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Mine Seismology: Seismic Response to the Caving Process

A Case Study from Four Mines

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Experto credite

Virgil, *Aeneid, Book XI, line 283*

For Jagoda my wife and my son Michał

Foreword

The book "Mine Seismology: Seismic Response to the Caving Process—A Case Study from Four Mines", by Stefan Glazer, is aimed at the topic of mine-generated seismic data, analysis and interpretation. The title is an understatement. This book, as well as Stefan's "trilogy", provides significantly more—it offers us new perspective and insight into where mine seismology fits in the ecosystem of the mine. This book makes clear where mine seismology should be, what its role in the mining environment currently is and what has lead to the deviance between the two. It is crucial to bring home the understanding that these questions are not purely academic, after all the primary role of mine seismology is to provide information on the stage of the mined rock mass—information which translates directly into the safety of people working underground.

I have a very personal relationship with the questions raised in Stefan's books. More than 25 years ago, being associated with the mining industry in South Africa, I participated in the opening of the first digital seismic network in one of the gold mines in Klerksdorp. The emotions of the day are etched deeply in the hearts of all who were there. We saw it as beginning of something entirely new—the nascent era in mine seismology where finally we would be able to predict fatal seismic events. The decade which followed was the decade of enthusiasm, hopes and high expectations as we installed hundreds of top quality 3D digital seismic networks in mines. We nurtured a dream about early warning systems in the mines that one day we would be able to understand the stage of the mined rock mass to the extent that we would install a set of three lights—red, orange and green, at every mine to reliably tell miners the danger levels.

After the decade of enthusiasm, slowly but steadily it became clear that installing highly sophisticated recording systems and accumulating top quality of seismic records will not be enough. It became clear that we would not succeed in predicting mine events until we understood the physics behind the generation of seismic events. Nevertheless, the damage was done. The endless unfulfilled promises that prediction is just around the corner came back to haunt us and have made it more and more difficult to get funds for mine seismology. Rightly, the management of mines has started asking difficult questions. Thus, the era of big expectations has ended and the community of mine seismologist has dispersed. It does not help that some of today's key players in mine seismology continue in the vein of misleading and making false promises in order to secure funds and save face.

Stefan is the antithesis of these people. He continues his diligent, localized work on interpretation of mine-induced seismicity in the best way possible, steering clear of illusory early warning systems. He uses a fine scientific scepticism for which he has often paid a high price even as he continues work with the highest integrity.

Stefan's book "Mine Seismology: Seismic Response to the Caving Process—A Case Study from Four Mines" summarizes his vast experience in the interpretation of mine-induced seismicity. Whether seismicity is induced by deep gold mines or by the caving process, Stefan brings rationality to the role of the mine seismologist. In typical style, he simply and straightforwardly explains what is possible and how to get there. In his judgments, he is not pessimistic, nor optimistic, he is a realist and he is a realism based on enormous experience.

Stefan is strongly against the latest phenomenon of removing mine seismologist from mines to distant isolated environments where he believes their observations will be impaired. Rather, to be successful, mine seismologists must interact with the geologists, geo-technicians, rock mechanics and mine managers on a daily basis. In addition, he strongly emphasizes the role of theoretical studies.

I found the parts of his books where he summarizes his experience and gives concrete conclusions to be the most valuable. Since these gems are salted across all three of his books, I would recommend reading them all, especially for young mine seismologists and mine managers, which would address and clarify role of seismologist in the mine and clearly define what one can and cannot expect from his work.

We must be reminded again and again that the role of the seismologist in a mine is to make use of available knowledge to improve underground safety standards and save lives.

Pretoria, South Africa Andrzej Kijko

Preface

Henryk Sienkiewicz (1846–1916) a Polish writer and novelist wrote a famous trilogy which, when all is set and done, boils down to presenting a simple fact that when the country was in danger, the knights and noblemen proved capable of making huge sacrifices to save Poland. In the first book, they pushed back the rebellious Cossacks, in the second they stopped the Swedish invasion and in the last they were victorious over the Tartar hordes. It is important to understand that Sienkiewicz lived in era when Poland did not exist as a country—the area that now constitutes Poland was divided between Russia, Prussia and Austria. It was Sienkiewicz's intention to raise the morale of the Polish people by stating that in the end courage and patriotism would restore Poland on the map of Europe.

This book completes my own trilogy and it deals with seismic data analysis and interpretation. The first book described how to interpret seismicity induced by the caving process. The second was about interpreting seismicity induced while mining for gold in a deep mine and then making use of that knowledge to improve the underground safety standards. In the first two parts, the action was set in the mine and illustrated how mine seismology was used for mining and safety improvements. The final book is about seismicity induced by the caving process. While part one and two are based on data recorded in one mine, the third is based on data recorded in several mines. Not only does it describe the seismic signature of the caving process, it also presents what possibilities exist when dealing with data that originate from different mines.

I know that my writing doesn't even come close to Sienkiewicz skills. Two years after he died, Poland was back on the map of Europe. This did not happen because of reasons presented in his trilogy, and Sienkiewicz's rationale appears to be naïve and idealistic. The purpose of my trilogy is practical and down to earth. I want the mine seismology scholars and these practicing it to understand that this science has sound principles and theory which are no more complicated than those of other sciences (even rocket science). As in case of other sciences what is required is sound understanding of the data. The concept of understanding is wide and includes knowledge not only of how the data was initially collected and then formatted but also awareness of its limitations. Awareness of limitations is the key to remaining within the boundaries of science. Those who are not bothered with data limitations pass this frontier and find themselves in realms of pseudoscience, and unfortunately their ignorance tends to influence the general perception of mine seismology.

What at present is most devastating for the mine seismology is that the mine managers perceive it in a wrong way they do not understand how it can contribute to the mining process. It is my opinion that today's mine seismology is about interpretation of the currently recorded data and its integration with other available data. Results of this analysis should be used in mining on daily basis to improve mining operations and underground standards; this is why the mine seismologist must be located at the mine. He must cooperate with the mine geo-technicians and managers on daily bases. Mine seismology will never become a useful mining tool while it is performed away from the mine. At present because of its remoteness from the mine, it has become an exhibition room display rather than mine seismology. I do understand the value of back analysis and while it is important but not when the proportions between practice and theoretical studies are in favour of the former. It is obvious that the theoretical studies should be concentrated on solving genuine and practicable goals.

Phalaborwa, South Africa S.N. Glazer

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Chapter 1
Introduction

Abstract Question—“Is mine seismology quantitative or qualitative?” The answer is straight forward as by its very nature the seismic source parameters are only estimates and in being objective they can be described as a conclusion of an educated guess. Once the main reason for mine seismology being qualitative is removed this may be a matter for future debates. Up to now, the dividing wall from it being considered qualitative is the measuring device the seismological software itself. With each software update, the resulting source parameters are different from the previous ones and the differences can be significant. It is as if with every new version of the software something fundamental is changed. As an example, take the definition of a metre. The metre is defined as the length of the path travelled by light in a vacuum in 1/299 792 458th of a second. Now just imagine the resulting pandemonium if various industries or research institutions used whatever definition of a metre they wanted at any specific time. It is for this very reason that I did not agree to an update to the PMC’s seismic processing software and right up to the end of 2013 all recorded data was processed using one version of the software. As a result, the PMC seismic database was consistent and allowed for a very detailed analysis of the caving process as evidenced by the recorded seismicity. All analysis and interpretation of this nearly perfect database was based on trends and their changes with the process of caving. This is typical for qualitative analysis (Glazer 2016).

Third part of my seismology trilogy is based on my experience with research. The research was done for the Mass Mine Technology Project II and it lasted 3 years (2009–2012). My research project was entitled “Seismic signature of the caving process”. This project involved analysis and interpretation of seismicity recorded at four cave mines namely: El Teniente, Chile, PT Freeport DOZ Mine Indonesia, Northparkes Mine Lift 2 Australia and PMC, South Africa. The objective of this project was to analyse the seismic data originating from several caving operations in order to identify characteristic seismic signatures for each of the caving stages and followed up by a description of the resulting impact on underground safety. The outcomes of this research project were:

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1. Improved understanding of the caving process
2. Methodology for monitoring of the caving process for mine practitioners

Before delving into the details of my research, I would like to present my views on several aspects associated with research:

1. Basic research, applied research and implementation
2. Predicting mine induced seismic events
3. Quantitative versus qualitative seismology
4. Research versus pseudo-research

The New Encyclopaedia Britannica (edition 1985) defines research as follows: "In modern industrial research and development programs basic research, defined as scientific investigation persuaded without conscious goals, is directed toward a generalized goal related to a given industry. Applied research uses then the findings of basic research to meet the industry's specific needs, and the results of applied research are developed to bring a new or modified product or process into industry". Basic research to make sense should be presented in such a way that it can be understood by those who will be using it for applied research and then implementing results into practice. If that is not the case then basic research is useless except in the case when the people or organizations doing the basic research also do the applied research as well as its implementation. In such cases, it all stays in one family, as the saying goes. Research should not be treated as a mystique matter that can only be performed by the chosen few. Research that serves only research is of no value. It is comparable to ancient Egypt where priests were very important but only because they served the gods. This service on its own was so crucial that they had no obligations at all to the living. The priests cared only for the needs of gods and made comfortable lives because they and they alone were able to decide what the gods needed. My personal interests centre on mine seismology basic research and its results. It seems that during the last 30 years, this research was focused on predicting larger size seismic events in the mines even when the prediction concept in global seismology was given up by the end of last century (Glazer 2016). I don't believe that predicting is possible and already made my position in this matter clear (Glazer 2016 and 2017). Some hope that the larger the event the easier it might be to predict but this is incorrect. In my experience, the largest mine seismic events of magnitude above $M_L = 3.5$ at least in the Klerksdorp area take place not because of present mining but because years of mining in the whole region (Glazer 1997, 1998, 1999, 2017). For this reason, there is nothing taking place today that might allow predicting this type of events. Such events are described by Fernandez and van der Heever (1984), Midzi et al. (2015) and Glazer (2016). Views stating that it is impossible to predict large mine induced events can be found in Spottiswoode (2009) or (2010). Durrheim and Ogasawara (2012) hope that predicting large events in mines may still be possible at some future point in time: "Past efforts to identify reliable precursors of damaging tremors in South African mines and great earthquakes in Japan have failed to produce convincing results. This may be due to limitations in the sensitivity and resolution of past observations. We hope to remedy this by monitoring deformation and rupture with unprecedented detail at research sites in three deep gold mines". For now, basic research into prediction resulted in a number of new seismicity parameters Mendecki (1997). Application of these parameters for routine seismic hazard assessment is described by van Aswegen (2005). Is there anything new from those assessments 12 years on in 2017? I do not think so. From Spottiswoode (2009): "More recently, Durrheim et al. (2007) reported on work towards "best practice" on mines. Two quotes are relevant to the work presented here: "Dr G van Aswegen (ISSI, pers. comm., 2007) comments that the short-term seismic hazard assessment procedures have not changed significantly since 1995, the success rates are variable, and in some cases the seismic rock mass response to mining is too fast or too slow for the methods to be useful on a daily basis." and "Mines should continue with their current practice, evaluating retrospectively whether working places receiving high hazard ratings was actually exposed to greater event frequency and/or severity. Concurrently, seismic analysts should seek to supplement the existing parameters with any found useful by other mines. If, after 2 years, a parameter and/or method cannot be demonstrated to provide useful results, it use should be discontinued." I am certain as I closely follow seismological literature that nothing of the above took place. This indicates that there is no progress in short-term seismic hazard determination. From year 2000 what was previously regarded as prediction became known as seismic warning or short-term seismic hazard evaluation (Glazer 2017).

It is claimed (Mendecki 1997) that the source parameters (time of the event, location of the event, seismic moment, seismic energy radiated) are the result of quantitative seismological processing. Only size and the stress release are estimates. In consequence, description of seismicity is also quantitative. In Riemer and Durrheim (2012) and Durrheim and Riemer (2015), there are statements that with digital seismic recording an era of quantitative seismology had begun. I do not agree with such statements, for a number of reasons. Mine seismology is not a quantitative discipline as the seismic source parameters are not measured but only approximated. This approximation depends on a number of factors one of which is the seismic processing software version itself. There is no need to delve deeply into an investigation if seismology is quantitative or qualitative. At present, seismic processing software provides all evidence that is required to demonstrate that seismology is a qualitative discipline. If this problem could be solved only then other reasons can be considered. Seismic source parameters change every time there was an upgrade of software. My experience is that the seismic processing software is not a proper tool for "measuring" seismic moment and seismic energy. This is because when changing this tool for a new one (new software version) the "measured" values change. And they can differ considerably. If in the case of a 2 months seismic data catalogue, the measurement of ΣE decreased 100 times while the ΣM_O increased more than 10 times then this certainly too much for quantitative measurement (Glazer 2016). Given this, how such quantitative seismology can survive and still be even considered a tool for monitoring seismic hazard? It is difficult to understand how this problem remained unnoticed. It is obvious that the recorded characteristics of induced seismicity with new software in place had to change. Such variations are attributed to changes in mining sequence or in seismic hazard. Changes because of adjustments of mining sequences are not very rapid as mining sequence cannot be changed from day to day. That leaves only one possibility, that there must be a rapid change of seismic hazard which is always a matter of great concern.

I have been complaining about this problem since 1997 but no one took much notice. At mines who outsourced seismology the contractor would not complain about his own software and the rock engineer responsible for liaison with the contractor and signing invoices would not understand the problem. Lately, this issue has come to light. “Systematic errors are causing significant artefacts in seismic databases. Of the 20 databases investigated, 70% had one or more systematic shifts a year, and only one database showed no shifts at all. There is justified concern with respect to systematic inconsistencies in seismic databases in the industry. Such inconsistencies could lead to misinterpretation of seismic analysis results which will have a carry-on effect on other parts of the operations” (Morkel and Wesseloo 2017). What this really means is that such seismic databases cannot be used for any back analysis which is one of the reasons for seismic monitoring. Back analysis is done so we learn from the past (Mendecki et al. 1999). This problem does not end with straight forward back analysis based only on seismic data. In rock engineering recommendations for mine design modelling is an important part of the procedure. For example, in Malovichko (2017), we find the following: “An approach to assess seismic and ground motion hazard associated with scenario(s) of future mining is suggested. The key element of the approach is the modelling of expected seismicity (……) and combining the catalogues of modelled and observed seismic events”. In this modelling, seismic data is used for calibration to allow this modelling to be as close as possible to reality. In these cases, it is obvious that with defective inputs the results will be incorrect. This is a major problem as it probably applies to most of the existing seismic databases. This is the reason why I did not agree for updating the PMC seismic processing software, and up to the end of 2013 all recorded data was processed by one software version. As a result, the PMC seismic database was consistent and for this reason allowed for a very detailed analysis of the caving process as evidenced by the recorded seismicity. All analysis and interpretation based on this nearly perfect database are based on trends and their changes with the process of caving. This is typical for qualitative analysis (Glazer 2016). As described in Glazer (2017), the success story of the Vaal Reefs No 5 Shaft experiment ended once new version of the processing software was installed. It is easy to distinguish between qualitative and quantitative. If I measure for example a length width and thickness of a board, the result would not change with the tool alteration. A 2 m, 3 m or 5 m measuring tape would not change the result. I could use a tape made in Brazil 15 years ago and one from Japan that is 3 years old and the result of the measurements would be the same. There would be an attached error but still the measuring process would be quantitative. Result of that measurement could be then used to solve some practical problems for example to calculate the number of boards required to build a certain fence. This then would lead to transport requirements and budget. This measurement would at some stage allow for calculating man-hours required for the job. In the end, this simple quantitative measurement process would be the base for calculating the profit. What’s more it could be used for advertising purposes as it would allow setting a discount (for senior citizens) that would still allow for profit. Measurement done using metres as units are in the end converted into money. In this process, there are several parameters with various units as m^3, tonnes, price for example Rands per kilometre and so on. Each parameter in this example while based on the initial measurement introduces new information that doesn't double the previous one. Unfortunately, this is not the case with seismic moment and energy. Their summaries can be studied in certain time and space limits. These are the activity rates. Activity rates can be tested for trends: increasing, decreasing or continuous. They have their limits as they cannot be converted into anything else. Now let's assume that there is a building company that has a job to do. Based on plans, they calculate all required materials, transport and production cost and finally their profit. If the profit is appropriate they decide to take the job. They place the material order with a supplier. This supplier is a modern outfit that has most of its process automated. This automation is run by a computer for which there is specialized software that is upgraded from time to time. Up to this point, the presented process doesn't seem to be complicated or out of character. The material supplier has just updated his software with a new version of the operational software. This is still nothing extraordinary as this process is done all around the world. It becomes different when the new software has a new metre length based on a new standard. The new metre length could then be shorter or longer from the previous one perhaps by ten or hundred times. Those values are taken as an example but it is precisely what happened with the new seismological software version. It is obvious that such changes in the length standard would create havoc at the building site and would influence not only the cost per unit but also the profit. If the length standard change is not noticed it would then probably bankrupt either the construction company or the material supplier. It is difficult to imagine that such change could go unnoticed in any business but this is what happened in the business of mine seismology.

My interest in pseudo-research originates from the fact that I am a researcher myself. I always wanted my research to stay in the realm of research and away from the pseudoscience sphere. Oxford English Dictionary (OED) defines pseudoscience as follows: "A pretended or spurious science: a collection of related beliefs about the world mistakenly regarded as being based on scientific method or as having the status that scientific truths now have." According to RationalWiki.com, pseudoscience can be described as: "any belief system or methodology which tries to gain legitimacy and authority by wearing the trappings of science, but fails to abide by the rigorous methodology and standards of evidence that are the marks of true science." According to Boyd (2016): "Since pseudoscience is wearing the trappings of science, and is claiming to provide the same explanatory power obtained as one would see when closely following the ideal scientific method, there is no way possible way to live side by side. Pseudoscience seems to aim at taking over the evidence based, explanatory role of the honest scientific method, and discards the principles it is built upon, with wide-spread doubt and mistrust within the public opinion as consequence" Theocharis and Psimopoulos (1987) wrote: "Having lost their monopoly in the production of knowledge, scientists have also lost their privileged status in society. Thus the rewards to the creators of science's now ephemeral and disposable theories are currently being reduced to accord with their downgraded and devalued work, and with science's diminished ambition. This is then the reason that for the uninformed public, pseudoscience and true science are hardly distinguishable". There is a lot of literature that lists indicators of pseudoscience for example Beyerstein (1995) or the PDF version of the Wikipedia article on pseudoscience. http://en.wikipedia.org/wiki/Pseudoscience. The following are some of the indicators of the possible presence of pseudoscience:

1. Use of vague, exaggerated or un-testable claims
2. Over-reliance on confirmation rather than refutation
3. Lack of openness to testing by other experts
4. Absence of progress
5. Use of misleading language

My latest adventure with research was preceded with over 40 years of industry experience. While researching for the Mass Mine Technology Project II, I also worked as a mine seismology consultant solving real problems. Through whole of my professional life, I was also in some way involved in research and development. When working for a geophysical company in Krakow, Poland (1974–1980), I was part of the company coal division. At the time, we were implementing and performing underground seismic measurements in Polish coal mines. These were done for the following reasons:

1. To uncover micro-tectonic faults in coal bed prior to its mining
2. To determine the if there are any sedimentary disturbances in the coal bed and rocks around it
3. To establish the rock mass stress regime and to monitor it changes due to mining
4. To monitor the strength parameter of the shaft linings

Results of these measurements were used to decide on the mining strategy and to avoid production stops when approaching a washout in the seam. Geophysical measurements allowed saving in costs and time as they were done instead of exploration works and drilling. The method used for these measurements was inseam seismic. Seismic waves generated and detected within a seam can in principle be used to delineate faults, seam-splits, wash-outs, and intrusions of dimensions less than a seam thickness. Dispersive channel waves of both Rayleigh and Lowe type are potentially most suitable for in-seam mapping. Our work had to start with adopting some recording equipment and construction of three component geophone probes. At that time, I had the unique possibility to plan the measurement lay-out, perform the underground measurement, interpret the results and compile the report. More uniquely in many cases, I could compare my interpretation with reality in the field while the coal seam was mined out, and in some cases I was wrong. I then had to face a furious mine manager when due to slight coal seam dip, the long wall stopped and the hydraulic support following it was collapsing. Development and introduction of a new method into the industry is a challenge and not all in our profession had this opportunity. I have only one paper published from that period (Glazer et al. 1980). Then as a geophysicist with the Research Centre of Mine Geophysics (1980–1981), I was involved in preparation of long wall documentation that included geophysical, geological, hydro-geological and geotechnical data. In 1982, I moved to England where I joined Horizon Exploration Ltd. This company was in business of oil and gas exploration. My first position was of a seismologist on a seismic land crew. From that period, two things spring to mind. First, on joining the crew, I quickly found my way around. This was because of my experience with a Polish seismic land crew. I discovered that both Polish and English land crews consisted of the similar type of people. The question I had was it the same type of people are attracted to this type of work or was it the work itself that shaped them? The second incident was of different character. On the land crew during the day only the seismologist was in the office so his job was extended to answering the phone. At that time, we were working in Kent and the profiles were following the country roads. One day I received a call from which I understood that in a village that our vibroseis trucks will be passing is a large bomb. It was dropped by a German plane during WW II. It was now berried in thick mad below a water pound. When I reported this to the crew manager he could not believe this. He was sure that I misunderstood as I just came from Poland and my English was still far from perfect. But he had to send the permit man to the land owner where the bomb was located and to the police station. He found that there really was a bomb of which the whole village was very proud. We had to adjust our plans in order to save the village artefact. The seismologist had to establish the distance from this object to ensure that the vibrations not to trigger the bomb. After a couple of months, I joined the R&D department where I was responsible for all aspects of field work concentrating on refraction static. I was involved in designing a package called FIRST which means First–Break Interactive Refraction Statics Technique. The FIRST package was a suite of programmes designed to automate many of the computations involved in the determination of an accurate static model. This package utilized a comprehensive database and a set of interactive modules that allowed for ready examination of various aspects of data at any stage in the process. The flexibility of FIRST permitted handling of all 2D and 3D arrangements of land and transition acquisition. Years after I left Horizon my son meet somebody that worked at Horizon and found out that FIRST is still in use and that it is coupled with my name. I prepared a manual for the land crews titled “Field Statics Corrections a Guide to their Calculation”. This manual was intended to be useful both to people with no previous knowledge of computing and to people who had been working in the field for some time. To the former, it provided both the basic idea of what is involved and a more detailed approach when needed. To the latter it was a reference manual, back to which they could refer if and when confronted with a new problem. From that period of my career, I have three publications Hall and Glazer (1986), Glazer and Hail (1987) and Glazer (1988). In 1988, I relocated from the UK to South Africa to work as a mine seismologist at Vaal Reefs Gold Mine. My experience with research done at this mine is described in Glazer 2017. It is worth mentioning that this research resulted in me becoming a doctor of mine geophysics. My Ph.D. thesis were titled “Practical applications of stress index and other seismological parameters in combating rock burst hazard in deep gold mine of Vaal Reefs, South Africa”. In 2002, I moved from gold mining to cave copper mines. The applied research I have undertaken based on seismicity induced by cave mining is described in Glazer (2016).

Based on my experience outlined above, I applied for a research project with Mass Mine Technology Project II. Over and above my experience research, I was able to offer my knowledge in mine seismology but more specifically my knowledge of seismology associated with the caving process. At the time, this application of mine seismology was very new. It was my PMC experience that indicated that seismic monitoring is a very valuable and useful tool not only for monitoring the caving process but also for managing the transition phase from open pit into underground mining. In order to satisfy the aims of my Mass Mine Technology, there had to be an adequate amount of input data. This input data had to fulfil two conditions. Not only its quantity had to be sufficient but its quality also had to be satisfactory. This applied both to the recorded seismicity and to the documented caving milestones. The results of my research will be presented in the next three chapters of this book.

Chapter 2 of this book is titled “Seismic data assessment”. In this chapter, there is a summary of the available seismic databases. For the project, I used seismic data recorded in the following mines:

1. El Teniente Initial Esmeralda Sector
2. El Teniente Diablo Regimento Sector (DR Sector)
3. Northparkes Mines Lift 2 (NPM)
4. PT Freeport Indonesia DOZ Mine (PTF)
5. Palabora Mining Company (PMC)

The fact that all seismic data available for the project (about 1,000,000 seismic events) were recorded and then processed with the same seismic system made direct comparisons possible and reliable. All analyses presented in this project and interpretations of the seismic databases were done using this same seismic interpretation software which was developed specifically for seismicity induced by the caving process. Originally, this software was developed only using the experience from PMC. Further development of this software was based on data recorded at all these cave copper mines and customized to specific requirements of this project. Several changes and new options, for example for testing the database quality and integrity, were included. Seismicity recorded in these mines contained information about the following caving milestones:

1. Initiation of the caving process
2. Pillar failure
3. Cave break through
4. Caving process reaching mature stage

Seismic databases should be constantly tested for quality and integrity. I have presented two seismic database quality tests. The first one is based on PT Freeport Indonesia seismic database and the second example is based on data recorded at the El Teniente Diablo Regimento Sector. Further on I presented the analysis of the average seismic energy release rates of low magnitude size seismicity (from −1.0 up to 0.0) recorded at PMC, PT Freeport Indonesia, Northparkes Mine, El

Teniente Diablo Regimento Sector and El Teniente Esmeralda Sector. Data recorded at Diablo Regimento Sector was divided into two sub-catalogues: “Whole” which consists of all seismicity recorded in this Sector and “Hydro” which consists only of seismicity recorded while mining the hydro-fractured rock mass volume. These average seismic energy release rates are based on data recorded during different time spans depending on the mining sequence. For these data sets to be not only consistent but also compatible with each other, the averages are based on monthly seismic energy release rates. This analysis indicated that the Northparkes Mine average seismic energy releases were extremely high and did not follow the observed trends for the other mines. This section then contains further investigations in order to establish the reason for this data being so different. And yet again the problem of a different software version popped out. This chapter ends with a section titled: Comparison of Seismicity Induced by Cave Mining at Palabora Mining (South Africa) and at PT Freeport Indonesia Copper Mines. This section is a paper I wrote during 2006 and then published in Poland (Glazer and Townsend 2006). It was a first attempt at comparing recorded seismicity in two copper cave mines. By the end of 2005, the Palabora block cave was more mature than the PT Freeport Indonesia (Deep Ore Zone) DOZ cave. This paper describes how the recorded seismic data at Palabora was been used to monitor the stresses around the cave and the stress distribution associated with successive phases of the caving process. Each of the caving phases was associated with a different seismic hazard level. The authors used the Palabora mining experience and seismic history to forecast the future seismic response of the rock mass at DOZ at more advanced cave development stages. Since the seismic histories of the PMC and DOZ mine footprints show a lot of similarities then based on this experience from PMC, the DOZ Mine can expect to experience more of the high energy release seismic events in the near future. At the end of this chapter, I added a section titled “Eleven years later” in which I tested if the prediction done in 2006 turned out to be correct or false.

Chapter 3 is titled “Seismic signature of the caving process” In this chapter, I have analysed seismicity recorded at Palabora Mining Company, at PT Freeport Indonesia DOZ Mine, at Diablo Regimento Sector of El Teniente Mine and at Northparkes Lift 2 Mine. The aim of this examination was to establish common to all mines seismic response to the caving process. I then used seismicity recorded at PMC to benchmark the milestones of the caving process. It is my opinion that seismicity recorded at PMC due to the quantity and quality as well as its time duration is appropriate for this task. This database includes seismicity that was recorded when the caving process was initiated, when the crown pillar failed and during the initial break through. In addition, this seismicity includes data relating to the east break through, which took place nearly 4 years after the initial one. What is more important is the fact that these caving milestones were evidenced by other independent of the seismicity. The position of the cave back was monitored for some time by TDR’s and open holes. The position of the aseismic zone around the cave was confirmed by several holes drilled from the bottom of the open pit. The failure of the 200 m thick crown pillar was first recognized and documented only by interpretation of the seismic data. This was subsequently verified when storm water nearly flooded a section of the mine. The fact that there was a break through was later confirmed by survey measurements based on areal photographs. I have, therefore, a lot of confidence in the timing of these caving milestones. Another important matter is the fact that the PMC seismic database is supplemented by complete information about the various production rates. This information is accurate as it was collected right from the start of seismic recording on a day to day basis (Glazer 2016). The seismicity parameters that I made use of were 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 the mass mining is three-dimensional, I have used the volume of the seismically active area. The seismically active area is derived from the seismically active volume and its height. The height additionally allows for monitoring the trends of the minimum (shallow) and maximum (deep) seismicity elevations. These values are not specifically 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. I also made use of the 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 convenience as it is part of the software code. These two functions proved to be of great importance for a simple reason: the seismic energy releases by nature are of extremely wide range and because of this are difficult but more often impossible to present visually as graphs. This then prohibits finding their trends. The parameters I selected to define the seismic signature of the caving process were:

1. Seismic activity rates
2. Percentages of seismicity locating above the mine extraction level
3. Energy release rates
4. Seismic deformation rates
5. Energy index time history
6. Average monthly seismicity elevations
7. Seismically active volume
8. Space distribution of seismicity
9. Monthly percentages of events with ratio Es/Ep > 10
10. Seismic activity and production rates

The main problem I encountered was associated with the seismic energy release rates. Each of the seismic catalogues analysed contained a wide range of magnitudes. For this reason, the energy release scale is also of significant size. This on its own makes it more complicated to analyse the seismic energy release trends as one large size seismic event can obscure the resulting trend. Additionally, I discovered that some of the analysed databases contain a number of seismic events with incorrect and extremely high energy releases. These events were not the largest ones and usually their size was below magnitude 1.0. This problem illustrates the importance of proper maintenance of a seismic database. Still it seems strange that these extremely high energy releases were not noticed at the time when they occurred, which is at the time when the recently recorded data was added to the database. This might indicate that the problem occurred while the seismic database was being recalculated with the new software version. I noticed this problem much earlier when I had recalculated 2 months data from the PMC database (Glazer 2016). Here, the extremely high energy releases were associated not with real events, but with noise that somehow passed through the filter. Only because of the limited amount of data I was able to eliminate these false events. The problem illustrated with the average energy release by various magnitude sizes has indicated that any analysis based on energy release might be unreliable in practice, with the presently available data sets and so it must be performed with caution.

Chapter 4 is titled "Comparison of seismicity induced while mining hydro-fractured and non-preconditioned rock mass volumes". In this chapter, I am comparing seismicity recorded in the Diablo Regimento hydro-fractured cave with the seismicity recorded in two non-preconditioned caves of PMC and DOZ. The Diablo Regimento Sector seismic data spans the period from 01 January 2005 up to on 31 July 2009. The PMC seismic data started on 01 January 2001 and ended on 30 June 2010. The DOZ seismic database started on 01 August 2004 and ended on 31 July 2009. These three seismic databases used for this comparison are consistent not only because they were recorded with the same type of seismic network but also because their data was processed with the same version of the processing software. There are sufficient amounts of recorded seismicity to allow for the comparison to be reliable. The sizes of recorded events are compatible because of their amounts of released energy and their seismic moment sizes. Additionally, the seismic source mechanisms as indicated by the amounts of seismicity with high Es/Ep ratios recorded in the three mines are also the same. The above similarities on their own should make the comparison of the recorded seismicity in the three different mines possible but still do not secure the reliability of the results. This is due to the diversity in some of the other parameters. These include the following data that was used in the analysis:

1. Monthly production rates
2. Cumulative production rates
3. Cave volumes

The PMC and DOZ databases include the main milestones of the caving process, while at the DOZ seismic monitoring was introduced after the caving process was initiated and after the east break through took place. Presented analysis resulted in the following conclusions:

A. The hydro-fracturing of the Diablo Regimento Sector had to result in substantial fracturing of the rock mass. Similar condition of the rock mass at PMC was achieved only after nearly 3 years of production. At PMC, the rock mass was preconditioned gradually by the caving process.
B. The high percentages of recorded seismicity with high Es/Ep ratios in the three mines indicate that the primary caving process mechanism is shear failure.

C. The reason that PMC has lower indices that normalize the seismic moment over the loaded tonnes or the cave volumes than the DR can be explained by the observed poor fragmentation. At PMC, the average oversize tonnage contribution from 2002 up to the end of 2009 was close to 30%. These amounts of oversize indicate that the seismic deformation taking place in the cave has not always resulted in good breaking of the rock mass.

The above conclusions would not be possible if they were only based on one input data set. The value of the above conclusions is based on the fact that they were derived from data that originates from three different input data sets.

Chapter 5 is titled “Summary and Conclusions” From the analysis presented, it is evident that the caving process can be monitored by the recorded seismicity. Seismicity is defined as a number of seismic events in a unit of time. From the practical point of view, the lowest time unit that can be used, but only in some specific cases, is a week (or 10 days) but in most cases the lowest realistic time unit will be 1 month. In the presented analyses, I have often used much longer time spans, for example, a couple of months or a number of years. Such long time spans were used for example with the energy index time history, cumulative graphs for seismic moment or seismic energy or the average seismicity elevation changes. From this, it is evident that the presented analysis does not take into account any single seismic event (even the largest ones) but at any time makes use of vast number of events. Again vast as such is not a specific term but in this case it means from hundreds up to hundreds of thousands of events. The lowest numbers of events will be used in cases for the seismicity rates. Usually with the seismicity rates the shortest time will be 1 month. Monthly seismicity rates can vary from a couple of events up to thousands of events. Still in all the presented analyses, I did not investigate any single monthly rate as such but their changes over longer time spans. The same applies to any other parameter, for example, the energy index or the average monthly seismicity elevation. I was studying their trends. Trend analysis is about collecting data and then trying to extract a pattern or trend. In statistics, trend analysis refers to techniques for extracting an underlying pattern of behaviour in a time series which would otherwise be partly or nearly completely hidden by noise. A simple description of these techniques is trend estimation. Uncovering a trend involves a number of techniques such as, filtering the input data using time and/or space and/or some of its dimensions. Then the filtered data is smoothed for example by applying a regression analysis. By definition, such techniques result in reliable and consistent results when applied to rather large data sets. All seismic catalogues analysed in this project contain from a couple of thousand events up to a couple of hundred thousand events. In total, I have analysed close to a million seismic events. These seismic data sets are not only consistent as separate input catalogues but as whole. All mines are not only using the same seismic system for recording the seismicity but the recorded data was then processed with the same software version. In this way, the input data is not only of sufficient quantity but also quality.

For the Mass Mine Technology Project 2 research I was on my own. I did not have a team. I did not have any one to whom I could delegate some part of the research or administrative work. There was no one to discuss any matters with. Still this is not totally correct. I had some discussions while walking my two dogs. During a walk, I would present them a specific problem. They would then look at me with a clear expression on their faces: Are you serious that you have a problem with something so simple? They do understand seismology, as for years they have been sleeping under my desk while I work. They learn by sleeping which is the latest fashion in learning. For example learn new language in a couple of minutes or less. This is not a new method of learning as it was there when I was young. I did not fancy it then, as at that time I regarded sleeping as a waste of time. When I write that I have analysed something it means exactly that. I consider research to be subjective not objective. Research is done by individuals that have feelings, expectations and go through various emotions. This influences their research results. Yes there is a trend to write up research in a cool impersonal and so-called objective manner. Other descriptions that come into mind are: distant, formal, remote or reserved. All these terms describe something that is unfriendly. I always found research very interesting and enjoyable. It can also provide a lot of satisfaction not only when things are going right or falling into place. It was interesting to deal with details which often came to my attention while I was "doing things by hand". I know that today this is something to be ashamed of, as everyone knows that the modern way of doing things is on a computer. Yes I must admit that for example plotting contour lines by hand was for me very interesting. It allowed me for understanding the data I was dealing with. This is really important, as I already mentioned it a number of times. I do not believe that, for example, rotating a great amount of data that is expressed in a number of sizes, colours and shapes on a small size computer screen really allows understanding what it represents. In the past, I have seen people studying the rotating balls and expressing understanding. As they say anything is possible. If research is enjoyable then its presentation also must be enjoyable and done in such a way that it is easy to understand. Presenting research as being much more complex than it is in reality is not acceptable. My research resulted in developing simple tools which I used successfully in solving complex problems. On the other hand, if the tools are too complicated they distort the problem for which they were developed. Such a tool then becomes more important than the problem that it was supposed to have helped to solve.

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Chapter 2
Seismic Data Assessment

Abstract In this chapter, I presented seismic data that was made available for analysis and interpretation. This data originated from four mines: El Teniente Diablo Regimento Sector (DR Sector), Northparkes Mines Lift 2 (NPM), PT Freeport Indonesia DOZ Mine (DOZ) and Palabora Mining Company (PMC). I have compared small size events that were recorded at the different mines against each other. The presented very basic data analysis leads to two important conclusions:

Hydro-fracturing resulted in seismicity with lower seismic energy releases than in other mines.
One of the mines was using a different and faulty version of the seismic processing software.

These conclusions were only possible because the analysis involved seismic data recorded in several mines. With regard to quality control of some of the seismic databases, the facts indicate that the quality decreases when the processing task is given to external contractor who is operating outside of the mine. Most of the recorded small size seismic events are an indication of the cave propagation process. This seismicity is a natural process indicating that the cave is progressing. The space and time distribution of these seismic events along with the changes of their source parameter values over time should be associated directly with what is happening in the rock mass around the cave and the mining excavations. Unfortunately, this is not always true as in some cases these changes can also be attributed to the difference in software versions or to the reprocessing after a new version of the software was installed.

I have practical knowledge of seismicity induced in cave mines as between 2002 and 2013, I worked and consulted on several mines:

- I am familiar with seismic data recorded at PMC since 2002; this is due to the fact that from 2002, I worked for PMC first as a seismologist then as a seismic consultant.

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- During 2005, I started working as a seismic consultant for PT Freeport Indonesia and also during 2005, I did some work for Rio Tinto based on seismic data recorded at Northparkes Mines Lift 2.
- From the beginning of 2009, I have been involved in analysis of seismic data recorded at the Diablo Regimento Sector of the El Teniente Mine.

However, due to the confidentiality clause which is a part of each contract between the consultant and the mine, there was no sharing of seismic experience between the mines. In practice, each contract was limited to working with its own data and then making conclusions applicable to a given mine. Only the PMC has given me permission to share seismic knowledge with other mines. Each cave mine made use of recorded seismicity only in accordance with their experience to date.

2.1 Introduction

This chapter is a review of seismic data made available first for the project and then for the book. Data from the following six copper cave mines has been brought together:

- El Teniente Initial Esmeralda Sector
- El Teniente Esmeralda Sector
- El Teniente Diablo Regimento Sector (DR Sector)
- Northparkes Mines Lift 2 (NPM)
- PT Freeport Indonesia DOZ Mine (DOZ)
- Palabora Mining Company (PMC)

All acquired seismic data was recorded with the same seismic system, the ISS International seismic system. Most of the seismic data was then processed or reprocessed using the same software version (V9). Only data from Northparkes Mines Lift 2 starting from January 2008 was recorded and then processed with software version 10, this data accounts for 3% of the total data available. It will be interesting to test this data against the other ones and analyse the difference if there are any. For the purpose of this book, I will be using one type of magnitude for all of the seismicity that was recorded in several mines.

2.2 Magnitude Definition for the Book

Magnitude is the most widely used parameter for describing seismicity. Some regard it as a very inaccurate source parameter. During 1935, Richter (1935) defined an earthquake magnitude as the logarithm of maximum amplitude of a waveform (measured in micrometres) on the standard Wood–Anderson seismograph at a distance of 100 km. This definition was later modified into the following form:

$$M_L = \log_{10}(\mathrm{Amp}) + B\log_{10}(D) - C + E(D) \tag{2.1}$$

where

D—Distance from site in kilometres

Amp—Amplitude

B and C—Numerical constants

E—Correction depending on distance

Because these parameters vary between different regions, this magnitude is called the local magnitude M_L. The South African Council for Geosciences definition for the magnitude is as follows:

$$M_L = \log_{10}(\mathrm{Amp}) + 1.11\log_{10}(D) - 2.09 + 0.00189\,D \tag{2.2}$$

where

D—Distance in kilometres

Amp—Amplitude in nanometres

All modern digital mine seismic networks estimate the seismic source parameters (E radiated energy, M_o seismic moment) from the waveform spectra. Then those two seismic source parameters are used to define the magnitude.

In the ISS seismic system, there are three magnitudes:

- Energy magnitude (Gibowicz 1963) M_E:

$$M_E = 0.526\log_{10}E - 1.160 \tag{2.3}$$

- Moment magnitude (Hanks and Kanamori 1979) M_M:

$$M_M = 0.667\log_{10}M_o - 6.067 \tag{2.4}$$

- Local magnitude:

$$M_L = a\log_{10}E + b\cdot\log_{10}M_o + c \tag{2.5}$$

where

E—Radiated energy

M_o—Seismic moment

a,b,c—local parameters

Parameters a,b and c are not the same for different mines, for example, while working at the Vaal Reefs Gold Mine (Glazer 1998). I have defined the local magnitude as:

$$M_L = (M_E + M_M)/2 \tag{2.6}$$

Table 2.1 Summary of seismic databases

Mine	Seismic database		No. of events	Production file
	Starts	Ends		
El Teniente Esmeralda[a]	January 1997	August 2009	205,155	Complete
El Teniente DR Sector	January 2004	August 2009	26,257	Complete
Northparkes Mines Lift 2	September 2002	April 2008	129,893	Complete[b]
PMC	January 2000	August 2009	128,018	Complete
PT Freeport DOZ Mine	August 2004	July 2009	478,356	Complete

[a] In this table, data for Esmeralda also contains information about Initial Esmeralda

[b] Northlake's Lift 2 production file has information about daily production rates up to the end of January 2006, from then only monthly rates are available

And the Vaal Reef parameters at the time were:

$a = 0.263$ $b = 0.333$ $c = -3.613$

In South Africa during recent years there was a tendency to calibrate the mine magnitudes in such way that they would correspond to the magnitude used by the Council of Geosciences (at least for the larger magnitude range). Current default values in ISS system are as follows:

$a = 0.272$ $b = 0.392$ $c = -4.630$

El Teniente uses the Hanks Kanamori definition for the magnitude. In order to compare directly the seismicity recorded in these four mines for this report I will use only one magnitude definition. As the default magnitude of the ISS system is more suitable for the South African mines then I will make use of the magnitude as defined by the El Teniente Mine:

$$M_L = 0.667 \log_{10} M_o - 6.01 \tag{2.7}$$

2.3 Summary of the Seismic Databases

The El Teniente Esmeralda Sector seismic database contains over 200,000 seismic events recorded over 12 years. The El Teniente Diablo Regimento Sector consists of over 26,000 events recorded over 6 years. The Northparkes Mines Lift 2 seismic database contains nearly 130,000 seismic events also recorded over 6 years. The Palabora Mining Company seismic database contains nearly 128,000 events that were recorded over a 10-year period. The PT Freeport Indonesia seismic database contains nearly 478,000 events that were recorded over 5 years. In total, these five seismic databases contain over 950,000 seismic events. Table 2.1 lists information regarding the databases:

Table 2.2 Seismic catalogue completeness

Mine	Catalogue complete from magnitude
Esmeralda Sector	−0.5
DR Sector	−0.3
Northparkes Lift 2	−1.2
PMC	−0.1
PT Freeport DOZ Mine	−0.3

Table 2.3 Recorded extreme values

Parameter	Esmeralda	DR Sector	Northparkes Lift 2	PMC	PT Freeport DOZ Mine
Minimum magnitude	−2.1	−1.5	−2.5	−2.1	−2.2
Maximum magnitude	2.7	2.0	2.3	1.9	2.8
Minimum energy (log E)	−2.0	−1.0	−2.2	−1.0	−3.0
Maximum energy (log E)	8.6	6.8	8.5	7.0	9.5
Minimum moment (log Mo)	6.0	6.8	5.5	6.0	6.0
Maximum moment (log Mo)	13.1	12.0	12.5	11.5	13.2

- Start and end date of the seismic database
- Number of seismic events
- Availability of the production rates

Table 2.2 indicates the completeness of each seismic catalogue. The Northparkes Mines Lift 2 seismic catalogue is complete from magnitude −1.2; the Esmeralda catalogue is complete from magnitude −0.5. Both Diablo Regimento Sector and PT Freeport DOZ seismic catalogues are complete from magnitude −0.3. The PMC seismic catalogue is complete from magnitude −0.1. The listed completeness of the seismic catalogues implies that the most sensitive seismic network was at Northlake's while the seismic system with the lowest sensitivity was that operating at PMC.

According to data listed in Table 2.3, the largest magnitude size event recorded in these five mines was an event of magnitude 2.8. This event was recorded in the DOZ Mine of PT Freeport Indonesia. The largest events recorded in descending order at other mine are:

- Event of magnitude 2.7 in El Teniente Esmeralda Sector
- Event of magnitude 2.3 in Northparkes Mines Lift 2
- Event of magnitude 2.0 in El Teniente DR Sector

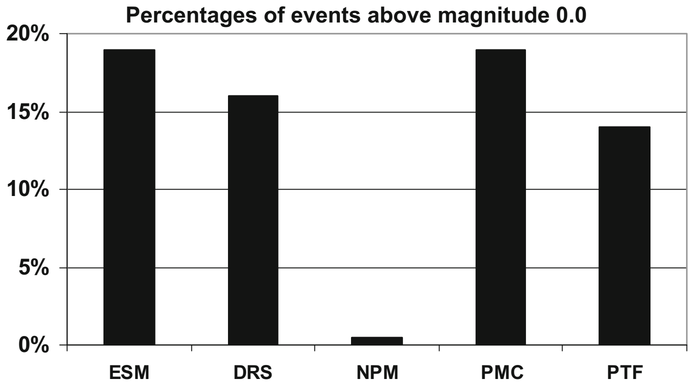


Fig. 2.1 Percentages of events above magnitude 0.0

- Event of magnitude 1.9 in Palabora Mining Company

Examination of each mine maximum energy release indicates that these maxima do not follow the order of the maximum magnitudes. The maximum energy release recorded (according to the available data) in the descending order are:

- At PT Freeport Indonesia DOZ Mine Log E = 9.5
- At El Teniente Esmeralda Sector Log E = 8.6
- At NPM Lift 2 Log E = 8.5
- At PMC Log E = 7.0
- AT El Teniente DR Sector Log E = 6.8

The maximum values for recorded seismic deformation follow the maximum magnitude pattern which is not surprising, as the magnitude is based on the seismic moment:

- At PT Freeport Indonesia DOZ Mine Log Mo = 13.2
- At El Teniente Esmeralda Sector Log Mo = 13.1
- At NPM Lift 2 Log Mo = 12.5
- AT El Teniente DR Sector Log Mo = 12.0
- At PMC Log Mo = 11.5

Figure 2.1 illustrates the percentages of recorded events above magnitude 0.0. In each case the total number of events for each catalogue is equal to 100%. The highest percentages of events above magnitude 0.0 (19%) were recorded at El Teniente Esmeralda and PMC. The percentage at El Teniente Diablo Regimento is at 16% while at PT Freeport Indonesia DOZ Mine this percentage is 14%. The lowest percentage of events above magnitude 0.0 was recorded at Northparkes Mines Lift 2. Here this percentage was at 0.5%.

Figure 2.2 illustrates the percentage distribution of the largest size events. Here, the number of recorded events of magnitude 0.0 and above was equal to 100%. It is interesting to note that the highest percentages of events above magnitudes 0.5, 1.0

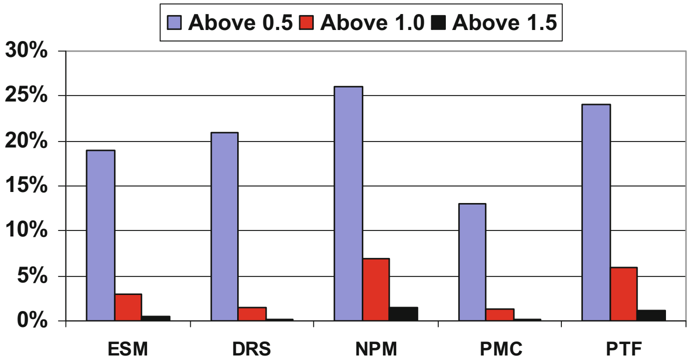


Fig. 2.2 Percentages of events above magnitude 0.5, 1.0 and 1.5

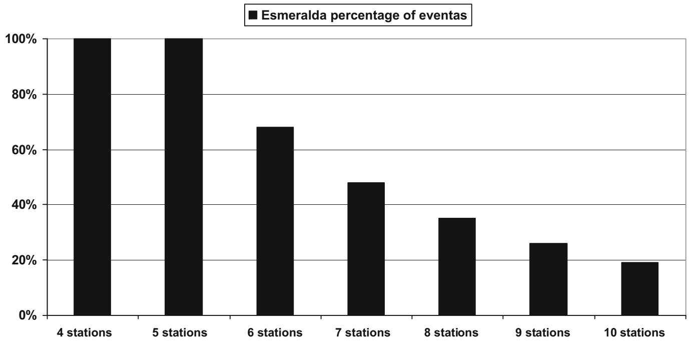


Fig. 2.3 ESM—percentages of events processed with number of stations

and 1.5 were recorded at Northparkes Mines Lift 2. These percentages are 26, 7 and 1.5%, respectively. The second mine with high percentages of these large size events is PT Freeport Indonesia DOZ Mine. The sequences of mines with percentages of events above 1.0 and 1.5 are the same:

- Northparkes Mines Lift 2 (7.0 and 1.5%)
- PT Freeport Indonesia DOZ Mine (6.0 and 1.1%)
- El Teniente Esmeralda Sector (3.0 and 0.5%)
- El Teniente DR Sector (1.5 and 0.2%)
- PMC (1.4 and 0.1%)

The next five figures illustrate the percentages of events processed with four and more, five and more, six and more, seven and more, eight and more, nine and more, ten and more stations at each mine (100% is the number of events recorded with minimum four stations):

Figure 2.3 presents this information for El Teniente Esmeralda Sector.
Figure 2.4 presents this information for El Teniente Diablo Regimento Sector.
Figure 2.5 presents this information for Northparkes Mines Lift 2.
Figure 2.6 presents this information for PMC.

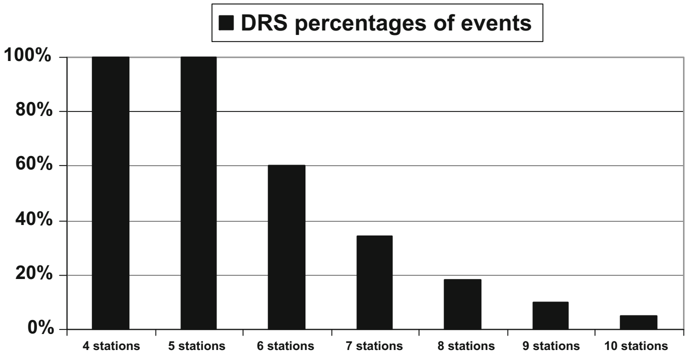


Fig. 2.4 DRS—percentages of events processed with number of stations

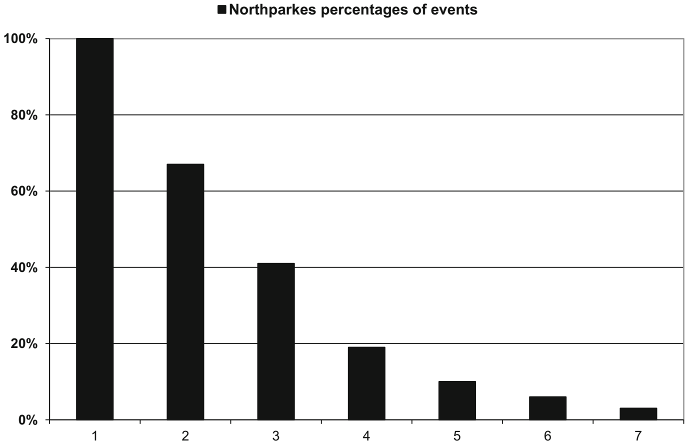


Fig. 2.5 NPM—percentages of events processed with number of stations

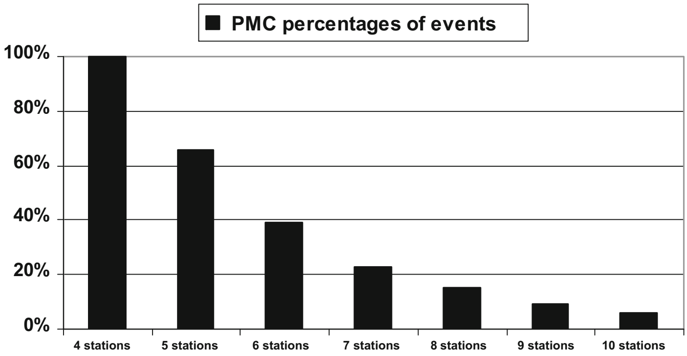


Fig. 2.6 PMC—percentages of events processed with number of stations

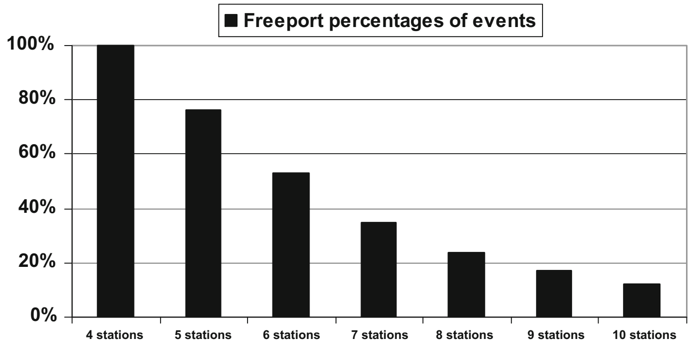


Fig. 2.7 PTF—percentages of events processed with number of stations

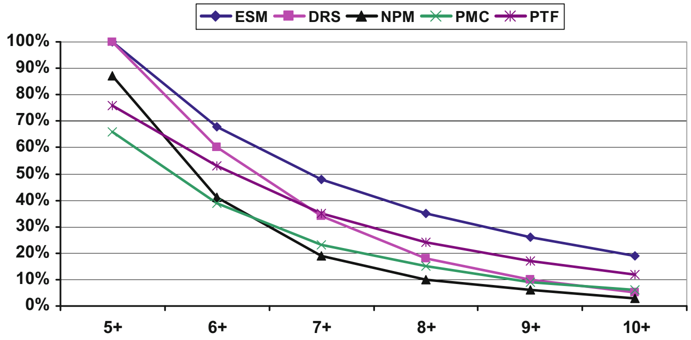


Fig. 2.8 Collective information about data processing

Figure 2.7 presents this information for PT Freeport Indonesia DOZ Mine.

Only at El Teniente, there is 100% of recorded data which was processed with a minimum five stations. At all the other mines the standard was four stations. Figure 2.8 illustrates this processing information in a joint form. From this figure, it appears that the highest numbers of events recorded with a highest number of stations are at El Teniente Esmeralda Sector while the lower number of events recorded with a high number of stations was at Northparkes Mines Lift 2.

The next five figures illustrate the five different seismic databases using the monthly activity rates and the monthly production rates (Figs. 2.9, 2.10, 2.11, 2.12, 2.13).

2.4 Test of Seismic Database Quality

While data recording is the first then data processing is the second important factor in the data interpretation procedure. Seismic databases should be constantly tested for quality and integrity.

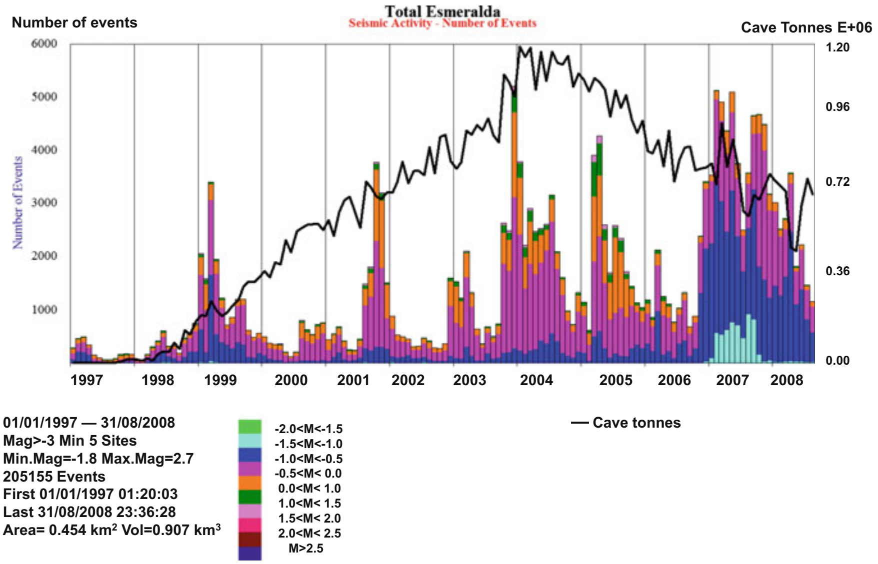


Fig. 2.9 Esmeralda sectors—monthly seismic activity rates

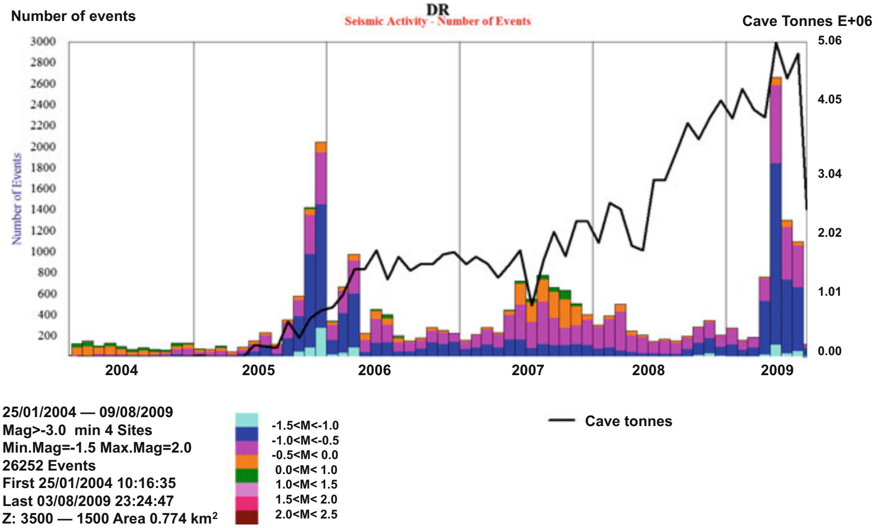


Fig. 2.10 DR Sector—monthly seismic activity rates

2.4.1 Example Based on DOZ Seismic Database

The number of recorded events as indicated in Fig. 2.14 has increased from about 10,000 monthly during 2007 to over 26,000 in December 2008 and again to over

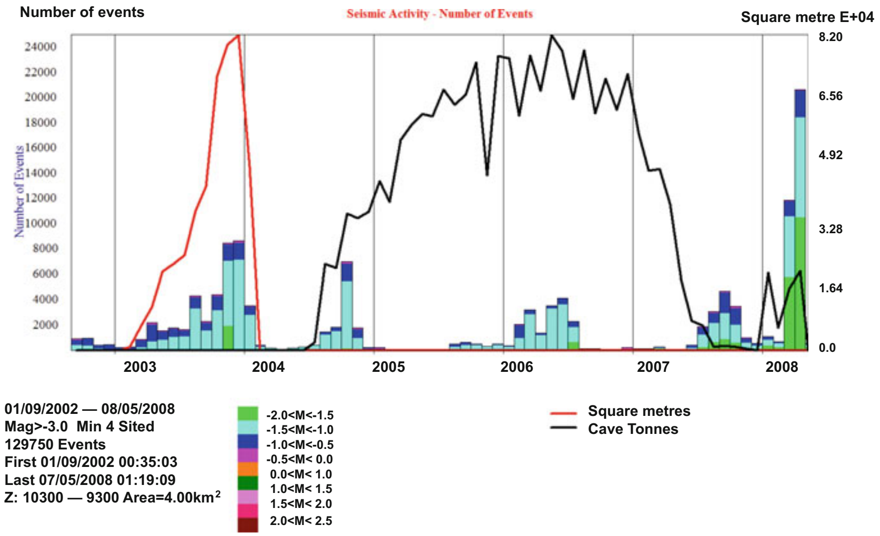


Fig. 2.11 NPM—monthly seismic activity rates

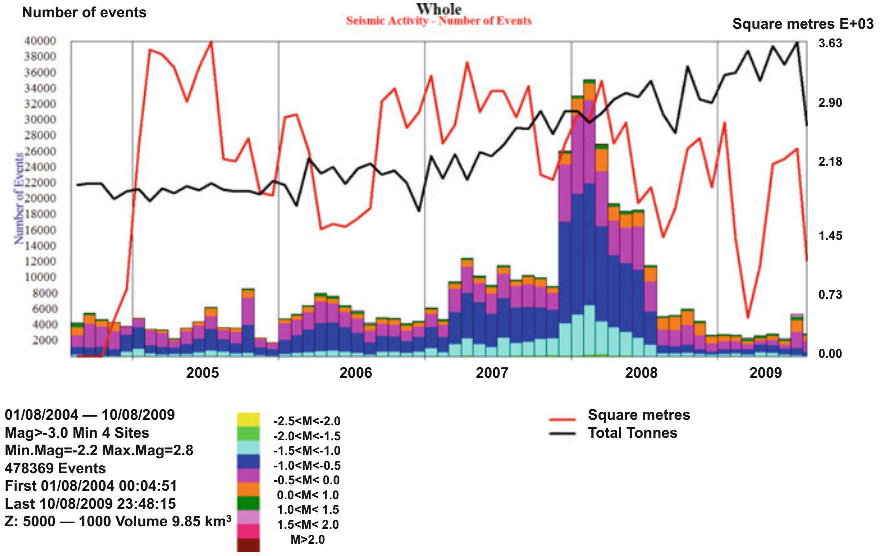


Fig. 2.12 PTF—monthly seismic activity rates

33,000 in January and February 2008. For this reason, I have decided to test if this quantity increase was not accompanied by a quality decrease. One of the quality parameters is the number of events recorded with more than four stations.

I analysed what the percentages are for events that were processed with:

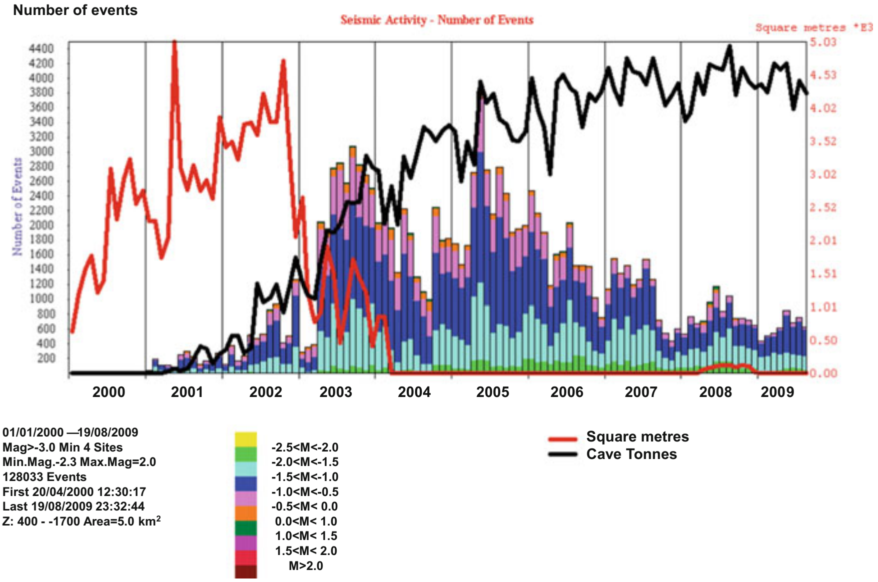


Fig. 2.13 PMC—monthly seismic activity rates

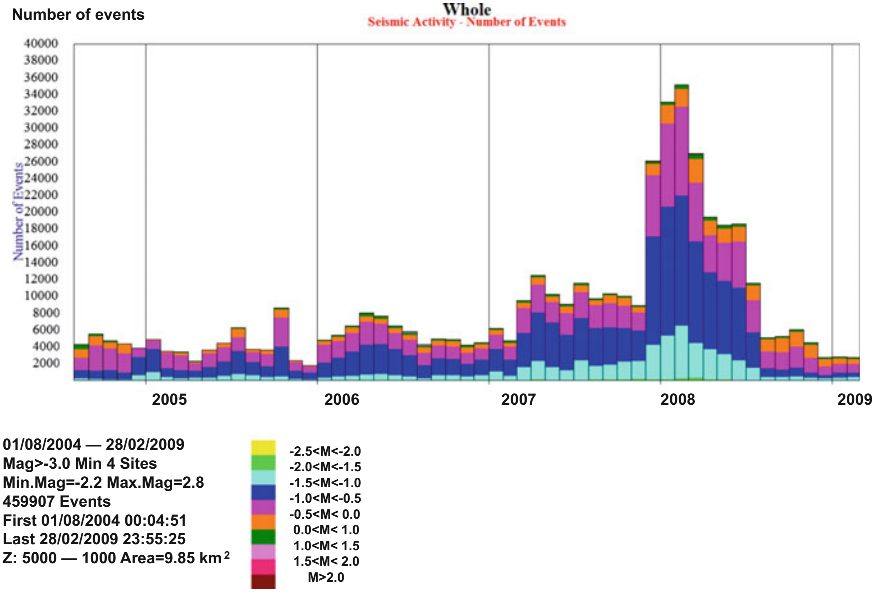


Fig. 2.14 PT Freeport Indonesia monthly seismic activity rates

- More than five stations
- More than with six stations

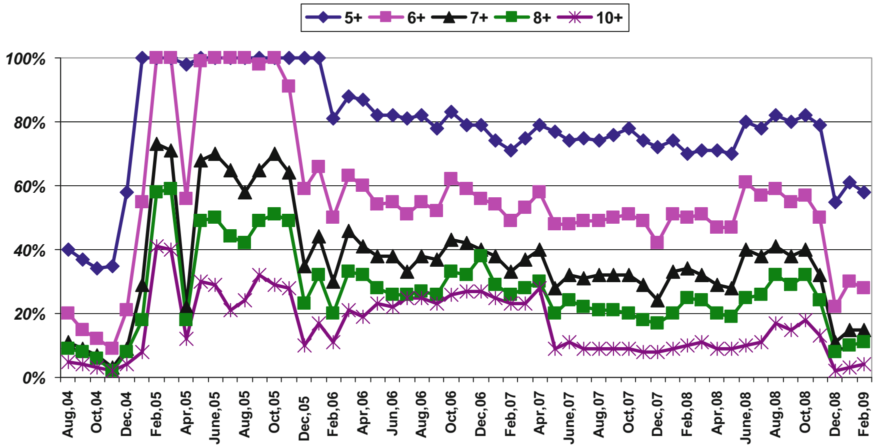


Fig. 2.15 Percentages of events processed with more than four stations

- More than with seven stations
- More than with eight stations
- More than with ten stations

This analysis was done for the time period: from August 2004 to the end of February 2009. Hundred percent is the number of events processed with a minimum of four stations. Figure 2.15 illustrates the results.

Data recorded during 2004 should be excluded from further analysis for two reasons. First because the network started to operate in August 2004 but without complete number of recording stations as these were added to the network subsequently. Second because that the first few months during which the network operated was also a learning period for the people who operated it. From the beginning, right up to the end of 2005, the number of events recorded with more than four stations was consistently very high:

- Nearly 100% of all seismic events were processed with a minimum of five and six stations
- 70% of all recorded events were processed with a minimum of seven stations
- 50% of all recorded events were processed with a minimum of eight stations
- 30% of all recorded events were processed with a minimum of ten stations

From the beginning of 2006, these percentages decreased initially by a large quantity and then by low percentages but in a continual manner until January 2008. By January 2008, the percentages of recorded events that were processed with more than four stations decreased to:

- 70 from 100% for events processed with more than five stations
- 50 from 100% for events processed with more than six stations
- 30 from 70% for events processed with more than seven stations

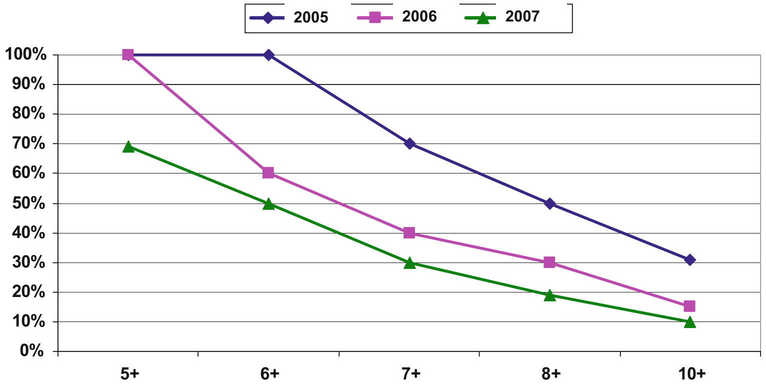


Fig. 2.16 Percentages of events processed with more than four stations

- 20 from 50% for events processed with more than eight stations
- 10 from 30% for events processed with more than ten stations

The percentages decreases range, for example, from 50% down to 20% is large decrease and as such it is difficult to understand change at least from the presented data. The other aspect illustrated in Fig. 2.15 is a slight but consistent percentage decrease in all event categories at the beginning of 2007. During 2006, on average, there were about 5600 events per month while during 2007 there were nearly 10,700 events per month. The decline in number of events recorded and then processed with more than four stations seems to be inversely proportional to the number of recorded events. The next interesting feature illustrated in Fig. 2.15 is the fact that all the graphs show exactly the same trend. According to the data presented in Fig. 2.15, there were, over time, fewer and fewer events recorded and then processed with a higher number of stations. It is of interest to note that during 2005, when events were processed at the mine, the percentages of events processed with a higher number of stations were at their peak. From 2006, the processing has been done by a contractor. During 2006, on average, there were about 5600 events per month while during 2007 there were nearly 10,700 events per month. The number of events recorded and then processed with more than four stations seems to be inversely proportional to the total number of recorded events. Figure 2.16 illustrates this fact. The vertical axis of Fig. 2.16 is in percentages (from 0 up to 100%). On the horizontal axis:

5 plus are the events recorded with more than 5 stations.
6 plus are the events recorded with more than six stations, and so on.

Each year is presented in different colour. The decrease in the number of events recorded with higher number of stations with time is evident. In any event, the observed trends indicate a general decrease in the quality of recorded events and as such at the time would require further investigation. This is not possible to perform at present but could have been done in the past when such observations could have been made routinely. Quality control over the processed events should be a standard

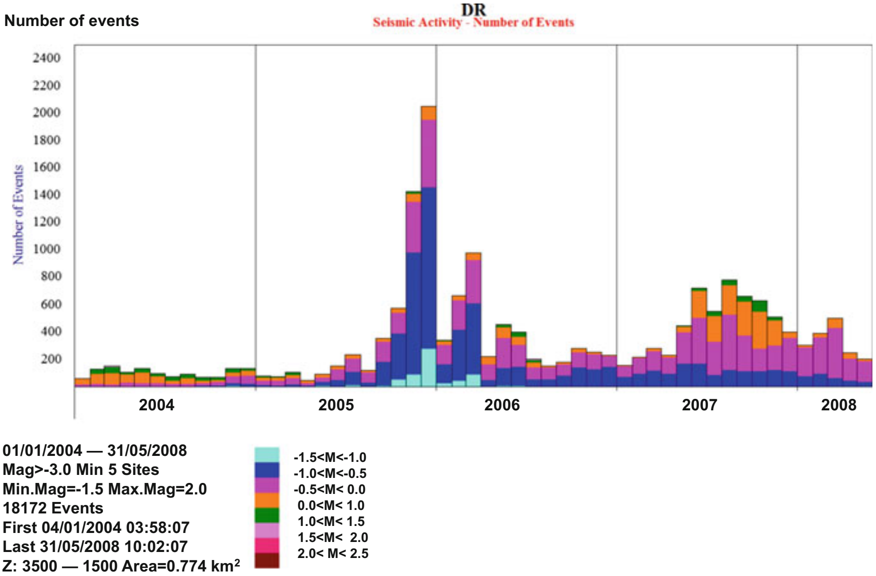


Fig. 2.17 Monthly seismic activity rates—DR Sector

routine practice regardless of the time it takes especially when the task of processing is given to an outside contractor. A high quality of the seismic database is very important for all present and future analysis.

2.4.2 *Example Based on DR Sector, El Teniente*

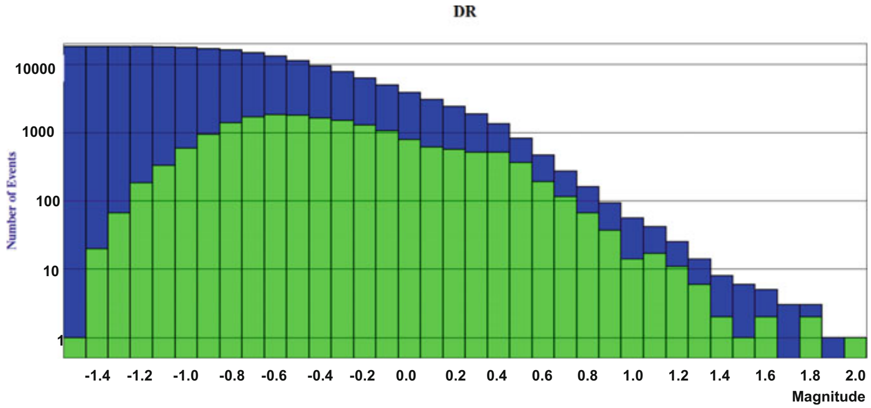
Figure 2.17 shows monthly seismic activity rates. This plot makes use of all events recorded with a minimum of five stations from the beginning of January 2004 up to the end of May 2008 at the DR Sector. In total, there are 18,165 events. The monthly rates vary from less than 100 to over 1000 per month. The highest monthly activity rates were recorded during November 2005 (1425 events) and December 2005 (2049 events). In this case, as a quality parameter, I will use the distribution of the number of events recorded with more than five stations. Table 2.4 shows the percentages of events from this catalogue processed with different numbers of stations and indicates that this data set was processed with a minimum of five stations.

Figure 2.18 illustrates the magnitude distribution. This catalogue is complete up to magnitude −0.3. The lowest magnitude event in this catalogue is an event of magnitude −1.5. There is only one event of this size. The largest event was of magnitude 2.0. There are 56 events with magnitudes 1.0 and above.

Figure 2.19 illustrates how over time the percentages (100% are the events recorded with minimum of five stations) of this catalogue, events recorded and then

Table 2.4 Percentages of events recorded with different number of stations

Events recorded with a minimum of stations	No. of events	Percentages
5	18,165	100
6	10,426	57
7	5664	31
8	2964	16
9	1506	8
10	807	4
11	403	2
12	212	1



01/01/2004 — 31/05/2008
Mag>-3.0 Min 5 Sites
Min. Mag =-1.5 Max.Mag=2.0
18172 Events
First 04/01/2004 02:58:07
Last 31/05/2008 10:02:07
Z: 3500 — 1500 Area=0.774 km^2

Fig. 2.18 Magnitude distribution

processed with a higher number of stations (six and more, eight and more, ten and more) have changed. It is interesting to note that the number of events recorded with a minimum of six stations during 2004 was close to 80%. Then from October 2004 until March 2006, this percentage decreased by nearly 20% to about 60%. The percentage changes for events processed with a higher number of stations do not follow this trend. This indicates that this decrease in the percentage of events recorded with a minimum of six stations is not associated with some seismic outstations being offline during this time period. Figure 2.20 shows that there is no relationship between the monthly activity rates (red) and the percentages of events recorded with a minimum of six stations (blue). It seems that this percentage change must be associated with seismicity of this specific time period taking place in some specific rock mass volume. It is probable that this volume had a different seismic coverage.

