active volume

Month	Area (km^2)	Z min (m)	Z max (m)	Volume (km^3)
January 2013	0.482	−603	−1050	0.215
February 2013	0.273	−674	−1020	0.095
March 2013	0.374	−681	−1006	0.122
April 2013	0.316	−689	−1022	0.105
May 2013	0.415	−689	−1021	0.138
June 2013	0.354	−717	−1039	0.114
July 2013	0.408	−706	−1022	0.129
August 2013	0.360	−694	−984	0.104
September 2013	0.323	−714	−994	0.090
October 2013	0.305	−691	−995	0.093
November 2013	0.309	−674	−1030	0.113
December 2013	0.160	−695	−1004	0.097
January 2014	0.358	−685	−1024	0.121

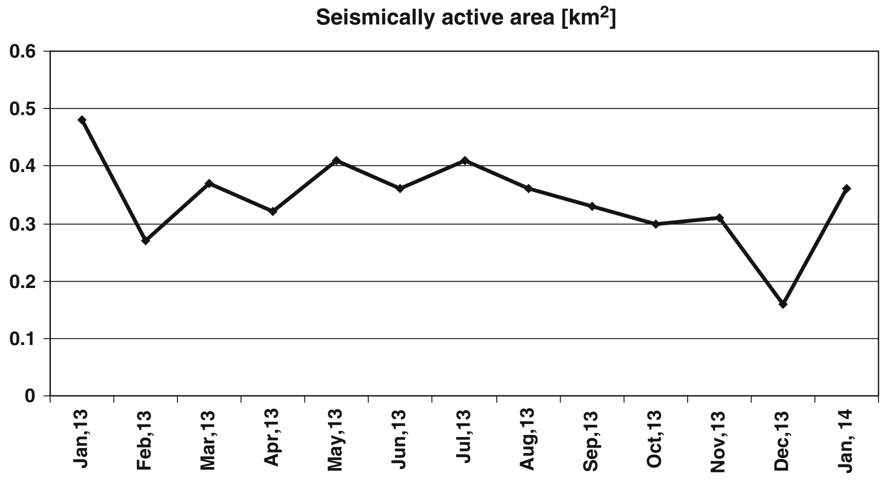

Fig. 12.15 Time history of seismically active area

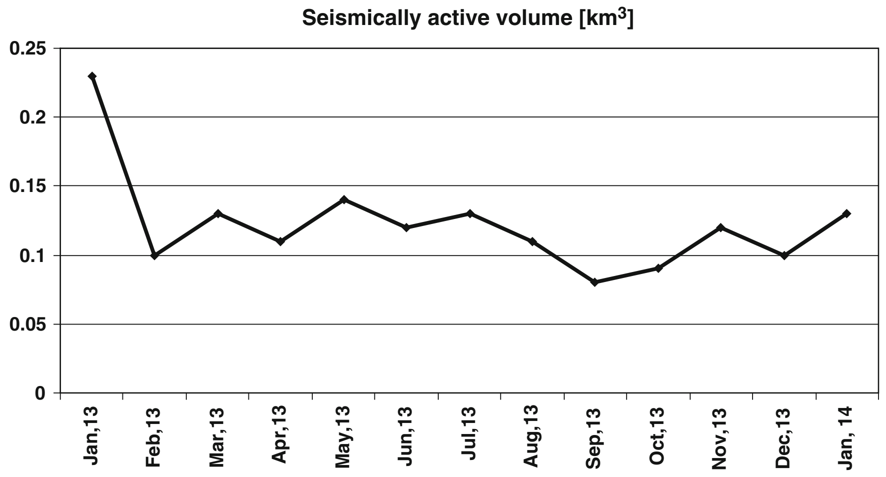

Fig. 12.16 Time history of seismically active volume

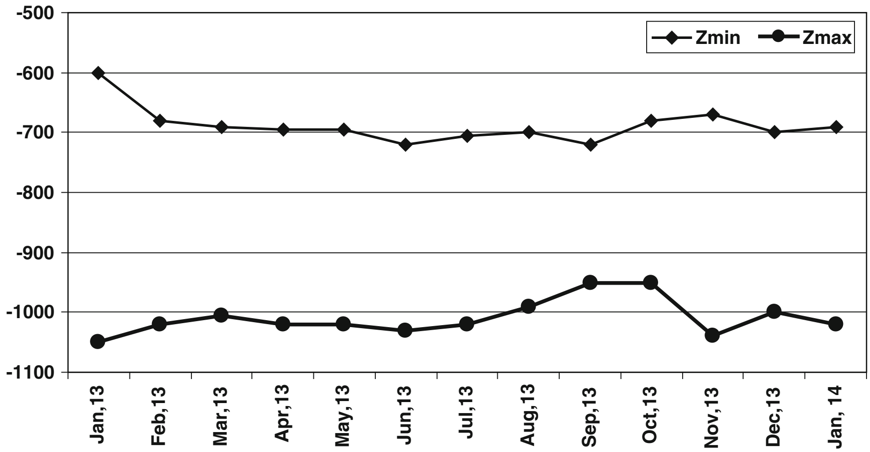

Fig. 12.17 Time history of minimum and maximum elevation

indicating any changes. Figure 12.17 illustrate the location of the minimum and maximum elevation of the recorded seismicity during the time period between January 2013 and January 2014.

