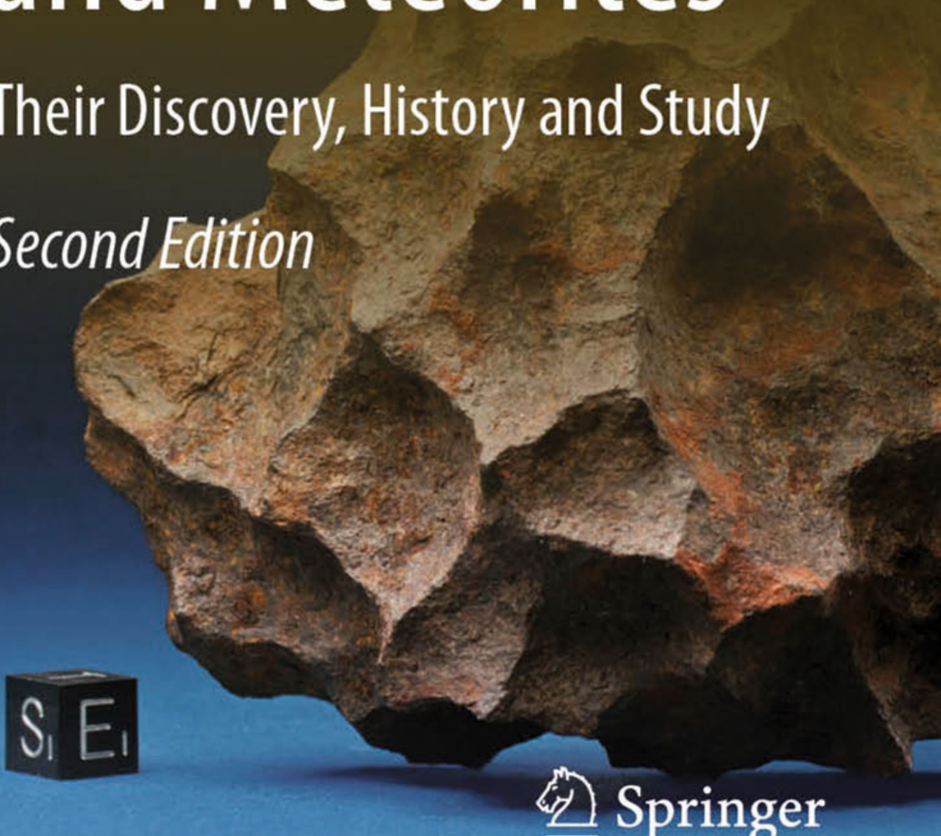
GeoGuide

Svend Buhl · Don McColl

Henbury Craters and Meteorites

Their Discovery, History and Study

Second Edition



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GeoGuide

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Franz W., Paris, France

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“Henbury.” Individual of 2,260 g from the Southwest Meteorite
Laboratory Collection curated by Kitty & Marvin Kilgore.
Photo: Regine Petersen

PREFACE

The recognition, in the early 20th century, of the Henbury Craters and associated meteorites has played an important part in our understanding of the process of impact cratering and effects on the surrounding environment and on the impactor itself. Whilst the Henbury Craters may not be the largest or best known, their excellent state of preservation has allowed for detailed studies of the morphology and geological context of a rather complex crater field. The large amount of meteoritic iron, impact glasses and impactites that have been recovered have enabled many detailed geochemical studies elucidating our understanding of the Henbury meteorites – from their formation early in the Solar System's history, about 4,560 million years ago, to their eventful arrival on Earth only ~4,200 years ago. In more recent times, the Henbury Craters have played an important part in the human exploration of space. In the 1960s the geologist Daniel Milton carried out an extensive geological and morphological study of the craters as part of the US Apollo program, using the Henbury crater field as a terrestrial analogue for lunar craters.

The risks and dangers associated with the arrival of large meteorites is increasingly being recognised. Of course, many Hollywood blockbusters, such as Deep Impact, have visualised and dramatized the effects of >kilometre sized bodies impacting the Earth, with disastrous results for the major characters and the rest of life on Earth! However, even relatively small objects in the size range less than 50 m in diameter can cause major damage and, if occurring over a populated area, could cause a large number of fatalities. For example, the air burst and resulting shockwave of the Chelyabinsk meteorite on the morning of 15th February, 2013, injured over 1,000 people in the city of Chelyabinsk in eastern Russia. This object entered the Earth's atmosphere travelling at ~18.6 kilometres per second and is estimated to have been between 17 and 20 metres in diameter. It exploded at a height of 23 km with the explosive energy of ~440 kT, the equivalent of 30 Hiroshima-sized atomic bombs. The resulting shockwave from this huge blast was the cause of the damage and injuries to the citizens of Chelyabinsk. Many people had gone outside after witnessing the fireball and to look at the spectacular smoke and vapour trail. Unfortunately for them, two and a half minutes later the area was hit by the shockwave from the explosion, resulting in many injuries from flying glass. Whilst the Henbury impact occurred over 4,000 years ago, there is good evidence to suggest that this spectacular event was also witnessed by the local Aboriginal people and is recorded in their oral traditions and sacred stories.

The Natural History Museum in London is privileged to curate one of the most significant collections of Henbury meteorites and impactites as well as a large amount of correspondence from Robert Bedford regarding his expeditions to the area in the 1930s. This material still has scientific and educational impact today, with Henbury specimens from the NHM being sent to researchers around the world to study the formation conditions and history of the IIIAB irons (the classification of the Henbury meteorite) and used in exhibitions seen by the Museum's 5 million yearly visitors.

This second edition of 'Henbury Craters and Meteorites - Their Discovery, History and Study' is a comprehensive and well-researched work covering all the major aspects of these fascinating, important and unique craters.

Dr. Caroline Smith
Curator of Meteorites, Natural History Museum, London

CONTENT

IN 1931,

the cluster of craters at Henbury Cattle Station south of Alice Springs in Central Australia was one of the first places on Earth where a group of impact structures could definitely be linked to the fall of iron meteorites. It was also the first place where radial rays and loops of ejected rock material, comparable to those seen around craters on the Moon, were observed. As such it was one of the primary observation sites associated with the science of meteoritics in its infancy. In this work the authors present previously unpublished documents covering early research at the Henbury site, provide an extended data set on the distribution of meteoritic material at Henbury craters, and compare recent discoveries on the mechanics of hypervelocity impacts with evidence collected over 80 years of research at the Henbury meteorite craters. In their conclusion, the authors suggest a new hypothesis for the fragmentation and incident direction of the crater forming bolide, on the basis of a more complete set of data compared with previous models.

Henbury meteorite of 1,740 g. The compact specimen exhibits sharp edges and exaggerated regmaglypts. These effects of chemical weathering are characteristic of Henbury meteorites embedded below the soil or recovered from the beds of the creeks and drainage channels. This piece was found in the main scatter ellipse about 2.5 kilometers northeast of the main crater. (Buhl Meteorite Collection # B-393). Scale cube is 1 cm. Photo: S. Buhl

EARLY PIONEERS

S. Buhl, D. McColl, *Henbury Craters and Meteorites,* GeoGuide,
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The written history of the Henbury meteorite craters begins with the brothers Edmund William and Walter Parke, who came to Australia for the sake of colonial adventure in the second half of the 19th century. In 1877, the Parke brothers founded a cattle station near the dry course of Finke River, some 120 km south of Alice Springs, and named it after their home estate Henbury in Dorset, South England.

In 1899, Walter Parke reported a peculiar discovery to the anthropologist Frank J. Gillen, who at that time was the officer in charge at the Alice Springs Telegraph station. Parke told Gillen of "one of the most curious spots I have ever seen in the country". He was referring to a group of circular and oval depressions which he had found 11 km southwest of Henbury station. Puzzled by their origin, Parke described the craters to Gillen: "To look at it I cannot but think it has been done by human agency, but when or why, Goodness knows!" (NT Government 2002).

Additional evidence indicates that the craters were known to land surveyors in the early 20th century. Spencer, for example, expressed surprise to find the exact location of the craters marked on plate 105 of the Times Atlas which was published in 1922 (Spencer 1932 a).

About 30 years after Walter Parke's mentioning of the Henbury craters, in January 1931, the prospector J. Max Mitchell of Oodnadatta, sent a meteorite fragment of

"Kyancutta Museum party's camp on Winzor Creek, outside Water crater. The man with the camel is the cook of Henbury station." The wall of the main crater, the "Double Punchbowl", can be seen in the background. Photo taken on Robert Bedford's 2nd trip to the Henbury craters, in March 1932. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p several pounds weight accompanied by a letter to Professor Kerr-Grant at the University of Adelaide. In his letter Mitchell informed Grant of the presence of five craters with scattered iron fragments near Henbury Station (*Sydney Morning Herald*, 1931). Mitchell stated that there were signs indicative of a large meteorite having fallen "many years ago" at the site. Mitchell was not only the first to correctly recognize the cosmic origin of the Henbury meteorite craters but was also the first to report the Aboriginal name of the site: "chindu chinna waru chingi yabu", meaning "sun walk fire devil rock" (Spencer 1932).

Mitchell would have been a rich source of additional information on the Henbury craters and their history, if only anyone had bothered to ask him the right questions (Apparently Robert Bedford did so in 1932, but only one brief quote found its way into Bedford's report). Three years after his letter to Professor Kerr-Grant, Mitchell shared some of his recollections about the Henbury site in a letter to the Adelaide newspaper *The Advertiser* (Mitchell 1934). According to Mitchell, the Parke brothers knew of the craters prior to 1916, as did the late A. John Breaden, who took over Todmorden station from the Parke brothers in 1902.

Mitchell recalls a trip to Todmorden station in 1916, where he, "while fixing up tools in the blacksmith's shop", noticed a slug of metallic iron which displayed a "ribbonlike structure". He concluded that it contained nickel, and, on request, he learned that "it came from the blowholes at Henbury". This occasion was not the only one when blacksmiths had tried to work the iron collected at Henbury. Mitchell recalled that at least one other blacksmith, Charley Flemming of Oodnadatta, had forged a piece of the metal from the craters.

As an avid mineral prospector, Mitchell was aware of the existence of meteorite craters and their general appearance. When Mitchell visited the Henbury craters, some time after his visit to Todmorden station, he found his theory on the meteoritic origin of the site confirmed. Furthermore, he not only recognized the general orientation of the strewn field, but also correctly interpreted the meteorites found at some distance from the craters as masses with an individual flight history: "The largest pieces of metal were some distance northeast of the craters, as though they had dropped from a molten mass falling at great speed." His assumption however, that large masses of iron lay buried in the craters, was wrong. As those familiar with the history of Meteor Crater in Arizona know — and to Mitchell's credit — the notion that large meteorites were buried beneath the bottom of meteorite impact craters was a very common misconception at the time.

In April 1931, three months after Professor Kerr-Grant had received Mitchell's letter and meteorite fragment, Bryan Bowman, manager of the Tempe Downs Station, independently called upon Professor Kerr-Grant and told him of three craters near Henbury Station. Kerr-Grant, who was largely instrumental in discovering the meteorite that had recently fallen at Karoonda, reported the find to the Museum authorities and urged that it should be investigated. Grant was supported in his efforts by the famous Sir Douglas Mawson, who at the time was Honorary Mineralogist to the South Australian Museum. The Karoonda meteorite incident had stirred a fair amount of interest in cosmic matters throughout Australia, so the timing for another meteorite discovery was opportune.

After a search for a daring and qualified individual willing to undertake the strenuous journey into the outback and able to conduct a scientific survey of the craters, the choice fell upon a young lecturer at Adelaide University, Arthur

“Mawson at Mt Eba. Burra Creek geological camp”. The photo was taken during a field trip in May 1922, and shows (left to right): Professor Sir Douglas Mawson; Dr. Arthur Alderman; Dr. Cecil Madigan; R.G. Thomas, and Mr. Pierce, Manager “The Gums” station, Mt Mary, S.A. Arthur Alderman succeeded the famous Sir Douglas Mawson as Professor of Geology at the University of Adelaide in 1953. Photo: Oliphant Papers, Barr Smith Library, The University of Adelaide, MSS 92 O4775p

Richard Alderman. Alderman was not new to meteorites, since at that time he had already completed the description and chemical analysis of the Karoonda meteorite which had fallen in November of the previous year (Grant 1931).

Together with a fellow lecturer from the chemistry department of Adelaide University, F.L. Winzor, Alderman accepted the task, and the two started out on the 1,380-kilometer-long journey to Rumbalara on the Alice Springs railway line in May 1931. From there the party continued another 160 kilometers by motorcar through Horseshoe Bend and up to Henbury Station at the dry watercourse of Finke River. A final journey of 11 kilometers took them to the craters, where they camped for two weeks during their investigation.

Photo of the "Punchbowl" or "Double Punch" showing the untouched state of the main crater at the time of its discovery by western settlers. The original caption reads "Another view of Main Crater taken from N.W. rim & looking S.E." Photo taken by Robert Bedford, 1931. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

"Camel team bringing stores to Henbury [Station]". The picture gives a good idea of the problems and hardships a trip to the outback involved in the 1930s. Photo taken by Robert Bedford in 1931. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

“The Water Crater. View inside taken near the mouth of Winzor Creek. The ridge at the back is the wall between the Water Crater and Main Crater.” Like the photo above, this shot was captured by Robert Bedford during his first expedition to the site in August 1931. Photo: Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

ALDERMAN'S SURVEY

"Henbury looking into main crater". This historic photo of the "Double Punchbowl", taken by Robert Bedford during his first expedition to the site in August 1931, was captured only two months after A.R. Alderman's initial expedition to the crater field. Photo: Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

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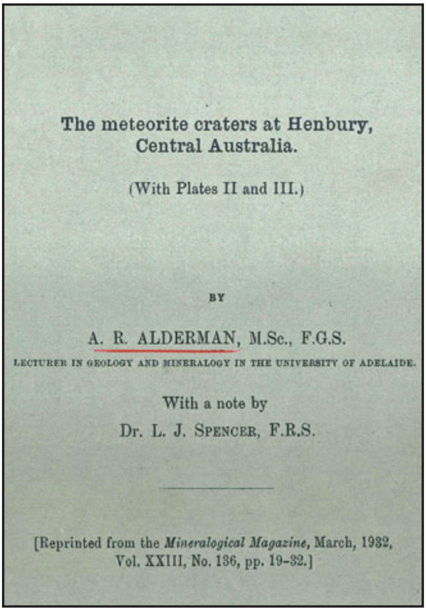
Arthur Richard Alderman photographed in 1960 when he was professor of Geology at Adelaide University. Photograph by Dr. Timothy O'Driscoll, Earth & Environmental Sciences Collection, University of Adelaide

Under the headline "Craters Discovered – Made by Meteorite", Alderman's successful mission was published in the 10 July, 1931 issue of *The Sydney Morning Herald*. While later reports credit Alderman with the scientific discovery, *The Sydney Morning Herald* still attributed the initial discovery and report to prospector J.H. Mitchell. The newspaper article ends with the suggestion that the institutional authorities should declare the site a national reserve.

On 3 November 1931, Alderman gave his account before the Mineralogical Society, and in December he published a first preliminary description of the craters in *Nature*. His full report, including a map of the crater field, which also gave the distribution patterns of the meteoritic fragments collected close to the craters, was published in March 1932 in the *Mineralogical Magazine*.

Alderman's designation of numbers to the craters has been followed by researchers up to the present day, this publication



The meteorite craters at Henbury,
Central Australia.

(With Plates II and III.)

BY

A. R. ALDERMAN, M.Sc., F.G.S.
LECTURER IN GEOLOGY AND MINERALOGY IN THE UNIVERSITY OF ADELAIDE.

With a note by
Dr. L. J. Spencer, F.R.S.

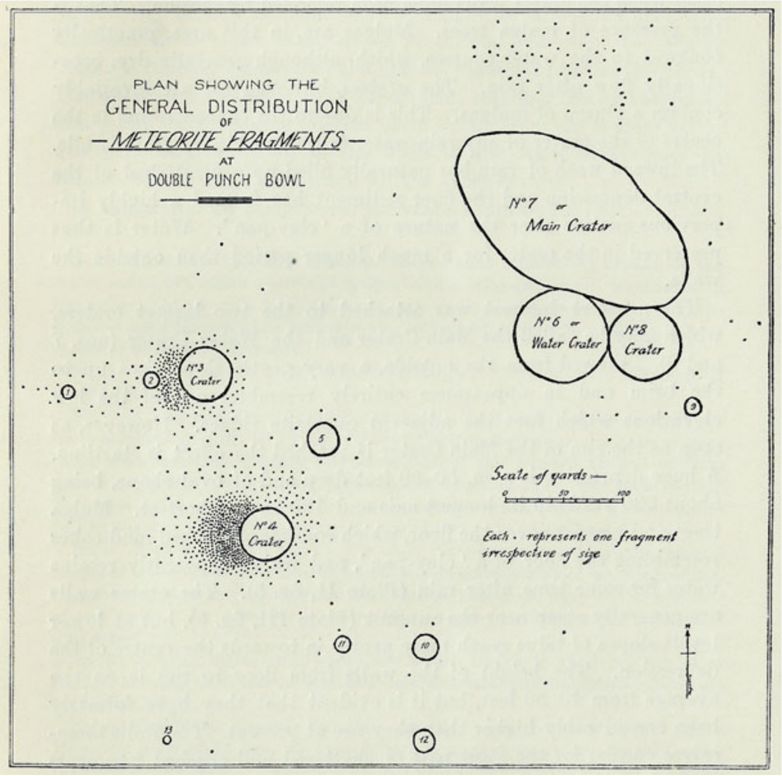
[Reprinted from the *Mineralogical Magazine*, March, 1932,
Vol. XXIII, No. 136, pp. 19–32.]

included. Alderman's account can be considered a major milestone in contemporary meteorite and impact crater research.

Alderman noted that the site was known among local settlers by the name of Double Punchbowl, referring to the two largest adjoining craters. Within an area of 500 by 500 yards, Alderman had mapped thirteen craters: "The largest is oval in outline, measuring 220 yd. by 120 yd. across, and with a depth of 50–60 feet. The other craters are roughly circular, with diameters ranging from 10 yd. to 80 yd." Crater no. 9, which is a small structure southeast of the three main craters (no. 6, 7 and 8) was considered a "potential" impact structure by Alderman and is often ignored in later publications. Alderman himself speaks of "at least twelve probable craters" (Alderman 1932).

In his account, Alderman gave a thorough topographical and geological

Henbury shrapnel (33.8 g, collection Klaus Becker). This specimen is typical of many hundreds of twisted and torn "slugs" which Alderman collected around the craters, particularly west of craters no. 3 and 4. Most of these meteorite fragments, like the one pictured, were found on top of the surface. Photo: S. Buhl



"Plan showing the general distribution of the craters and of the meteorite fragments around them." Fig. 2 from "The meteorite craters at Henbury" (Alderman 1932, front cover shown on opposite page)

description of each crater and also provided cross-sections of the main crater. While mapping the craters, Alderman came upon a number of shallow ridges radiating away from the craters, particularly near crater no. 3. Alderman interpreted these features as "percussion figures" and noted that some of the craters on the moon show similar radiating ridges. He concluded: "This may perhaps lend some support to the theory that the lunar craters are of meteoric origin" (Alderman 1932).

Alderman also reported on numerous pieces of metallic iron scattered around the craters. Most were "usually angular in shape", while others seemed to have fallen as "complete units". He noted that the torn and twisted fragments in particular, displayed obvious effects of shearing stress.

The meteoritic masses collected ranged in weight from only a few grams to 24 kg. In some places near the craters meteorites were densely scattered: "In one area of 6 ft. by 6 ft. more than a hundred fragments were collected". Only two masses (one of 6 kg) were found within the crater walls. Most shrapnel around the smaller craters was scattered west and southwest of the

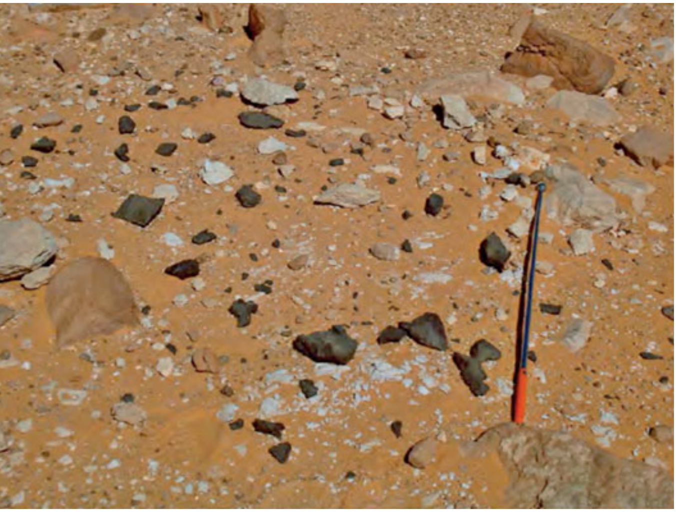
craters, and in close proximity to the rims.

Referring to the different shapes of the meteoritic debris, Alderman offered a hypothesis that also explained the fact that multiple craters were produced. In his model, "many of the fragments were torn off large masses immediately before or during impact with the Earth", while "others fell at the same time but separately" (Alderman 1932).

An interesting feature, which Alderman commented on as "extremely noticeable", was the fact that, at several spots, meteoritic fragments occurred in very concentrated patches, whereas adjacent areas were practically devoid of fragments. Near crater no. 4, "on an area measuring 6 by 6 feet over a hundred fragments were collected" (Alderman 1932).

The same was recently reported by D'Orazio *et al.* (2011) for the Kamil crater in Egypt, where researchers found several tight clusters of meteoric shrapnel arranged in irregular circles. The team around Luigi Folco and Massimo D'Orazio explained these concentrations as the result of larger shrapnel ejected from the crater that shattered upon impact with the ground. According to Luigi Folco, the project leader on the Kamil crater research, many of the shrapnel found at Kamil crater had delicate structures. Some were almost completely crosscut by open shear bands separating smaller fragments just about to detach. Thus, Folco concludes that some large shrapnel masses could easily break into pieces due to the weakness of their structures (Luigi Folco, personal communication). However, to the authors of the present publication, Buhl & McColl, it seems very unlikely that ejected fragments hitting the ground with a terminal velocity of only 80 m/s (D'Orazio 2011) retain sufficient energy to shatter into much smaller fragments at the end of their ballistic path, particularly given the extremely shallow impact angle that must be assumed for these secondary projectiles. Thus, the authors of the present work consider it much more probable that these clusters represent impacts of smaller masses that separated from the main projectile shortly prior to impact and which then rather impacted and shattered individually. This scenario would also be supported by the rather circular distribution of the cluster fragments. A distinctly oblique impact angle, as could be expected from a secondary projectile ejected from a crater, would tend to produce a fan-shaped cluster of shrapnel rather than a radial pattern.

With regard to the distribution of the meteoritic material in general, Alderman



"Clusters of meteorites consisting of tens of shrapnel specimens of variable size arranged in irregular circles up to 1.5 m in diameter." These clusters, photographed at the Kamil crater (Egypt) by the team of Luigi Folco, were also described by Alderman at Henbury. While D'Orazio *et al.* (2011) describe them to represent "large ejected meteorite fragments that shattered upon impact with the ground", the authors of the present publication (Buhl & McColl) are convinced that these clusters represent the impacts of smaller masses that separated from the main projectile shortly before impact and which then impacted and shattered individually. Photo courtesy *meteoritics & Planetary Science,* ©2011 by the Meteoritical Society. Photos: D'Orazio M. *et al.*: Gebel Kamil: The iron meteorite that formed the Kamil crater (Egypt). In: *Meteoritics & Planetary Science* 46, Nr 8, 2011

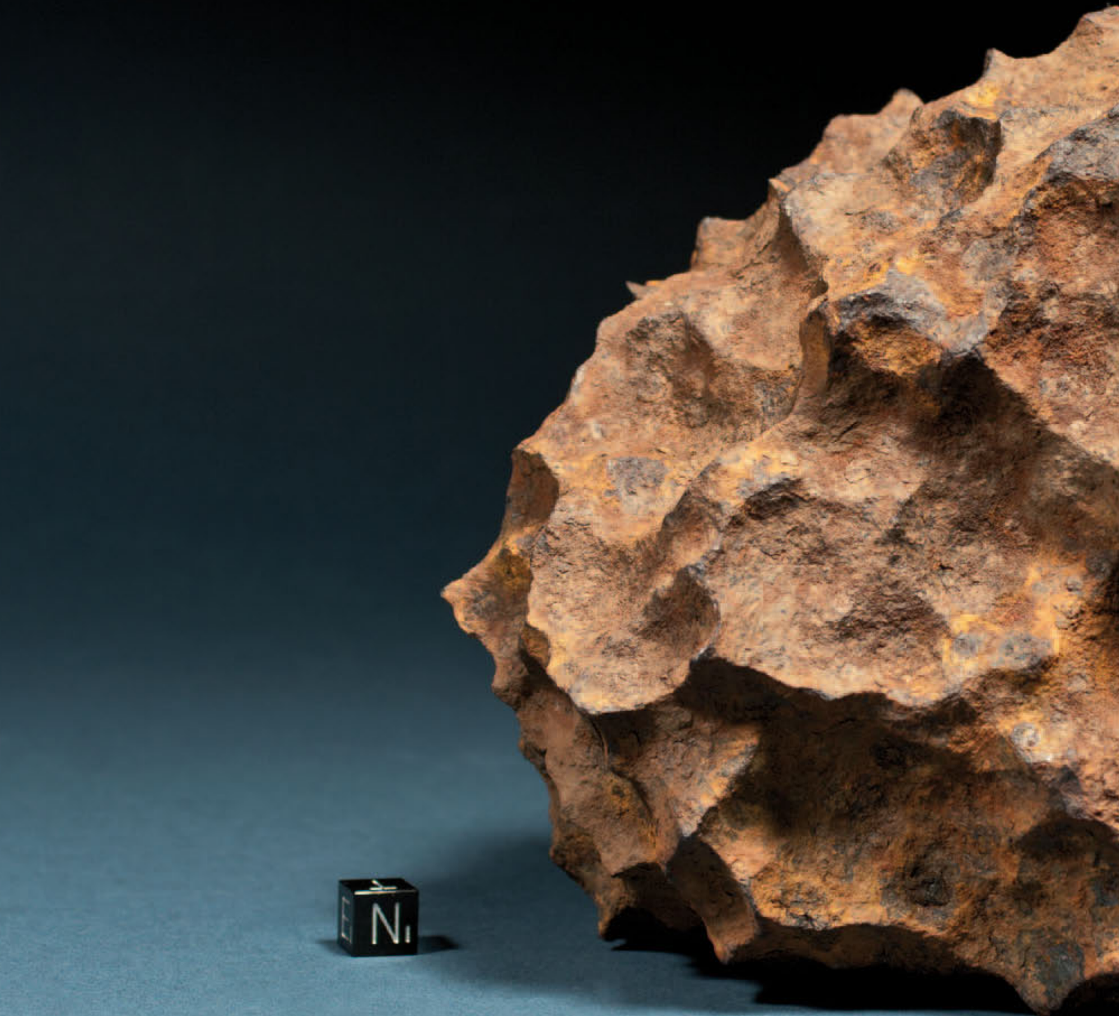
stated that, "the greatest number of fragments were found surrounding craters no. 3 and 4 and generally to the west of them." The fact that most of the meteoritic material was distributed to the west of the craters suggested to Alderman an indication of the direction of the meteorite fall. If the small, shrapnel-like fragments near the craters were formed by the cratering event (which is now considered certain as explained further below) then their presence west of the impact structures is explained by an "east to west movement" of the meteoritic bodies, which "splashed" the explosion fragments on the "farther side of the crater" (Alderman 1932).

Few fragments were found around the group of main craters. Alderman was convinced that material washed from the crater walls by erosion had buried any shrapnel in close proximity of the craters. As most of the fragments found near the main craters were found in shallow water courses (Alderman 1932), he suspected that additional meteorites could be found under the ejecta blanket. This theory, however, was refuted later, when by the aid of powerful metal detectors, only very few additional specimens were located in the near proximity of the main craters (McColl, personal communication).

In order to examine whether there were any larger masses of iron buried inside the craters, Alderman drilled a borehole 2.4 meters into the crater floor of the double punchbowl, which yielded no iron.

Alderman concluded: "These craters, which are very similar to the famous Meteor Crater in Arizona, though much smaller, were evidently formed by the impact of a shower of meteoritic irons at some remote period" (Alderman 1931 b). The idea of a shower of meteorites was also supported by Spencer in his paper "Meteorite Craters", a comparative discussion of craters that were known or believed to have been caused by meteorite strikes at that time (Spencer 1932 b).

IRON HARVEST



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11.2 kg Henbury individual in find condition (Buhl Meteorite Collection # B-383). This specimen was found in 1970 approximately 600 m east of the main craters. The meteorite is shaped like an arched headstone and shows deep regmaglypts which are only moderately eroded by subsoil corrosion. Scale cube is 1 cm. Photo: S. Buhl

"Bogged. Bill Bedford & Ben Peters. Truck unloaded and being pulled out with *Spanish windlass*". Photo taken on the way from Henbury to Coober Pedy, August 1931. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

As early as July 1931, a second expedition to the Henbury craters was undertaken, this time by Robert Bedford of the Kyancutta Museum, who travelled "3,000 miles by motor truck" from South Australia to the crater site (Alderman 1931 b). This expedition yielded "numerous masses of meteoritic iron, weighing from the fraction of an ounce up to 170½ lb".