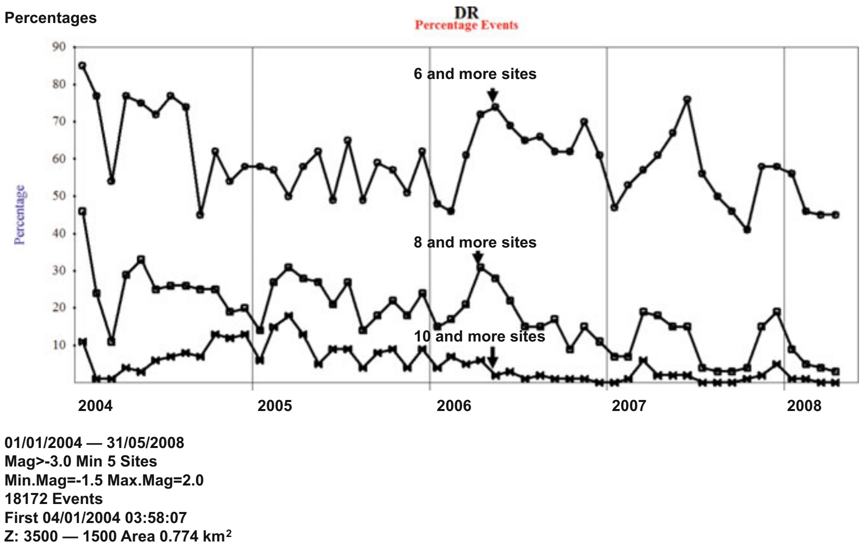


Fig. 2.19 Percentages of events processed with more than four stations

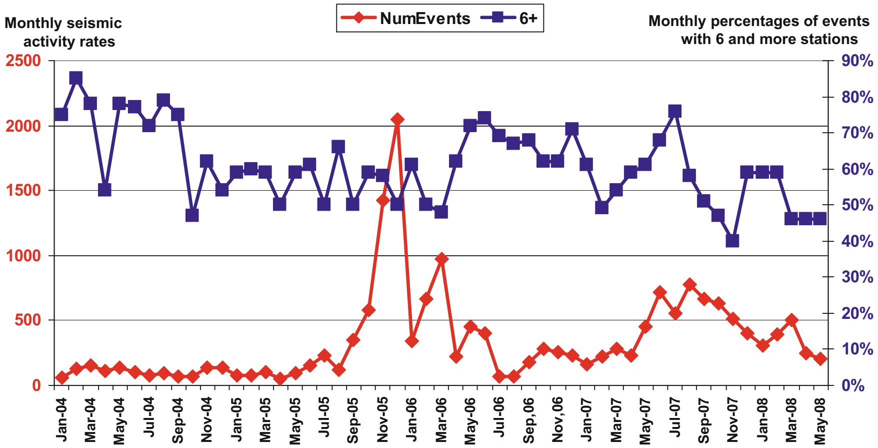


Fig. 2.20 Monthly activity rates and percentages of events with six stations

Figure 2.21 illustrates the monthly activity rates of low magnitude size events (in range from −1.5 up to −0.5). These activity rates from April 2006 to October 2008 were very low. For some months, the seismic system did not record a single event of this magnitude size. Due to the cave breaking through at the beginning of 2006, some of the seismic stations were lost. New ones were installed in October 2008. For the period indicated by the arrow, the seismic system lost its initial sensitivity. When interpreting seismic data recorded at the mine, it is important to be able to

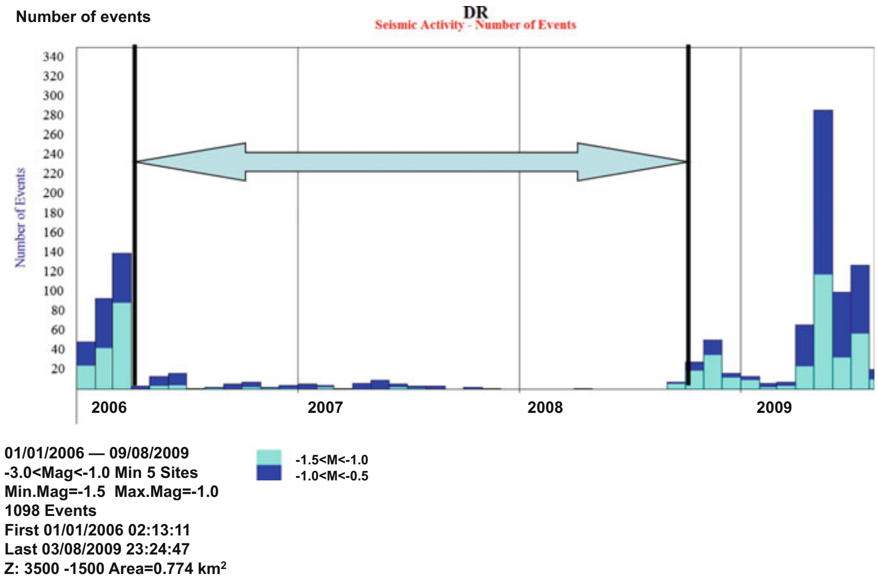


Fig. 2.21 DR Sector—decrease in seismic network sensitivity

assess the network performance in order to distinguish between changes due to the network performance and the rock mass response to the mining.

2.5 Radiated Seismic Energy

In this section, I have tested the average seismic energy release rates of low magnitude size seismicity (from -1.0 up to 0.0) recorded at PMC, PT Freeport Indonesia, Northparkes Mine, El Teniente Diablo Regimento Sector and El Teniente Esmeralda Sector. Data recorded at Diablo Regimento Sector is divided into two sub-catalogues: “Whole” which consists of all seismicity recorded in this Sector and “Hydro” that consists only of seismicity recorded while mining the hydro-fractured rock mass volume. These average seismic energy release rates are based on data recorded during different time spans depending on the mining. For the data sets to be not only consistent but also compatible with each other, the averages are based on monthly seismic energy release rates. This analysis indicated that the Northparkes Mine average seismic energy releases are extremely high and do not follow the observed trends for the other mines. Table 2.5 lists cumulative seismic energy releases for magnitude range from -1.0 up to 0.0 at six cave mines: PMC, PT Freeport Indonesia (Freeport), Northparkes Mine (NPM) and El Teniente. For El Teniente, this table lists seismic energy releases for the Esmeralda and Diablo Regimento (DR) Sectors. Data for Diablo Regimento is divided into two sections: DR whole and DR hydro. DR whole

Table 2.5 Cumulative energy per magnitude from −1.0 up to 0.0 [E+06 J]

Magnitude	Mine					
	PMC	Freeport	NPM	Esmeralda	DR whole	DR hydro
−1.0	0.153	1.66	0.99	0.049	0.008	0.018
−0.9	0.381	1.57	1.22	0.129	0.015	0.029
−0.8	0.842	2.26	2.73	0.289	0.026	0.056
−0.7	1.56	3.06	2.53	0.397	0.047	0.098
−0.6	2.30	5.28	4.47	0.687	0.045	0.102
−0.5	3.39	4.99	4.18	0.827	0.080	0.192
−0.4	4.73	7.40	3.22	1.56	0.060	0.164
−0.3	7.56	12.0	3.37	1.45	0.124	0.244
−0.2	7.41	17.1	9.16	1.79	0.123	0.341
−0.1	10.7	2.22	2.41	2.17	0.127	0.363
0.0	9.89	29.7	1.80	2.59	0.172	0.612

Table 2.6 Recording time limits

Mine	Start time	End time
PMC	01 January 2001	30 November 2009
PT Freeport Indonesia	01 August 2004	31 July 2009
Northparkes Mines	01 January 2003	31 December 2007
Esmeralda Sector	01 January 1998	31 July 2009
Diablo Regimento Sector	01 January 2005	31 July 2009

provides data for the whole Diablo Regimento Sector while DR hydro data is limited only to seismicity induced and recorded in the hydro-fractured volume. Data recorded in DR hydro forms part of the DR whole volume. Seismicity of the Diablo Regimento Sector is different from that recorded in the other mines as here prior to mining a large volume of the future cave volume was hydro-fractured in order to reduce seismic hazard (see Chap. 4).

Data presented in Table 2.5 as indicated in Table 2.6 was recorded in different time periods.

Data presented in Table 2.7 indicates that while the small size seismic events from moment magnitude −1.0 up to magnitude 0.0 account for nearly 80% of recorded seismicity their seismic energy release is very low at about 10% of the total seismic energy release. The Northparkes Mine data does not follow this pattern as there are less of these small size events in comparison to other mines. The next interesting observation based on data presented by this table is the fact that these small size events recorded during mining of the hydro-fractured volume of Diablo Regimento Sector emitted more energy from those recorded in the Esmeralda Sector.

Table 2.8 lists the average amounts of energy released by this small size seismicity. All these averages are based on monthly averages. These monthly averages were calculated for time periods as indicated in Table 2.6. Again as with data presented in

Table 2.7 Percentages of total energy released by small events

Mine	Percentages of events	Percentages of released energy
PMC	77	11.5
Freeport	73	0.7
NPM	27	2.1
Esmeralda	78	1.3
DR whole	83	7.7
DR hydro	83	8.5

Table 2.8 Average energy per magnitude from −1.0 up to 0.0 [J]

Magnitude	Mine					
	PMC	Freeport	Northparkes	Esmeralda	DR whole	DR hydro
−1.0	24.2	50.2	72.9	5.0	8.1	8.1
−0.9	36.8	40.3	120.0	7.7	9.7	9.9
−0.8	57.4	47.1	404.9	9.8	14.8	28.0
−0.7	96.2	73.9	394.9	13.6	28.3	22.1
−0.6	154.3	105.5	751.6	19.5	24.3	29.9
−0.5	228.0	132.6	2077.1	25.6	41.5	58.8
−0.4	309.0	212.9	8175.4	38.5	61.8	54.9
−0.3	386.6	369.9	4870.7	56.3	99.9	105.9
−0.2	595.8	691.7	16,059.0	89.7	149.9	148.9
−0.1	965.0	1136.2	9098.0	140.8	297.9	213.3
0.0	1456.5	874.1	7785.0	231.0	489.6	440.9

Table 2.7, the Northparkes Mine data differs from data recorded at the other mines as the average energy releases per magnitude size clearly deviate from the averages for the other mines. The Northparkes Mine average energy releases per magnitude rates are much higher than for all other mines' values. This is clearly illustrated in Fig. 2.22.

Figure 2.22 illustrates the fact that the average energy release for magnitude range −1.0 up to 0.0 at Northparkes Mine are in some cases over one thousand times higher than at the other mines. Figure 2.23 illustrates energy release rates excluding the Northparkes Mine data. Here, all the energy release rates are in very similar ranges. On average the small events of PT Freeport Indonesia and PMC released more energy than the same small size events recorded at El Teniente.

Before further analysis of the presented data, I will investigate the reason for the observed different seismic energy release pattern at the Northparkes Mine.

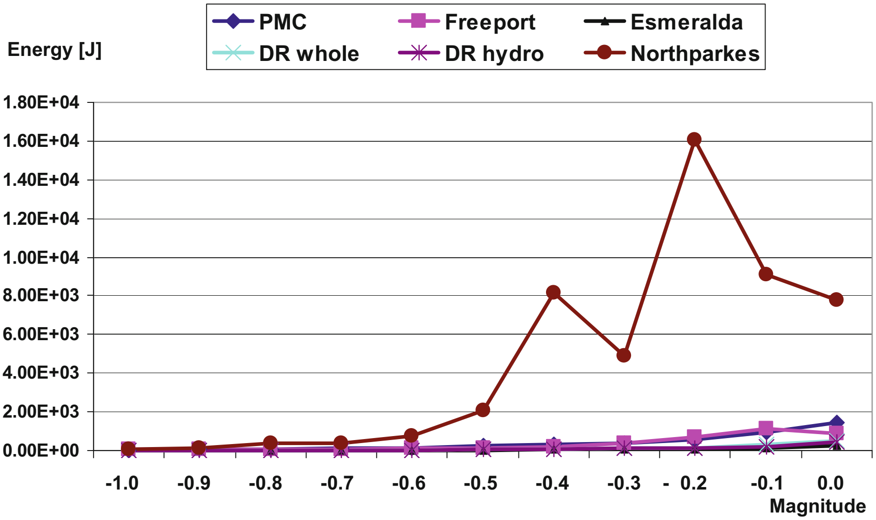


Fig. 2.22 Average monthly energy releases per magnitude size

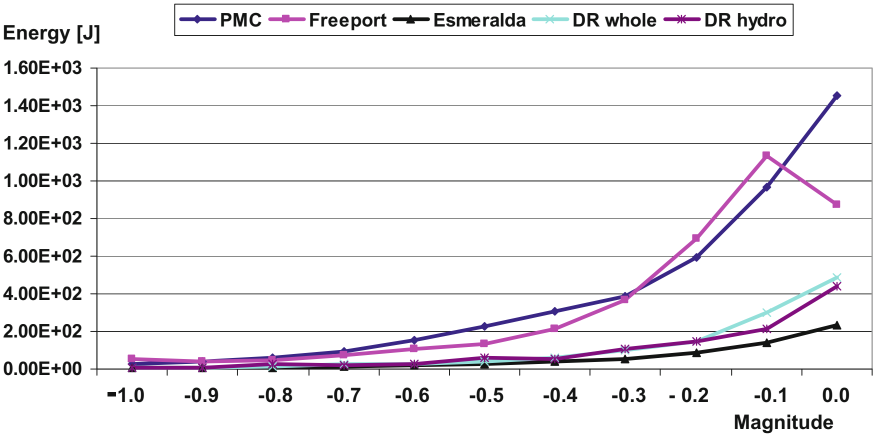


Fig. 2.23 Energy release per magnitude at El Teniente PMC and Freeport

2.5.1 Analysis of the Northparkes Mine Seismic Energy Release Pattern

Table 2.9 lists the total seismic energy released and the average monthly seismic energy release rates calculated for the number of months as listed in column 4 for all the mines. According to the data illustrated in this table, the seismicity recorded at Northparkes Mine released not only the largest amount of total seismic energy but also had the highest monthly average energy release rate.

Table 2.9 Average monthly seismic energy release rates

No	Mine	Σ E [J]	Months	Average per month	Notes
1	PMC	3.37E+08	119	2.83E+06	
2	PT Freeport	1.01E+09	60	1.68E+07	
3	Northparkes	1.62E+09	60	2.70E+07	high
4	Esmeralda	6.86E+08	141	4.86E+06	
5	DR whole	2.09E+07	55	0.38E+06	
6	DR hydro	7.01E+06	55	0.13E+06	

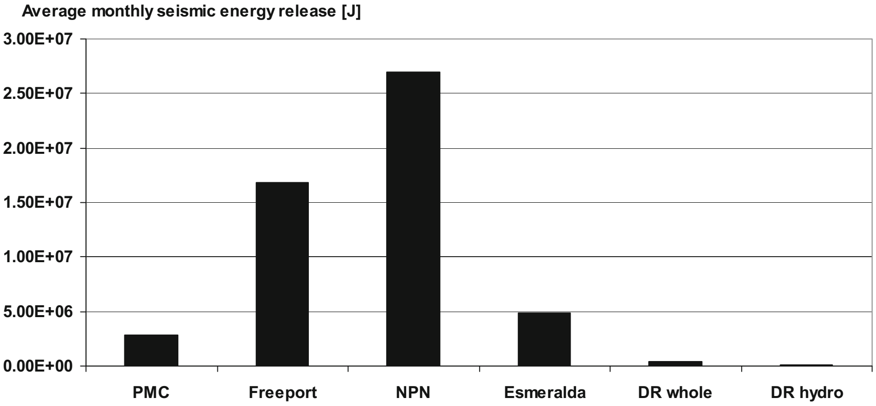


Fig. 2.24 Average monthly seismic energy release rates

According to data presented in Table 2.9 and Fig. 2.24, the average monthly seismic energy release at Northparkes Mine is 8.5 times larger than that at PMC, 1.6 times larger than at PT Freeport Indonesia, 5.5 larger than at Esmeralda Sector and more than 50 times larger than at the Diablo Regimento Sector. This appears to be anomalous and as such warrants further investigation.

I have two Northparkes Mine seismic databases. The first one is the original database (OLD) where the first seismic event was recorded on 1 September 2002 and the last one on the 31 January 2006. This database consists of 59,959 seismic events. During 2009, I received the second seismic database (NEW). This second database consists of 129,893 seismic events recorded between 1 September 2002 and 7 May 2008. In the first test, I will compare cumulative energy and moment for seismic events recorded with a minimum of four and five stations between 1 January 2003 and 31 January 2005 that are in the OLD and NEW databases. Tables 2.10 and 2.11 illustrate the results. The NEW seismic database has fewer events than the OLD one. This indicates that at some stage the OLD database was reprocessed and some of the previously accepted events were rejected. Most of the events in the NEW seismic database are in the magnitude range −1.5 up to −1.0 while in the OLD seismic database most of the events are in a lower magnitude range. In general,

Table 2.10 OLD and NEW seismic databases (four stations)

Magnitude range	No. of events		Cumulative energy [J]		Cumulative moment [Nm]	
	OLD	NEW	OLD	NEW	OLD	NEW
$-2.5<M<-2.0$	4216	34	2.58E+02	1.12E+01	2.96E+09	2.61E+07
$-2.0<M<-1.5$	43,819	2447	3.40E+04	3.62E+03	8.82E+10	5.90E+09
$-1.5<M<-1.0$	7863	39,128	1.91E+05	1.58E+06	8.42E+10	5.94E+11
$-1.0<M<-0.5$	1799	13,701	3.31E+05	1.16E+07	1.01E+11	7.12E+11
$-0.5<M<0.0$	270	1711	4.53E+06	2.14E+07	9.06E+10	5.52E+11
$0.0<M<0.5$	66	298	4.91E+06	9.37E+06	1.27E+11	5.16E+11
$0.5<M<1.0$	20	73	1.19E+09	1.07E+08	2.90E+11	8.00E+11
$1.0<M<1.5$	9	19	5.92E+06	1.06E+08	6.37E+11	1.29E+12
$1.5<M<2.0$	2	6	6.99E+06	2.07E+08	3.71E+11	2.20E+12
$M>2.0$		3		1.15E+09		5.10E+12
Total	58,066	57,420	1.22E+09	1.61E+09	1.79E+12	1.18E+13

there are larger magnitude events in the NEW seismic database. In the case of events recorded with a minimum of four stations (Table 2.10), the NEW total cumulated seismic energy is nearly 30% higher than the total energy released by the seismicity for the OLD database. The NEW seismic data cumulative seismic moment is over six times more than the OLD seismic data cumulative seismic moment. In case of events recorded with a minimum of five stations the OLD database cumulative seismic energy release is nearly three times higher than the NEW database cumulative seismic energy release. On the other hand the cumulative seismic moment of the NEW seismic database is nearly five times higher. These differences between seismicity recorded with a different number of accepted stations indicate that the problem with the Northparkes Mines seismic source parameters is complex. It now seems that the observed differences between Northparkes and the other mines' seismic source parameters are not only because of different processing software versions but also because of some issues with the recording stations.

In the second test, I will compare the average seismic energy release rates for the small magnitude size events. As previously these averages are based on monthly averages and were calculated for data recorded between the beginning of 2003 and the end of 2005. Figure 2.25 illustrates the results.

Based on both OLD and NEW databases, the average monthly seismic energy releases per magnitude ranges from −0.3 up to 0.0 are very large. For this reason, Fig. 2.26 illustrates only the average seismic energy releases for magnitude range −1.0 up to −0.3. This figure illustrates the fact that on average the seismic energy releases per magnitude size are higher in the case of the data belonging to the NEW seismic database.

Data illustrated in Fig. 2.27 provides a comparison of the average monthly seismic energy release rates per magnitude size for the NEW and OLD Northparkes Mine seismic events with data recorded at PMC, PT Freeport Indonesia and El Teniente.

Table 2.11 OLD and NEW seismic data bases (five stations)

Magnitude range	No. of events		Cumulative energy [J]		Cumulative moment [Nm]	
	OLD	NEW	OLD	NEW	OLD	NEW
−2.5<M<−2.0	4214	27	2.58E+02	2.91E+00	2.96E+09	2.08E+07
−2.0<M<−1.5	43,747	1917	3.39E+04	2.31E+03	8.79E+10	4.18E+09
−1.5<M<−1.0	6894	26,573	1.81E+05	1.21E+06	7.14E+10	4.19E+11
−1.0<M<−0.5	1274	10,174	2.83E+05	1.04E+07	7.03E+10	5.27E+11
−0.5<M<0.0	195	1345	4.49E+06	1.57E+07	6.92E+10	4.37E+11
0.0<M<0.5	51	239	1.18E+06	5.09E+06	9.93E+10	4.13E+11
0.5<M<1.0	11	47	1.19E+09	3.85E+07	1.64E+11	4.69E+11
1.0<M<1.5	5	9	5.37E+06	9.60E+07	4.11E+11	4.96E+11
1.5<M<2.0	1	5	6.63E+06	1.94E+08	1.71E+11	1.98E+12
M>2.0		1		1.84E+07		5.86E+11
Total	56,394	40,337	1.21E+09	3.79E+08	1.15E+12	5.63E+12

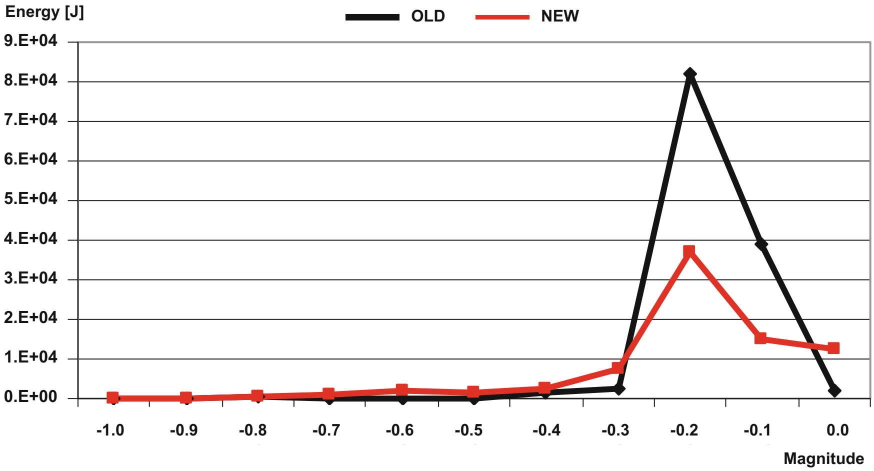


Fig. 2.25 OLD and NEW magnitude range −1.0 up to 0.0

Both the NEW and OLD Northparkes Mine seismic energy release rates are higher than the rates for the other mines.

In the third test, I will compare the relationship between seismic moment (moment magnitude) and the released seismic energy for events from the OLD and NEW databases. Figure 2.28 illustrates this relationship for events from OLD data recorded with a minimum of four stations. Figure 2.29 illustrates this relationship for NEW data that was recorded with a minimum of four stations. In both cases, there is an unusually wide range of released seismic energy. In case of OLD events, this wide energy range is for events of magnitude range between −2.0 and −1.5 (Fig. 2.28).

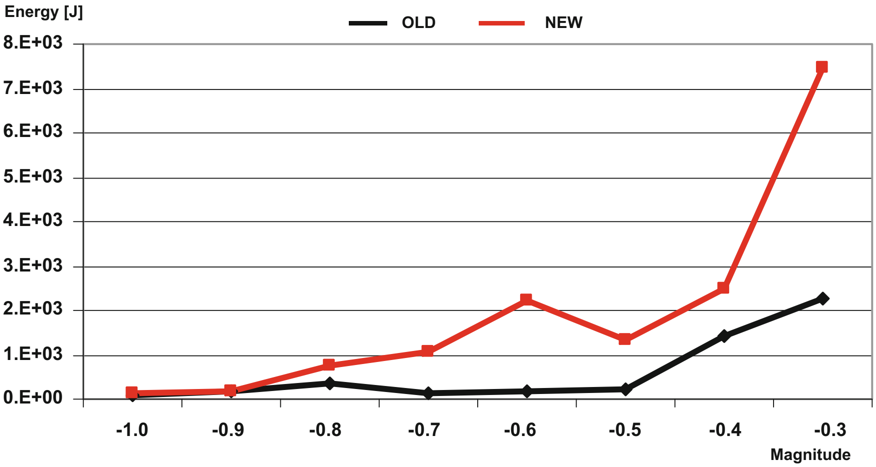


Fig. 2.26 OLD and NEW magnitude range −1.0 up to −0.3

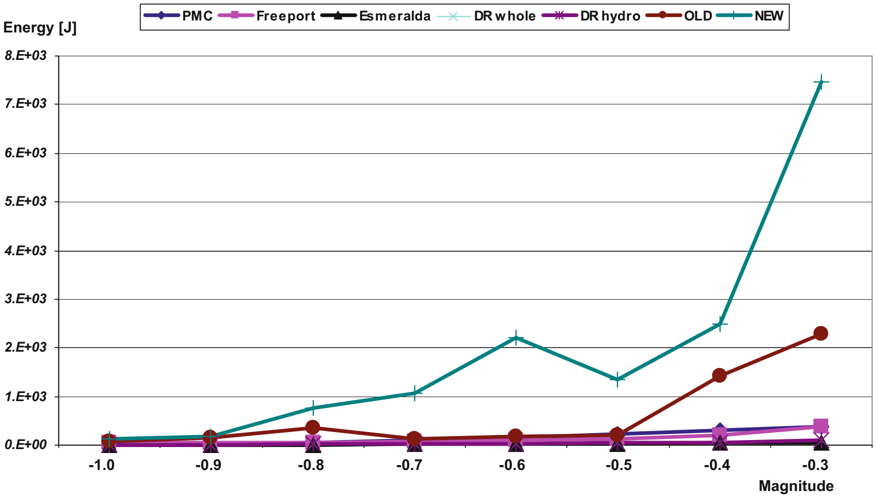


Fig. 2.27 Average monthly energy releases per magnitude size

In case of NEW events this wide energy range shifts closer to events of magnitude −1.0.

Data presented in Fig. 2.30 (events from OLD recorded with a minimum of five stations) and Fig. 2.10 (events from NEW recorded with a minimum of five stations) indicates that the unusual seismic energy release ranges are still present with data that should theoretically be of better quality (from the data recorded with a minimum of four stations) (Fig. 2.31).

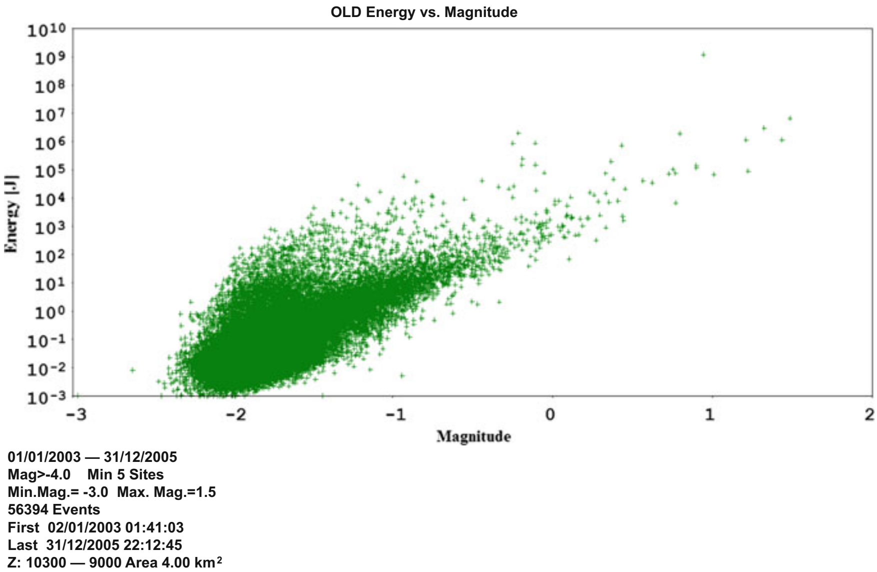


Fig. 2.28 OLD minimum four station events

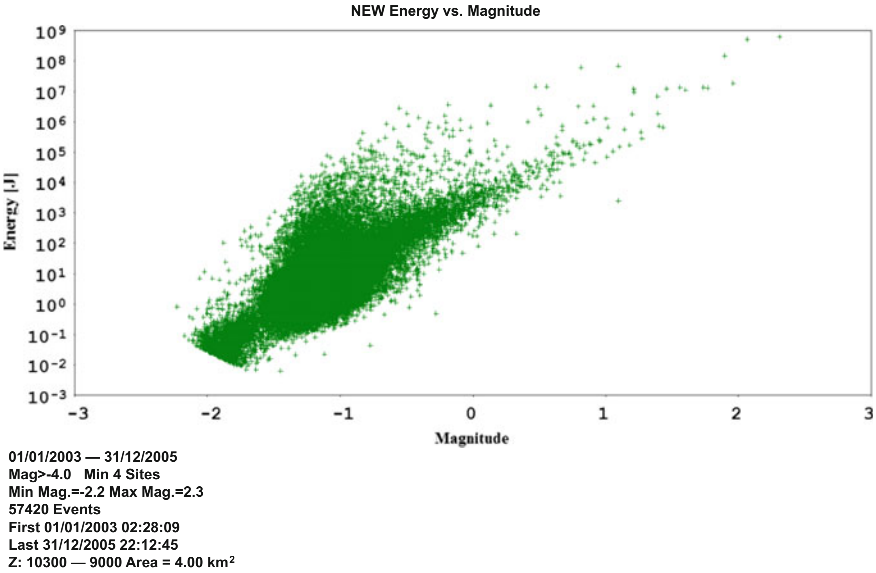
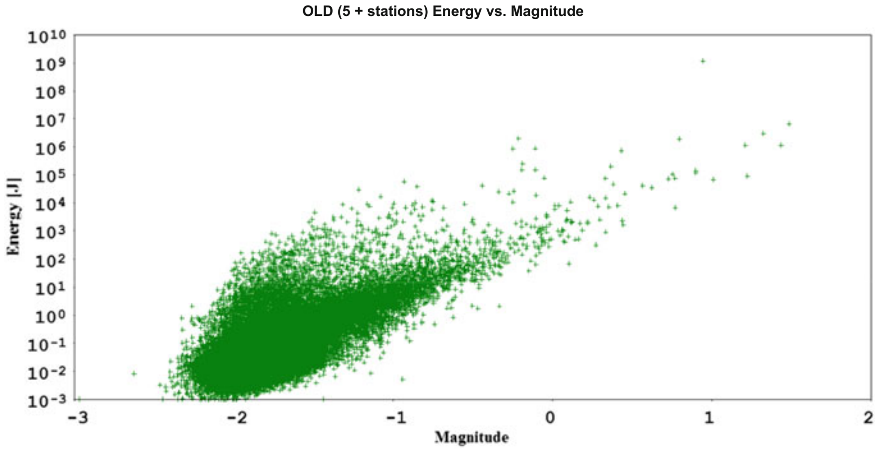


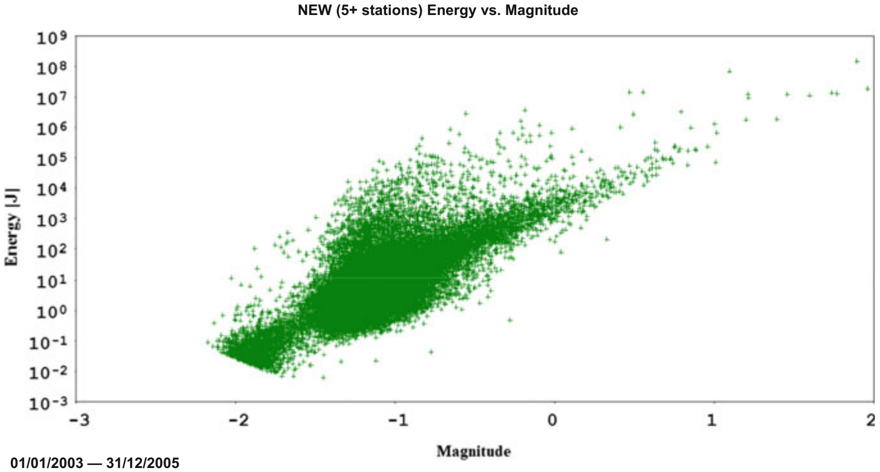
Fig. 2.29 NEW minimum four station events

As illustrated by the following four figures, data recorded at the other mines (Fig. 2.32 PT Freeport Indonesia, Fig. 2.33 PMC, Fig. 2.34 El Teniente Diablo



01/01/2003 — 31/12/2005
Mag> -4.0 Min 5 Sites
Min. Mag=-3.0 Max. Mag=1.5
First 02/01/2003 01:41:03
Last 31/12/2005 22:12:45
Z: 10300 — 9000 Area= 4.00 km^2

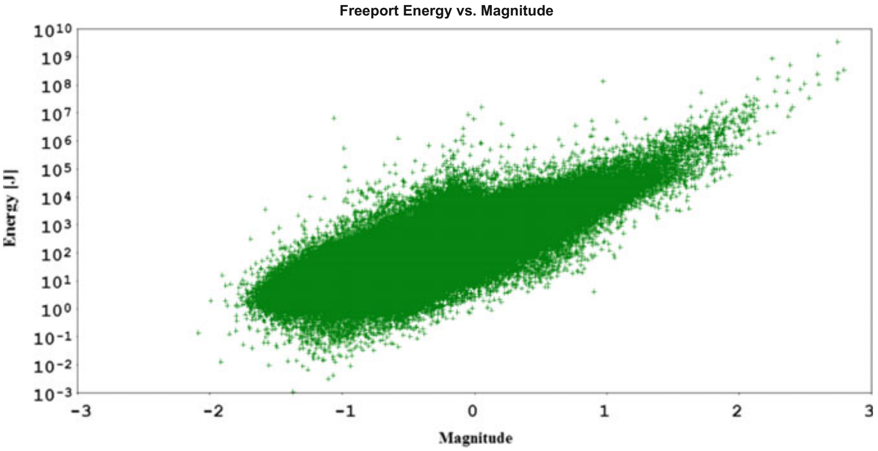
Fig. 2.30 OLD minimum five stations



01/01/2003 — 31/12/2005
Mag>-4.0 Min 5 Sites
Min.Mag=-2.2 Max.Mag=2.0
40337 Events
First 01/01/2003 02:28:09
Last 31/12/2005 22:12:45
Z: 10300 — 9000 Area=4.00 km^2

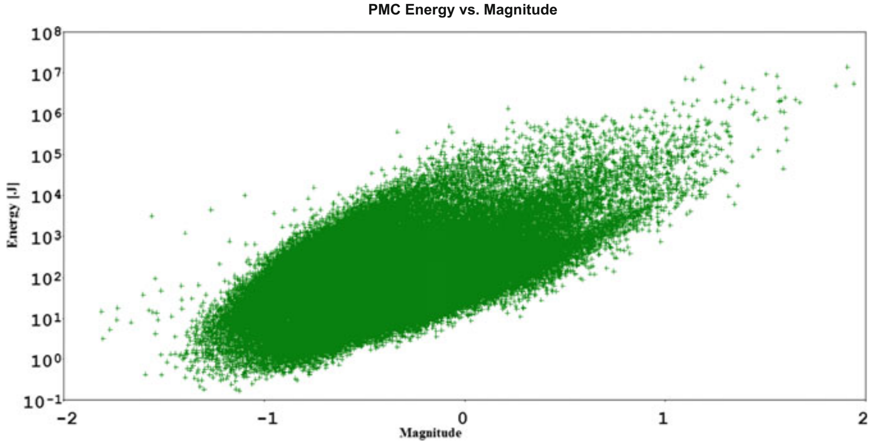
Fig. 2.31 NEW minimum five station events

Regimento Sector and Fig. 2.35 El Teniente Esmeralda Sector) do not exhibit such abnormal wide seismic energy release ranges, at least in the lower range of the magnitude (moment) range.


Freeport Energy vs. Magnitude

01/08/2004 — 31/07/2009
Mag>-3 Min. 5 Sites
Min.Mag=-2.1 Max.Mag=2.8
362359 Events
First 01/08/2004 00:03:35
Last 31/07/2009 23:51:35
Z: 5000 — 1000 Area=9.85 km^2

Fig. 2.32 PT Freeport Indonesia


PMC Energy vs. Magnitude

01/01/2001 — 30/11/2009
Mag>-3.0 Min 5 Sites
Min.Mag=-1.8 Max.Mag=1.9
85661 Events
First 02/02/2001 02:34:29
Last 30/11/2009 23:40:13
Z: 400 -1700 Area 5.00 km^2

Fig. 2.33 PMC

In the fourth test, I will investigate if there is any relationship between the events with wider and narrower ranges of emitted seismic energy and their vertical or time

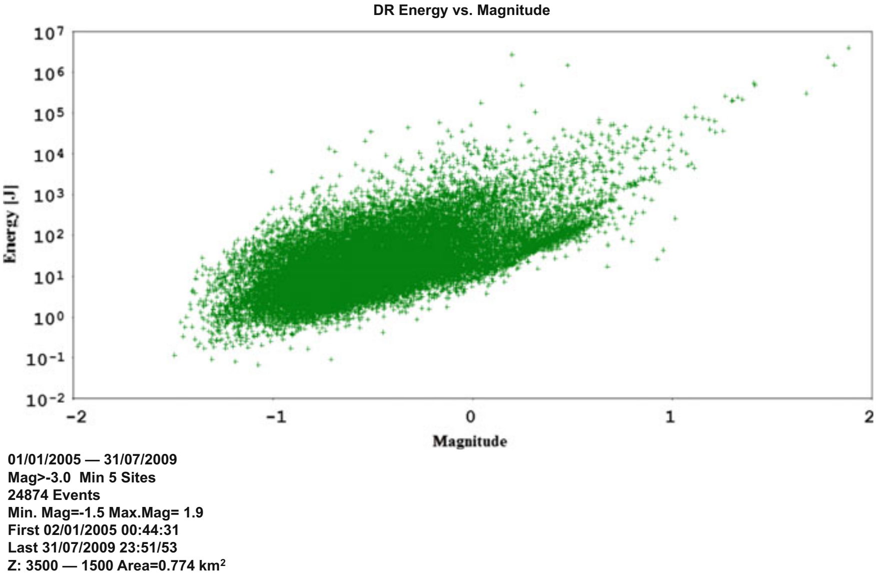


Fig. 2.34 El Teniente Diablo Regimento Sector

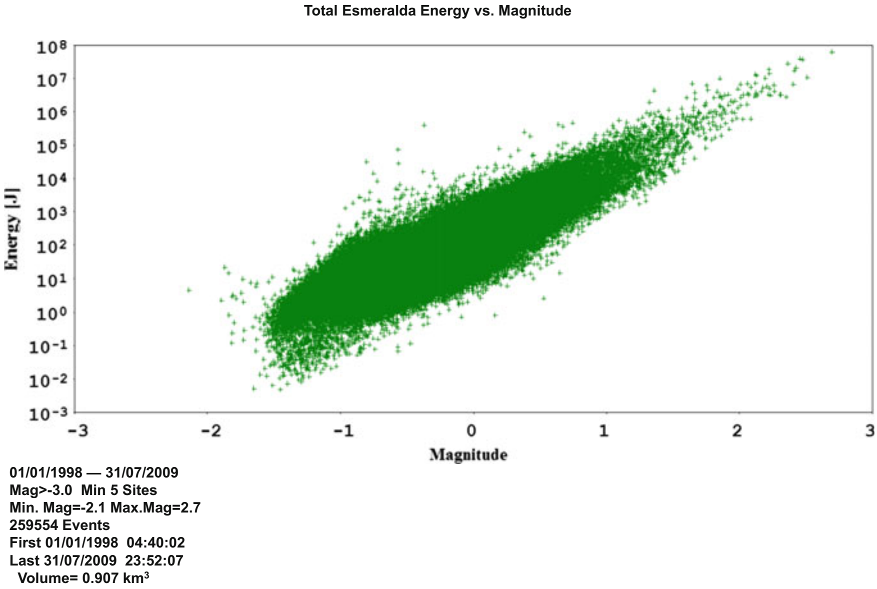


Fig. 2.35 El Teniente Esmeralda Sector

distributions. Figure 2.36 illustrates the fact that the Northparkes seismic stations were distributed on three elevations: all top stations are located around an elevation

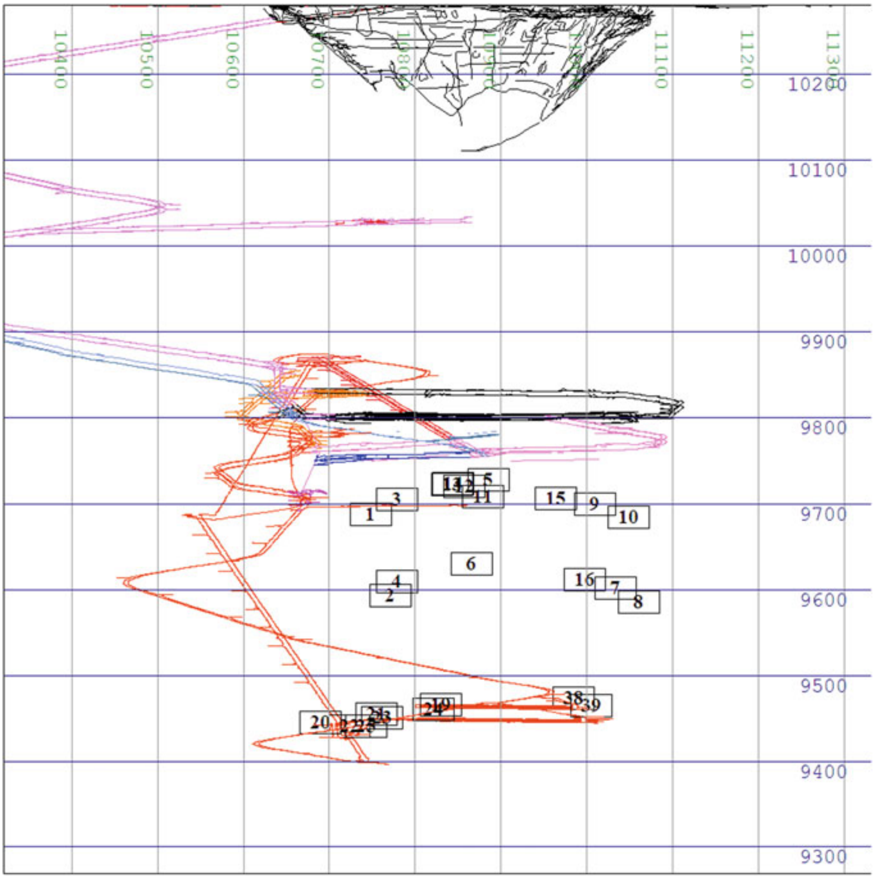
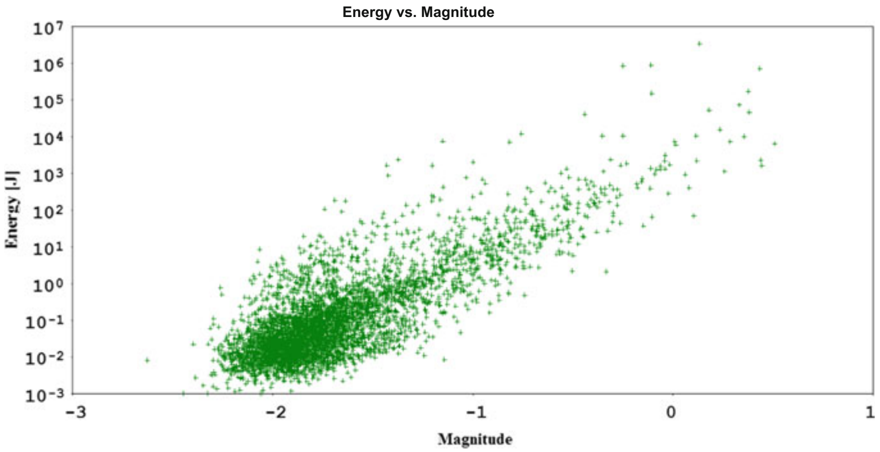


Fig. 2.36 NPM seismic network—vertical N–S section

of 9700, middle stations are located close to an elevation of 9600 and all the bottom stations are close to the elevation of 9450. These stations consisted of triaxial accelerometers and uniaxial geophones. The uniaxial geophones were located in the shallowest (five stations) and deepest (four stations) sets of stations (Hudyma et al. 2007). For the purpose of this test, I will use only the OLD database seismic events recorded with a minimum of four stations.

In order to investigate if the abnormally wide range of seismic energy observed was associated with a specific set of sensors that were located at one of the levels I will divide the database into three sub-catalogues:

1. Data recorded between elevations of 9650 and 10,300. Seismic events of this sub-catalogue are located close to the shallowest group of seismic sensors.
2. Data recorded between elevations of 9550 and 9650. Seismic events of this sub-catalogue are located close to the middle group of seismic sensors.



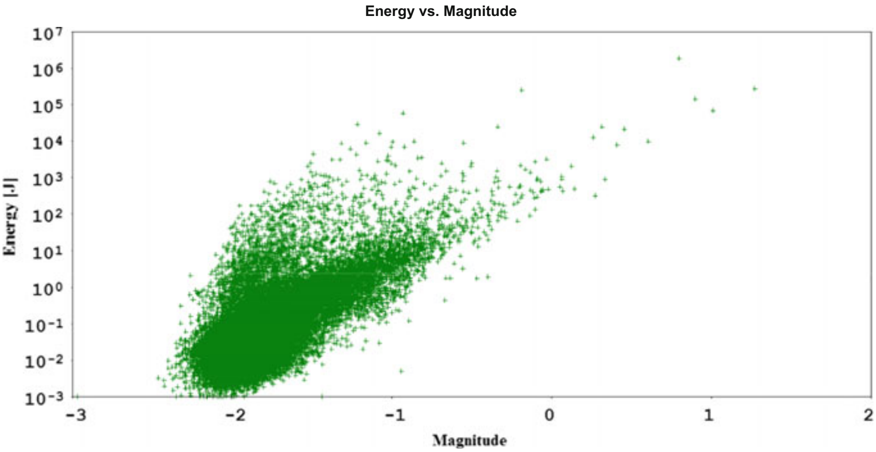
01/01/2003 — 31/12/2005
-4.0<Mag<0.5 Min 4 Sites
Min.Mag=-2.6 Max.Mag=0.5
4559 Events
First 02/01/2003 02:42:50
Last 31/12/2005 17:26:09
Z: 10300 — 9650 Area=4.00 km^2

Fig. 2.37 Elevation range 9650–10,300

3. Data recorded between elevations of 9400 and 9550. Seismic events of this sub-catalogue are located close to the deepest group of seismic sensors.

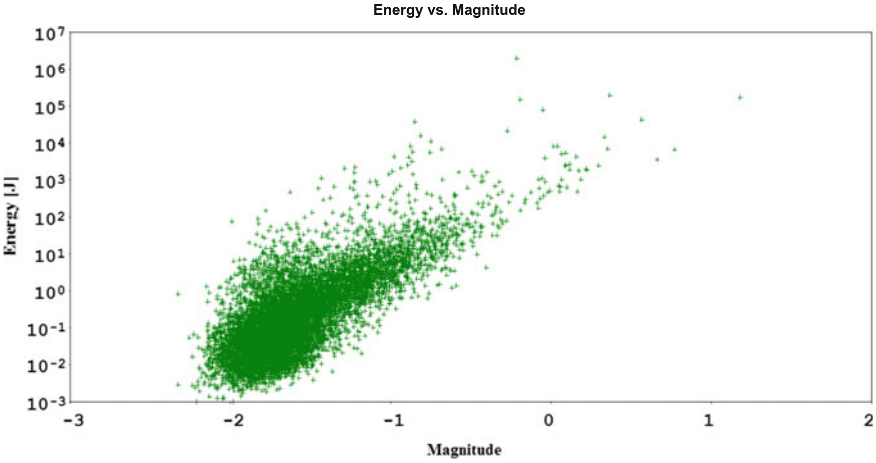
The idea is that smallest size events of each of these three sub-catalogues probably have triggered most of the closest stations and for this reason, their source parameter values will be mainly influenced by what these stations have recorded. The results are illustrated by the following three figures. Figure 2.37 presents the magnitude—seismic energy relationship for the shallowest sub-catalogue. Figure 2.38 presents the magnitude–seismic energy relationship for the middle sub-catalogue. Figure 2.39 presents the magnitude–seismic energy relationship for the deepest sub-catalogue. It seems that the abnormally wide range of seismic energy for moment magnitude close to -2.0 is in some way associated with all three sets of sensors. But for the middle section, this range seems to be more evident. Still, results of this test are not conclusive as the numbers of seismic events in each sub-catalogue are different. The shallowest sub-catalogue consists of about 4500 seismic events, the middle sub-catalogue consists of 42,000 events and the deepest catalogue consists of 11,000 events.

For the time distribution test, I have selected three sets of events. The first set was recorded during 2003 (from 1 April 2003 to 5 May 2003) the second set of data was recorded during 2004 (from 20 July 2004 to 13 September 2004) and data of the third set was recorded during 2005 (from 4 August 2005 to 30 December 2005). Each set consists of about 2500 events. Figure 2.40 illustrates the magnitude–energy relationship for the 2003 data, Fig. 2.41 illustrates the magnitude–energy relationship



01/01/2003 — 31/12/2005
Mag>-3.0 Min. 4 Sites
Min.Mag=-3.0 Max.Mag=1.3
42384 Events
First 02/01/2003 20:51:02
Last 31/12/2005 20:55:22
Z: 9650 — 9550 Area=4.00 km^2

Fig. 2.38 Elevation range 9550–9650



01/01/2003 — 31/12/2005
Mag>-3.0 Min 4 Sites
Min.Mag=-2.3 Max.Mag=1.2
11102 Events
First 02/01/2003 01:41:03
Last 31/12/2005 22:12:45
Z: 9550 — 9400 Area= 4.00 km^2

Fig. 2.39 Elevation range 9400–9550

for the 2004 data and Fig. 2.42 illustrates the magnitude–energy relationship for the 2005 data. Most of 2003 data is in magnitude range −2.0 up to −1.0, most of the

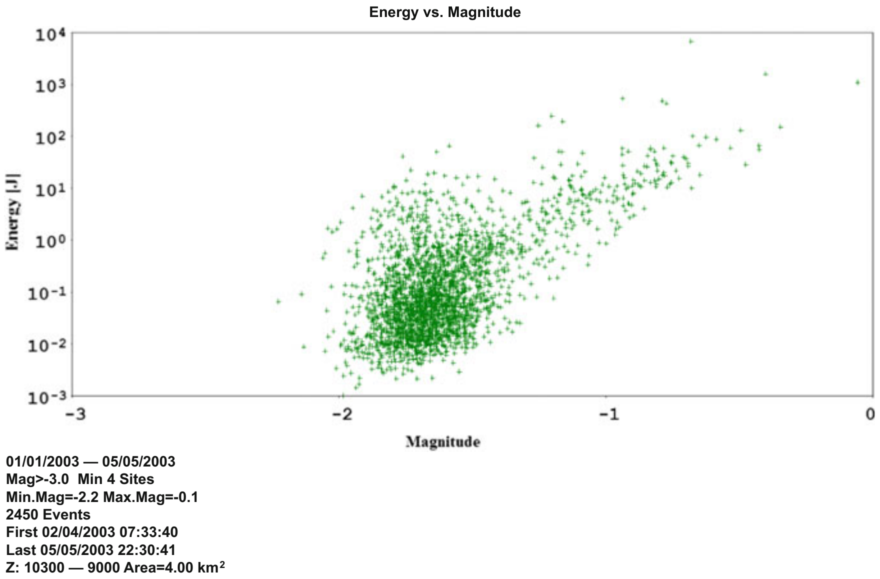
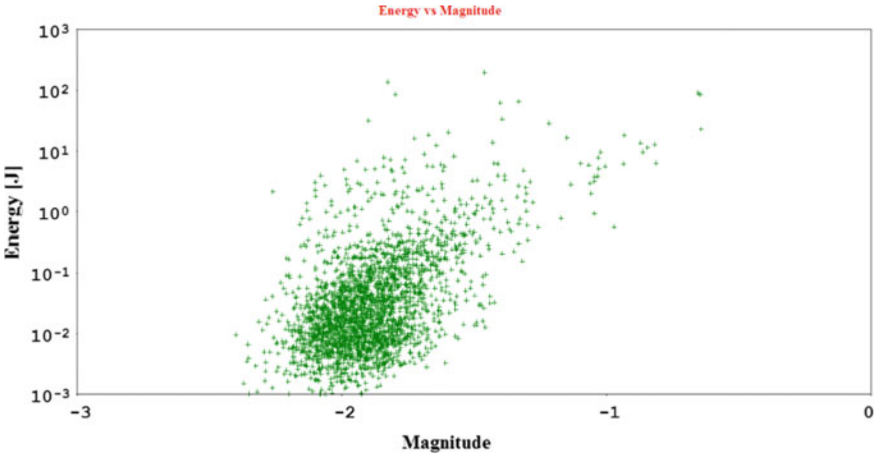


Fig. 2.40 Events recorded during 2003

2004 data is of magnitude close to −2.0, while most of the 2005 data is in magnitude range −2.0 up to −1.0 (as the 2003 data). It is interesting to note that the energy range for the 2003 data is from 10E − 03 J up to 10E + 01 J, while the range for the 2005 data is different and higher as it is between 10E − 01 J and 10E + 02 J. This indicates that the same magnitude range events recorded during 2005 emitted much more energy than the ones recorded during 2003. It is a fact that the same moment magnitude size event can emit different amounts of energy depending on the rock mass condition. In general, the more fractured the rock mass the less energy will be emitted. Three years in the life of the cave is a long time. One would expect that the rock mass during 2005 was much more fractured than it was during 2003. For this reason, one would expect to find that the 2003 seismic events would have a higher energy range from that recorded during 2005 however presented data indicates that this is not the case.

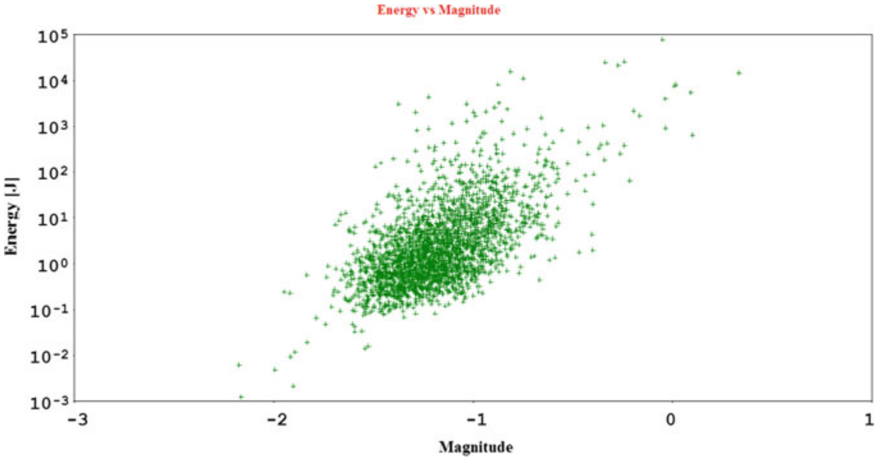
In the fifth test, I will analyse the seismicity recorded during April 2008. This seismicity was recorded with a new Lift 2 North Extension seismic network and all stations in this network had triaxial accelerometers. During April 2008, this network recorded nearly 21,000 events. Figure 2.43 illustrates locations of these events in a W–E horizontal plan while Fig. 2.44 shows these events in a vertical N–S section.

Figure 2.45 illustrates the magnitude–energy relationship for seismicity recorded during April 2008. All the events in Fig. 2.45 were recorded in the north part of the mine and for this reason, there are only 21,000 of events. The magnitude–energy distribution for this set of events is different from the OLD (Fig. 2.30) and the NEW (Fig. 2.31) sets of events, and it does not exhibit any unusual energy ranges. I have



20/07/2004 — 13/09/2004
Mag>-3.0 Min 4 Sites
Min.Mag=-2.4 Max.Mag=-0.6
2457 Events
First 20/07/2004 00:26:29
Last 13/09/2004 23:46:00
Z: 10300 — 9000 Area=4.00 km²

Fig. 2.41 Events recorded during 2004



01/08/2005 — 30/12/2005
Mag>-3.0 Min 4 Sites
Min.Mag=-2.2 Max.Mag=0.3
2481 Events
First 04/08/2005 19:51:15
Last 30/12/2005 23:07:33
Z: 10300 — 9000 Area=4.00 km²

Fig. 2.42 Events recorded during 2005

calculated average seismic energy releases per magnitude (from -1.0 up to 0.0) for the data illustrated in Fig. 2.45 (See Table 2.12). Figure 2.46 illustrates the energy

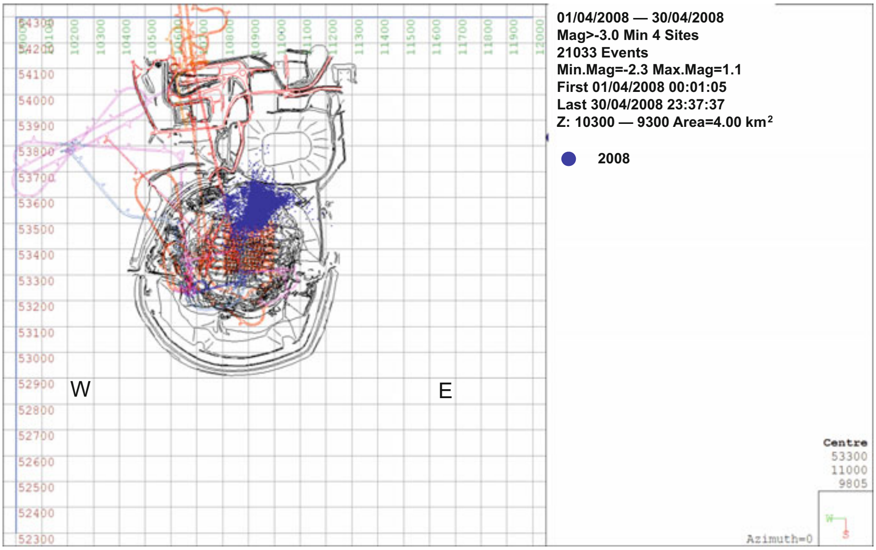


Fig. 2.43 Data recorded during April 2008—horizontal plan

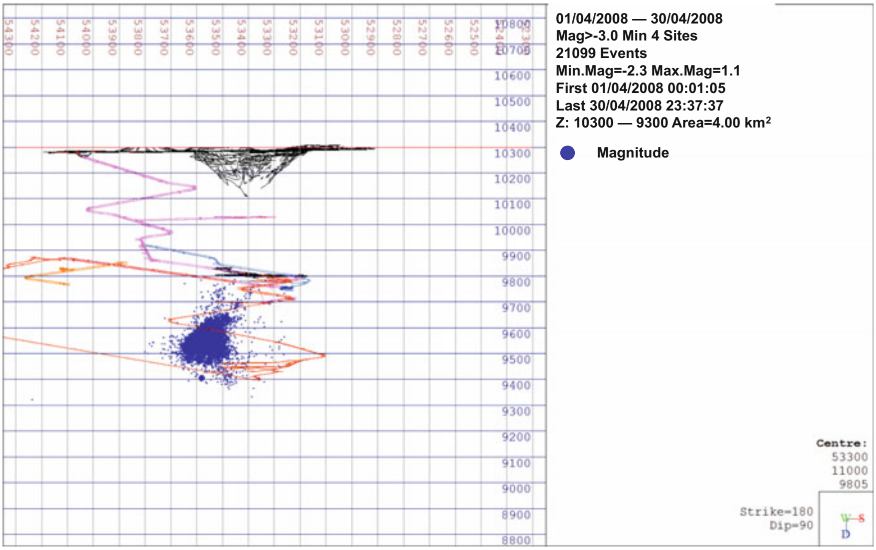


Fig. 2.44 Data recorded during April 2008—vertical section

release trends for the three Northparkes Mine seismic data sets. The NPN 2008 set is different as the energy releases per magnitude size are much lower than in case of the OLD and NEW seismicity. Figure 2.46 illustrates the energy release rates for

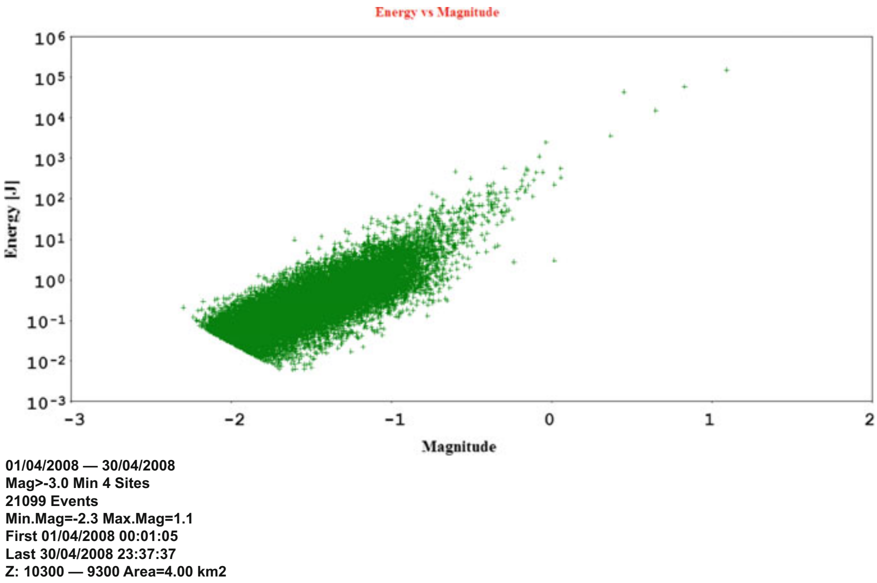


Fig. 2.45 Magnitude energy relation for April 2008 seismicity

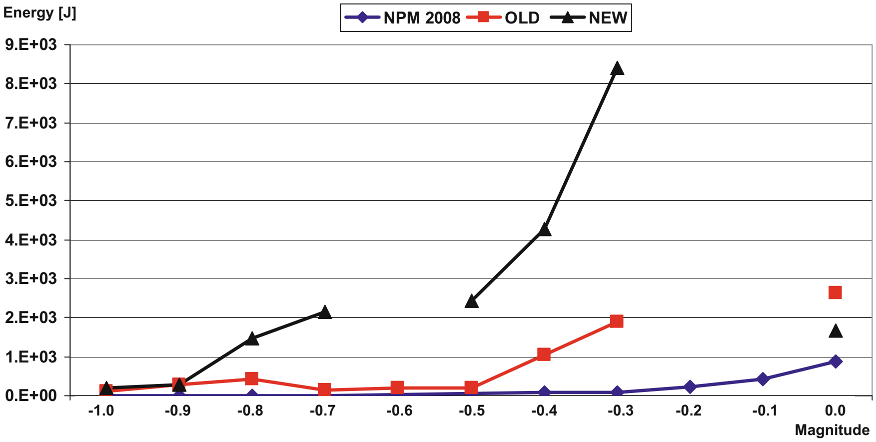


Fig. 2.46 Average monthly energy releases per magnitude size

magnitude range from −1.0 up to 0.0. Figure 2.47 illustrates the energy release rates for magnitude range from −1.0 only up to −0.5.

Figure 2.48 illustrates the energy release rates for magnitude range from −1.0 up to −0.5 for two data sets OLD, for which the energy release rates are lower than for NEW and for the NPM 2008 set. It is evident that the average energy releases of the NPM 2008 set are much lower than those for the OLD set.

Table 2.12 Average energy releases [J] per magnitude size

Mine	Moment magnitude										
	−1.0	−0.9	−0.8	−0.7	−0.6	−0.5	−0.4	−0.3	−0.2	−0.1	0.0
PMC	24	37	57	96	154	228	309	386	596	965	1456
PTF	50	40	47	74	105	132	213	370	691	1136	
ESM	5	8	10	14	20	26	38	56	89	140	231
DRW	8	10	15	28	24	41	61	99	149	297	489
DRH	8	10	28	22	30	58	55	105	148	213	441
NPM	2	3	6	13	23	47	78	95	220	423	880

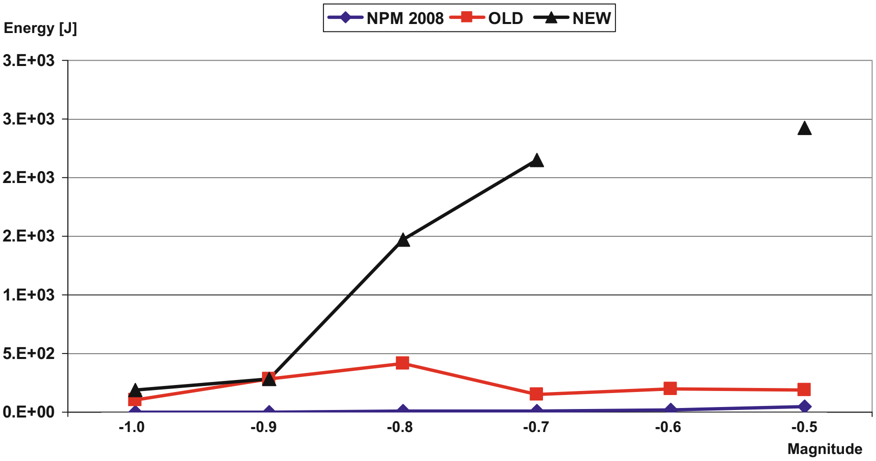


Fig. 2.47 Average monthly energy releases per magnitude size

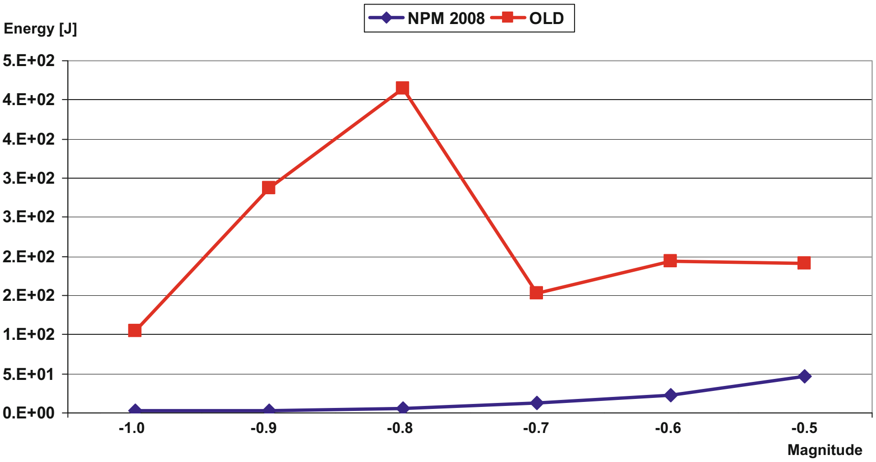


Fig. 2.48 Average monthly energy releases per magnitude size

2.5.2 Average Energy Release Rates of Small Size Events

Table 2.12 and Figs. 2.49 and 2.50 illustrate the average seismic energy release rates as calculated for PMC, PT Freeport Indonesia (PTF), El Teniente Esmeralda Sector (ESM), El Teniente Diablo Regimento Sector whole (DRW), El Teniente Diablo Regimento Sector hydro (DRH) and Northparkes Mine 2008 (NPM).

Figures 2.49 and 2.50 illustrate the fact that the NPM 2008 seismic catalogue fits with the other mines' catalogues. As indicated by these two figures the NPM 2008 seismic energy release rates are very similar to those recorded at El Teniente. The

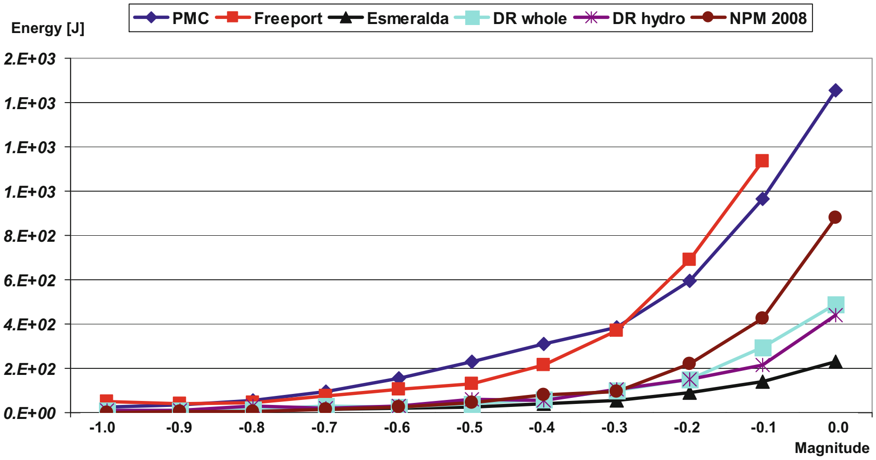


Fig. 2.49 Average monthly energy releases per magnitude size

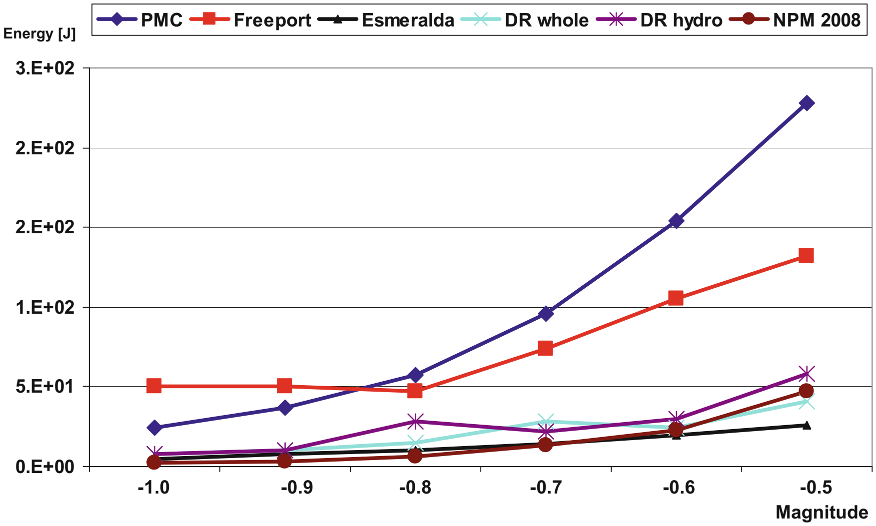


Fig. 2.50 Average energy releases per magnitude size

PMC and PT Freeport Indonesia seismic energy release rates for the given magnitude ranges are higher.

Figure 2.51 illustrates the average seismic energy release rates for magnitude range from −1.0 up to 0.0 at PMC and PT Freeport Indonesia. It is interesting to note that up to magnitude −0.3 the PMC rates are higher than the PT Freeport rates.

Figure 2.52 illustrates the average seismic energy release rates for magnitude range from −1.0 up to 0.0 based on data recorded at El Teniente (Esmeralda, DR whole and DR hydro) and at Northparkes Mine during April 2008. It is interesting

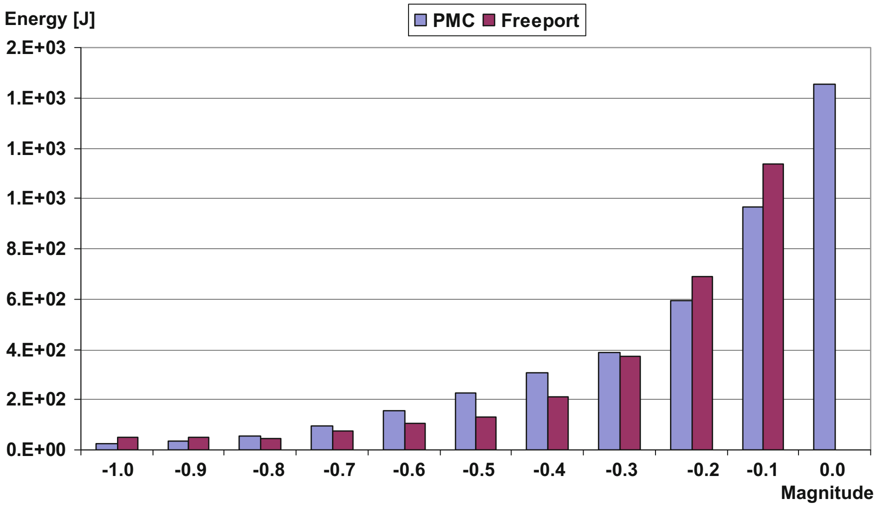


Fig. 2.51 Average seismic energy release rates at PMC and PT Freeport

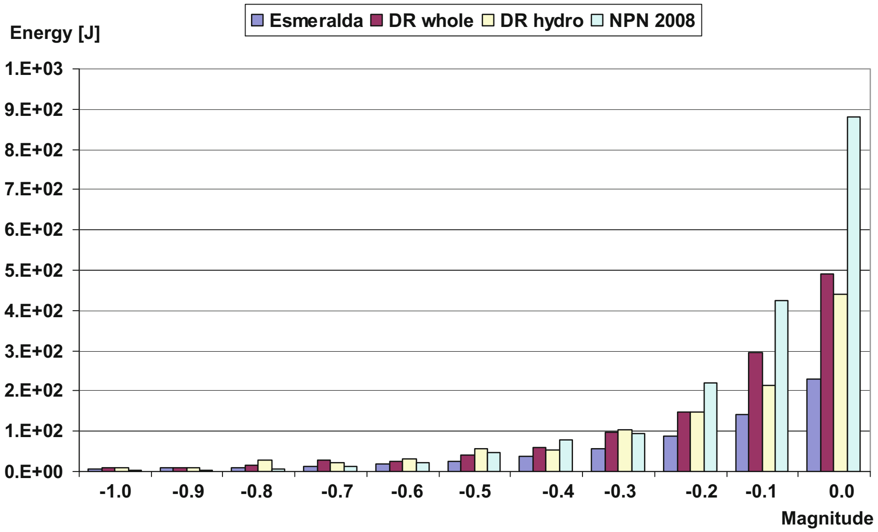


Fig. 2.52 Average seismic energy release rates at El Teniente and NPM 2008

to note that for the higher magnitude values (from −0.2) the NPM 2008 rates are higher than the EL Teniente rates.

Figure 2.53 illustrates the average seismic energy release rates for magnitude range from −1.0 up to 0.0 for the whole Diablo Regimento Sector and for the Diablo Regimento Sector that was hydro-fractured. Here a certain pattern might be of interest. For the lower magnitude sizes (up to magnitude size −0.5) the energy release

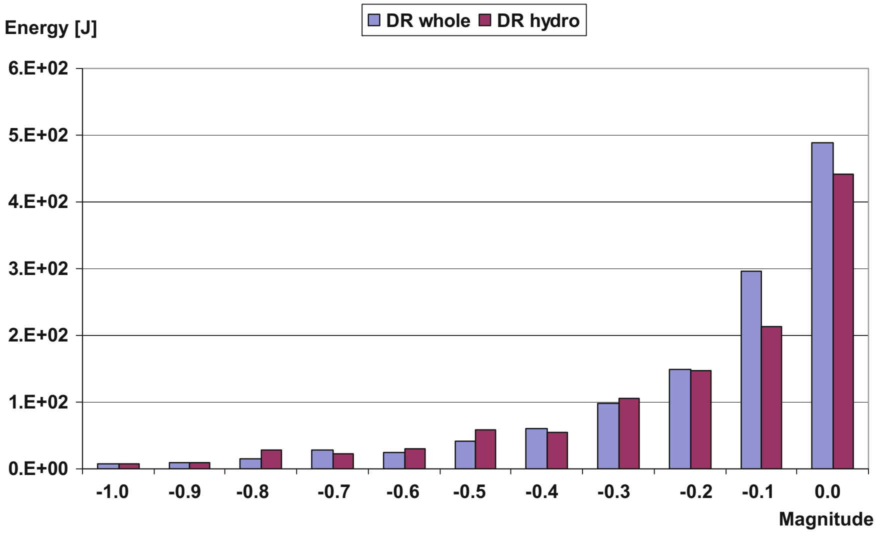


Fig. 2.53 Average seismic energy release rates—DR whole and DR hydro

rates for DR hydro are generally higher than the rates for DR as a whole. Average seismic energy release rates for magnitude sizes −0.3 and −0.2 for DR hydro and DR whole are very similar, while for the highest magnitude values (−0.1 and 0.0), the energy release for DR hydro is significantly lower from the rates observed for the DR whole. If still larger size seismicity (above magnitude 0.0) would follow this trend this would be then a direct observation suggesting the benefits of hydro-fracturing.

2.5.3 Energy Release Ranges for Different Magnitude Sizes—Comparison Between Mines

I will now compare energy release rates for small and larger size events that were recorded in four mines, namely:

- PMC
- Diablo Regimento Sector
- DOZ Mine
- El Teniente Mine (whole)

PMC database consists of 137,332 events (1 January 2002–31 April 2011)

Diablo Regimento seismic database consists of 24,909 events (1 January 2003–31 July 2009)

DOZ database consists of 526,000 events (1 August 2004–August 2010)

Table 2.13 Energy release ranges for low size magnitude events

Magnitude size	PMC minimum energy [J]	DR minimum energy [J]	DOZ minimum energy [J]	El Teniente minimum energy [J]
−1.0	1.58E+00	1.52E+00	3.23E+00	1.46E+00
−0.9	1.78E+00	2.01E+00	4.41E+00	2.99E+00
−0.8	3.16E+00	2.72E+00	7.15E+00	3.68E+00
−0.7	4.06E+00	3.25E+00	9.75E+00	6.19E+00
−0.6	4.53E+00	4.87E+00	9.96E+00	8.20E+00
−0.5	7.38E+00	7.82E+00	1.00E+01	1.17E+01
−0.4	2.02E+01	8.85E+00	1.42E+01	1.77E+01
−0.3	2.41E+01	1.77E+01	2.51E+01	2.66E+01
−0.2	3.39E+01	1.35E+01	4.22E+01	3.87E+01
−0.1	2.88E+01	2.04E+01	6.14E+01	5.32E+01
0.0	3.36E+01	2.51E+01	1.01E+02	7.77E+01

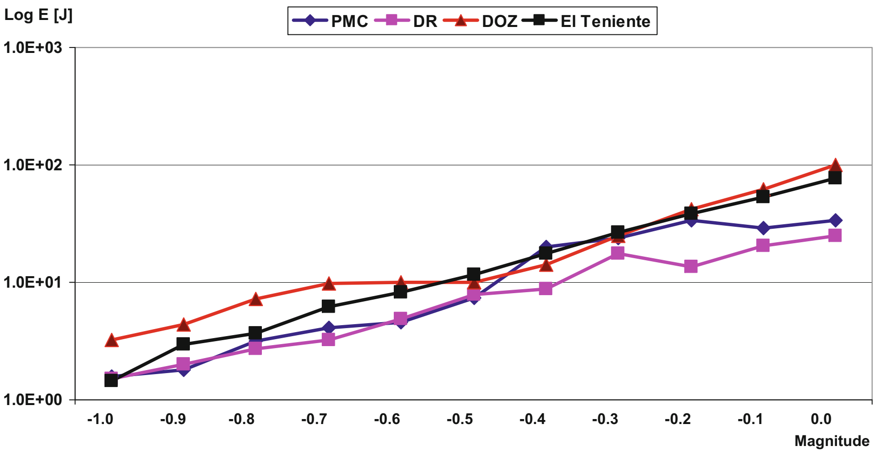


Fig. 2.54 Low magnitude range—minimum energy releases

El Teniente seismic database consists of 544,916 events (1 January 1995–May 2008)

2.5.3.1 Low Magnitude Range

The low magnitude range consists of events magnitude from −1.0 up to 0.0. Table 2.13 lists the minimum monthly energy releases for this size events recorded in four mines. This data is illustrated in Fig. 2.54

Table 2.14 Energy release ranges for low size magnitude events

Magnitude size	PMC maximum energy [J]	DR maximum energy [J]	DOZ maximum energy [J]	El Teniente maximum energy [J]
−1.0	2.54E+02	4.74E+01	7.67E+01	3.39E+02
−0.9	2.08E+02	4.38E+01	8.49E+01	3.41E+02
−0.8	2.96E+02	7.53E+01	9.46E+01	3.94E+02
−0.7	5.32E+02	1.40E+02	1.63E+02	4.46E+02
−0.6	8.61E+02	1.36E+02	2.58E+02	5.81E+02
−0.5	1.59E+03	2.31E+02	3.84E+02	7.66E+02
−0.4	2.54E+03	3.08E+02	4.55E+02	1.20E+03
−0.3	4.18E+03	9.11E+02	7.74E+02	1.83E+03
−0.2	6.35E+03	1.72E+03	3.38E+03	2.76E+03
−0.1	7.08E+03	3.13E+03	5.15E+03	5.81E+03
0.0	8.97E+03	3.68E+03	3.49E+03	5.50E+03

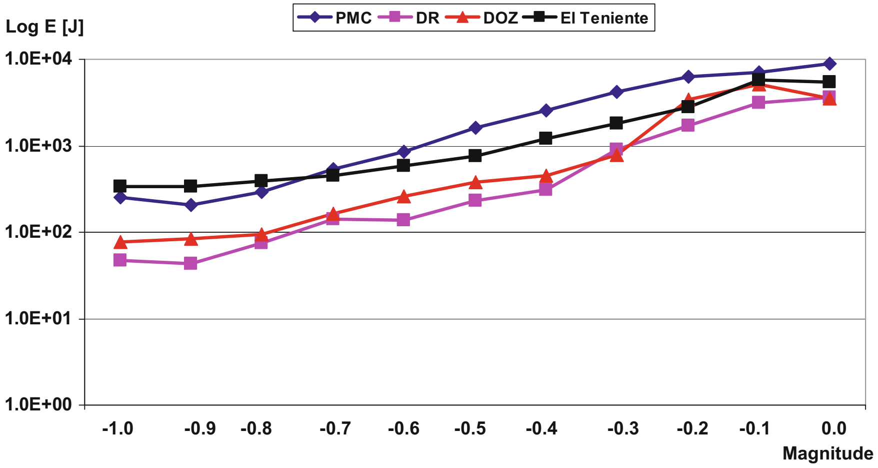


Fig. 2.55 Low magnitude range—maximum energy releases

In Fig. 2.54 the PMC data is presented in blue, DR data in pink, DOZ data in red and El Teniente data is in black. Magnitude sizes are listed on the horizontal axis. The differences between the four graphs are minimal but it seems that data recorded in the Diablo Regimento Sector has the lowest values.