12.5 Summary

In this last chapter I have used experience from Palabora Lift 1 Mine to establish interpretation practices to help in monitoring lift 2 cave and the associated with it progress seismic hazard. Before attempting any seismic interpretations one has to be sure that the seismic data is consistent and of proper quality. Additionally all presented interpretation methods require input data filtering. There are no precise rules as to exact values of these filtering parameters. The same applies to the parameters controlling the energy index time histories and the energy index contouring. Decision how to filter the input data and then how to produce the time histories or contour plots is subjective. For this reason the final results will strongly depend on the individual performing the analysis. All examples listed in this book for the application of seismic data for monitoring the caving process are based on parameters such as seismic moment, seismic energy (energy index is derived from seismic moment and seismic energy) or the space and time distributions of seismicity. These are parameters that are universally accepted and used around the world. To complete this discussion there is still one important matter that needs to be mentioned, namely the parameters objectivity. As in any analysis when the final outcome depends on comparing results obtained by using several parameters the reliability of final conclusions will be influenced by the inter dependency between these parameters. If the used parameters are dependent of each other then analysis of a number of such parameters does not contribute anything innovative towards the results apart from their shared outcome. The only benefit of such analysis that I can think of is that it allows to confirm if the applied mathematical algorithms are correct or not. On the other hand when there is no dependency between the used parameters then each of then provides independent of each other results that complement each other in the process of their interpretation.

In all presented analysis I have used two types of parameters. The first one is based on mining data and the second category is derived from seismicity. By definition the seismicity that I was analyzing is mine induced seismicity. This definition implies that there is some relationship between the mining and seismicity parameters. This relationship exists but it is not continuous in its nature nor is it constant. As I already have illustrated for example an increase in production rates will not always result in an increase in the seismicity rates or in larger size seismicity taking place. The dependency between production and seismicity changes over time with the caving process progress. This observation leads to the logical conclusion that analysis of the production and seismicity relationship contributes towards independent results. The seismicity parameters that I made use of are based on seismic moment and seismic energy which are independent of each other. I have also used the locations of this seismicity as well as their rates. It is obvious that the seismicity rates, their locations and source parameters are independent of each other and for this reason provide discrete results. As mass mining is three dimensional I have used the volume of the seismically active area. The seismically active volume is derived from the seismically active area and height. The height additionally allows for monitoring the trends of the minimum (shallow) and maximum (deep) seismicity elevations. These values are not exactly dependent on the seismicity rates but on its distribution around the cave. In the analysis I have also used a parameter based on seismic energy and seismic moment, the apparent stress. Apparent stress is also regarded as an independent seismic source parameter (Kijko and Gibowicz 1994). I have also used the so called energy index which also is a function of seismic energy and seismic moment. In the presented analysis I have used these two functions in an interchangeable manner. When I used one I did not use the other one. In some cases I had no choice but to use the stress parameter (apparent stress) instead of the energy index for the convenience as it is a part of the software code ("percentages of stress"). These two functions proved to be of great importance for the simple reason. The seismic energy releases by nature are of extremely wide range and for this reason are difficult but more often impossible to present visually as graphs. This then prohibits detecting their trends. Listed below are parameters that I have used while analyzing and interpreting the seismicity:

1. Seismic activity rate
   - Monthly seismic activity rate
   - Percentages of seismic activity rates
   - Increase/decrease of seismic activity rates

2. Seismic deformation rate
   - Monthly seismic deformation rates
   - Percentages of seismic deformation rates
   - Cumulative seismic deformation
   - Increase/decrease of seismic deformation rates
3. Seismic energy release rate
   - Monthly seismic deformation rates
   - Percentages of seismic deformation rates
   - Cumulative seismic deformation
   - Increase/decrease of seismic energy release rates
4. The seismicity rates
   - For the whole mine
   - Above and/or below the mine extraction level
   - Above and/or below the mine foot print
   - Inside and outside of the cave volume
5. Percentages of the seismicity rates
   - Above and below the mine extraction level
   - Above and below the mine foot print
   - Inside and outside of the cave volume
6. Monthly percentages of events with ratio of $Es/Ep > 10$
7. Clustering and scattering of seismicity
8. Seismically active volume
   - Seismically active area
   - Height of the seismically active volume
   - Minimum seismicity elevations
   - Maximum seismicity elevation
9. Average monthly seismicity elevations
   - For the whole mine
   - Above and/or below the mine extraction level
   - Inside and out side of the cave volume
10. Energy index time history
    - For the whole mine
    - Above and/or below the mine extraction level
    - Inside and out side of the cave volume

11. Stress (Apparent stress)
    - Percentages above and below the mine extraction level
    - Percentages above and below the mine foot print
    - Percentages in the cave volume

Finally it is obvious that each of the caving process milestones doesn't take place instantaneously. For this reason it is often impractical to use accurate occurrence timing. In some instances the milestone occurrence can be defined with-in a 1 month period. More often the milestone occurrence time can be described only by using longer time periods. For this reason in many cases I had to define the occurrence time not very precisely as for example "by the beginning of the year", "by mid of the year" or "by the end of the year".