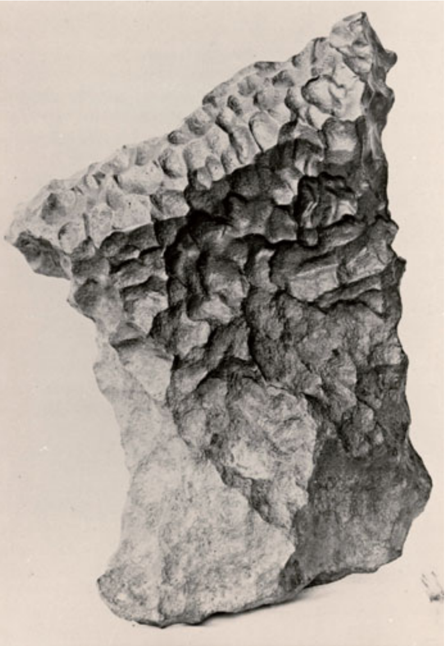
Bedford's idea of a trip to Henbury appears to have been born on the spur of the moment. In Bedford's biography his daughter Sylvia recollects the rather unconventional "planning and preparation" of the expedition, which started out on Tuesday, July 28, 1931:

"A news report came over the wireless about a large meteorite find in Central Australia and Robert was most interested in this. When deep in thought, Dad had a habit of pacing up and down, an unlit cigarette hanging from his mouth and twiddling a match between his fingers. This day, we eyed off the performance with apprehension and wondered what he was hatching. Eventually he quietly asked Bill if he could have the bus ready to leave for Henbury the next day. Bill thought he could; then all hell broke loose to get the show on the road." (Laube 1990)

The trip to Henbury across unbridged streams, along railroads, dirt roads and lost tracks, was an adventure in itself. It took the small party consisting of Robert and his son Bill Bedford and Bert Duggin ten days

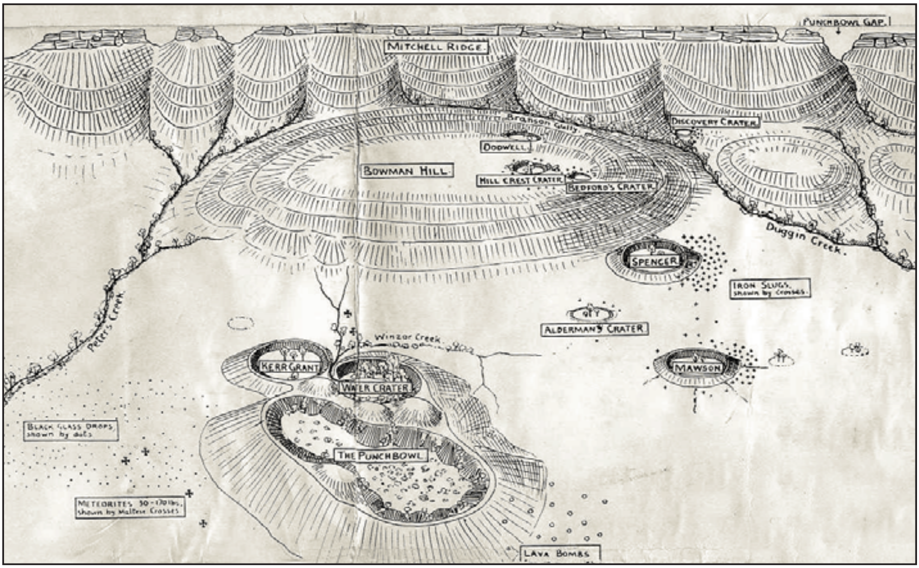
“Alderman‘s Crater. The wall has been washed nearly to ground level.” Part of the wall of the main crater can be seen in the left background. The trees which can be seen in the right background indicate the dry bed of Winzor Creek, which drains into Water Crater. The walls and trees of Water Crater are in the center background. Photo taken in August 1931. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

Top: “3 1/2 lb iron; pock-marked by atmospheric weathering, and with surface indications of the octahedral structure.” British Museum photo x1. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p



Right: The original caption by Bedford reads: “33 1/2 lb iron. Upper part shows original flight pitting. Lower part rusted.” Spencer had mistaken the regmaglypts seen on the top half of this specimen for effects of weathering. This meteorite was sent to the British Museum [BM. 1932, 1424]. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

"Ben Peters and Bill Bedford" conducting field work (Henbury main crater?). Photo taken during Bedford's 1st trip to Henbury in August 1931. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p



“Bird‘s-eye view of Henbury meteorite craters”. Map published in the Saturday, November 19, 1932 issue of *The Mail*, Adelaide. The map, which shows the crater field from the north, appears to be a composite of Alderman‘s distribution map (Alderman 1932) and Bedford‘s findings. In addition to Alderman‘s work, it contains not only topographic features that Bedford named after members of his expeditions (“Peter’s Creek”, “Duggin Creek”, “Bowman Hill”) but also an additional meteorite shrapnel field west of Discovery Crater (no. 13) that was not reported by Alderman. Apart from the find location of six larger meteorites (“30–170 lbs”) the map also shows the distribution pattern of Henbury impactites (“Lava bombs”, Black Glass Drops”)

until they reached the site. Finally, on 7 August 1931, they arrived at the crater field and built a field camp. Robert Bedford’s journal sums up their stay:

“Fri. Aug. 7, Sat 8, Sun 9: Two hard frosts at Henbury. Water solid in bowl. On our claim Meteorite field. Miners Right 969. Collecting – sketching and photographing.” And Bedford’s assistant Bert Duggin adds: “The craters were scattered over approx. 30 acres, the three main craters were about 50 yards across, thirty feet deep and sort of blown into one another, with 40 foot trees growing in them. We spent several days picking up specimens weighing from ounces to 40 lbs. Altogether we got about 400 lbs, which weighed the truck down.” (Laube 1990)

On August 10, the day of their departure, the party discovered a second area with a dense concentration of meteorites 5 km northeast of the main crater. During that day they continued collecting meteorites at this site.

After a brief detour to Coober Pedy, where Bedford dealt with opal diggers, the group arrived back in Kyancutta on August 19.

Typical examples of Henbury meteorites collected on the pediment slopes in the area 2.5–5 km northeast of the main craters. The two pictured specimens (top: 1.81 kg; bottom: 1.04 kg) exhibit the characteristic weathering pattern of exaggerated regmaglypts and knife-sharp edges as an effect of subsoil corrosion. Both specimens were found using a metal detector and were embedded several centimeters in the soil. Scale cube is 1 cm. Photos: S. Buhl


TORCH
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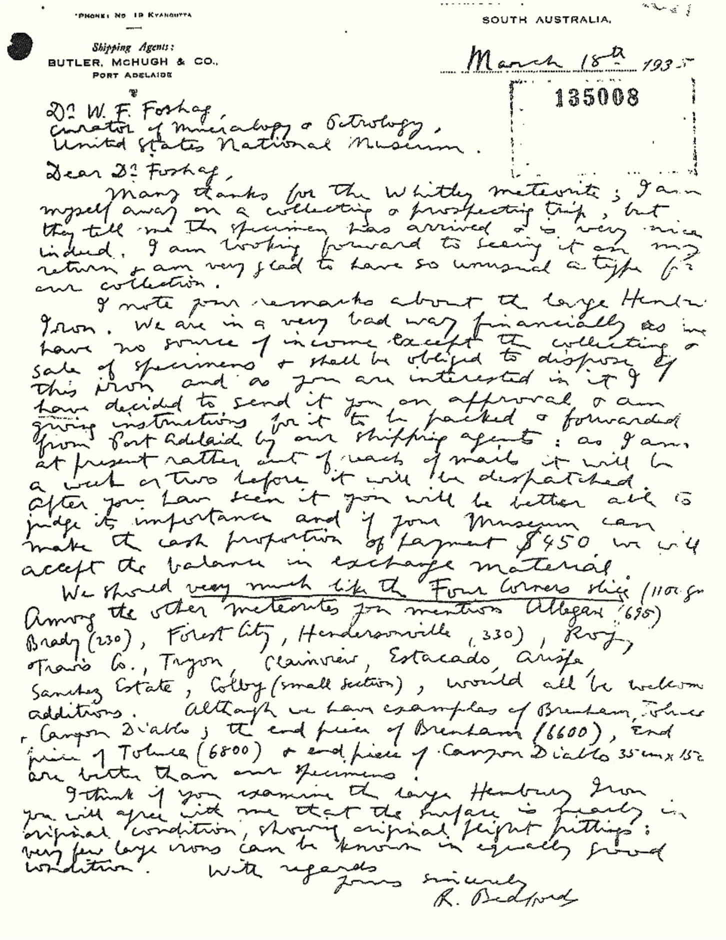
“Bert Duggin and Bill Bedford and an Aborigine from Henbury in the Punchbowl of the main crater”. Photo taken during Bedford‘s 1st trip to Henbury in August 1931. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p



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March 18th 1935

135008

Dr. W. F. Foshag,
Curator of Mineralogy & Petrology,
United States National Museum.

Dear Dr. Foshag,

Many thanks for the Whitley meteorite; I am myself away on a collecting & prospecting trip, but they tell me the specimen has arrived & is very nice indeed. I am looking forward to seeing it on my return & am very glad to have so unusual a type for our collection.

I note your remarks about the large Henbury Iron. We are in a very bad way financially as we have no source of income except the collecting & sale of specimens & shall be obliged to dispose of this iron and as you are interested in it I have decided to send it you on approval & am giving instructions for it to be packed & forwarded from Port Adelaide by our shipping agents: as I am at present rather out of reach of mails it will be a week or two before it will be despatched. After you have seen it you will be better able to judge its importance and if your Museum can make the cash proportion of payment $450 we will accept the balance in exchange material.

We should very much like the Four Corners slice (1100 gm). Among the other meteorites you mention Allegan (695), Brady (230), Forest City, Hendersonville (330), Roy, & Travis Co., Tryon, Plainview, Estacado, Arispe, Sanchez Estate, Colby (small section), would all be welcome additions. Although we have examples of Brenham, Toluca & Canyon Diablo; the end piece of Brenham (6600), end piece of Toluca (6800) & end piece of Canyon Diablo 35 cm x 15 cm are better than our specimens!

I think if you examine the large Henbury Iron you will agree with me that the surface is nearly in original condition, showing original flight pittings: very few large irons can be known in equally good condition.

With regards
Yours sincerely
R. Bedford

Letter by Robert Bedford to Dr. William F. Foshag, curator in the US National Museum, concerning the trade of a large Henbury individual. The meteorite, a beautiful shield-shaped mass of 181 kg (US National Museum no. 933) was later described by Buchwald as a distinctly oriented individual that "is well preserved and 0.1 mm thick fusion crusts are still present at the bottom of numerous regmaglypts" (Buchwald 1975). The document underlines the importance of the Henbury meteorites for Bedford's acquisition of new exhibits for the chronically underfunded Kyancutta museum (transcript on the opposite page). Scan: Department of Mineral Sciences, Smithsonian Institution, US National Museum of National History, 13,5008 (1935)

’Phone: No 19 Kyancutta
SOUTH AUSTRALIA

March 18th, 1935

Shipping agents:
BUTLER, McHUGH & CO.
Port Adelaide

Dr. W.F. Foshag
Curator of Mineralogy and Petrology
United States National Museum

Dear Dr Foshag,

Many thanks for the Whitby Meteorite; I am myself away on a collecting and prospecting trip, but they tell me the specimen has arrived and is very nice indeed. I am looking forward to seeing it on my return and am very glad to have so unusual a type for our collection.

I note your remarks about the large Henbury Iron. We are in a very bad way financially as we have no source of income except the collecting and sale of specimens and shall be obliged to dispose of this iron, and as you are interested in it I have decided to send it to you on approval, and am giving instructions for it to be packed and forwarded from Port Adelaide by our shipping agents. As I am at present rather out of reach of mails, it will be a week or two before it will be despatched. After you have seen it you will be better able to judge its importance, and if your museum can make the cash proportion of payment $ 450 we will accept the balance in exchange material.

We should <u>very much like the Four Corners slice</u> (1,100g). Among the other meteorites you mention Allegan (695), Brady (230), Forest City, Hendersonville (330), Roy, Travis County, Tryon, Plainview, Estacado, Arispe, Sanchez Estate, Colby (small section), would all be welcome additions. Although we have examples of Brenham, Toluca and Canyon Diablo; the end piece of Brenham (6,600), end piece of Toluca (6,800) and end piece of Canyon Diablo (35cmx15cm) are better than our specimens.

I think if you examine the large Henbury Iron you will agree with me that the surface is nearly in original condition, showing original flight pittings; very few large irons can be known in equally good condition.

With regards,
Yours sincerely,
R. Bedford

The meteorite described on the previous pages is today on display in the US National Museum in Washington D.C (no. 933). Currently the shield-shaped mass of 181 kg is the largest, unbroken individual of Henbury known. "It measures 60 x 40 x 22 cm and is an oriented individual, very similar to Oakley, Cabin Creek and Hraschina." (Buchwald 1975) In this photo of the meteorite room in the US National Museum, taken around 1960, the specimen can be seen on the front left corner of the pedestal. The meteorite to the left of Henbury is the 192 kg Owens Valley mass, the one to the right is the 1,117 kg Goose Lake meteorite. The Tucson ring can be seen in the background. Photo: Department of Mineral Sciences, Smithsonian Institution, US National Museum of National History (ca. 1960)

Another view of the 181 kg shield-shaped Henbury meteorite (flat specimen in the foreground on the right) which shows its distinct orientation. Photo: Department of Mineral Sciences, Smithsonian Institution, US National Museum of National History (ca. 1960)


THE MOON
AHEDRITES
MESOSIDERITES

"METEORITE IN A CRATER"

S. Buhl, D. McColl, *Henbury Craters and Meteorites,* GeoGuide,
DOI 10.1007/978-3-319-03955-8_4,

In March 1932, Robert Bedford started a second expedition to Henbury. Robert and Bill Bedford, accompanied by Ben Peters, arrived at the crater site on 26 March. This time they stayed for ten days, "investigating and excavating the meteorite craters".

Already on his first trip Bedford had devised a plan to locate large meteorites by digging within in the craters. With a serious effort Bedford's party excavated the structures no. 10, 11 and 13 (as numbered by Alderman), and also probed an additional structure nearby not listed by Alderman, which Bedford believed to be a crater as well.

At crater no. 13 (which was later named "Discovery Crater" by Bedford) Bedford's aspiring party was finally successful. Two meters below the crater floor a large block of iron came to light, which upon further excavation turned out to actually consist of four separate masses. In his memoirs, Ben Peters recollects the episode:

"Bill and I excavated and brought out the first meteorite ever found in a crater. (They were usually blown to bits on impact.) The crater was about 10 yards in diameter, we dug down 7 or 8 feet then got a couple of timbers and 2 ropes, blocked and tied it a number of times and gradually seesawed the 400 lb. meteorite up to the top. The job took us several hours. It was in four pieces loosely held together by masses of iron oxide." (Laube 1990)

"440 lb iron, rusted & shattered into four pieces: from Discovery Crater." This photo was taken by the British Museum and later returned to Bedford. It shows the four rearranged masses recovered from crater no. 13 by Bedford during his second trip to Henbury. The badly weathered meteorite exhibits little if any of its original surface. British Museum X1, 5–6. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

Left: "Shaft sinking in Hill Crest Crater. Shale-balls found but no mass of iron". Right: "Locating the Meteorite in Discovery Crater, using a trough compass. The meteorite weighs 440 lbs & was 7 feet below the surface. It is now in the British Museum." Photos taken during Bedford's second Henbury expedition in March 1932. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

The largest fragment of this find weighed 132 kg and measured 60 x 50 x 22 cm, the smallest measured 24 x 13 x 3 cm and weighed 2.2 kg. The total weight of the four masses, which fit together at their fracture planes, is 200 kg (British Museum 1932 a). When reassembled the four fragments have the shape of an asymmetrically elongated pyramid with a truncated cone. The masses are badly weathered, and no conclusions can be drawn whether they represent a flight ablated individual or a fragment produced in a late disruption immediately prior to the impact.

Bedford's discovery was enthusiastically received by the Australian and the British press. It triggered a wider interest from the media than the initial discovery of the Henbury craters itself. Bearing the headline "Sun Walk Fire Devil rock" in its Saturday, 19 November 1932 issue *The Mail (*Adelaide, SA*)* texted: "An expedition from the Kyancutta Museum located a meteorite in a crater – the first time a large iron has ever been found in such a meteorite depression." To add a little more weight to the story, the mass of 440 lb or ~ 200 kg "weighed about a ton" in their description. *The Mail* article continued: "By mathematical deductions, the expedition estimated that the largest crater at Henbury was caused by a meteorite whose weight did

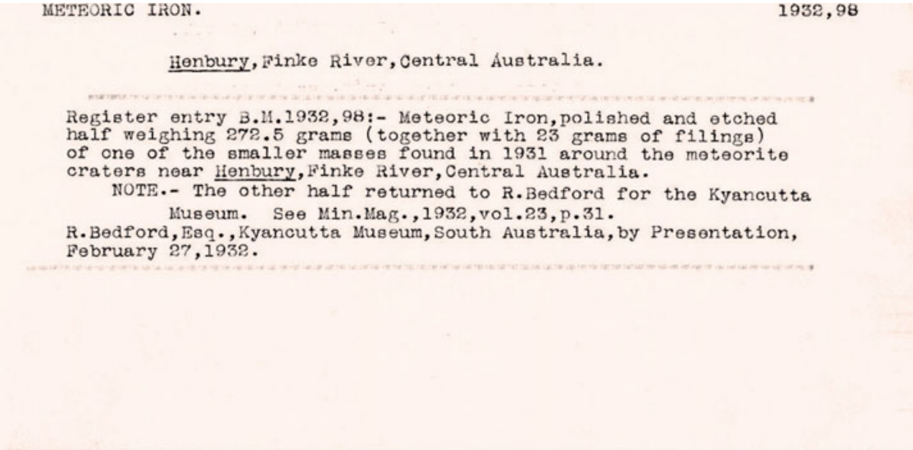
Meteorite fragments excavated from Discovery Crater rearranged for the photographer.
Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

not exceed 400 tons, and that it was buried 120 ft. below the original ground level."

The hope for larger masses buried beneath the crater floors was soon abandoned and, in 1937, the absence of larger meteoritic masses in the other craters was confirmed during a magnetic survey carried out by Jack Maxwell Rayner. All of the twelve craters traversed were found to be free of large magnetic anomalies. However, the magnetic survey produced ten small anomalies that were attributed to smaller meteoritic fragments. One signal was dug up from crater no. 5 and found to be a meteorite of 18 kg. The cause of other anomalies in craters 12 and 13 were believed to be other meteorites buried at shallow depths. Like a number of other signals found at considerable distance from the craters, they were left undisturbed.

In total, both parties, Alderman and Bedford, in 1931–1932 collected approximately 1,350 pieces of meteoritic iron from the site, of which Bedford's haul was well in excess of 425 kg. Unfortunately, no total weight records were given in their official reports. Shortly afterwards, and as a temporary loan of the Kyancutta Museum, a selection of 542 complete masses of iron, together with the sketches and photographs of the craters, were sent to the British Museum in London. Subsequently, these finds were exhibited in the Meteorite Pavilion of the Natural History Museum at South Kensington. In October 1932, the British Museum announced the acquisition of 172 pieces from the loan, with a total weight of 274 kg (Recent Acquisitions 1932).

Two years later, in 1934, the British Museum announced the acquisition of another 474 masses of Henbury iron meteorites with a total weight of 75 kg by means of exchange with the Kyancutta Museum. These included three larger masses with



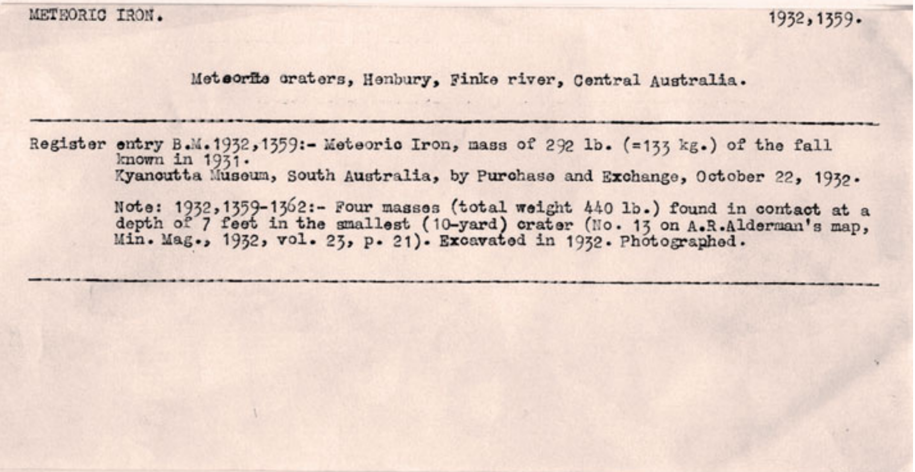
METEORIC IRON. 1932,98

Henbury, Finke River, Central Australia.

Register entry B.M.1932,98:- Meteoric Iron, polished and etched half weighing 272.5 grams (together with 23 grams of filings) of one of the smaller masses found in 1931 around the meteorite craters near Henbury, Finke River, Central Australia.

NOTE.- The other half returned to R.Bedford for the Kyancutta Museum. See Min.Mag., 1932, vol.23, p.31.

R.Bedford, Esq., Kyancutta Museum, South Australia, by Presentation, February 27, 1932.

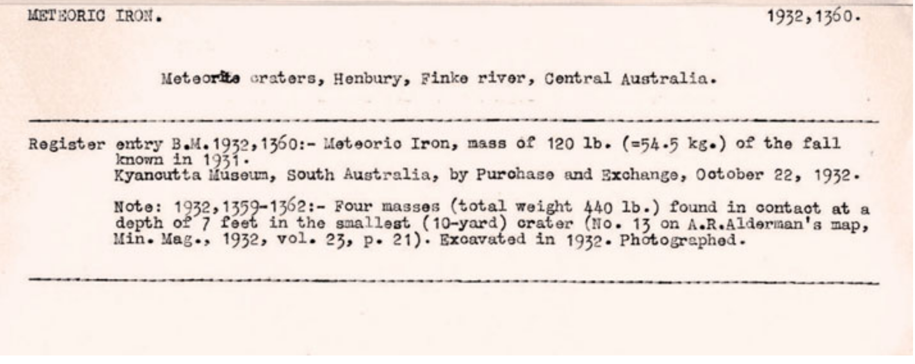


METEORIC IRON. 1932,1359.

Meteorite craters, Henbury, Finke river, Central Australia.

Register entry B.M.1932,1359:- Meteoric Iron, mass of 292 lb. (=133 kg.) of the fall known in 1931.
Kyancutta Museum, South Australia, by Purchase and Exchange, October 22, 1932.

Note: 1932,1359-1362:- Four masses (total weight 440 lb.) found in contact at a depth of 7 feet in the smallest (10-yard) crater (No. 13 on A.R.Alderman's map, Min. Mag., 1932, vol. 23, p. 21). Excavated in 1932. Photographed.

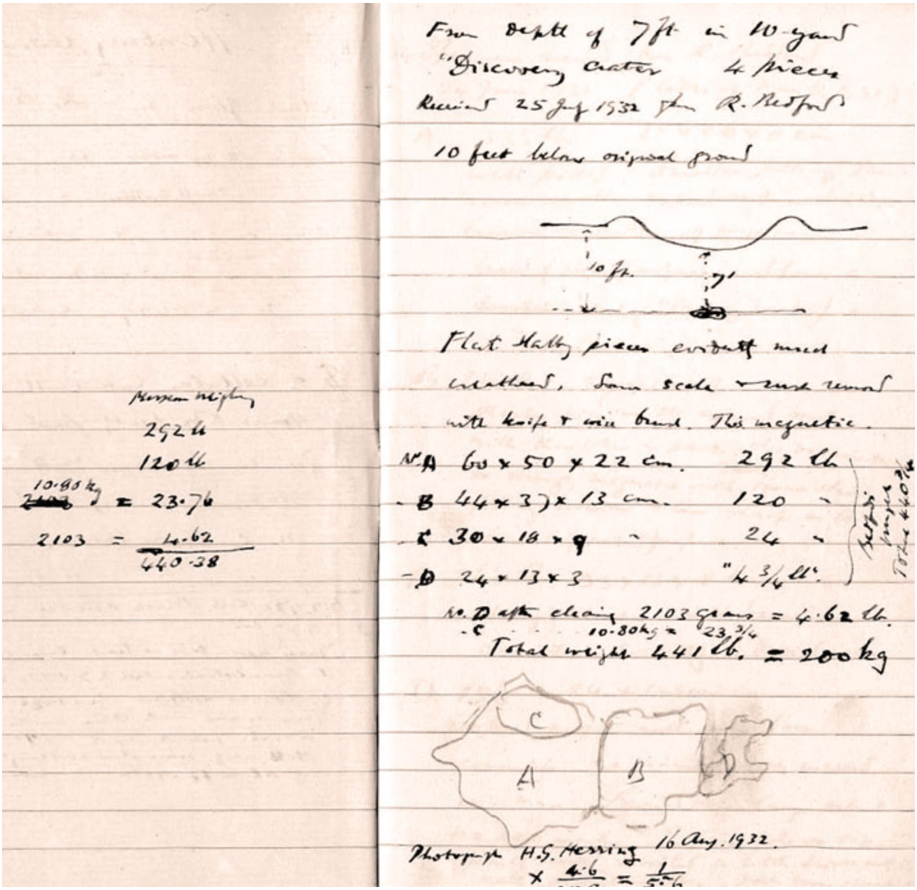


METEORIC IRON. 1932,1360.

Meteorite craters, Henbury, Finke river, Central Australia.

Register entry B.M.1932,1360:- Meteoric Iron, mass of 120 lb. (=54.5 kg.) of the fall known in 1931.
Kyancutta Museum, South Australia, by Purchase and Exchange, October 22, 1932.

Note: 1932,1359-1362:- Four masses (total weight 440 lb.) found in contact at a depth of 7 feet in the smallest (10-yard) crater (No. 13 on A.R.Alderman's map, Min. Mag., 1932, vol. 23, p. 21). Excavated in 1932. Photographed.



Museum weighing

292 lb

120 lb

10·80 kg
~~2103~~ = 23·76

2103 = 4·62

440·38

From depth of 7 ft in 10-yard
"Discovery Crater 4 pieces
Received 25 July 1932 from R. Bedford

10 feet below original ground

10 ft.
7'

Flat flatty pieces evidently much
weathered, some scale & rust removed
with knife & wire brush. This magnetic.

No A 60 × 50 × 22 cm. 292 lb
" B 44 × 37 × 13 cm. 120 "
" C 30 × 18 × 9 " 24 "
" D 24 × 13 × 3 "4 3/4 lb".

Bedford's figures
Total 440¾

No. D after cleaning 2103 grams = 4·62 lb.
" C " " 10·80 kg = 23 3/4
Total weight 441 lb. = 200 kg

C
A
B
D

Photograph H.S. Herring 16 Aug. 1932.
× 4·6 = 1

Top: British Museum transcript of Robert Bedford's journal describing the find situation of the four masses from Discovery Crater "10 feet below original ground". The drawing gives the outlines of the four fragments as recorded in situ. Natural History Museum London, British Museum Inventory, Henbury Note Book, B.M . 1932, 1359–1362

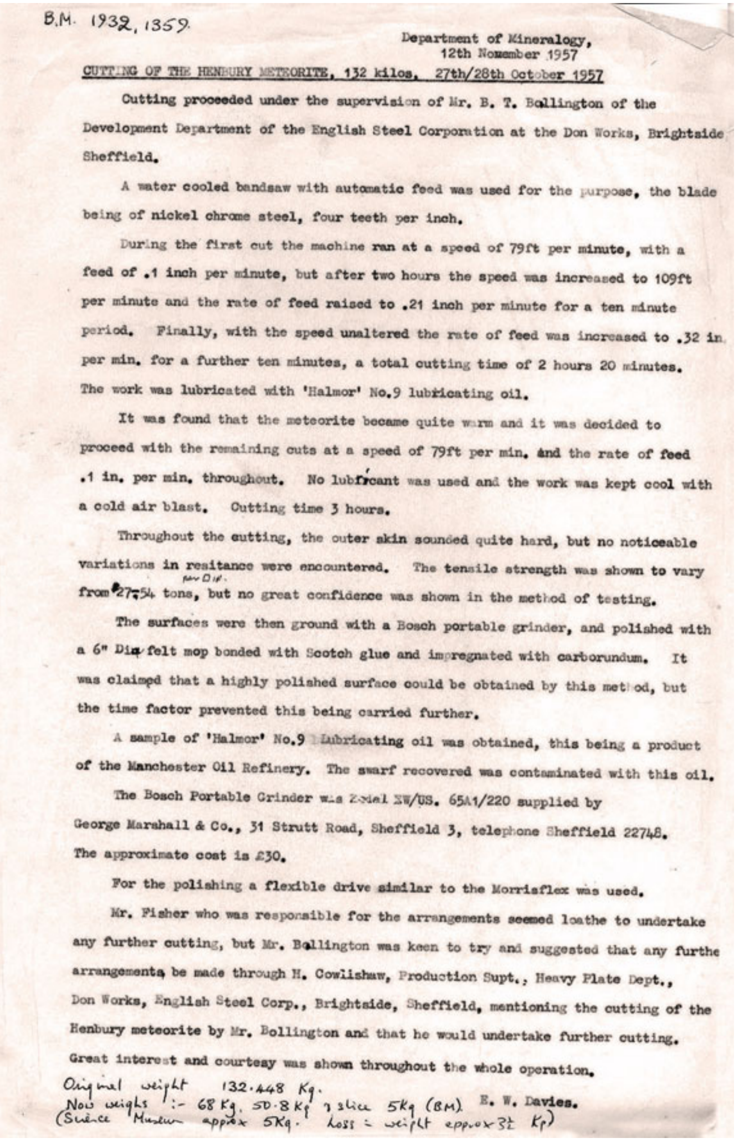
Left: British Museum Inventory, Henbury Register. The entries 1932, 1359–1362 refer to the four masses with a combined total weight of 440 lb (200 kg) which were recovered from Discovery Crater by Robert Bedford in 1932 and subsequently sent to the British Museum. Natural History Museum London, British Museum Inventory, Henbury Register, B.M. 1932, 1359 & 1360

"Prospecting shafts in Bedford's Crater. Shale-balls were found but no mass of iron".
Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

a respective weight of 21 kg, 11.5 kg and 11 kg, whereas the majority were small twisted pieces referred to as "meteoritic shrapnel" (Recent Acquisitions 1934).