Table 2.14 and Fig. 2.55 illustrate the maximum monthly energy releases for the low magnitude range. The colours used are the same as in the previous figure. The differences for each mine are evident. The highest maximum values were recorded at PMC. The lowest maximum values were recorded at Diablo Regimento.

Table 2.15 Minimum energy release ranges—higher magnitude ranges

Magnitude size	PMC minimum energy [J]	DR minimum energy [J]	DOZ minimum energy [J]	El Teniente minimum energy [J]
0.1	4.50E+01	1.38E+01	1.81E+02	1.15E+02
0.2	1.12E+02	3.48E+01	1.66E+02	1.72E+02
0.3	1.50E+02	5.35E+01	2.01E+02	2.30E+02
0.4	1.92E+02	5.28E+01	3.77E+02	2.66E+02
0.5	2.27E+02	4.49E+01	7.31E+02	4.43E+02
0.6	5.08E+02	1.59E+02	9.09E+02	6.17E+02
0.7	8.72E+02	1.06E+03	1.69E+03	9.49E+02
0.8	1.69E+03	2.64E+02	9.40E+02	9.05E+02
0.9	1.74E+03	3.59E+02	3.00E+03	1.47E+03
1.0	2.21E+03	4.63E+03	4.88E+03	1.32E+03
1.1	6.56E+03		1.31E+04	1.06E+03
1.2	9.48E+03		1.38E+04	3.60E+03
1.3	9.32E+03		1.83E+04	4.62E+03
1.4	1.72E+04		2.99E+04	8.09E+03
1.5			4.92E+04	1.87E+04
1.6	4.45E+04		8.80E+04	4.23E+04
1.7			6.16E+04	8.62E+04
1.8			1.14E+05	2.15E+05
1.9			3.25E+05	3.58E+05
2.0			5.53E+05	4.39E+05
2.1			1.08E+06	5.13E+05
2.2				1.48E+06
2.3				2.71E+06

2.5.3.2 Higher Magnitude Range

The higher magnitude range consists of events starting with magnitude 0.0. The upper value changes depending on the seismicity of a given mine. Table 2.15 lists the minimum monthly energy release rates. This data is complete for all mines up to magnitude 1.0. The amount of data available for comparing higher magnitude sizes becomes less and less and for this reason also becomes less reliable. Figure 2.56 illustrates the data listed in Table 2.15. The Diablo Regmento Sector graph seems to have the lowest values.

Table 2.16 and Fig. 2.57 illustrate the maximum energy release rates.

According to the data illustrated in Fig. 2.57, the highest maximum energy releases were recorded at PMC. The lowest values of the maximum energy release were recorded at Diablo Regimento Sector.

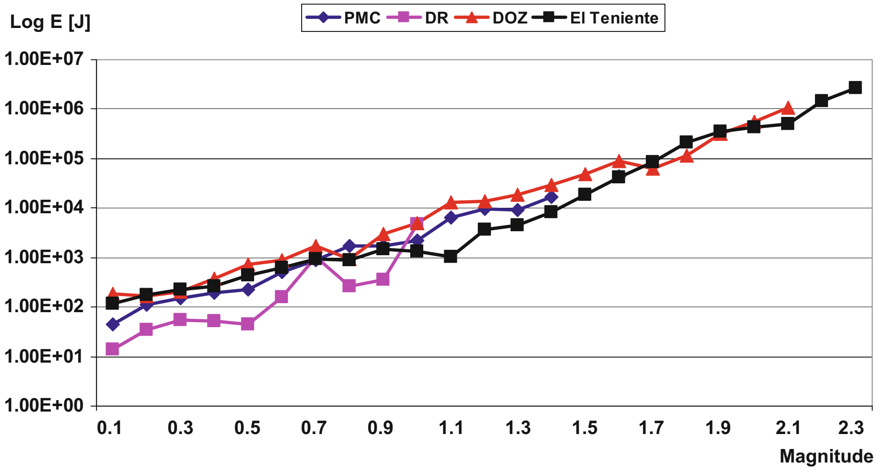


Fig. 2.56 Higher magnitude range—minimum energy releases

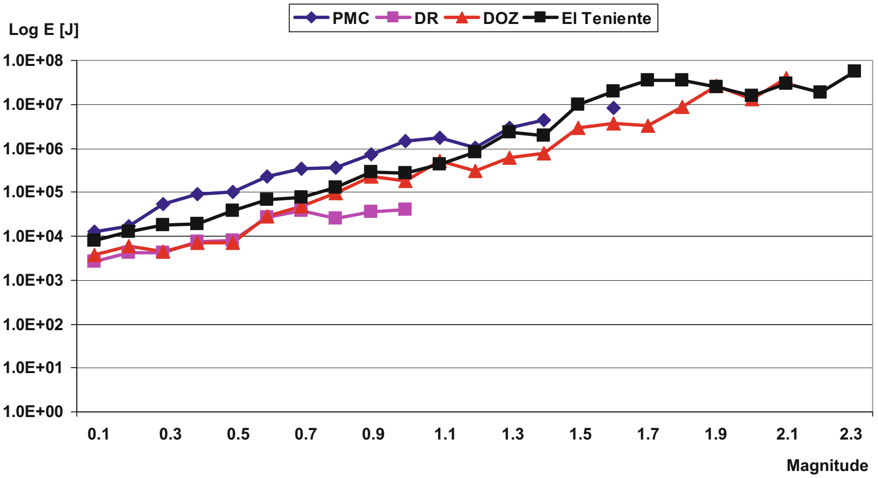


Fig. 2.57 Higher magnitude range—maximum energy releases

2.5.3.3 Energy Release Ranges for All Magnitude Sizes

As the seismic energy release sizes form an extremely large range thus a comparison based on the whole magnitude size range would be difficult to illustrate on one graph. For this reason, I will compare the ranges between the minimum and maximum energy releases for the whole magnitude range from −1.0 up to the maximum magnitude for the four mines. Tables 2.17, 2.18, 2.19 and 2.20 list complete data for each mine as well the ranges (column 5). The range is the ratio between the

Table 2.16 Maximum energy release ranges—higher magnitude ranges

Magnitude size	PMC maximum energy [J]	DR maximum energy [J]	DOZ maximum energy [J]	El Teniente maximum energy [J]
0.1	1.29E+04	2.59E+03	3.84E+03	7.84E+03
0.2	1.64E+04	4.28E+03	6.00E+03	1.26E+04
0.3	5.31E+04	4.10E+03	4.39E+03	1.78E+04
0.4	9.26E+04	7.36E+03	7.12E+03	1.88E+04
0.5	1.01E+05	7.72E+03	7.20E+03	3.89E+04
0.6	2.31E+05	2.70E+04	2.90E+04	6.71E+04
0.7	3.50E+05	3.84E+04	4.88E+04	7.75E+04
0.8	3.70E+05	2.54E+04	9.65E+04	1.29E+05
0.9	7.41E+05	3.52E+04	2.26E+05	2.94E+05
1.0	1.50E+06	4.09E+04	1.84E+05	2.75E+05
1.1	1.74E+06		5.03E+05	4.44E+05
1.2	1.05E+06		3.07E+05	8.38E+05
1.3	2.95E+06		6.07E+05	2.30E+06
1.4	4.32E+06		7.84E+05	1.98E+06
1.5			3.00E+06	9.86E+06
1.6	8.31E+06		3.72E+06	1.97E+07
1.7			3.21E+06	3.51E+07
1.8			8.94E+06	3.44E+07
1.9			2.59E+07	2.54E+07
2.0			1.30E+07	1.60E+07
2.1			3.87E+07	2.96E+07
2.2				1.86E+07
2.3				5.68E+07

maximum and minimum energy release and is calculated for each magnitude size. These tables also list the number of events for each magnitude size.

The energy release ranges listed in the above four tables are illustrated in Fig. 2.58. The vertical axis "Times" indicates that the difference between the minimum and maximum energy release varies not only between magnitude sizes but also between mines. The magnitude sizes are given on the horizontal axis. The PMC graph is in blue, the DR graph is in pink, the DOZ graph is in red and the EL Teniente graph is in black. The three graphs for PMC, Diablo Regimento and for the whole El Teniente mine follow a similar pattern. For the lower magnitude sizes, the energy release ranges are lower while for the higher magnitude sizes the energy release ranges are larger. In case of PMC, the larger energy release ranges are for magnitude range 0.3 up to magnitude 1.0. In case of the Diablo Regimento Sector this larger energy release range is shifted towards a lower magnitude range: from −0.3 up to 0.6. In case of the whole El Teniente Mine, this higher energy release range is shifted towards the higher magnitudes: from 1.1 up to 1.7. Only data from the DOZ Mine does not

Table 2.17 Energy release ranges for all PMC size magnitude events

Magnitude size	No. of events	Minimum energy [J]	Maximum energy [J]	Energy range [times]
−1.0	5897	1.58E+00	2.54E+02	160
−0.9	8381	1.78E+00	2.08E+02	116
−0.8	9730	3.16E+00	2.96E+02	93
−0.7	10,213	4.06E+00	5.32E+02	131
−0.6	10,575	4.53E+00	8.61E+02	190
−0.5	11,597	7.38E+00	1.59E+03	215
−0.4	13,204	2.02E+01	2.54E+03	125
−0.3	13,587	2.41E+01	4.18E+03	173
−0.2	12,684	3.39E+01	6.35E+03	187
−0.1	10,332	2.88E+01	7.08E+03	245
0.0	7826	3.36E+01	8.97E+03	266
0.1	5594	4.50E+01	1.29E+04	286
0.2	3932	1.12E+02	1.64E+04	146
0.3	2745	1.50E+02	5.31E+04	354
0.4	1741	1.92E+02	9.26E+04	482
0.5	1126	2.27E+02	1.01E+05	445
0.6	744	5.08E+02	2.31E+05	454
0.7	476	8.72E+02	3.50E+05	401
0.8	328	1.69E+03	3.70E+05	218
0.9	215	1.74E+03	7.41E+05	425
1.0	140	2.21E+03	1.50E+06	678
1.1	92	6.56E+03	1.74E+06	265
1.2	52	9.48E+03	1.05E+06	110
1.3	27	9.32E+03	2.95E+06	316
1.4	10	1.72E+04	4.32E+06	251
1.5	4			
1.6	13	4.45E+04	8.31E+06	186
1.7	1			
1.8	1			
1.9	2			

follow this pattern. Here, the energy release ranges are not only the lowest but also nearly continuous for the whole magnitude range. This might indicate that the stress levels did not change over time as much as at the other mines and stayed at nearly the same level (during the time period 1 August 2004–30 August 2010).

Figure 2.59 compares the energy release ranges for Diablo Regimento Sector (pink) with the ranges for the whole El Teniente Mine (black). It is interesting to note the differences in the average energy release range values for these mines.

Table 2.18 Energy release ranges for all DR size magnitude events

Magnitude size	No. of events	Minimum energy [J]	Maximum energy [J]	Energy range [times]
−1.0	984	1.52E+00	4.74E+01	31
−0.9	1609	2.01E+00	4.38E+01	22
−0.8	2331	2.72E+00	7.53E+01	28
−0.7	2830	3.25E+00	1.40E+02	43
−0.6	2964	4.87E+00	1.36E+02	28
−0.5	2760	7.82E+00	2.31E+02	29
−0.4	2394	8.85E+00	3.08E+02	35
−0.3	2001	1.77E+01	9.11E+02	51
−0.2	1607	1.35E+01	1.72E+03	127
−0.1	1256	2.04E+01	3.13E+03	153
0.0	857	2.51E+01	3.68E+03	146
0.1	611	1.38E+01	2.59E+03	187
0.2	511	3.48E+01	4.28E+03	125
0.3	382	5.35E+01	4.10E+03	76
0.4	367	5.28E+01	7.36E+03	139
0.5	246	4.49E+01	7.72E+03	172
0.6	125	1.59E+02	2.70E+04	169
0.7	64	1.06E+03	3.84E+04	36
0.8	33	2.64E+02	2.54E+04	96
0.9	24	3.59E+02	3.52E+04	98
1.0	13	4.63E+03	4.09E+04	9
1.1	7			
1.2	5			
1.3	6			
1.4	2			
1.5	0			
1.6	0			
1.7	1			
1.8	2			
1.9	1			
2.0				

These averages are based on the whole magnitude ranges (which are different for each mine).

These averages are as follows:

- Average energy release range for PMC is 266
- Average energy release range for whole El Teniente is 156
- Average energy release range for DR Sector is 85
- Average energy release range for DOZ Mine is 39

Table 2.19 Energy release ranges for all DOZ size magnitude events

Magnitude size	No. of events	Minimum energy [J]	Maximum energy [J]	Energy range [times]
−1.0	22,281	3.23E+00	7.67E+01	23
−0.9	27,665	4.41E+00	8.49E+01	19
−0.8	31,827	7.15E+00	9.46E+01	13
−0.7	32,769	9.75E+00	1.63E+02	16
−0.6	32,786	9.96E+00	2.58E+02	26
−0.5	30,837	1.00E+01	3.84E+02	38
−0.4	29,312	1.42E+01	4.55E+02	32
−0.3	26,684	2.51E+01	7.74E+02	31
−0.2	23,645	4.22E+01	3.38E+03	80
−0.1	20,379	6.14E+01	5.15E+03	84
0.0	15,965	1.01E+02	3.49E+03	34
0.1	13,074	1.81E+02	3.84E+03	21
0.2	10,543	1.66E+02	6.00E+03	36
0.3	8323	2.01E+02	4.39E+03	22
0.4	6463	3.77E+02	7.12E+03	19
0.5	4861	7.31E+02	7.20E+03	10
0.6	3529	9.09E+02	2.90E+04	32
0.7	2617	1.69E+03	4.88E+04	29
0.8	1931	9.40E+02	9.65E+04	102
0.9	1504	3.00E+03	2.26E+05	75
1.0	1077	4.88E+03	1.84E+05	37
1.1	906	1.31E+04	5.03E+05	38
1.2	668	1.38E+04	3.07E+05	22
1.3	501	1.83E+04	6.07E+05	33
1.4	373	2.99E+04	7.84E+05	26
1.5	253	4.92E+04	3.00E+06	60
1.6	190	8.80E+04	3.72E+06	42
1.7	114	6.16E+04	3.21E+06	52
1.8	94	1.14E+05	8.94E+06	78
1.9	61	3.25E+05	2.59E+07	79
2.0	33	5.53E+05	1.30E+07	23
2.1	27	1.08E+06	3.87E+07	35
2.2	6			
2.3	6			
2.4	7			
2.5	5			
2.6	3			
2.7	3			
2.8	2			

Table 2.20 Energy release ranges for all EL Teniente size magnitude events

Magnitude size	No. of events	Minimum energy [J]	Maximum energy [J]	Energy range [times]
−1.0	13,448	1.46E+00	3.39E+02	232
−0.9	20,567	2.99E+00	3.41E+02	114
−0.8	29,154	3.68E+00	3.94E+02	107
−0.7	38,381	6.19E+00	4.46E+02	72
−0.6	47,363	8.20E+00	5.81E+02	71
−0.5	52,382	1.17E+01	7.66E+02	65
−0.4	53,639	1.77E+01	1.20E+03	68
−0.3	49,474	2.66E+01	1.83E+03	69
−0.2	42,798	3.87E+01	2.76E+03	71
−0.1	37,266	5.32E+01	5.81E+03	109
0.0	31,000	7.77E+01	5.50E+03	71
0.1	26,249	1.15E+02	7.84E+03	68
0.2	21,295	1.72E+02	1.26E+04	73
0.3	16,463	2.30E+02	1.78E+04	77
0.4	12,710	2.66E+02	1.88E+04	70
0.5	9239	4.43E+02	3.89E+04	88
0.6	6881	6.17E+02	6.71E+04	108
0.7	4863	9.49E+02	7.75E+04	81
0.8	3337	9.05E+02	1.29E+05	142
0.9	2372	1.47E+03	2.94E+05	200
1.0	1480	1.32E+03	2.75E+05	208
1.1	940	1.06E+03	4.44E+05	418
1.2	618	3.60E+03	8.38E+05	232
1.3	396	4.62E+03	2.30E+06	497
1.4	277	8.09E+03	1.98E+06	244
1.5	184	1.87E+04	9.86E+06	527
1.6	132	4.23E+04	1.97E+07	465
1.7	97	8.62E+04	3.51E+07	407
1.8	73	2.15E+05	3.44E+07	160
1.9	47	3.58E+05	2.54E+07	71
2.0	33	4.39E+05	1.60E+07	36
2.1	28	5.13E+05	2.96E+07	58

(continued)

Table 2.20 (continued)

Magnitude size	No. of events	Minimum energy [J]	Maximum energy [J]	Energy range [times]
2.2	26	1.48E+06	1.86E+07	13
2.3	14	2.71E+06	5.68E+07	21
2.4	9			
2.5	6			
2.6	8			
2.7	2			
2.8	1			
2.9	1			
3.0	1			
3.1	1			

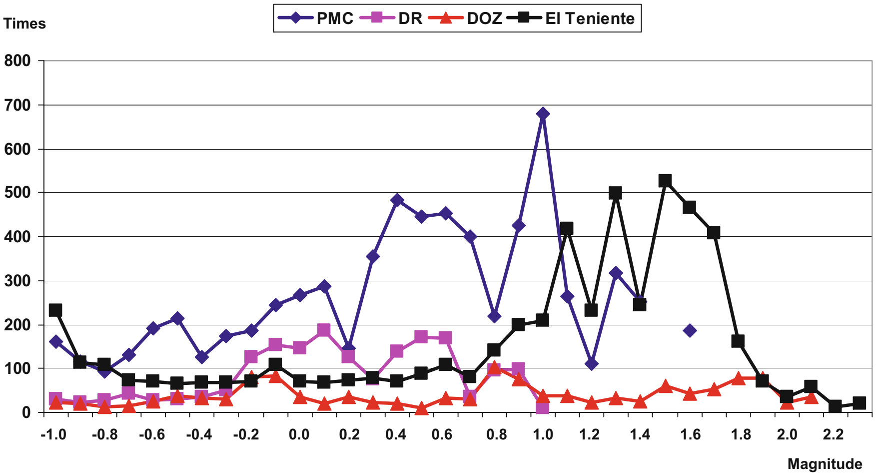


Fig. 2.58 Energy release ranges—all mines

Figure 2.60 illustrates the energy release ranges for the DOZ Mine. The input data was slightly edited (some values were deleted). Still, the DOZ ranges are very low but here they are increasing slightly with the magnitude sizes.

2.6 First Comparison of Seismicity Induced in Two Caving Mines

Caving induced seismicity is a process indicating that the cave is progressing and is connected with rock mass fracturing in front of the undercut and propagating

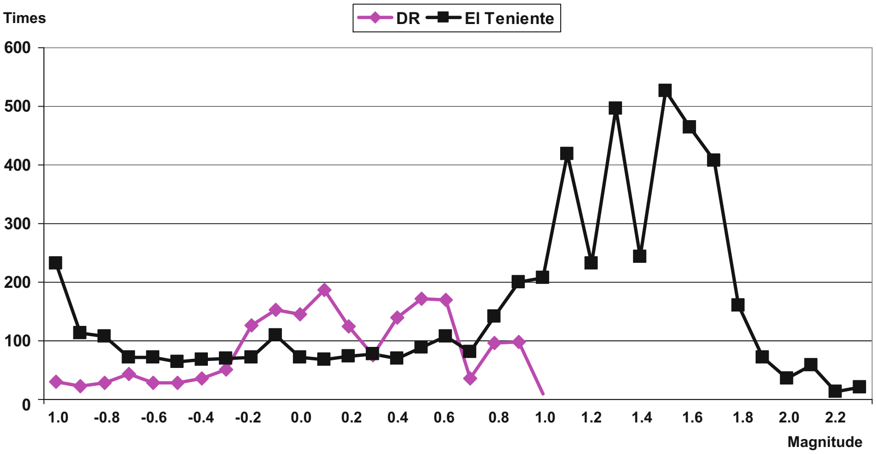


Fig. 2.59 Energy release ranges for DR and El Teniente

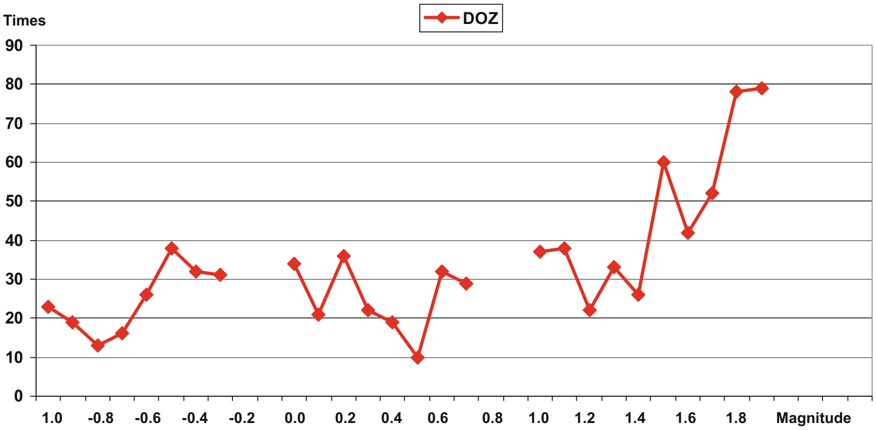


Fig. 2.60 Energy release ranges for DOZ

cave. The space and time distribution 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. This should not only be monitored in a passive way to confirm the cave progress, but should be also used in an active way to manage the cave development. Cave induced seismicity is the principal manifestation of the cave propagation and thus was considered as a positive feature that allows Palabora Mine to monitor and manage the caving process (Glazer and Hepworth 2004, 2005). The study of seismicity associated with cave mining at Palabora Mining has shown that it is an extremely reliable and powerful tool for monitoring the progression of the caving process. Seismology, by its nature, is superior to other cave monitoring methods, as the system allows for information to be gathered from all around the cave and is not confined to point measurements. The progression of the cave generates fractures in the more competent (intact) rock immediately ahead of the fracture zone, which changes the rock properties and lowers its load carrying ability. As the cave back approaches the fractured rock it will yield under the increased load and increased shear movement between the blocks of rock will create further propagation of fractures. The cave progression will also result in the breaking of asperities and other locking mechanisms in the fractured rock mass, creating a favourable environment for shear movement and extended growth of the fracture zone around the cave back. In addition to the fracturing around the cave back, which induces mode one seismicity, there is another mechanism of rock failure that is taking place. This mechanism is a-seismic deformation, which is either the process of propagation of already existing shear fractures or the creation of new fractures with little or no associated seismicity. While the asperities on the joint surfaces are being broken down there will be sliding and opening of the joints. This, firstly, does not produce significant seismic energy during movement and secondly, inhibits propagation of seismic energy through this zone of fractured rock. The seismic and a-seismic deformation of the rock mass around the cave results in stress redistribution, which in turn will lead to further fracturing. These fracturing mechanisms are very similar to the one described for de-stress blasting used to reduce the seismic hazard for underground excavations (Rorke et al. 2004).

Palabora Mining Company (PMC) and Deep Ore Zone (DOZ) Mine of PT Freeport Indonesia are mining copper and copper/gold ores, respectively, making use of cave mining methods. The two mines are using similar seismic monitoring systems and the same seismic data interpretation software. 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 (Glazer 2016). Both PMC and PT Freeport Indonesia DOZ mines by 2006 were using the ISS seismic monitoring system. The DOZ seismic network during 2005 consisted of 36 stations, while the PMC seismic system had 26 recording stations. All the recording stations of these two networks are triaxial 13 Hz geophone probes. Figure 2.61 shows the vertical distribution of the PT Freeport Indonesia Seismic Network. The DOZ Cave position is as it was estimated to be in January 2006.

Figure 2.62 shows the vertical distribution of the PMC seismic sensors. In both cases, the sensors are located around the cave area with the majority of sensors positioned around the cave on the extraction level. Both sensor distributions result in similar seismic event location accuracy. Local magnitude definitions for the two networks are the same.

The first seismic event at PMC was recorded on the 16 September 1999 and at PTFI on the 01 August 2004. At November 2006, the PTFI seismic database contained data recorded for a 28 month period while the PMC seismic database contained data recorded for the last 87 months. This represents a substantial difference in data recorded. Because of the time span, the PMC seismic database contains recordings relating to all major stages during the caving process. In the case of PMC, the caving process for the underground block cave was initiated in April 2002. The crown pillar

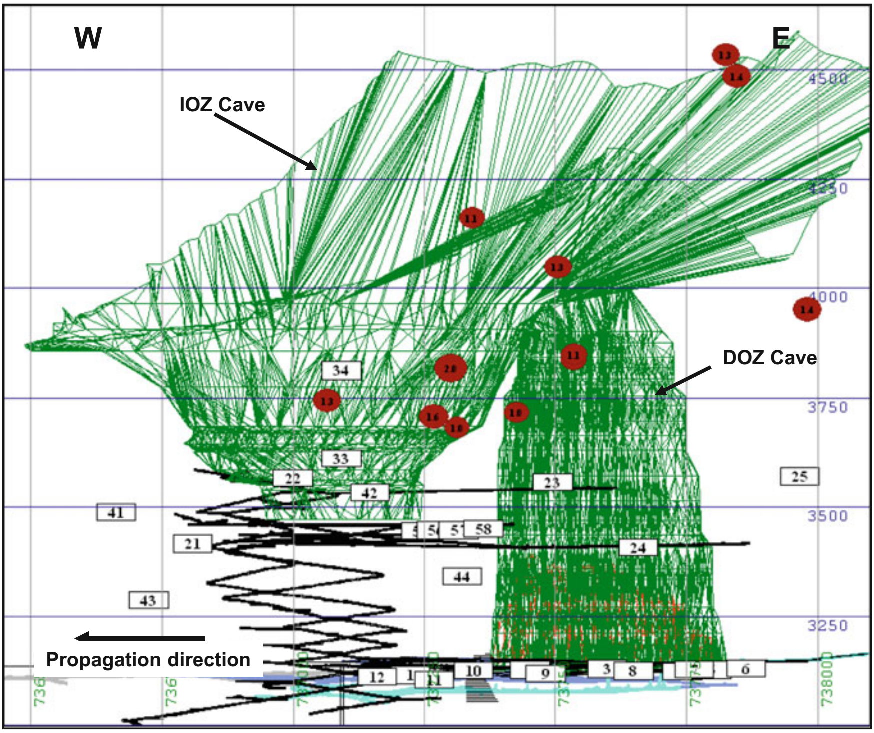


Fig. 2.61 Vertical distribution of the PTFI seismic network

located between the cave and the open pit was presumed to have failed by the end of 2002, which is only about eight months after the caving process had been initiated. By “failed” it was assumed that the crown pillar was fractured to the extent that it was no longer generating seismicity and was no longer transmitting any stress (Glazer and Hepworth 2006). The cave was considered to have broken into the open pit in May 2004. This was followed by a major failure of the open North Wall during October and November 2004 (Brummer et al. 2006; Moss et al. 2006).

The first seismic recording at PTFI took place only after the east side of the DOZ had merged with the GBT/IOZ cave. In Fig. 2.61, this is where the maximum elevation of the DOZ Cave connected with the IOZ Cave (DOZ Crown Pillar). The West Pillar of the DOZ Cave failed during October or November 2005. The seismic network recorded this phase of the DOZ Cave development. Installation of seismic network around the DOZ cave, apart from seismic hazard monitoring, has also resulted in using the recorded seismicity for monitoring the cave position and its propagation.

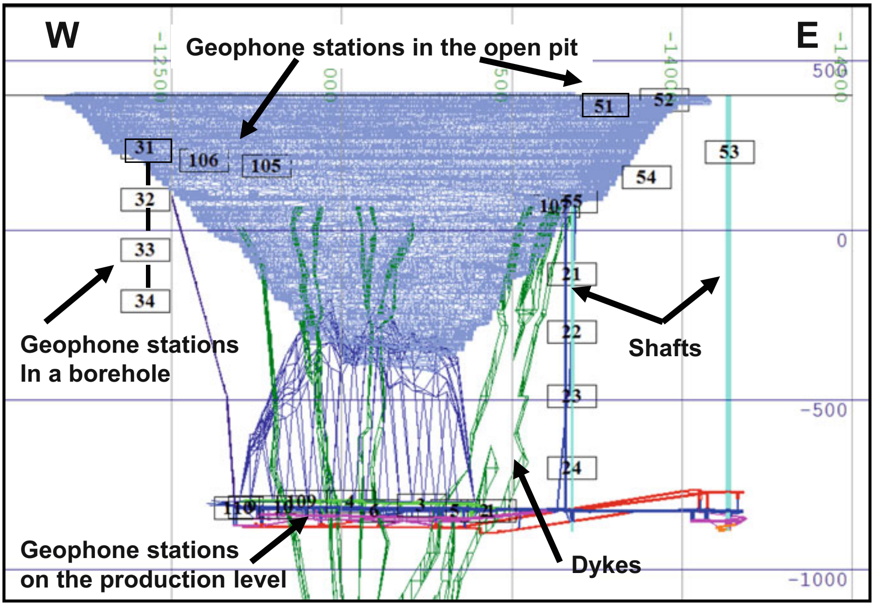


Fig. 2.62 Vertical distribution of the PMC seismic network

2.6.1 *Palabora Mining Company*

Palabora Mining Company is located to the south of the town of Phalaborwa, which is situated in the Limpopo Province in the northern part of the Republic of South Africa (Fig. 2.63). Palabora Mining Company was founded in 1956 and open pit mining operations commenced in 1966 at a rate of 30,000 tpd, increasing to 82,000 tpd prior to closure in 2002. In total, some 960 Mt of ore and 1300 Mt of waste has been mined from the open pit. The development of a 30,000 tpd blocks cave operation commenced in 1996. Target production of 30,000 tpd was achieved in May 2005. Undercutting of the cave footprint commenced in late 1999. The undercutting was advanced ahead of the construction of the production level to provide a stress relief shadow for the excavation of the production level draw points and draw bells (Moss et al. 2004). The underground mine exploits the ore below the open pit by means of mechanized block caving. The undercut level is at elevation of −800 m (1200 m below the surface) and approximately 400 m below the pit bottom at elevation of −417 m. The production level with its draw points is located 18 m below the undercut (Fig. 2.64). The Exploration and Ventilation Shafts are located in the open pit with the collar elevation close to 100 m above the sea level. The bank elevations of the Production and Service Shafts are close to 400 m above the sea level.

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.

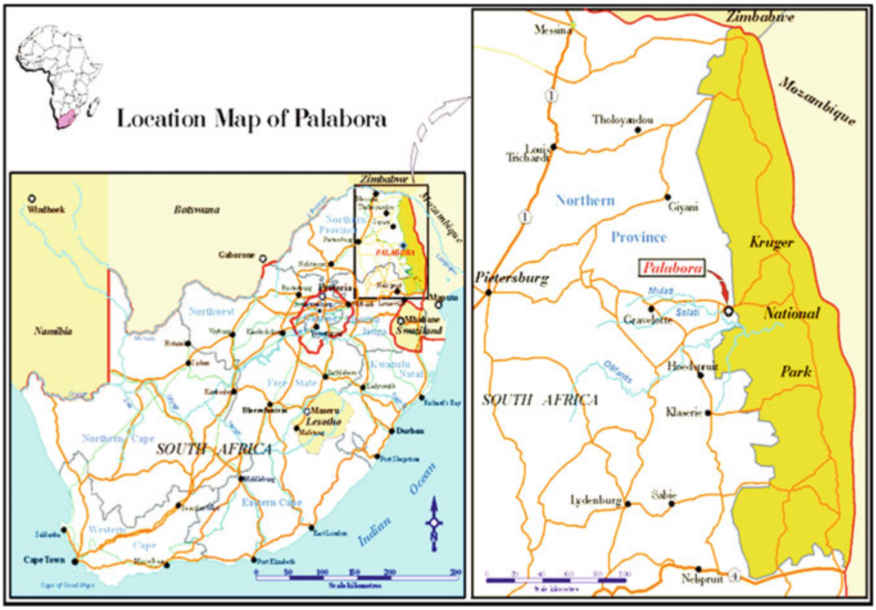


Fig. 2.63 Location of PMC Mine

The ore body is open at depth with mineralization 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.

2.6.2 Deep Ore Zone Mine of PT Freeport Indonesia

The Deep Ore Zone (DOZ) Mine is located the Ertsberg Mining District in Papua, Indonesia (Fig. 2.65). The mine is located in the Sudirman Mountain range of Papua, the most eastern province of Indonesia, on the western half of the Island of New Guinea. The ore deposits, discovered in 1936 and then acquired and developed by PTFI in 1967 are located approximately 96 km north from the southwest coast, between elevations of 2600 and 4000 m above the sea level. Access to the project is through the PTFI port of Amamapare, and from the international airport of Timika, some 43 km north of Amamapare. An access road to the mine site connects the port with the mill passing by the Timika airport (Casten et al. 2004).

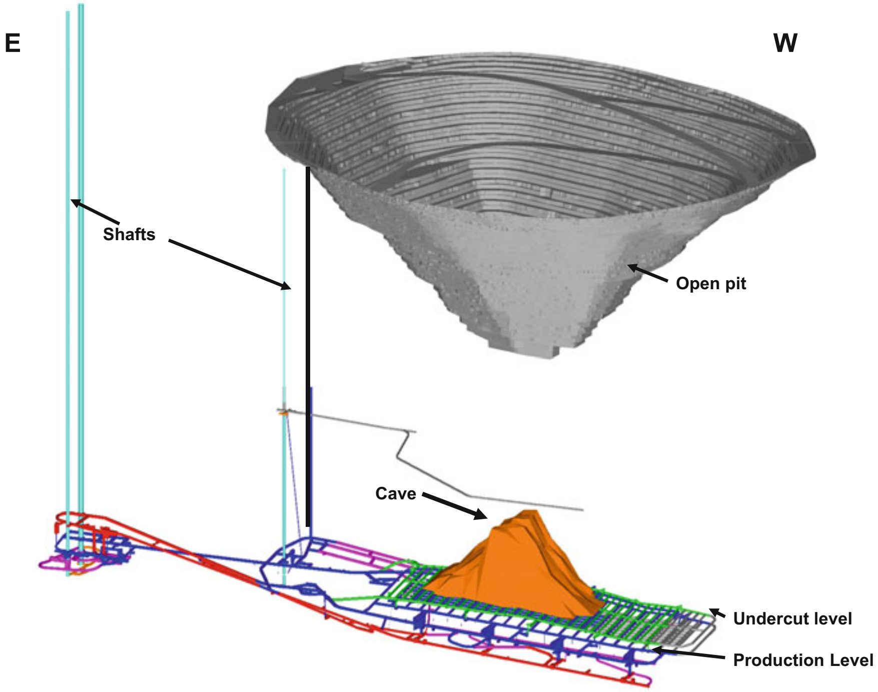


Fig. 2.64 PMC mining complex

DOZ is a copper–gold skarn deposit located on the northwest flank of the Ertsberg diorite intrusive body. It comprises the lower elevations of the East Ertsberg Skarn System (EESS). The EESS outcropped on surface at about 4000 metres, and the DOZ lift of EESS is located on the 3100 m level. Current operations in the district include the Grasberg open pit (200,000 tpd ore) and the DOZ block cave mine (40,000 tpd). DOZ is a mechanized block caving operation and is the third lift of the block cave mine that has exploited the East Ertsberg Skarn complex since 1980 (Fig. 2.66). DOZ is not the only mine there are others: Gunung Bijih Timur Mine (GBT) and the Intermediate Ore Zone lift (IOZ). The IOZ Mine was started in 1994 and ceased operations in 2003. The GBT cave is directly above the IOZ cave. The vertical distance between production level of the GBT and IOZ mines is 200 m. The DOZ Mine started in 2000 and by the end of 2003 had produced 22 million tonnes. The area of the DOZ undercut measured 79,300 m^2 and the perimeter of the undercut was 1.6 km (January 2004). The designed height of draw of DOZ mine was over 600 m in virgin areas, with the total cave height from the production level to the surface being in excess of 1200 m. The shape of the DOZ mining caving zone is ellipsoidal with the short axis being between 300 and 600 m (width of undercut) and the long axis being 1200 m (length of undercut). The east side of the DOZ cave merged with the GBT and IOZ caves in 2003 and is reflected on the surface (Casten et al. 2004).

Fig. 2.65 Location of PT Freeport Indonesia mines (Wildijano et al. 2004)

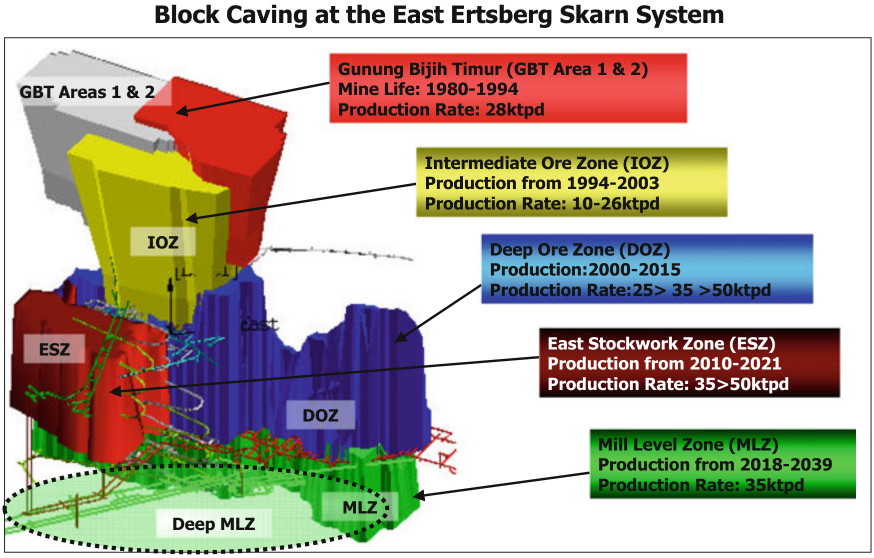


Fig. 2.66 PT Freeport underground mining complex (Widijano et al. 2004)

2.6.3 Comparison of Seismicity

The two mines are using similar seismic monitoring systems and the same seismic data interpretation software. 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 (Glazer 2016). During 2006, I had the opportunity to compare the seismicity induced by the caving process taking place in these two mines (Glazer and Townsend 2006). As during 2006 the PMC cave process was more advanced than the DOZ cave, the seismic history of PMC was used to forecast the future seismic hazard for the DOZ Mine. The PMC recorded seismicity contains information about the following mining milestones:

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 drawbells—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. Cave break through into the open pit—May 2004
8. Failure in the open pit—October 2004

Red graph of Fig. 2.67 illustrates the energy index history above the PMC mine footprint. The energy index graph represents the stress regime and, in this case, relates its changes and values to different stages of the caving process. The energy index at the beginning of 2002 was low and increased rapidly to reach the mean value of 1.0 in April 2002 (A), which was when the stress caving process was initiated. The cave Crown Pillar failed by the end of 2002 (B). Up to March 2003, the stresses increased and then subsequently decreased gradually. From April 2003, there was an acceleration in the rate of stress increase. This was associated with an increase in the monthly draw rates to above the value of 50% of the natural cave expansion rate. The stress reached its maximum roughly around July 2003. There was then a high stress plateau lasting until the end of 2003. Before the cave broke into the open pit (May 2004), there was a subsequent stress release. The rate of this stress release was approximately similar to the rate of stress increase during the second half of 2003. The stress release commenced about 5 months before the cave broke into the open pit. The mean energy index value of 1.0 was again reached in May 2004 (C). The green graph shows the trend of the average monthly depth of seismicity. When the hydraulic radius reached 45 m, the stress caving processes was initiated. Concurrent with this process the seismicity migrated upwards. By the end of 2002, the caving

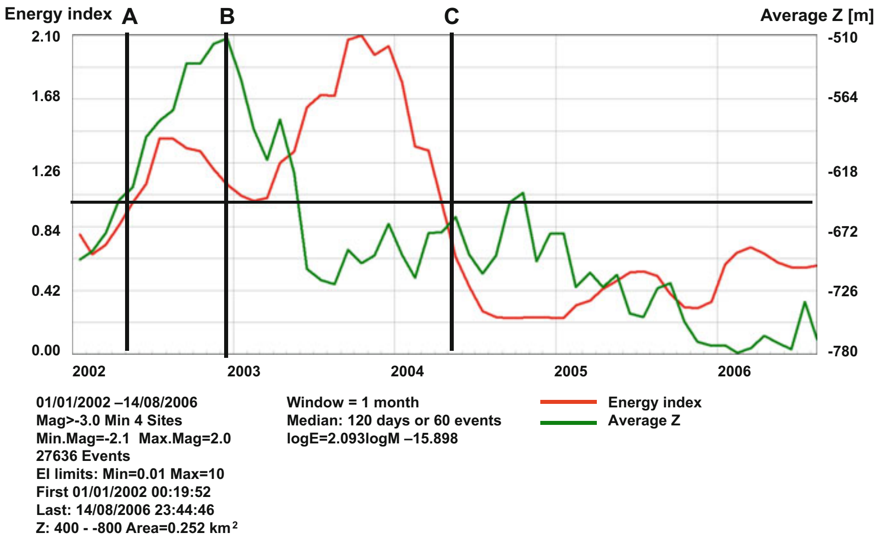


Fig. 2.67 PMC Mine—seismic history above the mine footprint

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 2006, there was a general downwards trend in the depth of seismicity. It is interesting to note that the downwards trend in seismicity depth becomes more evident as from the beginning of 2005, when the energy index reached the average value of 1.0.

The red graph in Fig. 2.68 illustrates the energy index history above the DOZ mine footprint. The energy index at the beginning of 2004 was low and subsequently increased rapidly to reach the mean value of 1.0 at about February 2005 (A). From then on, there was a slow but continuous stress increase lasting until the end of 2005. From January 2006 until end of June 2006, there was a high stress plateau. The average monthly seismicity elevation time history (green graph) indicated that its downwards trend ended at the time when the energy index reached its average value of 1.0. From 2005, this graph indicates a slow but continuous upwards trend.

Figure 2.69 indicates that all larger size seismicity (or seismic energy releases) at PMC took place between April 2002 (A) and May 2004 (C), while the stresses, as indicated by the energy index time history (Fig. 2.67), were high. The energy index values between April 2002 and May 2004 were above the average value of 1.0.

Figure 2.70 shows the seismic energy release rates above the DOZ mine footprint. Larger energy releases commenced only after the energy index reached the value of 1.0 during February 2005.

Figure 2.71 indicates that the largest seismic deformation rates above the PMC Mine footprint took place while the energy index was above the mean value of 1.0.

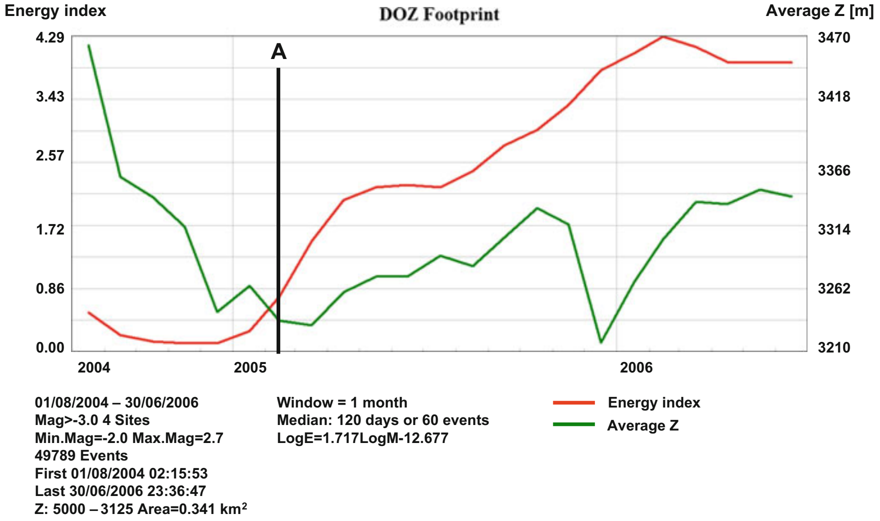


Fig. 2.68 DOZ Mine—seismic history above the mine footprint

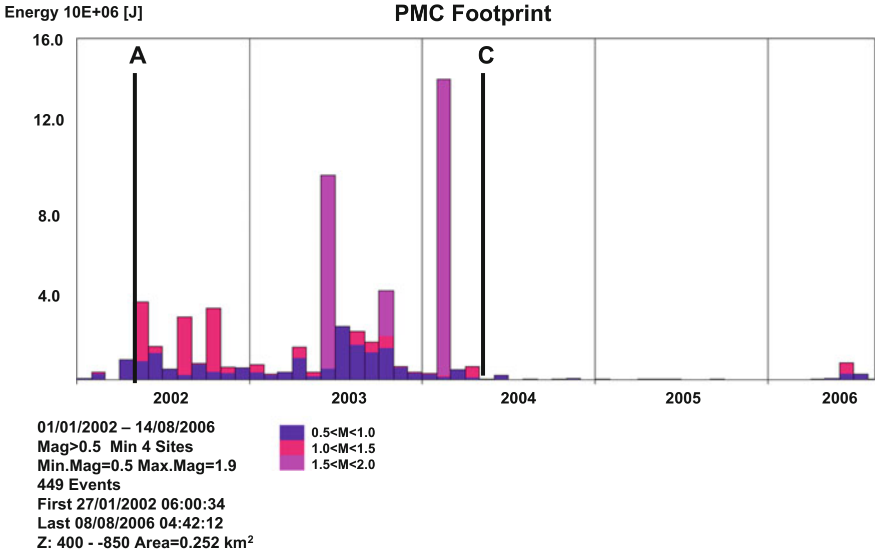


Fig. 2.69 PMC Mine—seismic energy release rates above the mine footprint

Figure 2.72 indicates that above the DOZ Mine footprint, there was more seismic deformation taking place from February 2005 when the energy index reached the mean value of 1.0.

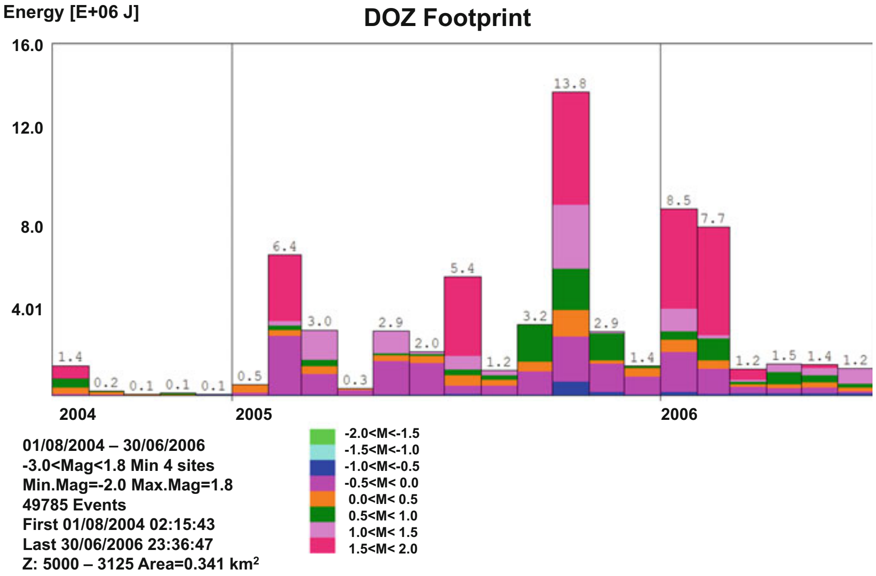


Fig. 2.70 DOZ Mine—seismic energy release rates above the mine footprint

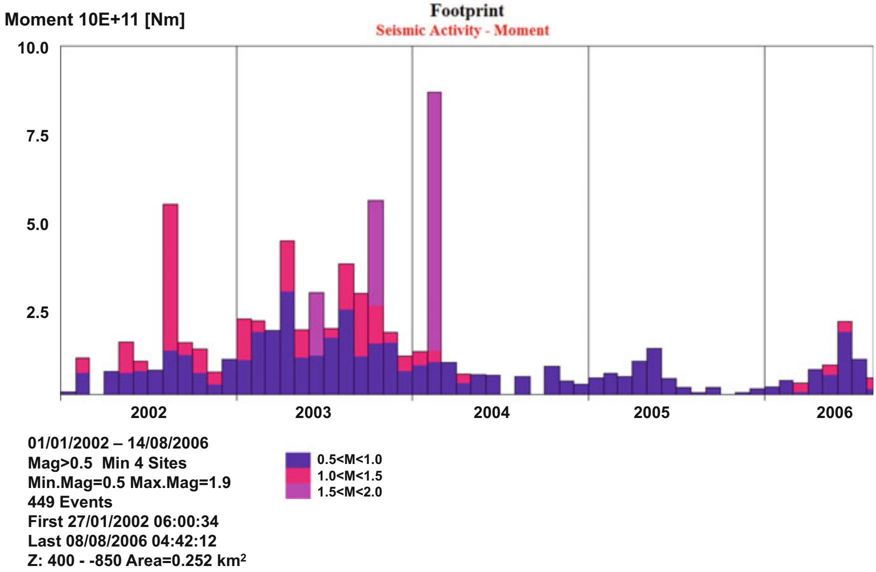


Fig. 2.71 PMC Mine—seismic deformation rates above the mine footprint

Figure 2.71 indicates also that in case of the PMC Mine, there was larger magnitude seismicity taking place when the energy index was above the mean value of 1.0

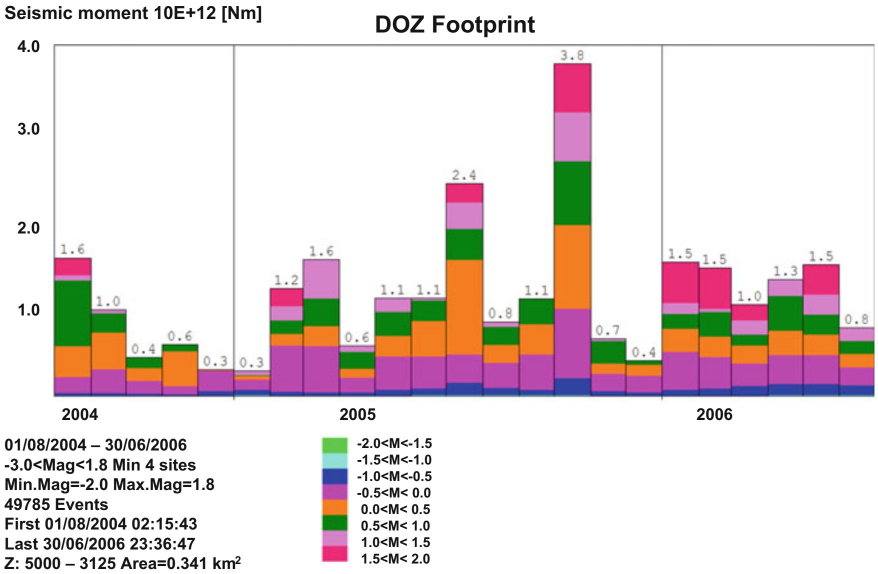


Fig. 2.72 DOZ Mine—seismic deformation rates above the mine footprint

than during the time period for which this value was below 1.0. Figure 2.72 indicates that at the DOZ Mine, from the time the energy index values were above the mean value of 1.0 (from February 2005), there was an increase in the seismic activity rates of events of magnitude larger than 0.5.

Experience from PMC has shown that the ratios of the seismic activities taking place above and below of the mine footprint are a good indicator of the seismic hazard level for the whole mine. Data from PMC demonstrates that during the time period when the energy index values are above the mean value of 1.0, that is when the seismic hazard was high, the seismic activity rates above the mine (number of events, energy and moment) were also high. When the energy index drops below the mean value of 1.0 there was an evident rapid decrease in all the three activity rates above the mine. Figure 2.73 and 2.74 show the percentages of the total seismic activity rates taking place above the mine footprint. Figure 2.73 is based on data recorded at PMC, while Fig. 2.74 is based on data recorded at Freeport Mine. At PMC all large size seismicity started (and with it an increased seismic hazard) only when the energy index reached values above 1.0 (A) and stopped when the energy index dropped to below the value of 1.0 (C). In June 2006, close to 80% of all DOZ seismicity took place above the mine footprint. Similar amounts of seismicity were recorded above the PMC Mine footprint just after the initiation of the stress caving process and the amount of seismicity remained high until the cave broke into the open pit.

Figure 2.75 shows the percentages of seismic energy released above the PMC Mine footprint. The general trend of the energy release ratios as indicated by this

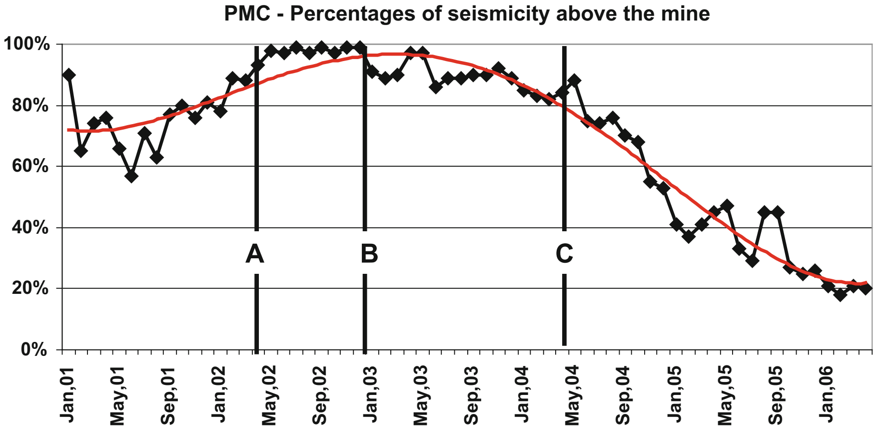


Fig. 2.73 PMC—percentages of seismicity above the mine footprint

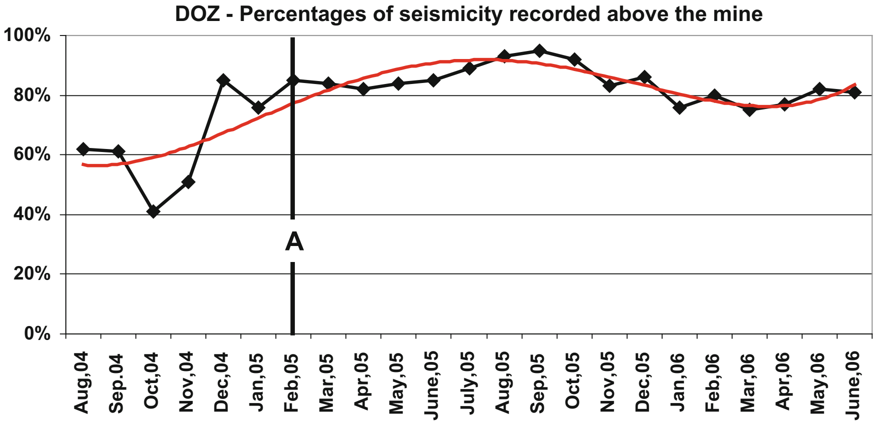


Fig. 2.74 DOZ—percentages of seismicity above the mine footprint

figure indicates that all of the large energy releases above the mine took place while the energy index for the mine was above the mean value of 1.0 and when more than 60% of all recorded seismicity took place above the mine footprint. Figure 2.76 indicates that by the end of June 2006, still more than 80% of seismic energy release at the DOZ Mine took place above the mine footprint. It is interesting to note that this value of 80% is virtually constant from the time the energy index reached the mean value of 1.0 during February 2005 (A).

Figure 2.77 shows the percentages of seismic deformation taking place above the PMC Mine footprint. As of the second half of 2001, there was a rapid increase in the seismic deformation percentage above the mine. When the energy index reached the mean value of 1.0 or when the stress caving process was initiated (A), nearly 100% of all deformation was associated with the rock mass volume located above the mine.

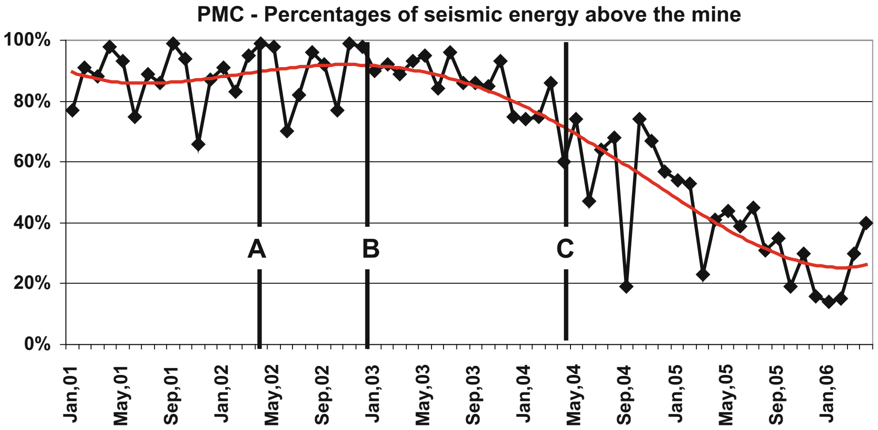


Fig. 2.75 PMC—percentages of energy released above the mine footprint

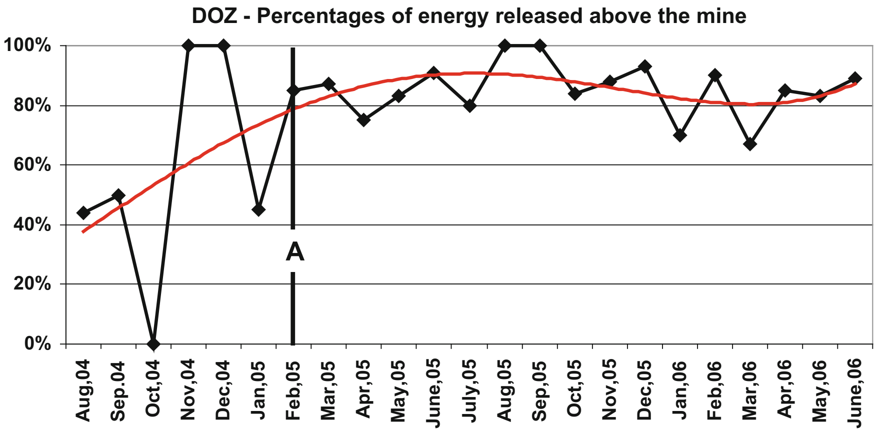


Fig. 2.76 DOZ—percentages of energy released above the mine footprint

With time this amount decreased gradually to about 80%. After the energy has index dropped to below 1.0 (C), there was an acceleration in the rate of decrease. By the end of 2006, only about 20% of all the seismic deformation was taking place above the mine footprint. At the time PMC cave was still developing on the east and west sides of the cave footprint. It must be assumed that until full break through into the open pit occurs, there will be some seismic deformation associated with this process. Figure 2.78 shows the percentages of seismic deformations above the DOZ Mine footprint. As in case of PMC, there is a gradual build-up until February 2005. From then on, more than 80% of all seismic deformation is taking place above the mine footprint.

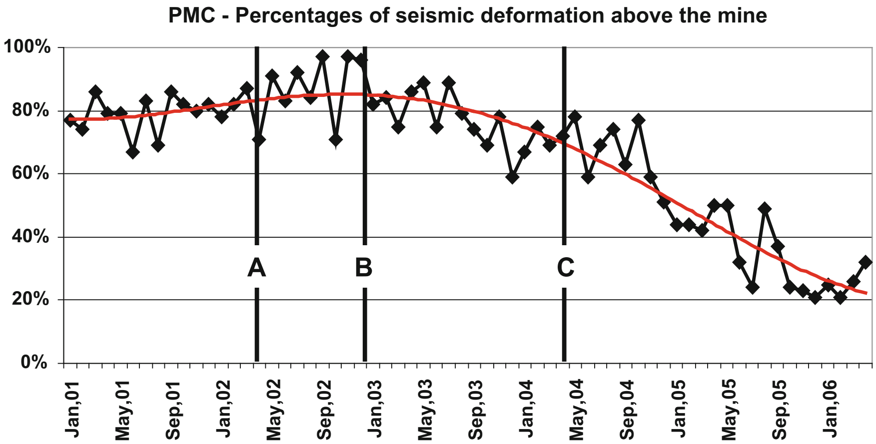


Fig. 2.77 PMC—percentages of seismic deformations above the mine footprint

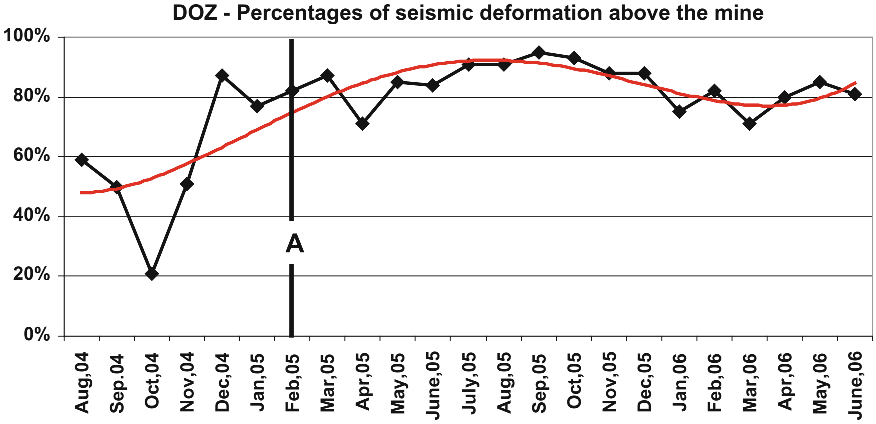


Fig. 2.78 DOZ—percentages of seismic deformations above the mine footprint

2.6.4 Conclusions

Seismic data recorded at PMC covers the time periods from before the initiation of the caving process, the Crown Pillar failure, the initial cave break through into the open pit and the present (end of 2006) mature phase of the caving process. On the other hand, the DOZ seismic database starts only after the DOZ Cave broke into the IOZ Cave. Time histories of the energy index and the average seismicity depths at PMC allowed for recreating the complete history of the caving process. This reconstruction is based on recorded and observed data and no assumptions had to be made as in the modelling process. Energy index time histories illustrate the stress changes that can then be related directly to the development and cave mining processes. The PMC seismic hazard was high while the energy index values, as indicated by their history graphs, were above the average value of 1.0. Most of the high seismic energy releases at PMC took place after the Crown Pillar failure and prior to the initial cave break through into the open pit. Some of these high energy releases resulted in rock bursts with associated damage to underground excavations. PMC also experienced during this time, stress-related damage to the underground excavations. Seismic histories of the PMC and DOZ mine footprints show a lot of similarities.

Experience with PMC seismic data has shown that the ratios of seismic activities taking place above and below the mine footprint are good indicators of the seismic hazard levels for the whole mine. Data from PMC demonstrates that during the time period when the energy index values are above the mean value of 1.0 (when the seismic hazard is high), the seismic activity rates above the mine are also high. When the energy index starts to drop from its maximum plateau, the seismic activity rates above the mine also decrease. This indicates that in general, the stresses started to migrate down and below the mine footprint. This stress migration accelerates once the energy index values drop below the mean value of 1.0. This acceleration of stress migration is also evident through the activity rates, as during this period there is a faster decrease in activity rates above the mine. Since the histories of the PMC and DOZ seismicity above the mine footprints show a lot of similarities then based on experience from PMC, the DOZ Mine can expect in near future more of high energy release seismic events. The energy index and the ratio of all seismic activity rates above and below the mine should be continuously monitored. This will allow not only for continuous stress (seismic hazard) monitoring but will also result in gaining additional information about the caving process status.

2.6.5 Eleven Years Later

When analysing and interpreting seismicity recorded up to the end 2006, it was concluded: "Since the seismic profiles/histories of the PMC and DOZ mine footprints show a lot of similarities, then based on experience from PMC, the DOZ Mine can expect in near future more of high energy release seismic events" (Glazer and Townsend 2006). I wrote Sect. 2.6.5 during August 2017 when I had access to seismicity recorded until the end of December 2009. Data presented in Fig. 2.70 is based on seismicity recorded for 23 months between 1 September 2004 and 30 June 2006. Figure 2.70 illustrates the monthly seismic energy release rates for a polygon named DOZ Footprint. This polygon's vertical range was from 5000 to 3128, and its area was 0.334 km^2. A simple test using data recorded from 1 July 2006 up to end of December 2009 in that polygon (DOZ Footprint) would prove if our prediction made in 2006 was true or false. Figure 2.79 presents the monthly seismic energy release rates in polygon DOZ Footprint for the time span from 1 July 2006 to end of December 2009 (42 months). During the 23 months from 1 September 2004 to 30 June 2006, the cumulated released seismic energy was 7.06E + 07 J while during the 42 months from 1 July 2006 to 31 December 2009, the cumulated released energy

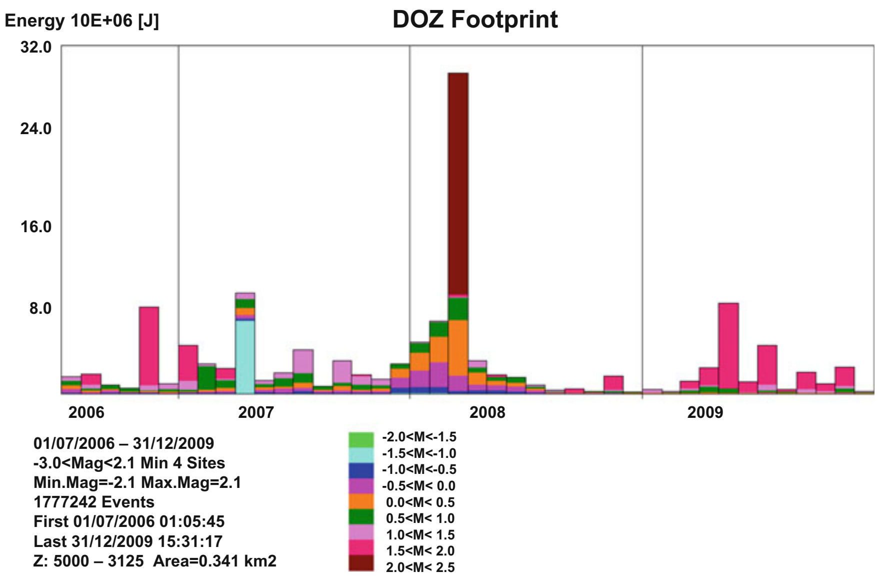


Fig. 2.79 DOZ Mine—seismic energy release rates above the mine footprint

was 1.15E+08 J. From this, the average monthly seismic energy rates for these two periods were:

1. For the time period 1 September 2004–30 June 2006, −11.7E+05 J per month
2. For the time period 1 July 2006–31 December 2009, −27.6E+06 J per month

From the above it appears that from the beginning of July 2006 the average seismic energy release was nearly twice as high from that recorded before July 2006. From this, it is clear that the prediction made in July 2006 was correct.

2.7 Conclusions

In this chapter apart of presenting seismic data that was made available for analysis and interpretation I compared against each other—small size events that were recorded in different mines. Presented analysis methods are so unsophisticated that they might appear not fit for the task. Additionally, a lot of work was done “by hand”. Method of presenting the results is also very crude not to say primitive. This has happened to me with one of my papers that I prepared for publishing. The reviewer of my paper pointed out that I used Office Excel to produce graph which in his opinion was probably not only unprofessional but inappropriate. Presented very basic data analysis resulted in at least two very important conclusions:

1. Hydro-fracturing resulted in seismicity of lower seismic energy releases

2. One of the mines was using different and faulty version of the seismic processing software

These conclusions were only possible because the analysis involved seismic data recorded in several mines. It would be impossible to get to these conclusions using data recorded in only one mine. Comparison to other data is very helpful in formulating conclusions. Still even with this approach one should be vigilant. It could be that the faulty software was the one used in most of the mines and the only outstanding results could be these with the fine (or better) software. Due to my experience, I was in position to trust the results from PMC. I used this data as reference. In this way, any data that was different from it had to be investigated for a reason. It seems logical that seismicity recorded in preconditioned rock mass would be of less energy. This is the reason for doing preconditioning. It so happens that preconditioning occurs also in a natural way when mining occurs in the same place for long time (years). This was the case of PMC where I defined this preconditioning as seismic preconditioning (Glazer 2016). I became aware of this after comparing energy release rates of small events below magnitude 0.0. It turned out that when comparing the energy release with time, there was a general trend that with time there is less and less of energy that is released. This is not unexpected as the energy index time histories indicate that with time this index value decreases. Both analyses of energy index and of small size events return same results. In the end, all small events are included in the energy index time history, and there are more of them than the larger ones. This does not change the fact that it was easy to proof that the hydro-fracturing changes the rock mass properties, in the required way by comparing data from different mines. This is direct proof in comparison to indirect prove (inference). Indirect prove would be comparison of energy released while mining in hydro-fractured rock mass of that in non-hydro-fractured rock mass. Even if there would be less seismicity or lower magnitude events while mining the hydro-fractured rock mass the conclusion about the benefit of preconditioning would not be without some reservations. In this case compared results originate from two different locations for which the rock mass conditions the geology or mining rates might have been different.

The second case when the analysed small events for one mine were different to these at the other mines was attributed to this mine recording system using different software version. I have already discussed this problem several times in this book and in Glazer (2016). Unfortunately, this is something that will not go away. While working at Vaal Reefs (Glazer 2017) it was the norm that we would report problems with the actual software version. We were told that this will be taken care of in new versions. Our requests to implement our interpretation ideas into this software were never accepted or implemented. The software provider knew better than us what we working on the mines need. That is the reason that we had developed our own interpretation software. While working for PMC I was able to order a version of this software that would be fit for cave mining.

Program HORNBILL is a part of Windows-based seismological software for the mining industry developed by HAMERKOP Scientific Services. Program HORNBILL enables visualization and analysis of seismicity induced in cave mines. Currently, it uses the seismic databases created by ISS International seismic system. First version of this software was released in 2002 at the request from PMC. At the time, it was clear that interpretation of seismicity induced by the caving process needed a different approach from that which was available in the ISS software. At the time, the ISS International interpretation software was being developed according to the needs of their main client (deep gold mines of South Africa). One of the problems was that the ISS software did not allow for direct comparison between the induced seismicity and the production rates or to continuously monitor the seismicity elevation changes with time. Development of this software was mainly based on experience gained at PMC. With time, this software was used to display and interpret seismicity at other cave mines. It was used at Northparkes Mines (V3) then at PT Freeport Indonesia (V4) and from 2009 I have been using it with data recorded at El Teniente. Software version 6.0 was released in June 2009. This software version was purchased by PMC. Based on specific requirements of The Mass Mine project a new version of this software was released during 2010. This new version (V7) among other features includes means for testing the quality and integrity of the seismic databases.

Review of the input seismic data for analysis and interpretation leads to the following conclusions: There is sufficient amount of seismic data available to reach the two objectives:

1. Improved understanding of the caving process
2. Methodology for monitoring the caving process for the mine practitioners

Collected seismic data is of high quality and consistent due to:

1. All data was recorded with the same type of seismic system
2. Most of recorded data was processed or reprocessed with the same version of software

Example of different seismic source parameters depending on the software version must act as a warning and we must be mindful of the following:

1. Seismic databases must be continuously tested for quality and consistency
2. It is recommended that before any seismic system software upgrade it is advisable to recalculate 2–3 months of recorded data and compare the results
3. Regardless of the comparison results it is recommended that the whole existing seismic database is always reprocessed with the new software version

Quality control of some of the seismic databases indicated that it is a fact that their quality decreases when the processing task is given to outside contractor who operates outside of the mine. Practice indicates that in such cases the mine seismologist must spend time on quality control this is assuming that data analysis and interpretation takes place at the mine.

Most of the recorded small size seismic events are an indication of the cave propagation process. This seismicity is a natural process indicating that the cave is progressing. The space and time distributions of these seismic events, as well as the changes of their source parameter values over time, should be associated directly with what is happening in the rock mass around the cave and the mining excavations.

Unfortunately, in some of the cases, that is not the case. These changes can be also attributed to different software versions or processing the events with a mixture of single and three components seismograms.

1. Small size seismic events from moment magnitude −1.0 up to magnitude 0.0 account for nearly 70–80% of recorded seismicity and their seismic energy release is very low at about 1–10% of the total seismic energy release. Only data from Northparkes Mine does not follow this pattern.
2. At Northparkes Mine, this size of seismicity makes up only 27% of the recorded seismicity and accounts only for 2.1% of the total released seismic energy.
3. The Northparkes Mine results are based on a seismic database that I received during 2009. This database consists of 129,893 seismic events recorded between 1 September 2002 and 7 May 2008.
4. On average, these small magnitude size events for PT Freeport Indonesia and PMC released more energy than the same size magnitude events recorded at El Teniente.
5. Comparison of the average seismic energy release rates for small size events recorded during mining of the hydro-fractured rock mass volume of Diablo Regimento Sector with the energy release rates of this same magnitude size recorded in the non-preconditioned rock mass volume revealed an interesting pattern. Depending on the event sizes the seismic energy release rates were as follows:

   5.1 For the lower magnitude size events from −1.0 up to −0.5 the energy release rates for seismicity induced in the hydro-fractured volume were higher than those events that originated from outside of this volume.
   5.2 Average seismic energy release rates for seismicity of magnitude sizes −0.3 and −0.2 for the two volumes are similar.
   5.3 Average seismic energy release rates for seismicity of magnitude size −0.1 and 0.0 were significantly lower in case of events originating from the hydro-fractured volume compared to those recorded outside of the hydro-fractured volume.

6. In order to establish the reason for the significant difference between the Northparkes Mine Seismicity and seismicity from the other mines, I have used two seismic databases: first being the original database (OLD) where the first seismic event was recorded during 1 September 2002 and the last one on the 31 January 2006. This database consists of 59,959 seismic events. Then during 2009, I received the second seismic database (NEW). This second database contained 129,893 seismic events recorded between 1 September 2002 and 7 May 2008.
7. Comparison between these two databases indicated large differences both in the released seismic energy and seismic moment values. In order to explain the reason for these differences I conducted five tests:

   7.1 In the first test I compared the cumulative energy and moment of seismic events recorded with a minimum of four and five stations between 1 January 2003 and 31 December 2005 that are in the OLD and NEW databases. This test indicated that at some stage the OLD database was reprocessed.

7.2 For the second test, I compared the average seismic energy release rates of the small magnitude size events. As previously these averages were based on monthly averages and were calculated for data recorded between the beginning of 2003 and the end of 2005. Both the NEW and OLD Northparkes seismic energy release rates are higher than the rates from the other mines. This indicates that the reason for the observed differences between Northparkes Mine and the other mines might be more complex and not just related to the version of processing software.

7.3 As a third test, I compared the relationships between seismic moment (moment magnitude) and the released seismic energy for events in OLD and NEW databases. In both cases, there is an unusually wide range of released seismic energy. In case of OLD events this wide energy range is reserved for events of magnitude range between -2.0 and -1.5. In the case of the NEW events this wide energy range shifts closer to events of magnitude -1.0.

7.4 In the fourth test, I investigated if there are any relationships between the events with wider and narrower ranges of emitted seismic energy and their vertical and time distributions. The result of the vertical distribution of seismicity is inconclusive while the time distribution analysis suggests that over time, some components of the triaxial stations might have been lost. This indicates that probably one component records were used to calculate the source parameters.

7.5 As a final and fifth test, I analysed the seismicity recorded during April 2008. This seismicity was recorded with a new seismic network and all stations had triaxial accelerometers. This seismic data set is very different and in general the energy release rates per magnitude are much lower than in case of the OLD and NEW seismicity. The average seismic energy releases for magnitude range -1.0 up to 0.0 are very similar to ones observed at the other mines.

7.6 In summation, these tests indicated that the main reason why the Northparkes Mine seismicity is very different from that recorded at the other mines are the seismic sensors. I think that over time some components of the triaxial accelerometer stations have been lost. This would then result in unusual seismic parameters as only three component recordings can be rotated before the process of estimating the seismic parameters. The another reason for these differences is the difference in software versions.