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Appendix A
References Relating to Palabora Mine

There are 48 references listed in this appendix. They all relate to the Palabora Mine. The first one is dated 1976 while the last one is from 2012. I have collected them while working at the mine. Not all of them I have used as book references. Palabora references can be divided into two groups: the early ones from 1976 up to 1997 and the later ones that were published in the time period between 2000 and 2012. The first group are papers about the Palabora ore deposit, the natural earthquake hazard in the Phalaborwa area, about some aspects of mining in the open pit, and about the design for the underground mine. The second group of papers covers a wide range of topics connected with the underground mine. These are: cave management, secondary blasting, fragmentation, dilution, ventilation, rock mechanics and obviously seismicity induced by the caving process. There are also papers connected with the failure in the open pit and describing modelling of this phenomenon. In this reference list I have included a book about the origins of the Phalaborwa town about its connection with mining industry and the animals. Palabora Mine neighbour is the Kruger National Park. The mine property because there is water is very popular with the wild animals. On the way from the mine gate to my office I often saw elephants, buffalo, kudu even a lion. This lion was sitting by the road about 100m from where I was parking. One day coming back from the office when it was already dark I nearly collided with an elephant standing on the road. Because it was so big I could not see it. Only when it moved I was alerted that there is an obstacle on the road. This is an experience I will remember as long as I live.

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Appendix B
Press Release

The announcement that there is capital available for Lift2 is an optimistic end to my book. But I wonder how it is possible. Capital cost of Lift 1 was US$ 410 million and the cost of Lift 2 (taking into account today's exchange rate) will be US$ 745 million. This is an 80 % increase of the capital expenditure. It is assumed that Lift 2 will be in operation until 2033 (from 2017?). Lift 1 Mine was in operation from 2002 and might close by the end of 2016 (due to ore dilution) that is sooner than it was planned. Return off Lift 2 capital expenditure will take about 12 years. That is assuming todays exchange rates, copper and magnetite prices as well as all other costs. This is also assuming that the average profit of 800 R'm per year will be achieved during the first 12 years of Lift 2 Mine life. Copper is not the only PMC's source of revenue. It is also not the largest one as more revenue comes from selling of the magnetite. The revenue from copper is only 37 %. If 800 R'm is the total revenue per year then the yearly revenue from copper is close to 300 R'm. In this case copper itself will pay back the investment of 9.4 billion Rand in about 30 years which is (from today) by 2045. That would be 12 years after the copper mine closure in 2033. Present exchange rate US$-Rand is very bad for any investment. It seems that whatever we purchase these days comes from other country than South Africa. For example I just got myself a power generator made in China and the box that is used to connect it to the existing home power network is from Italy. Data used for the capital return period is in public domain and can be found in the Palabora Mining Company Year Reports.

Palabora's R9.3bn life-of-mine extension project gets shareholder nod
Mining Weekly: 25th February 2015 By: Megan van Wyngaardt

Shareholders of Palabora Copper, a subsidiary of Palabora Mining Company, have given their approval for the R9.3-billion Lift II project that would extend the life of the Palabora mine to 2033.Lift II would involve a block-cave mine development.

The approval by shareholders, comprising a consortium that included steel manufacturer Hebei Iron & Steel and South Africa's Industrial Development

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Corporation, had followed extensive investment of R2-billion on prefeasibility and feasibility study work, as well as the critical early works development.

Palabora acting CEO Maboko Mahlaole said the completion of a bankable feasibility study (BFS) last year had proved the viability of the project. "[It] gave credence to the shareholders and the company in [the] understanding of the orebody and the overall technical and capital requirements," he noted. Further, Palabora Copper growth divisions GM Nick Fouche added that the BFS had presented an option, at a 90 % confidence level, to develop a new Lift II mining footprint to 450 m below Lift I, ensuring the continuation of copper mining. "Lift I is scheduled to reach [the end of] its lifespan during this year," he said.

Fouche said the project team had already achieved "some good results", having developed more than 10 km of tunnel infrastructure. "Lift II will make the company South Africa's first to operate electric [load-haul-dump loaders] and be identified as one of the deepest block-cave mines in the world. In addition, we intend to raisebore two 6.2-m-diameter holes to a depth of 1 200 m—such depth using this technology has never before been done in Africa," Fouche enthused.

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