Among Australia's scientific community, Robert Bedford's exchange of Henbury meteorites with the British Museum was met with mixed emotions. In particular, the representatives of the South Australian Museum in Adelaide were not too pleased to see Bedford's dealings with London. A number of officials in Adelaide were quite annoyed by Bedford's collection activities at Henbury and the large quantities of specimens which were sent to the British Museum. On the other hand, the South Australian Museum had not been very cooperative in the past, when Bedford had tried to have Kyancutta recognized as a significant country museum. The British Museum, by contrast, was to Bedford "the world authority on meteorites, and the best specimens must always be sent there for exhibition and analysis" (Laube 1990).

In 1957, a meteorite from Bedford's collection weighing 132 kg and measuring 60 x 43 x 17 cm was cut under the supervision of the Development Department of the English Steel Cooperation in Sheffield, UK. It was the main fragment hauled from Discovery crater. The band saw, lubricated with "Halmor no.9", progressed at a maximum rate of 0.81 cm per minute. The first cut took two hours and 20 minutes. Apart from the two end pieces, two further slices were cut, one of which, weighing 11.03 kg, was sent to the Science Museum for exhibition in the Metallurgical Gallery (B.M. 1934,135), whereas the other was returned to the Kyancutta Museum (British Museum 1932 b).



B.M. 1932, 1359.

Department of Mineralogy,
12th November 1957

CUTTING OF THE HENBURY METEORITE, 132 kilos. 27th/28th October 1957

Cutting proceeded under the supervision of Mr. B. T. Bollington of the Development Department of the English Steel Corporation at the Don Works, Brightside Sheffield.

A water cooled bandsaw with automatic feed was used for the purpose, the blade being of nickel chrome steel, four teeth per inch.

During the first cut the machine ran at a speed of 79ft per minute, with a feed of .1 inch per minute, but after two hours the speed was increased to 109ft per minute and the rate of feed raised to .21 inch per minute for a ten minute period. Finally, with the speed unaltered the rate of feed was increased to .32 in. per min. for a further ten minutes, a total cutting time of 2 hours 20 minutes. The work was lubricated with 'Halmor' No.9 lubricating oil.

It was found that the meteorite became quite warm and it was decided to proceed with the remaining cuts at a speed of 79ft per min. and the rate of feed .1 in. per min. throughout. No lubricant was used and the work was kept cool with a cold air blast. Cutting time 3 hours.

Throughout the cutting, the outer skin sounded quite hard, but no noticeable variations in resitance were encountered. The tensile strength was shown to vary from 27-54 tons, per □ in. but no great confidence was shown in the method of testing.

The surfaces were then ground with a Bosch portable grinder, and polished with a 6" Dia felt mop bonded with Scotch glue and impregnated with carborundum. It was claimed that a highly polished surface could be obtained by this method, but the time factor prevented this being carried further.

A sample of 'Halmor' No.9 Lubricating oil was obtained, this being a product of the Manchester Oil Refinery. The swarf recovered was contaminated with this oil.

The Bosch Portable Grinder was Z-Mel ZW/US. 65A1/220 supplied by George Marshall & Co., 31 Strutt Road, Sheffield 3, telephone Sheffield 22748. The approximate cost is £30.

For the polishing a flexible drive similar to the Morrisflex was used.

Mr. Fisher who was responsible for the arrangements seemed loathe to undertake any further cutting, but Mr. Bollington was keen to try and suggested that any further arrangements be made through H. Cowlishaw, Production Supt., Heavy Plate Dept., Don Works, English Steel Corp., Brightside, Sheffield, mentioning the cutting of the Henbury meteorite by Mr. Bollington and that he would undertake further cutting. Great interest and courtesy was shown throughout the whole operation.

E. W. Davies.

Original weight 132.448 Kg.
Now weighs :- 68 Kg. 50.8 Kg 7 slice 5Kg (BM).
(Science Museum approx 5Kg. Loss = weight approx 3½ Kg)

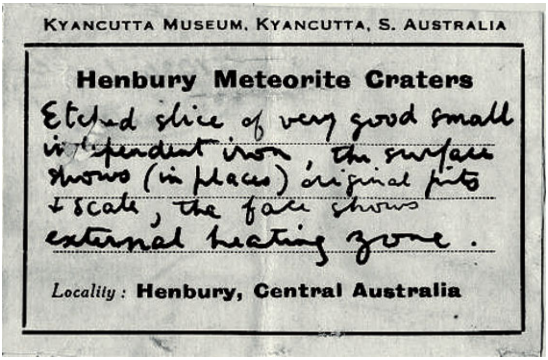
Cutting report of the 132 kg Henbury meteorite B.M. 1932, 1359. This is the main fragment excavated from Discovery Crater by Bedford in March 1932. Natural History Museum London, British Museum Inventory, B.M. 1932, 1359

"Museum in the Mallee. Mr. Bedford amongst some unique geological and zoological specimens in his private museum in Kyancutta, South Australia." *Walkabout*, May 1st 1949

The story of Robert and Bill Bedford's consecutive field trips to the Henbury Craters would not be complete without some further insight in Robert Bedford's personal background. When Robert Bedford emigrated from England he took up life in a typical Australian rural community of the early twentieth century. The Bedford family subsequently developed a lifelong association with the township of Kyancutta on the Eyre Peninsula of South Australia. The misfortune of Kyancutta at the time was, and still is today, that it is quite remote, and located near the northern border of the agricultural, wheat growing lands of Southern Eyre Peninsula, and southern extremities of the pastoral grazing lands of the Gawler Ranges. The rainfall is always rather uncertain, and greatly affects whether crops are a success or a disaster in any given year – one of the reasons why over many decades Kyancutta became one of the regular weather reporting centres in South Australia.

As Robert Bedford's son, Bill Bedford shared with his father the wide range of very practical skills typical of outback country people in the thirties. Robert had a museum background from the Plymouth Museum in England, following his education in science at Oxford University. Given this background, it is understandable that when the occurrence of meteorites at Henbury became public knowledge, he was quick to enlist family support and, at very short notice, pack camping equipment on an old truck which could cope with the bush tracks which passed for roads in those days. When they set out for their journey of several weeks and over a thousand kilometres to visit the location, the motivation clearly came from Robert Bedford. It was his background that made him recognize the enormous potential of a site where numbers of iron meteorites were 'simply lying around on the ground'.

In later times Robert became the principal instigator of the museum at Kyancutta, and negotiated the trading with museums in London and Washington. It was regrettable that his estrangement from the staff at the State museum in Adelaide resulted in an almost complete, lifelong, lack of communication and cooperation between these South Australian enthusiasts. It also meant that today almost all the larger pieces of meteorite from Henbury can only be seen in the great museums of the northern hemisphere.



KYANCUTTA MUSEUM, KYANCUTTA, S. AUSTRALIA

Henbury Meteorite Craters

Etched slice of very good small
independent iron, the surface
shows (in places) original pits
+ scale, the face shows
external heating zone.

Locality: **Henbury, Central Australia**

Top: The late Robert Bedford of Kyancutta, father of Bill Bedford. Photo: R. Laube

Bottom: “Etched slice of very good small independent iron”. Specimen card from Robert Bedford‘s Kyancutta Museum archived in the register of the British Museum. British Museum (N.H.), Mineral Department, 1934, 658

Below: Two pages from the Henbury Note Book which is part of the Register of the Natural History Museum London. The left column shows a series of calculations on the commercial value of iron meteorites, based on mineral dealer catalogues available at that time. The trading companies mentioned were the prominent contemporary suppliers of the Natural History Museums worldwide. The Note Book entry also gives an idea about the widespread commercial distribution of Henbury samples in the 1930s. The currency conversions are into British Pound (£) and the author of these notes must be assumed among the curators of the Meteorite Collection of the Natural History Museum. Scan: Natural History Museum London, British Museum Inventory, Henbury Note Book

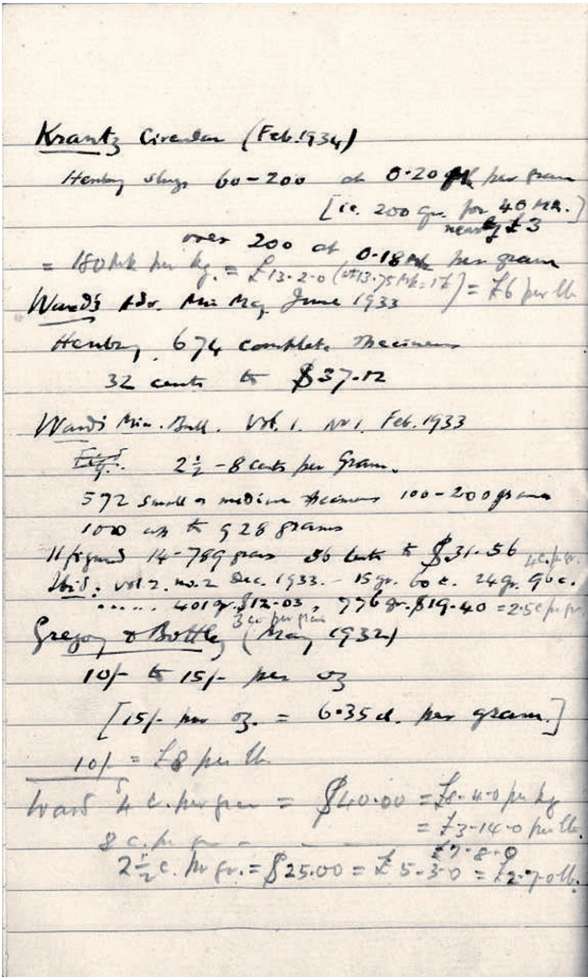
Transcript right page:
"Krantz Circular (Feb 1934)
Henbury slugs 6- 200 at 0.20 MR [Reichsmark, abbrev. RM, here "MR" is used] per gram
(i.e., 200 g for 40 MR nearly £3)
Over 200 at 0.18 MR per gram
= 180 MR per kg = £ 13-2-0 (at 13.75 MR = £1) = £ 6 per pound

Ward's Adv [advertisement] - Min. Mag. June 1933
Henbury 674 complete specimen
32 cents to $ 37.12

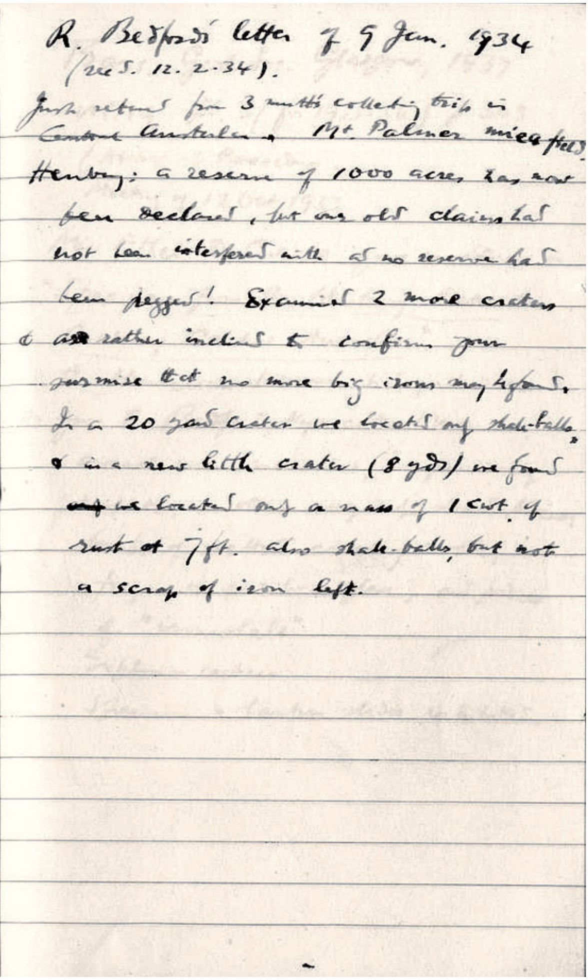
Ward's Min. Bull. Vol. 1, Number 1, Feb 1933
2½ - 8 cents per gram
572 small or medium specimens 100–200 grams
100 up to 928 grams
11 kgrams 56 lots $ 31.56
Ibid Vol. 2 November December 1933 15gr 60 c. 24 gr [?]
401 gr $ 12.03 776 gr $ 19.40 = 2.5 c per gram

Gregory & Bottley (May 1932)
10/- to 15/- per oz (10 to 15 shillings per ounce)

(15/- per oz = 6.35 d per gram)
10/- = £ 8 per lb
Ward 4 c per gram = $ 40.00 = £ 8-4-0 per kilogram
= £ 3-14-0 per lb
8 c per gram = £ 7-8-0 per lb
2½ c per gram = $ 25.00 = £ 5-3-0 = £ 2-7-0 per lb"



Krantz Circular (Feb. 1934)
Henbury slugs 60 – 200 at 0·20 M per gram
[i.e. 200 gr. for 40 MR. nearly £3]
over 200 at 0·18 M per gram
= 180 Mk per kg. = £13·2·0 (at 13·75 Mk = 1£) = £6 per lb
Ward's Adv. Min Mag. June 1933
Henbury. 674 complete specimen
32 cents to $37·12
Ward's Min. Bull. Vol. 1. No 1. Feb. 1933
[illegible] 2½ – 8 cents per gram.
572 small or medium specimens 100 – 200 grams
1000 up to 928 grams
11 kgrams 14-789 grams 56 lots to $31·56 4c. per gr.
Ibid: vol. 2. no. 2 Dec. 1933. – 15 gr. 60 c. 24 gr. 96 c.
...... 401 gr. $12·03, 776 gr. $19·40 = 2·5 c per gr.
3 c per gram
Gregory & Bottley (May 1932)
10/- to 15/- per oz
[15/- per oz. = 6·35 d. per gram]
10/- = £8 per lb
Ward 5 4 c. per gram = $40·00 = £8-4-0 per kg
= £3-14-0 per lb.
8 c. per gram £7-8-0
2½ c. per gr. = $25·00 = £5-3-0 = £2-7-0 lb.



R. Bedford's letter of 9 Jan. 1934
(see S. 12.2.34).
Just returned from 3 months collecting trip in
Central Australia & Mt Palmer mica field.
Henbury: a reserve of 1000 acres has now
been declared, but our old claims had
not been interfered with as no reserve had
been pegged! Examined 2 more craters
& am rather inclined to confirm your
surmise that no more big irons may be found.
In a 20 yard crater we located my shale-balls,
& in a new little crater (8 yds) we found
~~only~~ we located only a mass of 1 Cwt. of
rust at 7 ft. also shale-balls, but not
a scrap of iron left.

Transcript left page:
"R. Bedford's letter of 9 January, 1934
(see S. 12.2.34)

Just returned from 3 months collecting trip in Central Australia and Mt Palmer Mica Field. Henbury: A reserve of 1,000 acres has almost been declared, but our old claims had not been interfered with as no reserve has been flagged [?]!
Examined 2 more craters and am rather inclined to confirm your surmise that no more big items may be found. In a 20 yard crater we located my shale balls, and in a new little crater (8 yards) we found, we located only a mass of 1 CWT [hundredweight = 112 pounds] of rust at 7 feet, also shale balls but not a scrap of iron left."

BEDFORD'S MORPHOLOGICAL STUDIES

S. Buhl, D. McColl, *Henbury Craters and Meteorites,* GeoGuide,
DOI 10.1007/978-3-319-03955-8_5, © Springer International Publishing Switzerland 2015

Spencer (1932 a) had described the shape of the Henbury meteorites as sculpted by explosion forces and weathering processes only. He stated that "no clear evidence was detected that the original surfaces on any of the masses had been preserved". A verdict which Bedford felt had to be corrected. In *Nature* (Bedford 1934) he delivered the first complete and most extensive morphological description of the recovered meteoritic material.

Bedford admits that those irons which were buried to considerable depths were certainly heavily corroded and had lost all their original surfaces due to heavy weathering. The same was true, albeit to a lesser extent, for the buried portions of those irons that were only partly exposed. Beside the more weathered masses, two groups of irons remained which Bedford considered as exhibiting clearly the original surface markings. The most striking evidence was found in many of the twisted shrapnel torn from the crater-forming masses. These fragments had cuts, bruises and shear marks "as clear and fresh as if recently made". These could certainly not be attributed to weathering processes, he concluded.

Henbury meteorite weighing 2,765 g (formerly Buhl collection # B-099). The moderately weathered individual has the shape of a three-cornered pyramid with a flat concave base and extended corners. While the three frontal surfaces are covered with a dense array of distinct regmaglypts that morph into gorge-shaped furrows towards the edges, the rear surface shows only few shallow flight marks. The uncleaned specimen is coated by the laterite red caliche characteristic of specimens partly exposed or embedded at shallow depths on the pediment slopes at Henbury. This specimen was found ~ 3 km northeast from the craters in 1980 by Don McColl. Scale cube is 1 cm. Photo: S. Buhl

The second group with evident original surfaces were the individual masses that were found in an equally fresh condition. The term 'individual' refers to meteorites with an independent ablative flight subsequent to atmospheric breakup, which consequently exhibit regmaglypts shaped by atmospherical ablation. Apart from minor rust pitting and pock marks, which were the result of terrestrial weathering, these meteorites displayed blebs and rounded ridges "resembling brain convolutions", and gouge marks, as well as wide and shallow concavities. What Bedford described here in his own vivid words is the typical appearance of in flight-formed regmaglypts, which are quite distinctive.

Bedford made yet another observation, one which is commonly attributed to the Russian meteoriticist Yevgeny Leonidovich Krinov (Krinov 1963). Bedford noted that the dimensions of the cavities observed on the meteorites corresponded with the size of the respective individual:

"An interesting point is that the size of these markings corresponds roughly with the size of the iron. Thus the "gouge marks" in the iron of 33 lb. […] average 3/8 in. across; those on a very perfect little 4 oz. iron are only 3/16 in; and those on the largest iron I have seen average an inch." (Bedford 1934)

Krinov, in 1963 (1974) provided the formula to establish the relation of the size of

On describing Henbury meteorites Robert Bedford (1934) was the first to note that the size of the regmaglypts correlates with the dimensions of the respective meteorite. Krinov (1963, 1974), based on his study of meteorites from the Sikhote-Alin fall, later gave the ratio of the size of the regmaglypts to the size (cross section) of the meteorite as K = 0.09. Pictured on the opposite page is a Sikhote-Alin individual of 3,600 g (cross section 162 mm) with an average regmaglypt diameter of ~ 14 mm. Pictured above is a 2,765 g Henbury individual (cross section 145 mm) with an average regmaglypt diameter of ~ 12 mm (max. dimensions measured). Scale cube is 1 cm. Photos: S. Buhl

the regmaglypts to the size (cross section) of individual meteorites: "The average ratio of regmaglypt diameters to meteorite cross sections for meteorites with diameters of the order of tens of centimeters, is K=0.09." Krinov added that "the ratio, K, is inversely proportional to the size of the meteorites (Krinov 1974).

Bedford correctly assumed that the correspondence of the regmaglypts to the size of the individual meteorites which he observed would be difficult to explain by weathering processes. He concluded that the cavities must have been induced on the respective specimens as original flight markings. To back up this point, he presented additional evidence. At the bottom of some of these cavities Bedford had found "traces of a peculiar even scale", which he considered to be the original fused surface coating that the meteorite had developed in flight.

Two examples (top and bottom) of Henbury meteorites that show a weathering pattern characteristic of pieces embedded in the soil at shallow depth. The top photo is of a 1,531 g specimen still exhibiting few exaggerated regmaglypts on some portions while other parts have lost all of the original surface due to subsoil corrosion. Specimen from the Matthias Baermann Collection. Photo: S. Buhl

Weathered 1,881 g Henbury individual. This specimen was embedded in the soil at a depth of 14 cm. The part protruding from the soil cover (not visible in the photo) still shows distinct regmaglypts preserved in their original size. Photo: S. Buhl

Henbury meteorite in situ. The 950 g specimen is embedded in the top soil to a depth of 10 cm and surrounded by a relatively thin aureole of rust. Caliche has coated the portion of the meteorite near the surface. Note the characteristic spikes protruding from the top soil which indicate a strong degree of ablative weathering. Geologist hammer for scale comparison. Photo: D. McColl

Ablation regmaglypts and fusion crust on Henbury meteorites were later confirmed by Harvey Harlow Ninninger, who cut and prepared a large number of specimens, and also by Vagn Fabritius Buchwald, who explicitly mentioned an unbroken, shield-shaped mass of 181 kg (US National Museum no. 933), which he had studied in the Smithsonian in Washington, D.C. Referring to this distinctly oriented individual, he noted that "the mass is well preserved and 0.1 mm thick fusion crusts are still present at the bottom of numerous regmaglypts" (Buchwald 1975).

Of additional special interest to Bedford was the shiny coating that covered only

Henbury meteorite in the shape of an arched headstone showing distinct sculpting due to a long individual ablative flight. The 11.2 kg mass was found in 1970 about 600 m east of the craters. Although recovered from beneath the soil, the distinct regmaglypts show only moderate effects of corrosion. Large parts of the surface are coated by a laterite-colored layer of caliche indicating a thin soil cover. (Buhl Meteorite Collection # B-383). Scale cube is 1 cm. Photo: S. Buhl

Henbury individual in situ, 0.5 km northeast from the craters. The flat regmaglypted meteorite weighs 1.03 kg. The specimen shows a shiny dark brown to black patina known as desert varnish that forms not only on surface rocks in arid environments but also on undisturbed meteorites. Photo: D. McColl

those masses which were found on top of the soil. He described the phenomenon, which is nowadays known by the name of *desert varnish*, as "a limonite glaze of secondary origin due to hydration of a thin film" on the original surface. He observed that "this glaze forms an extremely hard protective patina, and may be responsible for the perfect preservation of the surface features".

Desert varnish or desert patina is a thin and shiny dark brown to black patina that forms on inactive and exposed surfaces in arid and semi-arid environments. It is mainly composed of clay minerals. Clays and silica minerals comprise more than 70 % of the varnish, with the clay minerals being the predominant factor responsible for the accretion of the glaze. Iron and manganese oxides make up the bulk of the remainder and are dispersed evenly throughout the clay layer. Although its formation is still controversially discussed, the metal oxide enrichment is thought to involve manganese-oxidizing and iron-oxidizing microbes which are common in desert environments. Desert varnish is recognized by a lack of texture and its semi-opaque smoothness and luster. Its color varies from shades of red and brown to black, depending on the pH-value of the micro-environment, which in turn controls the abundance of either manganese- or iron-oxidizing bacteria. On meteorites,

Henbury shrapnel (33.8 g). Like the individual on the opposite page this surface find is coated with a delicate layer of dark brown desert varnish. Photo: S. Buhl

even on those with a relatively long history of terrestrial surface weathering, the thickness of desert varnish is typically less than 0.2 mm.

While Henbury meteorites collected from the surface often show a distinct coating of desert varnish, finds embedded in the soil undergo a different weathering process. Firstly, a difference readily noticed is the exaggeration of the original surface features. Regmaglypts are often enlarged with the edges between them thinned and sometimes shaped into blade-like ridges or thorn-like spikes as a result of selective corrosion which progresses from the bottom of cavities outwards. Contaminants and moisture trapped in these cavities favor the chemical attack that leads to a continuous flaking and alteration of the meteorite's surface.

The second feature that can be observed on soil-embedded Henbury meteorites is a red to orange crust, either adhering as patches or covering whole portions of the mass. It is known as 'caliche' or 'calcrete'. Caliche or calcrete both consist of layers of a hardened calcium carbonate deposit that forms through minerals leaching from the upper layer of the soil and adhering to contacting surfaces. Owing to a high degree of laterization of the topsoil at Henbury, the caliche layers contain ferric iron oxides as well, which explains the red to orange color.

GEOGRAPHY & TOPOGRAPHY

S. Buhl, D. McColl, *Henbury Craters and Meteorites,* GeoGuide,
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During World War II, science was busy optimizing crater production in a different field of research, and understandably, there was little interest directed towards research at the Henbury site. However, in 1962, groups of researchers began visiting the Henbury craters again. Two expeditions, one in 1962 (Edward Ching-Te Chao) and one in 1963 (Edward P. Henderson and Brian Mason) were conducted to collect meteorites and impactites, but to our knowledge, no findings were published.

In 1965, Paul W. Hodge provided a set of superb photographs including aerial shots, in which the changes in the previously undisturbed crater floors (caused by Bedford's extensive excavations) of the craters no. 10, 11 and 13, could still be seen.

In 1968, Dan Milton, on behalf of the US Geological Survey, was the first researcher to conduct a thorough geographical and geological survey of the crater site which resulted in a geologic map of 1:360 scale. He gave the location of the craters as "within a quarter square mile near long. 133°09′ E. and lat. 24°′35′ S." The craters are located at the foot of the Bacon Range (locally known as the Chandler Range), a ridge rising from just south of the crater field to a crest 42 meters higher, and about 250 meters distant from the nearest crater (no. 12 according to Alderman). The crest is capped by a geologically recent silcrete layer and

"Henbury Meteorite Craters, Central Australia. 13 craters total. Diameter of the largest crater 198 meters, depth 18 meters. Photo taken in July 1974 by W. Zeitschel." This photo distributed as a postcard by the German Meteorite collector Walter Zeitschel shows the "Double Punchbowl" and the two adjacent craters no. 6, "Water Crater" and no. 8, "Kerr Grant". At the bottom of the picture Winzor Creek can be seen draining into Water crater. The image was taken from the southwest. Photo: W. Zeitschel

is part of the sandstone-dominated Winnal Beds of late Proterozoic age, which is the lateral equivalent of the predominantly shaly Pertatataka Formation that makes up the bedrock of the crater field (Milton 1968). The unaltered bedrock is moderately indurated, and dips homoclinally at 35° to the south. The largest four craters have been formed on a gently sloping surface covered by a thin layer of pediment gravel which forms a stony gibber plain typical of the surface of the general area. These surfaces consist of rounded cobbles and smaller pebbles of local sandstone and silcrete in a lateritic red silty matrix originating from the Bacon Range (Chandler Range).

During his survey, Milton documented nine smaller craters, some of which are completely filled by sedimentation, which range in diameter from less than 6 meters to 64 meters. The four larger craters form a close group comprising two overlapping craters about 119 and 146 meters in diameter which together form an oval structure 600 feet long and two other complete craters of 91 and 70 meters, respectively. The rim of the largest crater is raised 6 meters above the pre-impact surface, and its depth is given by Milton as 15 meters.

The following description of the individual craters is based on Alderman (1932) and Milton (1968), the numbering is according to Alderman (1932) and names in brackets refer to alternative names assigned to some of the craters by locals and various authors (Alderman 1932, Sun Walk 1932, Bedford 1934, Milton 1968, Laube 1990).

Craters no. 1 and 2 exhibit no raised rims or depressions. They are recognized only as clay pans free of pediment gravel. The diameter of the clay pans and the growth of Mulga trees indicate craters about 24 and 27 meters in diameter.