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Chapter 3
Seismic Signature of the Caving Process

Abstract The four seismic catalogues analysed in this chapter contain range from a couple of thousand events right up to a couple of hundred thousand events. The four seismic data sets are not only consistent as separate input catalogues, but also as a whole. The mines in question are not only using the same seismic system in the recording of the seismicity but the recorded data was subsequently processed using the same version of the software. Because of this the input data available was not only in sufficient quantity but also quality. I used two types of parameters in analysing the presented data. The first is based on the mining data and the second is derived from seismicity. By definition, the seismicity that I was analysing is mine-induced seismicity. The definition implies that there is a strong relationship between the mining activities and seismic parameters. This relationship is certainly there but it is not continuous in its nature, nor is it constant. As I have illustrated, an increase in production rates will not always result in an increase of the seismicity rates or in larger size seismicity taking place. The dependency between production and seismicity changes over time due to the progress of the caving process. The seismicity parameters that I have used are based on seismic moment and seismic energy, which are independent of each other. I have also used the locations of the seismicity as well as the rates. It is obvious that the seismicity rates, their locations and source parameters are independent of each other, and thus provide discrete results. The presented seismic data analysis and interpretation resulted in a description of precise and detailed seismic response to the caving process.

In this chapter, I will analyse seismicity recorded at:

- PT Freeport Indonesia DOZ Mine
- Diablo Regimento Sector of El Teniente Mine
- Northparkes Lift 2 Mine.

The aim of this examination is to establish the seismic response to the caving process that is common to all mines. I will be using the seismicity recorded at PMC, to benchmark the milestones of the caving process. In my opinion, the seismicity recorded at PMC is appropriate for this task; due to the quantity and quality, as well as its time duration. This database includes seismicity that was recorded when the

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caving process was initiated and when the crown pillar failed and also during the initial break through. In addition to this, seismicity includes data relating to the east break through, which took place nearly 4 years after the initial one. What is more important is the fact that these caving milestones were evidenced by other information independent of the seismicity. The position of the cave back was, up to some time, monitored by Time-Domain Reflectometer measurements (TDR) and open holes. The position of the a-seismic zone around the cave was confirmed by several holes drilled from the bottom of the open pit. The failure of the 200 m thick crown pillar was first recognized and documented only by interpretation of the seismic data. This was then verified when storm water nearly flooded a section of the mine. The fact that there was a break through was later confirmed by survey measurements based on aerial photography. As a result, I have a lot of confidence in the timing of these caving milestones. Another important point is the fact that the PMC seismic data base is supplemented by complete information concerning the various production rates. This information is accurate as it was collected right from the start of the seismic recording on a daily basis (Glazer 2016).

3.1 Introduction

Presented study not only illustrates the fact that seismic data analysis can be used successfully to monitor the caving process but also confirms 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 consist of all recorded data as in the cases of energy index time histories, or only rates of released seismic energy or seismic moment are used, 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 changes in the seismic activity rates were important, even when seismic migration trends were analysed only the monthly average seismicity elevations were taken into account. Again, in these cases, accurate location of each event was not that important. Accurate locations of seismicity are very difficult to achieve. For this, the 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. Such ideal sensor configurations are often not possible to implement due to technical problems but are also not warranted from the expenditure point of view.

The initiation of the caving process is the first milestone of the caving process. It was recognized as taking place in three mines. 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 progression 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 also evidence the occurrence of the initiation.

The crown pillar failure at PMC was first recognized only by analysis of seismic data and because of this was questionable but only up to the time when it was confirmed by nature as a fact. Directly after a heavy storm, excess water was reported underground. This indicated that there was a hydraulic connection between the open pit and the underground mine through the 200 m thick rock mass still remaining at the time. This could only mean that this rock mass was highly fractured and that the pillar had already failed. Up to date, I have only encountered one such milestone of this type, but its occurrence cannot be disputed.

The cave breaks through is the most common caving milestone as it appears seven times: twice at the PMC, three times at Freeport, once at Diablo Regimento and once at Northparkes. This is a significant advantage in the interpretation process. This should allow not only for more detailed analysis but also for deriving more general conclusions. All listed break throughs (apart from the PMC east break through) were confirmed by TDR measurements and production data. The PMC east break through was confirmed by seismic data 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.

The mature stage of the caving process is a concept rather than a fact. This concept is based on the assumption that at some stage 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 it can influence. In this concept, it is assumed that the caving process might come to its end before the end of the mining operations. In this case, most or all of the left behind volume of the ore body rock mass volume will be fractured to such an extend that it will continue to cave in.

In this chapter, I will analyse seismicity recorded at other mines rather than at Palabora Mining Company. I have already analysed and presented the interpretation of the seismicity recorded at PMC. This analysis is described in my first book (Glazer 2016) of which the subtitle is “Palabora Mine Caving Process as Revealed by Induced Seismicity”. I was working with seismicity recorded at PMC continuously from 2002, so I know and understand it very well. I will be using seismicity recorded at PMC as a benchmark for the seismic signature of the caving process. The PMC benchmark of the caving process seismic signature is of high-level and seems to be complete. In the seismic data analysis, I have used the following parameters in various forms:

- Seismic activity rates
- Seismic energy release rates
- Seismic moment rates
- Seismicity elevation trends
- Energy index time histories
- Seismically active areas and volumes.

I have developed and implemented a number of interpretation methods that are in some way independent of the seismicity location accuracy. In this, interpretation groups are procedures that analyse the trends of seismicity recorded in certain volumes of the mine in relation to seismicity recorded in other mine volumes. These volumes differ depending on the input data. Sometimes the volumes are rock mass volumes located above and below the extraction level. Mining data allows for comparison of the seismicity located above the mine footprint with those located below the mine footprint elevation. It is often possible to define the cave volume, and then compare the seismicity recorded in this volume with that recorded around this volume. All these parameter analyses are then combined with each other when the relevant parameters are independent of each other. The resulting seismicity trends are then related to the production rates. Before attempting any data analysis, it is important to understand its limitations and faults. In case of the presented three seismic catalogues, it seems that the main limitation is with the seismic energy release rates. I have found that all three seismic data bases contain a number of events that released exceptionally high amounts of seismic energy and these obscure the whole energy release trend. I assume that these events were first processed correctly but their energy release rates could be distorted in the process of database recalculation.

3.2 PT Freeport Indonesia DOZ Mine

Figure 3.1 shows the DOZ seismic data base. This figure illustrates the monthly seismicity rates together with the production (black line) and development (red line) monthly rates. By the end of August 2010, this seismic database contained over 522,000 seismic events recorded with four or more stations. During 2002, there was a test seismic network in operation. This network consisted only of a couple of stations which during the end of 2002 and beginning of 2003 were destroyed by the cave progression. The new seismic network came online in August 2004. For this reason, there is no seismic data recorded during whole year of 2003 and part of 2004. The lower seismic activity rates since the beginning of 2010 are due to the fact that at the time nearly one-third of the seismic stations were not operational.

The break through at the east took place before the seismic network was installed. The break through at the centre part took place at the end of 2005 (Fig. 3.2). Figure 3.3 shows the estimated DOZ cave back position at the beginning of 2006. Here, the centre pillar is shown already as part of the cave back. The cave mining was at that time taking place below the minimum elevations of the IOZ cave. Figure 3.4 illustrates the estimated DOZ cave position at the end of 2008 and beginning of 2009. According to this figure, the DOZ cave already broke into the IOZ cave at its central part. The presented cave back positions are based on production data and were confirmed by TDR data.

Figures 3.2, 3.3 and 3.4 imply that the DOZ seismic data base should contain information about:

- East break through (incomplete due to the interrupted seismic monitoring)
- The end of 2005 break through (at the east)
- The central break through (into the IOZ cave minimum elevation part).

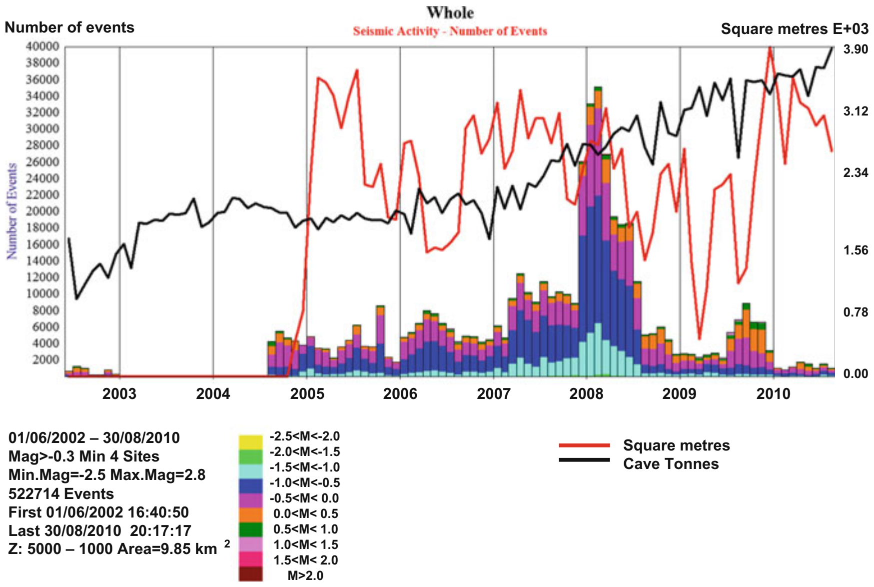


Fig. 3.1 DOZ seismic data base

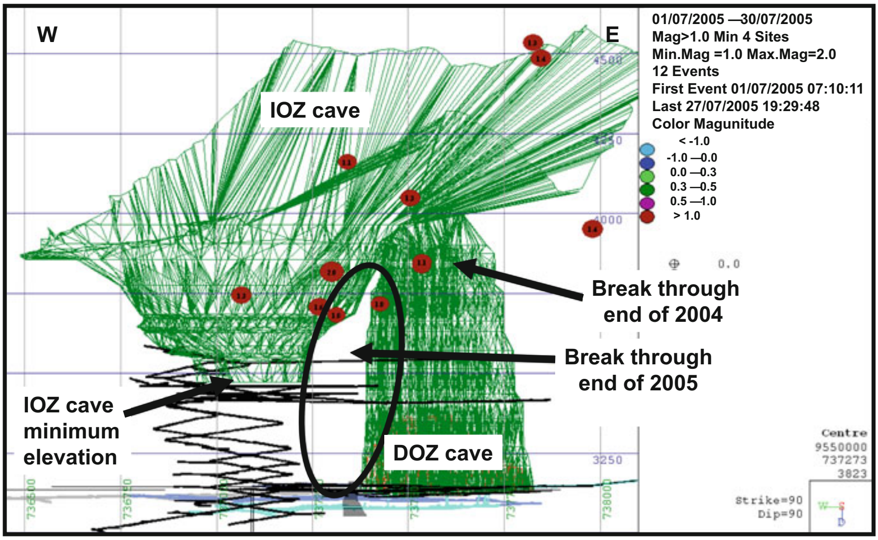


Fig. 3.2 DOZ and IOZ cave backs after the break through

For the purpose of presented analysis, I will use the following description for differentiating between the three breaks through:

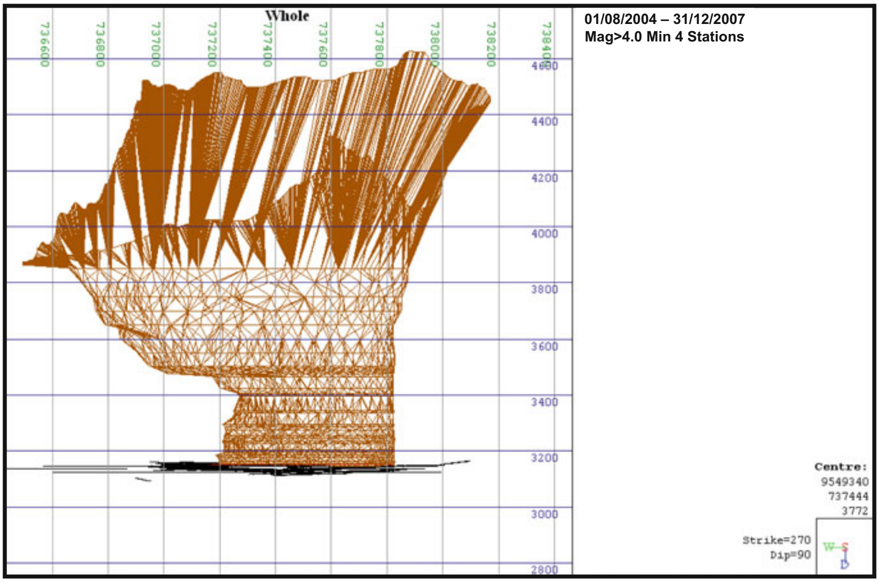


Fig. 3.3 Estimated DOZ cave back at the beginning of 2006

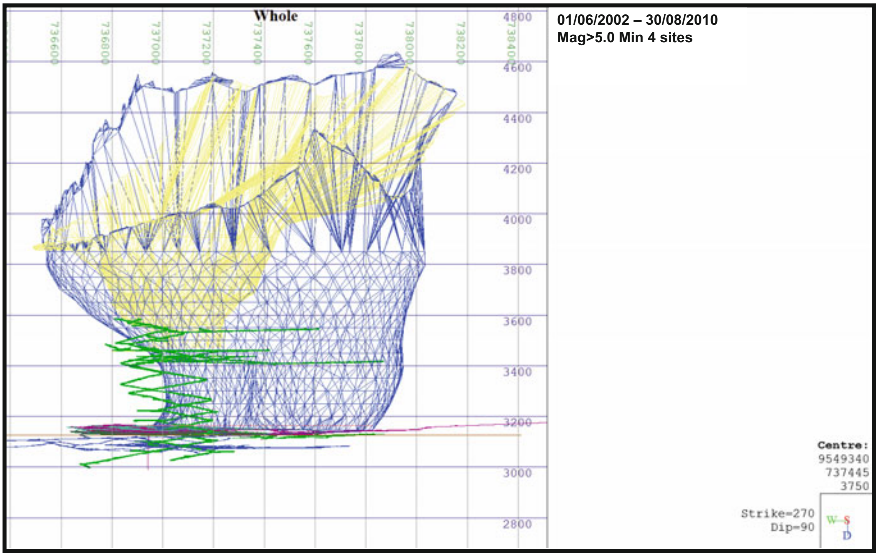


Fig. 3.4 Estimated DOZ cave back at the end of 2008

- The first break through that took place by the end of 2004 will be referred to as break through (1)

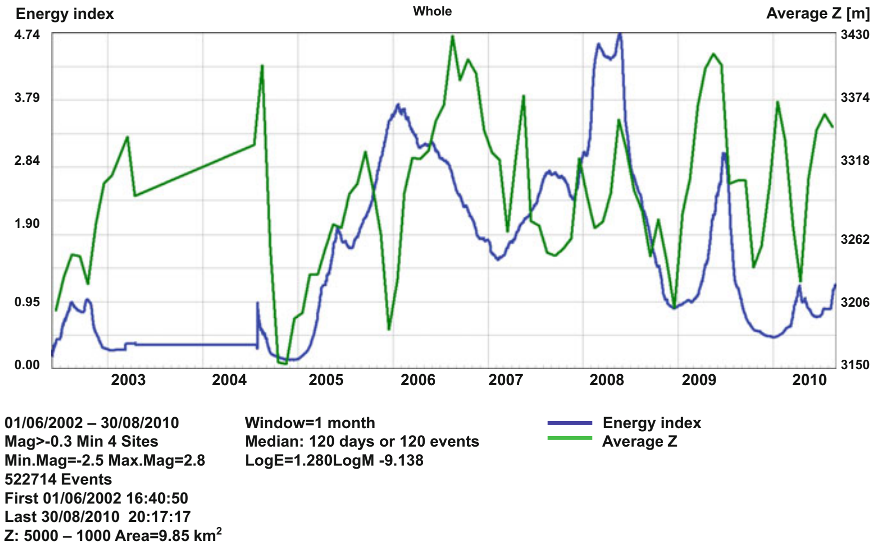


Fig. 3.6 Seismically active area time history

- The second break through that took place by the end of 2005 will be referred to as break through (2)
- The third break through that took place by the end of 2008 will be referred to as break through (3).

3.2.1 Analysis of the Whole DOZ Seismic Data Base

Figure 3.5 illustrates the energy index (blue) and the average monthly seismicity elevation (green) time histories. This figure indicates that:

- During 2003, the energy index probably reached a maximum and the average monthly seismicity elevations reached their minimum values. This incomplete seismic data would confirm the break through (1) taking place.
- The energy index time history has then two maximum points: at the end of 2005, and then by mid-2008. This would indicate that the caving process has gone through the following next two break throughs (2) and (3).
- The average monthly seismicity elevation time history at this point is inconclusive as the elevation changes do not coincide with the energy index time history.

Figures 3.6 and 3.7 illustrate the changes of the seismically active area and volume. The seismically active area was calculated using the 95% option (Glazer 2016). Both these figures confirm the break through (1) but do not contribute any information about the other two break throughs.

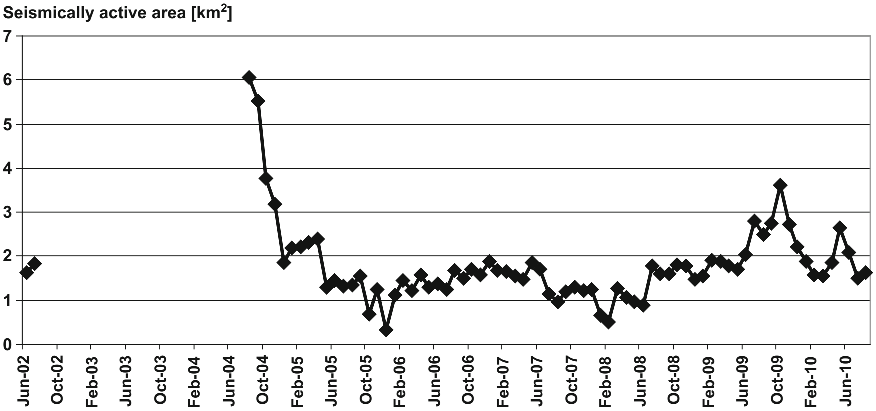


Fig. 3.5 Energy index time history

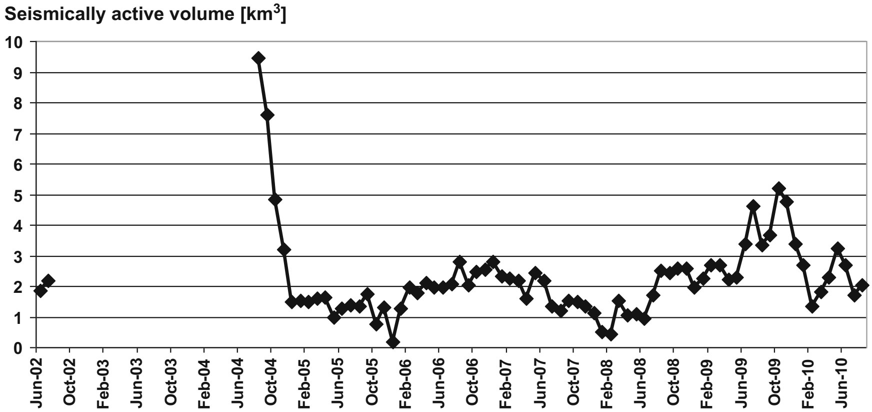


Fig. 3.7 Seismically active volume time history

Figure 3.8 illustrates the monthly maximum and minimum seismicity elevation changes from 2002 until 2010. This data indicates that during 2002 and 2003 there was a significant change in the minimum elevation values. This must be associated with the break through (1). The post-2004 minimum seismicity elevation changes suggest that, during 2005–2006, and then during 2008, there were some changes in the caving process.

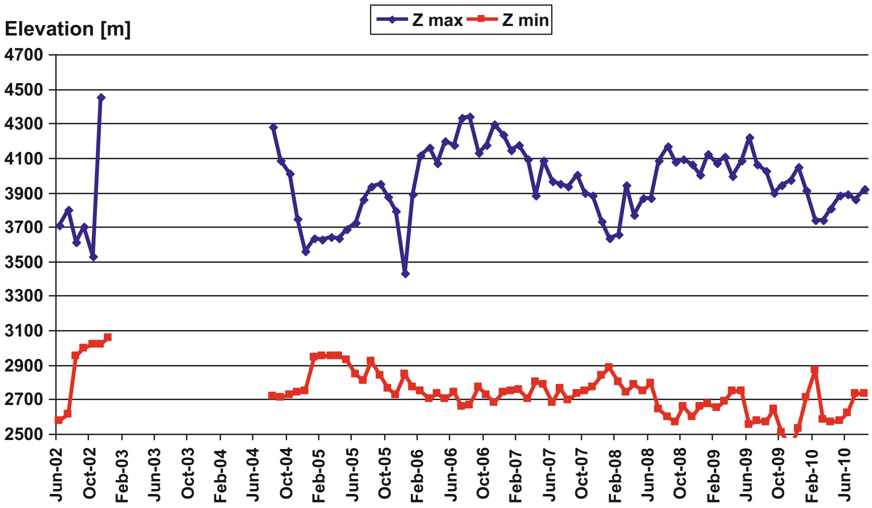


Fig. 3.8 Minimum and maximum elevation changes

3.2.2 *Analysis of Seismicity Recorded Inside of the DOZ Footprint*

Analysis of the whole DOZ seismic data basis resulted only in confirming the break through (1). There is no direct or reliable evidence that the other two break throughs took place. Presented analysis indicates only that the caving process went through some stages. From the presented data, it is only possible to conclude that the magnitude or size of the next two stages was less significant in comparison to the break through (1). This is due to the following:

- Break through (1) took place when the seismic data base was small in size and the recorded seismicity was limited only to the break through volume (and area).
- Further changes to the cave shape took place at the time when the seismic database was already large and contained seismicity associated not only with the caving process but also that induced by the development mining. It must be assumed that this database also contains large size seismicity associated with post breakthrough (1) period.

It is not easy to divide the mine into smaller volumes plotting some arbitrary polygons that can be backed up by some logic. But it is logical to reduce the number of seismic data by limiting it to that taking place directly above and below the mine footprint. The shape of the mine footprint is based on mining data which is real. In this way, the resulting polygon shape is based on sound assumptions. Figure 3.9 illustrates the shape of DOZ footprint. This footprint is based on mining data from the end of 2010. In this way, the number of seismic events was reduced by approximately 40% (from 522,000 to 330,000 events).

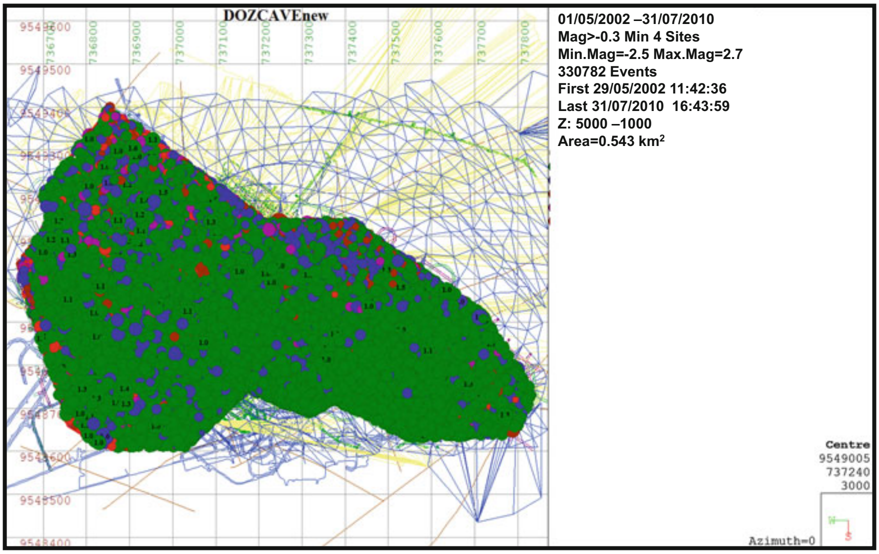


Fig. 3.9 DOZ mine footprint

Figure 3.10 illustrates the monthly seismic activity rates of the seismicity recorded above and below the mine footprint. This figure also illustrates the fact that the increased 2008 monthly seismicity rates are not associated with production rates but rather with mining through a specific rock mass formation.

The energy index and average monthly seismicity elevation time histories are illustrated in Fig. 3.11. The energy index time history trend changes as illustrated by this figure are more evident from the ones illustrated in Fig. 3.5 (for the whole seismic data base). Here, from the beginning of 2005, there were two distinctive peaks in the energy index time history. The stresses from the beginning of 2005 were increasing to reach the maximum value at the beginning of 2006. From the beginning of 2006, there was a stress decrease which lasted until the beginning of 2007. During 2007, right up to mid-2008, there was a following stress increase. After the stress reached its second maximum during the first months of 2008, there was a continuous and rapid stress release lasting until the beginning of 2009. During 2009 and 2010, the stress level was continuously low. It seems that these stress changes are associated with the two break throughs, the break through (2) and the break through (3) into the minimum elevations of the IOZ Cave. On the other hand, the trend of the seismicity elevations is not so easy-to-read. From the end of 2004, until the end of 2005, there was a continuous upward seismicity migration which was then followed by—a short in time but distinctive downward migration during the last quarter of 2005. Then, from the beginning of 2006, the seismicity started to migrate upwards. This migration is not continuous but its upward trend ended during the first months of 2008. During the following months of 2008, there was an evident downward migration. The 2005 seismicity migration pattern supports the concept of

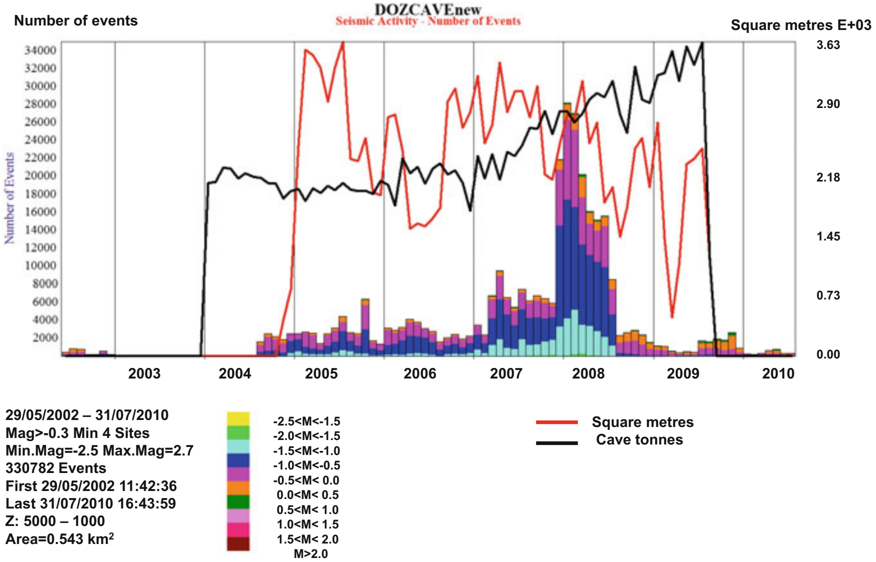


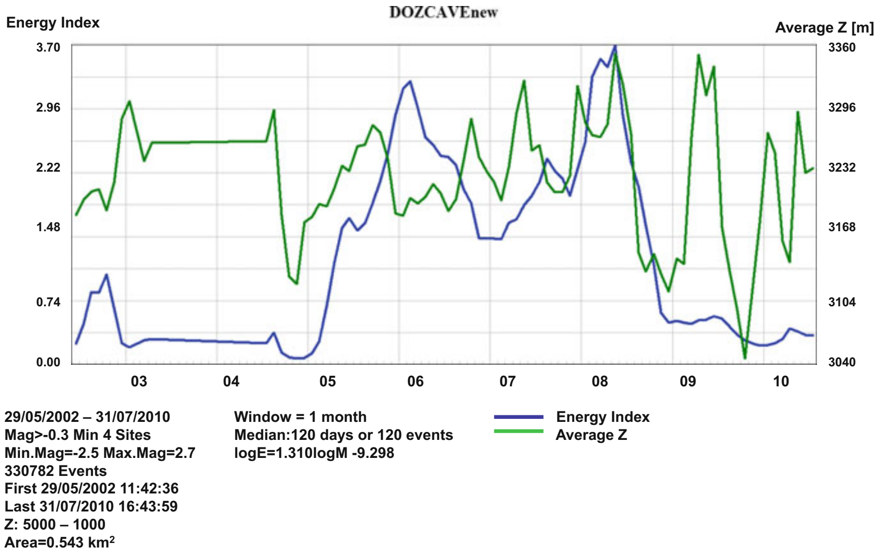
Fig. 3.10 Monthly seismic activity rates

the break through (2) taking place. Based on presented data, the 2008 break through (3) is only partially supported by the seismicity migration pattern. The seismicity upwards migration long-term (2.5 years) pattern but not its continuity (which could be influenced by the production rates), and then its downwards migration pattern at the beginning of 2008 support the concept of the break through (3) taking place.

The next four figures illustrate the monthly percentages of seismicity recorded above the extraction level. In all four cases, 100% is the amount of seismicity recorded above and below in one month. Figure 3.12 illustrates the percentages of the monthly seismicity rates, Fig. 3.13 illustrates the monthly percentages of seismic deformation, and Fig. 3.14 illustrates the stress percentages while Fig. 3.15 illustrates the seismic energy percentages.

Figure 3.12 indicates that during 2005 the amount of seismicity recorded above the mine footprint increased from 40% (November 2004) to more than 90% (during August and September 2005), and then decreased to less than 70% (March 2006). From mid-2006, the percentages of seismicity recorded above the mine footprint continuously increased to about 95% during the beginning of 2008. There is a substantial decrease in the percentages of seismicity recorded above the mine in the second half of 2008. This decrease is from 95% right down to 40%. Analysis of the monthly percentages of seismicity recorded above the mine footprint supports the concept of the two break throughs (2) and (3) taking place.

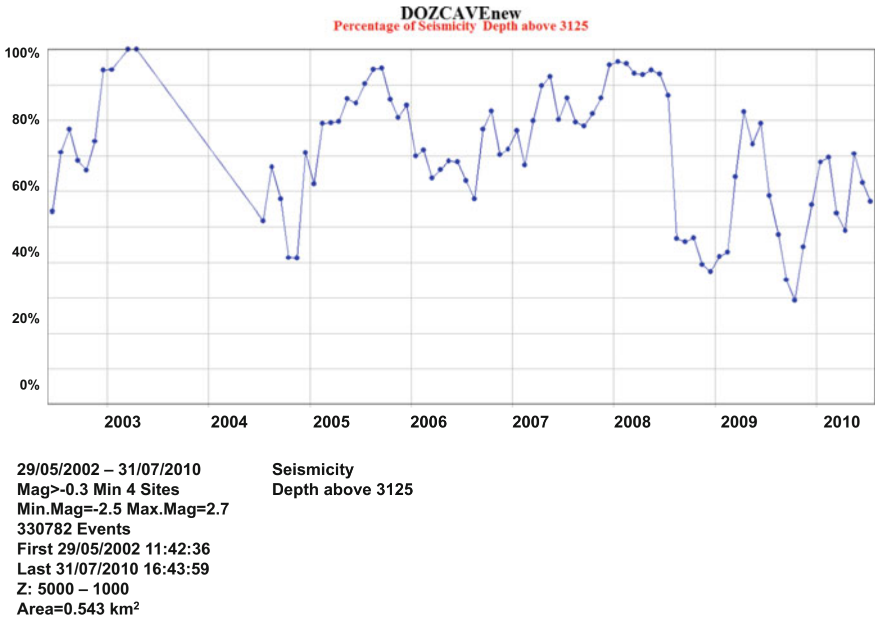
Analysis of data presented by the next two figures of the percentages of seismic deformation Fig. 3.13 and stress above the mine footprint Fig. 3.14 only partially supports the results of the analysis of the percentages of seismicity recorded above



29/05/2002 – 31/07/2010
Mag>-0.3 Min 4 Sites
Min.Mag=-2.5 Max.Mag=2.7
330782 Events
First 29/05/2002 11:42:36
Last 31/07/2010 16:43:59
Z: 5000 – 1000
Area=0.543 km²

Window = 1 month
Median:120 days or 120 events
logE=1.310logM -9.298

Fig. 3.11 Energy index and seismicity elevation time histories

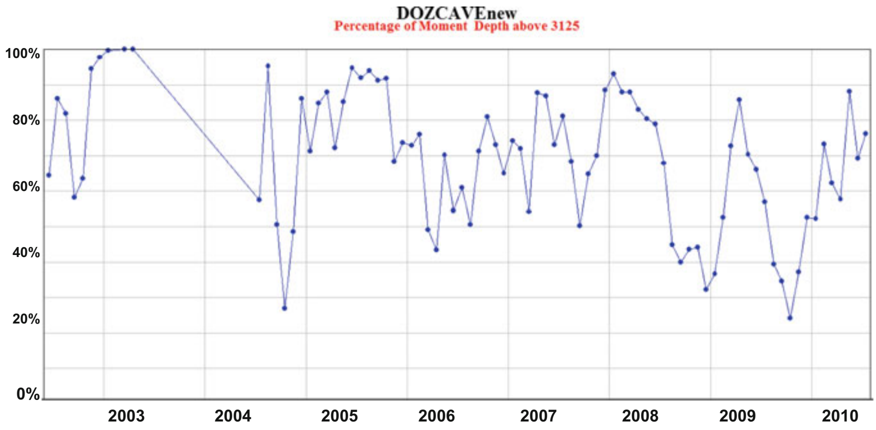


29/05/2002 – 31/07/2010
Mag>-0.3 Min 4 Sites
Min.Mag=-2.5 Max.Mag=2.7
330782 Events
First 29/05/2002 11:42:36
Last 31/07/2010 16:43:59
Z: 5000 – 1000
Area=0.543 km²

Seismicity
Depth above 3125

Fig. 3.12 Percentages of seismicity recorded above the DOZ footprint

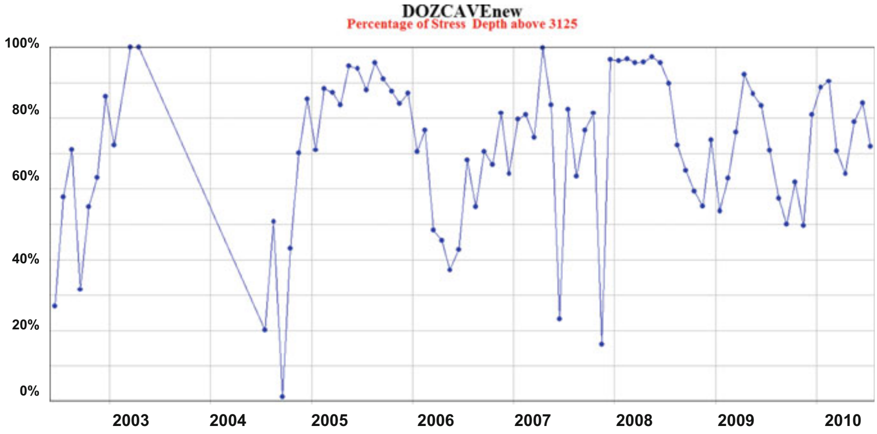
the mine footprint. In both cases, the break through (2) seems to be more evident than the subsequent break through (3).



29/05/2002 – 31/07/2010
Mag>-0.3 Min 4 Sites
Min.Mag=-2.5 Max.Mag=2.7
330782 Events
First 29/05/2002 11:42:36
Last 31/07/2010 16:43:59
Z: 5000 – 1000
Area=0.543 km^2

Moment
Depth above 3125

Fig. 3.13 Percentages of seismic deformation above the DOZ footprint



29/05/2002 – 31/07/2010
Mag>-0.3 Min 4 Sites
Min.Mag=-2.5 Max.Mag=2.7
330782 Events
First 29/05/2002 11:42:36
Last 31/07/2010 16:43:59
Z: 5000 – 1000
Area=0.543 km^2

Stress
Depth above 3125

Fig. 3.14 Percentages of apparent stress above the DOZ footprint

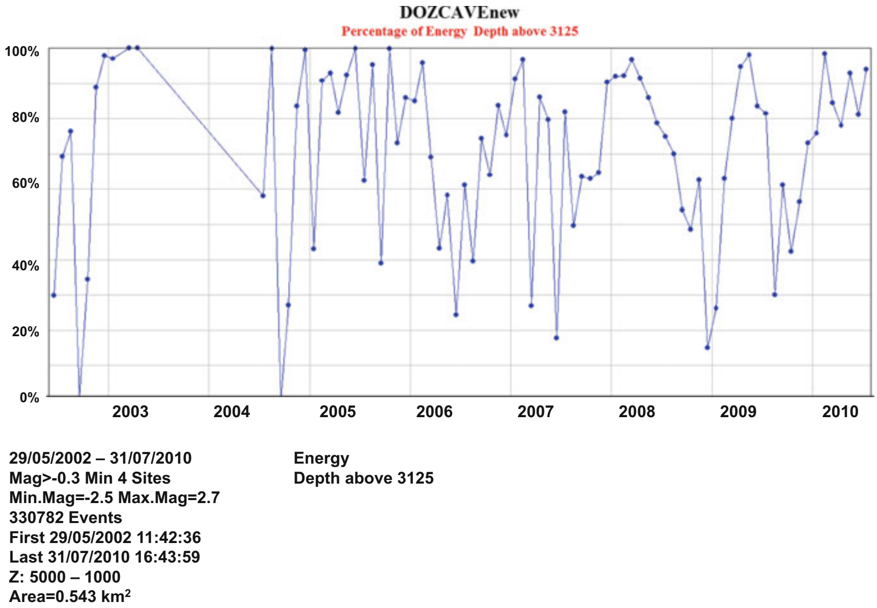


Fig. 3.15 Percentages of seismic energy released above the DOZ footprint

The trends of the percentages of seismic energy released above the mine footprint illustrated in Fig. 3.15 are difficult to recognize and can be only traced once the previous ones especially the one based on percentages of seismicity recorded above the mine footprint are acknowledged. This is not good enough and needs further analysis in order to find the reason.

Figure 3.16 illustrates the magnitude size distribution. The seismicity recorded above and below the mine elevation consists of events that have a wide range of magnitude sizes from −3.0 up to magnitude 2.7. It is obvious that there will be a large range of energy release sizes. In this catalogue, there are 755 events of magnitude above 1.0. Each of these events contributed substantially towards the data presented in Fig. 3.15. As a matter of fact, these 755 events emitted nearly 93% of the total seismic energy, which would then explain the considerable month to month changes in the percentage values as illustrated in Fig. 3.15.

While analysing the monthly seismic energy release rates, I noticed certain irregularities regarding the energy release sizes. Figure 3.17 illustrates the nature of this problem.

During September 2004, there was a very high seismic energy release rate. This high energy release was associated not with a large size event (above magnitude 1.0) but seems to be connected with an event in magnitude range 0.5 up to 1.0 (the dark green colour events on Fig. 3.17).

Figure 3.18 illustrates the average energy release by events magnitude size from 0.0 up to 1.0. Results are obscured by the extremely large average energy release

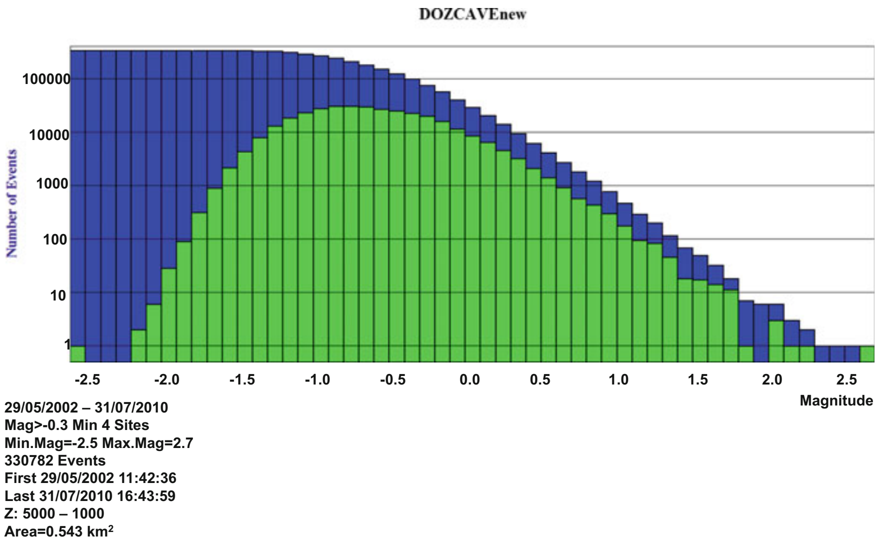


Fig. 3.16 Distribution of magnitude sizes above and below the DOZ footprint

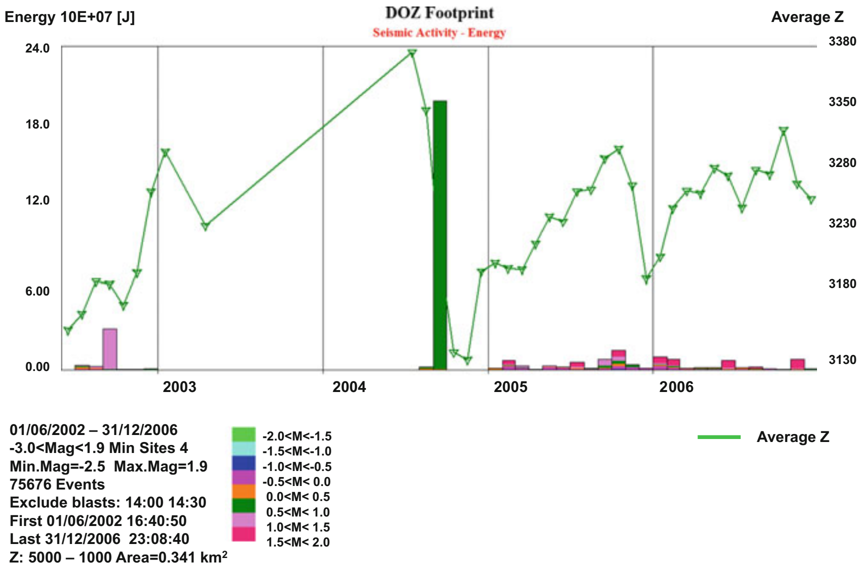


Fig. 3.17 Monthly energy release rates

of events magnitude size 0.7. According to presented data, an event of this size on average released much more energy than some of the larger size events.

Table 3.1 lists the energy release values of events magnitude 0.7 recorded during September 2004. According to this data, the event recorded on the 2 September 2004

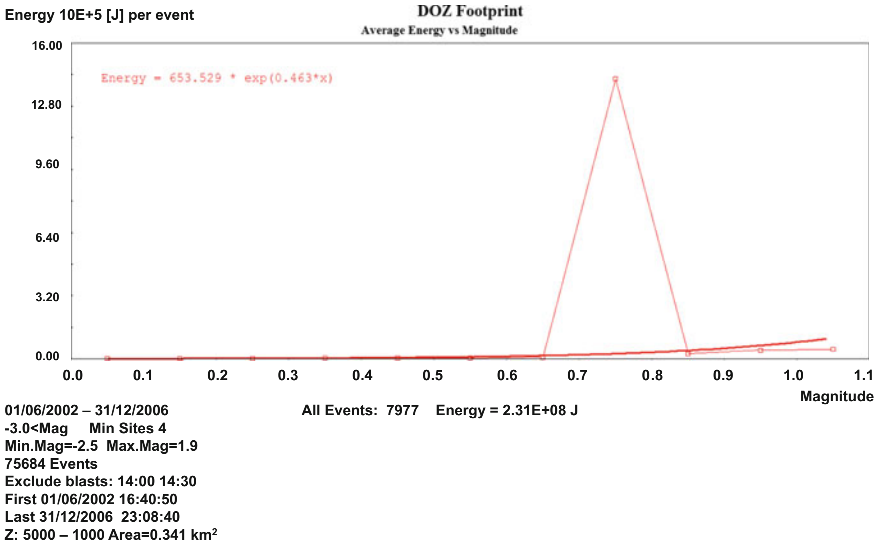


Fig. 3.18 Average energy releases version 1

Table 3.1 Energy release by events magnitude size 0.7

No.	Date	Time	X (m)	Y (m)	Z (m)	Mag.	Energy (J)
1	02/09/2004	09:31:53	737,165	9,548,975	2833	0.7	19.9E+07
2	23/09/2004	21:12:07	737,646	9,548,826	3270	0.7	2.7E+02
3	28/09/2004	12:18:46	737,693	9,548,705	2810	0.7	4.6E+02
4	29/09/2004	23:05:23	737,699	9,548,734	4071	0.7	6.5E+02

released nearly 1,000,000 times more energy in comparison to the other three events of this same magnitude size. I have removed this event from the specifically small seismic catalogue created for this exercise.

After removing the event magnitude 0.7 of 2 September 2004, the average seismic energy release by events size 0.0 up to 1.1 is now illustrated in Fig. 3.19. The presented new distribution seems to be correct and acceptable as with increase in magnitude (or moment) there is as would be expected an exponential increase in the released energy. Still, this is not the end of the problem. Figure 3.20 illustrates the monthly seismic activity rates of events greater than magnitude 0.5 during 2005 and 2006. There is a sizeable energy release increase during October 2004 which might be associated with break through (2). This is illustrated in Fig. 3.21.

Figure 3.21 indicates that practically all of these two years emitted seismic energy was due to two large events: of magnitude 2.2 (during October 2005) and of magnitude 2.3 (during June 2005). It is possible that an event of moment magnitude 2.2 can release more energy than event of magnitude 2.3 (this depends on the stress level)

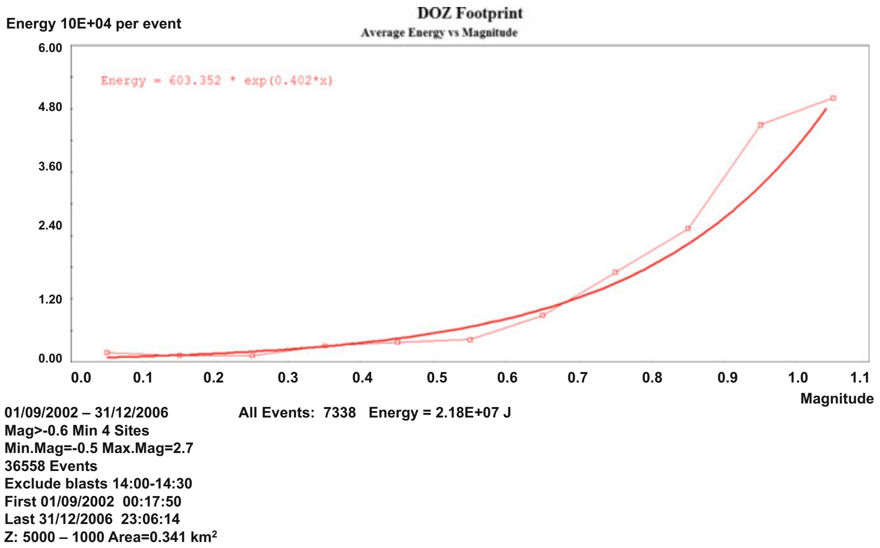


Fig. 3.19 Average energy releases version 2

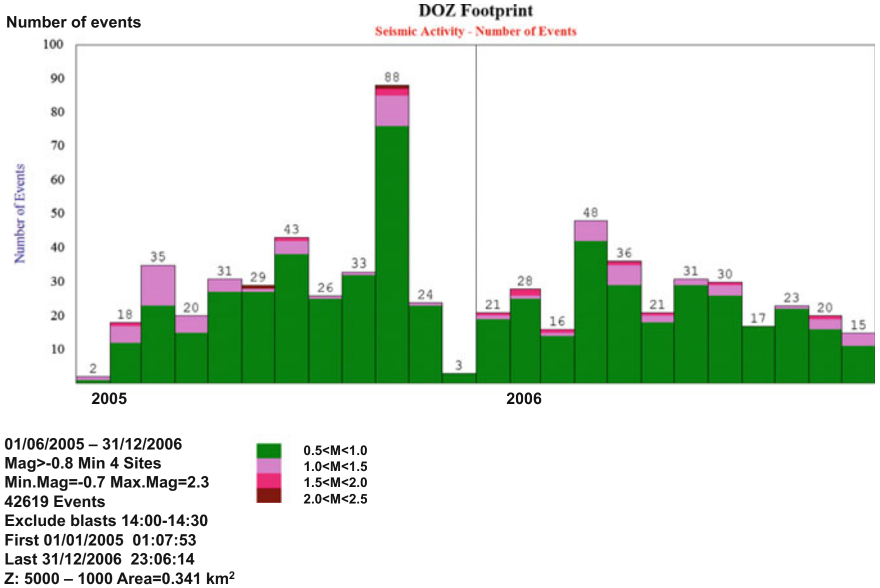
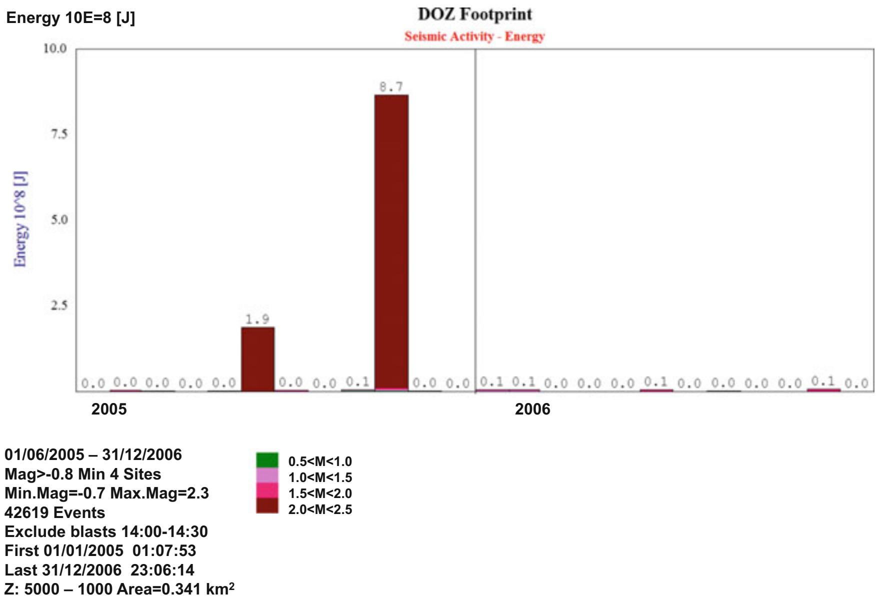


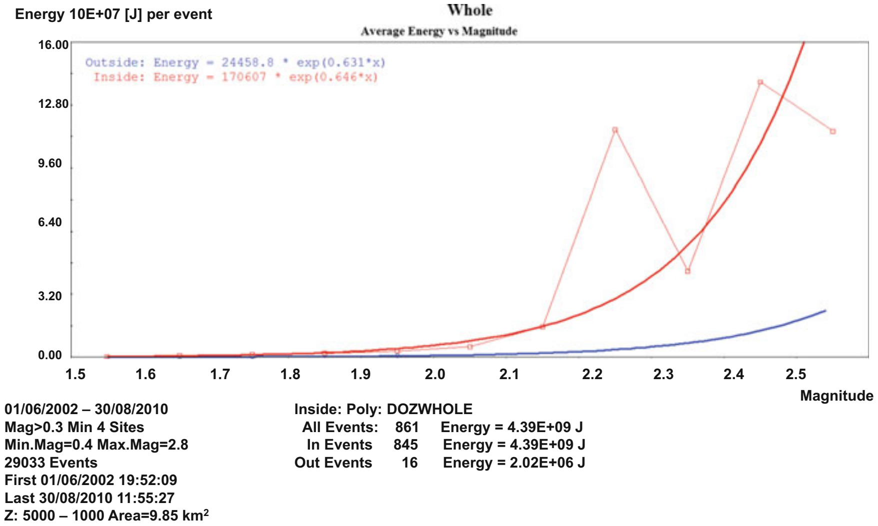
Fig. 3.20 2005–2006 activity rates of larger size seismicity

but with this limited catalogue (only two large size events) I am unable to correct for this possible irregularity.



01/06/2005 – 31/12/2006
Mag>-0.8 Min 4 Sites
Min.Mag=-0.7 Max.Mag=2.3
42619 Events
Exclude blasts 14:00-14:30
First 01/01/2005 01:07:53
Last 31/12/2006 23:06:14
Z: 5000 – 1000 Area=0.341 km^2

Fig. 3.21 2005–2006 seismic energy release rates



01/06/2002 – 30/08/2010
Mag>0.3 Min 4 Sites
Min.Mag=0.4 Max.Mag=2.8
29033 Events
First 01/06/2002 19:52:09
Last 30/08/2010 11:55:27
Z: 5000 – 1000 Area=9.85 km^2

Inside: Poly: DOZWHOLE
All Events: 861 Energy = 4.39E+09 J
In Events 845 Energy = 4.39E+09 J
Out Events 16 Energy = 2.02E+06 J

Fig. 3.22 Average energy release for magnitude size 1.5 up to 2.5

Data presented in Fig. 3.22 is based on the whole DOZ seismic catalogue. There are 88 events of magnitude size 2.0 up to 2.3. From this data, it is obvious that there must be one or more events of magnitude 2.2 that have far too large energy releases.

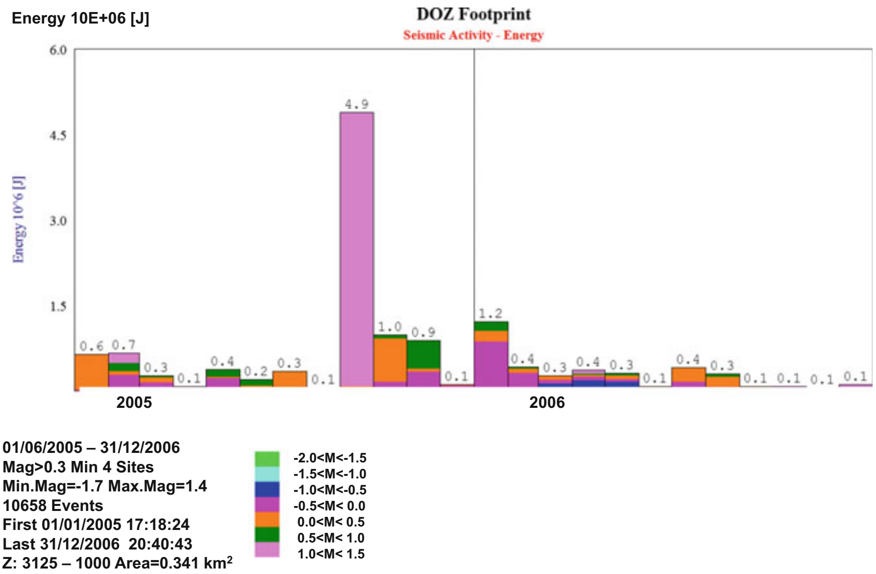


Fig. 3.23 2005–2006 seismic energy release rates below the footprint

Table 3.2 Events magnitude 1.1

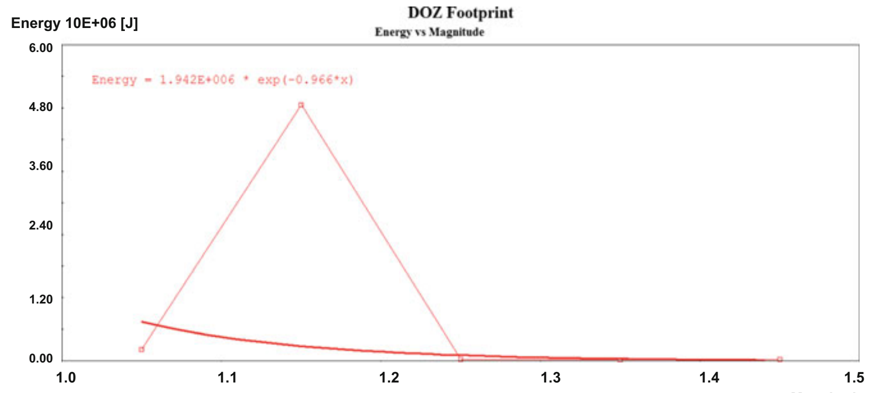
Date	X (m)	Y (m)	Z (m)	Mag.	Mom lg	Ene lg	Stress (MPa)	EI
08/04/2005	737,372	9,549,077	3125	1.1	10.7	3.9	0.005	0.336
21/04/2005	737,314	9,548,964	3108	1.1	10.7	2.2	0.000	0.007
05/09/2005	737,317	9,548,825	1808	1.1	10.6	6.7	3.444	214.8
09/12/2006	737,237	9,549,159	2329	1.1	10.6	4.6	0.034	1.984

Figure 3.23 illustrates the monthly seismic energy release rates, during 2005 and 2006, below the mine footprint. It seems that the September 2005 rate is too high and that this problem is associated with an event in the magnitude range 1.0 up to 1.5.

Figure 3.24 illustrates the seismic energy releases of seismic events magnitude 1.0 up to magnitude 1.5 and confirms that there is a problem within the magnitude size 1.1. In this catalogue, according to data presented in Table 3.2, there are four 1.1 magnitude size events. It seems that the event recorded during 5 September 2005 released too much energy.

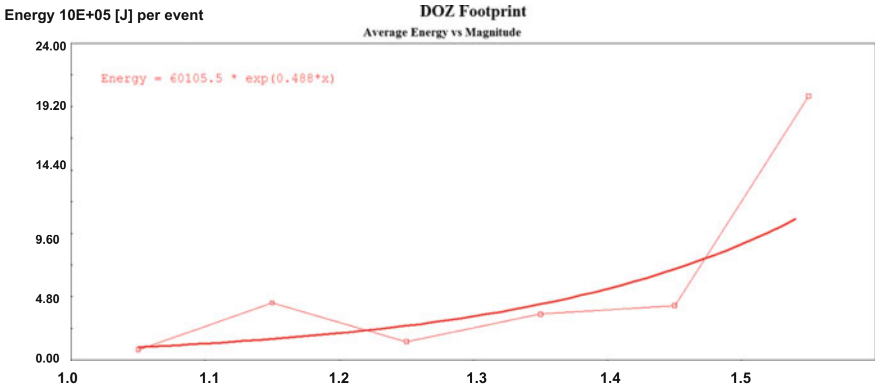
After eliminating this event the corrected average seismic energy release by events of magnitude 1.0 up to 1.5 for the whole DOZ footprint is presented in Fig. 3.25.

The general trend as presented by this figure is close to the expected energy release pattern but still is not totally correct.



01/01/2005 – 31/12/2006 All Events: 12 Energy = 5.15E+07 J
Mag>0.3 Min 4 Sites
Min.Mag=-1.7 Max.Mag=1.4
10658 Events
Exclude blasts 14:00-14:30
First 01/01/2005 17:18:24
Last 31/12/2006 20:40:43
Z: 3125 – 1000 Area=0.341 km2

Fig. 3.24 Energy release of events magnitude from 1.0 up to 1.5



01/01/2005 – 31/12/2006 All Events: 78 Energy = 2.41E+07 J
Mag>0.3 Min 4 Sites
Min.Mag=-1.7 Max.Mag=1.4
10658 Events
Exclude blasts 14:00-14:30
First 01/01/2005 17:18:24
Last 31/12/2006 20:40:43
Z: 3125 – 1000 Area=0.341 km^2

Fig. 3.25 DOZ average energy release by events magnitude from 1.0 up to 1.5

Presented problems with the average energy releases by various magnitude sizes indicates that any analysis based on energy release is unreliable and in practice with presently available data set cannot be done. This problem indicates how important the proper maintenance of the seismic data base is. Still, it seems strange that the extremely high energy releases were not noticed at the time when recorded data was processed and then added to the database. This might indicate that the problem occurred while the seismic database was recalculated with new software version. I noticed this problem when I had recalculated two months of the PMC database. Here, the extremely high energy releases were associated not with real events but with noise that somehow passed through the filter. Only because of the limited amount of data, I was able to eliminate these false events (Glazer 2016). It seems that in the case of the DOZ seismic database, the existing irregularities can only be eliminated by manual reprocessing of the whole database. Unfortunately, due to its size, this option is not feasible.

3.2.3 Comparison of Seismicity Recorded Above the DOZ Footprint with Seismicity Recorded in the Whole Mine

I have already analysed the trends of the percentages of various seismicity rates that were recorded above the DOZ footprint. In that analysis, I used only these seismic events that were located directly above and directly below the DOZ footprint. This type of analysis can be done differently while additionally making use of the whole seismic data base. Here, the percentages above the footprint are derived not only from the events located directly below and above the footprint but from all seismicity that located in the whole rock mass volume surrounding the volume above the mine footprint.

Figure 3.26 illustrates the percentages of seismicity that was recorded directly above the mine footprint. These percentages were calculated for each month. The resulting trend of this data is presented by the red curve. This data indicates that, from the beginning of 2002 to about mid-2010, there were three instances when the percentages of the seismicity recorded directly above the mine first increased then remained constant for some time period more or less at the same level, and then decreased quite rapidly. The time occurrence of these percentage changes coincides with the known caving milestones namely: the break through (1) which was completed before 2004, the break through (2) which was completed by the end of 2005 and the break through (3) which was completed by mid-2008 (see Figs. 3.2, 3.3 and 3.4). The percentages trends presented by this figure are similar to those presented in Fig. 3.12. The times during which the main changes occur are the same. The main differences are in the percentage values. The percentage values as illustrated in Fig. 3.12 are higher than those presented in Fig. 3.26. The reason for this is obvious: the absolute percentage values are directly related to the size of the input data from which they are derived.

Finally, the two trends of the seismic deformation (Fig. 3.27) and of the stress (Fig. 3.28) percentages above the DOZ mine footprint confirm the observations based on the seismicity percentages. In all three cases, the observed trends seem to be more

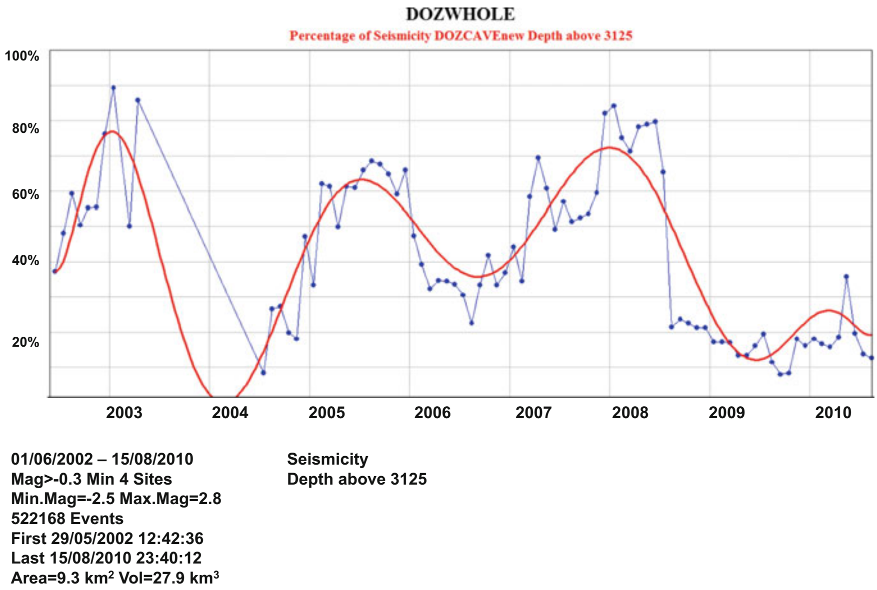


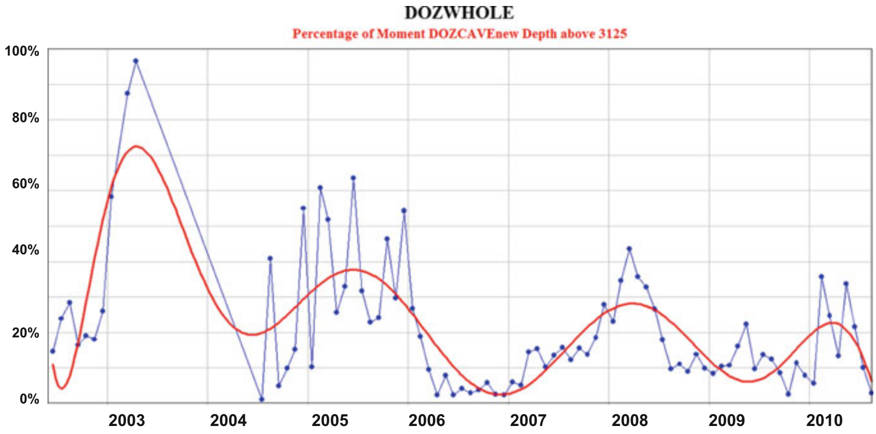
Fig. 3.26 Percentages of seismicity recorded above the DOZ footprint

evident from those that were based only on data recorded directly above and directly below the mine footprint.

3.3 Diablo Regimento Sector, El Teniente Mine

Figure 3.29 illustrates the monthly seismic activity rates. This plot makes use of all events recorded with minimum of four stations from the beginning of January 2002 up to the end of May 2008 at the DR Sector. In total, there are 19,217 events. The monthly rates vary from less than 100 up to over a 1000 per month. The highest monthly activity rates were recorded during November 2005 and December 2005. The black graph illustrates the monthly production rates. The following mining and caving process milestones will be displayed on most of the figures:

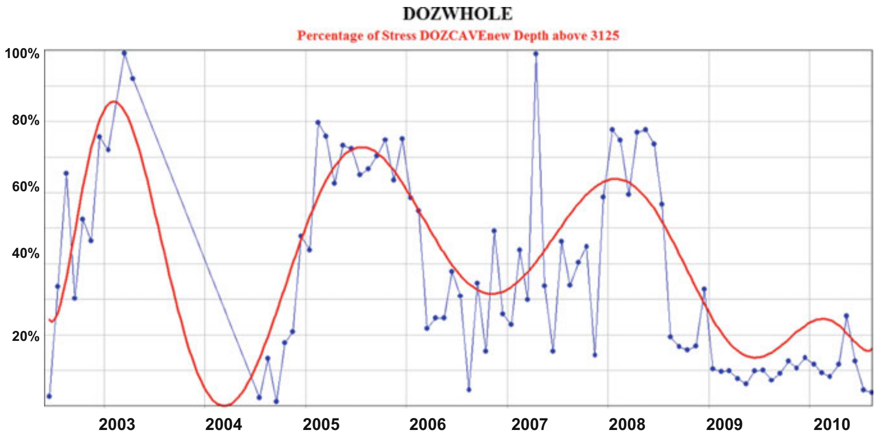
- Start of the development mining (A)—August 2004
- Start of the draw-bell opening (B)—end of 2004
- Start of production (C)—June 2005
- Initiation of the caving process (D)—October 2005
- Break through (E)—January 2006
- End of the first production build-up phase (F)—April 2006
- Start of the second production build-up phase (G)—October 2007



01/06/2002 – 15/08/2010
Mag>-0.3 Min 4 Sites
Min.Mag=-2.5 Max.Mag=2.8
522168 Events
First 29/05/2002 12:42:36
Last 15/08/2010 23:40:12
Area=9.3 km^2 Vol=27.9 km^3

Moment
Depth above 3125

Fig. 3.27 Percentages of seismic deformation above the DOZ foot print



01/06/2002 – 15/08/2010
Mag>-0.3 Min 4 Sites
Min.Mag=-2.5 Max.Mag=2.8
522168 Events
First 29/05/2002 12:42:36
Last 15/08/2010 23:40:12
Area=9.3 km^2 Vol=27.9 km^3

Stress
Depth above 3125

Fig. 3.28 Percentages of stress above the DOZ footprint

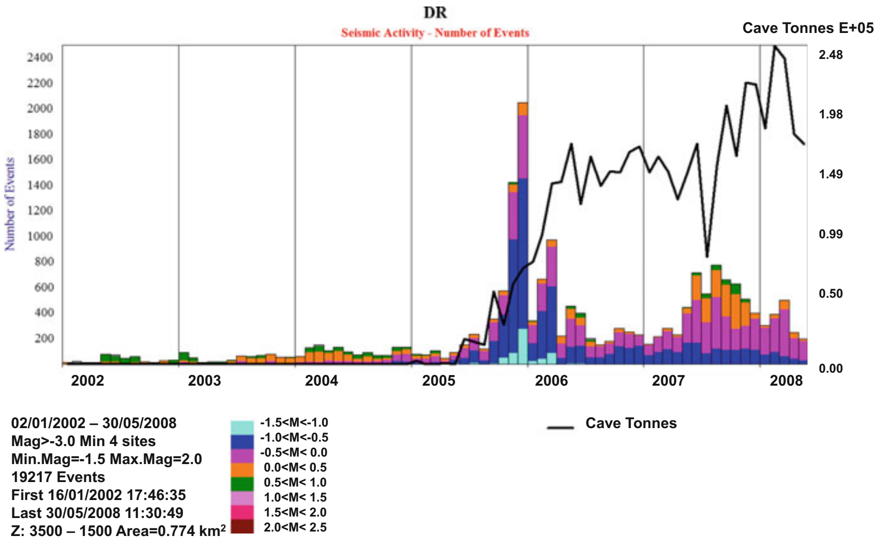


Fig. 3.29 Monthly seismic activity rates

3.3.1 Analysis of the Whole Diablo Regimento Seismic Data Base

Figure 3.30 illustrates the energy index (blue) and average monthly seismicity elevation (green) time histories. The energy index time history is based on all available data. Up to August 2004 (A) there were no mining activities taking place in the DR Sector. During this time period, the recorded seismicity is located well above the DR future extraction level (2190 m). During the second half of 2004, seismicity started to migrate downward indicating that development mining had started during August 2004 (A). Start of the development mining ended the downward migration of seismicity. From August 2004, the energy index time history started to indicate a continuous stress increase as it values started to be above the mean value of 1.0. The stress increase at the start was slow, and then this increase started to accelerate with the increase in the development rates when the draw bell opening operation started at the end of 2004 (B). Production started in June 2005 (C) and with this milestone there was more high energy index seismicity taking place which is indicated by a more rapid stress increase. There was a significant stress increase as indicated by the energy index time history from October 2005 when the initiation of the caving process took place (D). The energy index reached its maximum value by January 2006 (E) with the break through, and then its value started to decrease. The break through changed the stress pattern around the mine. This resulted in more seismicity taking place below the extraction level (Fig. 3.31). Some of this seismicity resulted in larger seismic energy releases (Fig. 3.32). There was more of the larger size seismicity associated with larger energy releases recorded below the mine from May

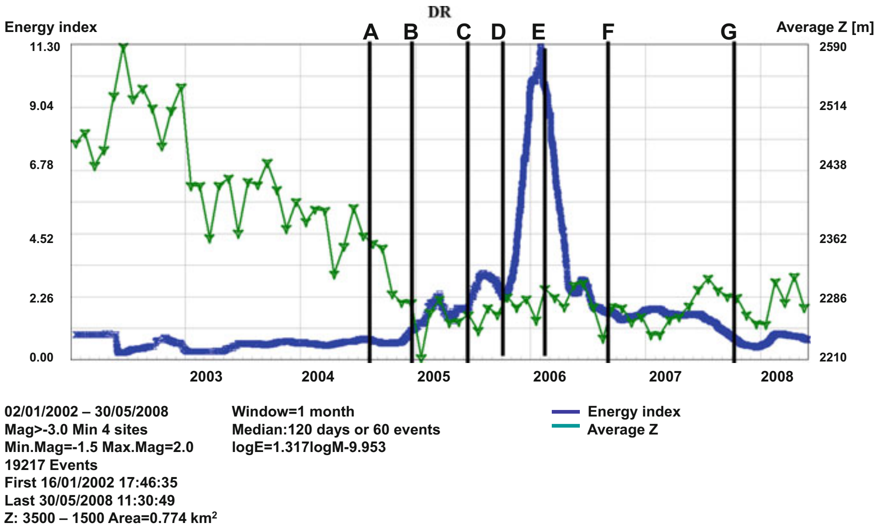


Fig. 3.30 Energy index and seismicity elevation time histories

2006. From about the same time, there were no further high energy release events in locations above the mine.

Figure 3.31 illustrates the monthly seismic activity rates above (top part of this figure) and below the extraction level (bottom part of this figure) from the beginning of 2004 until the end of May 2008. The vertical scales for the activity rates above and below the mine are the same. The seismic activity rates below the mine are very low in comparison to those above the mine. Additionally, this figure shows the monthly seismicity elevation changes above the production level. With the initiation of the caving process (D), there was a prominent change in the seismicity elevation trend. From October 2005, there was a slow but continuous upward seismicity elevation trend. Above the mine, the seismic activity rate increased at the time when the production mining operation commenced (C), and then reached its maximum rates after the initiation of the caving process (D). The break through (E) marks the end of the increased seismic activity rates.

Figure 3.32 illustrates the monthly seismic energy release rates above (top part of this figure) and below the extraction level (bottom part of this figure). The vertical scales for the seismic energy release rates above and below the extraction level are the same. This figure indicates that above the extraction level the energy releases towards the end of 2004 were associated with the development mining. Start of production mining (C) was marked by an increase in seismic energy release that ended directly after the break through (E). Larger size seismic energy releases below the mine started directly after the break through (E) took place.

Figure 3.33 shows the percentages of seismicity recorded above the extraction level. 100% of seismicity is the total amount of seismicity recorded every month

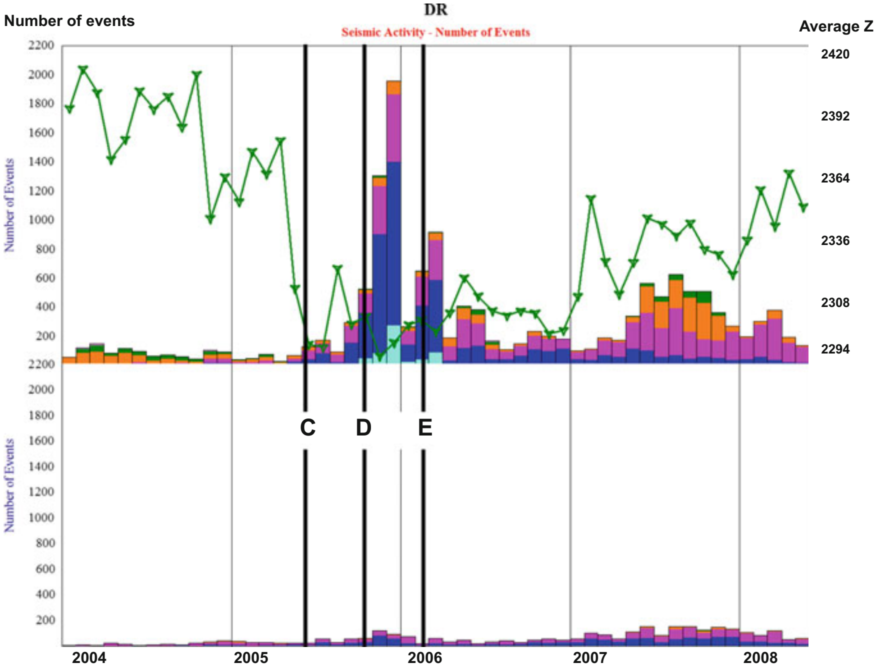


Fig. 3.31 Monthly seismic activity rates above and below the mine

above and below the mine level. Initially, during the first months of 2004, the amounts of seismicity recorded above the mine were close to 90%. With the start of increased development rates (B), the percentages of events recorded above the extraction level started to increase for the second time. The maximum percentages were recorded after the initiation of the caving process (D) and lasted until the break through. After the break through, the percentages of seismicity recorded above the extraction level started to decrease. Similar trend is presented in Fig. 3.34 which illustrates the percentages of stress recorded above the extraction level.

Figure 3.35 illustrates the monthly percentages of seismic energy released above the extraction level. The trend for this data set is not so clear as in case of the percentages of seismicity and stress above the extraction level. Figure 3.36 illustrates the magnitude distribution of the Diablo Regimento Sector seismic catalogue. This catalogue contains a wide range of magnitude sizes from -1.5 up to magnitude 2.0. It is obvious that such magnitude range will have a wide seismic energy release scale that could contribute towards the fact that the energy percentage time history displays no distinctive trend.

Figure 3.37 illustrates the average seismic energy of events from magnitude -1.0 up to magnitude 0.0 in 0.1 magnitude size increments. The energy emission for this magnitude range seems to be correct. Figure 3.38 illustrates the average seismic energy of events from magnitude 0.0 up to magnitude 1.0 in 0.1 magnitude size

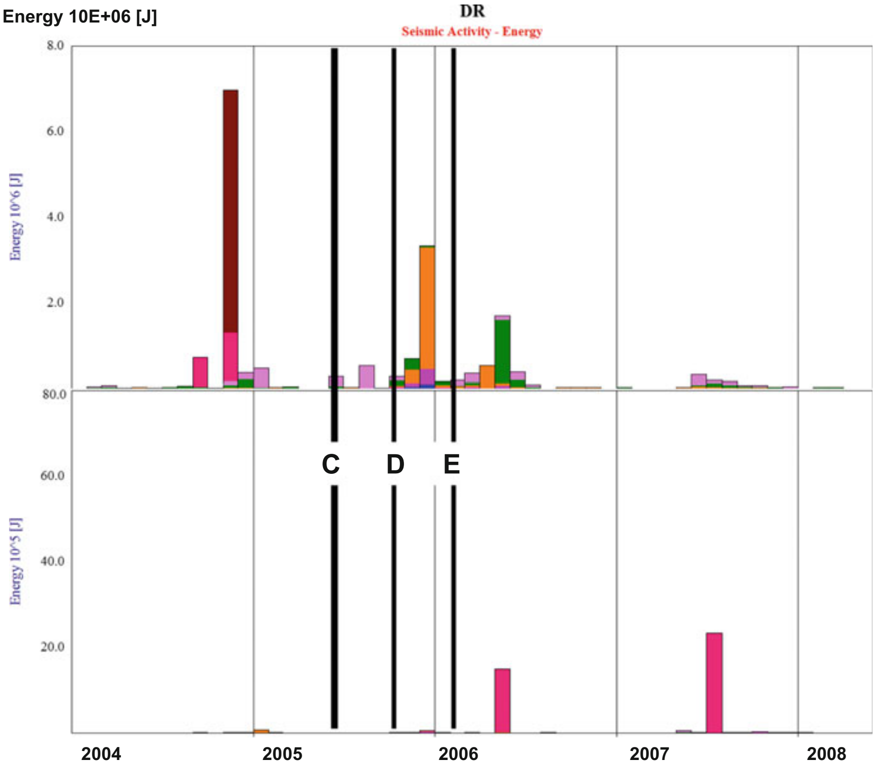


Fig. 3.32 Monthly seismic energy release rates above and below the mine

increments. Here, it appears that the average seismic energy releases of magnitude size 0.2 and 0.5 are much too large. Further investigation resulted in finding that, during December 2004, there was a magnitude 0.2 event that released an extremely high amount of energy. Similarly an event of magnitude 0.5 recorded during May 2006 released exceptionally a lot of energy. In both cases, these two events released about 10,000 more energy on average than other events of their magnitude sizes. I think that these events got into the database after recalculating the database with a new version of the software.