Crater no. 3 ("Mawson") has an elevated rim 1.2 m high at its maximum, and a diameter of 52 to 70 meters. Its depth is

Present state of crater no. 3 ("Mawson"), view from the northwest crater wall, Bacon Range in the background, Duggin Creek to the right. Photo: T. Brattstrom

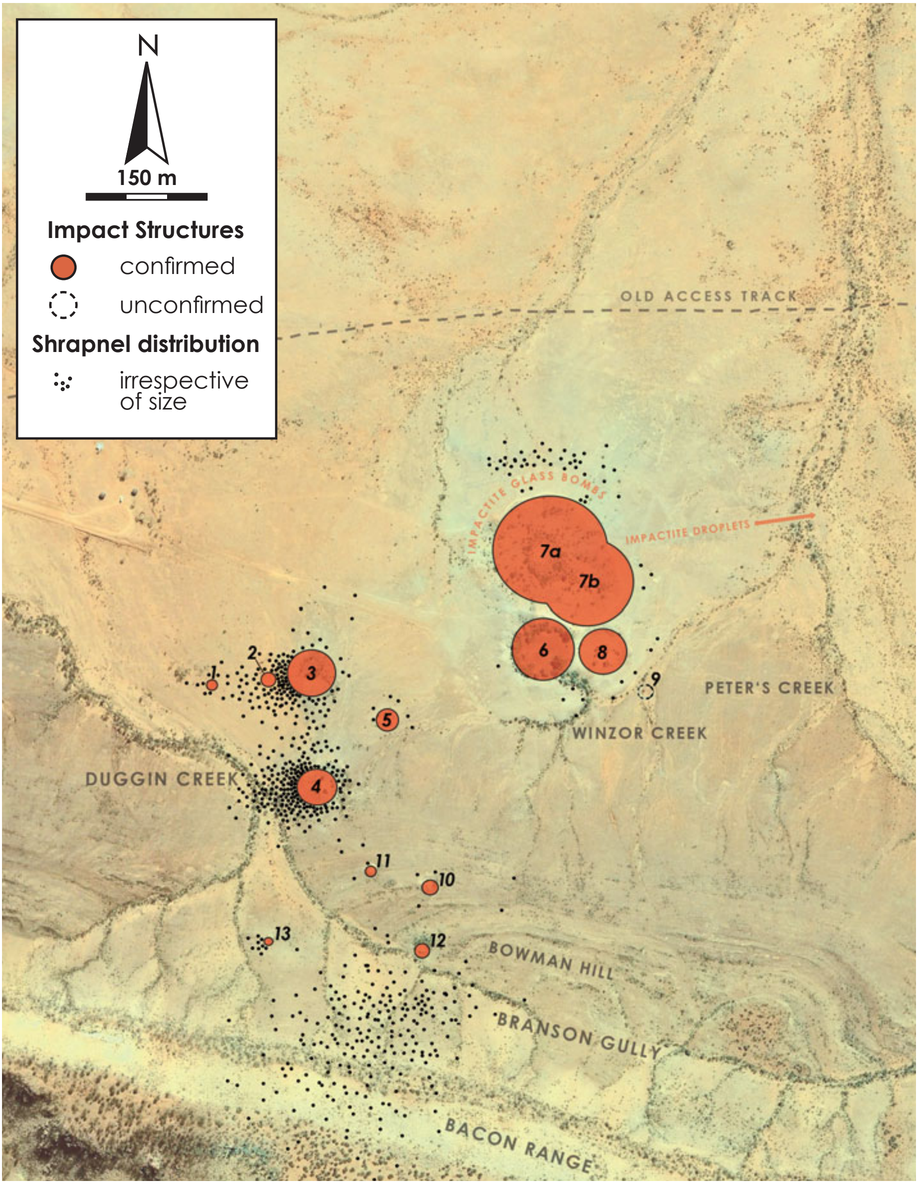
2.7–4.6 m. This crater is notable owing to its pattern of rayed ejecta loops that consist of ejected fragments from the sandstone bed. It was separately described by Milton (Milton *et al.* 1965). Alderman collected about 160 iron fragments near this crater, "and of this number about four-fifths were lying to the west" (Alderman 1932).

Crater no. 4 ("Spencer") has a 1.5 meter elevated rim, a diameter of 58 to 67 m, and a depth of 3.7 to 6 m. Similar to crater no. 3, it has a rayed ejecta system connected to it, which is composed of bedrock sandstone. One ray starts at the foot of the raised rim and extends radially westward for 70 m. About 400 meteoritic fragments were collected at crater 4, "of these nearly 400 were on the west side of the crater" (Alderman 1932).

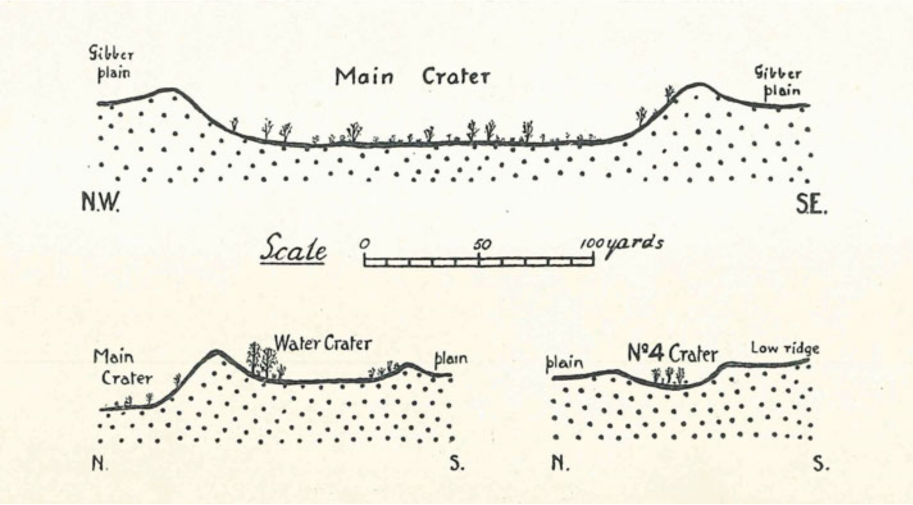
Crater no. 5 ("Alderman's Crater") is nearly completely destroyed by erosion. On its south and west side a 0.3 m-high rim is preserved. This structure is 17 m in diameter and the depth is less than 1 m. Alderman drilled a borehole in no. 5 to a depth of 2.5 m but no meteoritic fragments were found. In 1939, during his magnetic survey, Rayner found a meteorite fragment of 18 kg in no. 5.

Crater no. 6 ("Water Crater") has a rim with a general elevation of 1.5 to 3 m with the maximum height on its common wall with crater no. 7. The diameter of this crater is 85–97 m, and its depth is approximately 6 m. The southern wall of crater no. 6 has been breached by a drainage system, which, prior to the impact, drained to the northeast and now drains into the crater.

Crater no. 7 (Main crater or "The Punchbowl") has a maximum rim height of 6 m and is 11–15 m deep. It consists of



Crater numbers assigned by Alderman (1932). Shrapnel distribution according to Alderman (1932), Bedford (1932) and McColl. Ejecta radiants according to Bedford (Sun Walk 1932), Milton (1968) and McColl (1997). Note that only the shrapnel type meteorites are shown. Combined by S. Buhl. Map: © 2010 Google; Image © 2012 DigitalGlobe © 2012 Whereis® Sensis Pty Ltd



"Section through the craters." Fig. 3 from Alderman's "The Meteorite Craters at Henbury, Central Australia" (1932)

two coalescing craters designated 7a and 7b, which form an oval 182 m long. 7a is 146 m in diameter and 7b is about 119 m in diameter. An overturned flap from crater 7b, which extends into no. 6 crater (Water Crater), is evidence that no. 6 is fractionally older than the main crater. A broad belt of ejecta debris up to 0.6 m thick surrounds the main crater. The impact of the projectiles produced anticlinal folds visible in the lower wall of the main crater and synclinal folds nearer to the crater rim.

Milton also mentions fragments of crater glass abundant on the north rim of crater 7a. Other fragments of crater glass were found along narrow strips north and east of the craters as far as 600 meters away, indicating a distinctly asymmetric distribution pattern of the different types of fallout material.

Crater no. 8 ("Kerr Grant") has a rim height of 1.5 m. Where it borders on craters 6 and 7, its rim height increases. The diameter of crater no. 8 is 70 m and the depth is 1.5 to 3.6 m. South and east of crater no. 8, its ejecta has been removed by erosion as it is adjacent to a watercourse.

Except Alderman, who mapped a small circular structure in the southeast of crater no. 8, no other author apart from Milton was able to locate crater no. 9. Milton described the structure as a "depression along the beheaded drainage system" and added that it is "probably not a crater". In the aerial and high resolution satellite images from the site, the structure is, in contrast to the mentioned drainage system, not visible.

Crater no. 10 ("Hill Crest Crater") has a maximum rim height of 1.2 m and a diameter of 24–30 m. It is 0.9–2.1 m deep and markedly rectangular. This crater formed in more compact rock, as it lies on the crest of the bare sandstone ridge. The west and south crater walls show overturned bedrock on the rim crest. 11 m from the southern rim crest, Milton found a large sandstone block (1.2 x 1 x 0.5 m), the largest

chunk ejected from one of the Henbury craters. From the morphology of crater no. 10 Milton concluded that the centre of impact energy originated “somewhat north of the centre of the crater”.

Crater no. 11 (“Bedford’s Crater”) was very shallow and low rimmed and had a diameter of about 14 m. Its original shape was destroyed by Bedford’s unrewarded excavations for possible impactors remaining in the crater.

Crater no. 12 (“Doowell”) is the southernmost crater of the Henbury field. It is located on the south slope of a sandstone ridge. Whereas the depth of the north wall reaches 5.4 m, the southern wall is only 10 centimeters high. Crater 12 shows a rim raised less than a meter on its western and southeast side.

Crater no. 13 (Discovery Crater”) shows almost no raised rim; its diameter is about 6 m. From this crater Bedford recovered the 200 kg of meteorites described above. However, the excavations necessary to unearth the buried mass destroyed the crater’s original form.

Milton mentioned several other possible craters, one with a diameter of 7.6 m, about 60 meters west-southwest of Crater no. 13. Another probable impact structure is located just south of crater no. 8, and one more was suspected just southeast of crater no. 4. The latter was indicated by a deformation of the structures exposed in the gully which runs along the wall of crater no. 4.

Milton also described considerable changes to the crater field due to sedimentation, erosion and vegetation. Mulga (Acacia aneura) and Whitewood trees (Atalaya hemiglauca) did grow in the craters, whereas the crater wall of Water Crater (no. 6) had been breached, and the crater had captured a pre-impact drainage system, so that water collects in the crater floor after rains. Annual rain fall, according to Milton, is 8 inches, mostly attributed to the summer storms. Human activity and the fauna introduced by the settlers made the present rate of deterioration of the craters many times what it was in the pre- European area (Milton 1968).

Panoramic mosaic of Henbury main crater (no. 7a and 7b) seen from the north crater wall. Bowman Hill and Bacon Range are in the background. The trees behind the wall of the main crater mark Water Crater (no. 6). Photo: M. Bemmerl

Milton (1968) also observed a large number of disturbances within the crater field, one of which had already been described by Alderman. The latter had noted a number of low ridges of sandstone radiating from crater no. 3, which he interpreted as outcrops of rock more resistant to erosion. Milton and Michel (1965), in contrast, described these structures as rays, ray loops and blankets of ejected bed rock. To prove their hypothesis, they dug a cross-section across the blocky sandstone ray northwest of crater no. 3 and found a stratum only 12 cm thick overlying undisturbed pediment gravel. Subsequently a large number of rays and loop systems were mapped up to a distance of 70 m from that crater (no. 3). The most distinct main loop of ejecta, according to Milton and Michel, is composed of material similar to this near the pre-impact ground level. Its furthest deposits are therefore a likely candidate for the first relatively unchanged material ejected after the initial jets of liquid melt were produced in the crater forming process.

Similar ray structures were well-known from lunar meteorite craters, and Milton repeatedly quotes Shoemaker's theories on the formation of the Copernicus crater (Milton & Michel 1965). Unfortunately, official bulldozing in the vicinity of the craters, done in the 1970s with the aim of improving their access to tourism, has entirely removed many of these loops and rays of ejected sandstone fragments (McColl, personal communication).

In the 1980s, Roddy and Shoemaker published comprehensive studies of the crater field including low-altitude aerial stereophotography and geological mapping of the ejecta fields. Four new possible impact sites and a number of new ejecta deposits were located during their survey.

Crater no. 12, which was extensively studied by Roddy and Shoemaker, showed ejecta blankets extending to the north, west

"From L. to R.: Douglas Boerner, Oliver Chalmers; and Edward P. Henderson are prospecting with metal detectors in Henbury, Australia, location of the Henbury Crater. Edward P. Henderson, following his retirement as Curator of the Division of Meteorites in the Department of Mineral Sciences at the National Museum of Natural History, made a trip to Australia to gather meteorites." Photo taken in 1965. Smithsonian Institution Archives, History Division # 85–7038

Overturned flap on the south rim of crater no. 6. Photo: T. Brattstrom

and the east, but not to the south. The crater's bedrock was found strongly overturned only at its northern wall. Shrapnel from crater no. 12, according to the researchers, was distributed only to the north, west and east of the crater. Roddy and Shoemaker interpret their findings as consistent with an "inferred impact direction from southwest to northeast" (Roddy and Shoemaker 1988). The authors of the present publication find it difficult to comprehend why Roddy and Shoemaker decided that there was no shrapnel south of this crater, since hundreds of specimens were originally densely buried on the slopes of the Bacon Range (or Chandler Range) facing this crater on its southern side, and within just a few meters of the watercourse on its southern edge.

The shrapnel distribution pattern of crater no. 12, however, is contrary to the distribution pattern of craters no. 1, 2, 3 and 4 as mapped by Alderman. While the bulk of the shrapnel from the latter impacts was found west to southwest of these craters, the shrapnel fan ejected from structure no. 12 is clearly oriented to the south. Furthermore, crater no. 12 is on the northern side of a relatively steep south-facing ridge, bounded on its southern side by an east-west watercourse, and with several opposite smaller gullies running south of the watercourse, but quite close to the crater. Thus, we consider it probable that the area directly south of crater no. 12 may have been disturbed by post-impact erosion, which also dislocated potentially existent shrapnel on the original pre-impact surface.

This theory is supported by two islands of ejecta located southwest of the crater, on the opposite side of the dry gully. These islands on slightly higher ground appear to be the remains of a larger ejecta blanket which is now intersected by a seasonal

Remains of the western ejecta ray of crater no. 3. The bulldozed access road which erased the extended part of the ray can be seen in the upper right of the photo. The parking lot of the Henbury Meteorites Conservation Reserve is visible to the left. Photo: T. Brattstrom

active drainage system. Originally, an abundance of shrapnel-formed pieces of meteoritic iron could be found both on the slopes and even on the top of the high ridge about 250 meters further south (the Bacon- or Chandler Range). Large blocks of sandstone ejecta can still be seen on the top of this ridge which is 42 meters above the craters and 250 meters to the southwest (McColl, unpublished work).

If we consider this evidence, the present day situation indicates a subsequent modification of the original ejecta distribution pattern at crater no. 12, which might explain differences in regard to the ejecta and shrapnel distribution at the other craters investigated by Alderman.

The location of no. 12 on the relatively steep south slope of a sandstone ridge provides yet another plausible explanation for the southern orientation of the shrapnel fan ejected from this crater. When the projectile impacted the south sloping target surface, the part of the shrapnel fan directed to the south was free to escape while the forming crater walls blocked the other directions of escape.

Buchwald (1975) suggested, no. 12 may have been a penetration hole, which would have produced little if any shrapnel. If this was true the meteorite fragments south of the structure must have originated from the craters no. 6 and/or no. 8 rather than from no. 12. However, the lack of shrapnel in the area between nos. 6, 8 and crater no. 12, as well as the beginning of the shrapnel field south of no. 12, speaks against this hypothesis.

HENBURY METALLURGY

S. Buhl, D. McColl, *Henbury Craters and Meteorites,* GeoGuide,
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Previous page:

Polished and etched endcut (825 g) taken from a Henbury specimen with individual ablative flight history. Henbury displays a medium octahedral structure with a bandwidth of 0.9 mm. Neumann lines visible in the kamacite phase are indicative of a shock-induced deformation due to impact events on the parent body. Specimen from the collection of Ali Rasekhschaffe-Aras. Scale cube is 1 cm. Photo S. Buhl

Alderman was the first to undertake a chemical analysis of the Henbury iron meteorites and reported values for Ni (7.54%), Co (0.37%), P (0.08%), C (130 ppm) and S (100 ppm) (Alderman 1932). A comparison of the Wolf Creek, Boxhole and Henbury meteorites by Wasson provided another set of values for Ni (7.44 %), Ga (17.4 ppm), Ge (34.2 ppm) and Ir (15.0 ppm) for the Henbury iron. According to Buchwald and Wasson, Henbury falls in the IIIA group (which was later combined with the group IIIB to form the group IIIAB. Hutchison 2004). The unique chemical composition of the three irons is proof that the three crater locations represent separate events that are not related to each other (Wasson 1967).

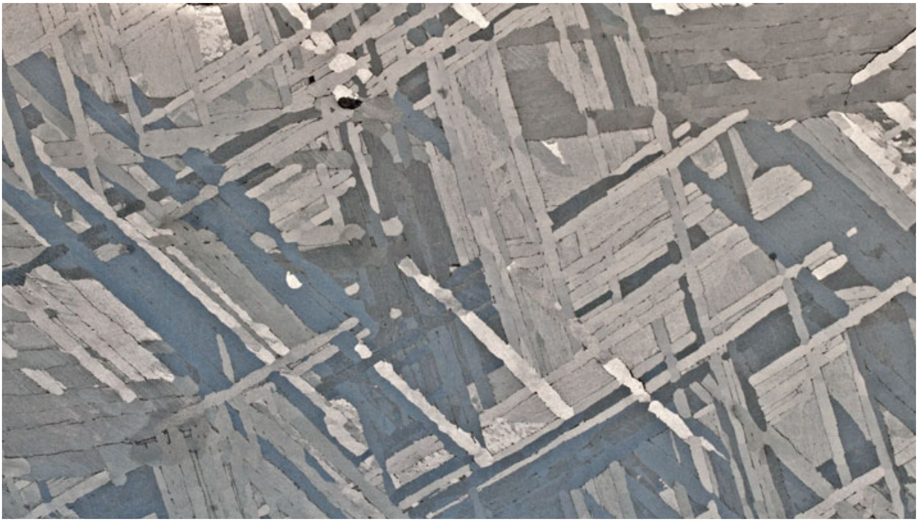
Buchwald, in 1975, provided an overview on the state of research and gave a synopsis on the dimensions of the craters. He agreed with Krinov that probably only craters "no. 3, 4, 6, 7a, 7b, and 8 are true explosion craters while the others are large impact holes" (Buchwald 1975).

In his morphological studies on several exemplary Henbury meteorite specimens, Buchwald also addressed the problem of terrestrial weathering. He determined the degree and character of soil covering to be the decisive key factor for the preservation of the meteoritic irons: "The parts exposed to the air are virtually unaltered (less than 0.5 mm lost in 5,000 years), while the buried parts show large shallow depressions with sharp ridges in-between".

As determined by Buchwald, Henbury consists of ~ 70–80 vol.% kamacite and 20–30 % taenite and plessite, with minor schreibersite ($(\mathrm{(Fe,Ni)_3P})$) precipitates and occasional troilite nodules. The microstructure is composed of large lamellar kamacite plates, in which abundant deformation

	percentage			ppm								
REFERENCES	**Ni**	**Co**	**P**	**C**	**S**	**Cr**	**Cu**	**Zn**	**Ga**	**Ge**	**Ir**	**Pt**
Alderman 1932	**7.54**	**0.37**	**0.08**	**130**	**100**							
Cobb 1967		**0.50**					**180**		**18**		**14**	
Smales *et al.* 1967						**58**	**156**	**<1**	**15**	**36**		
Wasson & Kimberlin 1967	**7.41**								**17.4**	**34.2**	**13.8**	
Lewis & Moore 1971	**7.62**	**0.47**	**0.09**	**70**								
De Laeter1972									**18.8**			
Rosman 1972												
Scott *et al.* 1973	**7.47**								**17.7**	**33.7**	**13**	
Wasson 1989	**7.47**	**0.49**				**129**	**151**		**18.6**	**<41**	**13.3**	**14.1**
Petaev *et al.* 2004	**7.47**										**13.8**	**18.3**

Chemical analyses of the Henbury meteorite after Buchwald (1975), Wasson (1989) and Petaev *et al.* (2004)



Top: Undisturbed kamacite/taenite interface of the octahedral Widmanstätten structure. Polished and etched cut section from an 825 g Henbury Individual. 5 cm width. Photo: S. Buhl

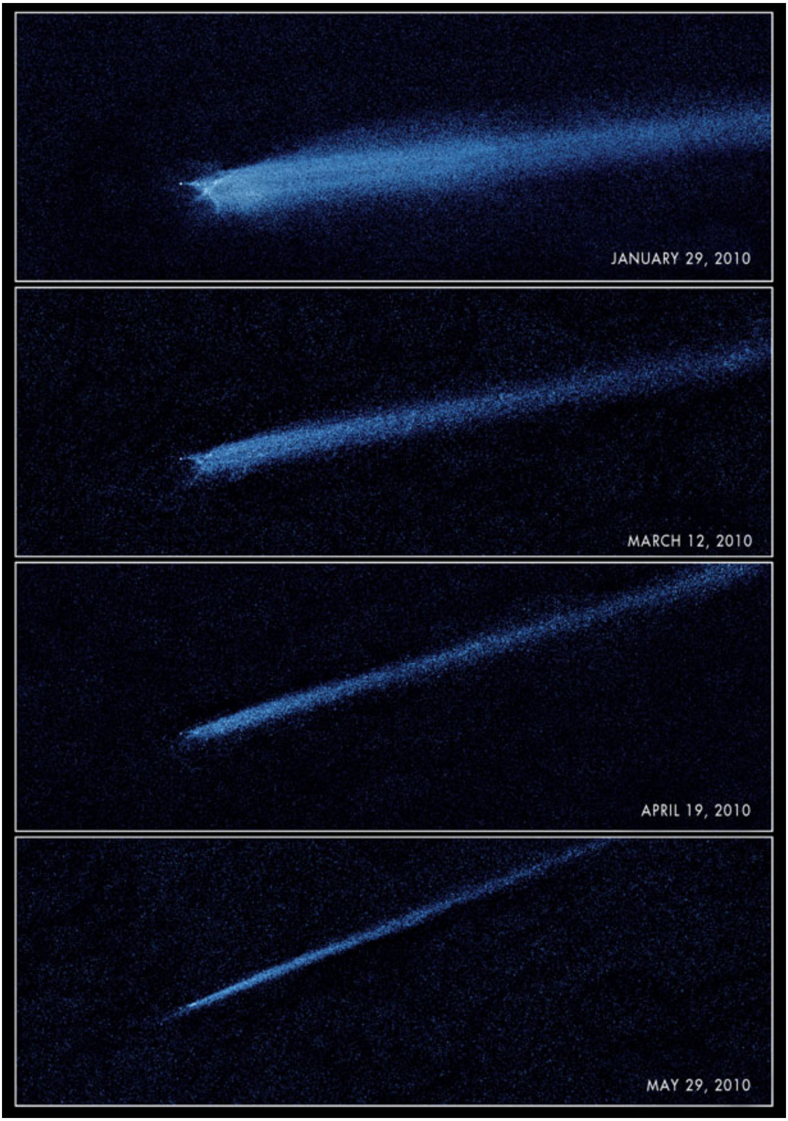
twins and mixed regions of taenite and plessite are common. The solidification age of Henbury is about 4 myr, the cosmic ray exposure age given by Buchwald is 780 ± 320 myr (Buchwald 1975).

Nogami *et al.* performed artificial ablation tests focusing on particles evaporated during the melting process. The melting point of the Henbury sample was determined at 1,550 °C and the change in elemental composition of the sample was studied in order to obtain values for the degree of elemental depletion induced through atmospheric ablation (Nogami *et al.* 1983).

Studies by Luck *et al.* (1980 & 1983) gave an ^{187}Re/^{186}Os ratio for the Henbury meteorite and obtained a formation age of 4,580 ± 210 myr. Petaev *et al.* (2004) reported a set of trace element patterns including Mo, Ru, Rh, Pd, W, Re, Os, Ir, Pt, for a number of iron meteorites, among them Henbury, which shows relatively higher levels for Re, Os and Ir in Henbury in comparison to other members of the IIIAB group (for example Cape York and Grant). A recent study about the timing of core crystallization for the IIIAB body by Cook *et al.* (2004) based on Mn-Cr age of IIIAB phosphates gave an absolute age for the crystallization of the IIIAB core of 4,517 ± 28 myr (Cook *et al.* 2004).

Furnish *et al.* (1994) conducted a suite of ultrasonic measurements and impact tests in order to measure the dynamic properties of the Henbury impactor. The studies covered wave profile compression/release tests over a stress range of 2–20 GPa as well as a cryogenic impact test to evaluate brittle/ductile transition effects.

The waveforms resulting from the impact testing were found to be similar to Armco steel, and despite the high strain rates no evidence for a ductile-brittle



Asteroid collisions like the one that has destroyed the Henbury parent body, are rarely captured with present day space observation tools. The sequence of images above is a scarce exception. It shows the aftermath of a catastrophic collision of the 35 m diameter asteroid P/2010 A2 and a smaller body 3–5 m in diameter as observed by the Hubble Space Telescope from January until May 2010. P/2010 A2 was impacted at ~ 5 km/s by the much smaller body which was destroyed in the event. The comet like debris tail created by the impact extends about 40,000 km into space. Particle sizes in the tail are estimated to vary from about 1 mm to 2.5 cm in diameter. Images taken in visible light and artificially colored blue. Photos: Wide Field Camera 3, Hubble Space Telescope, NASA, ESA, and D. Jewitt (UCLA) transition was detected in the Henbury material. The yield strength of ~ 300 MPa suggested that the material is in a work-hardened state; a fact that Furnish *et al.* relate to the abundant deformation twins in the kamacite lamellae and dislocation substructures in both phases. Furnish *et al.* argue that the deformations in the Henbury structure are due to shock pulses caused by cosmic collisions on the Henbury parent body rather than having been induced through atmospheric breakup or the impact of the material on Earth (Furnish *et al.* 1994).

What do we know about the origin of the Hebury body? Given that the empirical base provided by the recovered IIIAB meteorite suite may represent only a relatively minor core fragment and thus be biased, the IIIAB group parent body should be considered with caution. Trace elemental composition varies significantly even among single meteorites of the same fall, for example the Ir and Au contents in the Agpalilik, Thule and Savik masses of the IIIAB Cape York meteorite (Chabot *et al.* 2006, Wasson and Richardson 2001). Therefore, it is advisable to assume a quite complex structure of the IIIAB and other asteroidal cores that have yet been fully determined.

Nevertheless, the solidification time of the IIIAB core as derived from Ag-Pd isotope dating is known to be ~ 50 myr. The absolute age of core crystallization is 4,517 ± 28 myr (Cook *et al.* 2004). The cooling rate of the IIIAB group, according to Rasmussen, is 49K/myr. (Rasmussen 1989), although it should be noted that more recent studies are tending towards a considerably quicker cooling time.

According to Wasson, the compositional and O-isotopic data of IIIAB irons, main-group pallasites and HED achondrites are consistent with an origin from the same parent body (Wasson 1995). However, while asteroid 4 Vesta is commonly accepted as the parent body of most HED achondrites, Vesta is certainly not the parent body of the IIIAB irons.

There is a simple reason: Because we have close to 200 samples from the IIIAB parent body core in our collections, it is safe to assume that it was stripped from its crust and mantle and significantly disrupted during its history. Another valid point against a common origin from Vesta is provided by Haack *et al.* (1990), who estimated the radius of the IIIAB parent body to be approx. 50 km (Moeller 1998). Chabot's estimate is even lower 20–30 km only (Chabot *et al.* 2006), whereas asteroid 4 Vesta has an average radius of 265 km.

In contrast to the scarred but intact asteroid 4 Vesta, the disruption of the IIIAB body must have been catastrophic and quite complete. After the collision, the resulting debris was little more than meter-sized pieces. The complete shattering greatly contributed to our ability to narrow down the time of the breakup event. Since the resulting fragments became exposed to cosmic radiation, their exposure time can be measured, provided the sample was located within 1 m of the surface of the asteroid fragment ejected into space.

In light of this finding, it comes as little surprise that almost all ^{41}K/^{40}K cosmic exposure ages of IIIAB irons cluster around 675 ± 100 myr (Voshage *et al.* 1979). The common exposure ages indicate not only that the IIIAB samples represented in our collections have their origin in a single parent body, but also that this body was disrupted catastrophically 675 myr ago.

MCCOLL'S DISTRIBUTION MAP

S. Buhl, D. McColl, *Henbury Craters and Meteorites,* GeoGuide,
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Earlier researchers understood the distribution pattern of irons scattered around the Henbury craters as a function mainly of the explosive fragmentations caused by the impact of the crater-forming masses. McColl's work (McColl 1997) considerably developed our understanding of the fragmentation dynamics and distribution pattern of masses in the strewn field. Collating information about approximately 1 MT of specimens collected by local finders in the Alice Springs region, with the data gathered during numerous field trips to Henbury, resulted in a distribution map which allowed us to theorize a more precise trajectory of the impacting masses.

Collecting of Henbury iron meteorite specimens was relatively slow during the 1940s to 1960s, since most of the surface specimens had been picked up, and the better models of the modern generation of portable metal detectors did not appear on the market until about 1970. During the 1970s, these gadgets were manufactured with ever increasing capabilities, and private ownership of these detectors in Australia expanded because of the traditionally widespread enthusiasm for alluvial gold prospecting.

Initial searches were restricted to the areas adjacent to the craters, and the specimens found were treated as curiosities of minimal value. For example, the museum shop in Alice Springs formerly sold many small Henbury meteorite specimens at very cheap prices. However, during the

Henbury meteorite in situ on the characteristic gibber plain surface. Note the distinct coating of desert varnish on the exposed portion of the specimen. Specimen weight 74.0 g, dimensions: ~37 x 30 x 20 mm. Photo: D. McColl

1980s and 1990s, the area of interest expanded, and quite spectacular specimens of appreciable value were found in large quantities up to 3 kilometers from the craters. Unfortunately, very few meteorite finders either kept records or produced maps of their discoveries. During the period from 1982 to 1992, one of the authors (McColl) visited the area frequently, and was, during some of these years, a resident in Alice Springs. This provided the opportunity to meet some local collectors and to endeavor to collate their recollections of the places where they found the more notable fragments.

Apart from the shrapnel fans and shrapnel clusters mapped by Alderman, McColl's survey was able to confirm two additional areas with a dense concentration of meteoritic shrapnel. The first of these areas begins just south of crater no. 12 and extends 300 meters to the south and up onto the top of the Bacon Range. Approximately 500 pieces of the shrapnel type material were collected there in the years from 1970 to 1990. While the specimens collected at the foot of the Bacon Range, in closer proximity to crater no. 12, were usually in the weight range from 5 to 50 grams, most of the specimens recovered from the slopes and the top ridge of the Range itself were larger and weighed from 50 up to 300 grams. Less than 100 specimens were found on top of the range during the years from 1970 to 1990. As explained above, it is most probable that the shrapnel in the scatter area south of crater no. 12 originated from the impact which caused this structure.

The second area with a dense concentration of meteoritic shrapnel is located 500 m east-southeast from the main crater. It extends about 300 m along a north-south oriented axis and has a maximum width of 100 m. Its eastern and western borders are marked by dry channels of the drainage system originating at the foothills of the Bacon Range. This area yielded an estimated number of 1,500 pieces of tiny to small shrapnel specimens in the weight range of 2 to 20 grams which were collected in the years from 1970 to 2000.

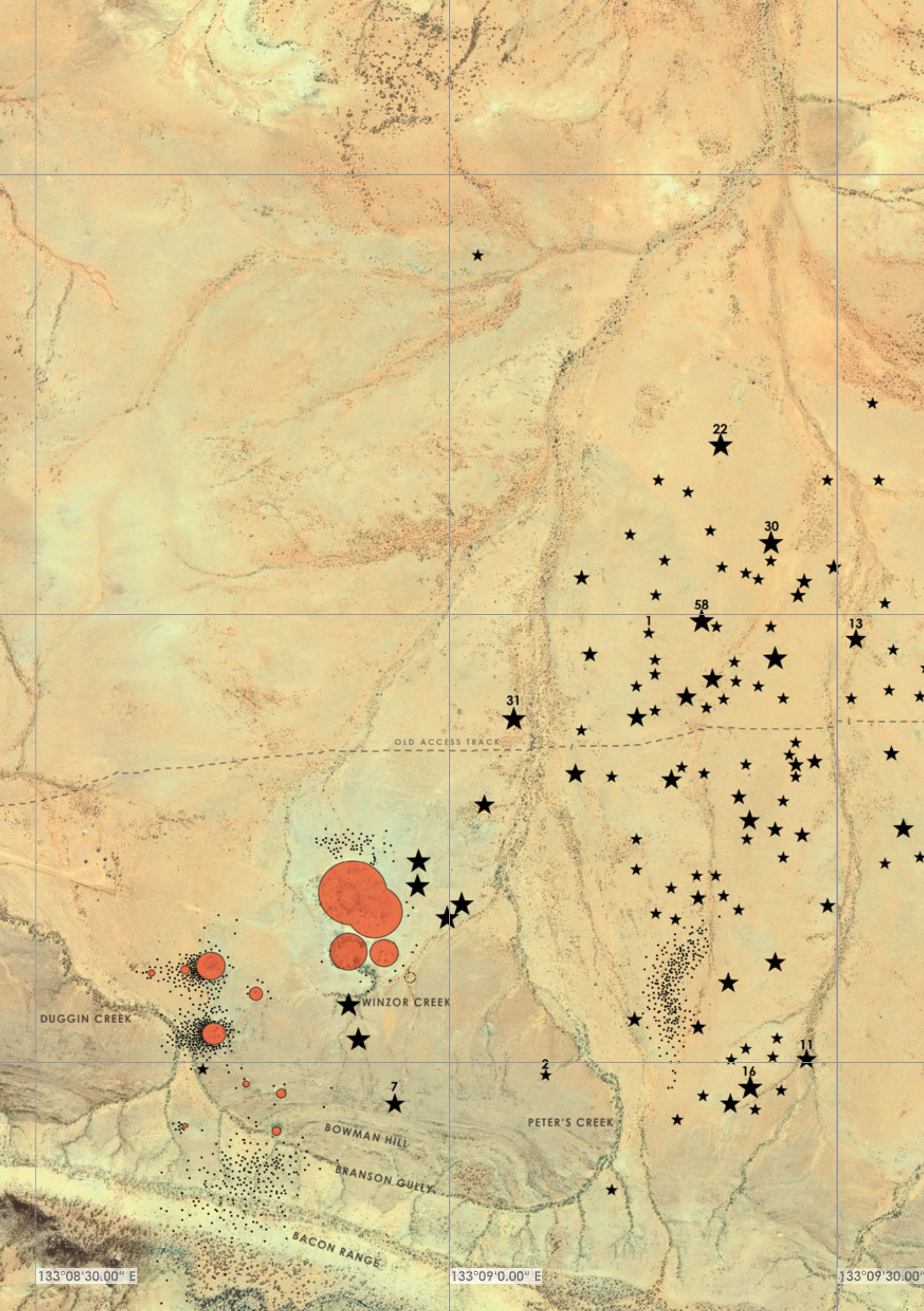
The peculiar location of this locally confined shrapnel deposit raises some interesting questions: Were these meteorites produced by an in-flight fragmentation during the latest stage of the trajectory or rather by one of the 12 impacts? If the latter is the case, what mechanism could have dispersed this dense cloud of tiny shrapnel into the southeastern radiant of the crater field and over the considerable distance of half a kilometer from the craters? Because no mass distribution has been recorded for the specimens within this shrapnel field, there is little evidence for either theory of origin. Although an origin in an in-flight fragmentation appears improbable, a low altitude airburst cannot be ruled out as a source.

In order to evaluate the possibility of an origin in one of the crater-forming impacts, it is necessary to determine a plausible azimuth of the trajectory for the impactor at first. If we assume an approach of the incoming swarm of projectiles from the southwest, as commonly supposed in the literature (Passey and Melosh 1980, Roddy and Shoemaker 1988, Melosh 1989), then the distribution of a dense shrapnel field 500 meters to the east-southeast must be considered as a contradictory piece of evidence. Because the meteoritic fragments produced in a non-vertical explosion-analog cratering event tend to retain a considerable portion of their forward momentum, one would expect them to land downrange – and this would be in the general northeast of the craters in case of an approach from the southwest. If we instead, as the authors of this work propose, assume an approach from the northeast, then the shrapnel deposit in the east-southeast

The finders Lois and Don McColl with the largest Henbury meteorite found in recent years (1986): A heavily regmaglypted individual of 58 kg discovered 0.5 km northeast of the craters. This meteorite was donated to the Strehlow Centre Museum of the Northern Territory in Alice Springs where it is on public display. Photo: D. McColl

becomes increasingly probable, provided that the interfering flow fields resulting from the simultaneous impacts close by are taken into account as a major factor controlling the dispersion of meteoritic debris in the crater field: On impact, the remaining forward momentum carried the shrapnel ejected from impact no. 7b towards the southwest, where it immediately collided with the simultaneously expanding hemispherical shock waves of the adjacent impacts of no. 6 and 8. The result would have been a considerable deflection of the 7b-shrapnel stream towards the east-southeast, particularly, if the material in question consisted of low mass-fragments, like the light, flaky shrapnel collected in the east-southeast area.

The theory of the incoming Henbury bolide descending from the northeast is also supported by the find location of the many masses with a distinct individual flight history. A few of these individual meteorites weighing up to 10 kg were found as much as 3 km away from the craters, and this almost exclusively in the northeast and east sector. Several meteorites with masses less than 10 kg were found even further northeast, up to 5 km from the main crater. The largest piece documented in this


22
30
58
1
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31
OLD ACCESS TRACK
WINZOR CREEK
DUGGIN CREEK
2
11
16
7
PETER'S CREEK
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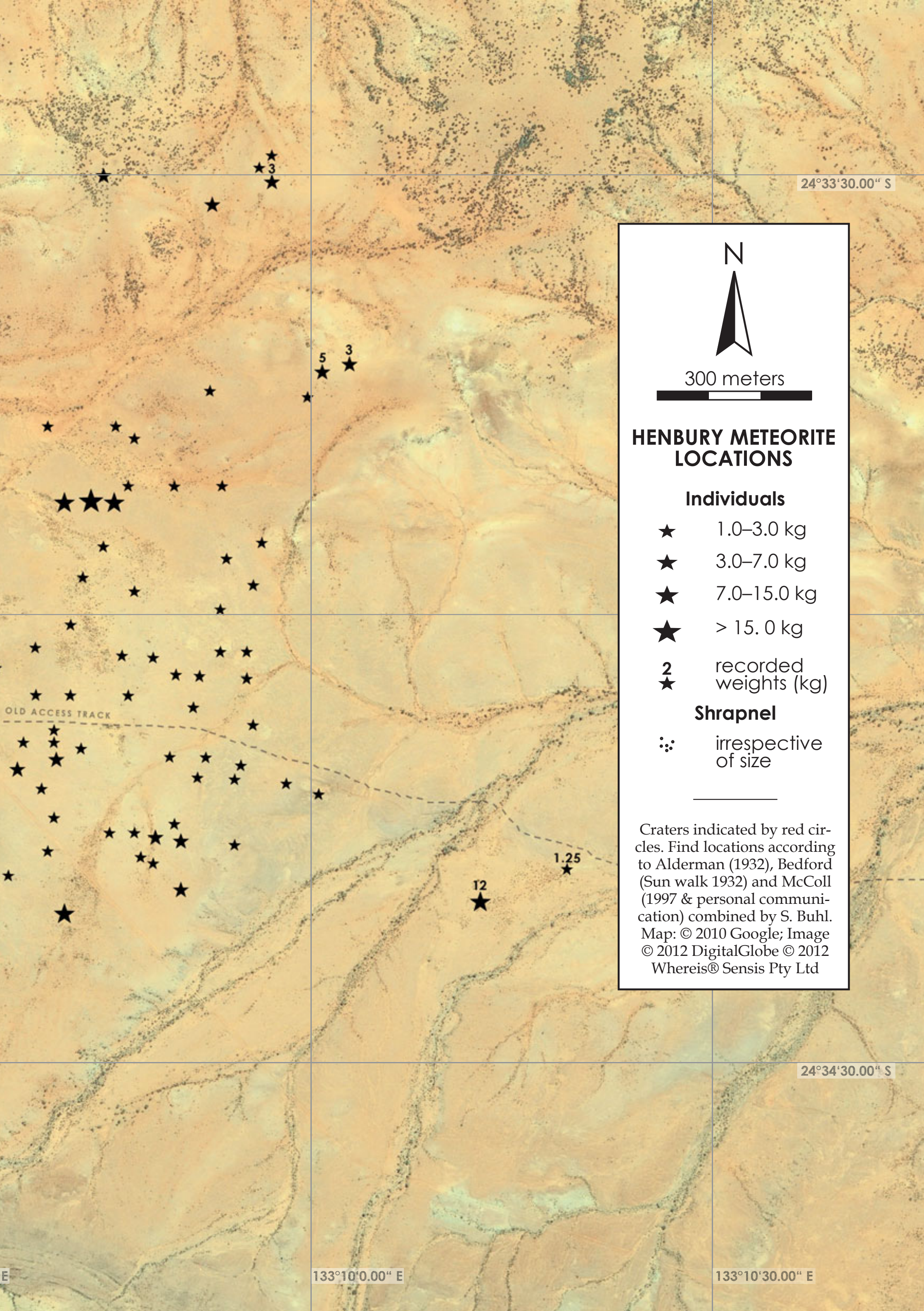

HENBURY METEORITE LOCATIONS

Craters indicated by red circles. Find locations according to Alderman (1932), Bedford (Sun walk 1932) and McColl (1997 & personal communication) combined by S. Buhl. Map: © 2010 Google; Image © 2012 DigitalGlobe © 2012 Whereis® Sensis Pty Ltd undertaking weighed 58 kg and was found buried at a very shallow depth on the pediment slopes about half a kilometer east of the craters. Most collectors' memories were vague with respect to the increasingly smaller pieces, so little effort was made to keep records of pieces which weighed less than 1 kg.

In total the find locations of over 140 individual meteorites and several hundred pieces of shrapnel were mapped or reconstructed and recorded. The meteorites collected along the northeastern radiant of the craters were either regmaglypted individuals or had already lost significant material due to soil etching, which made it impossible to confirm whether they were individual masses or of the shrapnel type. Four heavily corroded samples collected in the northeastern radiant were cut and prepared by one of the authors (Buhl) and no signs of a disturbed Widmannstätten pattern or other evidence characterizing them as shrapnel were found. No specimens with definite exterior or interior shrapnel morphology were observed among the specimens recorded in the northeastern part of the scatter ellipse.

Most specimens recorded during McColl's survey were found buried at shallow depth within the pediment slopes of the gibber plain, which covers most areas extending for at least three kilometers north from the Bacon Range. The gradient is very slight on these slopes and they are covered with a distinctive layer of silicified sandstone pebbles which can be identified quite easily with a little practice. This layer also dries very quickly after the infrequent rains, and the surface preservation of the meteorites from this environment is unquestionably much better than those buried in deeper soils. Meteorites from the pediment slopes have clear and obvious regmaglypts and usually have very little rust shale in the ground surrounding them.

Perhaps 10–20% of the area which is within the strewn field consists of alluvial sandy soil filling former drainage channels. The meteorites found in this environment

Top: Polished and etched cut section of a Henbury meteorite showing several small troilite nodules. The section taken from a flight ablated individual shows an undisturbed Widmannstätten pattern. Scale cube is 1 cm. Photo: S. Buhl. Left page: Henbury specimen of 45 kg exhibiting distinct atmospheric sculpting. This meteorite was donated to the Strehlow Centre Museum in Alice Springs where it is on display. Photo: D. McColl

are invariably buried in an aureole of rust flakes; the regmaglypts are vague and poorly defined, and some have clearly been almost totally destroyed by rusting.

Collecting of meteorite specimens at Henbury was prohibited by Northern Territory legislation in 1988. This, however, does not seem to have reduced collecting efforts, but has, on the contrary, increased the difficulties of collating location information, owing to the increasing reluctance of discoverers to divulge the location of the specimens. It does appear, however, that at the present time, very few specimens are being found, and it now seems increasingly likely that the majority of them have been removed from the strewn field.

ATMOSPHERIC BREAKUP

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The breakup of a meteoroid during its descent through the atmosphere generally occurs at altitudes between 12–40 km and the respective fragmentation dynamics are controlled by the mass and the yield strength of the material. Disruption of the meteoroid occurs when the dynamic loading exceeds the tensile strength of the material. The latter depends on the type of material: stony meteoroids are usually weaker than stony-iron, which in turn are weaker than iron meteoroids (Bland and Artemieva 2006).

In general the dynamic strength of meteoroids rarely exceeds 5 × 10^6 Pa (Ceplecha *et al.* 1993) because large bodies usually have pre-atmospheric internal structure-faults and cracks. It is, however, possible that a very strong object reaches our planet's surface without any fragmentation, while a very weak object is subjected to continuous fragmentation, with no large

Front and rear surface of a well preserved 255 g Henbury meteorite recovered 1.5 km northeast of the craters. Prior to its final fragmentation this specimen underwent atmospheric ablation as an individual mass long enough to develop distinct regmaglypts. Subsequently the meteorite fragmented in flight along a pre-existing fracture plane. After this terminal fragmentation the remaining duration of the ablative flight was not sufficient to form flight marks on the new fracture surface. The size of the regmaglypts of the recovered half indicate that prior to its final fragmentation the mass was not much bigger (Based on Krinov's (1963) regmaglypt size - mass size - formula, the maximum cross section diameter of the complete individual prior to fragmentation was < 90 mm). Masses this size and with an individual flight history of considerable duration are decelerated to a terminal velocity long before reaching the ground. The resulting terminal velocity of this specimen (90– 180 m/s) was insufficient to cause the observed fragmentation pattern as a result of an impact. The specimen is proof of the fact that successive in flight fragmentation of individual Henbury masses continued in the final stage of the trajectory. Photo: D. McColl fragments reaching the surface (Bland and Artemieva 2006).

The subsequent ballistic paths of the resulting fragments are then influenced by several factors: gravity; tropospheric wind velocities, transversal velocities resulting from violent fragmentations; differential lift of the fragments; bow shock interaction just after breakup; centripetal separation by a rotating meteoroid; and possibly a dynamical transverse separation resulting from the crushing deceleration in the atmosphere (Passey 1980).

Usually, the resulting swarm of meteorite fragments will strike the surface in a strewn field with its major axis aligned in the same direction as the trajectory of the meteoroid. Because of their greater momentum, the larger fragments tend to impact further downrange along the trajectory, while the smaller masses decelerate more quickly, and impact at the up-range end of the resulting distribution ellipse. However, depending on the specific dynamics of the atmospheric disrupture and other poorly understood factors, this idealized strewn field pattern is not always produced.

The strewn field of the Gibeon iron meteorites in Namibia, for example, shows an atypical distribution pattern: Large and small masses seem to be scattered in a radial pattern in the strewn field, with most of the smallest masses concentrated in the central area. Because glacial and fluvial transport of the individual meteorites subsequent to impact can be ruled out in the case of Gibeon, other reasons for this uncommon pattern must exist (Buhl 2010).

The little available evidence for Gibeon, points to one or several terminal mid-air explosions of significant force, and it appears that the final flight parameters of the Gibeon meteoroids were controlled by transversal velocities resulting from the kinetic impulses of these disruptions, rather than by gravity alone. Hence, the Gibeon meteoroid created a radial distribution fan instead of an ellipse (Buhl 2010). Unfortunately, in the case of Gibeon, no impact structures have been preserved and only the find locations and recorded weights of a number of masses must serve as indicators for distribution dynamics.

In the case of Henbury, the close spatial distribution of the craters and impact pits of the Henbury crater field provide sound evidence for an atmospheric breakup of the Henbury bolide at low altitude. Passey and Melosh (1980), in their numerical model for the fragmentation of the Henbury bolide, derive a possible breakup altitude of 10 km with an entry angle of 10° to 20°. Their model, however, does not consider the extension of the strewn field by several hundred flight ablated individuals 2–5 km northeast of the craters, and the researchers point out that theirs is only one among many potential scenarios.

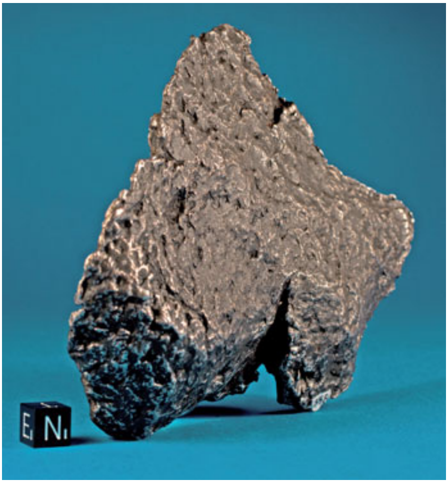
While the larger Henbury masses retained some of their cosmic velocity sufficient to form the explosion craters and deep penetration holes, the atmospheric fragmentation of the Henbury projectile also produced many hundreds of smaller masses, from several grams up to 181 kg in weight. Due to their lower mass and kinetic momentum during the final stage of their atmospheric passage, these smaller masses decelerated quickly and lost most, if not all, of their cosmic velocity. Their final descent speed was thus largely controlled by atmospheric drag and the Earth's gravitational pull alone.

The significant signs of atmospheric ablation that these individual Henbury meteorites display is evidence of a considerable duration of their ablative flight. If we assume an average rate of ablation of IIIAB irons similar to the average 0.18 cm/s ablation rate of ataxites (Lovering *et al.* 1960), and given that the large majority of individual Henbury meteorites show their complete surfaces have been shaped by ablation, it is safe to assume that the ablative flight lasted at least several seconds. This may indicate that the fragmentation or spallation of the main body started at a relatively early stage of its atmospheric passage. It is probable, but not necessarily the case, that the fragmentation that produced the crater-forming masses occurred subsequent to the initial spalling process which produced the smaller fragments.

What we know from the distribution of the Henbury craters and penetration holes is that the larger masses impacted as a relatively tight swarm. Apparently, at least two large masses simultaneously shaped the no. 7 double crater in the northeastern part of the crater field while at least twelve smaller masses formed impact craters and penetration holes west and southwest of this crater.

In the case of a simple distribution pattern controlled by mass separation alone, the southwest-to-northeast oriented crater assembly points to a flight path towards 55°, with the impact of the largest masses downrange and the smaller structures uprange (Passey 1980). This scenario, however, is contradicted by the find locations of hundreds of regmaglypted individuals to the northeast, up to at least 5 km from the main crater, and by the fact that the shrapnel fans produced by the crater forming impacts point to the west, the southwest and the south.

Not all multiple crater fields can, therefore, be explained by simple mass-separated distribution. Apart from the two sets of large complex craters in Mauritania (Aouelloul, Tenoumer and Temichat Ghallaman) and Canada (Clearwater Lake craters), there are several simple-type crater fields which show anomalies in their spatial distribution with little to no apparent mass separation controlled distribution at all. Morasko, Campo del Cielo and Sikhote-Alin are prominent examples for multiple crater fields that cannot be explained by simple mass separation alone.



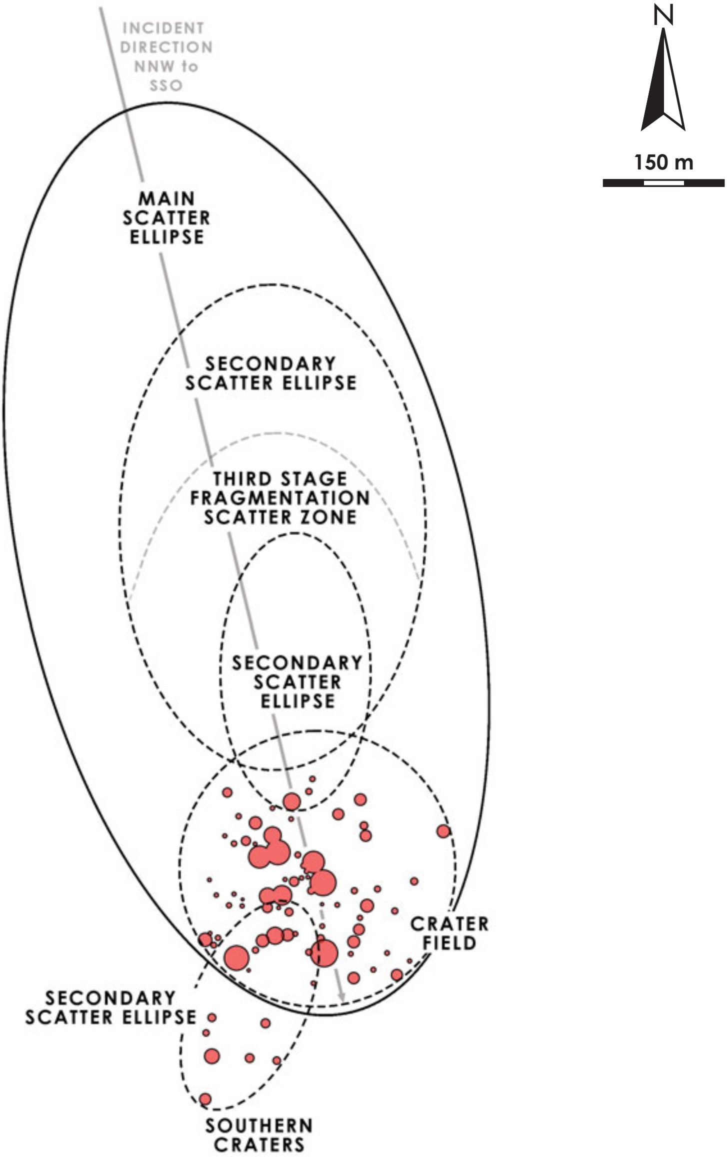
Shrapnel from a crater forming impact of the Campo del Cielo IAB main group iron meteorite from Chaco, Argentinia (1,015 g, Buhl Meteorite Collection # B-398). The lobe-shaped specimen is almost torn in half by a large torsional rupture. Photo: S. Buhl

In the case of the Morasko crater field, the interpretation of the crater morphologies indicate a south to north trajectory, while the find location of the paired Seeläsgen iron as well as other evidence suggest a trajectory towards the east-northeast (Korpikiewicz 1978, Passey and Melosh 1980, Czegka 1996 and Bartoschewitz *et al.* 2001). None of these solutions, however, do agree with a mass-separated model for the distribution of the Morasko craters, because the largest main crater is surrounded by smaller structures in the northwest, northeast, south and the southwest.

Another well-documented example of an anomalous mass distribution of a multiple crater field is the Campo del Cielo strewn field in Argentina. The IAB Campo del Cielo iron meteorite fall occurred

Henbury individual of 1,740 g (Buhl Meteorite Collection # B-393) exhibiting typical effects of subsoil corrosion. This specimen was found about 2.5 kilometers northeast of the main crater. Photo: S. Buhl

Front (top) and rear surface (bottom) of a 1,030 g Henbury meteorite found on top of the pediment gravel 0.5 km northeast of the main crater. Note the well preserved regmaglypts on the exposed surface (top) that indicate an individual flight with extensive atmospheric ablation. Photo: D. McColl



Crater fields and meteorite distribution of the Sikhote-Alin meteorite fall redrawn from Krinov (1974). Note the smaller craters at the southern end outside the main scatter ellipse

~4,000 years ago and produced an 18 km x 4 km distribution ellipse containing at least 20 impact structures. Four of these are true analogs of explosion craters, shaped by the largest masses (Passey et Melosh 1980, Cassidy 1996, Wright *et al.* 2007, Vesconi *et al.* 2011). Instead of being at the downrange end, where one would expect them, the largest craters are located near the centre of the strewn field. Although most of the penetration funnels produced by smaller masses are located uprange, there are also several impact structures of smaller masses far downrange from the large explosion analog craters. Consequently, Cassidy and Renard (1996) point out that "this is not the pattern expected in an ordinary meteorite strewn field, in which the fragments […] undergo aerodynamic size-sorting with the largest fragments carrying the farthest."

Yet another multiple crater field with anomalous mass distribution is the one produced by the Sikhote-Alin meteorite, which fell on 12 February 1947 in the Primorsky district, near Vladiwostok, Russia. In the case of Sikhote-Alin, the distribution anomalies are attributed to multi stage fragmentation that resulted in several different meteorite populations dispersed through the strewn field area (Krinov 1974). According to this model, the first fragmentation produced about a dozen large fragments, of which the majority continued to disintegrate and thus produced a scatter ellipse of ablated individuals along the path of the large masses which continued their flight. One of the initial fragments remained largely complete until it disrupted at low altitude and produced a tight cluster of craters and impact pits. Additionally, a second fragment continued along its trajectory as a single mass before it fragmented, and created a second cluster of smaller impact structures even further downrange.

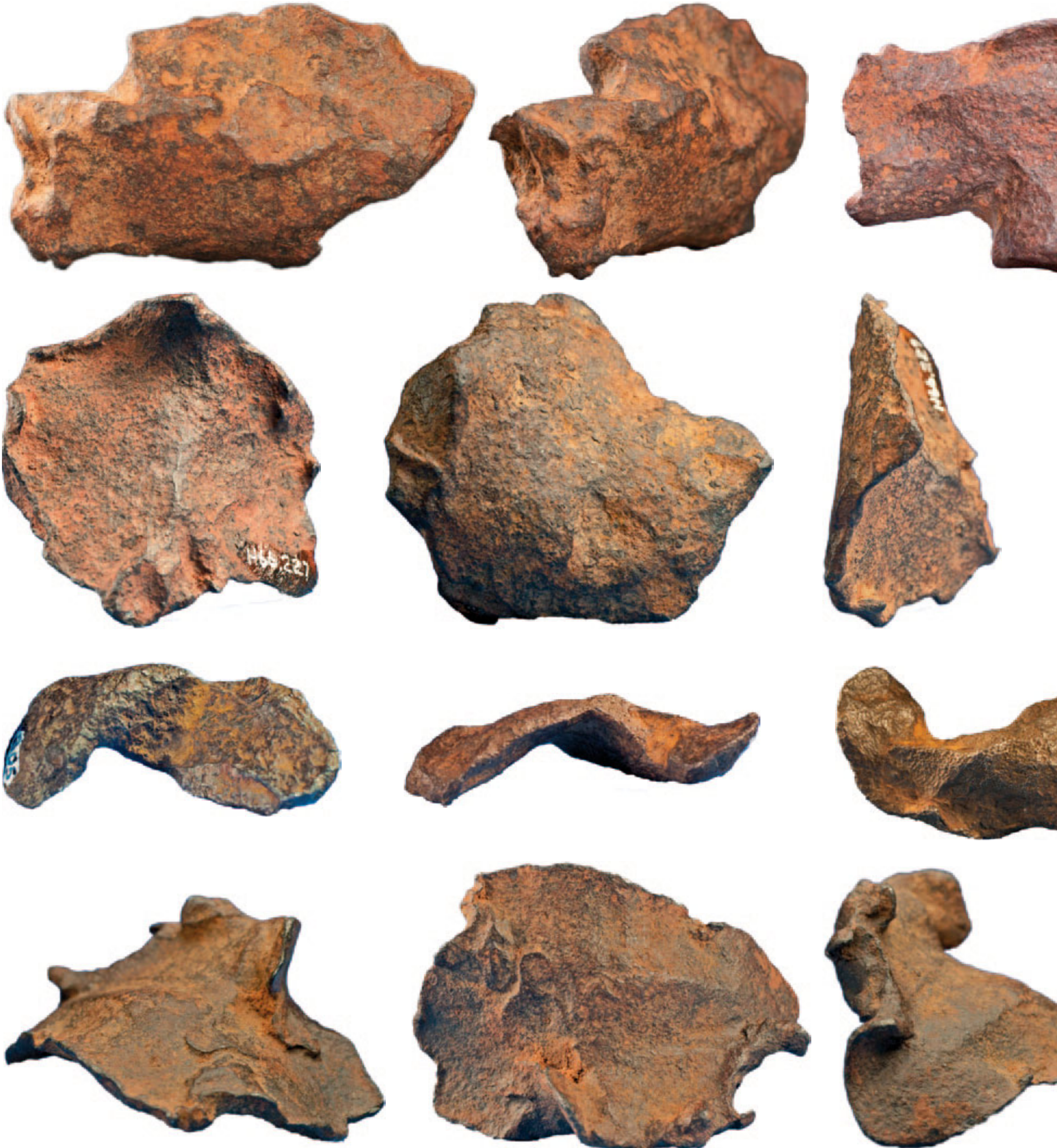
The lateral transport and downrange impact of these fragments is attributed to the irregular shape of the "mother fragment" (Krinov 1974). Passey (1980) describes the necessary condition for the production of smaller craters downrange from a main crater as a lift to drag ratio of a tumbling fragment which is higher than 10^{-3}.