Figure 3.39 illustrates the average seismic energy of events from magnitude 1.0 up to magnitude 2.0 in 0.1 magnitude size increments. The energy emission for this magnitude range seems to be correct.

Figure 3.40 illustrates the energy index time history (blue) and the monthly production rates (black). This energy index time history is not based on the whole seismic catalogue as the one presented in Fig. 3.30. In order to track down more details, this energy index time history is based only on seismicity with the energy index lower than 10.0. This reduced the input catalogue from 21,711 events to 18,521 events (by approximately 15%). For this reason, the maximum energy index time history is

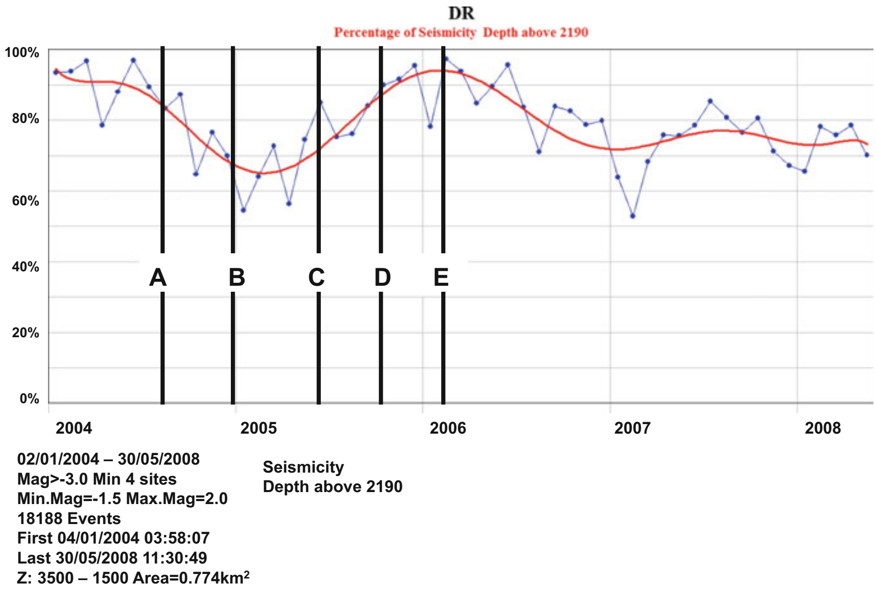


Fig. 3.33 Percentages of seismicity recorded above the mine

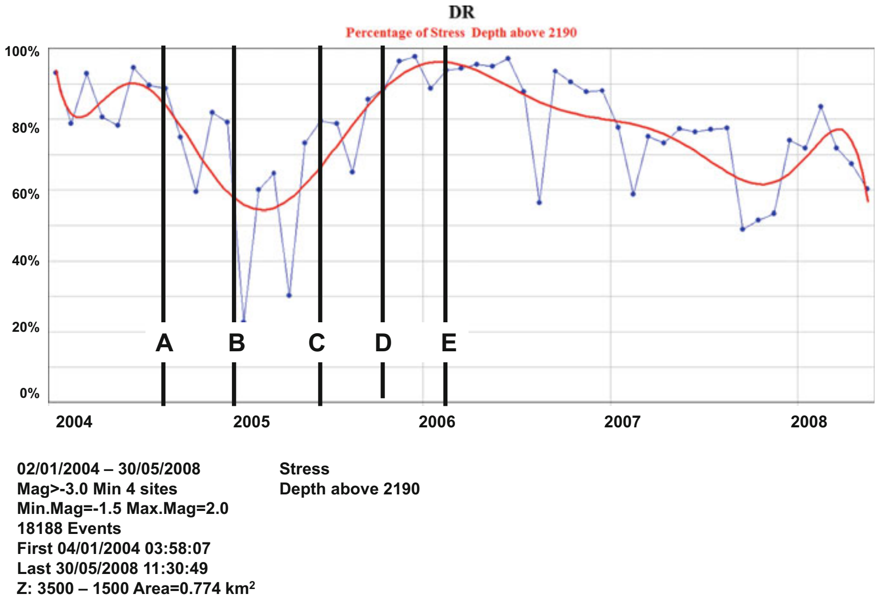
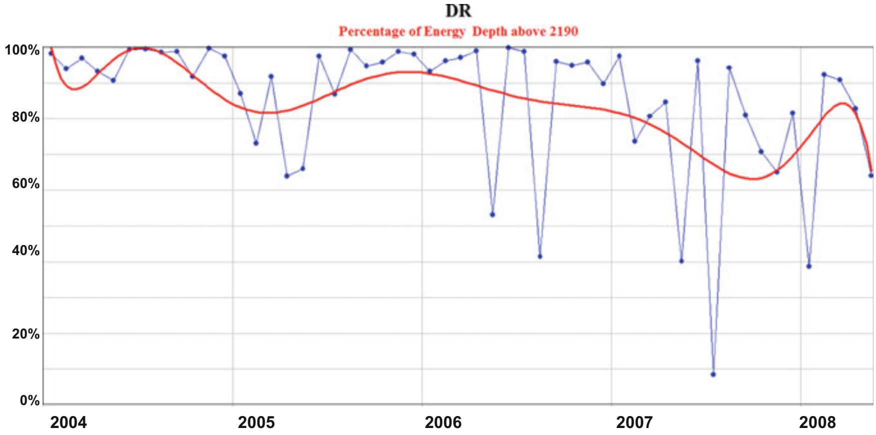


Fig. 3.34 Percentages of stress recorded above the mine

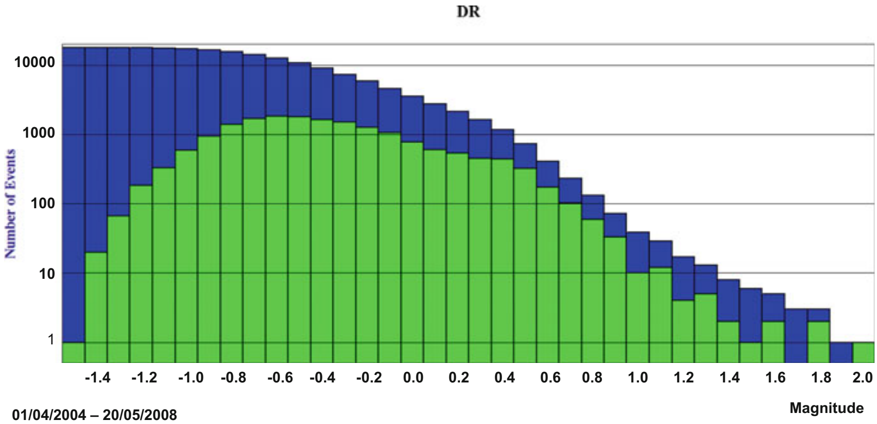
lower at 3.5. For the energy index time history based on the whole data, the maximum



02/01/2004 – 20/05/2008
Mag>-3.0 Min 4 sites
Min.Mag=-1.5 Max.Mag=2.0
18125 Events
First 04/01/2004 03:58:07
Last 20/05/2008 21:27:11
Z: 3500 – 1500 Area=0.774 km^2

Energy
Depth above 2190

Fig. 3.35 Percentages of seismic energy released above the mine



01/04/2004 – 20/05/2008
Mag>-3.0 Min 4 sites
Min.Mag=-1.5 Max.Mag=2.0
17760 Events
First 01/04/2004 02:32:04
Last 20/05/2008 21:27:11
Z: 3500 – 1500 Area=0.774 km^2

Fig. 3.36 DR distribution of magnitude sizes

was 11.3. In both cases, the general trends as well as the time period during which the energy index values are above 1.0 are similar. This figure illustrates the fact that the start of the development mining (A) did not really increase the stress levels. The

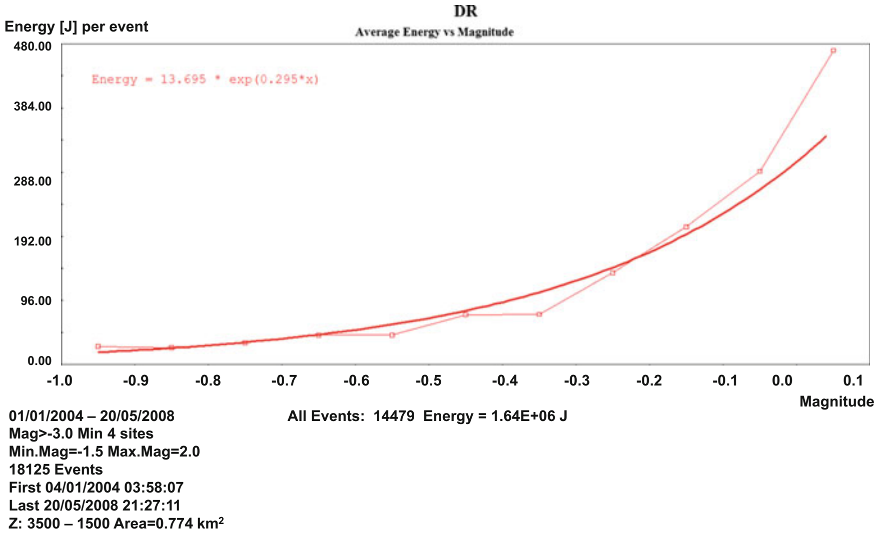


Fig. 3.37 Average energy release of seismicity magnitude −1.0 up to 0.0

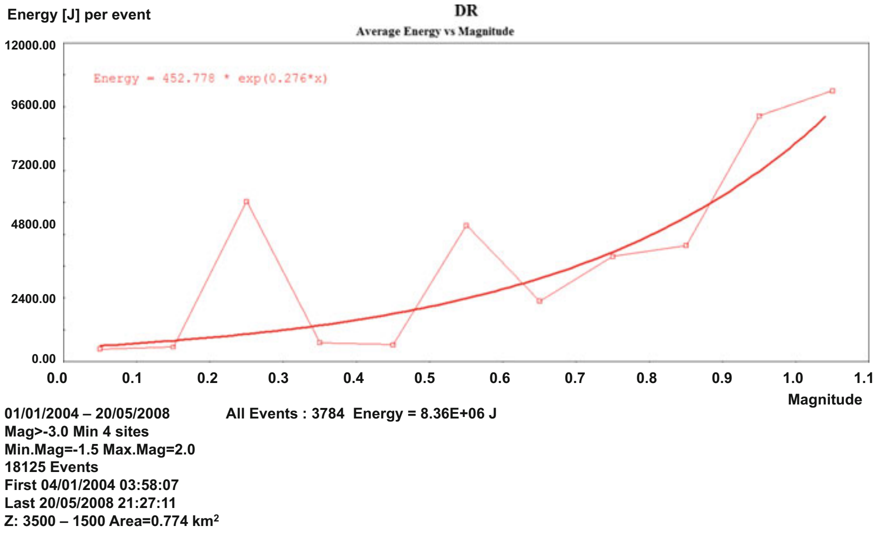


Fig. 3.38 Average energy release of seismicity magnitude 0.0 up to 1.0

start of draw point opening (B) resulted in some stress increase. Then, when the cave production commenced (C) the energy index values just reached their mean value of 1.0. The start of the cave mining, and then the initiation of the caving process (D) resulted in rapid stress increase that lasted until the cave breaking through (E). The following stress release was rapid and probably due to the fact that from April 2006

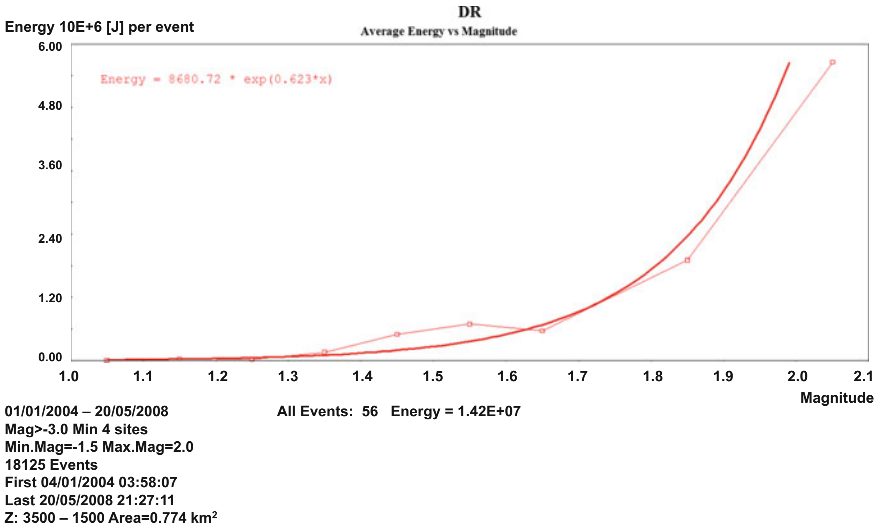


Fig. 3.39 Average energy release of seismicity magnitude 1.0 up to 2.0

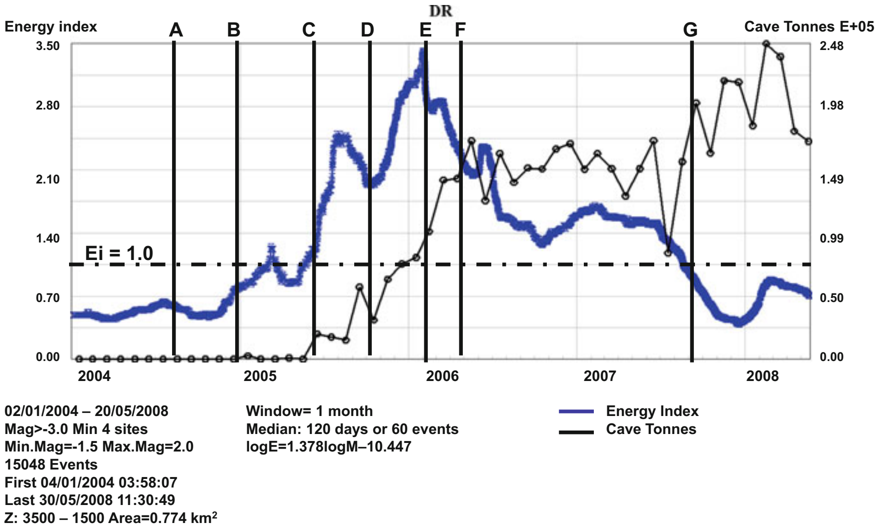


Fig. 3.40 Energy index time history and production rates

(F) until October 2007 (G) the production rates were kept at the same low level, the energy index returned to its mean value of 1.0 in a relatively short time period. The time of the second production rates build-up (G) coincides with the time when the energy index time history started to decrease below its mean value of 1.0.

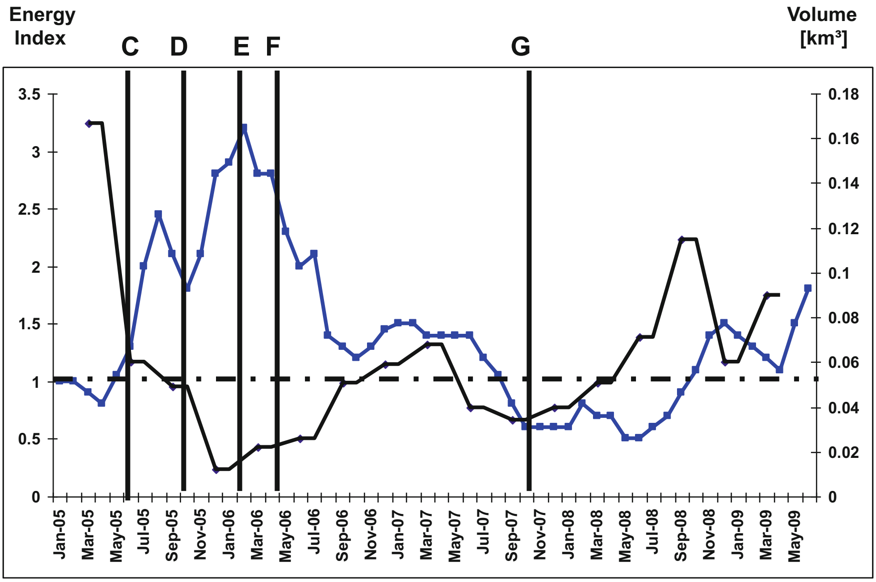


Fig. 3.41 Energy index and active seismic volume time histories

Figure 3.41 illustrates the energy index time history (blue) and the seismically active volume changes (black). The start of the cave production (C) resulted in more seismic activity taking place around and closer to the production level. For this reason, the seismically active volume indicates a decrease. The seismically active volume increase started only after the initiation of the caving process (D) and then continued well after the cave break through (F). The second increase in the seismically active volume was then associated with the second production build-up (G). This is illustrated in Fig. 3.42. Here, the seismically active volume is in red while the monthly production rates are in black.

Figure 3.43 illustrates the elevation changes of the maximum seismicity elevations (red) and the minimum seismicity elevations (blue). From the time of the caving process initiation (D), the seismicity vertical extension was close to 300 m metres (200 m above the extraction level and 100 m below the extraction level). After the break through (F), the seismicity migrated upwards and downwards. Just before the time of the second production build-up (G), the seismically active volume vertical extension increased to about 400 m. This production build-up resulted in more upward migration of seismicity. During mid-2008, the vertical extension of seismicity reached 500 m (300 m above the extraction level and 200 m below the extraction level).

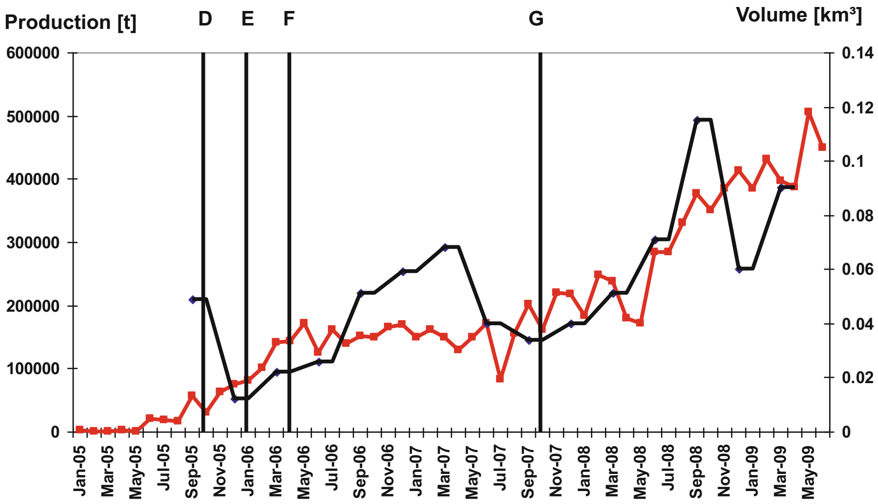


Fig. 3.42 Seismically active volume and production rates

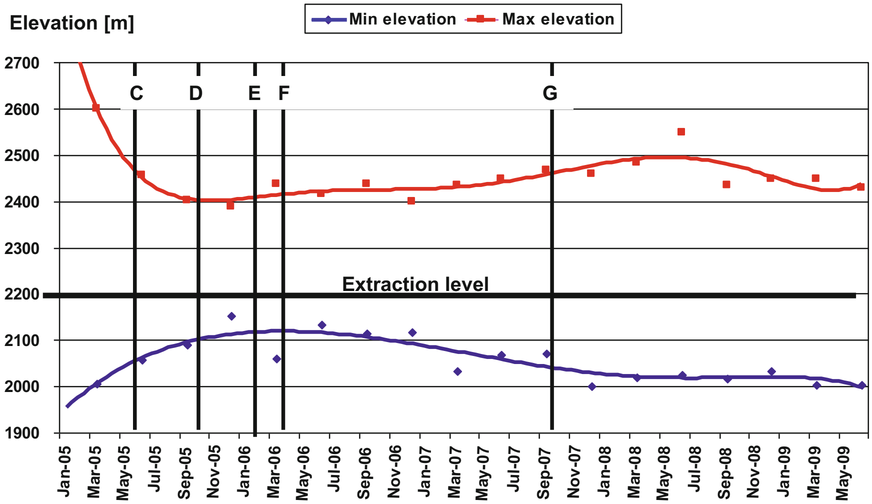


Fig. 3.43 Minimum and maximum seismicity elevations

3.3.2 Comparison of Seismicity Recorded Above the DR Footprint with Seismicity Recorded in the Whole Mine

Figure 3.44 illustrates the monthly percentages of seismicity locating inside of the cave volume. Here, the 100% values are the amounts of seismicity locating in the whole DR volume (below, above and around the cave volume). The trend of these

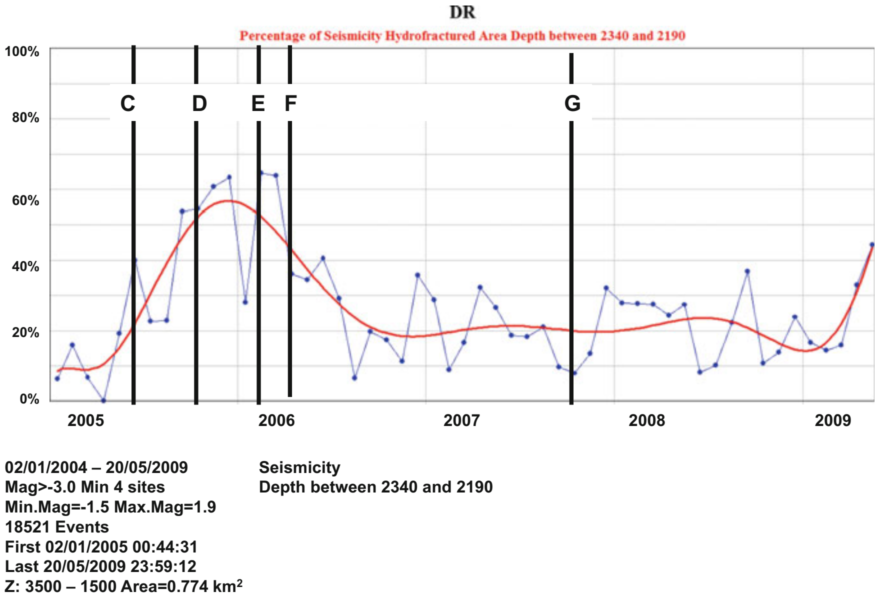


Fig. 3.44 Percentages of seismicity in the cave volume

percentages is illustrated by the red curve. With the start of production in June 2005, the percentages of seismicity locating in the cave volume started to increase from about 20% to reach its maximum 65% just before the break through (E). After the break through, the percentages of seismicity locating in the cave volume started to decrease. From about mid-2006, these percentages remained constant at about 20%. Figure 3.45 illustrates the monthly percentages of stress in the cave volume. These percentages are calculated in a similar way as the seismicity percentages of Fig. 3.44. Both trends presented by these two figures are similar in shape but slightly different as far the absolute values are concerned.

3.4 Northparke's Lift 2 Mine

Figure 3.46 illustrates the Northparke's Mine Lift 2 seismic data base. This figure shows the monthly seismic activity rates. This graph also illustrates the development (red) and cave production (black) rates. The development mining commenced in March 2003 and was then completed by January 2004. Cave production commenced in July 2004. From February 2004 until the end of June 2004, there was no mining taking place. The monthly activity rates increased with the start of development mining and then substantially decreased with the end of development mining. More seismicity appeared with the start of production from the cave. During this

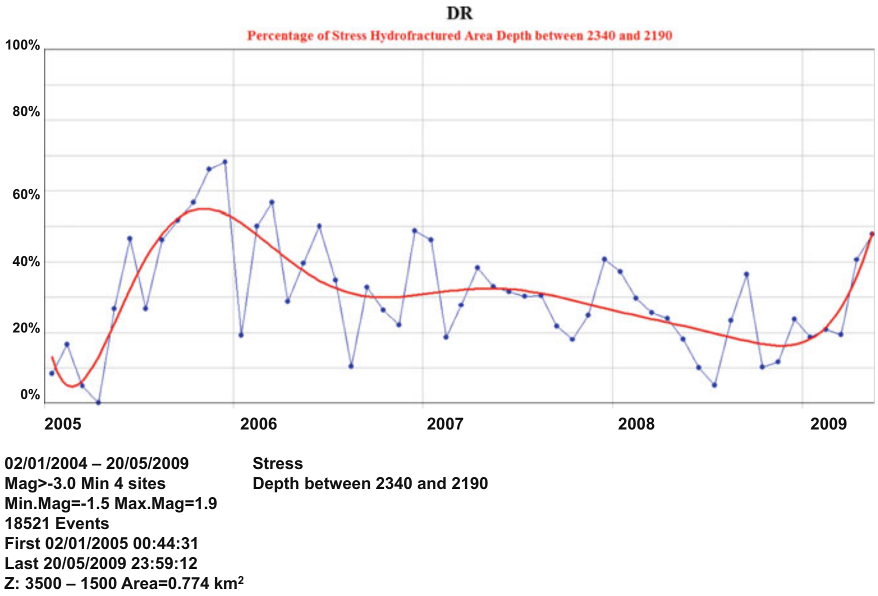


Fig. 3.45 Percentages of stress in the cave volume

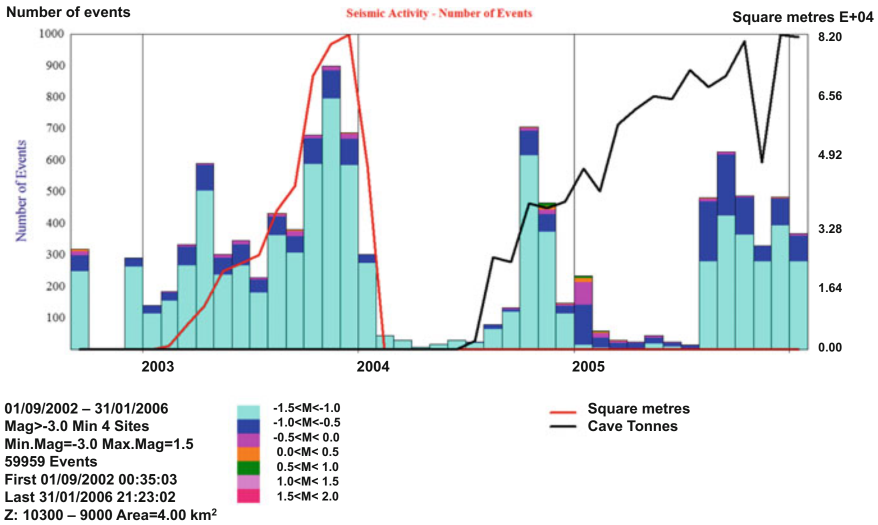


Fig. 3.46 Northparkes Lift 2 seismic data base

time period, the monthly seismicity rates were lower than those recorded during the development mining. They then very quickly decreased by December 2004 which was during the sixth month of cave production.

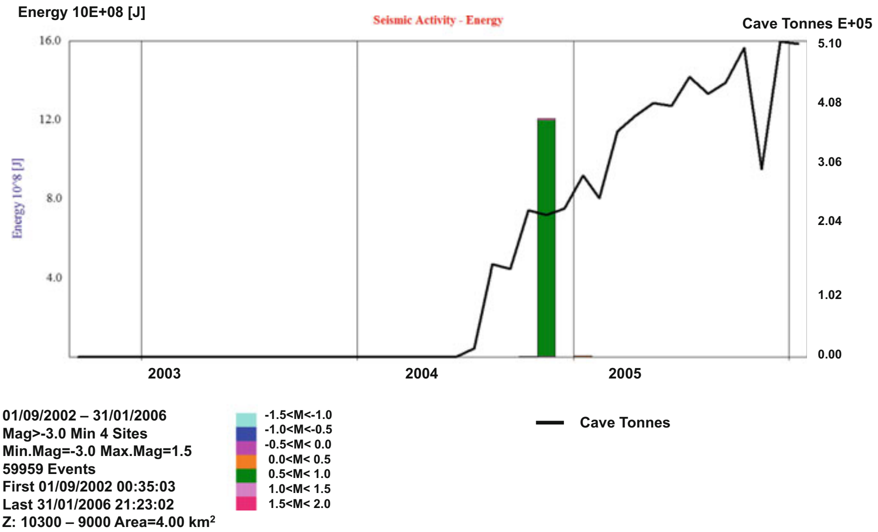


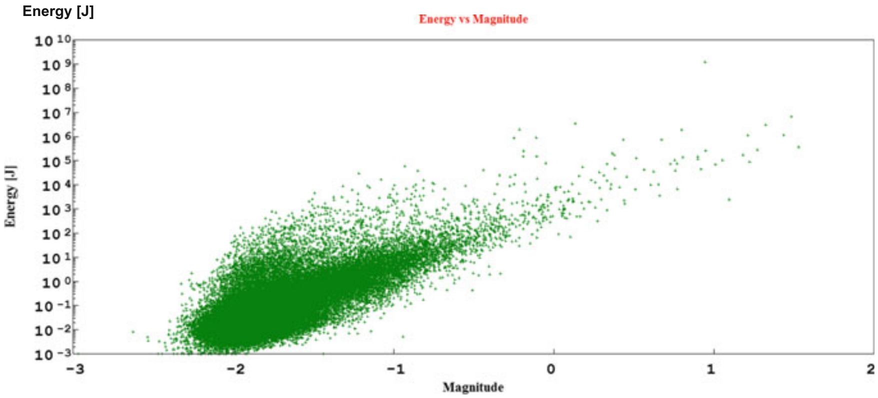
Fig. 3.47 Monthly seismic energy release rates

Figure 3.47 illustrates the monthly production rates (black) and the monthly seismic energy release rates. This figure suggests that practically all of the seismic energy that was released from the beginning of September 2003 until the end of January 2006 was released during November 2004. The total released energy for this catalogue is 12.2E+08 J while the November 2004 seismic energy release amounts to 12.1E+08 J. According to data presented in Fig. 3.47, there are 21 events in magnitude range 0.5 up to 1.0, 9 events in magnitude range 1.0 up to magnitude 1.5 and two events of magnitude above 1.5. The largest event in this catalogue is an event of magnitude 1.5. Still according to Fig. 3.47, practically all of the seismic energy released during November 2004 was by events in magnitude range from 0.5 up to magnitude 1.0 (green part of the vertical bar). This doesn't seem to be correct and needs further investigation.

Figure 3.48 illustrates the relationship between the magnitude size and the seismic energy release based on the Northparkes's Mine Lift2 seismic data base. Apart of the fact that the lowest magnitude range (up to magnitude −1.0) has a very wide energy release rate, there are some events of magnitude range above 0.0 with very high energy releases. The maximum on the energy scale is 10E+10 J. The next three figures illustrate this relationship for the other three mines:

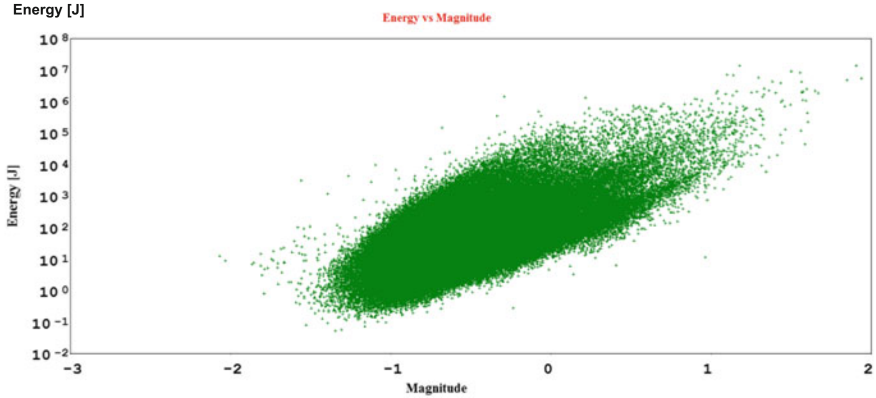
- Figure 3.49 for the PMC Mine
- Figure 3.50 for the PT Freeport DOZ Mine
- Figure 3.51 for the Diablo Regimento Sector, El Teniente Mine.

For ease of comparison, the magnitude in all these three figures is in the same range as in Fig. 3.48. In these three figures, the maximum values of the energy scale are lower from the maximum displayed in Fig. 3.48 (for data recorded at Northparke's



01/09/2002 – 31/01/2006
Mag>-3.0 Min 4 Sites
Min.Mag=-3.0 Max.Mag=1.5
59959 Events
First 01/09/2002 00:35:03
Last 31/01/2006 21:23:02
Z: 10300 – 9000 Area=4.00 km²

Fig. 3.48 Northparkes—Magnitude versus seismic energy release

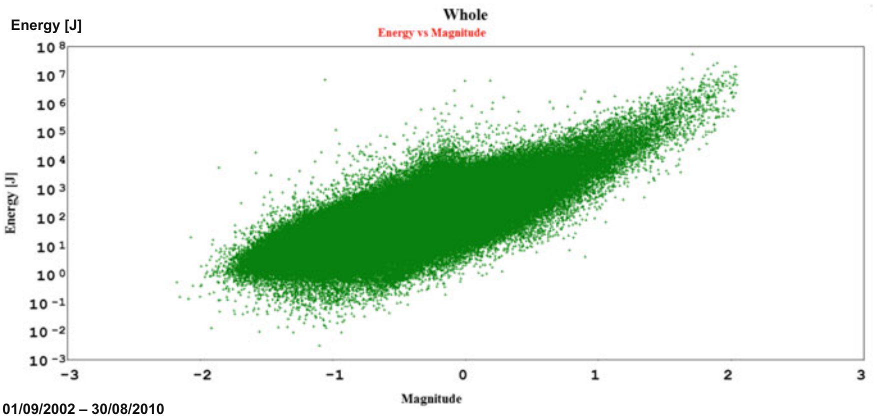


01/01/2002 – 12/01/2011
Mag>-3.0 Min 4 Sites
Min.Mag=-2.1 Max.Mag=1.9
137379 Events
First 07/01/2001 12:45:41
Last 12/01/2011 21:23:02
Z: 400 – -1700 Area=5.00 km²

Fig. 3.49 PMC—Magnitude versus seismic energy release

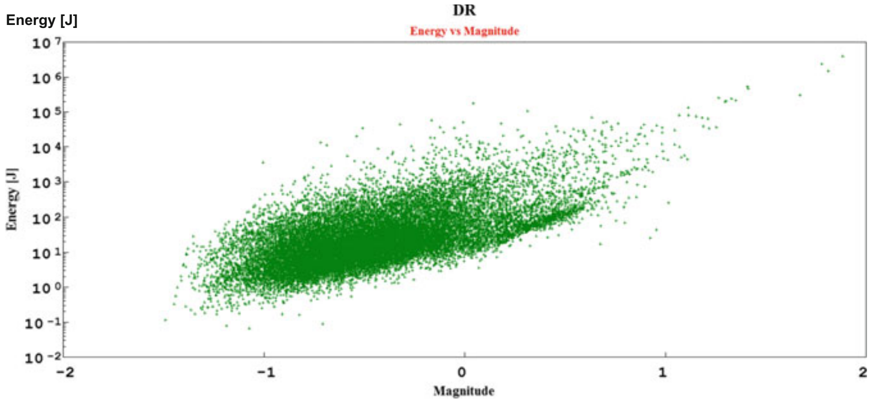
Lift 2 Mine). In general, events of the same magnitude size recorded at Northparke's emitted more energy than events recorded at other three mines.

Figure 3.52 illustrates the average energy released by events magnitude size from 0.0 up to 0.5 recorded at Northparkes Mine. This figure indicates very high average energy releases of events magnitude sizes 0.1 and 0.4. Table 3.3 lists some of the 0.1 magnitude events recorded during January 2005. According to the data presented in



01/09/2002 – 30/08/2010
-3.0<Mag<2.0 Min 4 Sites
Min.Mag=-2.2 Max.Mag=2.0
421797 Events
First 01/09/2002 00:17:50
Last 30/08/2010 20:17:17
Z: 5000 – 3125 Area=9.85 km²

Fig. 3.50 Freeport—Magnitude versus seismic energy release



02/01/2005 – 20/05/2009
Mag>-3.0 Min 4 Sites
Min.Mag=-1.5 Max.Mag=1.9
21711 Events
First 02/01/2005 00:44:31
Last 20/05/2009 23:59:12
Z: 3500 – 1500 Area=0.774 km²

Fig. 3.51 DR—Magnitude versus seismic energy release

this table, an event recorded on the 13 January 2005 released nearly 1000 times more energy than the rest of the listed events. Table 3.4 lists some of the recorded events magnitude size 0.4. There seem to be three events that released much more energy in comparison to the other seismic events.

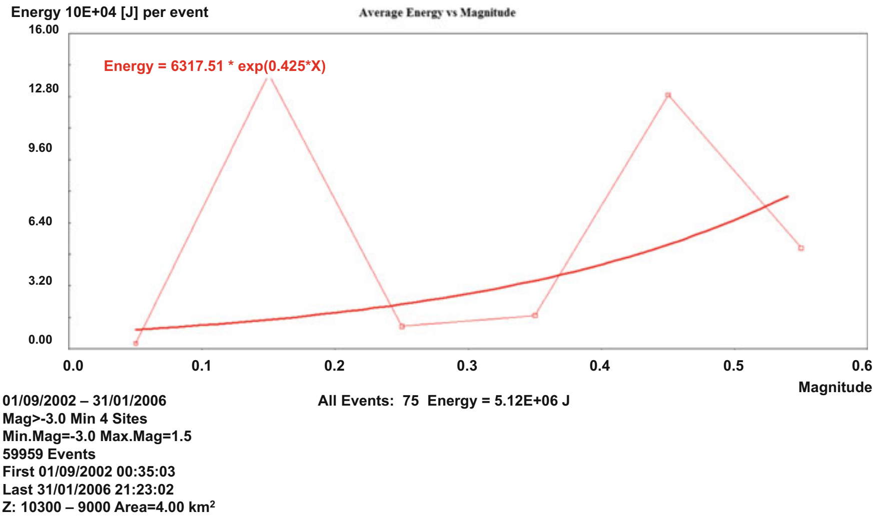


Fig. 3.52 Northparkes—average energy release magnitude range 0.0 up to 0.5

Table 3.3 Magnitude 0.1 data

Date	Time	X (m)	Y (m)	Z (m)	Mag.	Mom lg	Ene lg	Stress (MPa)
08/01/2005	08:36:06	10,804	53,342	9532	0.1	9.1	3.7	0.115
13/01/2005	10:32:12	10,767	53,385	9821	0.1	9.2	6.5	63.70
21/01/2005	04:24:01	10,914	53,429	9380	0.1	9.1	3.3	0.047
21/01/2005	04:24:02	10,800	53,241	9733	0.1	9.2	4.0	0.209
09/02/2005	16:32:29	11,068	53,328	9403	0.1	9.1	2.8	0.015
26/02/2005	21:01:48	10,793	53,205	9417	0.1	9.2	3.4	0.052
17/03/2005	11:58:04	10,660	53,617	9534	0.1	9.1	2.7	0.012
19/05/2005	18:36:17	10,992	53,540	9569	0.1	9.1	2.7	0.013
19/06/2005	02:36:01	10,823	53,270	9619	0.1	9.1	3.0	0.021
28/11/2005	04:26:14	10,968	53,415	9421	0.1	9.2	2.8	0.013
04/12/2005	23:59:48	10,773	53,415	9422	0.1	9.1	3.7	0.114

Figure 3.53 illustrates the average energy releases by events of magnitude range from 0.5 up to magnitude 1.0. Here, the average energy release of an event magnitude 0.9 seems to be extremely high. Table 3.5 lists all events of magnitude 0.9 from the Northparkes catalogue. It appears that the event recorded 13 November 2004 emitted about 10,000 times more energy than the other four events listed in this table.

Figure 3.54 illustrates the average energy release by events of magnitude 0.5 up to magnitude 1.0. This data is displayed after the event of magnitude 0.9 recorded on the 13 November 2004 was removed from the catalogue. This data indicates that there are also some events of magnitude 0.7 and 0.8 with very high energy releases.

Table 3.4 Magnitude 0.4 data

No.	Date	Time	X (m)	Y (m)	Z (m)	Mag.	Mom lg	Ene lg	Stress (MPa)
1	17/06/2003	23:41:57	10,807	53,363	9501	0.4	9.5	3.8	0.060
2	06/11/2004	07:22:04	10,714	53,334	9675	0.4	9.7	3.2	0.010
3	08/11/2004	07:12:08	10,671	53,239	9722	0.4	9.7	3.4	0.015
4	19/11/2004	02:34:34	11,214	53,360	9796	0.4	9.7	5.9	4.707
5	19/11/2004	19:00:33	10,987	52,707	9407	0.4	9.6	5.3	1.629
6	04/01/2005	04:42:00	10,826	53,336	9809	0.4	9.6	5.2	1.372
7	09/01/2005	07:12:57	10,745	53,318	9628	0.4	9.6	3.9	0.056
8	14/01/2005	21:58:10	10,840	53,220	9727	0.4	9.6	4.7	0.362
9	20/01/2005	11:49:22	10,945	53,370	9759	0.4	9.5	4.0	0.087

Table 3.5 Magnitude 0.9 data

No.	Date	Time	X (m)	Y (m)	Z (m)	Mag.	Mom lg	Ene lg	Stress (MPa)
1	13/11/2004	21:10:37	10,499	54,035	10,080	0.9	10.4	9.1	1342
2	20/11/2004	02:34:10	10,581	53,297	9649	0.9	10.4	5.2	0.190
3	06/12/2004	03:44:11	10,798	53,080	9007	0.9	10.4	5.1	0.151
4	17/01/2005	03:34:28	10,761	53,318	9702	0.9	10.4	4.6	0.055
5	27/02/2005	05:36:44	10,896	53,761	9671	0.9	10.4	5.4	0.282

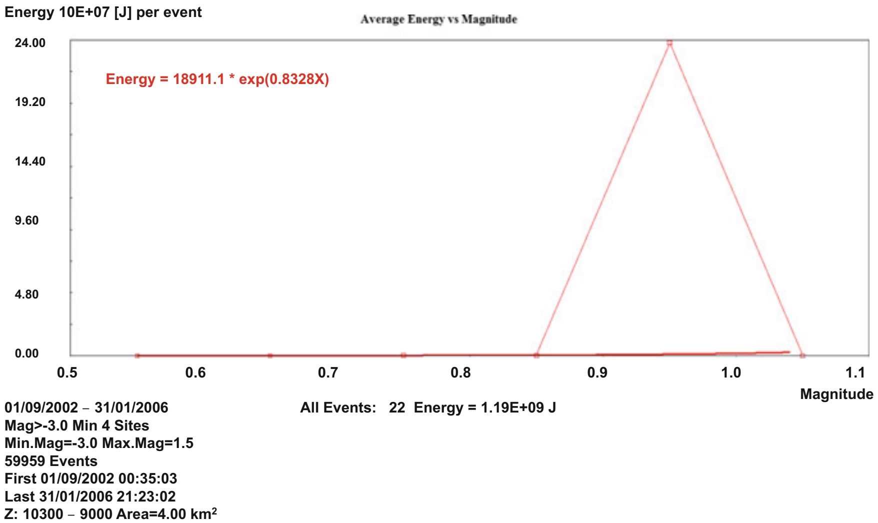


Fig. 3.53 Northparkes—average energy release magnitude range 0.5 up to 1.0

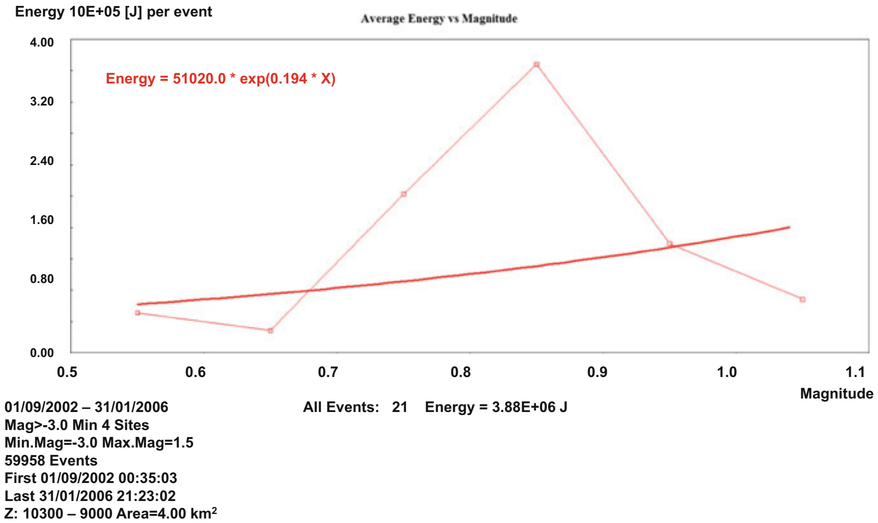


Fig. 3.54 Energy release magnitude 0.5 up to 1.0 with correction for event 0.9

Finally, Fig. 3.55 illustrates the monthly seismic energy release rates for the same time period as Fig. 3.47. The difference is that now the event magnitude 0.9 of 13 November 2004 was removed from the catalogue. The November 2004 seismic energy release on Fig. 3.47 amounted to 12.1E+08 J while according to Fig. 3.54 it only is at 17.4E+06 J (nearly 70 times less). Removal of this event resulted in

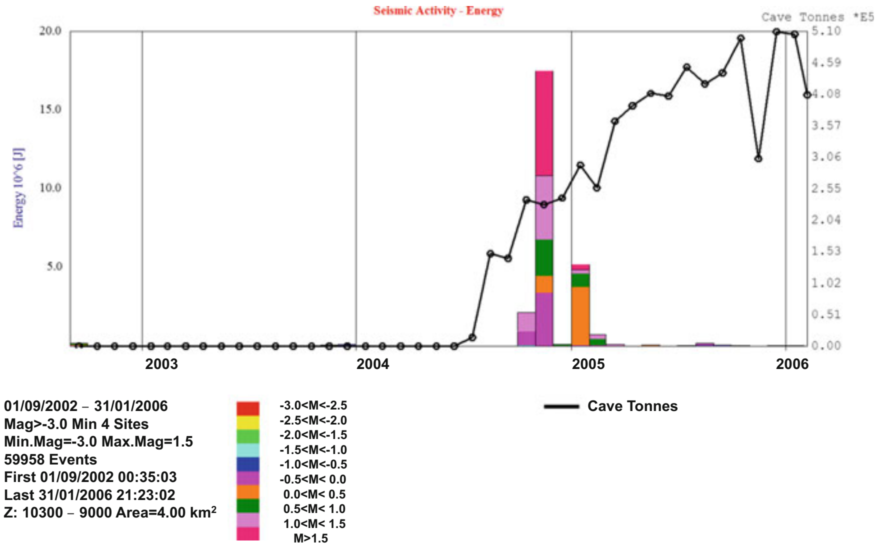


Fig. 3.55 Monthly seismic energy release rates, removed event magnitude 0.9

reduction of the maximum on the energy scale. According to Fig. 3.55, there were also some significant energy release not only during November 2004 but also during October 2004, January and then also during February 2005. This analysis indicates that in case of data from Northparkes it might not be possible to make use of the energy release rates in further analysis.

3.4.1 Analysis of the Whole Seismic Data Base

Figure 3.56 illustrates the energy index time history (blue) from the beginning of 2003 up to the end of March 2005. With the beginning of the development mining (red) in March 2003, the stresses as indicated by the energy index time history started to increase and reached their maximum by October 2003. When the development rates decreased during January 2004 the stress level started to decrease. The stress levels during the time period during which no mining took place decreased as did the seismicity rates (see Fig. 3.46). With the start of the cave production (these rates are in black), the stresses started to increase again. The next maximum of the energy index time history was reached during October 2004 and it lasted only until November 2004. From November 2004, the stresses started to decrease.

In the subsequent figures, I will be indicating the following mining and caving milestones:

A—Start of development mining (March 2003)
B—End of development mining (January 2004)

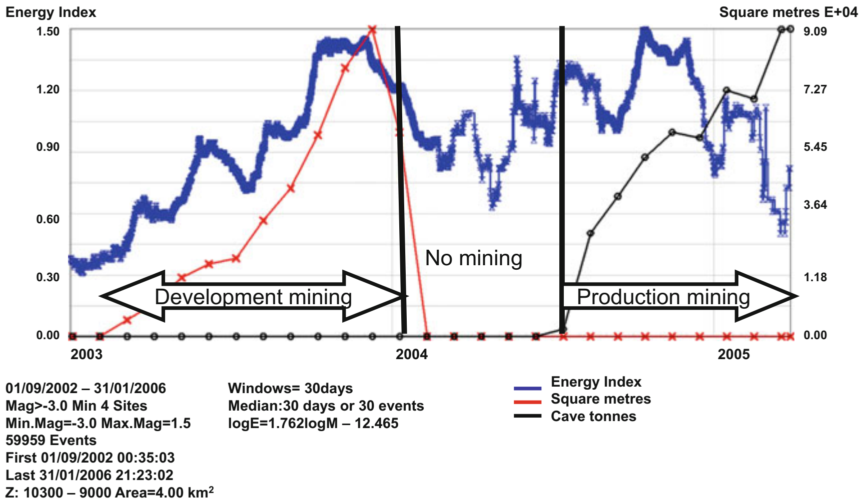


Fig. 3.56 Energy index and mining histories

C—Start of cave mining (July 2004)
D—Break through (November/December 2004)

The break through was confirmed by TDR observations.

Figure 3.57 illustrates the energy index time history and the cumulative seismic energy from January 2002 until February 2005. As indicated in this figure, the maximum energy release took place during November 2003 and coincides with the time of the cave breaking through.

Figure 3.58 illustrates the cumulative seismic moment (pink) and the average monthly seismicity elevations from January 2002 until February 2005. According to this figure, the development mining did not result in a lot of seismic deformation taking place. The seismic deformation rates increased only after the cave mining started and then decreased after the break through took place. The maximum seismic deformation rates were associated with the break through. Development mining resulted in some upward seismicity migration that reached its minimum elevations by the end of this mining. Initiation of the cave mining resulted not only in further upward migration of seismicity but also in increasing of its rates. The minimum elevation was reached in November and December 2004 at the time of the cave breaking through.

3.4.2 *Analysis of Seismicity Recorded Inside of the Cave*

Some of the largest size seismicity took place outside of the cave volume at the time of the break through. Limiting the seismic catalogue only to events located inside

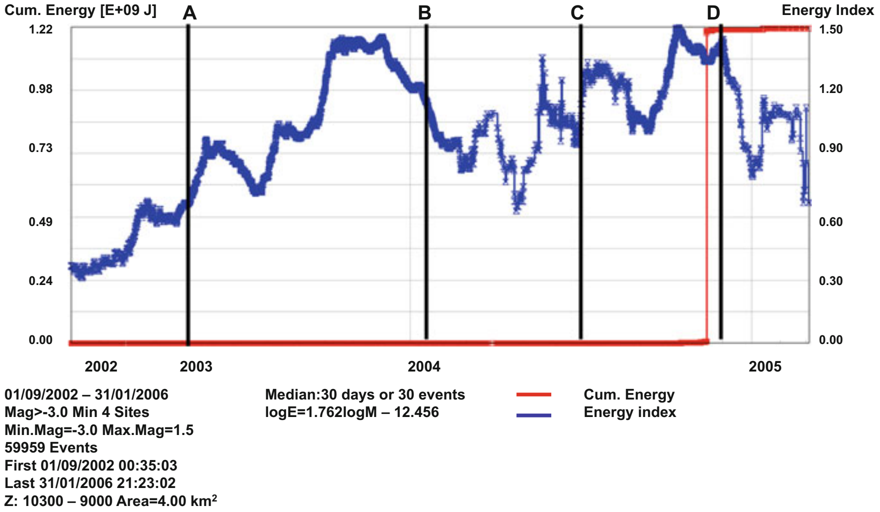


Fig. 3.57 Energy index time history and cumulative energy

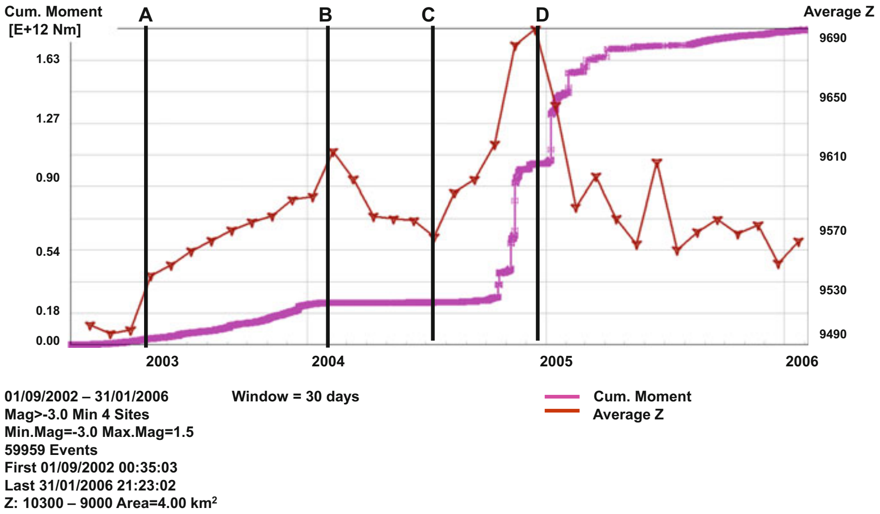


Fig. 3.58 Average seismicity elevations and cumulative moment

of the cave volume resulted as indicated by Table 3.6 in creating a database with slightly less seismicity but considerably lower total seismic energy release. In this case, I am comparing seismicity recorded from 1 September 2003 until 31 January 2006.

With the largest size seismicity (largest size individual energy releases) excluded from the input data the number of events with fictitiously large energy releases that

Table 3.6 The two seismic data bases

Database	No of events	Total energy released (J)
Whole	45,643	1.22E+09
Cave	37,666	6.63E+05

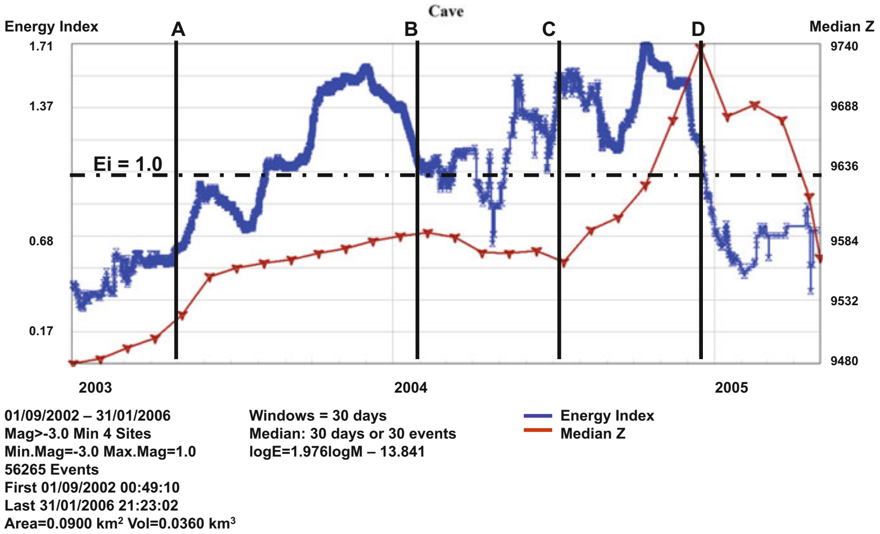


Fig. 3.59 Energy index and average monthly seismicity elevation time histories

remains in this new database should also be reduced considerably. This should allow for including the seismic energy release trends into the analysis. Figure 3.59 illustrates the energy index and average monthly seismicity elevation time histories in the cave volume from January 2003 until mid-2005. The trends of these two-time histories in shape and absolute values are similar to those presented in Fig. 3.57 (energy index). As illustrated in Fig. 3.60, reduction of input data only to that recorded in the cave volume, as expected resulted in exposing the seismic energy release trend (red) rates in the mining and cave history. During the development mining, the energy releases were not only low but continuous in size. With the end of the development mining (B), the energy release stopped. The cave production mining (C) did not result in immediate increase of seismic energy release rates. The energy release rates first increased gradually and then rapidly during November 2004. The increase in the seismic energy release rates is associated with the break through. After the break through was completed, there was more high energy releases taking place but this time outside of the cave volume.

Figure 3.61 illustrates the energy index time history (blue) and the cumulative seismic moment graph (pink) from mid-2003 until end of January 2005. The development mining resulted in a lot of seismic deformation. During the time of the development mining, the seismic deformation rates were continuous in size. As with

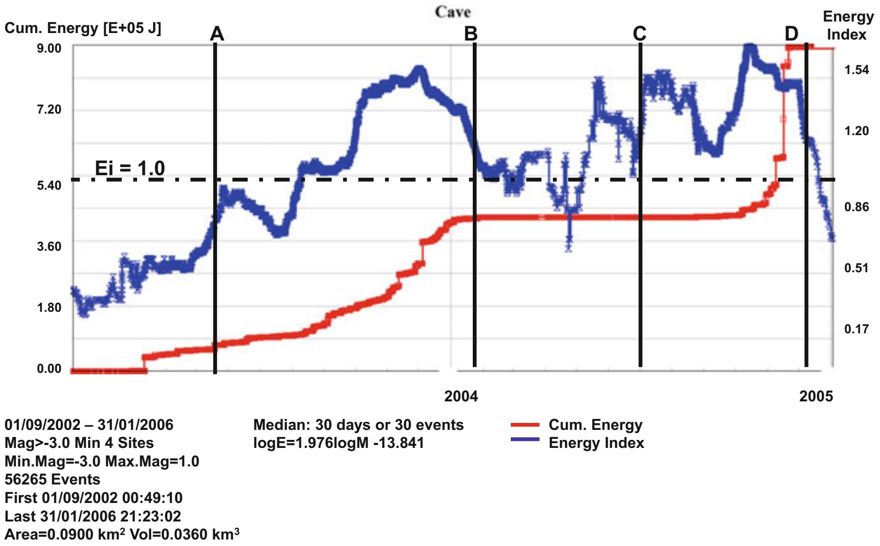


Fig. 3.60 Energy index time history and cumulative energy graph

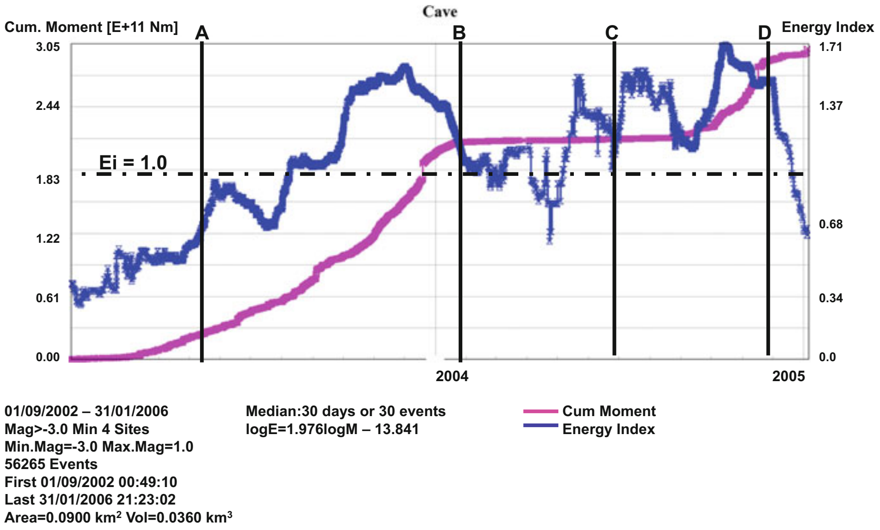


Fig. 3.61 Energy index time history and cumulated moment graph

the seismic energy release rates, the start of production mining did not result in obvious increase in the seismic moment rates. There was more seismic deformation towards the end of 2004 which was connected with the break through.

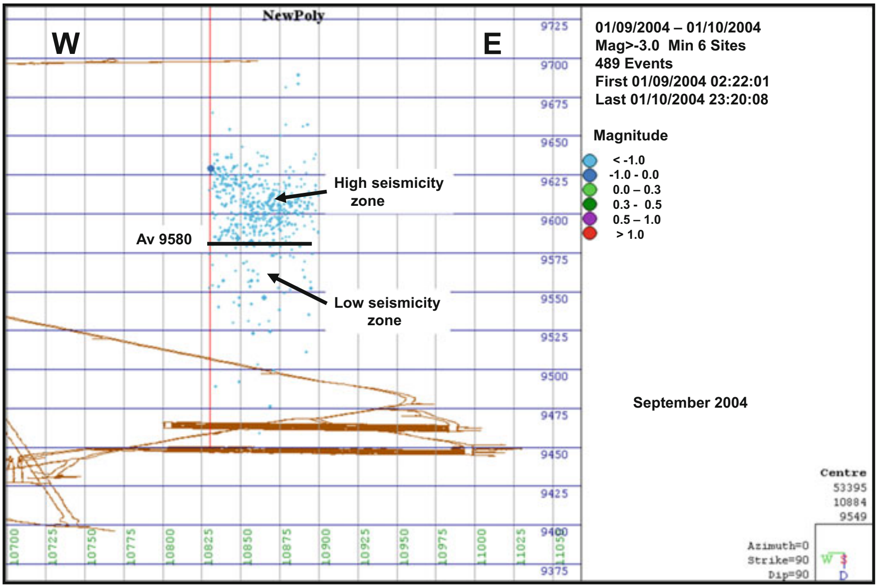


Fig. 3.62 W-E section, elevation of seismic zone in August 2004

3.4.3 Estimation of Cave Back Position

Seismic data should, when possible, be used to monitor the elevation changes of the increased seismicity zone. This zone is located directly above the a-seismic zone in which the rock mass is already fractured and not able to emit any more of seismic energy. As illustrated in Fig. 3.59 there was some substantial upward migration of seismicity after the initiation of the production mining. I used data recorded in the cave during September and November 2004 to establish the elevation changes of the seismically active zone. It appears that the seismic zone migrated up by about 100 m from August 2004 (RL 9580) to November 2004 (RL 9675). Additionally, it appears that the thickness of the seismically active zone was different during September and November 2004.

Figure 3.62 indicates the elevation of the seismic zone in September 2004. The elevation of the seismic zone in September 2004 was at RL 9580. Above this elevation, there was some seismicity up to elevation of RL 9625. The thickness of the seismic zone in September 2004 was about 50 m.

Figure 3.63 illustrates the elevation of the seismic zone based on data recorded in November 2004. This elevation in November 2005 was at RL 9675 that is about 100 m above the September 2004 one. The September 2004 elevation is also shown in this figure. This figure indicates that the November 2004 thickness of the seismic zone was greater than it was in September 2004, as there is evidence of seismic activity right up to the elevation of Lift 1 Extraction Level (RL 9800).

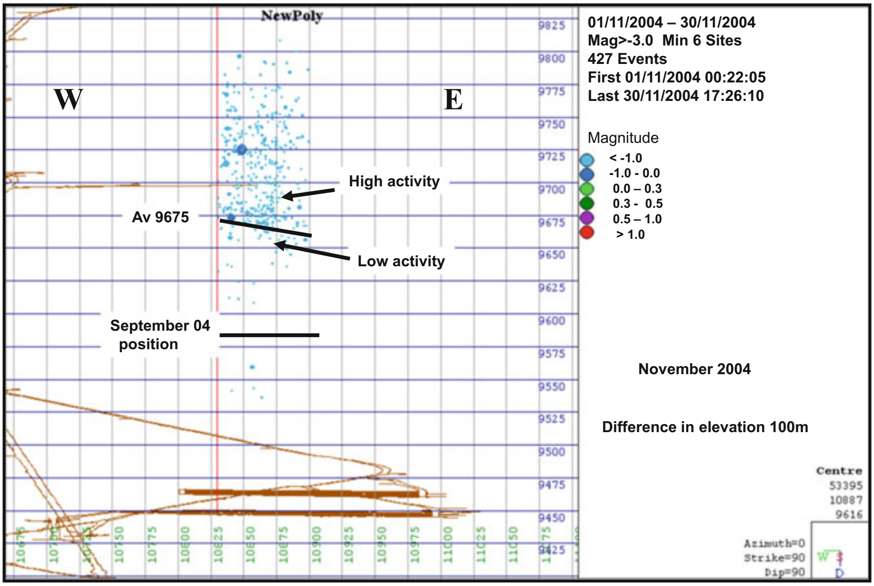


Fig. 3.63 W-E section, elevation of seismic zone in November 2004

3.4.4 Comparison of Seismicity Recorded Above the Cave Footprint with Seismicity Recorded in the Whole Mine

Finally, as with all other mines' data in this part of this chapter I will investigate the trends of seismicity recorded inside of the cave volume in comparison to the seismicity recorded in the whole mine. From the analysis of seismicity recorded in the cave volume, it is evident that not much of seismicity was recorded outside of the cave but the largest in size seismic energy releases took place outside of the cave volume.

Figure 3.64 illustrates the monthly seismic activity rates of events above magnitude 0.5 for the whole mine. During the development mining (from A to B), there was only one such size event. Most of these size events took place towards the end of 2004 and at the beginning of 2005. In total, there were 32 events of this size. Only two of these events were located inside of the cave volume. These two events were recorded in January 2005 already after the cave break through was completed. The other 30 events were all located outside of the cave volume. As indicated in Fig. 3.65, these events located around the cave at different elevations both above and below the extraction level (RL 8450). The events of 2004 are in red while the events of 2005 are in blue. It is obvious that these increased seismic energy release rates were associated with the break through that took place at the end of 2004. Due to the mentioned problems with the seismic energy release sizes of some of the larger size seismicity, it is not possible to analyse the energy release rate changes over time.

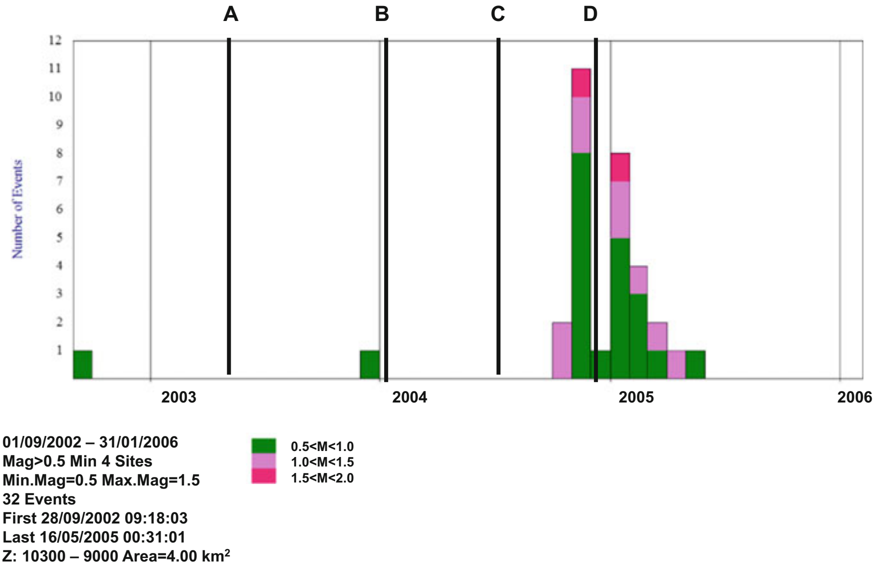


Fig. 3.64 Events of magnitude above 0.5—monthly rates

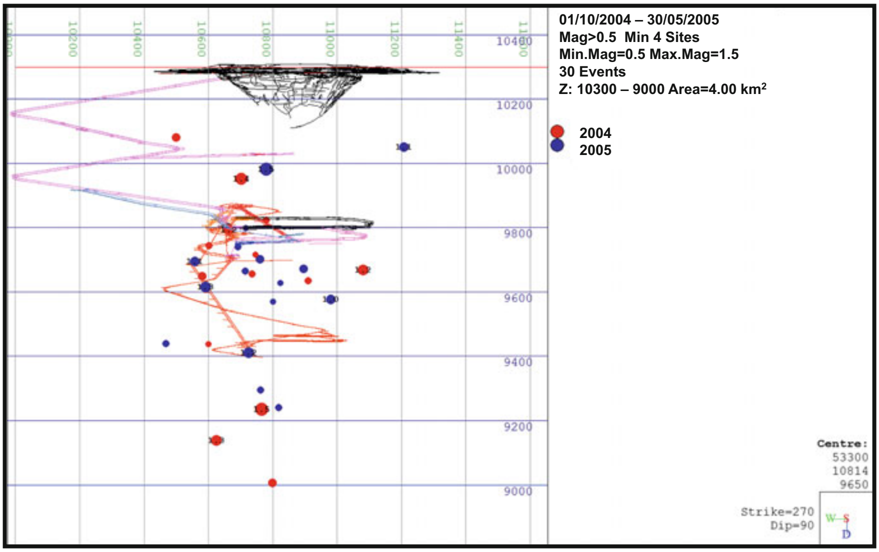
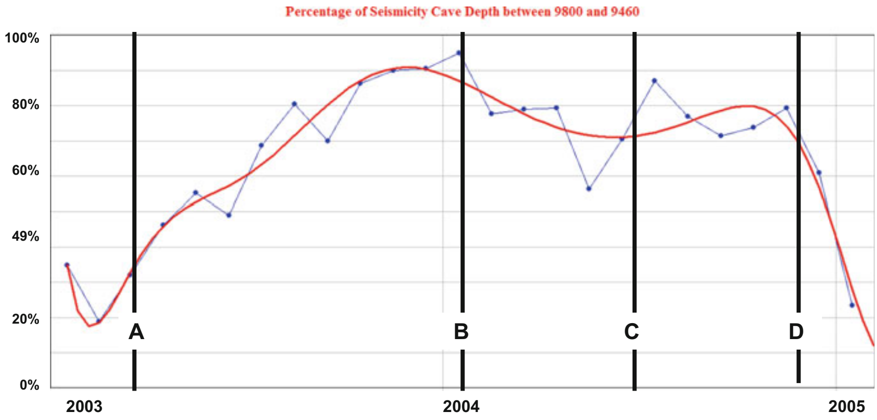


Fig. 3.65 Locations of larger size seismicity in vertical W-E section

Figure 3.66 illustrates the monthly percentages of seismicity recorded in the cave volume from January 2003 until end of February 2005. With the start of the development mining (A), these percentages started to increase. This increase was continuous



01/09/2003 – 06/02/2005
-1.9>Mag<0.0 Min 4 Sites
Min.Mag=-1.9 Max.Mag=0.0
42585 Events
First 02/01/2003 01:41:03
Last 05/02/2005 00:30:01
Z: 10300 – 9000 Area=4.00 km^2

Seismicity
Depth between 9800 and 9460
Mag> -1.8

Fig. 3.66 Percentages of seismicity in the cave volume

and the percentages increased from about 30% during March 2003 to nearly 100% by the end of the development mining in January 2004(B). During the time period, when there was no mining taking place the seismic activity rates were relatively low (Fig. 3.46) but still at about 100 up to 200 events per month. During this time, the percentages of seismicity locating in the cave volume decreased but not considerably. During this time, about 70–80% of seismicity was still located in the cave volume. The start of the production mining (C) did not immediately result in higher seismicity percentages locating inside of the cave. The break through by the end of 2004 (D) resulted in a significant and rapid end of seismic events taking place inside of the cave. During November 2004, still 80% of recorded seismicity was located in the cave volume. The December 2004 percentage was lower at 60% and during January 2005 only 20% of the recorded seismicity was located in the cave. Figure 3.67 illustrates the monthly percentages of seismic energy released in the cave volume. During the development mining on average more than 50% of monthly seismic energy was released in the cave volume. After the completion of the development mining the amounts of seismic energy released in the cave volume indicate a general decreasing trend. From October 2004, no seismic energy was released any more in the cave. The reason for such result has already been explained: most of the larger seismicity by the end of 2004 took place outside of the cave volume.

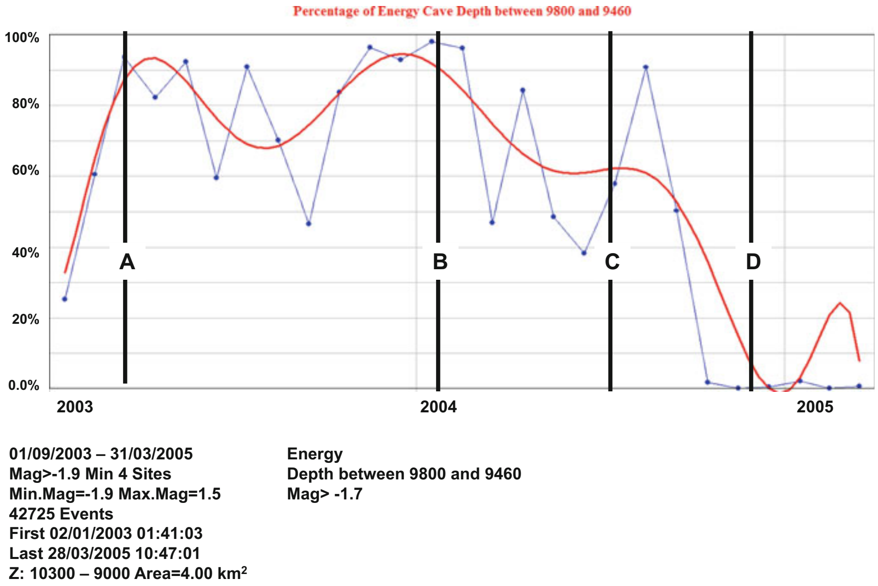


Fig. 3.67 Percentages of seismic energy in the cave volume

3.5 Summary

In this chapter, I have analysed three seismic data bases from the following mines:

1. PT Freeport Indonesia DOZ Mine (DOZ)
2. Diablo Regimento Sector, El Teniente Mine (DR)
3. Northparkes Mine Lift 2 (NPM)

Palabora Mine caving process, as revealed by induced seismicity, is described in details in Glazer (2016). Recorded in these four mines seismicity, contains information about the following caving milestones:

1. Initiation of the caving process
2. Pillar failure
3. Cave break through
4. Caving process reaching its mature stage

The four mine seismic catalogues were used to investigate how some of the seismicity parameters change once the caving milestone occurs. Table 3.7 lists all of the identified caving process milestones, in each database. This table also lists their occurrence numbers. According to this table, the following information was available:

1. Initiation of the caving process was evidenced three times in three different mines
2. Pillar failure was evidenced only once

Table 3.7 Occurrence and number of the caving milestones

Caving milestone	Mine			
	PMC	DOZ	DR	NPM
Initiation of the caving process	Yes	No	Yes	Yes
Pillar Failure	Yes	No	No	No
Cave break through	Yes (2)	Yes (3)	Yes (1)	Yes (1)
Mature stage of the caving process	Yes	No	No	No

3. Cave break through was evidenced in total seven times and it is documented by all four mines
4. Mature stage of the caving process was reached probably only in one case

Initiation of the caving process is the first milestone of the caving process. It was recognized as taking place in three mines. 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 measurements done in open holes. It is also evident that the further caving milestones would not have taken place without the initiation of the caving process. In this way, the following caving milestones also evidence the occurrence of the initiation.

Crown pillar failure at PMC was first recognized only by analysis of seismic data, because of this it was questionable but only up to the time when it was confirmed by nature as a fact. Directly after a heavy storm water was reported underground. This indicated that there was a hydraulic connection between the open pit and the underground mine through the 200 m thick at the time pillar. This could only mean that this rock mass is highly fractured and that the pillar had already failed. For this type of occurrence, I have only one event of this nature but its occurrence is not in question.

Cave break through is the most common caving milestone as it appears seven times: twice at the PMC, three times at Freeport, once at Diablo Regimento and once at Northparkes. This is a significant advantage for the interpretation process. An event of similar nature took place several times. This should allow for more detailed analysis but also for deriving more general conclusions. All listed break throughs (except for the PMC east break through) were confirmed by TDR measurements and production data. The PMC east break through was confirmed only by seismic data (Glazer 2016). This was done 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. In two cases, it was possible to investigate the seismicity trends after the break through. These two cases were: the seismicity recorded at PMC after the initial break through and the seismicity recorded after the

Diablo Regimento Sector break through. In case of the DOZ Mine, the consecutive break throughs were not only close to each other in time but it is difficult to separate the cave-induced seismicity from that induced by the development mining. In case of the Northparkes Lift 2, there was no seismicity recorded after the break through.

The mature stage of the caving process is more of a concept rather than a fact. This concept is based on the assumption that at some stage 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 the rock mass volume, it can influence. In this concept, it is assumed that the caving process might come to its end before the end of the mine lifetime. 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 will cave in.

In the next part of this section, I will describe the seismic signature of the caving process milestones. This review will be based on the following parameters:

Seismic activity rates
Percentages of seismicity locating above the mine extraction level
Energy release rates
Seismic deformation rates
Energy index time history
Average monthly seismicity elevations
Seismically active volume
Spatial distribution of seismicity
Monthly percentages of events with ratio $Es/Ep > 10$
Seismic activity and production rates

3.5.1 Initiation of the Caving Process

Initiation of the stress caving process was observed in three mines. It was not recorded at the DOZ Mine because the seismic network was installed after the caving process was initiated. The cave initiation process is indicated by the following seismic parameters changes:

1. Upwards migration of seismicity that is monitored by average monthly seismicity elevation changes
2. General increase in seismic activity rates with time
3. General increase in seismic energy release rates with time
4. General increase in seismic moment rates
5. Evident increase of the energy index which is monitored using its time history
6. Direct proportional correlation between seismicity and production rates
7. Direct proportional correlation between the energy index time history and production rates

Table 3.8 Seismicity trends after initiation of the caving process

No	Parameter	Mine		
		PMC	DR	NPM
1.	Seismic activity rate	General increase	General increase	General increase
2.	Percentages of seismicity locating above the mine	Increase (from 80 to 100%)	Increase (from 80 to 100%)	Continuous (at 80%) (1)
3.	Energy release rates	General increase	Slight increase	Slight increase
4.	Seismic deformation rates	General increase	General increase	Increase
5.	Energy index time history	Rapid increase	Rapid increase	Increase
6.	Average monthly seismicity elevations	Rapid upward trend	Rapid upward trend	Rapid upward trend
7.	Seismically active volume	Slow increase	Low increase	unknown
8.	Space distribution of seismicity	Only above the mine foot print	Only above the mine foot print	Some of seismicity located outside of the cave
9.	Monthly percentages of events with $Es/Ep > 10$	Continuous (60%)	Slow increase (Up to 70%)	Increase (From 40 to 70%)
10.	Seismic activity and production rates	Direct proportional	Direct proportional	Direct proportional

8. Location of seismicity—directly after the initiation process until the pillar failure or the cave break through most of the recorded seismicity will locate above the mine footprint
9. All cave-induced seismicity located in clusters around the cave allowing for monitoring the upward progress of the seismic zone
10. Slow but continuous increase of the seismicity active area and volume (Table 3.8).