The multistage fragmentation of the Sikhote body produced a main scatter ellipse of the Sikhote-Alin meteorite which is overlapped by several secondary ellipses (Krinov 1974, Stroganov *et al.* 1998). The resulting distribution pattern is a cluster of large craters quite close to the downrange end of the distribution ellipse and a number of additional smaller craters at the far tip of the downrange end.

The calculation of the Sikhote bolide's trajectory based on no other evidence than the size distribution of the craters alone, would have led us to conclude the flight path was from the southwest. In fact, and as observed by the many eye-witnesses of the fall, the Sikhote bolide descended from the opposite direction from the north-northwest, and fragmented along an axis oriented towards the south-southeast. The axis of the bolide's trajectory is marked with a dense field of regmaglypted individuals scattered along its approach path in the north-northwest of the crater field (Krinov 1974).

The parallels to Henbury are obvious: Assuming a multi-stage atmospheric fragmentation model for a Henbury projectile traveling along a northeast to southwest trajectory would not only explain the presence of smaller craters and impact pits downrange from the main crater, but also the existence of a large field of individual masses uprange from the crater field. In addition, this model is consistent with the orientation of the shrapnel fans ejected from the explosion craters no. 3 and 4 as mapped by Alderman and confirmed by McColl and others.

FRAGMENTATION ON IMPACT



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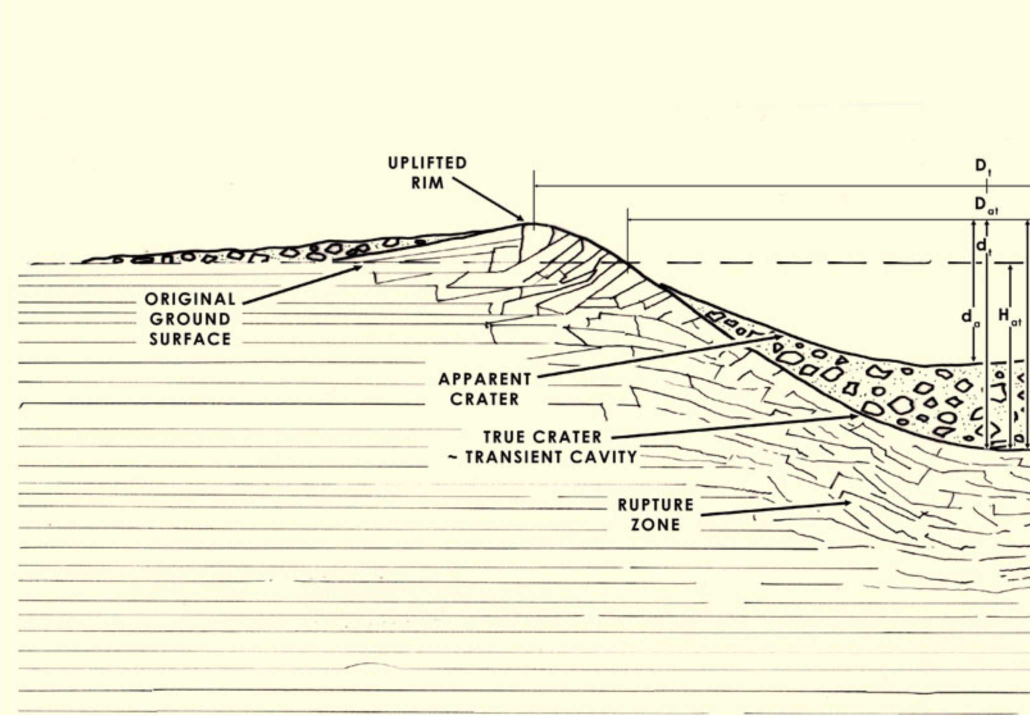
When the Henbury projectile entered Earth's atmosphere its internal structure was already weakened through fractures, cracks and shear planes obtained in the initial breakup event which disrupted the IIIAB parent body. When the accumulating atmospheric drag tore the Henbury meteoroid apart, it disintegrated into numerous fragments along these planes.

Structures indicating a pre-atmospheric shock event in the Henbury material include recrystallized kamacite around shock melted troilite. The recrystallized grains display new generations of Neumann bands which show an independent orientation in respect to the previously existing patterns. Severe cracks along the Widmannstätten planes now filled with terrestrial corrosion products further point to the event when Henbury was violently dislodged from its parent body (Buchwald 1975).

After the first stage of atmospheric disruption the main body (or bodies) of the Henbury meteoroid continued their descent with a velocity of several kilometers per second. It took the main bodies of the Henbury meteoroid swarm only seconds to cross Earth's lower atmosphere and impact the surface. The collision of the largest bodies with the target occurred with a terminal velocity of at least 3 km/s (Fair 1987), more probably 6–8 km/s, and led to the explosive excavation of the double crater

Henbury shrapnel from the crater-forming impacts. Top row: 101.8 g (Buhl Meteorite Collection # B-393). Second row: 62.0 g (The Tricottet Collection, formerly American Meteorite Laboratory with G. Huss hand-painted number H66.227). Third row: 24.2 g (Buhl Meteorite Collection # B-395). Bottom row: 33.8 g (Klaus Becker Collection). Specimens shown approximately in original size. Photos: S. Buhl

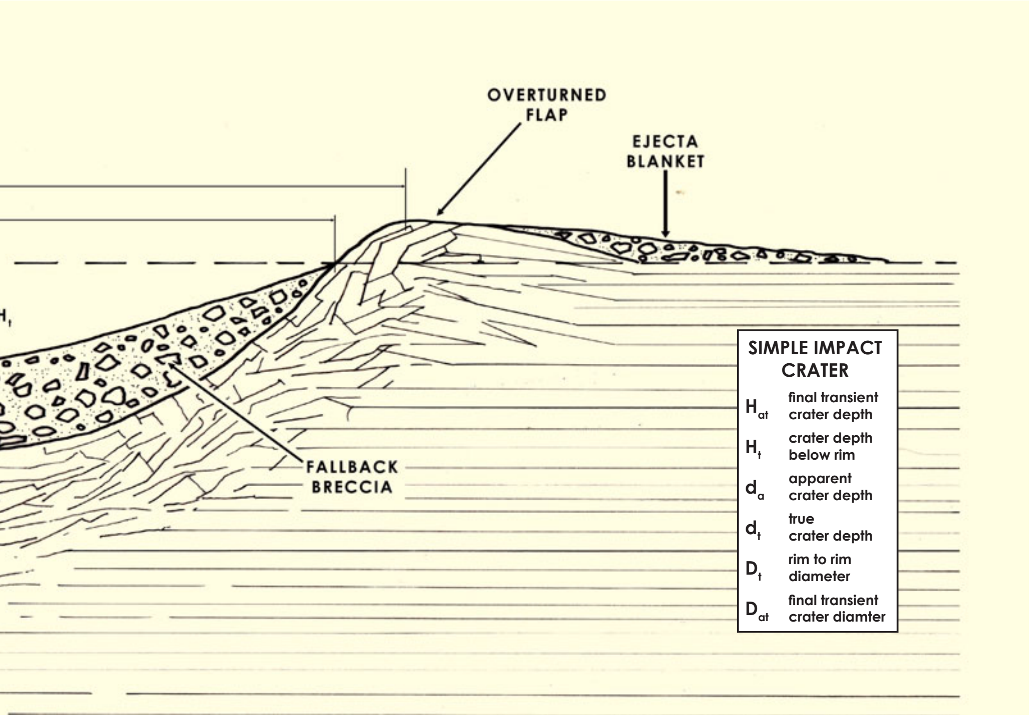


no. 7 (a and b) and the other true explosion craters no. 3, 4, 6, 8 and 12. Upon the hypervelocity impact, the main projectiles were disrupted, a substantial part of them vaporized, while the remainder of the impactor was ejected from the crater as a jet of fragments. This process was accompanied by some melting both of the projectile and of the target rocks.

The tangible signs of this hypervelocity impact lay scattered all over the site when Alderman arrived at the Henbury craters in 1931. Among the first peculiarities that caught his attention was the presence of a large number of iron fragments in close proximity to the craters, and he correctly concluded that they were impact shrapnel: "It is, of course, difficult to realize how a huge mass of iron would behave under the conditions which must have prevailed when the meteorite landed, but one would expect that the impact would cause the bodies to be at least partly shattered. This idea is supported by the shape of many of the fragments" (Alderman 1932).

When cutting Henbury shrapnel one will find proof of Alderman's assumption in the shape of violently deformed Widmanstätten patterns. The kamacite commonly shows lenticular deformation and fields of twisted Neumann lines. On the exterior, slickenside surfaces from shear-rupturing are commonly seen.

Axon *et al.* (1975) conducted a metallurgical analysis of such shrapnel, along with cross sections cut from larger fragments

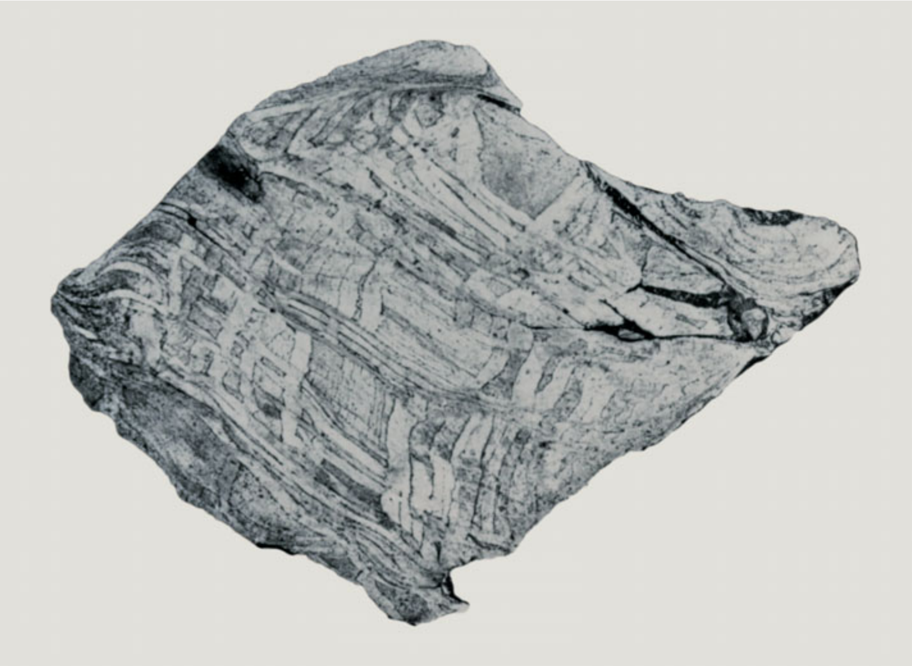


Simple type hypervelocity impact crater. Adapted from Melosh (1989), French (1998), Pirrus (1995) and Glasstone (1977). Note that the cross section shows the rim crests eroded free of fallback ejecta as is the case at Henbury. S. Buhl

recovered from impact pit no. 13. In the shrapnel pieces they found internal cracks merging into pronounced displacement faults. Other fault displacements traversed these cross sections parallel to the outer edge of the respective samples. The authors concluded that the outer fracture surfaces represented the extreme situation in which limited shear displacement gave way to physical separation along fault surfaces (Axon *et al.* 1975).

The same features have recently also been observed by D'Orazio *et al.* (2011) during examination of meteorite shrapnel collected at the Kamil impact crater in southwest Egypt. Meteoritic shrapnel from the Kamil crater displayed distinct curvilinear shear bands which were superimposed on the deformational bending – a process to which the majority of the specimens studied were subjected to.

Along these shear faults the crystals of schreibersite, troilite and daubréelite, and the duplex pattern of the plessite are displaced in zones of just a centimeter or so by mylonitized material. Consistent with the findings of Axon *et al.*, D'Orazio and his fellow researchers attribute the presence of



"Cut & etched *slug* with distorted figures". This cut surface of a shrapnel exhibits extensive compression and torsional deformation of the Widmanstätten structure. Photo: British Museum B.M. X1, Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

these shear bands to extreme strain during progressive deformation by the impact. It is interesting to note that a large majority of the shrapnel pieces collected at Kamil crater show an external morphology which is readily explained by these curvilinear displacements. The cut samples revealed that the curved shear bands were parallel to external surfaces of the specimen. Thus, D'Orazio *et al.* (2011) concluded that the rounded morphologies so common in Gebel Kamil shrapnel were due to separation along these curved surfaces of shear displacement. This mechanism also controlled the morphology of Henbury shrapnel. In the case of the IIIA irons the shear bands developed along the Widmanstätten planes.

Other evidence for fracture by separation along shear faults is found in pieces of Henbury shrapnel which were not significantly reheated during breakup. In these pieces the bulk of kamacite was shock hardened but not recrystallized. Axon *et al.* attributed the presence of shock hardened kamacite in Henbury shrapnel to fragmentation on impact, which must have occurred under a shock load of at least 13 GPa. Because the shear folds seemed to be superimposed upon the already shock-hardened structure they must have formed subsequently (Axon *et al.* 1975).

Henbury Shrapnel of ~ 50 g embedded in a silcrete block as found on Bacon Range. The specimen is one of a few hundred small shrapnel pieces which were found on the slopes and the crest of the Bacon Range (or Chandler Range) up to 250 m south and southwest of crater no. 12. Photo: N. Kammel

HENBURY IMPACTITES

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Among the different types of ejecta at the Henbury craters, no low-shock, lithic breccias were observed like those found at large complex impact craters, e.g. the Ries structure in Germany (Osinski *et al.* 2011). There is, however, one piece of evidence found scattered around the main Henbury crater which indicates the enormous pressures and temperature loads which occurred when the large masses impacted: impactite crater glass. Alderman (1932) described it as a "black glassy material greatly resembling the glass of fulgurites", and he concluded that "there is little doubt that this has been formed by the fusing of the country rock by the enormous heat of impact of the meteorite."

When the Henbury meteorite impacted the target rock, an initial curtain of molten droplets was ejected and its constituents solidified in oxide phases of meteorite and rock components (Hopper *et al.* 1990). These melts are abundant in the shape of small brown to black beads which are found within the wall of the main crater and in the ejecta radiating from it. At some spots the impact glass forms isolated clasts, sometimes wrapped around unmolten target material, and even layers extending tenths of square centimeters within the shocked target material are observed.

In analogy to Alderman (1932), McColl (1990) describes three different morphologies of impact glass found during various field trips to Henbury up to a distance

Henbury crater glass typical of the scoriaceous morphology found in close proximity of the main craters. Bedford named this material "Lava bombs" due to its resemblance to volcanic ejecta (here referred to as *type 1*). Weight 39.0 g, dimensions: ~60 x 36 x 24 mm. Scale cube is 1 cm. Photo: S. Buhl

Type 3 Henbury impact glass coating an angular fragment of sintered sandstone rock. The authors presume that these fragments were brecciated in the impact, ejected from the crater and distributed by the initial hot flow field. Photo D. McColl

of 700 meters from the main crater. Most common are the type 1 impactites which are lumps of frothy to scoriaceous black glass, some with internal reddening, which occur as rounded masses up to diameters of 5 to 6 cm, and usually weighing up to 100 grams, although occasional larger pieces have been found. They are formed by liquefaction of the target rock and soils directly under and adjacent to the meteorite impactor. This first type of impactite ejecta found at Henbury is highly siliceous in composition. The specimens have clearly been melted only briefly, but at quite high a temperature, so that volatiles they contained led to violent frothing of the liquid, with bubbles being formed up to 1 cm in diameter, but most being just a few millimeters in size. This molten rock has then been "frozen" very quickly without any apparent separation or stratification of the froth. Fragments of the type 1 impact glass are generally found immediately adjacent to the largest craters on the northwestern, northern, and northeastern sides of the craters, and are distributed up to 400 m from the rim of the main crater. These fragments closely resemble volcanic scoriae.

Henbury type 1 crater glass typical of the scoriaceous morphology found in close proximity of the main craters. Weight 27.0 g. Scale cube is 1 cm. Photo: S. Buhl

Cut section of a type 1 Henbury impactite glass exhibiting a vesicular structure and small clasts of sintered target rock. Photo: S. Buhl

Type 2 crater glass typical of the small black glass beads and threads which are only found along a narrow east radiant from the main crater. Weights 0.2–1.1 g. Photo: S. Buhl

The second type of impact glass which is somewhat similar to the one described above, is black glass droplets and threads, which are much less frothy, and contain just a few submillimter-sized vesicles. The type 2 material is much smaller than the type 1 scoriaceous glass fragments, and samples are rarely more than 1 cm long and just 2 or 3 mm in width. Type 2 specimens generally weigh less than a gram, and are commonly quite lustrous and shiny, suggesting that there has been no perceptible tendency of this glass to devitrify. The original fluidal liquid state of these specimens is emphasized by the rounded droplet shapes, and the elongated, clearly stretched threads which must have formed in a void of some type. This morphology is distributed mainly along an eastern radiant from the main crater, which the sources cited consistently described as a very narrow corridor extending approximately one kilometer to the east (Sun Walk 1932, McColl 1997, McColl personal correspondence). It appears that these glass droplets were deposited by a single jet of liquefied ejecta.

The type 3 glassy impact material consists of actual fragments of local country rock. These fragments have become coated with the black impact glass. Such specimens are quite uncommon, and much rarer than either of the other types. We presume that these mainly angular fragments of either sandstone or shale were brecciated by the shock of the impact and then coated by melted rock produced by the intense but very brief initial hot flow field. Since the internal rock core was so intensely heated

Don McColl standing between large ejected sandstone blocks on the east rim of crater no. 4. Single blocks of ejected sandstone were found up to a distance of 250 m from the craters on the very top slopes of the Bacon Range. Photo: D. McColl by this process, it has been noted to have a sintered surface texture, similar to a brick.

Most of these type 3 impactite glass materials are found on the northern and eastern sides of the largest craters, and most abundantly at a distance of between 200 m and 400 m from the craters. The impactite glass fragments are only very rarely found on the actual crater rims, but they do occur on the pediment slopes immediately past the rims themselves.

Other materials ejected from the craters, include blocky pieces of shattered sandstone, which can be up to 30 cm or 40 cm in diameter. These can be found randomly scattered in any and all directions from the craters, and often at considerable distance from them. There is also what must amount to many tons of shattered but relatively unweathered Pertatataka grey shale, which is commonly seen on the pediment slopes among the sandstone pebbles which occur in the general area. This blanket of grey shale fragments is quite common in the northeast direction from the craters and up to a kilometer or more distant. It is best observed in seasons of relative drought when the plains have very little vegetation covering them.

In addition to the types of impactites, Newsom and Boslough (2008) report impact melt rinds can be found on samples of the Henbury meteorite itself. The latter are explained as a result of melting due to incorporation of soil materials into the hot flow field, which Newsom and Boslough associate with a hot flow field caused by a low altitude airburst. The authors of the present publication are unaware of any evidence suggesting a low altitude airburst in the case of Henbury and see the hot flow field as a result of the impact of the large crater-forming Henbury masses only.

Although shrapnel coated with impact melt from the target rock has been confirmed at Henbury, these specimens are comparatively rare and hard to find at the site. At Henbury, surface weathering has removed or turned into rust flakes the outermost layers of the soil-embedded shrapnel, thus any potentially adhering impact melt rinds are stripped off as well. In the case of the Kamil meteorite impact crater in Egypt, the associated shrapnel is much better preserved and many pieces are known to display adhering melt components. D'Orazio *et al.* (2011) describe impact melt masses adhering to the surface of some Gebel Kamil shrapnel.

In comparison to the few melt-covered shrapnel at Henbury, actual target rocks coated with melt rinds are comparatively common. We documented several samples recovered from the surface near the main craters. These samples show a 0.1–0.3 mm glassy brown to semi-opaque rind, similar to the fusion crust on some achondrites.

The abundance of Henbury crater glass as well had been noted early, but it took almost thirty years after the discovery of the craters before scientists developed a more than casual interest in the Henbury impactites. At that time, tektites previously found in Australia had already been under intense study for decades but the question of their origin remained. Of the few meteorite craters known on the continent, none matched as a source that could have produced such a large number of impactites. The Henbury craters, however, are too small to come into play as a possible source of the Australasian tektites, and to the best knowledge of the authors, they were at no stage considered as a plausible candidate.

In 1964, Taylor and Kolbe from the University of Canberra investigated the loss of elemental constituents in crater glass at temperatures exceeding 1,000 °C. They were investigating whether the present elemental compositions in impactites can be used to identify possible parent materials, or, whether selective loss of volatile

Shrapnel (835 g) of the Gebel Kamil meteorite that formed Kamil crater. While the exposed surface (not pictured) shows a wind-polished desert varnish, the surface protected in situ exhibits a thin coating of melted target rock. Photo: S. Buhl

elements would raise difficulties in the identification of the parent material. Previous studies, based on the composition of australites, for example, had found no indication for selective loss of volatile elements such as cesium and rubidium. However, since the source for the australites is still a matter of doubt and debate, a comparison of parent material was not possible. With the impact glass from the Henbury craters, researchers had material available that was ideal for comparison because both the parent material and the impactites could be studied.

Taylor and Kolbe (1964) collected Henbury glass from two areas, one on the rim of the main crater, and the other 100 m north. In addition, rock samples from near the crater were taken, both from the sandstone strata and the underlying sub-greywacke. Major and trace elements of the glass as well as the parent sediments were subsequently determined. The spectrochemical analysis resulted in a surprise: The glass did not match the composition of the sandstone at all. Instead it showed a close correspondence only to the underlying subgreywacke. Except for iron, cobalt and nickel, which

Large type 1 impact glass specimen photographed in situ north of the Henbury main crater. Photo: N. Kammel were present in enriched concentrations in the glass, the elemental composition of the impact glass matched the underlying sediment. The iron/nickel and the nickel/cobalt ratios derived from the impactite samples, mirrored the elemental ratios gathered from samples of the Henbury iron meteorites. Therefore it is evident that the high concentrations of these elements originates in the contamination of the glass by the impacting meteorite (Taylor and Kolbe 1964).

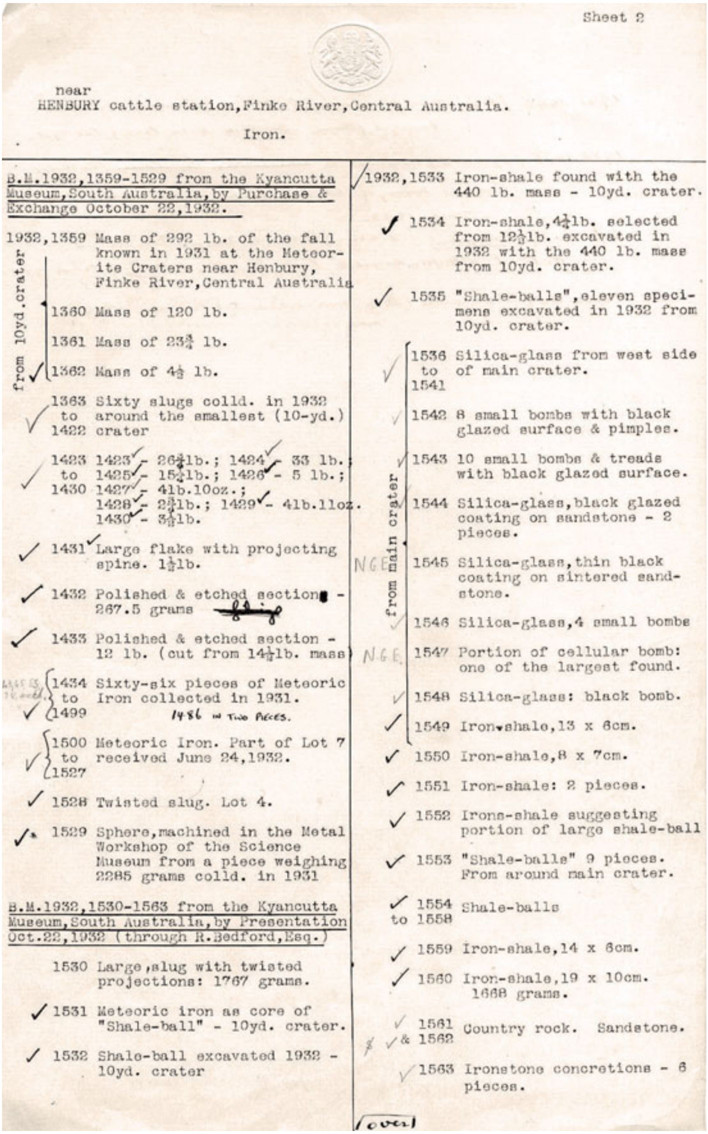
While the overall match of elemental composition derived from impact glass and source rock is quite close, slight differences between the respective samples were observed. Taylor and Kolbe (1964) attribute these differences to minor divergences in composition of the source rock. In the early days of impact glass study, it was initially assumed that siderophile abundance ratios were approximately preserved during mixing of the projectile constituents with the impact melt (Attrep *et al.* 1991). However, more recent research showed that this is not always the case. Particularly fractionation of the melted and partially vaporized meteoritic material is more important than previously thought.

Ding and Veblen (2004) take this into account and offer a more complex explanation for divergences in elemental composition of Henbury impact melts. In their detailed study of multiple crystalline phases in Henbury impactites, they suggest that Henbury glass suffered dramatic phase transformation, chemical redistribution and fractionation processes during the impact. This implies that the chemical divergence of the impact glass is rather a function of the limited diffusion time available for mixing of Fe and silica during the rapid cooling history of the impactites. Hence Henbury glass represents a chaotic mixture of equilibrium, metastable, and non-equilibrium domains at close proximity within the samples.

In addition to the macro-sized types of crater glass described above, another type of impact ejecta in the sub-milimeter dimension can be found in and around the Henbury craters. These are µm-sized meteoritic spherules which are significantly richer in iron and nickel than the impact glass. Hodge (1970) mentions two different types of these spherules. One is made up of a mixture of meteoritic nickel-iron and minerals from the soil, and the other is composed mainly of metallic or iron oxides. While the former show a composition which makes an impact-related origin plausible, the latter could as well be attributed to meteoritic dust which fell in the wake of the incoming bolide. Although Hodge mentions that the soil-related type could only be located at one specific location near the craters, he does, unfortunately, not indicate where exactly his samples had been collected. The authors were advised that Cassidy (1996) had also investigated the considerable quantities of these nickel-iron spherules that can be collected by an electro-magnet at Henbury, but that no report had been published.

El Goresy (1968) and also Gibbons *et al.* (1976) analyzed spherical droplets 2–90 µm in diameter in Henbury impact glasses, and found them to be enriched in Ni and Co and depleted in Fe relative to the projectile composition. These microscopic spherules formed by instantaneous dissemination of the projectile at the contact meteorite/target. Within a few microseconds they were injected into the host rock melts (Gibbons *et al.* 1976).

Today, the general consensus is that the crystalline phases observed in Henbury glass are the result of instant shock-heating up to temperatures between 850 °C and 1,600 °C and subsequent rapid cooling. This process of heating and crystallization during the post-shock phase, took place within just a few seconds.



Sheet 2

near
HENBURY cattle station,Finke River,Central Australia.

Iron.

B.M.1932,1359-1529 from the Kyancutta Museum,South Australia,by Purchase & Exchange October 22,1932.

from 10yd.crater

1932,1359 Mass of 292 lb. of the fall known in 1931 at the Meteorite Craters near Henbury, Finke River,Central Australia

1360 Mass of 120 lb.

1361 Mass of $23\frac{3}{4}$ lb.

✓ 1362 Mass of $4\frac{1}{2}$ lb.

✓ 1363 to 1422 Sixty slugs colld. in 1932 around the smallest (10-yd.) crater

✓ 1423 to 1430 1423✓ - $26\frac{3}{4}$lb.; 1424✓ - 33 lb.; 1425✓ - $15\frac{3}{4}$lb.; 1426✓ - 5 lb.; 1427✓ - 4lb.10oz.; 1428✓ - $2\frac{3}{4}$lb.; 1429✓ - 4lb.11oz. 1430✓ - $3\frac{3}{8}$lb.

✓ 1431✓ Large flake with projecting spine. $1\frac{1}{2}$lb.

✓ 1432 Polished & etched sections - 267.5 grams

✓ 1433 Polished & etched section - 12 lb. (cut from $14\frac{1}{2}$lb. mass)

✓ 1434 to 1499 Sixty-six pieces of Meteoric Iron collected in 1931.
1486 in two pieces.

✓ 1500 to 1527 Meteoric Iron. Part of Lot 7 received June 24,1932.

✓ 1528 Twisted slug. Lot 4.

✓ 1529 Sphere,machined in the Metal Workshop of the Science Museum from a piece weighing 2285 grams colld. in 1931

B.M.1932,1530-1563 from the Kyancutta Museum,South Australia,by Presentation Oct.22,1932 (through R.Bedford,Esq.)

1530 Large,slug with twisted projections: 1767 grams.

✓ 1531 Meteoric iron as core of "Shale-ball" - 10yd. crater.

✓ 1532 Shale-ball excavated 1932 - 10yd. crater

✓ 1932,1533 Iron-shale found with the 440 lb. mass - 10yd. crater.

✓ 1534 Iron-shale,$4\frac{1}{4}$lb. selected from $12\frac{1}{3}$lb. excavated in 1932 with the 440 lb. mass from 10yd. crater.

✓ 1535 "Shale-balls",eleven specimens excavated in 1932 from 10yd. crater.

from main crater

✓ 1536 to 1541 Silica-glass from west side of main crater.

✓ 1542 8 small bombs with black glazed surface & pimples.

✓ 1543 10 small bombs & treads with black glazed surface.

✓ 1544 Silica-glass,black glazed coating on sandstone - 2 pieces.

NGE 1545 Silica-glass,thin black coating on sintered sandstone.

✓ 1546 Silica-glass,4 small bombs

NGE 1547 Portion of cellular bomb: one of the largest found.

✓ 1548 Silica-glass: black bomb.

✓ 1549 Iron-shale,13 x 6cm.

✓ 1550 Iron-shale,8 x 7cm.

✓ 1551 Iron-shale: 2 pieces.

✓ 1552 Irons-shale suggesting portion of large shale-ball

✓ 1553 "Shale-balls" 9 pieces. From around main crater.

✓ 1554 to 1558 Shale-balls

✓ 1559 Iron-shale,14 x 6cm.

✓ 1560 Iron-shale,19 x 10cm. 1668 grams.

✓ 1561 ✓ & 1562 Country rock. Sandstone.

✓ 1563 Ironstone concretions - 6 pieces.

(over)

Sheet 2 from the Henbury Register of the British Museum. The material traded by Bedford with London included many samples of Henbury impactites and crater ejecta. Among them were type 1 impactites (B.M. 1547), type 2 glass droplets (B.M. 1542, 1543) and fragments of sandstone coated with type 3 glass (B.M. 1544, 1545). Natural History Museum London, British Museum Inventory, Henbury Register, sheet 2, B.M. 1932, 1359–1563

OTHER HOLOCENE IMPACTS

S. Buhl, D. McColl, *Henbury Craters and Meteorites,* GeoGuide,
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Small meteorite impact events resulting in explosion craters <200 m in diameter are rare in Earth's impact record. Most of these smaller impact craters are soon modified by erosion and sedimentation processes and are thus quickly erased from Earth's ever changing surface.

Considering their rarity and brief terrestrial lifetime, it is not surprising that only a dozen of these events were known up to the end of the 20th century (Campo del Cielo, Dalgaranga, Haviland, Henbury, Ilumetsä, Kaalijärvi, Morasko, Odessa, Sikhote Alin, Sobolev and Wabar). Fortunately, in recent years, two impact events (Sterlitamak and Carancas) and the discovery of two additional impact craters (Whitecourt and Kamil) have extended the known impact record, and provided us with additional data to improve our understanding of high- energy crater-forming impacts.

These relatively small impact structures are simple craters, being bowl-shaped

The Sterlitamak meteorite fell on May 17, 1990 at 23 h 20 min local time. It formed a crater in a field 20 km to the west of the town of Sterlitamak in South Bashkiria. The original impact crater was 4.5–5 m in depth and had a continuous rim 0.7 m high. An asymmetric continuous blanket and distinct radial rays of ejecta surrounded the crater. Apart from several meteorite fragments found in the ejecta field, a partly fragmented 315 kg individual was recovered from the crater at a depth of 12 m (Petaev 1992, Ivanov and Petaev 1992). During excavation work with heavy machinery the original shape of the Sterlitamak crater was completely destroyed and the structure subsequently turned into a lake with a diameter of ~ 45 m. Photo: Pjotr Muromov

Carancas, 27.20 g fragment (Buhl Meteorite Collection # B-203). The Carancas meteorite fell at 16:40 UTC on September 15, 2007 in Chucuito province, Peru. The impact of the mass, which had not fragmented prior to impact, formed a crater 4.5 m deep and 13 m in diameter. Carancas is a H4–5 ordinary chondrite. The surface pictured shows a black shock plane. Photo: S. Buhl

depressions with structurally uplifted rims, and including an overturned flap and ejecta (Grieve *et al.* 2004). If the impact structure is caused by an impact angle > 10°–15°, its original post- impact shape is usually circular. In contrast, extremely oblique impact angles below 10°–15° result in elliptical crater shapes. Most terrestrial impact craters are circular, and ninety percent of all planetary impacts occur at angles between 15° and 70° to the Earth's surface (Davison *et al.* 2011).

Meteorite impacts involve a virtually instantaneous transfer of a considerable amount of kinetic energy of the impacting projectile to a spatially limited, near-surface portion of a planet's surface. Rather than by an "explosion", the ejection and displacement of target material of simple-type impact structures is caused by a cratering "flow-field" which controls the downward and outward movement of target materials induced by shock and rarefaction waves (Grieve *et al.* 2003).

The two recently discovered simple-type meteorite craters at Whitecourt in Canada (Herd *et al*. 2008; Kofman *et al.* 2010), and near Gebel Kamil in Egypt (Folco *et al.* 2010, 2011) are of particular interest because they appear to be of relatively young terrestrial age. Both craters resulted from Holocene impact events dated at < 5,000 years and thus are of similar age to the Henbury craters. Both craters, Whitecourt and Kamil, show an extraordinary degree of preservation, and both remained largely unaltered despite terrestrial erosion/sedimentation and human activities. Of utmost importance in this context is the fact that both impacts created well-preserved ejecta patterns including macroscopic fragments of meteoritic material.

Sikhote-Alin, 471 g shrapnel (Buhl Meteorite Collection # B-377). Sikhote-Alin fell on 12 February 1947 in Primorsky kray, USSR. The impacts of many thousand masses formed in several subsequent atmospheric fragmentation events excavated 120 craters and impact pits, the largest with a depth of 6 m and a diameter of 28 m. Around 30 MT of meteorites were recovered, the largest mass weighed 1,750 kg. The specimen pictured here is in uncleaned, as-found condition and displays numerous shear marks, folded edges and secondary impact grooves. Photo: S. Buhl

KAMIL CRATER

S. Buhl, D. McColl, *Henbury Craters and Meteorites,* GeoGuide,
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The circular 45 m–diameter Kamil crater was located in 2008, in a rocky desert plain in the East Uweinat district of southwestern Egypt (Folco *et al.* 2010, 2011). The iron impactor of the Kamil crater was classified as an ungrouped Ni-rich ataxite. Not only have several types of shock-metamorphosed material been preserved intact at the Kamil crater, but also a distinct pattern of ejecta rays plus a complete suite of fragments from the impactor have survived.

Kamil is a bowl-shaped impact crater with a raised rim and is similar in many respects to the largest Henbury craters. Ejecta material in the shape of a radial blanket covers the original ground outward for 50 m from the crater wall. Three large ejecta rays which are clearly visible in aerial images extend as far as 350 m from the crater. Explosion fragments of the crater-forming iron meteorite are abundant up to a distance of 1.6 km from the crater.

After diligent mapping of the Gebel Kamil meteorite fragments by a field team of researchers led by Luigi Folco, it became evident that, unlike the ejected target material, the meteoritic shrapnel was not distributed uniformly in and around the crater. Instead it was found that the shrapnel specimens recovered from within the crater were scattered along its southeastern wall. Most shrapnel fragments collected from outside the crater walls were located due southeast of the crater in a sector between 125° and 160° N, with the densest concentration of finds at a distance of between 150 to 200 m from the crater rim (D'Orazio *et al.* 2011).

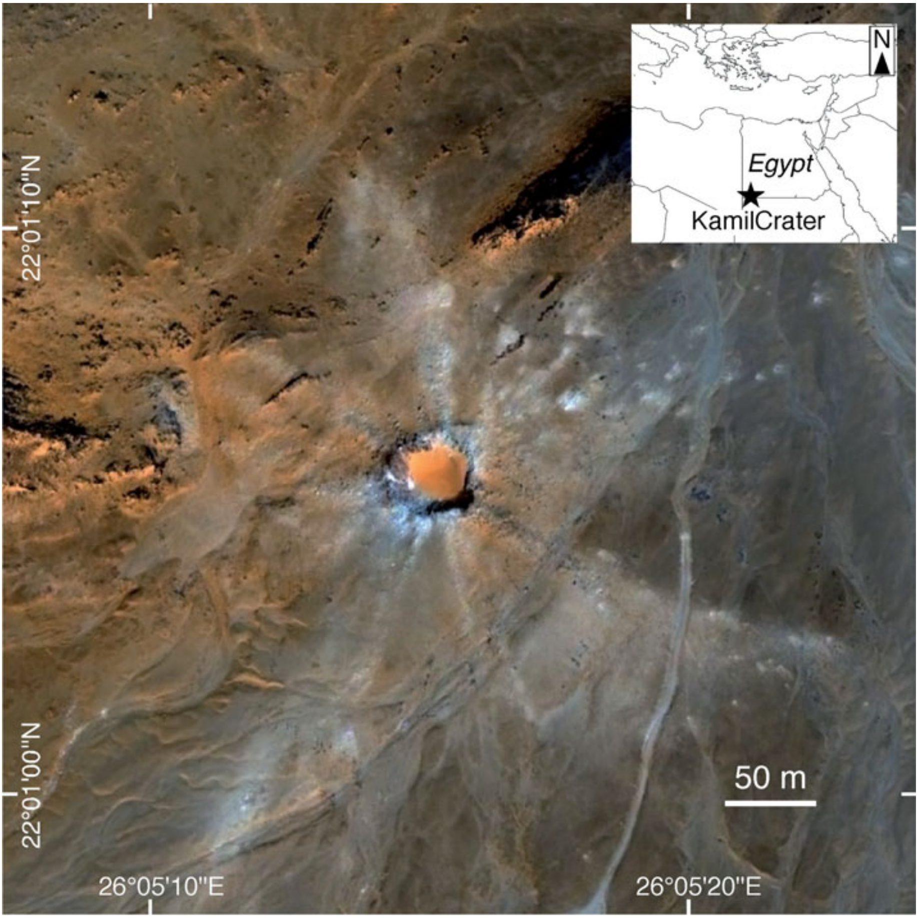
Kamil Crater (East Uweinat Desert, Egypt), view from the western crater rim. Members of the February 2010 Italian-Egyptian geophysical expedition are running GPR survey. Photo courtesy of Luigi Folco, Dipartimento di Scienze della Terra Università di Pisa

In order to estimate the trajectory of the impacting body from this data, it is necessary to consider the dynamics of hypervelocity impacts. In the case of an oblique hypervelocity impact, a roughly hemispherical shock wave originates from the point of impact and expands radially, ejecting a similar pattern of more or less metamorphosed target material. The material resulting from the initial impactor behaves differently. While the impactor's vertical momentum is significantly absorbed by shock, some pre-impact horizontal momentum remains. Although the projectile is replaced by a jet of impactor debris, the resulting explosion fragments maintain a considerable proportion of their down-range momentum, and thus are mainly distributed in the initial direction of flight.

In the case of the Kamil crater the main distribution of meteoritic shrapnel to the southeast indicates the projectile's trajectory was from the northwest. Consequently the research team around Luigi Folco suggested that the incident direction of the Gebel Kamil bolide was between 305° N and 340° N.

This conclusion is also supported by the finding of a complete regmaglypted individual of 83 kg 230 m north of the Kamil crater. This individual separated from the incoming main mass prior to, or during the ablative flight. It maintained its general previous flight direction, but due to its lower mass decelerated more quickly and fell uprange, following the impact of the main body on a relatively shorter trajectory. Like the shrapnel specimens the individual was found in an in-situ position, which is why its find location provides additional evidence for the bolide's flight path coming from the north or northwest.

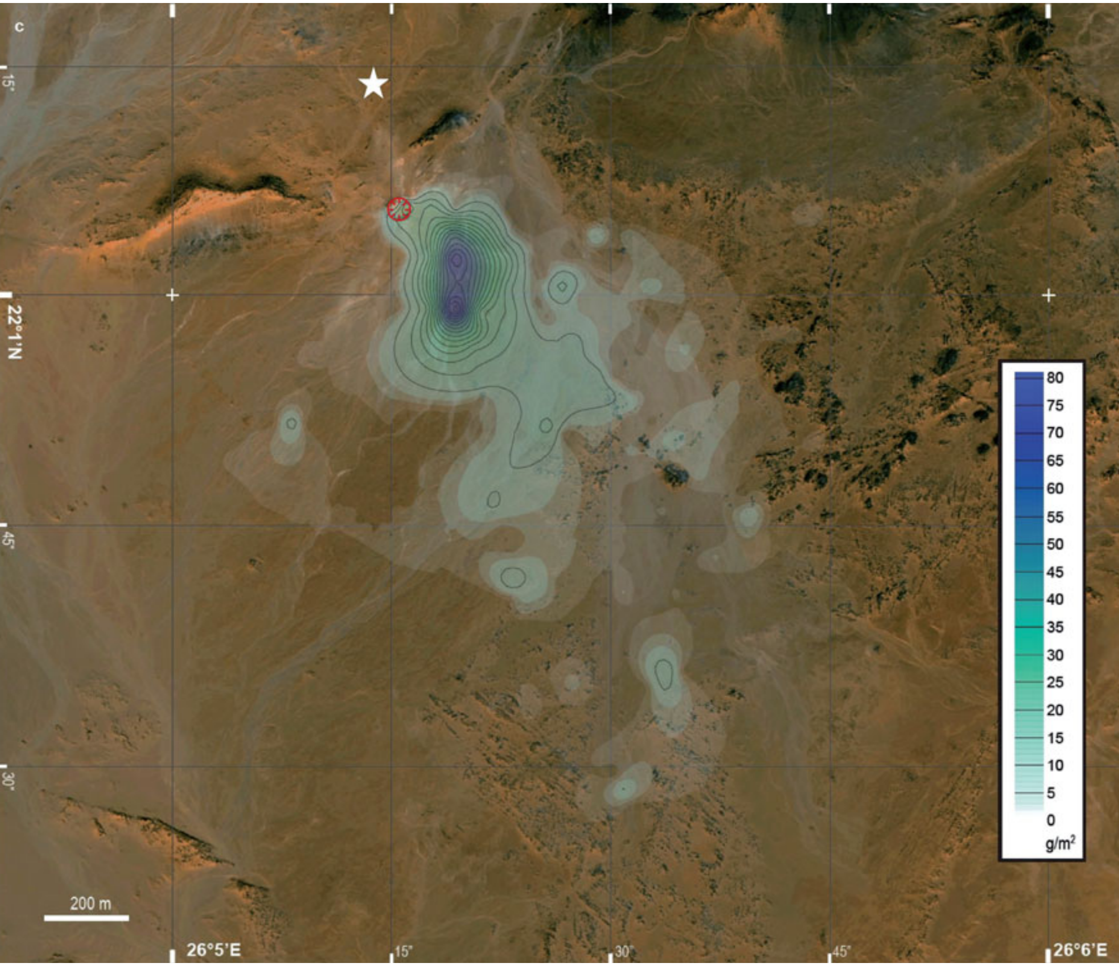
Kamil crater, view from the southeast. The target rock is composed of pale sandstones (mainly quartz-arenites) belonging to the Gilf Kebir Formation (Lower Cretaceous). The bowl-shaped simple type impact crater is 16 m deep, and has an upraised rim approximately 3 m above the average pre-impact surface. Photo: Folco L., Di Martino M., El Barkooky A.,D'Orazio M., Lethy A., Urbini S., Nicolosi I., Hafez M., Cordier C., van Ginneken M., Zeoli A., Radwan A.M., El Khrepy S., El Gabry M., Gomaa M., Barakat A.A., Serra R., El Sharkawi M. (2011) Kamil Crater (Egypt): ground truth for small scale meteorite impact on Earth. *Geology* 39, 2011, 179–182



Map based on a quickBird satellite image (22 October 2005; courtesy of Telespazio, S.p.A.) showing the Kamil Crater, southern Egypt (22°01′06″N, 26°05′15″E). The eolian sand deposit covering the crater floor and the ejecta rays radiating from the crater are clearly visible. The three longest ejecta rays extend northward, southeast and southwest as far as 350 m. Source: Folco L., Di Martino M., El Barkooky A.,D'Orazio M., Lethy A., Urbini S., Nicolosi I., Hafez M., Cordier C., van Ginneken M., Zeoli A., Radwan A.M., El Khrepy S., El Gabry M., Gomaa M., Barakat A.A., Serra R., El Sharkawi M. (2011) Kamil Crater (Egypt): ground truth for small scale meteorite impact on Earth. *Geology* 39, 2011, 179–182

739 g shrapnel of the Gebel Kamil meteorite. The center of the pictured the surface still shows original shear marks and secondary impact grooves. The patches of bright material coating the shear surface are impact melt composed of heat-altered target rock. Photo: S. Buhl

Opposite surface of the 739 g Gebel Kamil shrapnel. On its upper surface the specimen shows the typical weathering-pattern of iron meteorites exposed to corrasion (mechanical erosion) in hyper-arid climates and extreme temperature fluctuations. Photo: S. Buhl



Meteorite density map of the area surrounding Kamil crater. The data was obtained through linear interpolation of average meteorite density values of 50 x 50 m cells. Contour lines are shown at 5 g m^{-2} intervals. 5,217 meteorite specimens with a total mass of 1,710 kg were found in the search carried out by the team of Luigi Folco during the geophysical survey in February 2010. Except one regmaglypted individual of 83 kg all meteoritic material was of the shrapnel type. The data shows that meteorite fragments are concentrated due southeast of the crater in terms of mass and the concentration of the meteoritic material ejected from the crater indicates an incident direction of the projectile of 305°–340° N.

On the map the Kamil crater is indicated by the red circle, the 83 kg regmaglypted individual is marked by the white star. Map: D'Orazio M. *et al.*: Gebel Kamil: The iron meteorite that formed the Kamil crater (Egypt). In: *Meteoritics & Planetary Science* 46, Nr 8, 2011

WHITECOURT CRATER

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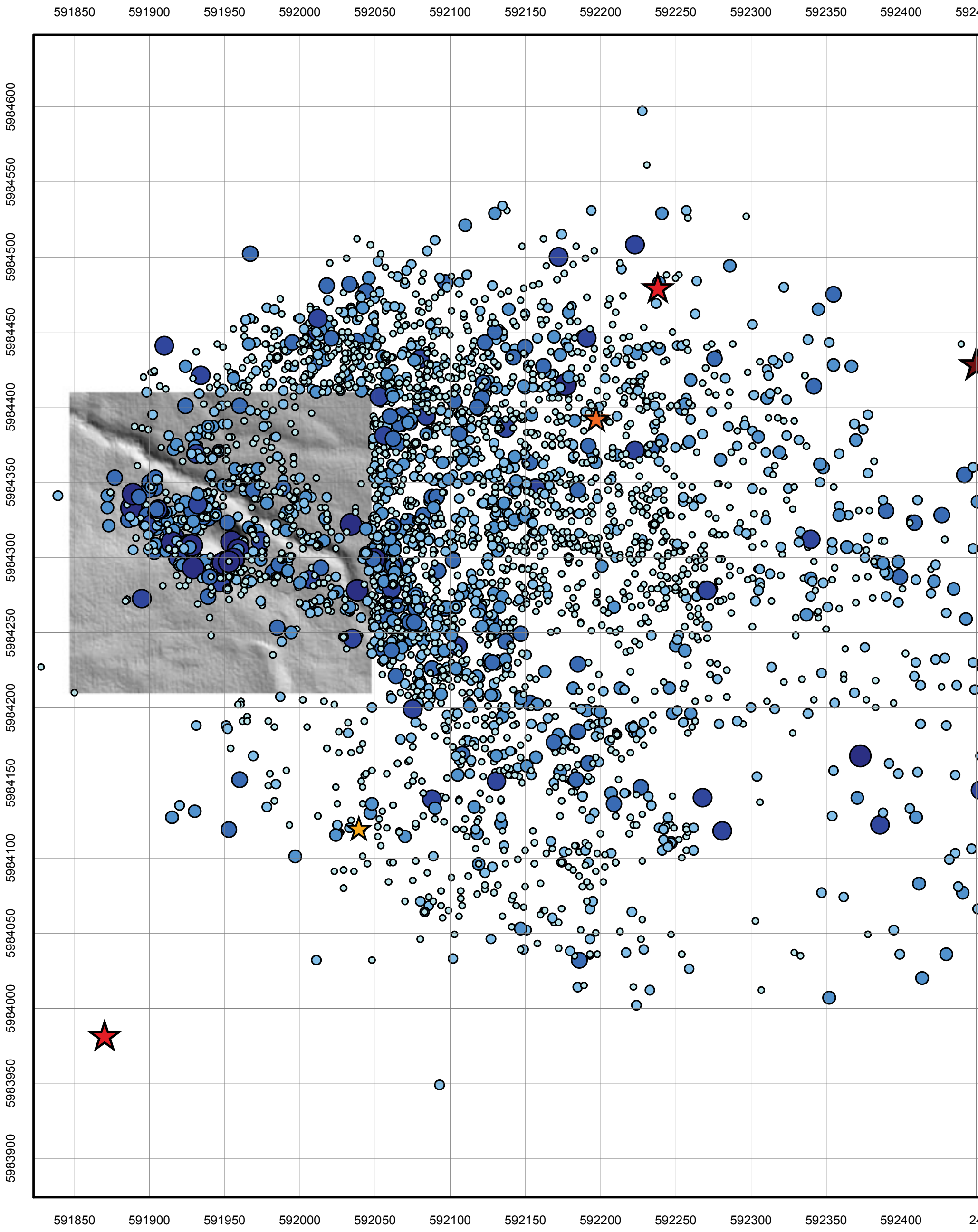
The other recently discovered and well-preserved meteorite impact crater is the late Holocene impact structure near Whitecourt in Canada. The structure was recognized as a meteorite impact crater in 2007 after local residents contacted University of Alberta Earth and Atmospheric Sciences professor Chris Herd with metallic fragments which were being found around a depression believed to be a sinkhole in a wooded area 17 km southeast of Whitecourt (Herd *et al.* 2008). Herd and his team subsequently used LiDAR (Light Detection and Ranging) imagery originally applied in the forest industry to locate the structure. The 3D aerial imagery was purchased by the university from Airborne Imaging, before it was used to precisely map the topography of the crater. While the initial LiDAR images naturally showed the surface covered by forest, the university team used special computer imaging software to remove the obstructing trees in order to reveal the crater beneath (Smith 2008).

While Whitecourt is recognized as the 30th crater of meteoritic origin in Canada, it is the first in Alberta exposed at the surface. Furthermore, Whitecourt is not only the youngest of the Canadian meteorite craters; it is also the only one that has meteorites associated with it. The Whitecourt crater, like the Kamil crater, is a simple-type bowl-shaped meteorite impact crater with a depth of six meters and a diameter of 36 meters.

Whitecourt crater, Alberta, Canada. Photo taken in the fall of 2007, Matthew Wangler (head of Alberta Historic Resources) is standing at the bottom of the 6 m deep simple type meteorite impact crater. Photo: Chris Herd, Earth and Atmospheric Sciences, University of Alberta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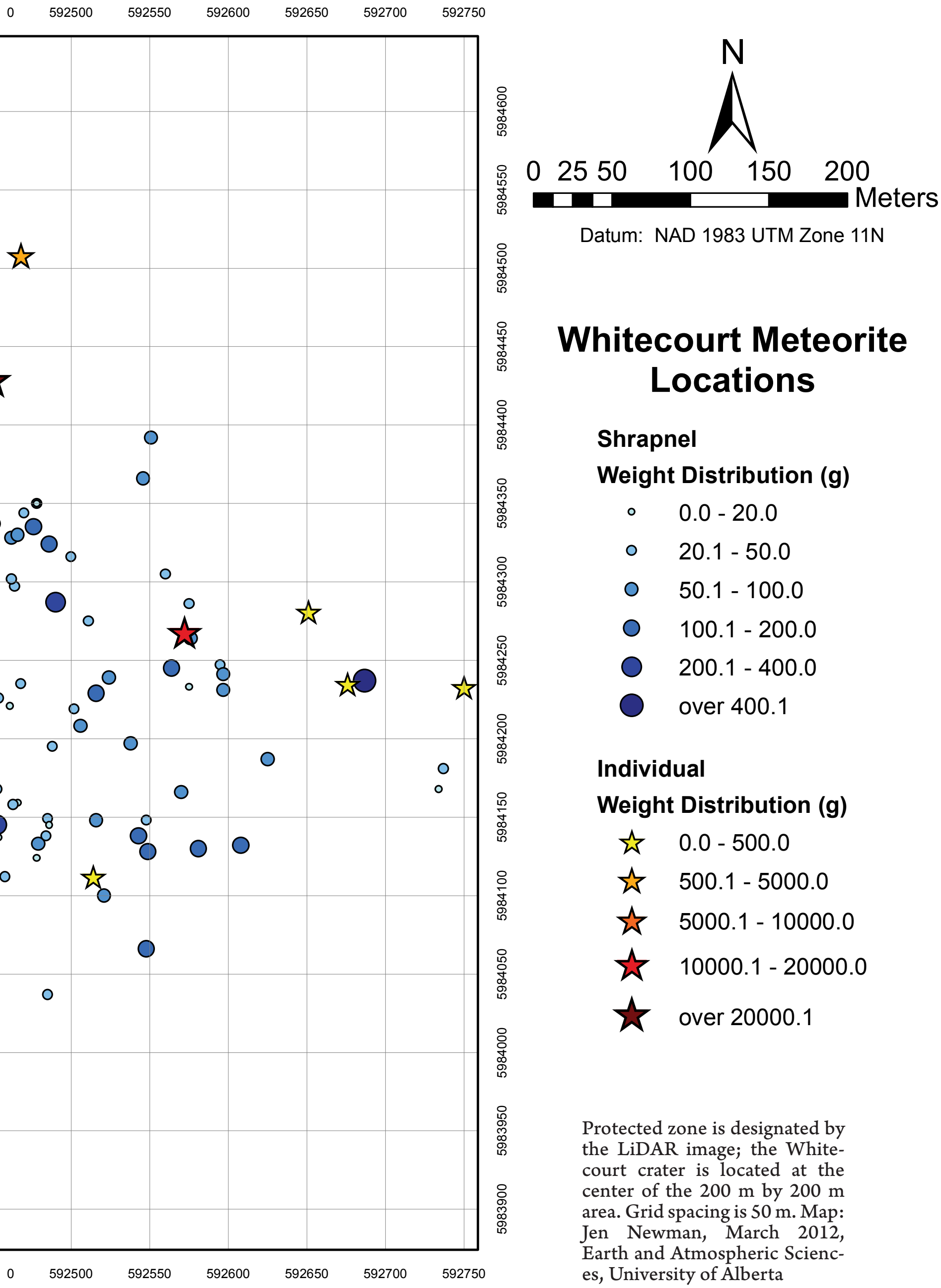


Protected zone is designated by the LiDAR image; the Whitecourt crater is located at the center of the 200 m by 200 m area. Grid spacing is 50 m. Map: Jen Newman, March 2012, Earth and Atmospheric Sciences, University of Alberta

Situated in Quaternary deglacial sediments of the retreating Laurentide Ice Sheet, the soil horizon extends to depths of 1 m in the target area and is made up of the weathered parent diamict. The target sediments are comparatively young with a sedimentation age of ~ 10 ka. Both the bowl-shaped crater floor and the crater walls underwent only moderate modification in recent history. Boreholes in the center of the crater floor show a 10 cm thick blanket of organic-rich silty soil covering a fallback breccia of heterogenous pebble diamict. At a depth of 2.9 m below the present crater floor the pebble diamict rests on medium-grained sand. Small meteorite fragments were recovered from the drill cores immediately above the 2.9 m contact zone.

The age of the crater was determined by radiocarbon dating of charcoal samples obtained from the A-horizon of a paleosol buried by the impact ejecta. The resulting data provided a maximum age for the overlying ejecta of 880–990 AD and indicated that the event likely occurred within the last 1,000 years (Herd *et al.* 2008).

Whitecourt crater is circular and was formed from the impact of an approximately 1 m-diameter type IIIAB Om iron meteorite (Kofman *et al.* 2010) which fragmented and showered the surrounding area with angular fragments. Like in the case of Kamil (and Henbury), ejected target material surrounds the Whitecourt crater in the shape of an ejecta blanket ranging in thickness from ~ 0.20 m to 0.85 m.

More than 3,000 pieces of meteoritic shrapnel were found in and near the structure, the vast majority of them at the base of the modern soil overlying the ejecta. With few exceptions, among them several regmaglypted individuals (6.5, 17, 18, 20 and 31.5 kg), these meteorites have the common jagged and angular morphologies of meteoritic explosion fragments and many of them still bear distinct shear marks.

The Whitecourt structure is located on a northeastward sloping terrace immediately south of an ephemeral stream. In early publications it was expected that this specific local topography was a major controlling factor of the crater morphology and the distribution pattern of target ejecta and meteorite debris (Kofman *et al.* 2009). But Dr. Chris Herd's research group at the University of Alberta discovered that this was not the case.

Only one specific peculiarity of the crater's morphology could be attributed to the impact angle and flight path of the crater-forming projectile. A raised rim was detected on the northeastern crater wall, directly opposite a section of the southwest rim showing no evidence of structural lift. The same feature has been seen and described in the case of much larger Lunar and Venusian craters, where the raised and depressed rim forms along the impactor's trajectory at impact angles between 40° and 45°.