(1) There was a continuous increase in seismicity inside of the cave (from 30 to 90%) during the development mining.

3.5.2 Pillar Failure

By failed, I define that the pillar has fractured to the extent that it no longer generates seismicity and is no longer capable of transmitting stresses. The pillar failure is indicated by the following seismic parameters changes:

Table 3.9 Seismicity trends during a pillar failure

No	Parameter	Mine
		PMC
1.	Seismic activity rate	Increased around the pillar
2.	Percentages of seismicity locating above the mine	At 100%
3.	Energy release rates	Increased
4.	Seismic deformation rates	Increased
5.	Energy index time history	At maximum values
6.	Average monthly seismicity elevations	Reached the shallowest elevations
7.	Seismically active volume	Slow increase
8.	Space distribution of seismicity	Still above the mine but also outside of the mines footprint
9.	Monthly percentages of events with Es/Ep > 10	Reached its maximum (90%)
10.	Seismic activity and production rates	Still directly proportional

1. End of the upwards migration of seismicity and in fact seismicity starts to migrate down
2. End of the rapid increase of the energy index time history
3. The energy index time history reaches its highest levels
4. No seismicity (or limited amount) is recorded in the pillar volume
5. Most of the seismicity is still recorded above the extraction level, but
6. There is already some seismicity locating outside of the mine footprint
7. The relation between recorded seismicity rates and production rates start to change and no longer is entirely direct proportional
8. Increase of the seismically active area and volume (Table 3.9).

3.5.3 Time Period After the Pillar Failure and Before the Break Through

Only in case of PMC I could distinguish between the pillar failure and the break through milestones. It seems that the pillar failure must take place before the cave breaks through. The time period between these two milestones will differ and will depend on many variables (for example the pillar size, the mining rates). As it happened at PMC after the central pillar failure, it took nearly one and a half years for the cave to break through into the open pit. It is possible that those two milestones can be apart of each other for a very short time period so for all practical reasons they can not be recognized using the recorded seismicity as separate milestones of the caving process. An example of such a case might be the break through at the Diablo Regimento Sector during January 2005. In this case, the energy index started

Table 3.10 Seismicity trends after the pillar failure up to the cave break through

No	Parameter	Mine
		PMC
1	Seismic activity rate	At highest rates
2	Percentages of seismicity locating above the mine	Continuously high at above 90%
3	Energy release rates	At highest rates
4	Seismic deformation rates	At highest rates
5	Energy index time history	Continuously at highest values
6	Average monthly seismicity elevations	Start of the downwards trend
7	Seismically active volume	Continuously increasing
8	Space distribution of seismicity	Strong clustering of seismicity
9	Monthly percentages of events with Es/Ep > 10	Highest (90%)
10	Seismic activity and production rates	With time the direct proportional relation disappears gradually out

to increase directly after the initiation of the caving process during October 2004 to reach its maximum values just before the break through during January/February 2005. In this case, it took only 3 or 4 months after the caving process was initiated for the cave to break through. In this case, the pillar failure and the break through had to take place at the same time. In case there is a pronged time between the pillar failure and the break through this time period is indicated by the following seismic parameters changes:

1. The energy index time history stays at the same level until the break through
2. The average monthly seismicity elevations will start to indicate downward migration
3. There will be more seismicity locating below the extraction level
4. There will be an increase of high energy release below the mine
5. The seismically active area and volume will increase
6. There will be no longer any relation between seismicity and production rates (Table 3.10).

3.5.4 Break Through

The break through was recorded seven times and in all four mines. Table 3.11 lists the seismicity trends observed at PMC, Diablo Regimento and Northparkes Lift 2 Mines while Table 3.12 lists these changes for the DOZ Mine. The caves break through among other is indicated by the following seismic parameter changes:

1. Evident decrease in the energy index time history

Table 3.11 Seismicity trends during the cave break through

No	Parameter	Mine			
		PMC (Initial)	PMC (east)	DR	NPM
1	Seismic activity rate	Increased	Increased	Increased	Strong increase
2	Percentages of seismicity locating above the mine	Start of decrease	Generally low	Start of decrease	At 80% then rapid decrease
3	Energy release rates	Increased	Increased	Increased	Increased
4	Seismic deformation rates	Increased	Increased	Increased	Increased
5	Energy index time history	Start of rapid decrease	Start of decrease	Start of rapid decrease	Start of rapid decrease
6	Average monthly seismicity elevations	Downwards migration	Downward migration	Still upward	Start of downward migration
7	Seismically active volume	Rapid increase	Rapid increase	Slow increase	unknown
8	Space distribution of seismicity	Increase in seismicity locating below the mine	All around the mine	Increase in seismicity locating below the mine	Some of the seismicity located around the mine
9	Monthly percentages of events with Es/Ep > 10	Decrease (From above 90% to 60–70%)	No trend	Increase (From 45 to 90%)	At the break time at 70% (2)
10	Seismic activity and production rates	No relation	No relation	Unknown (1)	Unknown (2)

2. Migration of seismicity below the mine level
3. Evident decrease in the amount of seismicity locating above the extraction level
4. High-energy events start to locate below the extraction level
5. Evident and rapid increase in size of the seismically active area and volume.

(1) After the break through the production rates were kept at the same low level but the seismic activity rates displayed a gradually decreasing trend

(2) After the break through there was practically no seismicity recorded.

Table 3.12 Seismicity trends during the cave break through

No	Parameter	Mine		
		DOZ (1)	DOZ (2)	DOZ (3)
1	Seismic activity rate	Unknown	Increased	No trend
2	Percentages of seismicity locating above the mine	Decreasing	Strong decrease	Strong decrease
3	Energy release rates	Increased after	Unknown	Increased during
4	Seismic deformation rates	Unknown	Unknown	Increased during
5	Energy index time history	Unknown	Strong decrease	Strong decrease
6	Average monthly seismicity elevations	Decrease after	Decrease after	Decrease after
7	Seismically active volume	Decrease after	No trend	No trend
8	Space distribution of seismicity	Unknown	All around the mine	All around the mine
9	Monthly percentages of events with Es/Ep > 10	Unknown	Decrease (from 80% down to 50%)	No trend
10	Seismic activity and production rates	Unknown	None	None

3.5.5 *Seismicity Trends After the Cave Break Through*

This caving process milestone is important as it might be in place for the longest time period during the mines life and while the mine infrastructure is already fully developed. This caving milestone seems the best indicated by the following seismicity trends:

1. Continuous decrease of the energy index into values below its mean of 1.0
2. Continuous decrease in percentages of seismicity locating above the mine elevation. These percentages at some stage reach their minimum values
3. The average monthly seismicity elevations are at values below the extraction level elevations
4. The seismically active volume does not change considerably and its trend indicates continuity in size
5. In general all seismicity activities are low
6. There is no relationship between the production and seismicity rates (Table 3.13)

(1) After the break through the production rates were kept at the constant low level and the seismic activity rates displayed a slow decreasing trend. During the

Table 3.13 Seismicity trends after the cave break through

No	Parameter	Mine		
		PMC (Initial)	PMC (East)	DR
1	Seismic activity rate	General decrease	General decrease	Low
2	Percentages of seismicity locating above the mine	Start of rapid decrease	Slow decrease	Slow decrease
3	Energy release rates	General decrease	Initially increase then general decrease	Increase
4	Seismic deformation rates	General decrease	General decrease	Some increase but associated with the production build-up
5	Energy index time history	Rapid decrease starts	General decrease below the mean value	Continuous decrease
6	Average monthly seismicity elevations	Continuous downward migration	Continuous downward migration	Firstly at the same elevation then decrease
7	Seismically active volume	Continuous in size	Decrease	General increase
8	Space distribution of seismicity	All around the cave and mine	All around the mine	All around the cave and mine
9	Monthly percentages of events with $Es/Ep > 10$	Continuous (60–70%)	Continuous (60–70%)	First decrease (down to 30%) then increase up to 100% after the production build-up
10	Seismic activity and production rates	No relationship	No relationship	Unknown (1)

second production build-up there was only an initial increase in seismic activity rates, which then after some time started to decrease.

3.5.6 Mature Stage of the Caving Process

This caving milestone indicates that the caving process already reached its outermost boundaries and has started to reduce in its intensity and size. It seems that this caving stage is best indicated by the following seismicity trends:

1. General decrease in all seismic activity rates
2. Decrease of the seismically active area and volume
3. Increased scattering of seismicity

Table 3.14 Seismicity trends during the mature stage of the caving process

No	Parameter	Mine
		PMC
1	Seismic activity rate	Generally low
2	Percentages of seismicity locating above the mine	Low at 30% or less
3	Energy release rates	Generally low
4	Seismic deformation rates	Generally low
5	Energy index time history	Low and below the average of 1.0
6	Average monthly seismicity elevations	Below the mine level
7	Seismically active volume	Decreasing
8	Space distribution of seismicity	The seismicity becomes scattered
9	Monthly percentages of events with Es/Ep > 10	Continuous between 60 and 70%
10	Seismic activity and production rates	No relation

4. Energy index time history displays continuous with time values that are close or are below its mean value of 1.0 (Table 3.14).

3.6 Conclusions

From the presented analysis, it is clear that the caving process can be monitored by the recorded seismicity. Seismicity is defined as a number of seismic events in a unit of time. From the practical point of view, the lowest time unit that can be used but only in some specific cases is week (or 10 days) but in most cases the lowest realistic time unit will be one month. In the presented analyses, I have also used much longer time spans, for example a couple of months or a number of years. Such long time spans were used with the energy index time history, cumulative graphs of seismic moment or seismic energy or the average seismicity elevation changes. From this, it is evident that the analysis does not take into account any single seismic event (even the largest ones) but at any time makes use of vast number of events. Term vast, as such is not specific, but in this case it means from thousands up to hundred thousands of events. The lowest numbers of events will be used in cases of the seismicity rates. Usually with the seismicity rates the shortest time will be one month. Monthly seismicity rates can vary from a couple of events up to thousands of events. In all presented analyses, I have not investigated single monthly rates as such but their changes over long time periods. The same applies to any other parameters, for example, the energy index or the average monthly seismicity elevation. I am studying their trends. Trend analysis is about collecting data and attempting to extract a pattern from this data. In statistics, trend analysis refers to techniques for extracting an underlying pattern of behaviour in a time series which would otherwise be partly or nearly completely hidden by noise. A simple description of these techniques is trend estimation. Uncovering a trend involves a number of techniques such as filtering the input data using time and/or space and/or some of its dimensions. Then, the filtered data is smoothed, for example, by applying a regression analysis. By definition such techniques result in reliable and consistent results when applied to rather large data sets. The four seismic catalogues analysed contain from, a couple of thousand events up to a couple of hundred thousand events. In total, I have analysed close to a million seismic events. These four seismic data sets are not only consistent as separate input catalogues but also as whole. All mines are not only using the same seismic system for recording the seismicity but the recorded data was then processed with the same software versionversion. In this way, the input data has not only sufficient quantity but also quality. Presented seismic data analysis and interpretation leads to the following conclusions:

1. Mining data was used to confirm the following caving milestones taking place:
    - Initiation of the caving process
    - Pillar failure
    - Time period after the pillar failure and before the break through
    - Break through
    - The time period after the cave break through
    - Mature stage of the caving process
2. For the presented results of seismicity analysis to have credibility it is fundamental that these milestones are evidenced by additional means not seismicity only
3. The initiation of the caving process was evidenced three times in three different mines
4. The pillar failure was evidenced only once
5. The cave break through was evidenced in total seven times and it was documented in all four mines
6. The mature stage of the caving process was reached probably only in the one case
7. It is obvious that each of these milestones doesn't take place instantly. For this reason, it is often impractical to use accurate occurrence timing.
8. All seismicity analysis resulted in qualitative results
9. At this stage it appears that the most effective seismicity parameters trends that can be used to indicate the caving process and its stages are (in importance order)
    - Energy index time history
    - Percentages of seismicity above the mine
    - Average monthly seismicity elevation time history
    - Seismic deformation trends
    - Changes in size of the seismically active volume.

10. The seismic energy releases by nature are of extremely wide ranges and for this reason are difficult and more often impossible to present visually as graphs.

In all the presented analysis, I have used two types of parameters. The first one is based on mining data and the second is derived from seismicity. By definition, the seismicity that I was analysing is mine-induced seismicity. This definition implies that there is strong relationship between the mining and seismicity parameters. This relationship is certainly there but it is not continuous in its nature, nor is it constant. As I have illustrated it does not always follow that increase of production rates will result in increase of the seismicity rates or in larger size seismicity taking place. The dependency between production and seismicity changes over time with the caving process progress. The seismicity parameters that I used 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 its 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 the 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 its height. Additionally height 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. I have used the so-called energy index which is also 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 convenience as it is a part of the software code. These two functions proved to be of great importance for a 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 finding their trends.

The main problem I encountered was associated with the seismic energy release rates. Each of the seismic catalogues analysed contained a wide range of magnitudes. For this reason, the energy release scale is also of significant size. This on its own makes it difficult to analyse the seismic energy release trends as one large size seismic event can obscure the resulting trend. Additionally, I have discovered that some of the analysed databases contained a number of seismic events with incorrect and extremely high energy releases. These events were not the largest ones, and usually their size was below magnitude 1.0. This problem indicates how important the proper maintenance of the seismic data base is. It seems strange that these extremely high energy releases were not noticed at the time when these events were processed. This might indicate that the problem occurred while the seismic database was recalculated with the new software version. I noticed this problem much earlier when I recalculated two months of the PMC database. Here, the extremely high energy releases were associated not with real events, but with noise that somehow passed through the filter

(Glazer 2016). Only because of the limited amount of data was I able to eliminate these false events. The problem illustrated with the average energy release by various magnitude sizes would indicate that any analysis based on energy release might be unreliable and in practice, with the presently available datasets, must be performed with caution.

Reference

Glazer SN (2016) Mine seismology: data analysis and interpretation. Palabora mine caving process as revealed by induced seismicity, Springer International Publishing, Switzerland (ISBN 978-3-319-32611-5)

Chapter 4
Comparison of Seismicity Induced While Mining Hydro-fractured and Non-preconditioned Rock Mass Volumes

Abstract In this chapter, I will be comparing seismicity recorded in the Diablo Regimento hydro-fractured cave with the seismicity recorded in the two non-preconditioned caves of PMC and DOZ. For comparison between mines, I will be using cave volumes. At Diablo Regimento Sector, the cave volume that will was used is the volume that was reconditioned with the hydro-fracturing technique. Analysis of the seismicity recorded in the three caves presented in this chapter leads to a number of conclusions. The most important one is that the preconditioning of the DR rock mass had to result in substantial fracturing of the rock mass. A similar rock mass condition to what was already in place at DR right from the commencement of the cave mining, was achieved only after nearly 3 years of production at PMC. The PMC rock mass was gradually preconditioned by the caving process.

The three seismic data bases used for this comparison are consistent not only because they were recorded with the same type of seismic network but also because the data in each database was processed with the same version of the processing software. The presented seismic data indicated that the sensitivity of the three networks was similar. There is sufficient amount of recorded seismicity to allow a reliable comparison. The sizes of recorded events are compatible with regard to released energy and seismic moment size. In addition, the seismic mechanisms as indicated by the amounts of seismicity with high Es/Ep ratios recorded in the three mines are also the same. Mentioned similarities on their own should make the comparison of the recorded seismicity in the three different mines possible, however, they do not guarantee the reliability of the results. This is due to the diversity in some of the other parameters. These amongst others include the following data that was used for the analysis: lengths of seismic data bases, amounts of recorded seismicity, monthly production rates, cave volumes, presence or lack of caving milestones. For this reason, in most of the comparisons, I had to normalize the recorded seismicity over the cave volume or over the cave production and make use of percentages and seismicity trends rather than directly make use of the recorded seismicity values. This analysis resulted in the following conclusions:

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A. The hydro-fracturing of the Diablo Regimento Sector had to result in substantial fracturing of the rock mass. A similar condition of the rock mass at PMC was achieved only after almost 3 years of production. Here, the rock mass was preconditioned gradually by the caving process
B. The high percentages of recorded seismicity with high Es/Ep ratios in the three mines indicate that the primary caving process mechanism is shear failure
C. The reason that PMC has lower indices which normalize the seismic moment over the loaded tonnes or the cave volumes compared to the DR can be explained by the observed poor fragmentation. At PMC, the average oversize tonnage contribution from 2002 up to the end of 2009 was close to 30%. These amounts of oversize indicates that the seismic deformation, which was taking place in the cave, did not always result in good breaking of the rock mass.

The above conclusions would not have been possible, if they were only based on one input data set. The value of the above conclusions is based on the fact that they were derived from data that originates from three different input data sets.

4.1 Introduction

In this chapter, I will be comparing seismicity recorded in the Diablo Regimento hydro-fractured cave with the seismicity recorded in the two non-preconditioned caves of PMC and DOZ. For these comparisons, I will be using the following three databases:

1. Diablo Regimento Sector, El Teniente Mine
2. Palabora Mining Company
3. Deep Ore Zone Mine, PT Freeport Indonesia.

Figure 2.10 (Chap. 2) illustrates the monthly seismic activity and production rates for Diablo Regimento Sector from the beginning of January 2005 until the end of July 2009. The seismic activity rates vary from about 100 recorded events per month to nearly 2600 events per month. The average monthly seismic activity rate for this 55 month period is 450 events per month. Production at the Diablo Regimento Sector commenced in June 2005. The initial build-up of production was gradual (black curve), from 20,000 tonnes in June 2005 to 150,000 tons in April 2006. Then, for the next 18 months (until October 2007), the monthly production rate remained stable at around 150,000 tons per month. From November 2007, there was a continuous production build-up from 150,000 tonnes per month up to 500,000 tons per month during July 2009. Figure 2.13 (Chap. 2) illustrates the monthly seismic activity and production rates of the Palabora Mining Company Mine from the beginning of January 2001 until mid-August 2009. The monthly seismic activity rates vary from about 100 events per month up to nearly 3800 events per month. The average monthly seismic activity rate for this 126 month period is 1060 events per month. The cave production (black curve) at PMC commenced in May 2001. The initial build-up of

Table 4.1 Seismicity of specific magnitude ranges recorded in the three mines

Magnitude range	DR	PMC	DOZ
$-1.5<M<-1.0$	914	5453	64,278
$-1.0<M<-0.5$	10,681	43,736	194,534
$-0.5<M<0.0$	9950	59,286	147,514
$0.0<M<0.5$	2712	21,916	51,447
$0.5<M<1.0$	491	2935	12,283
$1.0<M<1.5$	32	326	2867
$1.5<M<2.0$	3	21	608
$M>2.0$			75

Table 4.2 Production rates

Mine	Cumulative production (tonnes)	Maximum monthly rate (t/month)
DR	1.05E+07	500,000
PMC	8.03E+07	1,000,000
DOZ	9.15E+07	2,200,000

Notes

1. DR total production from 1 January 2005 until 31 July 2009
2. PMC total production from 1 January 2001 until 30 June 2010
3. DOZ Total production from 1 August 2004 until 31 July 2009

production was gradual, from 10,000 tonnes in June 2001 up to about 1,000,000 tonnes in April 2006. Figure 2.12 (Chap. 2) illustrates the monthly seismic activity and production rates of the Deep Ore Zone Mine from the beginning of August 2004 until the end of July 2009. The monthly seismic activity rates vary from about 2000 events per month to nearly 36,000 events per month. The average monthly seismic activity rate for this 60 month period is 7900. The production (black curve) rate at the DOZ up to the end of 2006 was around 1,200,000 tonnes per month and then, started to increase gradually up to 2,200,000 tonnes per month during July 2009.

Table 4.1 lists the number of seismic events recorded in the three mines grouped by magnitude range. This table indicates that the lowest number of seismicity for each range was recorded at Diablo Regimento Sector while the highest amounts of seismicity per each magnitude range were recorded at the DOZ Mine. This table indicates that at the PMC mine, there were 10 times more events of magnitude 1.0 and above than at the DR Mine. At DOZ, the number of recorded events of this size is 100 times higher than that recorded at the DR Mine.

Figures 4.1, 4.2 and 4.3 illustrate the monthly production rates at DR Sector, PMC Mine and at the DOZ Mine, respectively. For direct comparison, the vertical axis of these three figures is the same. These three figures illustrate the fact that the monthly production rates at DR are the lowest and the DOZ the highest. The PMC rates are about halfway through. This is illustrated by data presented by Table 4.2.

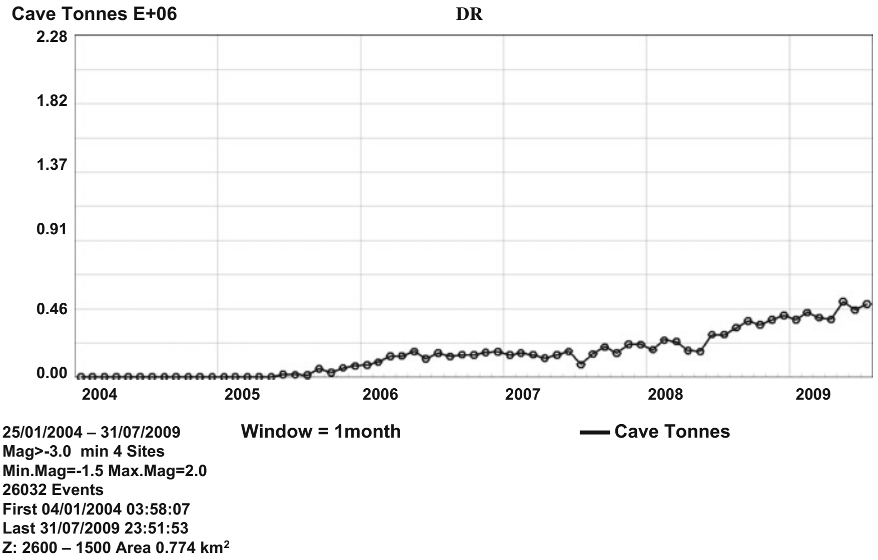


Fig. 4.1 DR monthly production rates

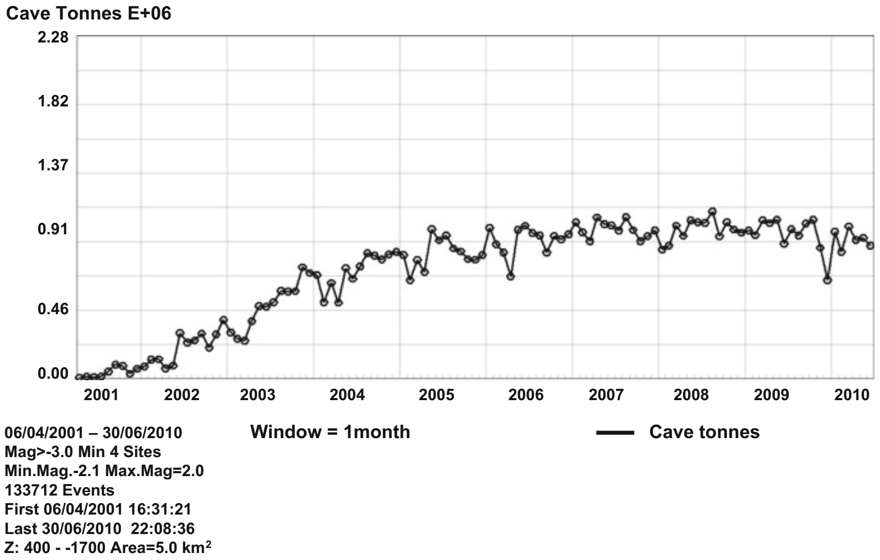


Fig. 4.2 PMC monthly production rates

Table 4.2 lists the cumulative production and the maximum monthly production rates at the Diablo Regimento Sector, PMC and the DOZ Mines. Both cumulative production and the monthly production rates for the DR Sector are the lowest while

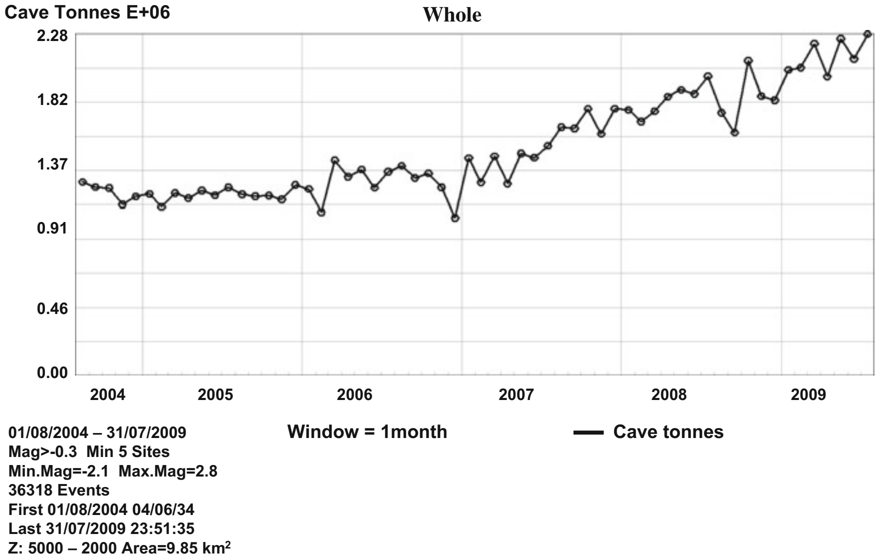


Fig. 4.3 DOZ monthly production rates

the highest are for the DOZ Mine. The monthly production rates at DOZ are twice as high as the PMC rates and four times higher than the DR rates.

For comparison between mines, I will be using cave volumes. At Diablo Regimento Sector, the cave volume that will be used is the volume that was preconditioned with the hydro-fracturing technique. Based on this information, I have created a polygon (Fig. 4.4) named ‘Hydro-fractured Area’. Figures 4.5 and 4.6 illustrate the PMC areas that were used to calculate the cave volume and the volume surrounding the cave volume.

At PMC, the first seismic event was recorded on the 16 September 1999, so the PMC seismic database contained just over 10 years of data. This recorded seismicity contains information about the following PMC mining milestones (Glazer 2016):

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

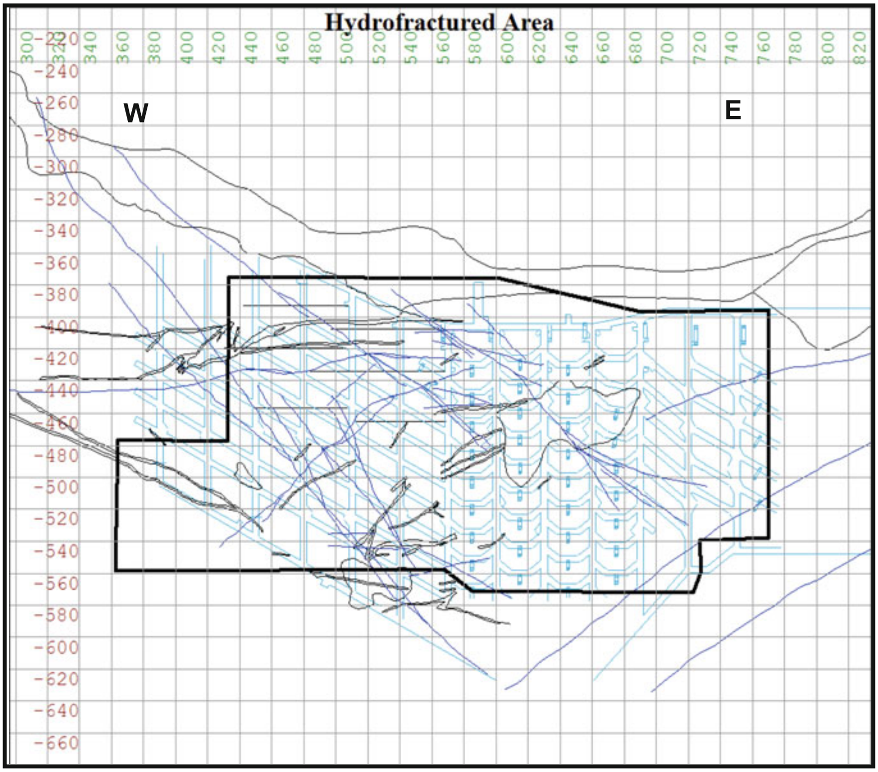


Fig. 4.4 W-E horizontal plan—the hydro-fractured area

8. Failure of the open pit North wall (D)—October 2004
9. East breakthrough (E)—May/June 2008.

Figures 4.7 and 4.8 illustrate the two areas that were then used to calculate the two DOZ volumes, the cave volume and the volume surrounding the cave.

The DOZ break through in the east took place before the seismic network was installed. The break through at the centre part took place during October 2005 (Fig. 3.2, Chap. 3). Production in the west commenced at the beginning of 2006—see Fig. 4.9. During December 2007, the total DOZ monthly production was 1,780,500 tonnes, while from the west, it was close to 714,000 tonnes which is about 40% of the total production—see Fig. 4.10. Figure 4.11 shows the development rates. From the beginning of 2005, all development mining was taking place in the western section of the DOZ Mine. These figures indicate that both the cave and development mining induced the recorded seismicity.

Figure 3.3 (Chap. 3) shows the estimated DOZ cave back position at the beginning of 2006. Here, the central pillar is shown as part of the cave back. Based on available seismic data, I assume that the pillar located below the minimum IOZ elevation broke through by mid-2008.

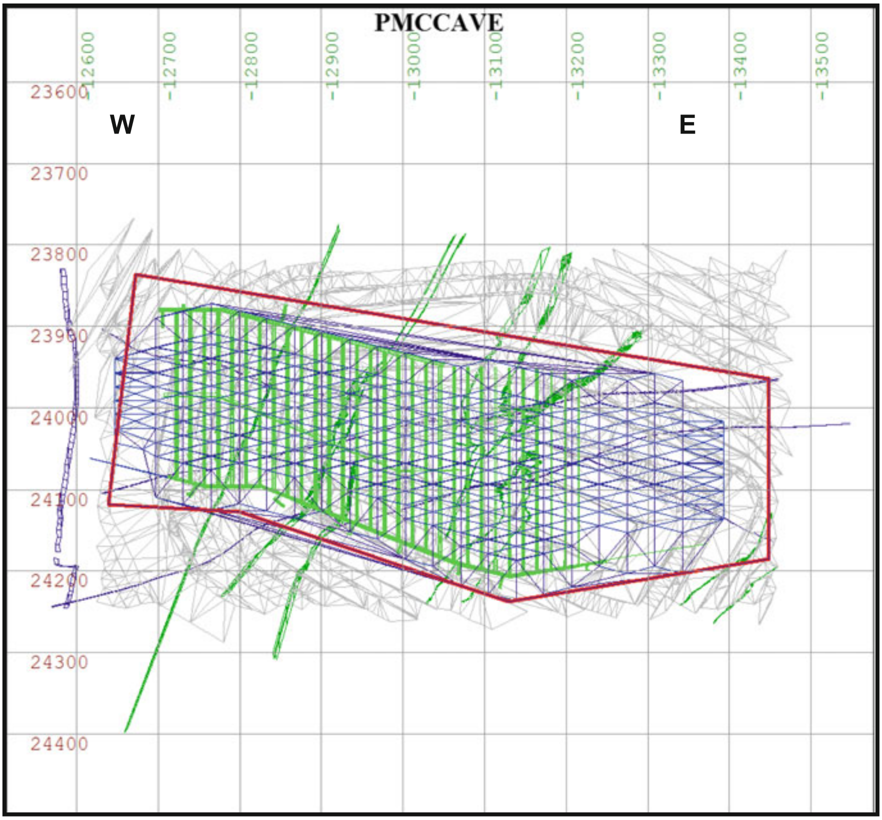


Fig. 4.5 PMC cave area

Table 4.3 Areas and volumes

Volume	DR		PMC		DOZ	
	Area	Volume	Area	Volume	Area	Volume
Cave (km^2)	0.0659	0.007249	0.225	0.23	0.602	0.435
Out of cave (km^2)	0.774	1.540	4.04	8.1	9.3	27.0

Table 4.3 lists the areas and volumes that will be used for comparison purposes. The volume of the Diablo Regimento cave is the smallest while the DOZ cave volume is the largest of the three caves.

The following three tables illustrate the number of events (Table 4.4), the released seismic energy (Table 4.5) and the cumulative seismic moment (Table 4.6) in the three cave volumes and the three volumes surrounding the caves. In all cases taking into account, the cave volumes and the surrounding volumes, the lowest amounts of

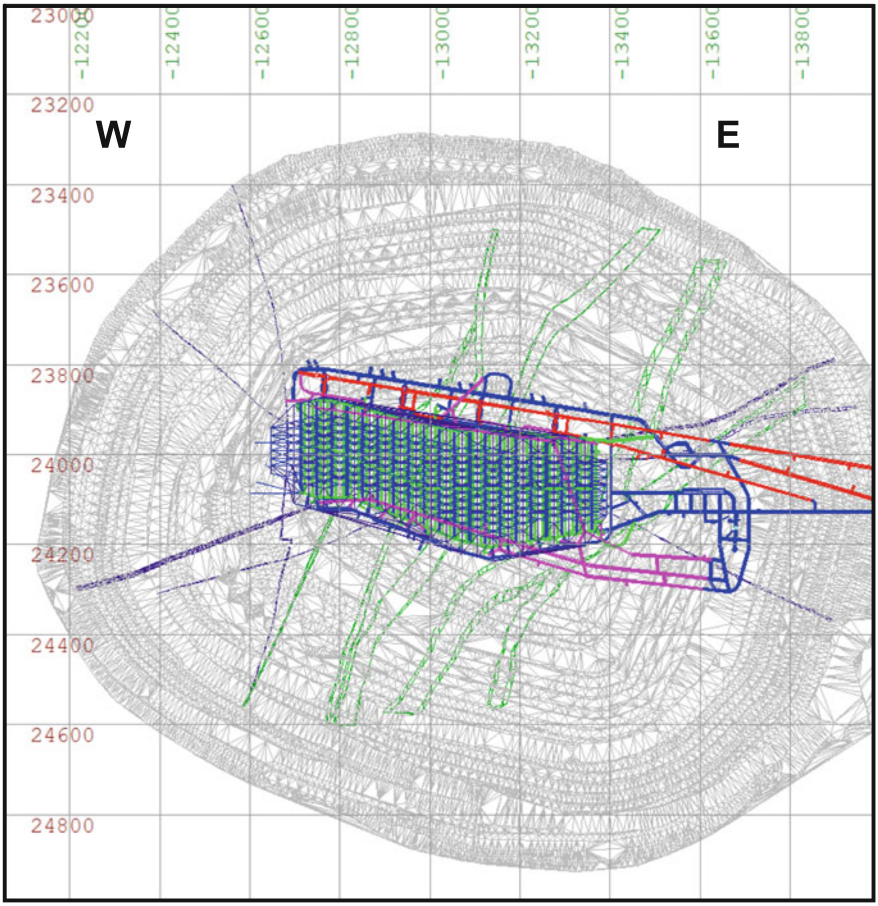


Fig. 4.6 PMC mine

Table 4.4 Number of recorded seismic events

Volume	DR	PMC	DOZ
Cave	6573	36,459	258,327
Out of cave	18,235	97,374	217,061
Total	24,808	133,833	575,388

seismicity, seismic energy and seismic moment were recorded at the DR Mine while the highest amounts were recorded at the DOZ Mine.

Figures 4.12, 4.13 and 4.14 illustrate the seismic energy versus seismic moment relation for the three mines. Data from these three figures is collated by Table 4.7.

Data presented by Table 4.7 indicates that most of the recorded seismicity at all three mines fit into similar seismic energy and seismic moment ranges. The fact that the lower range values are the same indicates that the three seismic networks

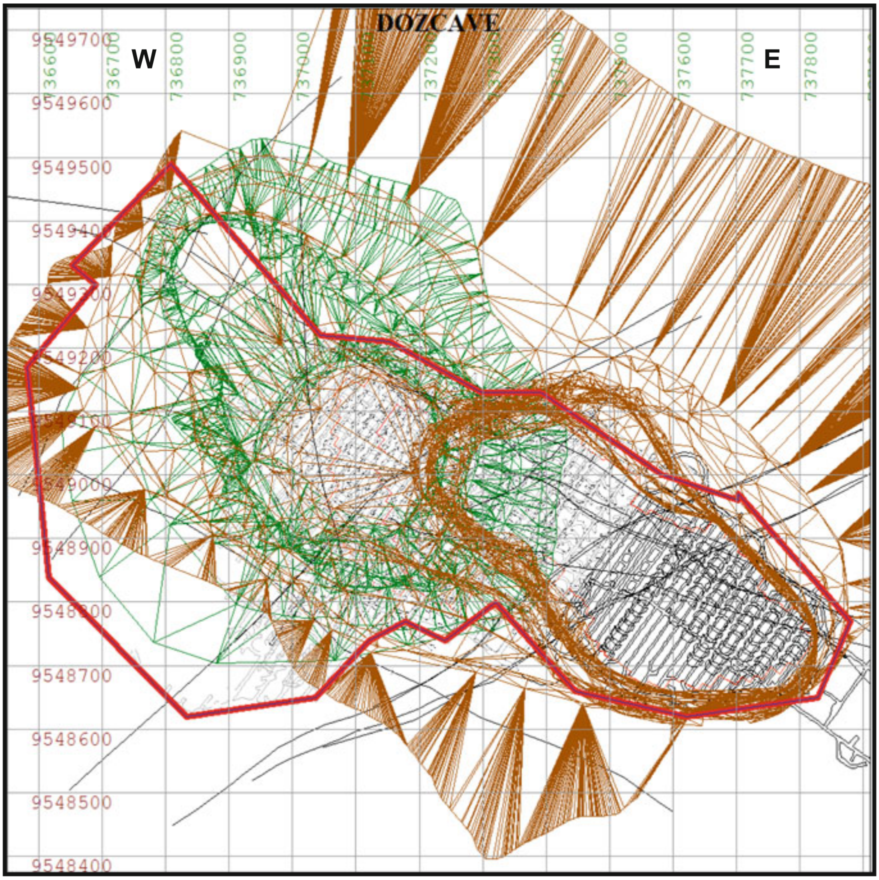


Fig. 4.7 DOZ cave area

Table 4.5 Cumulative seismic energy

Volume	DR (J)	PMC (J)	DOZ (J)
Cave	7.01E+06	9.36E+07	1.02 E+09
Out of cave	1.33E+07	2.41E+08	8.93E+09
Total	2.03E+07	3.35 E+08	9.95E+09

had similar sensitivities. The upper limits are different, indicating that the largest size seismicity was recorded at the DOZ Mine while the lowest size seismicity was recorded at the Diablo Regimento Sector.

The next three figures illustrate the monthly percentage values of seismicity with the Es/Ep ratio greater than 10.0. Figure 4.15 illustrates how this ratio changes month-on-month in the Diablo Regimento cave; Fig. 4.16 illustrates the data for the PMC cave while Fig. 4.17 presents this relationship for the DOZ cave. In all three cases,

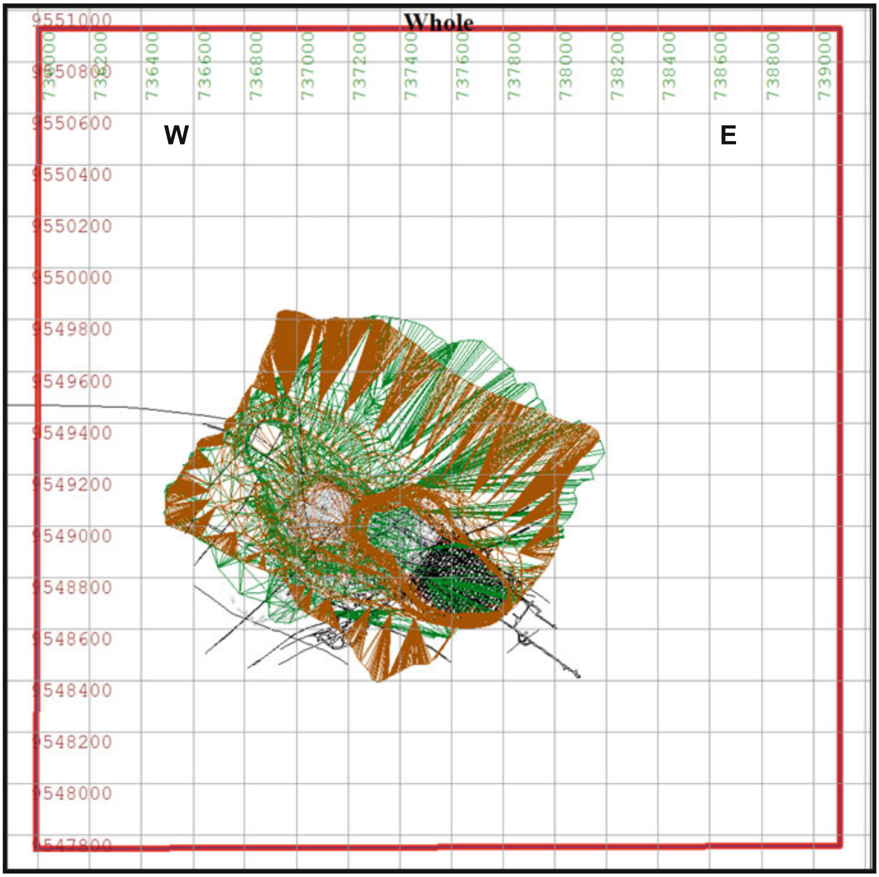


Fig. 4.8 DOZ mine area

Table 4.6 Cumulative seismic moment

Volume	DR (Nm)	PMC (Nm)	DOZ (Nm)
Cave	3.26E+12	1.97E+13	1.02E+14
Out of cave	1.44E+13	9.75E+13	7.62E+14
Total	1.67E+13	11.72E+13	8.64E+14

the percentages of events with this ratio greater than 10.0 are high. In fact, they are around the 60% mark.

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 (not one of these mines

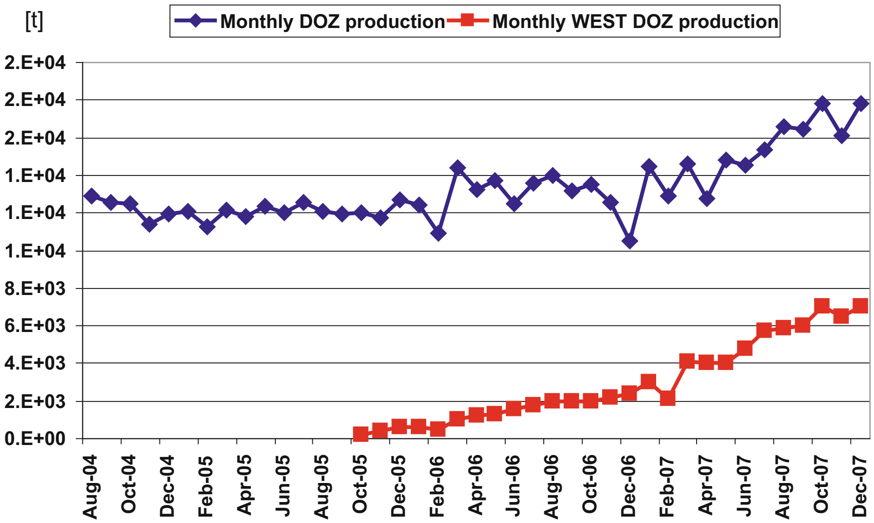


Fig. 4.9 DOZ production rates

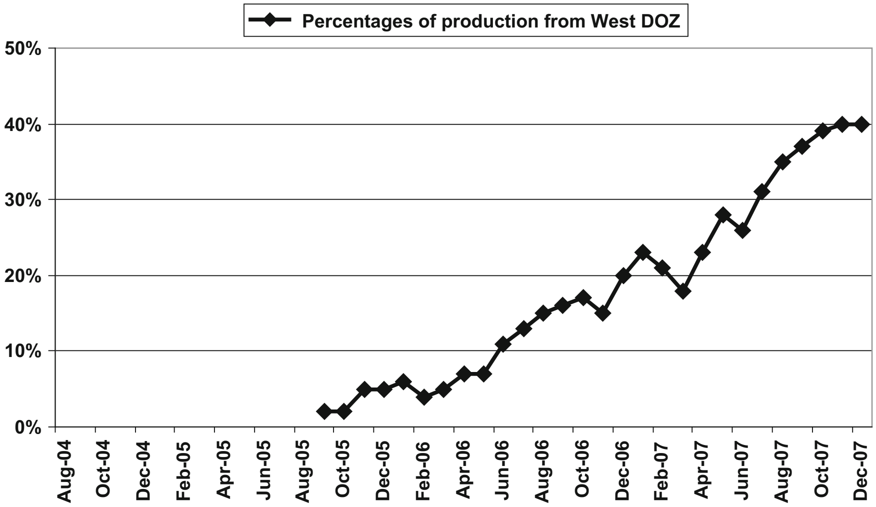


Fig. 4.10 West DOZ percentages of total production

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. Table 4.8 presents the percentages of seismicity with this ratio above 10.0 in the three cave volumes and in the three volumes surrounding the caves. Only in case of the volume surrounding the DOZ cave, is the percentage of these events at 50%. In all other caves, these percentages are between 60 and 70%. The lower is the Es/Ep ratio the more energy was released

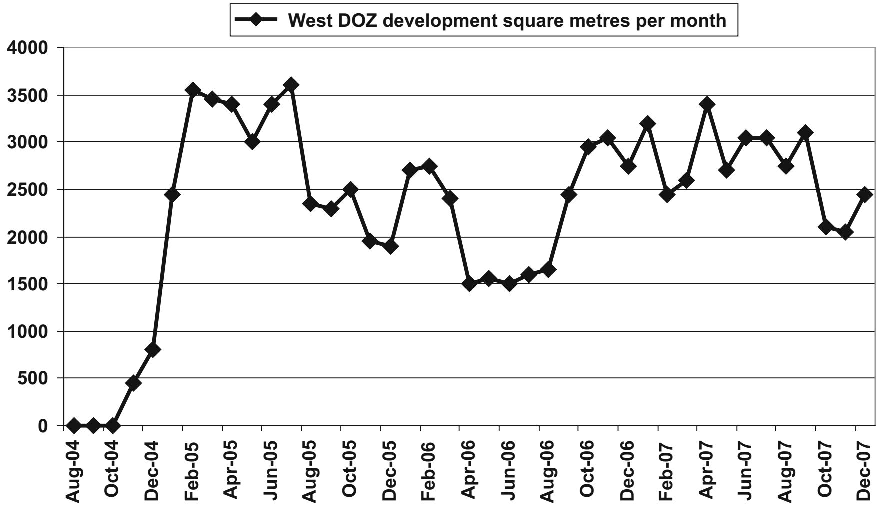
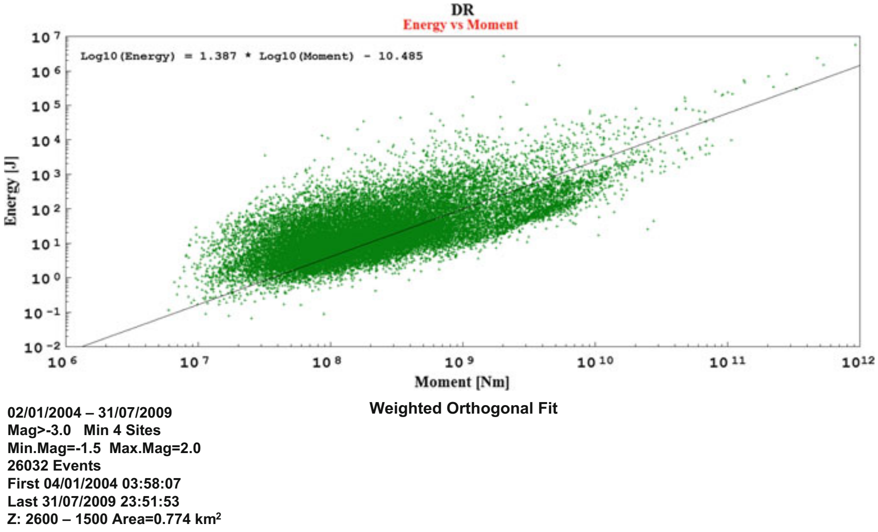


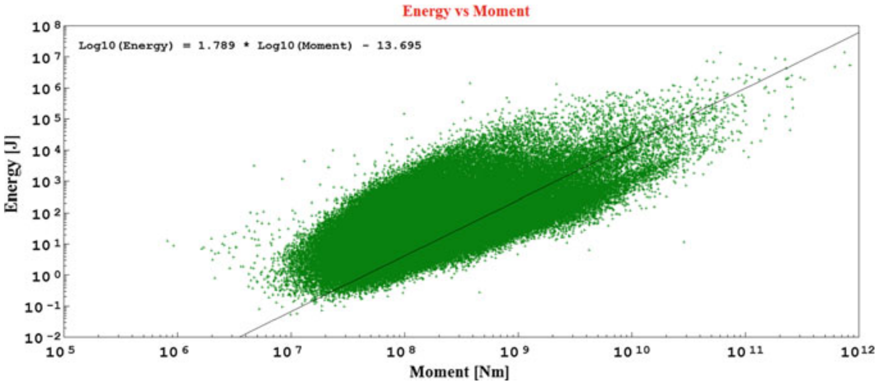
Fig. 4.11 West DOZ development rates



02/01/2004 – 31/07/2009
Mag>-3.0 Min 4 Sites
Min.Mag=-1.5 Max.Mag=2.0
26032 Events
First 04/01/2004 03:58:07
Last 31/07/2009 23:51:53
Z: 2600 – 1500 Area=0.774 km^2

Fig. 4.12 DR the energy moment relation

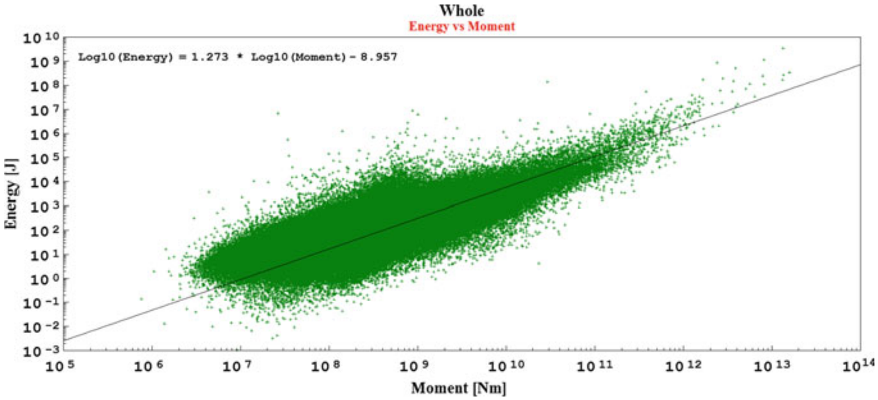
by the P-waves indicating a higher tensile component in the source mechanism. On the other hand, the higher this ratio, the higher is the contribution of energy released by the S-wave indicating a higher component of the double couple mechanism in the source. For this reason, the high percentages of seismicity with ES/Ep ratios above 10.0 indicates that the principal caving process mechanism is shear failure.



06/04/2001 – 30/06/2009
Mag>-3.0 Min 4 Sites
Min.Mag=-2.1 Max.Mag=2.0
133712 Events
First 06/04/2001 16:31:21
Last 30/06/2009 22:08:36
Z: 400 – 1700 Area=5.00 km^2

Weighted Orthogonal Fit

Fig. 4.13 PMC the energy moment relation



01/08/2004 – 31/07/2009
Mag>-3.0 Min 5 Sites
Min.Mag=-2.1 Max.Mag=2.8
362318 Events
First 01/08/2004 04:06:34
Last 31:07:2009 23:51:53
Z: 5000 – 2000 Area=9.85 km^2

Weighted Orthogonal Fit

Fig. 4.14 DOZ the energy moment relation

4.2 Diablo Regimento Sector Seismicity Induced in the Cave and in the Surrounding Volumes

In this section, I will be comparing seismicity in two volumes created from the DR Sector volume. The first volume is the preconditioned volume (cave volume) and

Table 4.7 Seismic energy release and seismic moment ranges

Mine	Seismic energy range		Seismic moment range	
	Minimum (J)	Maximum (J)	Minimum (Nm)	Maximum (Nm)
DR	10E−01	10E+06	10E+07	10E+11
PMC	10E−01	10E+07	10E+07	10E+11
DOZ	10E−01	10E+08	10E+07	10E+12

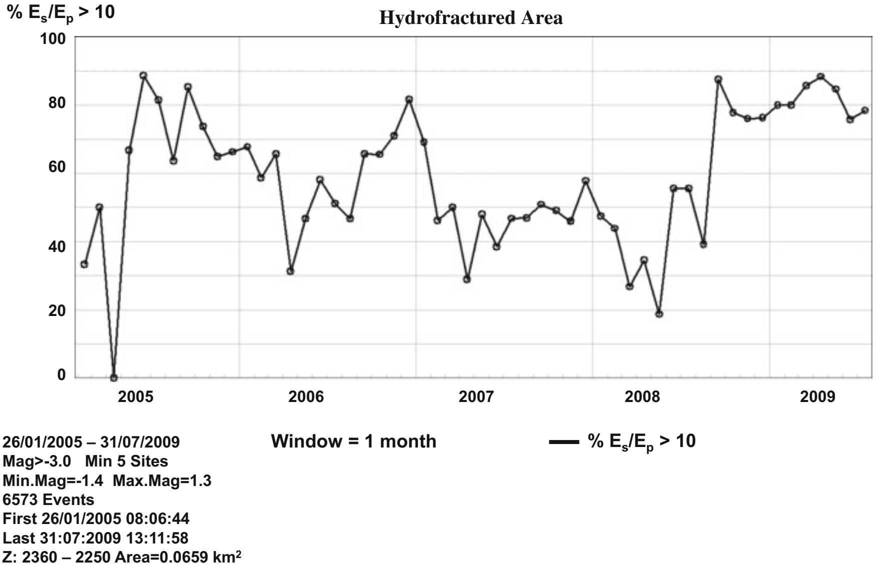


Fig. 4.15 Percentages of high Es/Ep ratio events at DR cave

Table 4.8 Percentages of seismicity with Es/Ep > 10.0

Volume	DR (%)	PMC (%)	DOZ (%)
Cave	62	78	60
Out of cave	65	69	52

the second volume is the non-preconditioned volume (out of cave), which is located around the preconditioned volume. For this comparison, I will be using seismicity recorded from 1 January 2005 until 31 July 2009. Table 4.9 compares seismicity recorded in these two volumes.

According to data presented by Table 4.9, more events (2.8 times), more seismic energy released (1.8 times more) and more seismic deformation (4.5 times more) took place outside of the cave volume in the surrounding rock mass. Figures 4.18, 4.19, 4.20, 4.21 and 4.22 illustrate the seismicity time distribution in the two volumes. In all these figures, the top part shows the seismicity in cave volume while the bottom part illustrates the seismicity recorded in the rest of the Diablo Regimento volume. In all cases, the vertical scales for data recorded in these two volumes are the same allowing

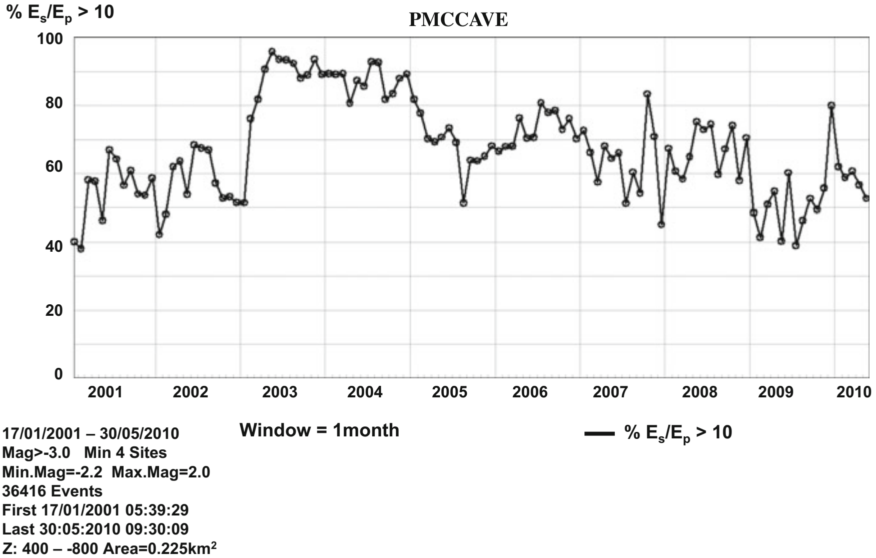


Fig. 4.16 Percentages of high Es/Ep ratio events at PMC cave

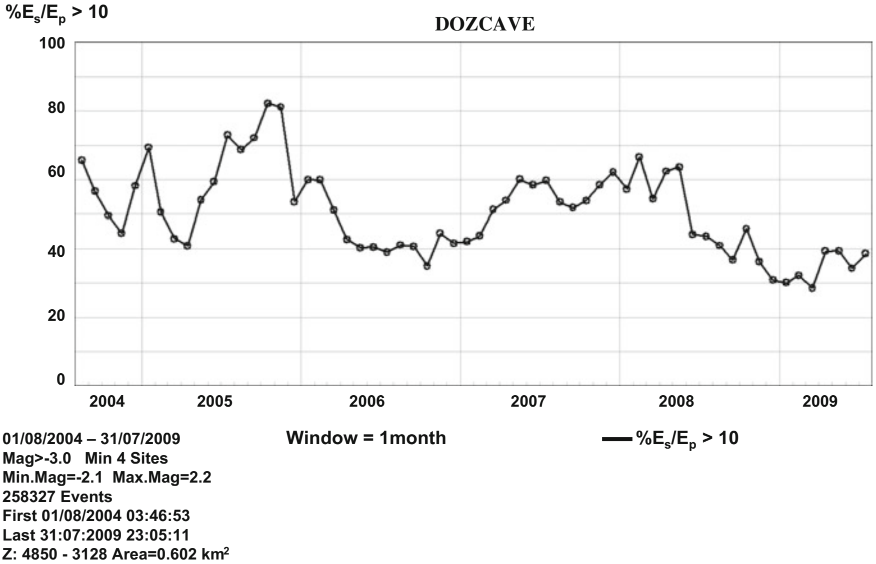


Fig. 4.17 Percentages of high Es/Ep ratio events at DOZ cave

for direct comparisons. The horizontal axes on all figures indicate time. Additionally, all these figures indicate the following milestones of the caving process:

- Start of production (**C**)—June 2005

Table 4.9 Seismicity of the two volumes

Volume	No. of events		Cumulated energy		Cumulated moment	
Cave	6573	26%	7.01E+06 J	35%	3.26E+12 Nm	18%
Out of cave	18,235	74%	1.33E+07 J	65%	1.44E+13 Nm	82%
DR sector whole	24,808	100%	2.03E+07 J	100%	1.67E+13 Nm	100%

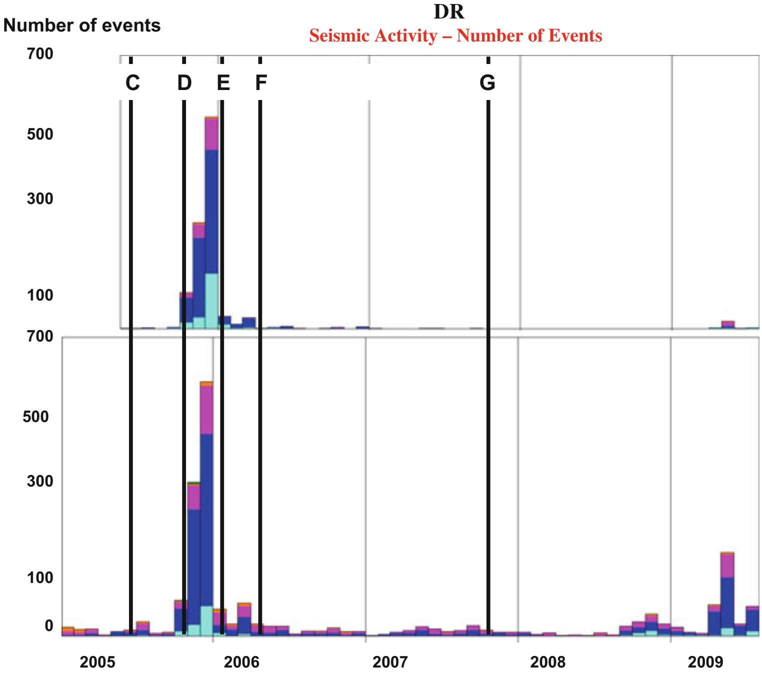


Fig. 4.18 Monthly seismic activity rates

- Initiation of the caving process (**D**)—October 2005
- Failure of the pillar (**E**)—January 2006
- End of the first production build-up phase (**F**)—April 2006
- Start of the second production build-up phase (**G**)—October 2007.

Figure 4.18 illustrates the fact that the highest monthly seismic activity rates in the cave volume were recorded at the end of 2005 and at the beginning of 2006, which was from the time when the caving process was initiated (D) up to the end of the first production build-up (F). From then on, the seismic activity rates to the end of July 2009 were not only constantly low but also lower from those recorded between October 2005 and April 2006. In the surrounding volume, the monthly seismic activity rates indicate an increase after the initiation of the caving process

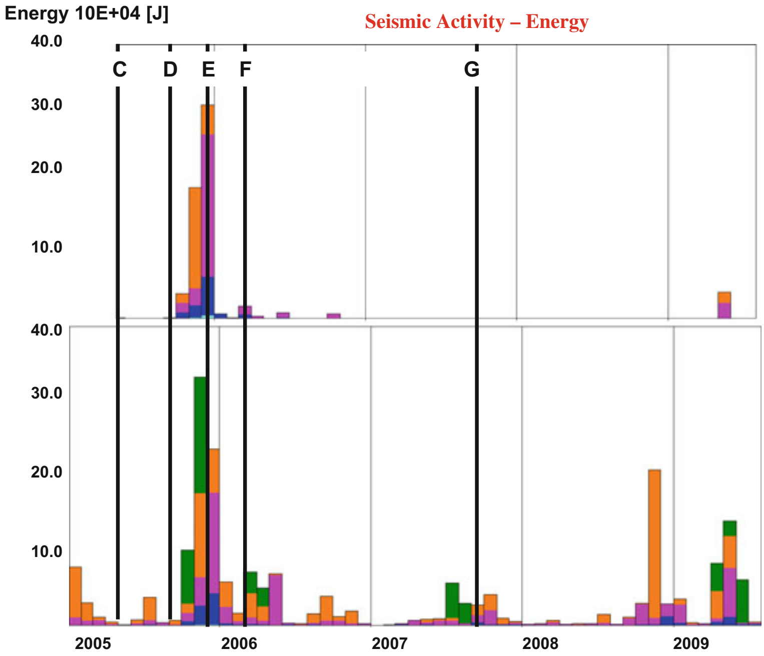


Fig. 4.19 Monthly seismic energy release rates

but then for the rest of the time are constantly higher from those recorded in the hydro-fractured volume.

Figure 4.19 illustrates the monthly seismic energy release rates in the cave and the surrounding volumes. To start with the seismic energy released in the cave volume was much lower than in the surrounding volume. For the analysed time period, the total seismic energy released in the cave volume amounted to 7.01E+06 J, while in the surrounding volume the seismic energy release was higher at 1.33E+07 J. More important are the time distributions of the high energy releases. In the cave volume, most of the seismic energy was released after the initiation of the caving process (D) and before the failure of the pillar (E). The high energy release in May 2006 by a single event of magnitude 0.5 (green) is probably greatly overestimated. The same applies to the extremely high energy released by an event of magnitude 0.2 (orange) recorded during December 2005. If this would be the case, then the total seismic energy released in the cave volume would be much lower. In the surrounding volume, the high energy releases took place every year and these energy releases appear not to be related either to the caving process or the production rates.

Figure 4.20 illustrates the monthly seismic deformation rates. According to data presented by Table 4.9 in the cave volume, the cumulative seismic deformation was 3.26E+12 Nm while in the surrounding volume, it was 4.5 times more at 1.67E+13 Nm. As far as seismic deformation distribution over time is concerned, it is different

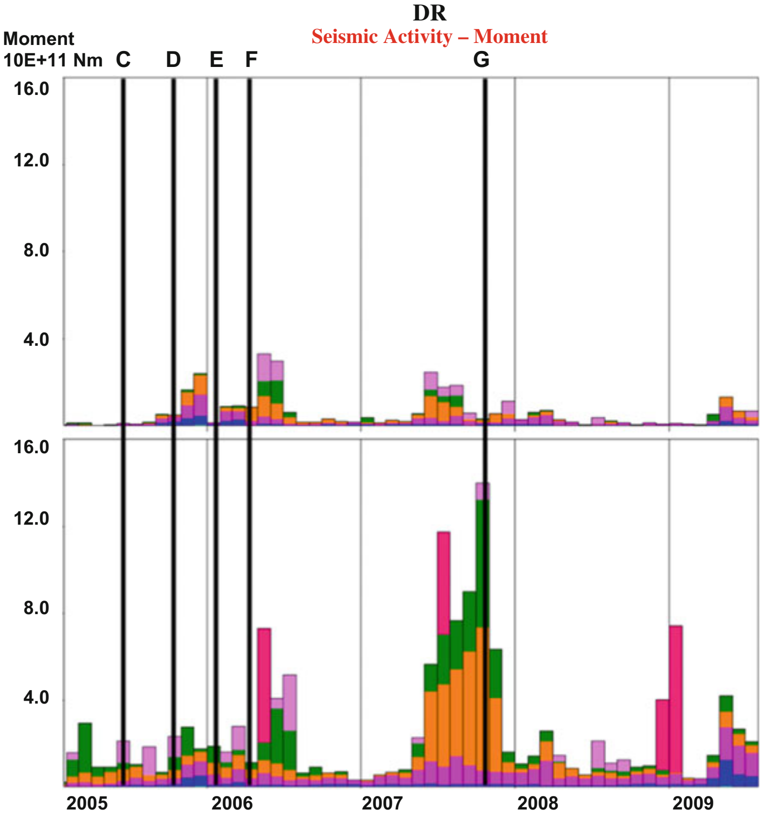


Fig. 4.20 Monthly seismic deformation rates

in these two volumes. In the cave volume, there is more seismic deformation recorded up to mid-2005, while in the surrounding volume, the maximum rates were recorded during 2007.

Figure 4.21 illustrates the energy index time histories in the two volumes. In both volumes, the energy index started to increase with the initiation of the caving process (D) and the maximum index values were at the time of the pillar failure (E). The maximum value of the energy index in the cave volume was slightly lower from the maximum value recorded for the surrounding volume. The other difference between these two energy index time histories is that in the cave volume, the energy index after the decrease from about May 2006 had in general lower values than those in the surrounding volume. From the time of the second production build-up (G), the energy index values in the cave volume remained below the mean value of 1.0 while in the surrounding volume, there was a continuous increase and by the end of 2008, the energy index values were above the mean value. The reason for these differences

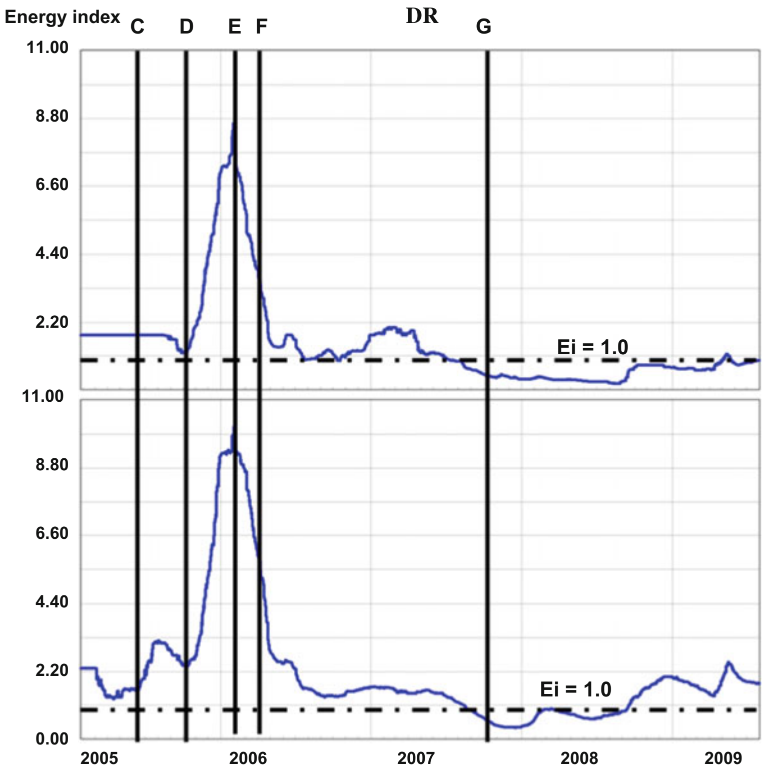


Fig. 4.21 Monthly seismic deformation rates

in the two energy index time histories is the time distribution of the high energy index events in these two volumes.

Figure 4.22 illustrates the monthly seismic activity rates for seismicity with the energy index values above 10.0. In the hydro-fractured volume (Table 4.10), there were 1042 such events (16% of the total seismicity recorded in this volume) while in the non-preconditioned volume of DR Sector, there were 2206 such events (12% of the total). In the cave volume, nearly 93% of these events took place during the last months of 2005 and the first months of 2006 while in the rest of the DR non-preconditioned volume during this time period, only 58% of the high energy events took place. Over 90% of high energy index seismicity that was recorded in the cave volume was associated with a specific time period starting with the cave initiation and ending with the pillar failure.

Figure 4.23 illustrates the monthly energy release rates of events with the energy index above 10.0. By the end of April 2006 (F), already 64% of energy released by events with energy index above 10.0 had been released while in the surrounding volume, this percentage was only at 16%. This indicates that most of the high energy release events in the cave volume ended at the time when, as indicated by the energy

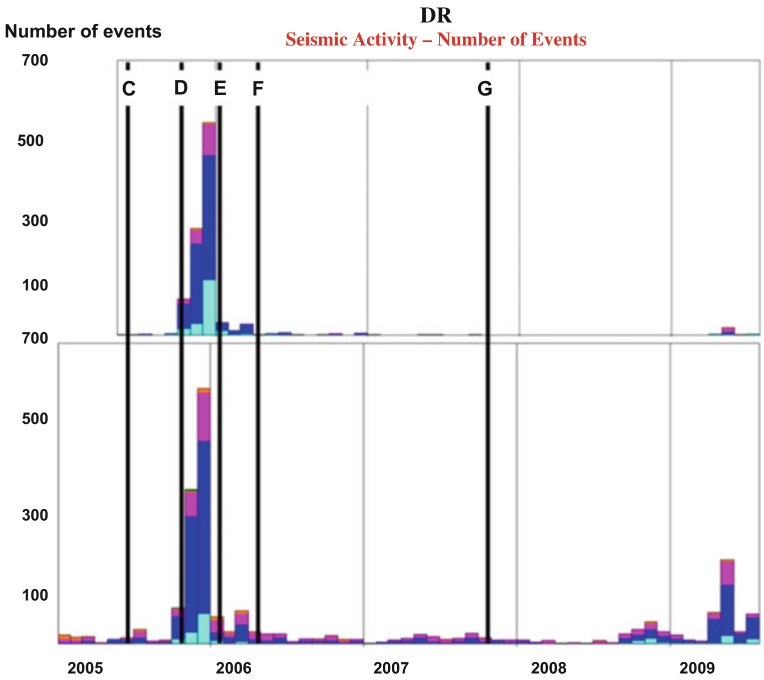


Fig. 4.22 Events with energy index above 10.0—monthly activity rates

Table 4.10 Seismicity of Ei > 10 in the two volumes

Volume	No. of events			Released seismic energy (J)		
	Total	Events with Ei > 10.0	%	Total (J)	Events with Ei > 10.0 (J)	%
Cave	6573	1042	16	7.01E+06	6.25E+05	9
Out of cave	18,235	2206	12	1.33E+07	2.04E+06	15

index time history, the stress reached its average value. In the surrounding volume, most of the high energy release took place after failure of the pillar which took place in January 2006.

Figure 4.24 illustrates the energy index time histories (blue) based only on these events with energy index values that were above 10.0 together with their monthly seismic energy release rates (violet). This figure indicates that in the cave volume, practically all of the high energy releases associated with the high energy index seismicity took place just after the cave initiation and before the pillar failure. In the surrounding non-preconditioned volume, the high energy seismic events took place not only during this time period but were distributed over the whole time period.

Figures 4.25 and 4.26 illustrate the space distributions of the high energy index seismicity. In both these figures, different colours indicate the year in which these

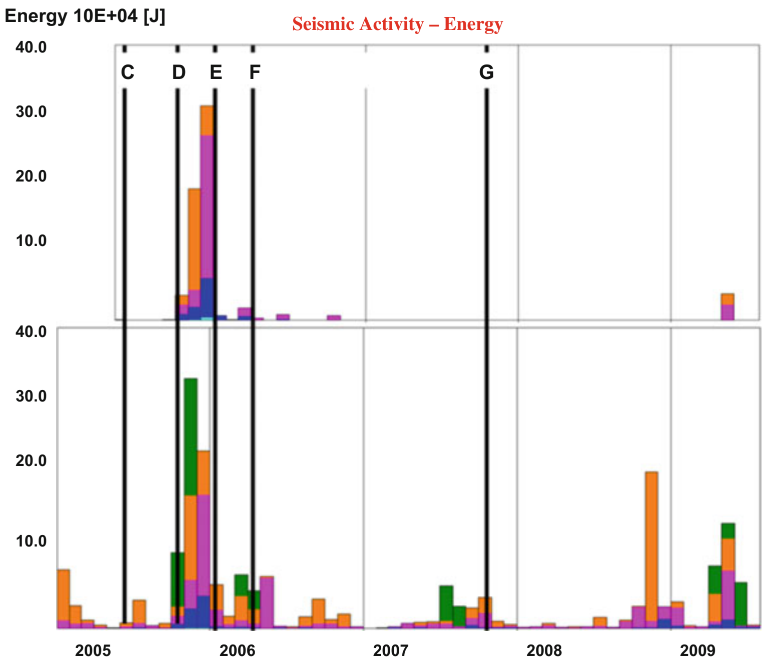


Fig. 4.23 Events with energy index above 10.0—monthly energy release rates

events were recorded. It is interesting to note that that the high energy index seismicity recorded during 2005 (light blue) in the cave volume seems to be distributed over the whole volume (Fig. 4.25). The high energy index seismicity associated with the non-preconditioned volume seems to be spread over large areas located not only at the cave elevations but also above and below this volume (Fig. 4.26).

In the next section, I will investigate the energy release rates per magnitude (moment magnitude) and then compare the average energy release per magnitude in the two volumes. In the following, three figures the ‘Inside’ (red) stands for the cave volume while the ‘Outside’ (blue) stands for the surrounding volume, the volume that was not hydro-fractured. Figure 4.27 illustrates the cumulative seismic energy released inside and outside of the cave volume by events of magnitude from −1.0 up to magnitude −0.1. In this magnitude range, there were more events recorded in the cave volume (Inside) than in the surrounding volume (Outside). This seems to be correct as the network sensitivity would be usually better around the mined volume than outside of it. Accordingly, Fig. 4.27 indicates that these size seismic events emitted more energy in the inside volume than in the outside volume.

Figure 4.28 indicates the average seismic energy released by a single event of magnitude range from −1.0 up to −0.1. Data presented by this figure indicates that on average this size seismicity recorded in the cave volume released more energy than the seismicity recorded outside of this volume.

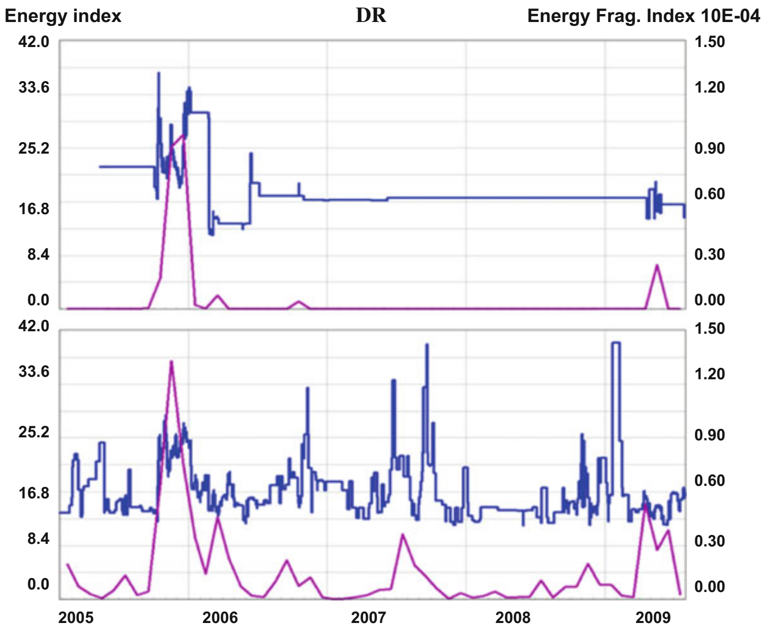


Fig. 4.24 Energy index time histories based on events with Ei > 10

Figure 4.29 indicates the average seismic energy released by a single event of magnitude range from 0.0 up to 1.1. Data presented by this figure indicates that on average this size single event recorded in the cave volume released more energy than the seismicity recorded outside of this volume. Data presented by Figs. 4.28 and 4.29 indicate that on average every single event in magnitude range from −1.0 up to 1.1 that was recorded in the cave volume released more energy than any event of the same magnitude recorded outside of this volume. One would expect that the hydro-fractured cave volume would be more fractured than the outside volume and for this reason on average, each event recorded in the cave volume should release less energy that the same magnitude event originating from outside of this volume.

Table 4.11 lists amongst other values the average energy release per magnitude size in the cave volume (column 6). The average energy release rates for events of magnitude sizes—0.5, 0.2 and 0.5 seem to be well out of the expected sizes.

Figure 4.30 indicates the monthly percentages of seismicity recorded in the cave volume (100% is the total monthly seismic activity rate recorded in the whole DR Sector). This figure clearly illustrates the fact that between initiation of the caving process and failure of the pillar, nearly 50% of the whole DR seismicity was associated with the hydro-fractured volume. After the failure of the pillar, the amounts of seismicity recorded in the hydro-fractured zone decreased to about 20%. It is interesting to note that the start of the second production build-up in October 2007 did not change this trend.

Table 4.11 Cumulative and average energy released per magnitude sizes

Energy per magnitude 1 January 2005–31 July 2009						
Magnitude	Number of events		Energy release (J)		Average energy (J)	
Range	Inside	Outside	Inside	Outside	Inside	Outside
$-1.5 \le M < -1.4$	1	1	1.13E−001	7.35E−001	1.13E−001	7.35E−001
$-1.4 \le M < -1.3$	21	2	1.12E+002	2.98E+000	5.34E+000	1.49E+000
$-1.3 \le M < -1.2$	79	14	2.74E+002	4.75E+001	3.46E+000	3.39E+000
$-1.2 \le M < -1.1$	199	74	1.48E+003	4.93E+002	7.46E+000	6.66E+000
$-1.1 \le M < -1.0$	290	232	4.01E+003	1.68E+003	1.38E+001	7.23E+000
$-1.0 \le M < -0.9$	479	504	8.79E+003	9.04E+003	1.83E+001	1.79E+001
$-0.9 \le M < -0.8$	673	930	1.55E+004	1.30E+004	2.30E+001	1.40E+001
$-0.8 \le M < -0.7$	860	1468	2.71E+004	2.87E+004	3.15E+001	1.96E+001
$-0.7 \le M < -0.6$	959	1870	5.16E+004	4.63E+004	5.38E+001	2.48E+001
$-0.6 \le M < -0.5$	1021	1938	5.29E+004	4.94E+004	5.18E+001	2.55E+001
$-0.5 \le M < -0.4$	891	1865	8.67E+004	1.05E+005	9.73E+001	5.65E+001
$-0.4 \le M < -0.3$	828	1560	7.49E+004	8.90E+004	9.04E+001	5.71E+001
$-0.3 \le M < -0.2$	693	1304	1.34E+005	1.09E+005	1.94E+002	8.38E+001
$-0.2 \le M < -0.1$	567	1038	1.24E+005	2.17E+005	2.19E+002	2.09E+002
$-0.1 \le M < 0.0$	481	775	1.51E+005	2.12E+005	3.14E+002	2.73E+002
$0.0 \le M < 0.1$	344	513	1.70E+005	4.42E+005	4.95E+002	8.61E+002
$0.1 \le M < 0.2$	288	322	1.29E+005	2.12E+005	4.47E+002	6.59E+002
$0.2 \le M < 0.3$	283	230	3.31E+006	1.31E+005	1.17E+004	5.69E+002
$0.3 \le M < 0.4$	216	165	1.40E+005	2.16E+005	6.48E+002	1.31E+003

(continued)

Table 4.11 (continued)

Energy per magnitude 1 January 2005–31 July 2009

Magnitude	Number of events		Energy release (J)		Average energy (J)	
Range	Inside	Outside	Inside	Outside	Inside	Outside
$0.4 \le M < 0.5$	210	157	1.31E+005	1.84E+005	6.24E+002	1.17E+003
$0.5 \le M < 0.6$	133	113	1.61E+006	2.15E+005	1.21E+004	1.90E+003
$0.6 \le M < 0.7$	55	70	2.35E+005	2.47E+005	4.28E+003	3.52E+003
$0.7 \le M < 0.8$	17	47	3.47E+004	3.67E+005	2.04E+003	7.82E+003
$0.8 \le M < 0.9$	10	23	9.90E+004	1.22E+005	9.90E+003	5.31E+003
$0.9 \le M < 1.0$	1	23	3.52E+004	2.24E+005	3.52E+004	9.75E+003
$1.0 \le M < 1.1$	3	10	6.30E+004	1.30E+005	2.10E+004	1.30E+004
$1.1 \le M < 1.2$	2	5	1.59E+005	1.58E+005	7.95E+004	3.16E+004
$1.2 \le M < 1.3$	3	2	1.40E+005	1.37E+005	4.68E+004	6.87E+004
$1.3 \le M < 1.4$	4	2	6.88E+005	4.53E+005	1.72E+005	2.27E+005
$1.4 \le M < 1.5$	0	2		1.00E+006		5.00E+005
$1.5 \le M < 1.6$	0	0				
$1.6 \le M < 1.7$	0	0				
$1.7 \le M < 1.8$	0	1		2.97E+005		2.97E+005
$1.8 \le M < 1.9$	0	2		3.82E+006		1.91E+006
$1.9 \le M < 2.0$	0	1		3.95E+006		3.95E+006

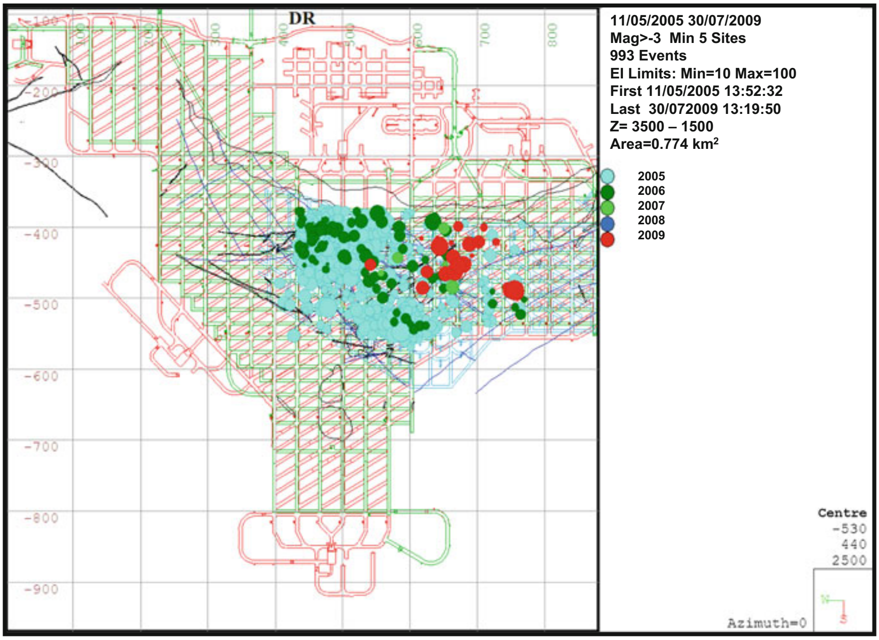


Fig. 4.25 Hydro-fractured volume—high energy index events

Figure 4.31 indicates the monthly percentages of seismicity with Ei > 10.0 recorded in the cave volume (100% is the total monthly seismic activity rate recorded in the whole mine). This figure illustrates the fact that between the initiation of the caving process (D) and failure of the pillar (E), nearly 50% of the whole Diablo Regimento Sector high energy index seismicity was associated with the cave volume. After the failure of the pillar, the amounts of seismicity recorded in the cave volume gradually decreased to almost 0% during 2008.

4.3 PMC Seismicity Induced in the Cave and in the Surrounding Volumes

In this section, I will be comparing seismicity in two volumes created from the PMC mine rock mass volume. The first volume is the cave volume based on the mines footprint and the second volume is the surrounding volume, which is located around the cave volume. For this comparison, I will be using seismicity recorded from 1 January 2001 until 28 June 2010. Table 4.12 compares seismicity recorded in these two volumes.

According to the data presented by Table 4.12, more events (2.7 times), more seismic energy released (2.6 times more) and more seismic deformation (4.9 times more)

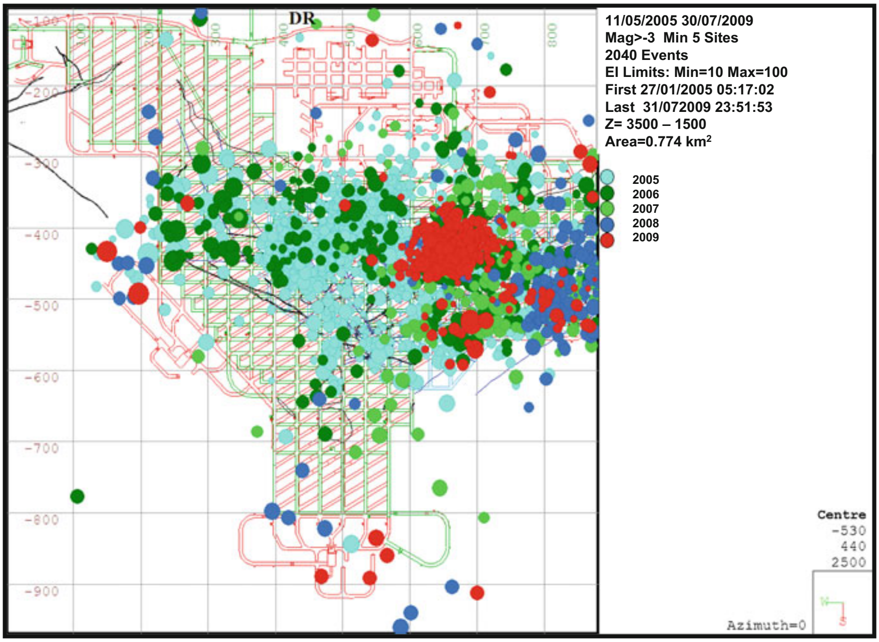


Fig. 4.26 DR non-preconditioned volume—high energy index events

Table 4.12 Seismicity of the two volumes

Volume	No. of events		Cumulated energy		Cumulated moment	
Cave	36,459	27%	9.36E+07 J	28%	1.97E+13 Nm	17%
Out of cave	97,374	73%	2.41E+08 J	72%	9.75E+13 Nm	83%
Whole mine	133,833	100%	3.35E+08 J	100%	11.72E+13 Nm	100%

took place outside of the cave volume, in the surrounding rock mass. Figures 4.32, 4.33 and 4.34 illustrate the seismicity time distribution in the two volumes. In all these figures, the top part shows the seismicity in the cave volume while the bottom part illustrates the seismicity recorded in the rest of the PMC mine volume. In all cases, the vertical scales for data recorded in these two volumes are the same to allow direct comparisons. The horizontal axes on all figures indicate time. Additionally, all these figures indicate the monthly production rates (in black) and the following milestones of the caving process:

- Initiation of the caving process (**A**)—May 2002
- Failure of the crown pillar (**B**)—end of 2002
- Initial break through (**C**)—May 2004
- Failure in the open pit (**D**)—October 2004

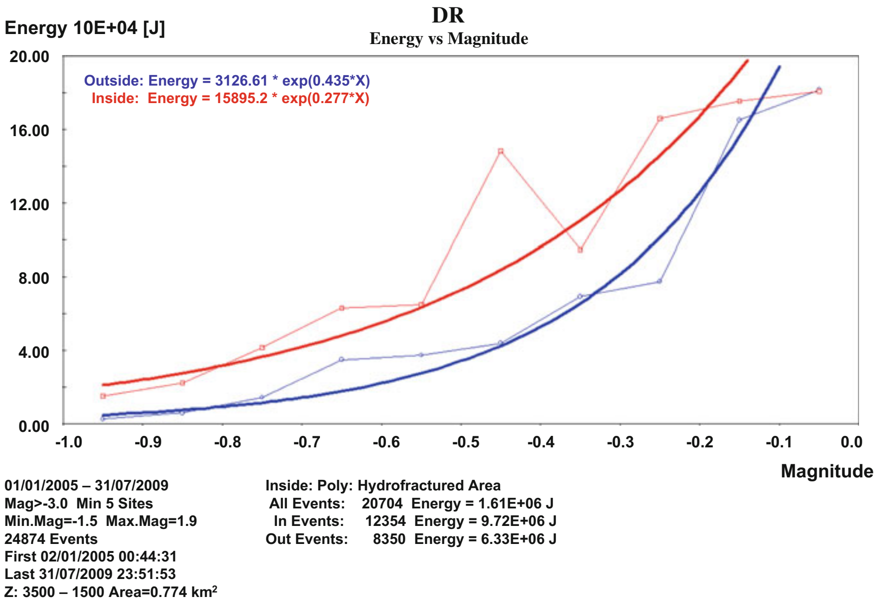


Fig. 4.27 Energy release in magnitude range −1.0 up to −0.1

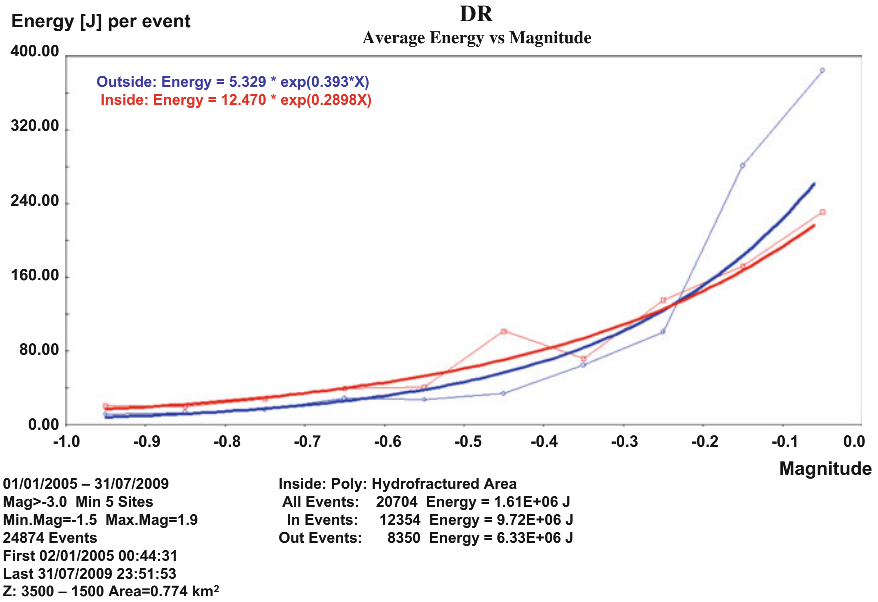


Fig. 4.28 Average energy releases per single event (magnitude range −1.0 to −0.1)

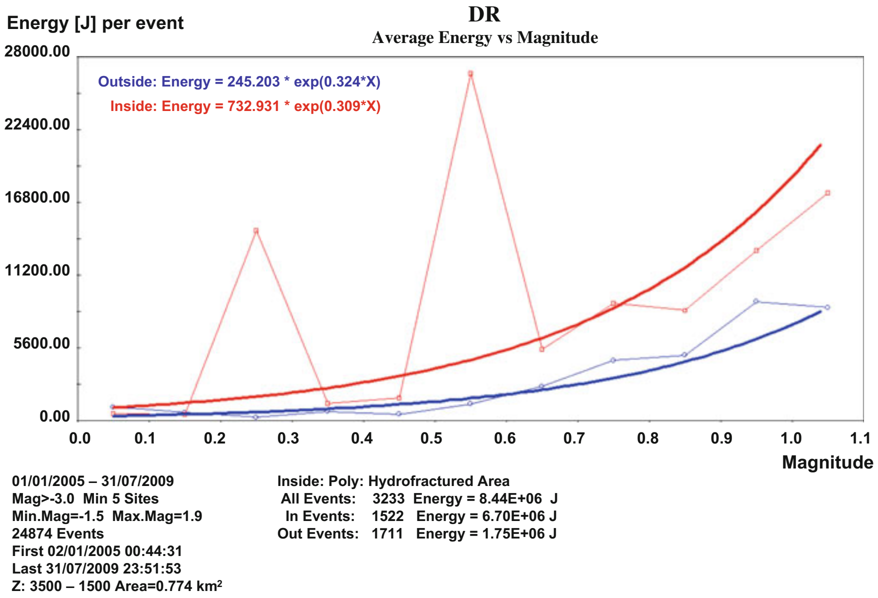


Fig. 4.29 Average energy releases per single event (magnitude range 0.0 to 1.1)

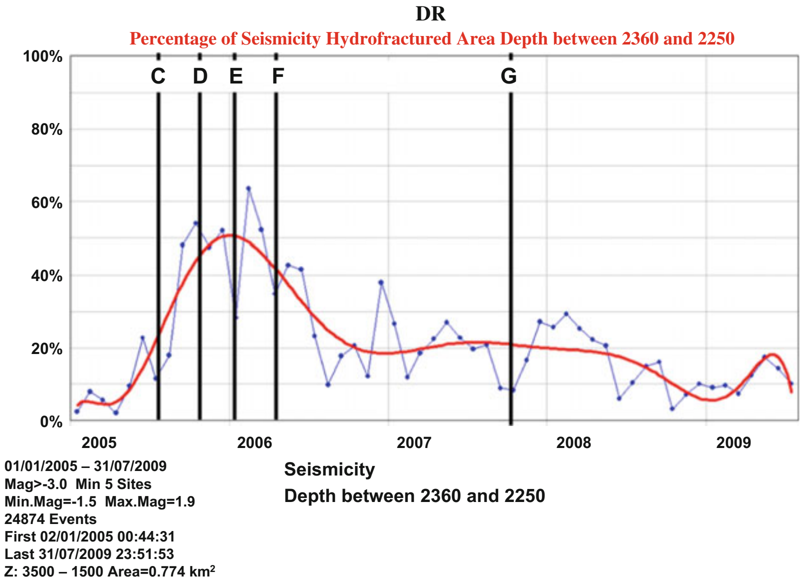


Fig. 4.30 Percentages of seismicity recorded in the hydro-fractured volume

- East break through (**E**)—May/June 2008

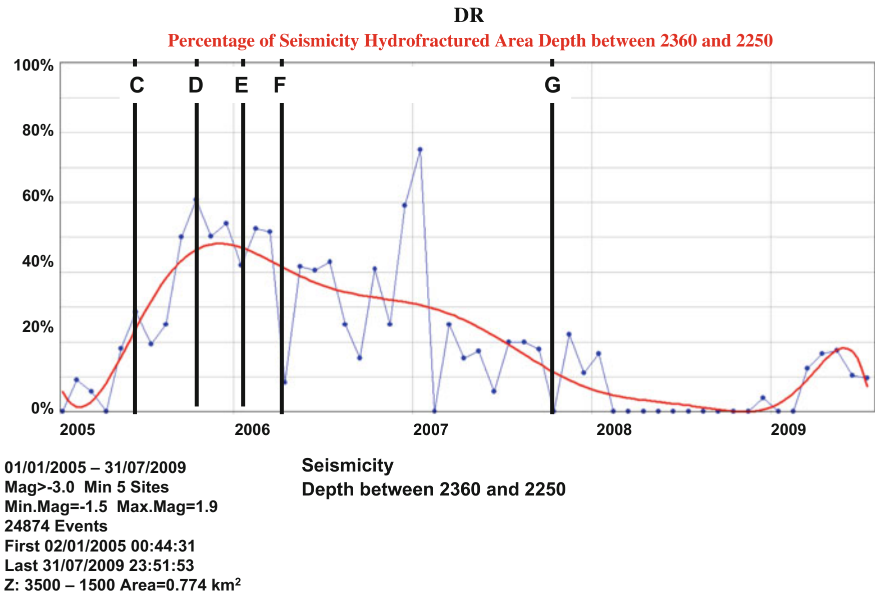


Fig. 4.31 Percentages of seismicity with Ei > 10 recorded in the hydro-fractured volume

Figure 4.32 illustrates the fact that the highest monthly seismic activity rates in the cave volume were recorded during 2002, 2003 and up to mid-2004 which was from when the caving process was initiated (A) up to the time of the crown pillar failure (C). From then on, the seismic activity rates up to the end of May 2010 were not only constantly low but also lower from those recorded during these 2.5 years time period. In the surrounding volume, the monthly seismic activity rates increased after the failure of the crown pillar (B) and then for the rest of the time are constantly higher from those recorded in the cave volume.

Figure 4.33 illustrates the monthly seismic energy release rates in the cave and the surrounding volumes. For the analysed time period, the total seismic energy released in the cave volume amounted to 9.37E+07 J, while in the surrounding volume the seismic energy release was higher at 2.41E+08 J. More important are the time distributions of the high energy releases. In the cave volume, most of the seismic energy was released after the initiation of the caving process (A) and before the initial break through (C). The slightly higher energy release during 2008 was associated with the east break through (E). In the surrounding volume, the higher energy releases took place only after the crown pillar failure (B) and lasted until the end of 2004. The higher energy releases during 2006 were associated with seismicity taking place at deeper elevations compared to 2003 and 2004. The high energy releases of 2008 were associated with the east break through and were ten times larger from these recorded in the cave volume.

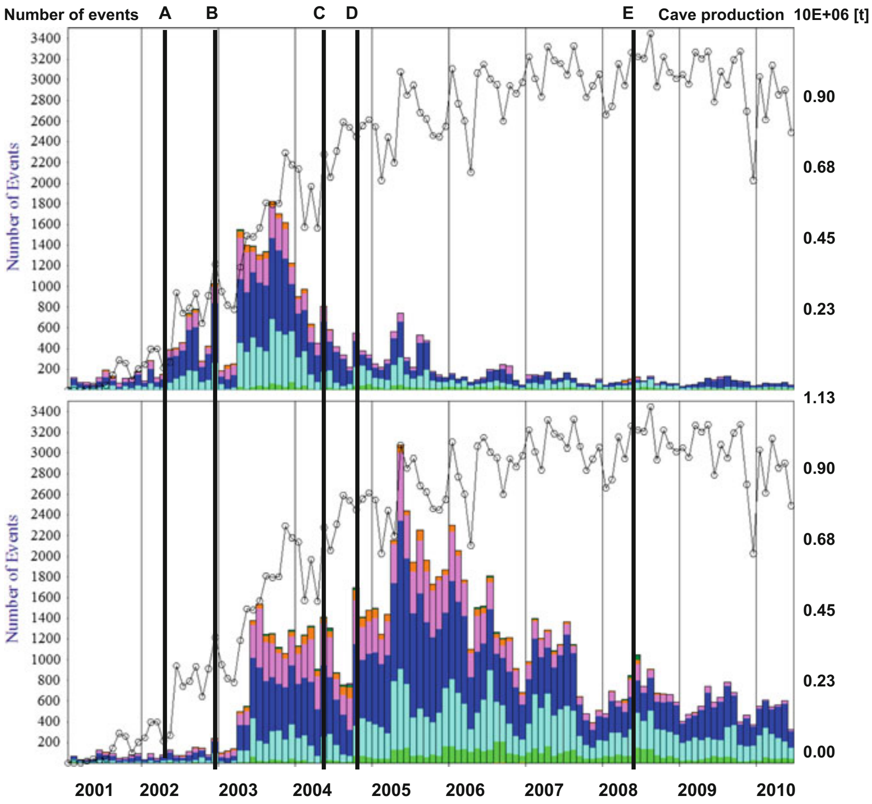


Fig. 4.32 Monthly seismic activity rates

Figure 4.34 illustrates the monthly seismic deformation rates. According to data presented by Table 4.12 in the cave volume, the cumulative seismic deformation was 1.97E+13 Nm, while in the surrounding volume, it was 4.9 times more at 9.75E+13 Nm. As far as seismic deformation distribution in time are concerned, there is difference in these two volumes. In the cave volume, there is more seismic deformation recorded up to mid-2004, while in the surrounding volume, the maximum rates were recorded after the initial break through (C). Figure 4.35 illustrates the energy index time histories (blue) in the two volumes. In both volumes, the energy index started to increase with the initiation of the caving process (A) and the maximum index values were reached just before the time of the initial break through (C). The maximum value of the energy index in the cave volume was higher than the maximum value recorded for the surrounding volume. The other difference between these two energy index time histories is that in the cave volume, the energy index increased much faster while the energy index increase in the surrounding volume was slower and more continuous.

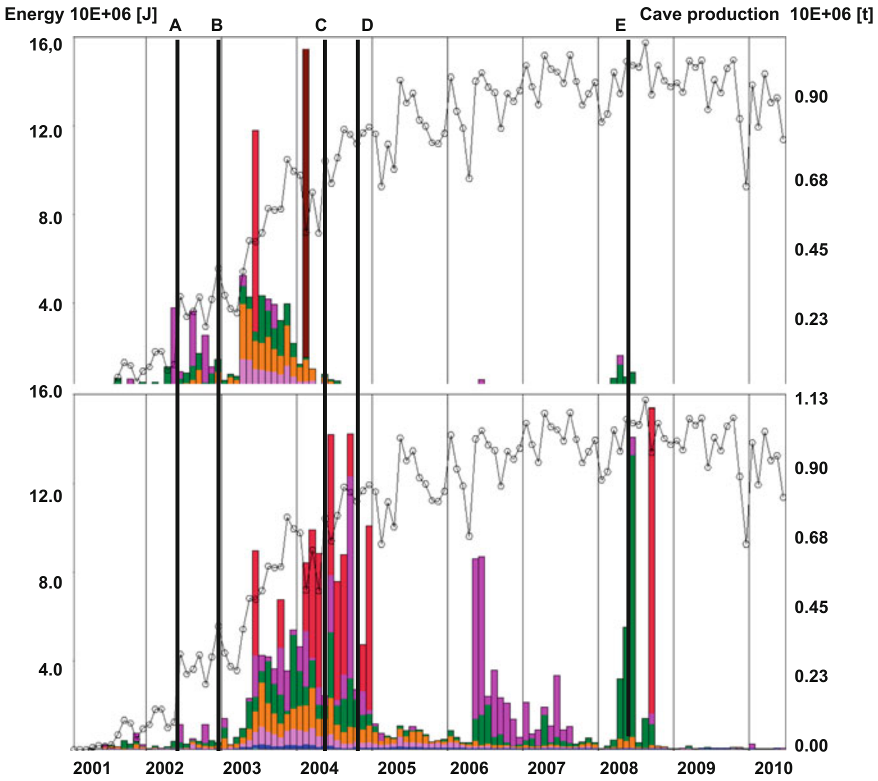


Fig. 4.33 Monthly seismic energy release rates

There is one more significant difference in the two energy index time histories. In the cave volume, the energy index from the beginning of 2006 until end of May 2010 was constantly below the mean value of 1.0 while in the surrounding area during this time period, it was always above this mean. The reason for this difference in the two energy index time histories is the time distributions of the high energy index events (above 10.0) in these two volumes.

Figure 4.36 illustrates the monthly seismic activity rates for seismicity with the energy index above values 10.0. In the cave volume, there were 14,453 such events (40% of the total seismicity recorded in this volume) while in the surrounding volume, there were 17,855 such events (18% of the total). In the cave volume, nearly 43% of these events took place during the time period starting with the initiation of the caving process (A) and ending with the initial break through (C), while in surrounding volume during this time period only 25% of the high energy events took place. This data is listed in Table 4.13

Figure 4.37 illustrates the monthly energy release rates of events with energy index above 10.0. By the end of 2004, already 84% of energy associated with events

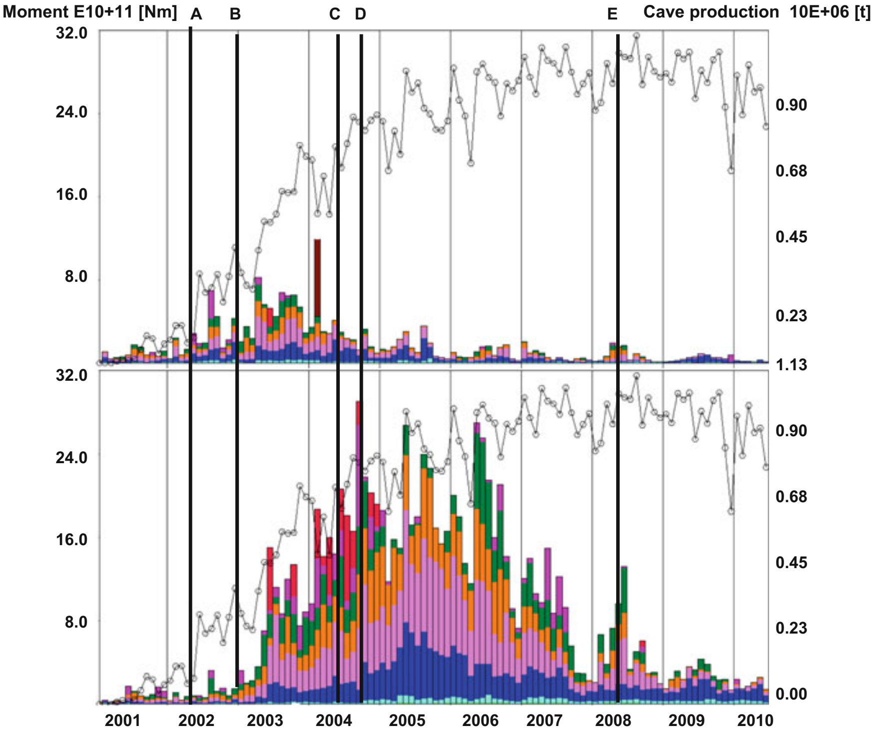


Fig. 4.34 Monthly seismic deformation rates

Table 4.13 Seismicity of Ei > 10 in the two volumes

Volume	No. of events			Released seismic energy (J)		
	Total	Events with Ei > 10.0	%	Total	Events with Ei > 10.0	%
Cave	36,459	14,453	40	9.36E+07	3.05E+07	32
Out of cave	97,374	17,855	18	2.41E+08	1.13E+08	47

of energy index above 10.0 was released, while in the surrounding volume, this percentage was only at 29%. This indicates that most of the high energy release events in the cave volume ended with the initial break through. In the surrounding volume, most of the high energy release took place after the two breaks through events (the initial and east break through).

Figure 4.38 illustrates the energy index time histories (blue) based only on events with energy index values above 10.0 together with their monthly seismic energy release rates (violet). This figure indicates that in the cave volume, practically all the high energy releases associated with the high energy index seismicity took place just after the cave initiation and before the initial break through. In the surrounding

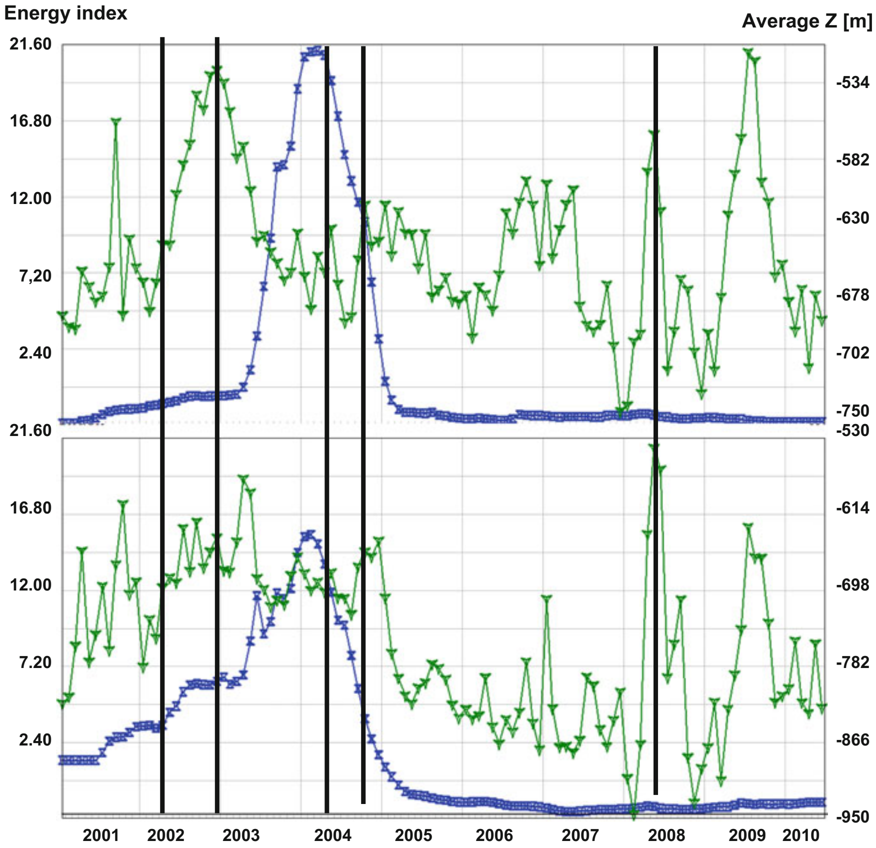


Fig. 4.35 Energy index time histories

volume, the high energy seismic events took place not only during this time period but were also distributed over the whole time period.

Figures 4.39 and 4.40 illustrate the space distributions of the high energy index seismicity. In both these figures, different colours indicate the year in which these events were recorded. It is interesting to note that that the high energy index in the cave volume concentrates at the east part of this volume. The high energy index seismicity associated with the surrounding volume concentrates around the mine footprint.

In the next part, I will investigate the energy release rates per magnitude (moment magnitude) and then compare the average energy release per magnitude in the two volumes. In the following three figures, the ‘Inside’ (red) stands for the cave volume while the ‘Outside’ (blue) stand for the surrounding volume. Figure 4.41 illustrates the cumulative seismic energy released inside and outside of cave volume by events of magnitude from -1.0 up to magnitude -0.1. In this magnitude range, there were

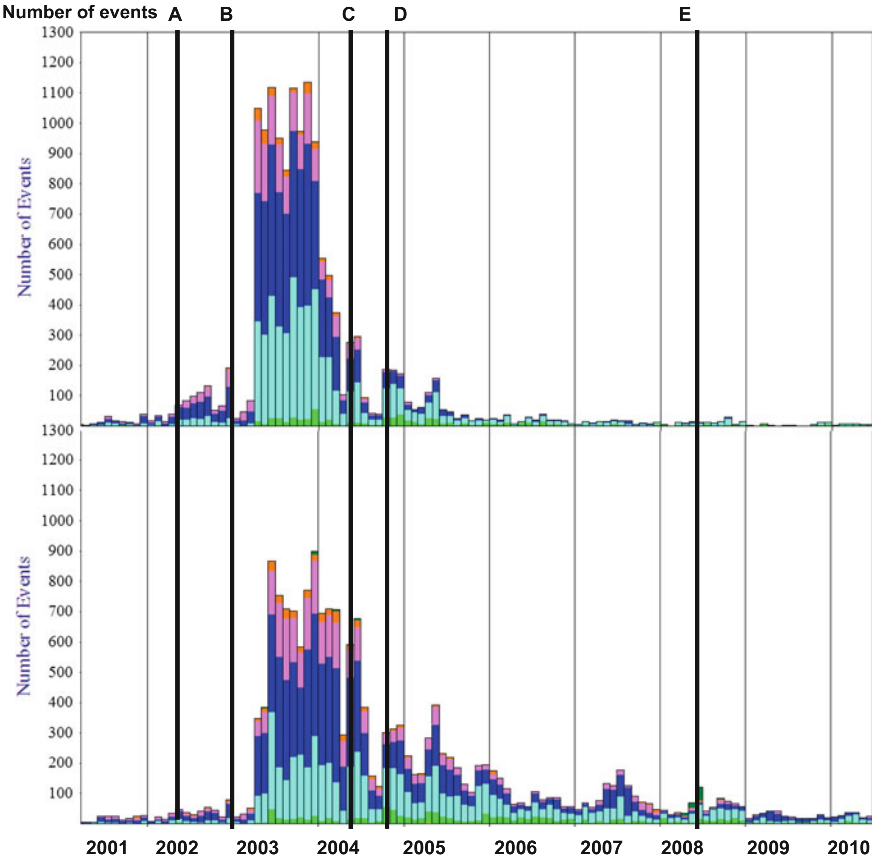


Fig. 4.36 Events with energy index above 10.0—monthly activity rates

more events recorded in the cave volume (Inside) than in the surrounding volume (Outside). Figure 4.41 indicates that these size seismic events emitted more energy in the surrounding volume than in the cave volume.

Figure 4.42 indicates the average seismic energy released by a single event of magnitude range from −1.0 up to −0.1. Data presented by this figure indicates that on average this size seismicity recorded in the cave volume released more energy than the seismicity recorded outside of this volume.

Figure 4.43 indicates the average seismic energy released by a single event of magnitude range from 0.0 up to 1.1. Data presented by this figure indicates that on average this size single event recorded in the cave volume released more energy than the seismicity recorded outside of this volume. Data presented by Figs. 4.42 and 4.43 indicate that on average every single event in magnitude range from −1.0 up to 1.1 that was recorded in the cave volume released more energy than any event of the same magnitude recorded outside of this volume. One would expect that the

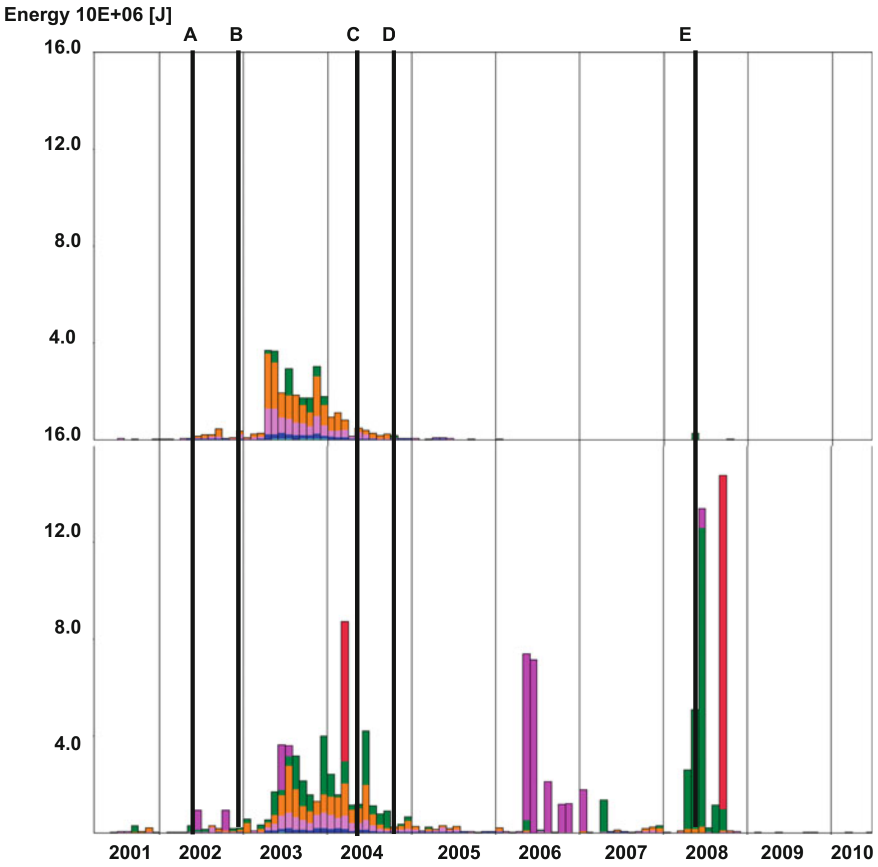


Fig. 4.37 Events with energy index above 10.0—monthly energy release rates

cave volume would be more fractured than the outside volume and for this reason on average each event recorded in the cave volume should release less energy that the same magnitude event originating from outside of this volume.

Table 4.14 lists amongst other values the average energy release per magnitude size in the cave volume (column 6) and the surrounding volume (column 7).

Figure 4.44 indicates the monthly percentages of seismicity recorded in the cave volume (100% is the total monthly seismic activity rate recorded in the whole mine). This figure illustrates the fact that between the initiation of the caving process (A) and failure of the pillar (B), nearly 80% of the whole PMC seismicity was associated with the cave volume. After the failure of the pillar, the amounts of seismicity recorded in the cave volume gradually decreased to about 30% at the time of the initial break through (C). From the beginning of 2006, the amount of seismicity taking place in the cave decreased to 10%. It is interesting to note that the east break through (E) did not result in much more seismicity taking place in the cave.

Table 4.14 Cumulative and average energy released per magnitude sizes

Energy per magnitude 17 January 2001–28 May 2010						
Magnitude	Number of events		Energy release (J)		Average energy (J)	
Range	Inside	Outside	Inside	Outside	Inside	Outside
$-2.0 \le M < -1.9$	0	1		8.79E+000		8.79E+000
$-1.9 \le M < -1.8$	0	2		1.46E+001		7.28E+000
$-1.8 \le M < -1.7$	0	6		3.46E+001		5.76E+000
$-1.7 \le M < -1.6$	0	11		1.14E+002		1.04E+001
$-1.6 \le M < -1.5$	2	16	1.49E+000	3.35E+003	7.45E−001	2.09E+002
$-1.5 \le M < -1.4$	7	30	1.14E+001	4.34E+002	1.63E+000	1.45E+001
$-1.4 \le M < -1.3$	45	93	1.23E+002	1.50E+003	2.74E+000	1.61E+001
$-1.3 \le M < -1.2$	200	358	9.73E+002	5.92E+003	4.86E+000	1.65E+001
$-1.2 \le M < -1.1$	531	975	4.42E+003	6.68E+003	8.32E+000	6.85E+000
$-1.1 \le M < -1.0$	1184	2013	1.91E+004	3.59E+004	1.61E+001	1.78E+001
$-1.0 \le M < -0.9$	2102	3641	7.27E+004	8.18E+004	3.46E+001	2.25E+001
$-0.9 \le M < -0.8$	2915	5260	2.00E+005	1.82E+005	6.85E+001	3.46E+001
$-0.8 \le M < -0.7$	3246	6252	4.36E+005	4.10E+005	1.34E+002	6.55E+001
$-0.7 \le M < -0.6$	3072	6879	7.34E+005	8.56E+005	2.39E+002	1.24E+002
$-0.6 \le M < -0.5$	3208	7025	1.15E+006	1.16E+006	3.57E+002	1.64E+002
$-0.5 \le M < -0.4$	3467	7654	1.75E+006	1.65E+006	5.04E+002	2.16E+002
$-0.4 \le M < -0.3$	3596	9022	2.46E+006	2.30E+006	6.84E+002	2.55E+002
$-0.3 \le M < -0.2$	3395	9564	3.30E+006	4.28E+006	9.72E+002	4.47E+002
$-0.2 \le M < -0.1$	2949	9332	3.82E+006	3.61E+006	1.30E+003	3.86E+002

(continued)

Table 4.14 (continued)

Energy per magnitude 17 January 2001–28 May 2010						
Magnitude	Number of events		Energy release (J)		Average energy (J)	
Range	Inside	Outside	Inside	Outside	Inside	Outside
$-0.1 \leq M < 0.0$	2307	7850	4.72E+006	5.55E+006	2.05E+003	7.08E+002
$0.0 \leq M < 0.1$	1568	6184	5.21E+006	4.69E+006	3.32E+003	7.58E+002
$0.1 \leq M < 0.2$	977	4675	5.24E+006	4.77E+006	5.36E+003	1.02E+003
$0.2 \leq M < 0.3$	570	3408	3.99E+006	7.11E+006	7.01E+003	2.09E+003
$0.3 \leq M < 0.4$	390	2396	3.10E+006	7.45E+006	7.96E+003	3.11E+003
$0.4 \leq M < 0.5$	222	1544	3.04E+006	9.06E+006	1.37E+004	5.87E+003
$0.5 \leq M < 0.6$	169	977	5.00E+006	1.13E+007	2.96E+004	1.16E+004
$0.6 \leq M < 0.7$	101	658	3.55E+006	1.39E+007	3.51E+004	2.11E+004
$0.7 \leq M < 0.8$	77	404	4.28E+006	1.17E+007	5.56E+004	2.90E+004
$0.8 \leq M < 0.9$	47	279	3.10E+006	8.32E+006	6.60E+004	2.98E+004
$0.9 \leq M < 1.0$	29	187	4.22E+006	1.11E+007	1.46E+005	5.92E+004
$1.0 \leq M < 1.1$	23	119	5.99E+006	1.15E+007	2.60E+005	9.70E+004
$1.1 \leq M < 1.2$	7	85	2.38E+006	2.46E+007	3.40E+005	2.90E+005
$1.2 \leq M < 1.3$	1	51	2.35E+005	2.38E+007	2.35E+005	4.67E+005
$1.3 \leq M < 1.4$	3	26	2.56E+006	1.73E+007	8.54E+005	6.65E+005
$1.4 \leq M < 1.5$	0	9		1.45E+007		1.61E+006
$1.5 \leq M < 1.6$	1	3	9.10E+006	1.63E+006	9.10E+006	5.44E+005
$1.6 \leq M < 1.7$	0	13		2.62E+007		2.02E+006
$1.7 \leq M < 1.8$	0	1		1.85E+006		1.85E+006
$1.8 \leq M < 1.9$	0	1		4.75E+006		4.75E+006
$1.9 \leq M < 2.0$	1	1	1.39E+007	5.38E+006	1.39E+007	5.38E+006

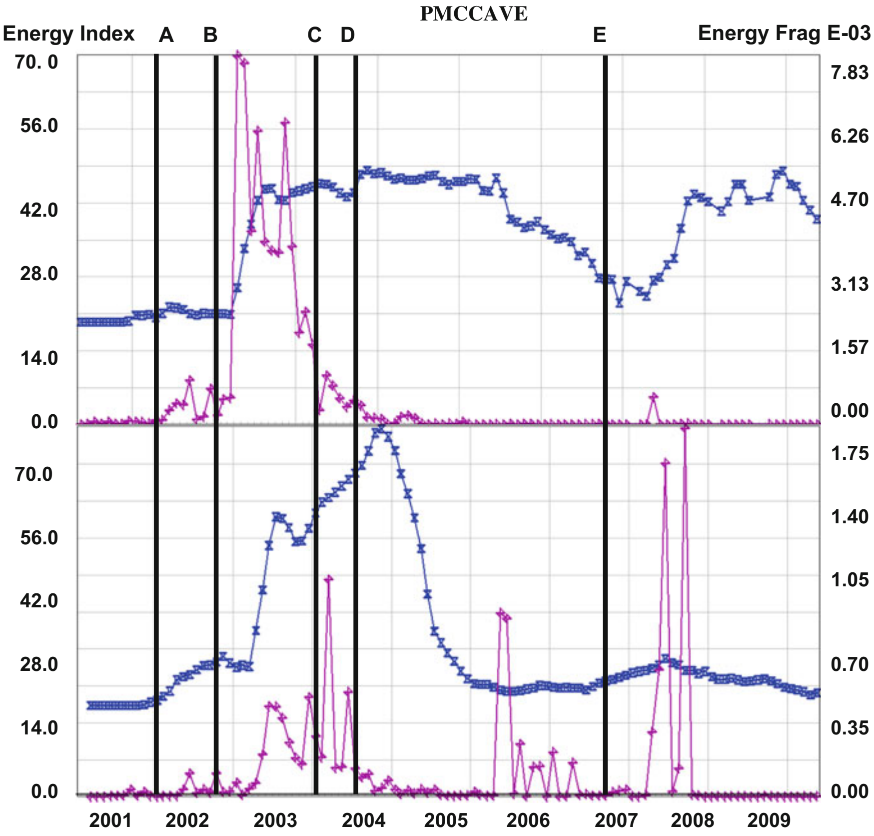


Fig. 4.38 Energy index time histories based on events with Ei > 10

Figure 4.45 indicates the monthly percentages of seismicity with Ei > 10.0 recorded in the cave volume (100% is the total monthly seismic activity rate recorded in the whole mine). This figure illustrates the fact that between the initiation of the caving process (A) and failure of the pillar (B) similarly, nearly 80% of the whole PMC high energy index seismicity was associated with the cave volume. After the failure of the pillar, the amounts of seismicity recorded in the cave volume gradually decreased to about 50% at the time of the initial break through (C). From the beginning of 2006, the amount of high energy index seismicity taking place in the cave has oscillated around 20%.

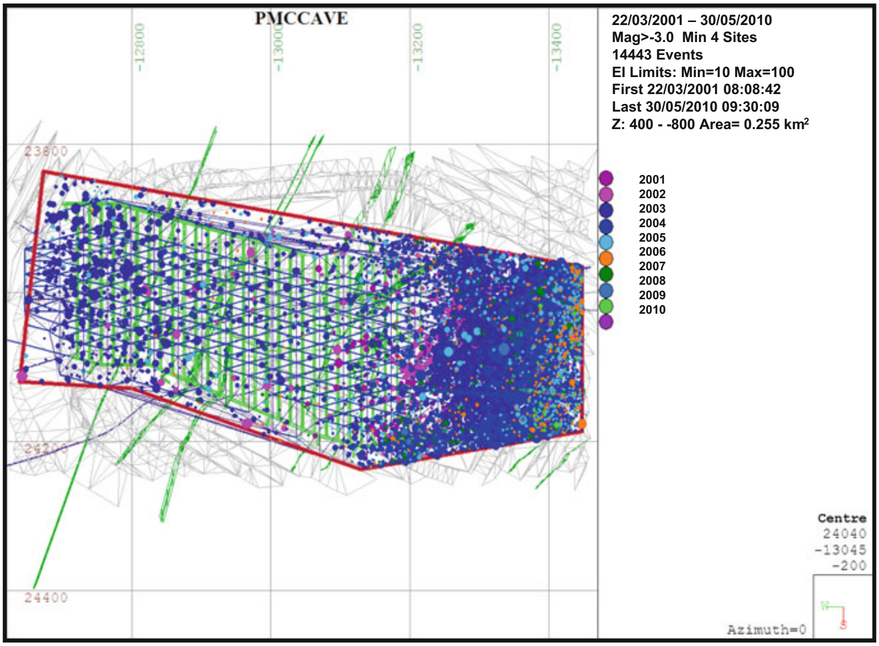


Fig. 4.39 Cave volume—high energy index events

Table 4.15 Seismicity of the two volumes

Volume	No. of events		Cumulated energy		Cumulated moment	
Cave	25,8327	54%	1.02E+09 J	10%	1.02E+14 Nm	12%
Out of cave	21,7061	46%	8.93E+09 J	90%	7.62E+14 Nm	88%
Whole mine	47,5388	100%	9.95E+09 J	100%	8.64E+14 Nm	100%

4.4 Deep Ore Zone Mine, Seismicity Induced in the Cave and in the Surrounding Volumes

In this section, I will compare seismicity in two volumes created from the DOZ mine rock mass volume. The first volume is the cave volume based on the mine footprint and the second is the surrounding volume, which is located around the cave volume. For this comparison, I will be using seismicity recorded from 1 August 2004 until 31 July 2009. Table 4.15 compares seismicity recorded in these two volumes.

According to data presented by Table 4.15, despite the fact that slightly more events were recorded in the cave (1.2 times), more seismic energy was released (8.7 times more) and more seismic deformation (7.5 times more) took place outside of

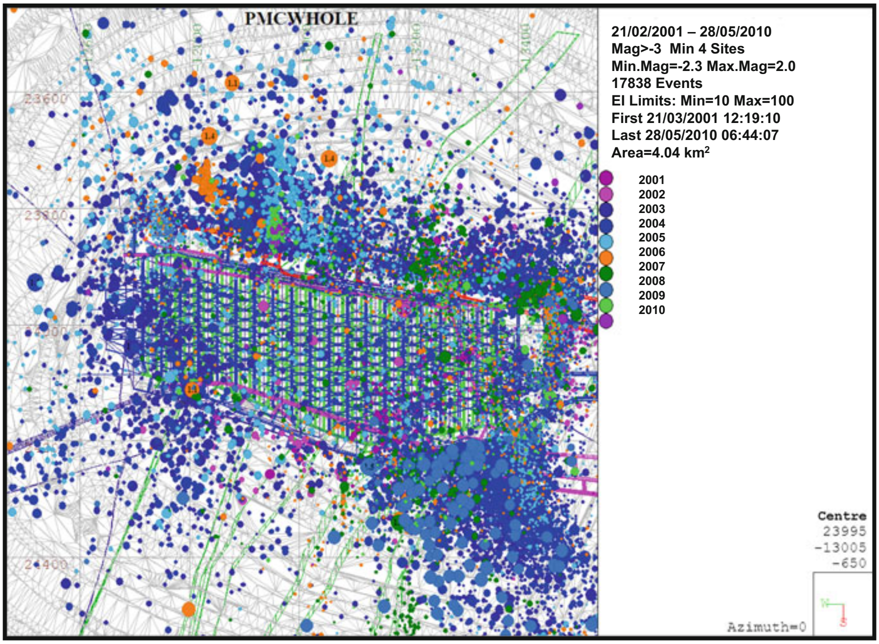


Fig. 4.40 Surrounding volume—high energy index events

the cave volume, in the surrounding rock mass. Figures 4.46, 4.47 4.48 illustrate the seismicity time distribution in the two volumes. In all these figures, the top part shows the seismicity in the cave volume while the bottom part illustrates the seismicity recorded in the rest of the DOZ mine volume. In all cases, the vertical scales for data recorded in these two volumes are the same allowing for direct comparison. The horizontal axes on all figures indicate time.

Figure 4.46 illustrates the fact that the highest monthly seismic activity rates in the cave volume were recorded during 2007 up to mid-2008. From then on, the seismic activity rates to the end of July 2009 were not only constantly low but also lower from those recorded during 2004, 2005 and 2006. In the surrounding cave volume, the monthly seismic activity rates pattern was different to that in the cave volume. Here, the monthly seismic activity rates were in general lower but with more consistent rates from these in the cave volume.

Figure 4.47 illustrates the monthly seismic energy release rates in the cave and the surrounding volume. For the analysed time period, the total seismic energy released in the cave volume amounted to 1.02E+09 J, while in the surrounding volume the seismic energy release was higher at 8.93E+09 J. Due to the fact that in both, the cave and in the volume surrounding, the cave a lot of seismic energy was released by large size events (above magnitude 2.0), data presented by this figure is unclear, it indicates only that there was much more of larger size events outside of the cave volume.

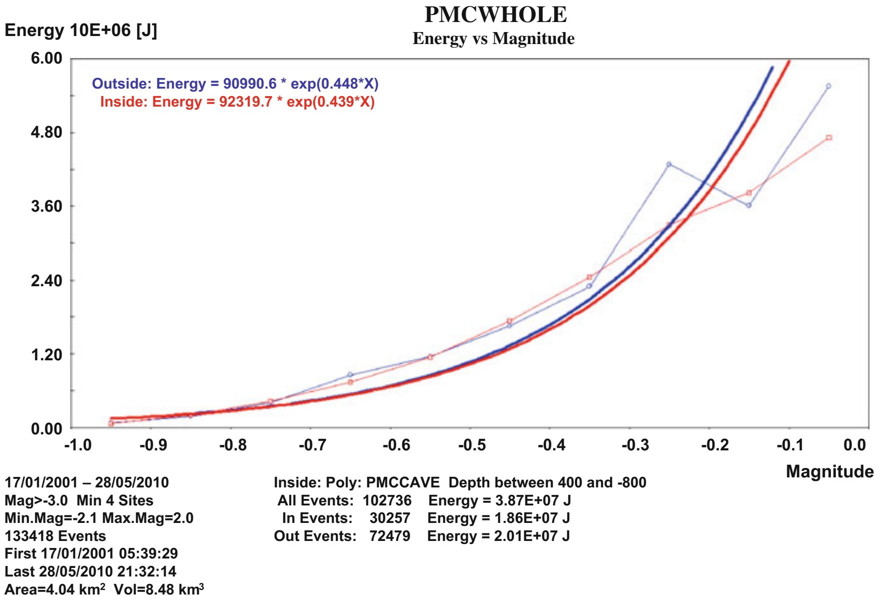


Fig. 4.41 Energy release in magnitude range −1.0 up to −0.1

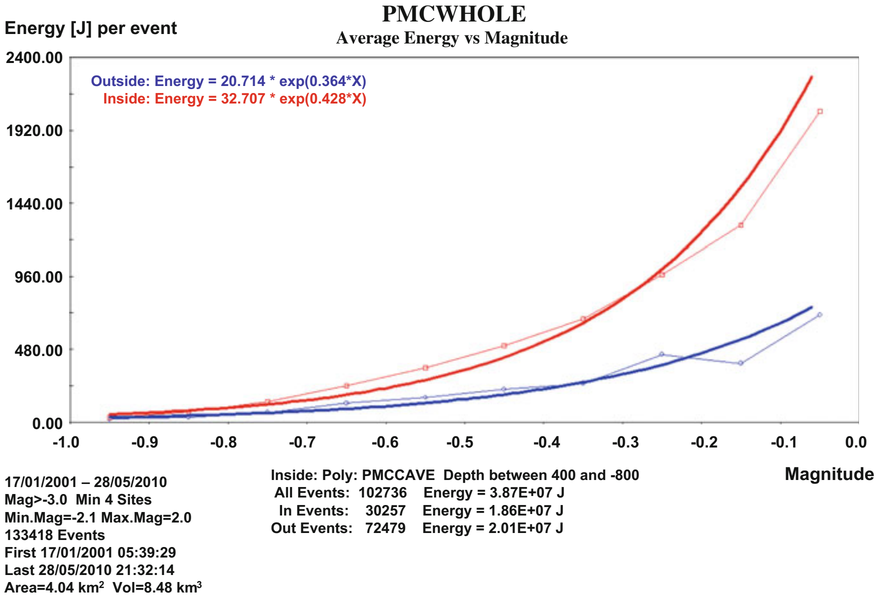


Fig. 4.42 Average energy releases per single event (magnitude range −1.0 to −0.1)

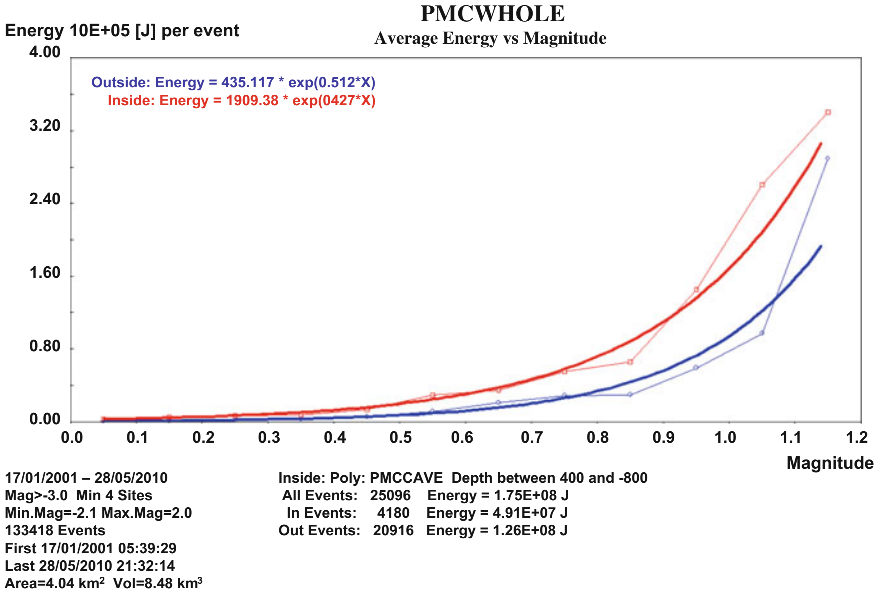


Fig. 4.43 Average energy releases per single event (magnitude range 0.0–1.1)

Figure 4.48 illustrates the monthly seismic deformation rates. According to data presented by Table 4.15 in the cave volume, the cumulative seismic deformation was 1.02E+14 Nm while in the surrounding volume, it was 7.5 times more at 7.62+14 Nm.

Figure 4.49 illustrates the energy index time histories (blue) in the two volumes. In both volumes, the energy index started to increase from the beginning of 2005 to reach the maximum values by the beginning of 2006. From then on, the values of the energy index started to decrease and then reached their minimum values at the beginning of 2007. During the rest of 2007, there was an increase in the energy index values until mid-2008. Here, the maximum value of the energy index in the volume located around the cave was higher than in the cave. From mid-2008 in the cave, the energy index started to decrease and by the end of 2008 reached values below the mean of 1.0. In the volume around the cave, the energy index first decreased but by the end of that year, it started to increase rapidly.

Figure 4.50 illustrates the monthly seismic activity rates for seismicity with the energy index above values 10.0. In the cave volume, there were 22,973 such events (9% of the total seismicity recorded in this volume) while in the surrounding volume, there were 217,061 such events (21% of the total). In the cave volume, nearly 63% of these events took place during the time period when the energy index as illustrated by Fig. 4.49 was at its highest values (in the two time periods between March 2005 and October 2006 and then from March 2007 up to May 2008). In the volume surrounding, the cave there was more of the high energy index events starting at the beginning of

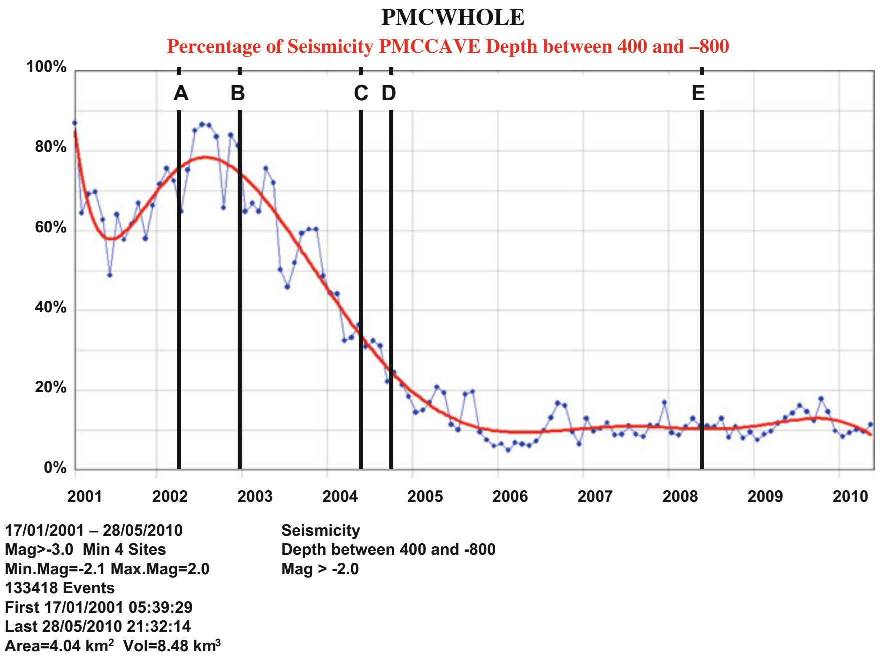


Fig. 4.44 Percentages of seismicity recorded in the cave volume

Table 4.16 Seismicity of Ei > 10.0 in the two volumes

Volume	No. of events			Released seismic energy (J)		
	Total	Events with Ei > 10.0	%	Total (J)	Events with Ei > 10.0 (J)	%
Cave	258,327	22,973	9	1.02E+09	8.93E+08	87
Out of cave	217,061	46,195	21	8.93E+09	6.29E+09	70

2005. Their maximum activity rates were associated with the highest values of the energy index during the first months of 2008. This data is listed in Table 4.16.

Figure 4.51 illustrates the monthly energy release rates of events with energy index above 10.0. According to data listed in Table 4.16, these high energy index events released nearly seven times more energy in the volume surrounding the cave than in the cave. In the cave, the energy released by these high energy events took place during 2005 and then from the beginning of 2007 up to May 2008. In the surrounding volume up to mid-2008, these high energy index are distributed more evenly. From the second part of 2008, there appeared to be less of these high energy release events.

Figure 4.52 illustrates the energy index time histories (blue) based only on these events with energy index values above 10.0 together with their monthly seismic

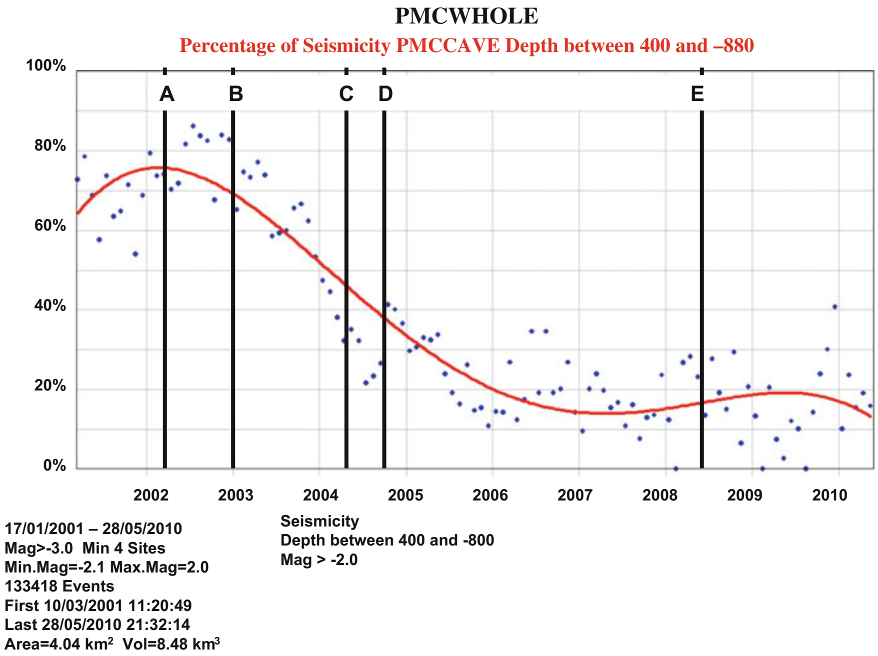


Fig. 4.45 Percentages of seismicity with Ei > 10 recorded in the cave volume

energy release rates (violet). This figure confirms observations based on data that is illustrated by Fig. 4.51.

Figures 4.53 and 4.54 illustrate the space distributions of the high energy index seismicity. In both these figures, different colours indicate the year in which these events were recorded. It is worthy of note that that the high energy index in the cave volume concentrates at the east part of this volume. The high energy index seismicity associated with the surrounding volume is concentrated around the DOZ cave.

Next, I will investigate the energy release rates per magnitude (moment magnitude) and then compare the average energy release per magnitude in the two volumes. In the following three figures, the ‘Inside’ (red) stands for the cave volume while the ‘Outside’ (blue) stand for the surrounding volume. Figure 4.55 illustrates the cumulative seismic energy released inside and outside of cave volume by events of magnitude from −1.0 up to magnitude −0.1. In this magnitude range, there were more events recorded in the cave volume (Inside) than in the surrounding volume (Outside). Figure 4.55 indicates that up to magnitude −0.3 seismic events located in the cave and the surrounding volumes emitted the same amounts of energy. Events larger than −0.3 magnitude that were located in the cave released more energy than same size events associated with the surrounding volume.

Figure 4.56 illustrates the average seismic energy released by single events of magnitude range from −1.0 up to −0.1. Data presented by this figure indicates that

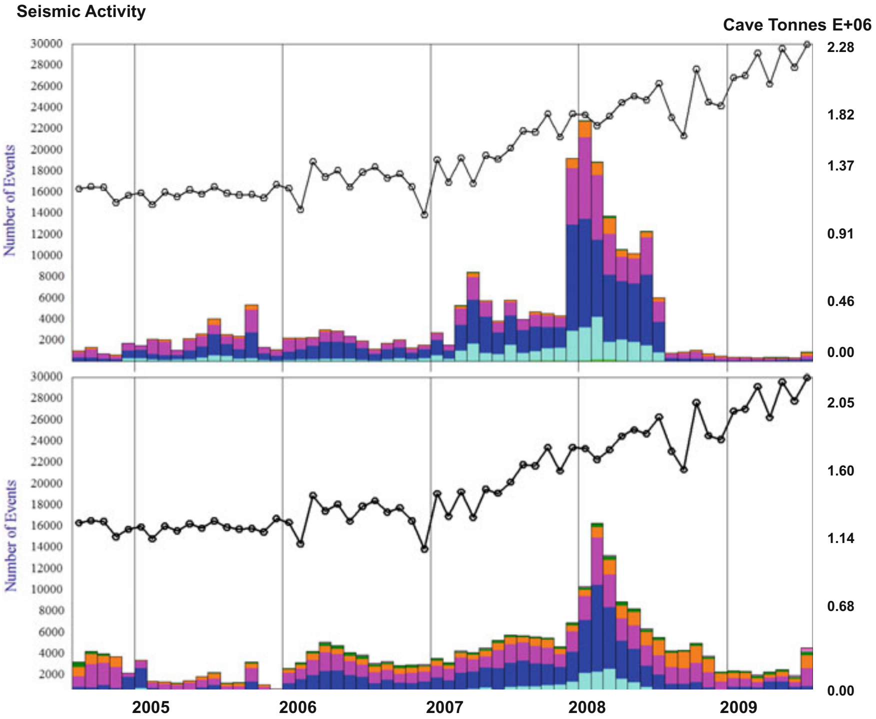


Fig. 4.46 Monthly seismic activity rates

on average from magnitude size −0.3, the seismicity recorded in the cave volume released more energy than the seismicity recorded outside of this volume.

Figure 4.57 indicates the average seismic energy released by single events of magnitude range from 0.0 up to 1.1. Data presented by this figure indicates that on average this size single event recorded in the cave volume released more energy than the seismicity recorded outside of this volume. Data presented by Figs. 4.56 and 4.57 indicate that on average every single event in magnitude range from −0.3 up to 1.1 that was recorded in the cave volume released more energy than event of the same magnitude recorded outside of this volume. One would expect that the cave volume would be more fractured than the outside volume and for this reason on average each event recorded in the cave volume should release less energy that the same magnitude event originating from outside of this volume.

Table 4.17 lists the average energy release per magnitude size in the cave volume (column 6) and the surrounding volume (column 7).

Figure 4.58 indicates the monthly percentages of seismicity recorded in the cave volume (100% is the total monthly seismic activity rate recorded in the whole mine). This figure illustrates the fact that during 2005 up to 60% of events were located in the cave volume. Then, the percentages of seismicity located in the cave started

Table 4.17 Cumulative and average energy released per magnitude sizes

Energy per magnitude 1 August 2004—31 July 2009						
Magnitude	Number of events		Energy release (J)		Average energy (J)	
Range	Inside	Outside	Inside	Outside	Inside	Outside
$-1.5 \le M < -1.4$	2019	869	1.35E+004	1.05E+004	6.68E+000	1.21E+001
$-1.4 \le M < -1.3$	4046	1962	3.59E+004	1.71E+004	8.87E+000	8.70E+000
$-1.3 \le M < -1.2$	7362	3784	8.57E+004	5.45E+004	1.16E+001	1.44E+001
$-1.2 \le M < -1.1$	11,959	6332	1.78E+005	1.20E+005	1.48E+001	1.89E+001
$-1.1 \le M < -1.0$	16,937	9008	7.05E+006	2.18E+005	4.16E+002	2.42E+001
$-1.0 \le M < -0.9$	21,106	11,739	5.42E+005	1.12E+006	2.57E+001	9.52E+001
$-0.9 \le M < -0.8$	24,534	13,849	8.45E+005	7.28E+005	3.44E+001	5.26E+001
$-0.8 \le M < -0.7$	26,558	15,404	1.29E+006	9.49E+005	4.84E+001	6.16E+001
$-0.7 \le M < -0.6$	25,378	16,028	1.72E+006	1.34E+006	6.79E+001	8.35E+001
$-0.6 \le M < -0.5$	23,671	16,269	2.05E+006	3.23E+006	8.68E+001	1.99E+002
$-0.5 \le M < -0.4$	20,873	15,547	2.80E+006	2.19E+006	1.34E+002	1.41E+002
$-0.4 \le M < -0.3$	18,269	15,628	4.33E+006	3.07E+006	2.37E+002	1.96E+002
$-0.3 \le M < -0.2$	15,415	14,957	5.81E+006	5.60E+006	3.77E+002	3.74E+002
$-0.2 \le M < -0.1$	12,080	13,625	9.65E+006	7.01E+006	7.99E+002	5.14E+002
$-0.1 \le M < 0.0$	8764	12,357	8.47E+006	1.37E+007	9.66E+002	1.11E+003
$0.0 \le M < 0.1$	5699	10,281	5.63E+006	2.32E+007	9.88E+002	2.26E+003
$0.1 \le M < 0.2$	3939	8646	4.25E+006	6.82E+006	1.08E+003	7.88E+002
$0.2 \le M < 0.3$	2806	7021	4.68E+006	1.87E+007	1.67E+003	2.66E+003
$0.3 \le M < 0.4$	1912	5561	5.23E+006	1.03E+007	2.74E+003	1.85E+003
$0.4 \le M < 0.5$	1303	4287	5.23E+006	9.11E+006	4.01E+003	2.12E+003

(continued)

Table 4.17 (continued)

Energy per magnitude 1 August 2004—31 July 2009						
Magnitude	Number of events		Energy release (J)		Average energy (J)	
Range	Inside	Outside	Inside	Outside	Inside	Outside
$0.5 \leq M < 0.6$	896	3316	4.94E+006	1.46E+007	5.51E+003	4.40E+003
$0.6 \leq M < 0.7$	558	2537	5.30E+006	1.35E+007	9.50E+003	5.34E+003
$0.7 \leq M < 0.8$	384	1821	4.80E+006	2.11E+008	1.25E+004	1.16E+005
$0.8 \leq M < 0.9$	240	1317	4.59E+006	1.83E+007	1.91E+004	1.39E+004
$0.9 \leq M < 1.0$	147	1069	6.60E+006	2.32E+007	4.49E+004	2.17E+004
$1.0 \leq M < 1.1$	68	784	4.54E+006	1.59E+008	6.68E+004	2.03E+005
$1.1 \leq M < 1.2$	46	685	5.05E+006	2.95E+007	1.10E+005	4.31E+004
$1.2 \leq M < 1.3$	18	538	2.17E+006	3.64E+007	1.21E+005	6.77E+004
$1.3 \leq M < 1.4$	22	404	4.12E+006	4.42E+007	1.87E+005	1.09E+005
$1.4 \leq M < 1.5$	10	292	4.54E+006	5.38E+007	4.54E+005	1.84E+005
$1.5 \leq M < 1.6$	4	209	4.47E+006	6.65E+007	1.12E+006	3.18E+005
$1.6 \leq M < 1.7$	6	154	7.66E+006	1.14E+008	1.28E+006	7.37E+005
$1.7 \leq M < 1.8$	1	101	5.11E+004	1.58E+008	5.11E+004	1.57E+006
$1.8 \leq M < 1.9$	3	79	9.16E+006	1.60E+008	3.05E+006	2.03E+006
$1.9 \leq M < 2.0$	0	52		1.60E+008		3.09E+006
$2.0 \leq M < 2.1$	0	27		1.46E+008		5.42E+006
$2.1 \leq M < 2.2$	1	24	2.04E+007	4.73E+008	2.04E+007	1.97E+007
$2.2 \leq M < 2.3$	1	2	8.57E+008	1.87E+007	8.57E+008	9.35E+006
$2.3 \leq M < 2.4$	0	4		2.68E+008		6.70E+007

(continued)

Table 4.17 (continued)

Energy per magnitude 1 August 2004—31 July 2009						
Magnitude	Number of events		Energy release (J)		Average energy (J)	
Range	Inside	Outside	Inside	Outside	Inside	Outside
$2.4 \leq M < 2.5$	0	6		7.52E+008		1.25E+008
$2.5 \leq M < 2.6$	0	3		2.15E+008		7.15E+007
$2.6 \leq M < 2.7$	0	3		1.48E+009		4.92E+008
$2.7 \leq M < 2.8$	0	3		3.88E+009		1.29E+009
$2.8 \leq M < 2.9$	0	1		3.35E+008		3.35E+008

Fig. 4.47 Monthly seismic energy release rates

to decrease until mid-2006 when they started to increase. During mid-2008, about 80% of all recorded events were located in the cave volume. The following decrease in the percentages of events locating in the cave was large and rapid. From mid-2008 onwards, less than 20% of all recorded seismicity was associated with the cave volume.

Figure 4.59 indicates the monthly percentages of seismicity with Ei > 10.0 recorded in the cave volume (100% is the total monthly seismic activity rate recorded in the whole mine). This figure illustrates the fact that the highest percentages of this type of seismicity in the cave volume were recorded during 2005 and then from the beginning of 2007 until end of May 2008.

4.5 Comparison Between the Mines

In this section, I have combined the data as well as the results presented in previous three sections. In next tables, I will be using the following abbreviations:

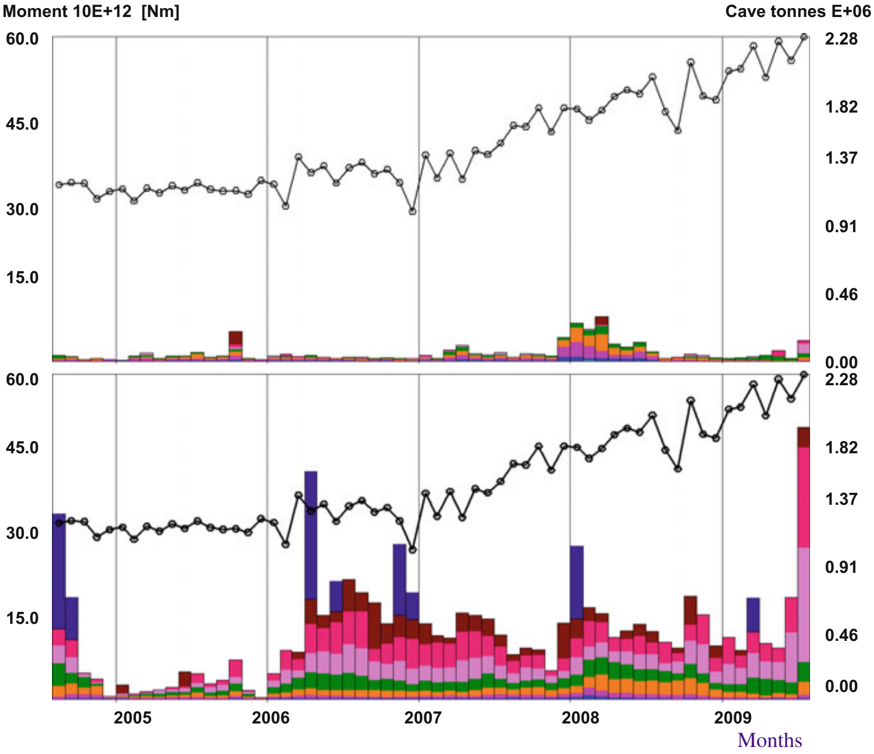


Fig. 4.48 Monthly seismic deformation rates

Table 4.18 Maximum recorded magnitude

Volume	DR	PMC	DOZ
Cave	1.3	1.9	2.2
Out of cave	1.9	1.9	2.8

- DR which means Diablo Regimento Sector
- PMC which means Palabora Mining Company
- DOZ which means Deep Ore Zone
- Cave which means cave volume
- Out of cave which means the rock mass volume around the cave volume.

Table 4.18 lists the highest magnitude seismic events recorded in the cave volumes and the rock mass volumes surrounding the caves. All magnitudes are moment magnitudes.

Table 4.19 indicates the percentages of seismicity recorded in the three caves and in the three volumes around the caves. 100% represents the total amount of seismicity, seismic energy and seismic moment recorded both in the cave and the surrounding volume.

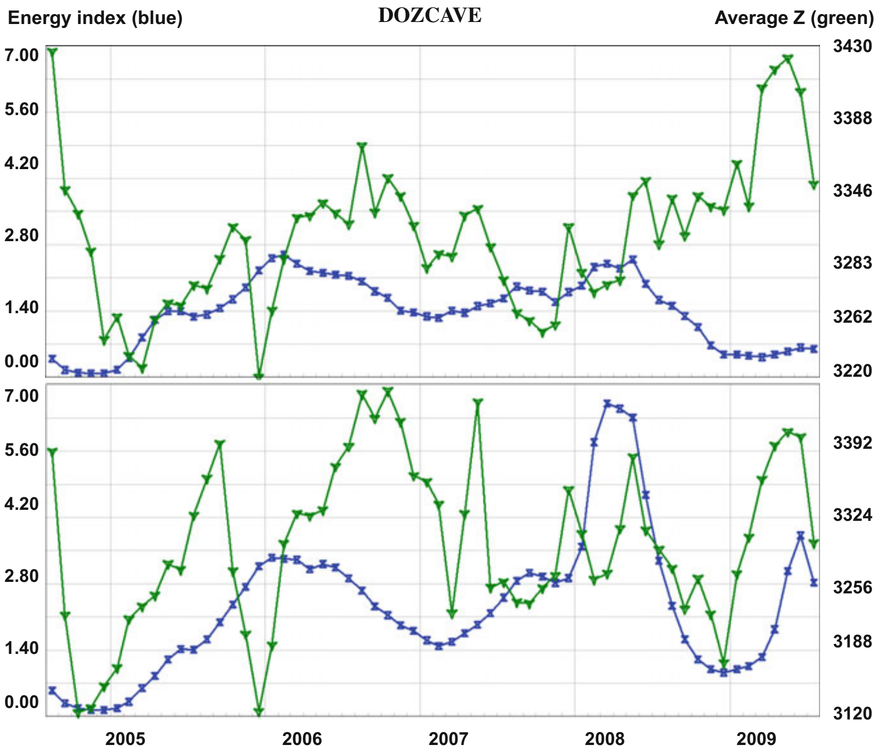


Fig. 4.49 Energy index time histories

Table 4.19 Percentages of seismicity recorded in the cave volumes

Cave	% of seismicity	% of energy	% of moment
DR	26	35	18
PMC	27	28	17
DOZ	54	10	12

Table 4.20 Number of events above magnitude 1.0

Volume	DR	PMC	DOZ
Cave	10	36	180
Out of cave	25	309	3370

Table 4.20 lists the number of larger size events (magnitude 1.0 and above) recorded in the three caves and their surrounding volumes.

Table 4.21 lists the cumulative amounts of seismic energy released by the events listed in Table 4.20. In case of the DR mine the amount of seismic energy released outside of the cave is 100 times more than inside of the cave. For the other two mines, this difference is less at ten times more.

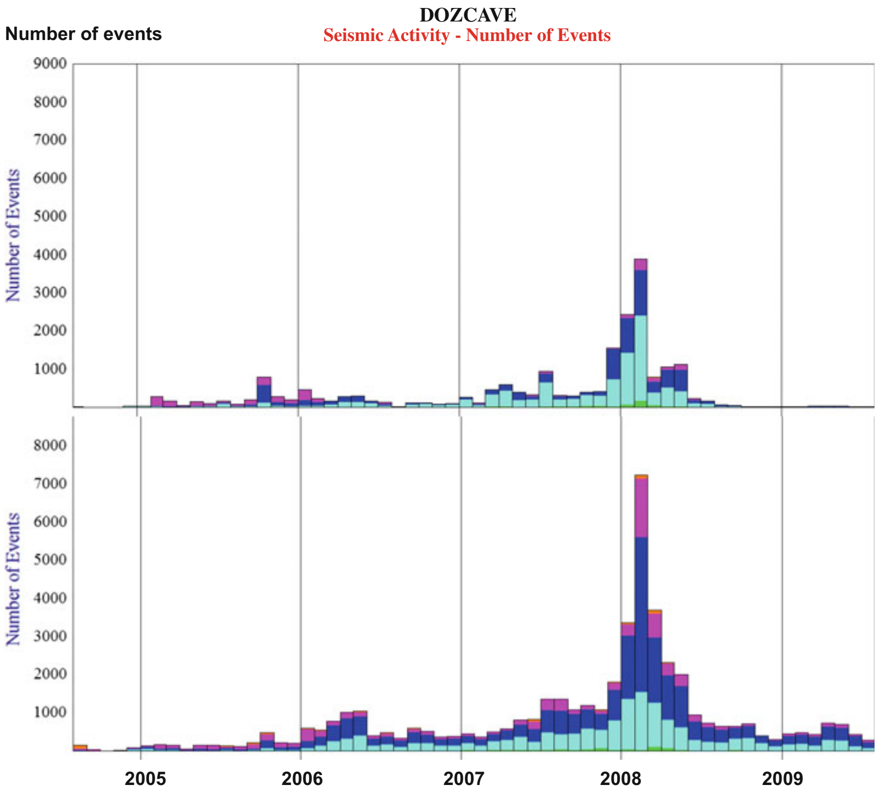


Fig. 4.50 Events with energy index above 10.0—monthly activity rates

Table 4.21 Energy released by events of magnitude above 1.0

Volume	DR (J)	PMC (J)	DOZ (J)
Cave	8.10E+05	3.42E+07	9.19E+08
Out of cave	9.71E+07	1.32E+08	8.55E+09

Table 4.22 Percentages of energy released by events of magnitude above 1.0

Volume	DR (%)	PMC (%)	DOZ (%)
Cave	34	36	87
Out of cave	73	54	70

Table 4.22 indicates the percentages of seismic energy released by events of magnitude size 1.0 and above. In the case of the ‘Cave’, the total seismic energy is calculated using all seismicity that was recorded inside of the cave volume. In the case of ‘Out of cave’, the total seismic energy was calculated for the whole rock mass volume that is located around the caves and does not include the cave volumes.

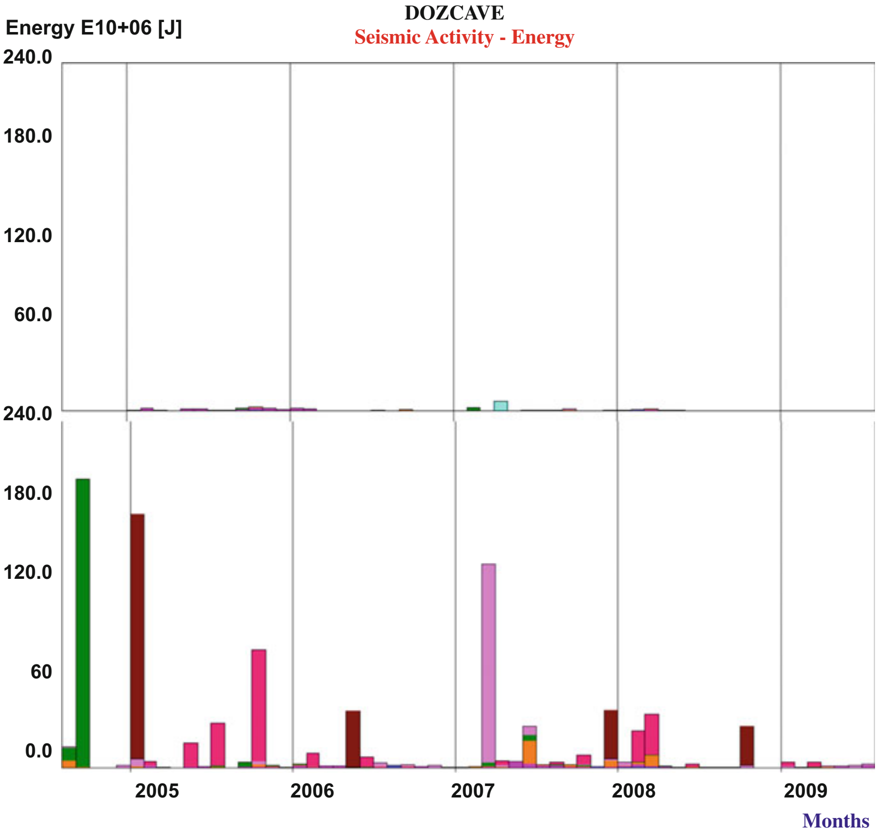


Fig. 4.51 Events with energy index above 10.0—monthly energy release rates

Table 4.23 Released seismic energy per mined ton

Volume	DR (J/t)	PMC (J/t)	DOZ (J/t)
Total seismic energy per ton	1.9	4.6	108.7
Cave energy per ton	0.7	1.2	11.1

Table 4.23 compares the energy released per mined tonnes in the three mines. Values listed in row 'Total seismic energy per tonne' were calculated with the total seismic energy released in the whole mine. Values listed in row 'Cave energy per tonne' were calculated using the total seismic energy released only in the caves.

Table 4.24 compares the seismic deformation per mined tons in the three mines. Values listed in row 'Total seismic moment per tonne' were calculated using the total seismic deformation for the whole mine. Values listed in row 'Cave moment per ton' were calculated using the total seismic deformation recorded only in the caves.

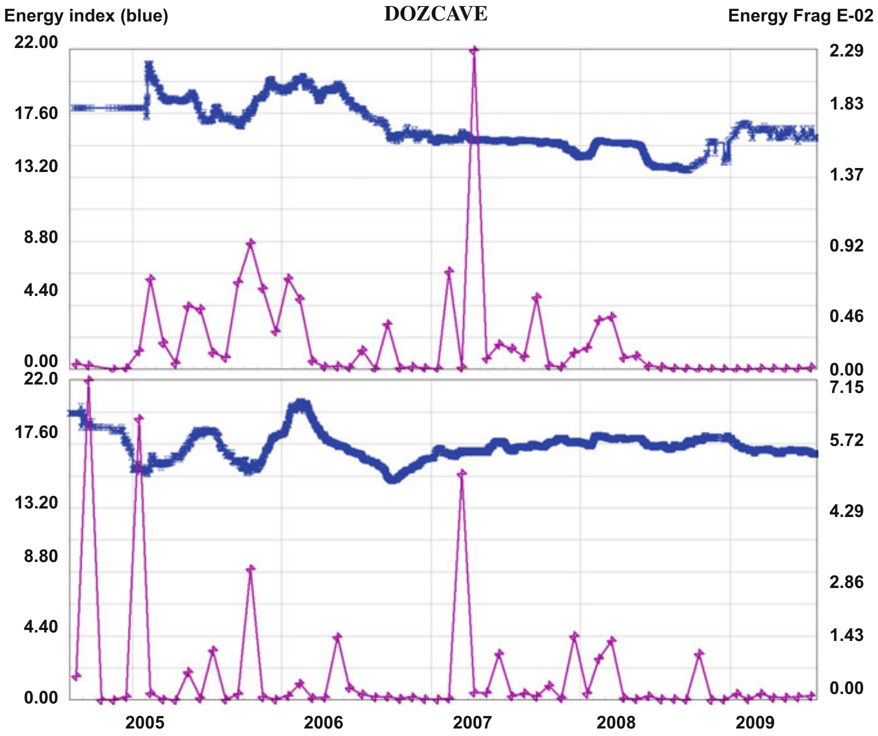


Fig. 4.52 Energy index time histories based on events with Ei > 10

Table 4.24 Seismic moment per mined ton

Volume	DR (Nm/t)	PMC (Nm/t)	DOZ (Nm/t)
Total seismic moment per ton	15.9E+05	14.6E+05	94E+05
Cave moment per ton	3.1E+05	2.5E+05	11.1E+05

Table 4.25 Energy fragmentation index (J/m^3)

Volume	DR	PMC	DOZ
Cave	0.33	0.40	2.3

Table 4.25 compares the energy index fragmentation indices while Table 4.26 compares the moment fragmentation indices for the three caves.

Table 4.27 list the percentages of seismicity with high energy index (above 10.0) recorded in the caves and the volumes located around the caves. In case of the caves 100%, seismicity is all of the seismicity recorded only in the cave volumes. For ‘Out of cave’ 100%, is all seismicity recorded in the volumes surrounding the caves.

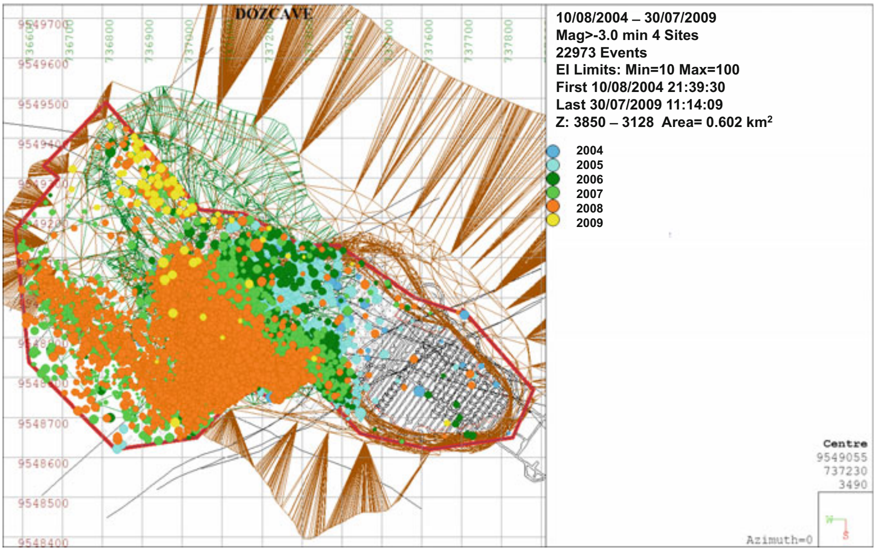


Fig. 4.53 Cave volume—high energy index events

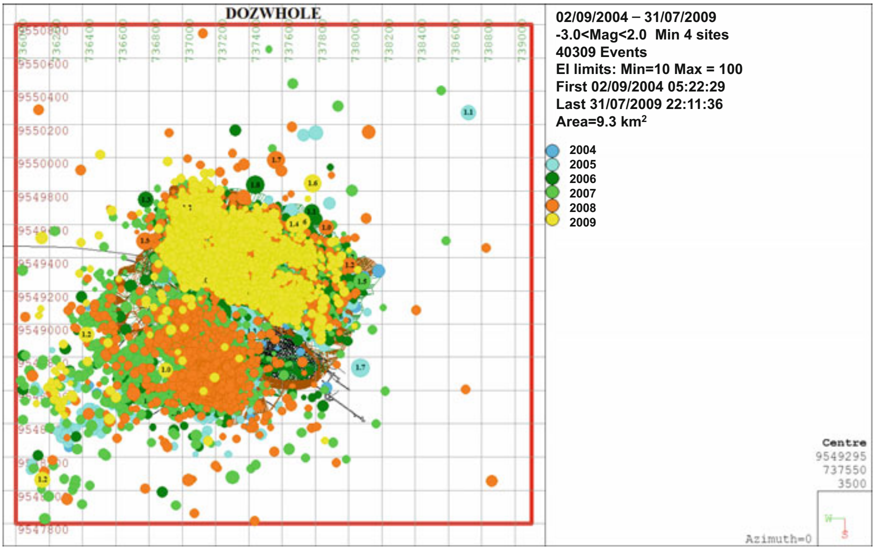


Fig. 4.54 Surrounding volume—high energy index events

Table 4.28 lists the percentages of seismic energy released by the seismicity listed in Table 4.27.

Figure 4.60 illustrates the yearly seismic energy release rates for the whole Diablo Regimento Sector. The energy release rates were calculated using seismic data

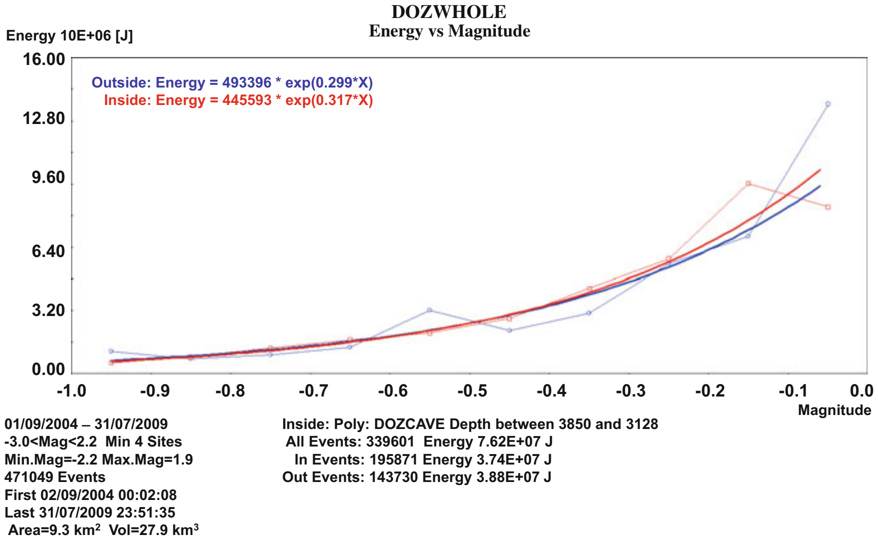


Fig. 4.55 Energy release in magnitude range −1.0 up to −0.1

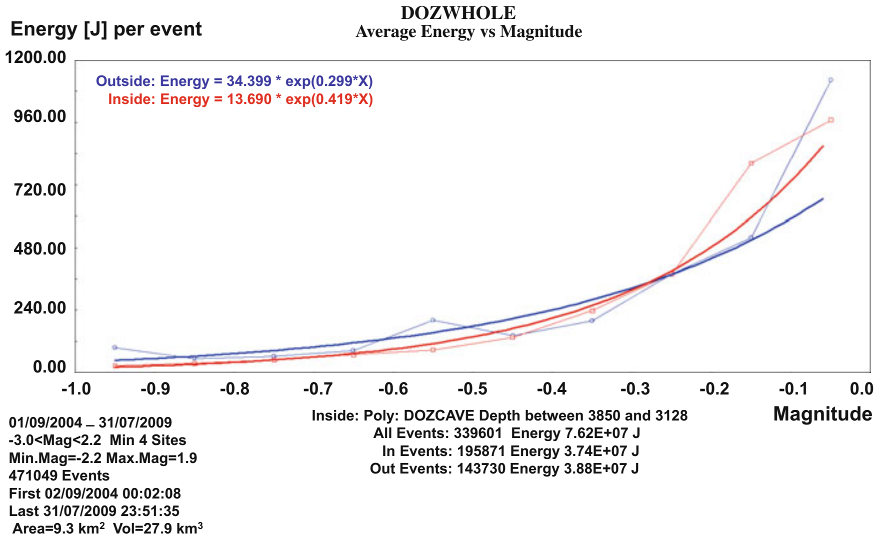


Fig. 4.56 Average energy releases per single event (magnitude range −1.0 to −0.1)

recorded from 4 January 2004 up to 31 July 2009 in an elevation range from 1500 m up to 2600 m.

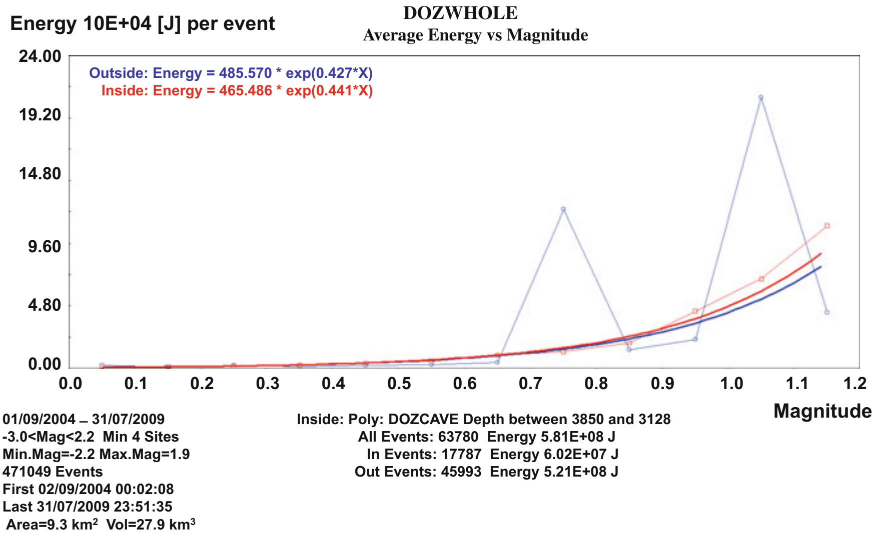


Fig. 4.57 Average energy releases per single event (magnitude range 0.0 to 1.1)

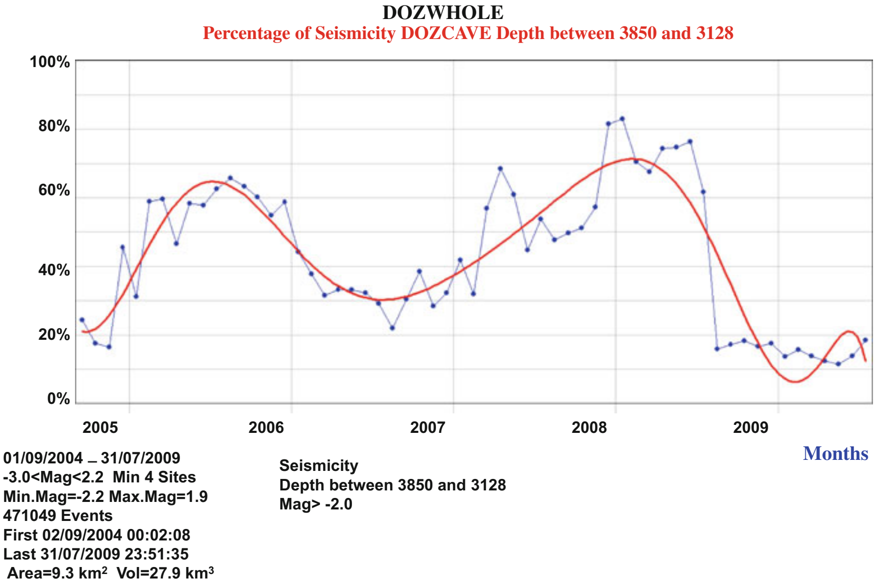


Fig. 4.58 Percentages of seismicity recorded in the cave volume

Figure 4.61 illustrates the yearly seismic energy release rates for the whole PMC mine. The energy release rates were calculated using seismicity recorded from 6 April 2001 to 15 July 2010 in an elevation range from −1700 m up to 400 m.

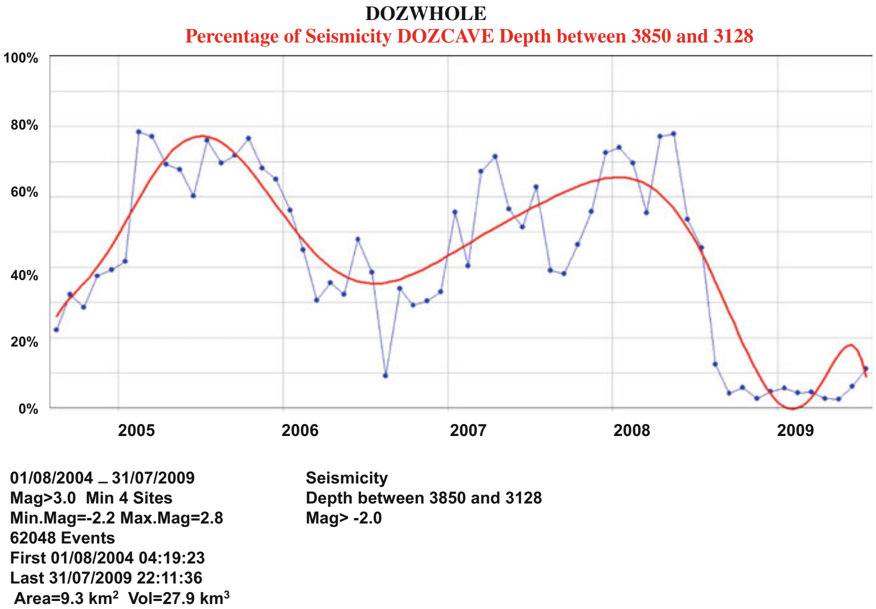


Fig. 4.59 Percentages of seismicity with Ei > 10 recorded in the cave volume

Table 4.26 Moment fragmentation index (Mm/m^3)

Volume	DR	PMC	DOZ
Cave	4.5E+05	0.85E+05	2.3E+05

Table 4.27 Percentages of seismicity with Ei > 10 recorded in the mines

Volume	DR	PMC	DOZ
Cave	16	40	9
Out of cave	12	18	21

Table 4.28 Percentages of seismic energy release by high energy index seismicity

Volume	DR	PMC	DOZ
Cave	9	32	87
Out of cave	15	47	70

Figure 4.62 illustrates the yearly seismic energy release rates at the DOZ Mine. These energy release rates were calculated for all seismicity recorded from 1 August 2004 until 31 July 2009 in an elevation range from 2000 m up to 5000 m. In order to make the data presented by this figure comparable with that which is presented in Figs. 4.60 and 4.61, I had to use a maximum magnitude above which the energy release is excluded from the calculations. For this purpose, I used a magnitude 1.9 which is the maximum magnitude size recorded at PMC.

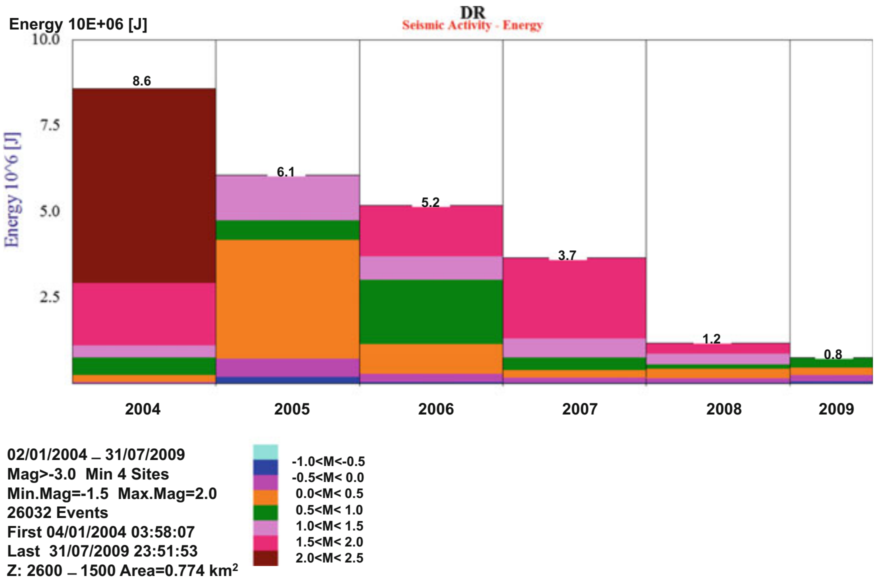


Fig. 4.60 DR yearly seismic energy release rates

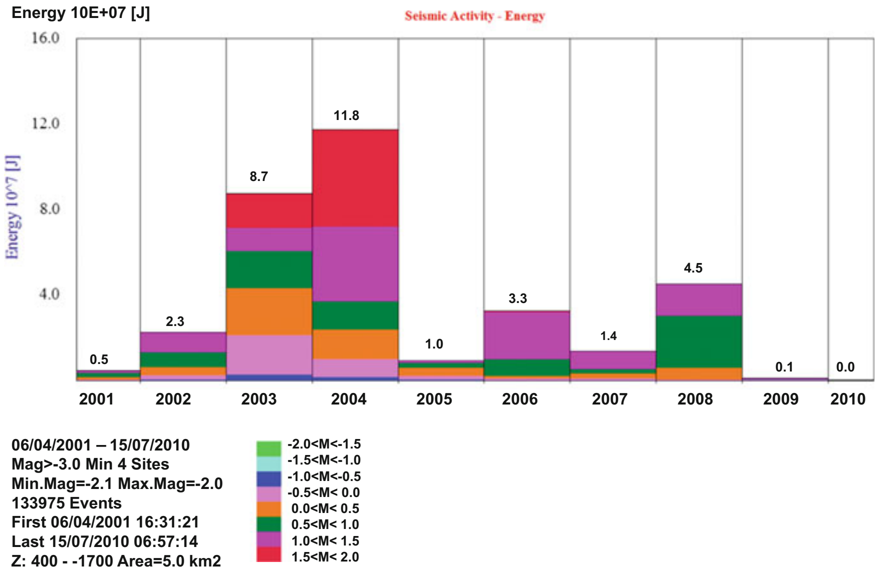


Fig. 4.61 PMC yearly seismic energy release rates

Direct comparisons of the average energy releases of events in magnitude range from −1.0 up to 1.0 in the cave and the surrounding volumes indicate that in all three

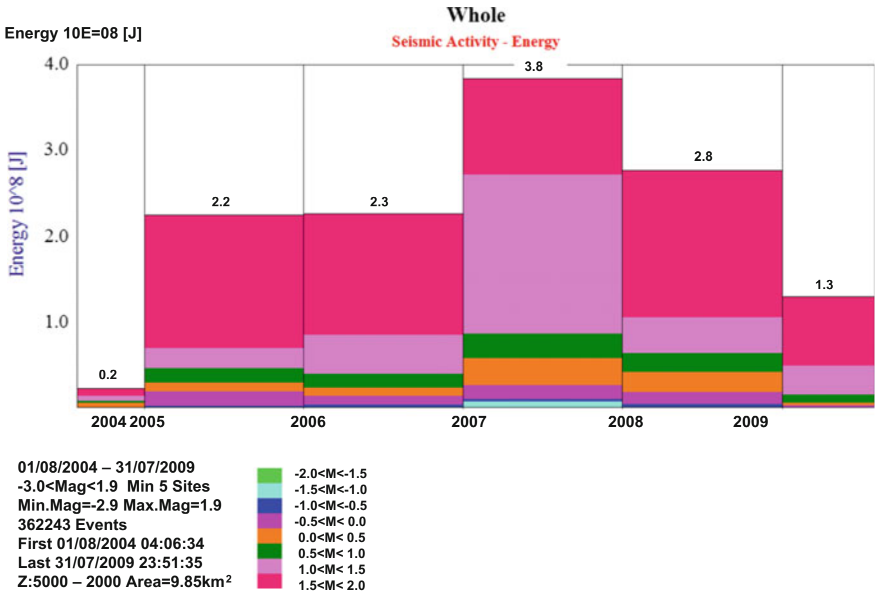


Fig. 4.62 DOZ yearly seismic energy release rates

cases, the average energy release per magnitude size in the cave is always higher than in the surrounding volume. Time distributions of seismicity indicates that most of the seismicity associated with the cave volume took place when the stresses as indicated by the energy index time histories were at their high values. This explains the reason why, on average, the seismicity recorded in the cave volume released more seismic energy in comparison to seismicity recorded outside of this volume. These observed different seismic energy release patterns indicate not only that the seismic hazard changes over time, but it is also different because of the seismicity taking place in the cave volume and in the surrounding volume.

Table 4.29 merges parts of the data listed in Tables 4.11, 4.14 and 4.17. This table lists the average seismic energy releases values of seismicity in magnitude range from −1.0 up to 1.0 at the PMC cave, DR cave and DOZ cave. Column 5 (‘PMC/DR cave’) and column 6 (‘DOZ/DR cave’) lists the ratios between the relevant energy release values for the two caves. This data is illustrated by Figs. 4.63 and 4.64.

Figure 4.63 illustrates the average seismic energy release of seismicity in magnitude range from −1.0 up to 1.0 which was recorded in the cave volumes. The PMC cave seismicity is in blue, DR cave seismicity is green while the DOZ cave seismicity is in red.

Figure 4.64 illustrates the ratios between the energy releases per magnitude size in the caves. The ratios between the PMC and DR values are in blue while the ratios between the DOZ and the DR values are in red. The broken lines indicate the trends.

Table 4.29 Average energy release [J] per magnitude size

Magnitude	PMC cave	DR cave	DOZ cave	PMC/DR cave	DOZ/DR cave
−1.0	34.6	18.3	25.7	1.89	1.40
−0.9	68.5	23	34.4	2.97	1.49
−0.8	134	31.5	48.4	4.25	1.53
−0.7	239	53.8	67.9	4.44	1.26
−0.6	357	51.8	86.8	6.89	1.67
−0.5	504	97.3	134	5.17	1.38
−0.4	684	90.4	237	7.56	2.62
−0.3	972	194	377	5.01	1.94
−0.2	1300	219	799	5.93	3.64
−0.1	2050	314	966	6.52	3.07
0.0	3320	495	988	6.70	1.99
0.1	5360	447	1080	11.99	2.41
0.2	7010		1670		
0.3	7960	648	2740	12.28	4.22
0.4	13,700	624	4010	21.95	6.42
0.5	29,600		5510		
0.6	35,100	4280	9500	8.20	2.21
0.7	55,600	2040	12,500	27.25	6.12
0.8	66,000	9900	19,100	6.66	1.92
0.9	146,000	35,200	44,900	4.14	1.27
1.0	260,000	21,000	66,800	12.38	3.18

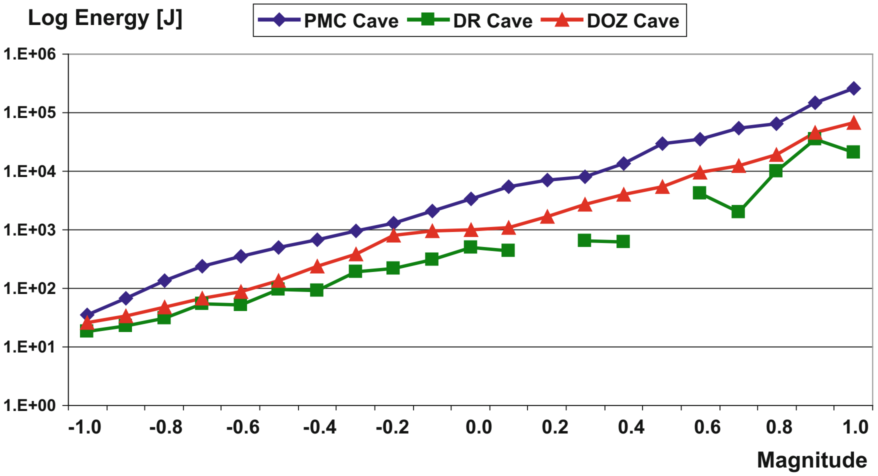


Fig. 4.63 Average energy releases for magnitude range −1.0 up to 1.0 in caves

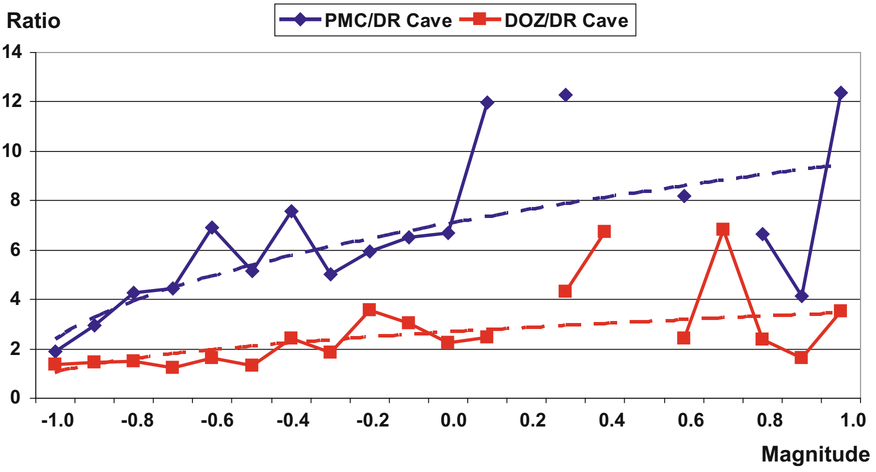


Fig. 4.64 Ratios between the energy releases per magnitude

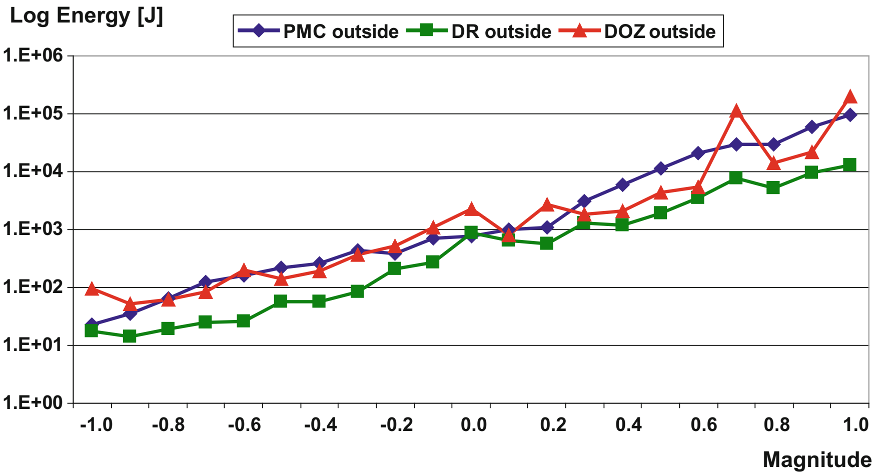


Fig. 4.65 Average energy releases for magnitude range −1.0 up to 1.0 outside of the caves

Table 4.30 combines parts of the data listed in Tables 4.11, 4.14 and 4.17. This table lists the average seismic energy release values of seismicity in magnitude range from −1.0 up to 1.0 in the rock mass volumes located around the PMC cave, DR cave and DOZ cave. Column 5 ('PMC/DR cave') and column 6 ('DOZ/DR cave') lists the ratios between the relevant energy release values for the two volumes located outside of the caves. This data is illustrated by Fig. 4.65 and Fig. 4.66.

Figure 4.65 illustrates the average seismic energy release of seismicity in magnitude range from −1.0 up to 1.0 of the seismicity recorded in the volumes located

Table 4.30 Average energy release [J] per magnitude size

Magnitude	PMC outside	DR outside	DOZ outside	PMC/DR outside	DOZ/DR outside
−1.0	22.5	17.9	95.2	1.25	5.31
−0.9	34.6	14	52.6	2.47	3.75
−0.8	65.5	19.6	61.6	3.34	4.14
−0.7	124	24.8	83.5	5	3.36
−0.6	164	25.5	199	6.43	7.80
−0.5	216	56.5	141	3.82	2.49
−0.4	255	57.1	196	4.46	3.43
−0.3	447	83.8	374	5.33	4.46
−0.2	386	209	514	1.84	2.45
−0.1	702	273	1110	2.57	4.06
0.0	758	861	2260	0.91	2.62
0.1	1020	659	788	1.54	1.19
0.2	1090	569	2660	1.91	4.67
0.3	3110	1310	1850	2.37	1.41
0.4	5870	1170	2120	5.01	1.81
0.5	11,600	1900	4400	6.10	2.31
0.6	21,100	3520	5340	5.99	1.51
0.7	29,000	7820	116,000	3.70	14.8
0.8	29,800	5310	13,900	5.61	2.61
0.9	59,200	9750	21,700	6.07	2.22
1.0	9,7000	13,000	203,000	7.46	15.6

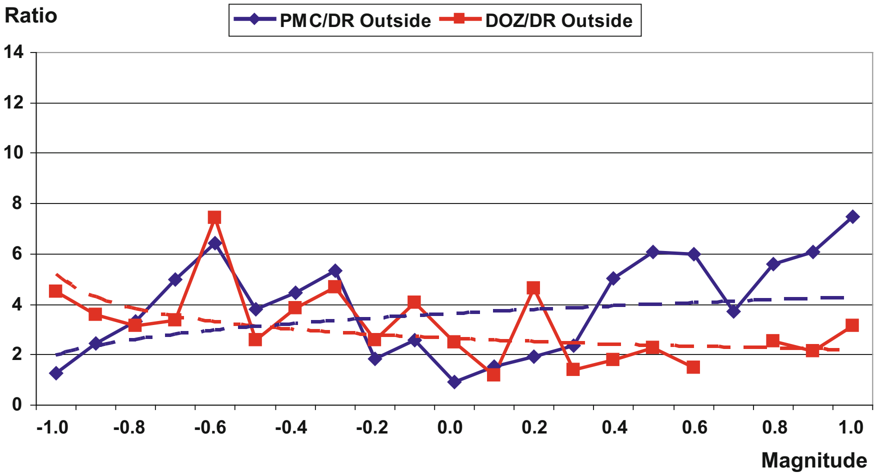


Fig. 4.66 Ratios between the energy releases per magnitude

around the caves. The PMC seismicity is in blue, DR seismicity in green while the DOZ seismicity is in red.

Figure 4.66 illustrates the ratios between the energy releases per magnitude sizes in the volumes of rock mass located around the caves. The ratios between the PMC and DR values are in blue while the ratios between the DOZ and the DR values are in red. The dotted lines indicate the trends.

4.6 Summary of Observations

Because of the different periods of the seismic data bases, different cave volumes, different production rates, different amounts of recorded seismicity and different rock mass properties direct comparisons are impossible. For this reason, I had to normalize the recorded seismicity over the cave volume or over the cave production and make use of percentages as well as the seismicity trends, rather than directly use of the recorded seismicity. The presented analysis resulted in the following observations:

1. The lowest maximum magnitude was recorded in the DR cave. The size of this magnitude was 1.3. The second highest maximum magnitude of 1.9 was recorded in the PMC cave. The highest maximum magnitude of 2.2 was recorded in the DOZ cave
2. Distribution of seismicity
    - 2.1 In the DR and PMC mines, only about 25% the seismicity was recorded in the cave volumes. This means that in case of these two mines, most of the recorded seismicity was located in the rock mass volume surrounding the caves. In case of the DOZ cave, nearly 50% of recorded seismicity located in the cave volume
    - 2.2 The distribution of released seismic energy in these three caves does not follow the distributions of the recorded seismicity. While in the DR and PMC caves, about 30% of the total released seismic energy took place in these two cave volumes in case of the DOZ cave this percentage is only 10%.
    - 2.3 The distributions of total seismic deformations in the three caves follow the pattern of the seismic energy distributions. In case of the DR and PMC caves, only about 20% of the total seismic deformation was associated with the cave volumes. In case of the DOZ cave, only about 10% of the total seismic deformation took place in the cave volume
3. Larger size seismicity
    - 3.1 In the DR cave, there were only ten seismic events of magnitude 1.0 and above, in the PMC cave, there were 36 events of this size and in the DOZ cave, there were 180 such large size events
    - 3.2 These large size events released about 35% of the total seismic energy released in the two caves at DR and PMC. In the case of DOZ cave, these

large size events released nearly 90% of the total seismic energy released in the cave

4. Seismicity and production

    4.1 Normalization of the released seismic energy over the tonnes lashed from the caves revealed that the lowest amounts of the released total seismic energy for the whole mine per production tonne were released at the DR cave. Here, this parameter value is 1.9 J/t. The same parameter for the PMC is twice as high at 4.6 J/t while at DOZ it is at 108 J/t which is nearly 50 times higher than at DR

    4.2 In the case of normalization of the seismic energy released in the cave volumes, only this parameter remains twice as high for PMC compared to DR. The DOZ parameter is nearly 16 times higher when compared to that at DR

    4.3 When normalizing seismic moment over the tons lashed from the caves, the results are different from those when the normalizing was done using the seismic energy. In this case, this parameter for the PMC cave has the lowest value both for the total mine and the total cave seismic moment. The other important difference is that the variations of this parameter for the three caves are lower than in the case of the seismic energy. This parameter value for the PMC mine is 14.6E+05 Nm/t, versus 15.9E+05 Nm/t for DR mine and for DOZ mine is the highest at 94E+05 Nm/t

5. Energy and moment fragmentation index

    5.1 Examination of the energy fragmentation index, which normalizes the released seismic energy over the cave volumes, indicates that this index has the lowest value for the DR cave (0.33 J/m^3), a slightly higher value for the PMC cave (0.40 J/m^3) and the highest value for the DOZ cave (2.3 J/m^3). The distribution of this parameter is similar to the one resulting from comparing the released seismic energy with the production tonnes.

    5.2 Examination of moment fragmentation index which normalizes the seismic moment over the cave volumes results in similar findings as in the case of seismic moment normalized over the production tonnes. This index has the lowest value for the PMC cave (0.85E+05 Nm/m^3). The difference is that here this index has the highest value for the DR cave (4.5E+05 Nm/m^3). For DOZ this index cave has an intermediate value of 2.3E+05 Nm/m^3.

6. High energy index seismicity

    6.1 Seismic events with high energy index are events that on average release more seismic energy compared to events of the same seismic moment with lower index values. In case of the DR cave, about 16% of all events recorded in its volume had this index higher than 10.0. In the PMC cave, there was 40% of such seismicity while in the DOZ cave it was only 9%

    6.2 These high energy index seismic events released only 9% of the energy released in the DR cave and 32% of all energy released in the PMC cave but these high energy index events accounted for as much as 87% of the seismic energy released in the DOZ cave.

7. Seismic energy release trends
    - 7.1 The seismic energy release trends for the three mines are different. At DR mine, the maximum seismic energy was released during 2004 and then year-on-year, there was a considerable decrease in the yearly seismic energy release rates. In case of the PMC cave, there was a 3-year increase in this rate from 2002 until 2004. After 2004, the yearly rates were much lower. With the DOZ cave, the trend was different to the other two mines trends. Here, the seismic energy released per year was more or less constant for the 4 years of data
    - 7.2 Direct comparisons of the average energy releases of events in magnitude range from -1.0 up to 1.0 in the cave and the surrounding volumes indicate that in all three cases examined, the average energy release per magnitude size in the cave is always higher than in the surrounding volume
    - 7.3 This is due to the fact that most of the cave seismicity took place when the stresses as indicated by the energy index time histories were highest
    - 7.4 Comparison of the average seismic energy released per magnitude size indicates that the PMC seismicity—recorded in the cave released the highest amounts of seismic energy. The DOZ cave seismicity released on average less energy than at PMC. The lowest energy releases per magnitude size were recorded in the DR cave
    - 7.5 As far as the average energy release per magnitude size of seismicity recorded outside of the cave, the observed trend is similar but not so evident
    - 7.6 The seismicity recorded in the PMC cave per magnitude size on average released 2–10 times more energy than the same size seismic events recorded in the DR cave. This ratio for the DOZ cave is lower at 2 up to 4 times.
    - 7.7 In case of the rock mass, volumes surrounding the caves these ratios are much lower at between 2 and 4 times for the PMC/DR ratio and the DOZ/DR ratio.

4.7 Conclusions

Analysis of the seismicity recorded in the three caves of Diablo Regimento Sector, PMC Mine and DOZ Mine as presented in this chapter leads to the following conclusions which can be divided into three categories:

A. General nature of the seismicity induced by the caving process
B. Comparison of seismicity induced in a preconditioned cave with that induced in non-preconditioned caves
C. Observations related to the individual caves.

General nature of the seismicity induced by the caving process

1. The vast percentages of high Es/Ep ratio seismicity in all three mines indicate that the principal caving process mechanism is shear failure
2. In all three mines on average, each seismic event of the same magnitude released more seismic energy when it took place in the cave volume compared to surrounding rock mass volume. This is for two reasons, there is less seismicity in the cave than in the surrounding rock mass and the most of the cave seismicity takes place when the stress regime, as indicated by the energy index time history, is at its highest level.

Comparison of seismicity induced in a preconditioned cave versus that induced in non-preconditioned caves

1. The seismic energy release pattern at DR Sector is different from that in the other two caves. Here, the maximum energy release was recorded during 2004 when only the development mining was taking place. During 2005, which was the year that cave production commenced (June 2005) and the caving process was initiated (October 2005), the yearly seismic energy release decreased. From 2005 up to 2008, there was a continuous decrease in the yearly seismic energy release rates
2. The initiation of the caving process at PMC took place in April 2002. This was the year in which the total seismic energy release was very low. The highest seismic energy release rates were recorded during the next 2 years that is during 2003–2004. During these 2 years, there was a continuous build-up of the production rates. Only from 2005, was there a substantial decrease in the yearly seismic energy release rates
3. Of the three caves the lowest maximum magnitude event was recorded in the DR cave
4. The number of events above magnitude 1.0 recorded in the DR cave is very low in comparison to the number of these size events recorded in the other two caves
5. The DR cave has the smallest ratio of released seismic energy per mined out tonne of ore. This ratio for PMC is twice as high while the DOZ ratio is 50 times higher compared to the DR
6. The DR cave has the lowest ratio of released seismic energy per cave volume. These ratios for DR and PMC are very close to each other and they are nearly six times lower than the DOZ ratio
7. It is interesting to note that the indices that normalize the seismic moment over the mined out ore tonnes or over the cave volumes for DR are higher than those for PMC. This indicates that at the PMC cave on average, there was less seismic deformation than at DR
8. For the three caves, the high energy index seismicity in the DR cave released the lowest percentage of the total energy released by these caves

9. On average, each magnitude size event recorded in the DR cave released less energy than the same size event recorded in the other two caves.

The above points indicate that the preconditioning of the DR rock mass had to result in substantial fracturing of the rock mass. A similar rock mass condition to what was already in place at DR right from the commencement of the cave mining, was achieved only after nearly 3 years of production at PMC. The PMC rock mass was gradually preconditioned by the caving process.

Observations related to the individual caves

1. The energy release and seismic moment patterns at the DOZ mine are different from that observed at the other two mines. This is mainly due to the fact that at the DOZ mine the development and production mining was done at the same time
2. The reason the PMC has lower indices that normalize the seismic moment over the lashed out tonnes or the cave volumes compared to DR can be explained by the observed poor fragmentation. Here, the average oversize tonnage contribution from 2002 up to the end of 2009 was close to 30%. These amounts of oversize indicate that the seismic deformation taking place in the cave did not always result in good breaking of the rock mass. Although at DR, there was less seismic deformation, this combined with the rock mass deformation due to the hydro-fracturing process resulted in much better fragmentation.

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Gibowicz SJ, Kijko A (1994) An introduction to mining seismology. Academic Press, New York

Glazer SN (2016) Mine seismology: data analysis and interpretation. Palabora mine caving process as revealed by induced seismicity. Springer International Publishing, Switzerland (ISBN 978-3-319-32611-5)

Chapter 5
Summary and Conclusions

Abstract Everything I have presented in my mine seismology trilogy appears to be very simple and uncomplicated. The most complicated tool used in research was the concept of Energy Index or Apparent Stress Index. The second most difficult element presented was the percentages perception. It seems that what I consider to be research might not come close to genuine research. What is then genuine research? Genuine research must start with a question, which then can be turned into an idea. In my case, the first question I asked myself as early as 1990 was: "How to make use of all the recorded seismicity in the analysis and interpretation process?" (Glazer in Mine seismology: seismic warning concept. Case study from Vaal Reefs gold mine, South Africa, Springer International Publishing, Switzerland, 2017) The answer or the idea was the Apparent Stress Index concept. At the time, the mine was experiencing severe problems with underground safety due to seismicity. That was the rationale for the next question: "Can the Index be used to solve or at least reduce this problem?" During 2002, I asked myself another question: "Can the recorded seismicity be used to monitor the caving process and the related seismic hazard?" As a result, there is now a methodology available on how to use the recorded seismicity to monitor the caving process. It is described in detail so that it can be used by others. These in my opinion are examples of where genuine research was followed up by implementation. In conclusion, I do not feel embarrassed that my research ended with the development of some very simple tools. These uncomplicated tools were used to solve complicated and complex problems. When the end result of the research, is the development of some very complicated super tools, then it is easy to forget their purpose. It appears that these tools then have a life of their own in which they must be maintained nonstop by adding life support apparatuses just to keep them alive. They also require plastic surgery just to keep them beautiful and attractive.

From the presented analyses, it is evident that the caving process can be monitored by the recorded induced seismicity. Seismicity is defined as a number of seismic events in a unit of time. From the practical point of view, the lowest time unit that can be used, but only in some specific cases, is a week (or 10 days) but in most cases the lowest realistic time unit will be 1 month. In the presented analyses, I have

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often used much longer time spans, for example, a couple of months to a number of years. Such long time spans were used for example with the energy index time history, cumulative graphs for seismic moment or seismic energy or the average seismicity elevation changes. From this, it is evident that the presented analysis does not take into account any single seismic event (even the largest ones) but at any time makes use of vast number of events. Again vast as such is not a specific term but in this case, it means from hundreds up to hundreds of thousands of events. The lowest numbers of events will be used in cases for the seismicity rates. Usually with the seismicity rates the shortest time will be 1 month. Monthly seismicity rates can vary from a couple of events up to thousands of events. Still in all the presented analyses, I did not investigate any single monthly rate as such but their changes over longer time periods. The same applies to any other parameter, for example the energy index or the average monthly seismicity elevation. I was studying their trends. Trend analysis is about collecting data and then trying to extract from this data a pattern or trend. In statistics trend analysis refers to techniques for extracting an underlying pattern of behaviour in a time series which would otherwise be partly or nearly completely obscured hidden by noise. A simple description of these techniques is trend estimation. Uncovering a trend involves a number of techniques as for example filtering the input data using time and/or space and/or some of its dimensions. Then the filtered data is smoothed, for example, by applying a regression analysis. By definition such techniques result in reliable and consistent results when applied to rather large data sets. The four seismic catalogues analysed in this book range from a couple of thousand events up to a couple of hundred thousand events. In total, I have analysed close to a million of seismic events. These four seismic data sets are not only consistent as separate input catalogues but as whole. All mines were not only using the same seismic system for recording the seismicity but the recorded data was then processed with the same software version. In this way, the input data has not only sufficient quantity but also quality. In all presented analysis and interpretations, I have made use of the following trends of seismicity:

1. Trends of space and time distribution of seismicity
2. Trend of the average monthly seismicity elevation
3. Trends of the cumulative seismic moment and seismic energy release
4. Trend of the energy index time history.

Additionally, the input data consisted of mining rates (development and production) and mining plans. This allowed for comparison of trends of seismicity with mining rates. Mining plans were used for accurate setting of the volumes for the space trend analyses. I made use of the mine foot print elevations for analysing the seismicity trends above and below the extraction level. I also made use of the mine foot print plans for analysing the seismicity trends above and below the footprint. I have used the mining data to define the cave volumes, so it was possible to analyse the seismicity trends inside and outside of the cave volumes and then compare them with each other. The caving progress from a physical point of view is basically a progress of fracturing. This fracturing in case of mass mining involves large volumes of rock mass. This fracturing 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's 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 and it may also cause disruption to the production cycle. Over 90% of the seismic input consists of small or very small magnitude size events and 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 providing that the processing software is consistent. 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. If the two data subsets divide the entire seismicity for example 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. Furthermore 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) 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. Analysis of trends and changes in time in percentages of seismicity, released seismic energy and seismic deformation taking place for example above the mine already proved to be a very reliable indicator of the caving process.

For the presented results of the seismicity analysis to have credibility, it is fundamental that caving milestones were also evidenced by other means and not just by seismicity alone. Certain consistency of seismic results might be 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 more incidents of generally the similar nature (for example, the cave breaks through) cannot be exactly the same. Presented analyses not only illustrate the fact that seismic data analysis can be used successfully 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 consist of all recorded data like in the cases of energy index time histories, or only rates of released seismic energy or seismic moment are used, 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 changes in the seismic activity rates were important, even when seismic migration trends were analysed only the monthly average seismicity elevations were taken into account. Again in these 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. Such ideal sensor configurations are often not possible to implement due to technical problems but are also not warranted from the expenditure point of view.

Some of the presented analysis resulted in establishing a more general criterion for seismic monitoring of the caving process. The initiation of the caving process is the first milestone of the caving process. It was recognized as taking place in three mines. 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 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 also evidence the occurrence of the initiation.

Analysis and interpretation of seismic data originating from several caving operations resulted in identification of characteristic seismic signatures for each of the caving stages followed by a description of the resulting impacts on underground safety. The five cases selected were PMC, Northparkes Lift 2, El Teniente Diablo Regimento Sector, El Teniente Esmeralda Sector and PT Freeport DOZ Mine. All four mines used the ISS seismic system and hence the estimated source parameters were directly comparable as are the magnitude values. It was assumed that study of mine seismicity induced in different mines is important for gaining a universal understanding of the caving process. Research based on this data allowed for:

1. Analysis of seismic data with a focus on improving the general understanding of the caving process and caving mechanisms.
2. Determination of seismic indicators characteristic of the various stages of the caving process
3. Determination of relationships between various stages of the caving process and associated seismic hazard.
4. Creating a practical methodology for mine practitioners to monitor the caving process using seismic data.

Presented analysis and interpretation contributed towards not only improved understanding of the caving process but also in establishing methodology based on recorded seismicity for monitoring the caving process for mine practitioners.

My mine seismology trilogy consists of the following books:

1. Glazer SN (2016) Mine Seismology: Data Analysis and Interpretation. Palabora Mine Caving Process as Revealed by Induced Seismicity ISBN 978-3-319-32611-5, Springer International Publishing, Switzerland

2. Glazer SN (2017) Mine Seismology: Seismic Warning Concept. Case Study from Vaal Reefs Gold Mine, South Africa ISBN 978-3-319-62352-8, Springer International Publishing, Switzerland
3. Glazer SN (2018) Mine Seismology: Seismic Response to the Caving Process: A Case Study from Four Mines ISBN XXX-X-XXX-XXXXX-X, Springer International Publishing, Switzerland.

First book published during 2016 describes my practices in monitoring the caving process at Palabora Mining Company. Action of this book takes place between 2002 and 2013. The second book published during 2017 describes my knowledge of seismicity in deep gold mining in South Africa. This book covers years from 1988 to 2000 when I was employed by Vaal Reefs Gold Mine as a seismologist. In time, the action in the second book took place before that described in the first book. The final part of seismic trilogy is based on my experience as an independent Mine Seismology Consultant from 2004 until 2012. During that time I worked for: Rio Tinto, Palabora Mining Company, LKAB Sweden, Telfer Gold Mine Australia, New Afton Canada, Potgietersrust Platinum's Ltd South Africa, PT Freeport Indonesia, El Teniente Codelco, Natural Hazard Centre, Pretoria University, South Africa. This last part describes my research I conducted for Mass Mining Technology Project II (2009–2012). My research project was titled: "Seismic signature of the caving process". This project involved analysis and interpretation of seismicity recorded at El Teniente, Chile, PT Freeport DOZ Mine, Northparkes Mine Lift 2 and PMC. The aim of this research was to make maximum use of the recorded seismicity to monitor and manage the caving process.

Looking back at what I wrote I feel in some way embarrassed. Everything I presented in my three books seems to be very uncomplicated and simple. The most complicated tool used in this research was the concept of energy index. Second most difficult element is the percentages perception. It seems that what I consider to be research does not come close to genuine research. Because of that, in the past I wanted to tackle more complex matters that would result in development of brand new and intricate tools. For example, I tried to solve the multidimensional problem: in how many dimensions do I live? After some very tortuous and convoluted calculations that I did not really understand I came to a very perplexing result. The universe is six-dimensional but there is no fifth dimension. In fact, there is this fifth dimension but it is put aside. It is strange as this result was known already many years ago in 1935. This discovery was made by two Polish poets Słonimski and Tuwim and was then published in their book titled "In fumes of absurd" but only 40 years later. They did not understand the importance of their discovery and being poets they thought that it was amusing. So there we have the result and its elucidation or discernment is so austere that it doesn't require any attestation. So this was a dead end. Then I wanted to contribute towards better understanding of what was happening in the PMC cave after the failure of the open pit North Wall. The consequence of the pit wall failure is the potential sterilization and dilution of up to 25% of the original mining reserve (Glazer and Townsend 2008). This indicates the severity of this matter. My first idea was to model this situation. I was thinking about creating a physical and then a mathematical model. I give up after realizing that I already have a ready physical model at home. The model I am thinking of is the container of dog's food. I buy this food in plastic bags that contain seven kilograms of pellets. At home, I empty the plastic bag into a plastic container. I then feed them every day, dishing these pellets out from the container. There are no small crumbs to start with only full size pellets. When the food in container comes to the end, there are small crumbs to be seen at the bottom of the container. They are there not because they are squashed pellets because they found themselves covered by 7 kg of other pellets. These crumbs migrated downwards from all places in the container and this migration process started once the pellets were in the container. This is exactly what was going on in the cave. The small size rocks from the failure containing no copper were migrating down as they could make use of the space between the cave's large rocks containing copper ore. At this stage, I abandoned the project as I could not mess with my dog's food. I had to find something different to focus on for example what about predicting larger size seismicity in the mines. Why not and if I would be successful I would become famous. So many already tried and failed. Their reason for this fiasco was the angle from which they tried to tackle this problem. All I needed was an innovative starting point. In the old days, the coal miners used birds for detecting poisonous gasses in the working places. When going underground they would take the birds in cages with them. They then hang the cages as high as possible under the hanging wall. As long as the bird stayed alive all was well. If it died this was because of the gas concentrations under the hanging wall and this then indicated that now it could be their turn to die if they stayed underground. From this, I got an idea of using animals as they have better senses than us humans and maybe they could sense if there was to be an imminent tremor. In coal mines, I observed rats but they were small and few in numbers, they also had the habit of hiding and they were only visible while consuming your lunch, that you left hanging on the side wall. It is believed that rats can sense danger and take steps to avoid it for example leaving a sinking ship. They do it before the crew even notices the danger. I have read that in China it was noticed that before a large earthquake there was a massive exodus of frogs. Keeping frogs in the mine, for many reasons doesn't seem a practical idea as there would need to be thousands of them. It would be impossible to bring them all up, after the end of the shift. So they would have to be kept and feed underground to stay alive. This would then be a new and complex problem to solve. In a film about eruption of the famous Yellowstone National Park volcano there was a massive exodus of birds. Still the big eruption did not take place as the brave seismologists together with a brave park ranger managed to stop the eruption. So the birds' instincts were wrong and for this reason, they cannot be used to predict seismicity. I read somewhere that the elephants can communicate using seismic waves which they can generate and receive. In this note, it was mentioned that they probably can predict earthquakes. Well I live in Phalaborwa close to the Kruger National Park. There are still thousands of elephants in the park and the tourists would not notice if a few went missing. It could be possible to use a skip to transport them underground and then back to the surface after the shift. It would be impossible to keep then underground for longer as Animal Rights Organisations would object and protest. Just imagine that elephant rumble could be a signal for immediate evacuation of the underground working places. If it was possible to teach an elephant to predict, let's say at least 1 h before the event, then it would be possible to save the whole work force. Such success rate is not possible in a scram situation when the warning only sounds when the event is already taking place. I know that predicting future large seismic events is not possible. So what about predicting the past? It turns out that this again is extremely difficult if not impossible. The past is history and life indicates that predicting history is not possible as history is in process of continuous change. For example, today's hero turns up to be in fact not only a traitor but also a disgusting one.

So if for so many reasons as explained above I was not able to any basic research and develop complicated tools was my research genuine? What is genuine research? Typing into Google "Genuine research" I found the following: "Many students believe that doing research means copying facts and quotes from various sources, reorganizing and paraphrasing that information, typing it up, and calling it "research." This superficial approach to research merely reports and summarizes what is already known and goes no further. Genuine research, however, is a far more creative and challenging process. You are doing genuine research—i.e. not merely summarizing what is already known—when your research aims to answer a unique, appropriately narrowed research question. In other words, the key to doing authentic research is to find something that you think is worth investigating put it in the form of a question, and make that the focus of your research". From this, I gather that genuine research starts with a question which then can be turned into an idea.

(http://accounts.smccd.edu/wolbers/lsci100/lesson2_3.htm).

In my case, the first question I asked as early as 1990 was how to make use of all of the recorded seismicity in the analysis and interpretation process (Glazer 2017). The answer or the idea was the apparent stress index concept. At that time, the mine had severe problems with underground safety due to seismicity. This then was the rationale for the next question, can the index be used to solve or at least reduce this problem. I then started testing various concepts of analysing the recorded seismicity. It then appeared that some of these concepts might be useful in combating seismic hazard. The seismic system in existence at the time of recording data was not good enough to provide required data. A test system with specific parameters had to be installed in an area know for seismic related damages. This required finances and support from management team. Having gained both, a test seismic system was installed at 5B area on Vaal Reefs No 5 Shaft. Over a course of a year the experiment proved that, not only the concept of seismic warning was working but that the recorded seismicity could be used to improve underground safety standards. For this reason what I described in my second book (Glazer 2017) fails under the concept of genuine research. The experimental subnetwork of eight stations at the 5B area became fully operational in September 1994. The first seismic warning was issued on 8 October 1994, and an event occurred in the expected area three days later. The test area covered by the experiment was 1.5 × 0.5 km in size (750, 000 m^2). An average polygon for which a warning was given covered an area of 60,000 m^2 which represented 8% of the whole test area. From the seven warnings issued from the end of October to the end of December 1994, four ended in events of local magnitude above 2.5, and in two cases the underground working places were found to be too dangerous to continue mining and as a result were abandoned. With one warning still in place, it became clear that a procedure for handling this type of information had to be formulated. Giving a seismic warning had at least two practical consequences. It indicated that a larger size event (or events) could be expected, but on the other hand, it also allowed for continuous monitoring of the situation. There might be ways of reversing the situation and enough time for taking some precautionary actions. As the introduction and use of the seismic warning concept in the 5B area was becoming practical from the seismic point of view, and the record showed that the method had credibility, some follow-up procedures had to be implemented. These procedures had to have two separate elements. The first was communicating the information, and the second involved the actions that had to be taken by those responsible for safety and production. By February 1995, a procedure for handling seismic warnings was approved by mine management and put into practice. This procedure described preventive actions that had to be taken in all working places under seismic warning conditions. It also identified the person responsible for introducing them and described the control procedures. By the end of 1995, Vaal Reefs Gold Mine had established a clear concept for a seismic monitoring strategy. This concept was based at one central site, serving all Vaal Reefs shafts and mines and connecting all subnetworks and networks together. Consequently, the central site was rebuilt and equipped with new computer technology. A decision was taken to employ more staff in the seismic department. From June 1994, the seismic central site was manned 24 h a day, on a three-shift basis. This resulted in improved processing quality of all recorded seismic events, but more importantly, all events of damaging potential were immediately reported to the shafts. This allowed them to send proto teams without delay straight to the affected areas.

From the beginning of this experiment, Vaal Reefs senior management adopted a philosophy that the success rate should rather be measured by preventive actions taken rather than by the success of the warning itself. Several preventive actions were put into practice that included additional safety pillars, changes in mining sequences and directions, and a review of the mining strategy for the whole area. Vaal Reefs' rock engineers, as well as mine management, had no problem with the fact that seismic warnings were only limited to indicating an area where, at some future time, a large-sized seismic event might take place. It was well understood that the timing and the event sizing are impossible to predict and that this is not even the ultimate goal of the experiment. There had to be and were cases in which a seismic warning turned out to be false. No one blamed the seismologists or had second thoughts about the accuracy of the concept. The following example illustrates the attitude at the mine. This example describes the follow-up procedure following issuing a seismic warning in a polygon TRIBUTE2. At the time, this polygon included underground working places of mining section 56. It was found that all the panels in this section were mined in proper sequence and all of them had second escape routes in place and that they were clear. It was then decided to implement, with immediate effect, existing recommendations with regard to the use of two rows of hydraulic props with headboards in every working place. This recommendation, at that time, wasn't implemented due to a shortage of those props, but steps to overcome this problem became a priority. An underground inspection within the next couple of days was to take place to ensure that the recommended support was in place. The warning was then cancelled. The follow-up actions that were taken improved the underground safety standards and were therefore not a wasted effort from the point of view of the mining personnel. The experimental seismic network was used for more than just issuing seismic warnings.

The next example involves blast-timing and mining strategy changes for working places located along the Vos Dyke (Glazer 2017). Dykes in the 5B area were known for their seismic activities, and the Clemcor Dyke was called the "Killer Dyke". During May of 1995, a warning was issued for a workplace, located close to the Vos Dyke. After eleven days, two large-sized events occurred within 12 min of each other. Two days later in the same area, two people were killed due to a rock burst from the Vos Dyke, which was much closer to the face than the plans indicated. This rock burst resulted from blasting the panels located along the Vos Dyke on a different shaft, away from the place of the accident. In June 1995, a seismic warning was issued for an area also located along the Vos Dyke. As a result, the panel was stopped and drilling indicated that the dyke was much closer to the face than expected. Probably because of this, the mining in that location was then stopped permanently and the event did not take place. This is an example of an extremely successful warning, in spite of the fact that it was not followed by a seismic event. In this working place, located too close to the dyke, seismic event could have injured or killed people, as the recorded seismicity indicated that the dyke was highly stressed. Based on this type of information, it was decided to scrutinize blasting times for mining areas in the vicinity of the Vos Dyke. At that stage, that time varied from 14:10 in the 2 K area of No 2 Shaft to 16:10 in the 5B area at No 5 Shaft. In order to minimize the risk, it was then recommended that the earliest blast time be 15:20 for all production sections. This recommendation was then put into practice, and to date (May 1997) there were no fatal accidents associated with the Vos Dyke. It was also decided to minimize the number of working places that were located along the same seismically active fault or dyke. Another example is connected with analysis of seismicity at No 5 Shaft for the period February 1995 to July 1995. It was noted that there was a significant change in the pattern of seismicity in July, in comparison to the time period from February to June. It was then concluded that that the then-present method of mining is locking up the faults and dykes, not allowing the release of energy in a continuous manner. Safety and bracket pillars were designed, and, in general, mining towards dykes was stopped. Mining directions were changed to run along the dykes. In order to decide the pillar sizes (between the working places and the dyke), intensive drilling works were started immediately.

These two actions that resulted in increased underground safety were due to the fact that the area had good seismic cover and that the mine's professionals were making use of the recorded data. These examples indicate that it will be never possible to achieve such results by analysing only seismic data at a remote place from the mine. The No. 5 Shaft experiment was a success because it was supported in an active way by the mining and rock engineering personnel. Despite the fact that the seismic warning concept at the time was not a fully reliable management tool, its potential for underground safety improvement was recognized by management. This then resulted in the implementation of this concept over the entire Vaal Reefs mining area. It was a costly decision regarding capital expenditure and running costs.

My first book (Glazer 2016) explains and demonstrates other applications not only of the index but of other genuine seismicity parameters. During 2002, my question was: can the recorded seismicity be used to monitor the caving process and the related seismic hazard. It took time and effort. The mine had to come with capital to upgrade the existing recording seismic system. As a result, at present, there is a methodology available on how to use the recorded seismicity to monitor the caving process. It is described with a lot of detail so it can be used by others. This in my opinion is an example of genuine research that was followed up by implementation. Seismicity was 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 not only the development mining was still taking place but 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 analyse separately.

The start of the gravity caving (October 2001) resulted in a steady increase of seismicity locating at the caving elevation. With the mining still taking place in the open pit, there were some seismicity elevation decreases which become evident when observing the average monthly seismicity elevation trend. Still, this downward seismicity migration was not real. It was the result of two separate processes. Firstly present was shallower mining process (from the open pit) which induced 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 becoming the main mechanism of induced seismicity. During the gravity caving, the energy index time history graph remained low and 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.

Once the hydraulic diameter reached the size of 42 m, the stress caving process was initiated (May 2002). This was very strongly reflected by the induced seismicity. Initiation of the stress caving process is a very powerful physical phenomenon which was recorded by the seismic system very precisely. The initiation of the caving process took place inside of the seismic network. As a result, it was well 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 blasting times. The cave mining induced seismicity did not follow the same 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 upward 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 of 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 the difference between the position of the seismic zone and the estimated cave back position. The estimate of the cave back position was based on the production rates and subsequently 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 begin 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 further locations 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, but also because 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 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.

At the time of the crown pillar failure (end of 2002), the upwards migration of seismicity comes to an end. This resulted in seismicity starting to migrate downwards 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 had affected the stress distribution around the mine on a regional scale. The 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 becomes 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 threefold increase in relatively large seismic events.

The time period between the crown pillar failure and cave 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 a 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, the rock mass below the mine was not influenced by the caving process. This rock mass 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 they reached 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.

The initial break through (May 2004) 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 was 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 was more strongly associated with the caving process (it started to appear only after the pillar failure). It seems that after some time a relationship develops with the mining rates. 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 deeper and just after the initial break through, it reached its maximum depth.

At some stage, the caving process reached (end of 2007) its maximum stage as the fracturing of the rock mass due to the cave progress cannot go on forever 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 does not mean that there no longer was seismicity with high energy releases. It is true that at this stage, the caving process had already left the rock mass well fractured around the cave. However, it cannot 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. That is why by the end of 2012, the energy index time history indicated a stress increase.

The east break through took place only after the caving process reached its mature stage. The data presented up to this point 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 was the correct technique to gain a better insight into this break through process. The initial break through was a 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.

As everything has to come to end so too has the caving process (end of 2012). At this stage, all of the recorded seismicity was taking place close to the mine and below the mine elevation. This seismicity was induced only by the mining and no longer by the caving process. This was easy to prove by analysing the 24-h 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 proof that the caving process is no longer there.

To complete this discussion, there is still one important matter that needs to be addressed, namely the parameters 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 interdependency of these parameters. If the parameters used 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 one 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 proof, independent of each other's results and they complement each other in the process of their interpretation. In all analysis, I have used two types of parameters. The first one being 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 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 and with the progress of the caving process. This observation leads to the logical conclusion that analysis of the production and seismicity relationship contributes towards independent results.

This last part of my seismology trilogy, namely this book also started with a question. Is it possible to develop the already existing seismic method for cave monitoring into something more universal that would be of general nature and not related to one case or mine? Presented in this book results indicate that seismicity can be used for monitoring the caving process and related seismic hazard at any mine. This then is also genuine research.

I do not have to feel embarrassed that my research ended with developing some very simple tools. These uncomplicated tools which were in existence before I become a mine seismologist were used to solve complicated and complex problems. When research ends with very complicated super tools then it is easy to forget what they are for. It seems that such tools then have a life of their own in which then they must be maintained nonstop by adding life support apparatuses to keep them going. They also require plastic surgery to keep then beautiful and attractive.

What is the future of mine seismology? There are two options: mine seismology performed from outside of mines by a contractor that offers a wide range of services (Mendecki et al. 2010); or at the mines by mine personnel. This last is well described by Knobben (2017). The Rosenbery Mine (Tasmania) uses a seismic system purchased from Institute of Mine Seismology in 2013. The recording system consists of 26 geophone recording stations. “Over time, changes in mining sequences, depth and geology led to changes in the seismic hazard at the mine”. This paper lists the following methods used for estimating the seismic risk:

- Post firing events decay
- Spatial plotting of events
- Frequency–magnitude analysis
- Apparent stress time history
- Focal mechanisms
- Estimation of peak particle velocity.

It is clear that the connection between mining, geology and seismic risk is regarded as very important. What is significant to me is that this paper describes not only the applied methods but the cooperation between various mining staff (including management) in reaching the goals. This last is very important and I know this from practice (Glazer 2017). For me this is a happy ending to my mine seismology trilogy. There are still mines that practice mine seismology in a way that allows it to exist as an important tool to reduce the seismic risk. I know from personal experience that there are more such mines that have the same idea of applied mine seismology. Rosenbery version of applied mine seismology is very different from that described by Mendecki et al. (2010). In this paper, we read that “Routine seismic monitoring in mines enables the quantification of exposure to seismicity and provides a logistical tool to guide the effort into the prevention and control of, and alerts to, potential rock mass instabilities that could result in rock bursts”. As routine, the paper lists

Fig. 5.1 Elephants at the Sable Dam Kruger National Park

among others: seismic strain, stress and stiffness: seismic viscosity and relaxation time; seismic diffusivity and Schmidt Number, seismicity and stability. There is no reference to mining rates, geology or any other geotechnical data. It is very interesting to note that while the first paper was written during 2010, the second one based on concrete mine practice was written during 2017. This proves that presented during 2010 as fully developed routine methodology for some reason did not find much of in a way traction in practical application. "Tertium quid" doesn't seem possible. I would like to see a renaissance of mine seismology. For it to take place, a lot of present practice must change and change significantly. For a start with mine seismology to be of benefit to the mine, it must be performed at the mine. Mine seismologist (not virtual seismologist) must be an expert with appropriate background (geophysics). He must be employed by the mine manager or technical manager and should not be part of the rock engineering section. Unfortunately, he must also have his own budget. This will result in some administrative work but it is important for him to be independent. Rock engineers very often want to be well regarded by management and so they try to save on their budget and seismic is first for the cut. The recording seismic system must use triaxial geophone probes. Geophones are very robust and work for years. The seismograms must be three components in order to estimate the seismic moment and seismic energy. The mine seismologist must have full control over the quality of the data processing and over the seismic database. His work as a seismologist is a full time job and there should be no compromise in this point. He must understand the rock engineering and mining problems and be part of the mining operations on daily bases.

Finally, I do not want to leave any unaddressed matters. In the foreword to my first book, Prof Andrzej Kijko pointed out that my book has a weak point. This weak point is the lack of a photograph of an elephant. Palabora Mining Company is an immediate neighbour to the Kruger National Park. For this reason, elephants sometimes roam on the mine premises. Unfortunately, I do not have such photograph so instead, I present a photograph depicting a herd of elephants. This photograph

(Fig. 5.1) was taken less than 20 km from the mine by my friend Lonek who is not a seismologist but he is a bit of a character.

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