Although no features such as ejecta rays were found at Whitecourt, it was confirmed that an ejecta blanket completely surrounds the crater up to a thickness of 80 cm. The concentration of ejecta material was thickest on the east-northeast side of the crater. Meteorite fragments were found in a fan-shaped distribution area to the northeast, east and southeast of the crater. The most distant meteorite fragments were found over 800 m from the crater rim.

The distribution of shrapnel occurred between 000° and 180°, with most samples between 075° and 085°. According to the distribution mechanics of hypervelocity impacts as previously discussed, the densest concentration indicates the downrange movement of the shrapnel jet. Additionally, the raised crater rim along the northeast crater wall supports the interpretation of a flight direction towards the northeast. These findings constrain the projectile's

Shrapnel of the Whitecourt meteorite (192.2 g, University of Alberta trade). Specimen is only moderately weathered, the jagged, folded edges and shear marks are clearly visible despite the thin oxidation layer. Photo: S. Buhl

Reverse surface of the 192.2 g Whitecourt shrapnel. Photo: S. Buhl flight to a direction of approximately 65° towards the northeast with an impact angle between 40° and 55° (Kofman *et al.* 2010).

Because they have obviously been shaped by atmospheric ablation, the find locations of the regmaglypted individuals relative to the distribution fan does not fit into the picture: Since their respective masses were less than the mass of the main projectile one would have expected them to land uprange from the crater due to faster deceleration. Instead the vast majority was recovered downrange. Two scenarios may provide a plausible solution for the find location of these masses: The flight path of an individual fragment traveling in the wake of a main projectile can be deflected by differential lift once the smaller fragment separates from the bow shock wave of the main projectile. Under certain conditions (for example shapes with a high lift- to-drag ratio) this may lead to an elongated trajectory and a flight further downrange and beyond the impact location of the main body. Alternatively —and this is much more probable — a swarm of individuals trailing the main body tightly in its bow shock wave may receive a kinetic impulse when caught in the expanding impact plume. Trailing fragments, once engulfed in the expansion plume, tend to move away from the crater preferentially in the downrange direction (Artemieva *et al.* 2011).

Whitecourt "main mass" recently donated to the University of Alberta. The 31.5 kg meteorite, which exhibits distinct regmaglypts indicating an individual ablative flight history is the largest Whitecourt specimen recovered to date. Photo: Chris Herd, Earth and Atmospheric Sciences, University of Alberta

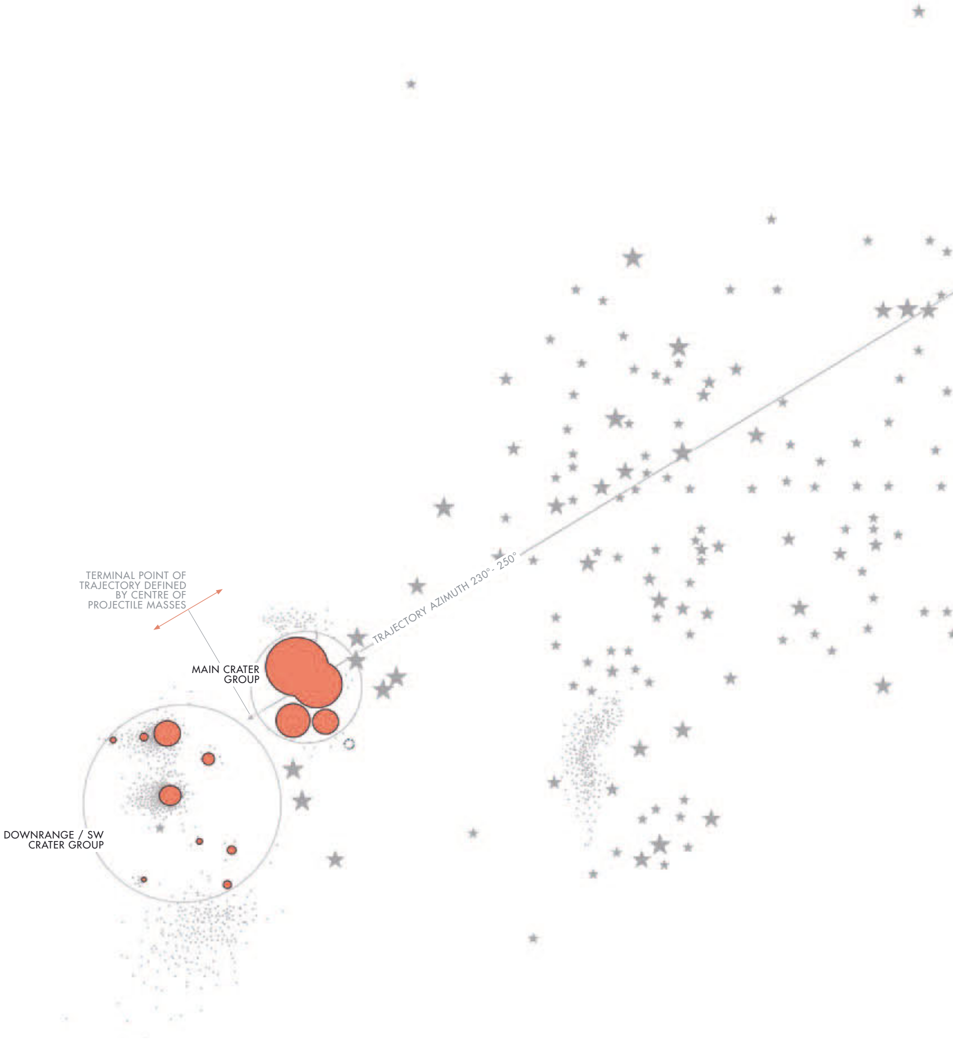
The mass distribution of the individuals recovered at Whitecourt, as well as the recent find of a regmaglypted individual south-southwest of the crater, seem to support the latter hypothesis. All other

“Sample 9” in as found condition. It is the largest shrapnel recovered at Whitecourt. The exceptionally well-preserved meteorite measures 12.5 cm across and weighs 1,196 g. Photo: Chris Herd, Earth and Atmospheric Sciences, University of Alberta

evidence combined strongly support a flight direction from the southwest towards the northeast.

As demonstrated by the examples of Kamil and Whitecourt, crater morphology, ejecta pattern and the distribution of meteoritic material produced in a hypervelocity impact can serve as indicators to determine impact angle and flight path of a projectile with relative certainty (D’Orazio *et al.* 2011, Kofman *et al.* 2010). Witnessed hypervelocity impacts, such as Sikhote-Alin (February 12, 1947), Sterlitamak (May 17, 1990), and Carancas (September 15, 2007), proved that the interpretations of these indicators are not only consistent with data derived from numeric models and experimental impact simulations but that they are also in agreement with the observations of eyewitnesses regarding the trajectory and impact angle of the bodies which caused these events (Petaev 1992 and 1992b, Kenkmann 2009 and Tancredi 2009).

HENBURY: RE-EVALUATION OF EVIDENCE



S. Buhl, D. McColl, *Henbury Craters and Meteorites,* GeoGuide,
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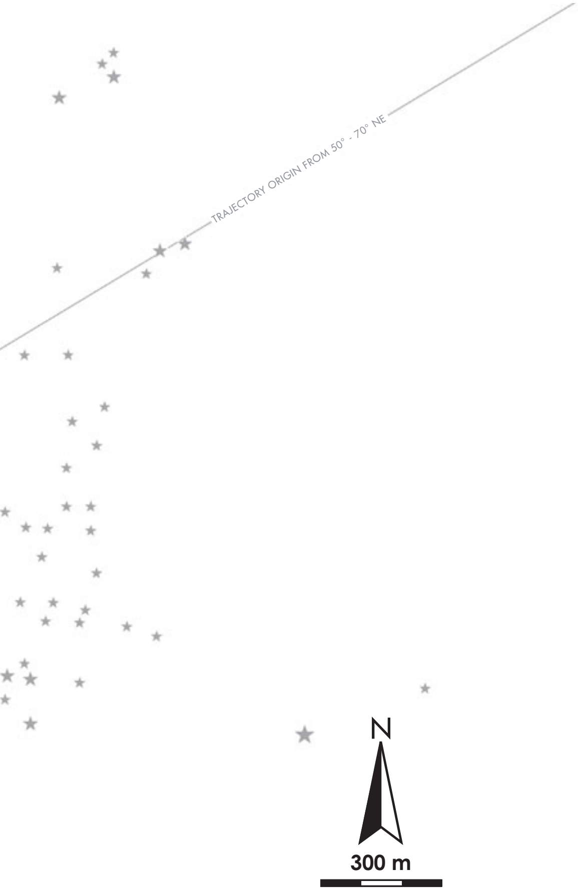


Henbury crater field, distribution of meteorites and incident direction. Individual meteorites in the North-East and East of the craters were produced by successive fragmentations of the incoming body at altitudes around 20–25 km. Secondary fragmentations contributed both, to a mixed mass-distribution pattern of meteorites on the ground and to a widening of the strewnfield. Note the general shift of lighter fragments to the south of the incident axis. The catastrophic final breakup occurred at between 3 km and 10 km altitude producing two projectile clusters with velocity components transversal to the pre-fragmentation flight path. Momentum conservation of this fragmentation event led to a "downward" directed thrust of one projectile cluster, resulting in the formation of the main crater group further uprange, and an "upward" acceleration of the other projectile cluster, resulting in the SW crater group further downrange ("downward" meaning a momentum orthogonal to the trajectory in reference to the ground, and "upward" towards the opposite direction). Craters are indicated by red circles. Location of shrapnel (dots) and flight ablated individuals (asterisks) are according to Alderman (1932), Bedford (1932) and McColl (1997 and personal communication). Combined by S. Buhl

If we take into account what we have learned from recent research concerning newly discovered simple-type meteorite impact craters, it is possible to deduce some of the parameters of the Henbury event by re-evaluating the old data.

Before we follow this path, however, we need to note that the data collected at Henbury is still far from complete. Probing and mapping the thickness, distribution and extension of the ejecta blanket has only been undertaken in a few selected places. Much of the ejecta near the main craters has been disturbed or removed by excavations and bulldozing in recent years. No studies on the respective erosion gradients for the different sectors of the crater field have been done, so there is little confirmation about which parts of the crater field represent the original post-impact distribution of meteoritic and target ejecta. And last but not least, many of the actual meteorites, particularly at some distance from the craters, were collected without recording the exact find locations (by researchers and local collectors alike).

Despite the inaccurate and incomplete data set, the available surveys and studies combined provide quite a comprehensive picture of the Henbury craters and the event that created them. In particular, we believe that there is sufficient information to suggest a projectile trajectory and fragmentation parameters consistent with recent findings on similar Holocene impacts and existing numeric models.

To begin with, the morphology of the Henbury craters offers minimal indications for an absolute trajectory of the impacting body. Their symmetry and circular outlines, however, rule out extremely low impact angles: Elliptical crater shapes, distinct asymmetries or different gradients of the crater walls within one crater would be expected from an extremely oblique impact angle. These are not observed at Henbury, and this is not surprising since approximately 90 percent of all impacts occur at steep angles to the Earth's surface (Davison *et al.* 2011).

The threshold angle for elliptical crater formation depends mainly upon the properties of the impacted surface, and to a lesser degree, on impact velocity. Numerical simulations, however, suggest impact angles of > 35–40° for circular simple type craters in rocky targets (Davison *et al.* 2011, see also Passey and Melosh 1980). Consequently the most probable impact angle for Henbury is 40–70°.

While asymmetries are not uniformly observed at Henbury, crater no. 10, with its rectangular shape, is an exception. It has a rather squarish outline, similar to Meteor Crater in Arizona. This is believed to have been caused by the bedrock composition of this specific target area, which is more compact and less fractured than the target rock of the other Henbury craters. The west and south crater walls of no. 10 show overturned flaps as does crater 7b, from which overturned bedrock extends into crater No. 6. The fact that most of these overturned flaps are oriented to the south and to the west may indicate a general momentum of the impactor towards the southwest. Given the advanced state of erosion of the crater structures, however, this should still be considered conjectural.

Milton's observation that crater no. 6 is fractionally older than the main crater 7b, is possibly significant and leads to interesting questions: Could the overturned rim material, which fell from 7b southwest-wards into crater no. 6, be an indication of a considerable longitudinal dispersion of the crater-forming swarm of meteorites? Was there a significant time lapse between the formation of these two craters, and how long did it take for each of them to actually form? Is there a time lapse necessary in order to achieve the effect observed by Milton?

The depth to diameter (H_t/D_t) ratio of a meteorite crater's transient cavity is one-third to one-fourth, which gives an initial maximum depth below the rim for crater no. 6 (average diameter 91 m) of 30 m and for crater 7b (diameter 119 m) of 40 m.

The time (T_d) required for the crater to reach its maximum depth is

$$T_d \simeq (2H_{at}/g)^{1/2}$$

where H_{at} is the depth below the pre-impact target surface and g the surface acceleration of gravity (Melosh 1989). If we subtract the height of the rim, H_{at} for no. 6 is 27 m and 33 m for no. 7b. Based on this data, crater no. 6 reached its maximum transient cavity after 2.35 seconds, while, due to its somewhat larger dimensions, the maximum transient cavity of 7b formed within 2.63 seconds. In this simplified calculation, about 2.35 seconds after the impact, while the collapse of the crater walls of no. 7b is still in progress, the resulting cavity of no. 6 has reached its final bowl shape and maximum depth, and can now receive material from the adjacent impact.

Assuming just the simultaneous impact of the nos. 6 and 7b projectiles, the resulting time difference in crater formation in order of magnitude of tenth of seconds is more than enough to allow the crater rim of 7b to partly collapse into no. 6. Hence no conclusions can be drawn from the prior formation of no. 6 on either a subsequent impact or a longitudinal separation of the no. 6 and 7b projectiles in the Henbury meteorite swarm.

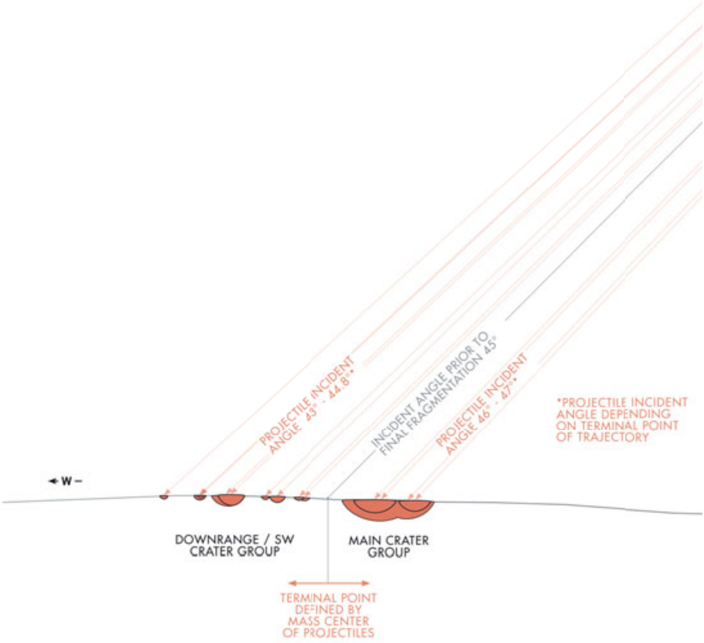
While crater shapes and ejecta distribution provide little or no evidence for a particular trajectory of the projectiles, the size-distribution within the crater field has, in the past, been repeatedly used to suggest a trajectory of the Henbury meteorites. These interpretations, based on the common mass distribution model, only take the location of the larger main craters to the northeast of the crater field to indicate a flight direction from the southwest to the northeast (Passey and Melosh 1980, Roddy and Shoemaker 1988, Melosh 1989, McColl 1997, NT Government 2002). However, as pointed out in the case of other multiple crater fields – Morasko, Campo del Cielo and Sikhote-Alin in particular – only considering the size distribution within a crater field can give a wrong impression concerning the trajectory of the impacting masses. As shown in the case of the Sikhote-Alin meteorite, multiple subsequent fragmentations, for example, can alter the size distribution of the craters towards an anomalous pattern, resulting in a crater field with larger craters uprange and smaller impact structures downrange.

What is true for the crater morphology also applies to the ejecta distribution around the Henbury craters. Ejecta blankets seem to cover the nearby terrain around the larger craters quite uniformly and provide no clue about the flight direction of the projectiles. Only those distinct rays, consisting of debris deposited by the high velocity ejecta of the initial and early phase of crater formation, show a preferred orientation to the west, southwest and the northwest (Milton and Michel 1965) and indicate a flight path roughly from east to west. Unfortunately, erosion may have erased similar rays south and east of the craters and the orientation of the few rays preserved only partially indicates the true flight direction.

Yet taking into account the combination of, distribution of the meteoritic shrapnel, the south and westward orientation of overturned flaps, and the orientation of ejecta rays, there is a consistent indication of an impactor coming from the east-northeast.

There are two distinct fans of shrapnel ejected from craters no. 3 and 4, and both are on the west-southwest sides of the craters. Another distinct shrapnel fan was documented south of structure no. 12, which represents shrapnel produced either in the no. 12 or in the nos. 6 and 8. impacts. In addition, there is a dense and locally confined shrapnel field 500 meters east-southeast of the craters 7a and 7b. The origin of the latter deposit is unclear. It may have been distributed by an airburst of a secondary fragment. Another scenario, which to the authors has a higher probability, is that shrapnel ejected from the main impact was deflected by the expanding flow field and shockwaves either of the impacts that simultaneously excavated the craters no. 6 and 8, or of one of the impacts from the 7a/7b complex.

As has already been pointed out in the case of the Kamil and Whitecourt craters, the distribution of fragments from a non-vertical explosion impact event is a very reliable indicator for the pre-impact flight direction of the impacting projectile. An even more reliable indication is given by the location of atmospherically ablated, regmaglypted individuals relative to the impact sites of the larger crater forming masses, which would be expected uprange of the impact craters themselves. This is given by the large number of ablated individuals concentrated two to five kilometers east and northeast from the craters (McColl 1997), on account of which the evidence for



Schematic W – E section through the Henbury crater field and incident angle scenario. The inclination of the trajectory prior to the final fragmentation is set at 45° and the altitude of the final catastrophic disruption in this scenario is 4 km. The incident angles of the projectiles in the two clusters produced by the final fragmentation are controlled by the position of the trajectory's terminal point, which in turn is defined by the projectile mass center. In this scenario the mass relation of main crater group and downrange crater group projectiles is set as ~ 3/1. Crater outlines are shown as transient cavities. Due to hypervelocity conditions ballistic curvature is not relevant at this scale. Numeric modeling by K. Wimmer, diagram S. Buhl

Schematic W – E lateral view of the final catastrophic disruption that produced the two crater-forming projectile clusters. The specific transversal velocities and resulting incident angles of the respective projectiles are controlled by the position of the trajectory's terminal point, which in turn is defined by the projectile masses. In order to reproduce the existing crater distribution pattern, the fragmentation-induced velocities transverse to the flight path were adjusted, and the resulting order of magnitude for the transversal velocities in this scenario is 200 m/s on average. The values for the masses producing the large craters are lower, those for small craters and big individuals are higher by a factor of around 2 in both directions, reflecting the momentum transfer by the fragmentation mechanism. Due to hypervelocity conditions ballistic curvature is not relevant at this scale. Numeric modeling by K. Wimmer, diagram S. Buhl

a WSW-azimuth of the Henbury bolide is striking. The orientation of the shrapnel fans plus the distribution of ablated individuals both agree with a flight path from NE to SW and a most probable origin of the incoming body between 50° and 70° NE (with a downrange azimuth of 230° -250°).

The distribution of glassy ejectamenta droplets along an eastern radiant of the main crater does not exclude the proposed trajectory, and perhaps even lends some additional proof to it. A single jet of high speed ejecta returning back along the direction of flight of the impactor appears perplexing at first sight. There is, however, a plausible model which supports such a single directional ray of ejecta. Trailing the bow shock wave and the hypervelocity projectile itself, there is a tunnel-shaped near vacuum zone (Short 2011). It is still present in the initial phase of the contact between the projectile and the target surface, and persists until the shock front reaches the trailing edge of the impactor. Models of hypervelocity impacts under certain conditions do predict jets, both in the downrange and uprange directions (Vickery 1990), but only the uprange jet can escape into the momentary partial vacuum tunnel left by the projectile's passage. If this was the case at Henbury, the radiant along which the glass drops are distributed is also the approximate axis along which the impactor descended.

It must be noted that the phenomenon of jetting in general is still controversial, and most theories limit its occurrence to low angles of incidence. The complex scenario of two (or more) projectiles forming one elliptical crater while impacting simultaneously, as is the case with Henbury, has not been studied experimentally. Consequently, one must be careful not to adopt the dynamics of large catastrophic impacts that produce tektites, and think that such dynamics will necessarily apply to the much smaller Henbury-size event. Nevertheless, the evidence in shape of a single ray of glass spherules suggests a very similar mechanism of origin.

In view of all of the above evidence, the authors consider a trajectory originating at 50° to 70° northeast and an impact angle between 40° and 70° to be most consistent with the field data at Henbury and the findings from similar impacts.

A complete reconstruction of the Henbury fall with narrow constraints for all parameters is not feasible due to incomplete information. As described above, the mass balance suffers from unknown numbers of individuals and impact shrapnel having been removed from the strewn field. Also we have only a vague idea of the masses producing the craters and essential dynamic parameters like the initial velocity are unknown.

It is, however, possible to develop physical scenarios to explain all the main features of the strewn field, including the anti-intuitive crater distribution. In an adhoc approach, numerical modeling was applied to prove the existence of at least one such scenario out of the many possible ones, with a simplified sequence of events and with plausible parameter values within the empirical constraints derived above.

Following its atmospheric entry, the increasing dynamic load exceeded the tensile strength of the Henbury body and initiated its disruption along pre-existing fracture planes. Our picture starts with a series of fragmentations at altitudes around 20–25 km, where fragments breaking from the main body descend as the individuals landing in the northeast of the strewn field. Secondary fragmentations probably contribute both a mixed pattern of meteorite masses on the ground, and to a widening of the strewn field. The 255 g specimen pictured in the chapter on atmospheric breakup is an example for atmospheric fragmentation of individual masses during the very last stage of the deceleration. With continuing loss of mass, the main body continued along its path until a final low-altitude fragmentation took place, which produced all crater-forming masses and perhaps also some associated individuals.

The model parameters were chosen so as to satisfy the constraints from the field evidence, e.g. the azimuth angle of 239°. Where the constraints were unknown, typical values were taken from meteorite fall statistics, such as the trajectory slope of 45° and the velocity at atmospheric entry of 18 km/s. The catastrophic final fragmentation was then found to have happened somewhere in between 3 km and 10 km altitude; we chose 4 km as parameter value. In order to reproduce the existing crater distribution pattern, we adjusted the velocities transverse to the flight path, which are produced by the final fragmentation. The resulting order of magnitude for the transversal velocities of the Henbury projectiles is 200 m/s on average, which compares to typically 500 m/s as found for chondritic falls. The values for the masses producing the large craters are lower, those for small craters and big individuals are higher by a factor of around 2 in both directions, probably reflecting the momentum transfer by the fragmentation mechanism.

Momentum conservation is also the reason for the existence of the two distinct crater groups: The group of large craters, which are further uprange, can be understood as a result of a “downward” directed thrust from the explosion, while the group of smaller craters further downrange were produced by masses accelerated “upward”. In this case “downward” means orthogonal to the trajectory towards the ground, and “upward” a momentum in the opposite direction. Such a bidirectional thrust

The Great Impact

The Henbury meteorite split into several pieces as it sped through the atmosphere. The four largest pieces excavated the craters beside you. Each was only about the size of a 200 litre fuel drum. So imagine the impact! Eight lighter fragments fell short, gouging out smaller craters to the south-west.

Henbury Meteorites Conservation Reserve

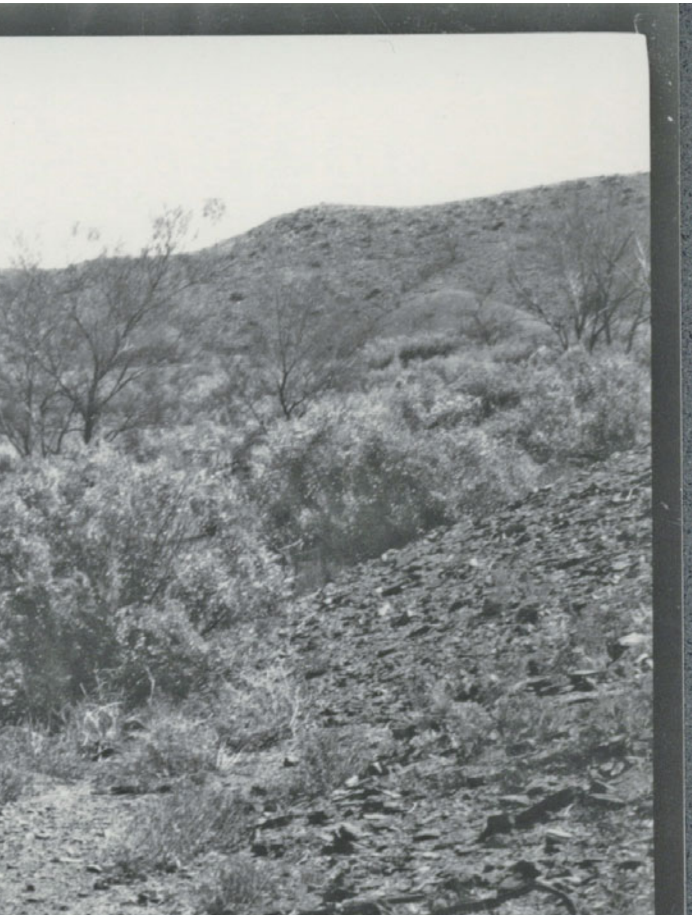
Visitor information sign at the Henbury Meteorites Conservation Reserve. Derived from the size distribution of the craters the incoming bolides are shown as approaching from the southwest. As demonstrated in the present publication the distribution of meteoritic material is in strong disagreement with this conception. The combined evidence in fact points to an approach from the opposite direction. Photo: T. Brattstrom

would be an expected consequence of a fracture plane through the meteoroid with its normal parallel to the thrust direction in the moment of fragmentation. Further refinement of this evaluation indicates that this plane normal was twisted by about 10° clockwise around the trajectory. It also seems that the fracture plane split the body asymmetrically with the resulting bigger mass being directed "downward".

It must be emphasized that the described scenario is the result of a quick approach with the aim of showing that a simple concept can account for the problem of the apparently atypical crater distribution. More detailed modeling of crater producing falls will be able to further constrain the physical parameters and to provide better insights into crater formation mechanisms and ejecta patterns. The same goes for the complex interference of simultaneously or near simultaneously expanding flow fields and shock waves and their influence on the distribution pattern of meteoritic impact shrapnel, as is the case at Henbury.

HENBURY IN THE ABORIGINAL TRADITION AND CULTURE

S. Buhl, D. McColl, *Henbury Craters and Meteorites,* GeoGuide,
DOI 10.1007/978-3-319-03955-8_16,



"Main crater Henbury: Aborigine & Bert Duggin." The knowledge of the Aboriginal guides on the origin and of the Henbury meteorite craters as well as the crater's importance for them has often been underestimated in the past. The Aboriginals' reluctance to share their mythological beliefs and oral traditions on the craters with westerners has been mistaken for ignorance. The local Aboriginal tribes told stories about the origin of the Henbury structures long before western prospectors and scientists developed any interest in them. The Aboriginal names for the craters strongly suggest that these stories involve theories on their meteoritic origin. Photo taken during Bedford's 1st trip to Henbury in August 1931. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

When Alderman investigated the craters in 1931, there was no response to his inquiries among Aboriginals of the district. None of the local tribesmen Alderman spoke to seemed to have any ideas about the origin of the craters. Thus he concluded: "If the fall had taken place since the human occupation of the area one would have expected accounts of such a notable happening to be handed down from generation to generation, and that also the locality would be regarded with superstitious awe. The Aborigines, however, showed no interest in the craters" (Alderman 1932). However, according to Brown (1975) the Henbury craters were an important water source to the local Aboriginals (although it has been observed that today, water does not persist in the craters for very long after rain).

Even though Robert Bedford had noted in his journals that Aboriginals who came to Henbury from distant areas had no taboos or inhibitions concerning the place (Laube 1990), he was still of the opinion that the fall "is comparatively recent". While at Oodnadatta, on his return journey from the craters, he interviewed Mr. J. M. Mitchell, a local prospector, who had already known about these masses of iron twelve years prior to the interview. To Bedford's surprise Mitchell was aware of Aboriginal myths connected to the craters and he asserted "that the old blacks would not camp within a couple of miles of the place" (Spencer 1932 a).

Mitchell also reported that older Aboriginal people would refer to the site as "chindu china waru chingi yabu", which can be roughly translated like this: "sun walk fire devil rock." Hamacher (Hamacher & Goldsmith 2013) undertook an investigation of these words and reported that that the language spoken by the Aboriginal informants was Luritja, a dialect of the Western Desert language that shares close similarities with Pintupi, Pitjantjatjarra, and Yankunytjatjara (Hamacher & Goldsmith 2013). The researchers identified the words quoted by Mitchell: "chindu" refers to the sun; "chinna" or "shinna" refers to feet or footprints but can also indicate a foot action like walking or running. "Waroo", according to Hamacher, refers to fire or heat; "chinka" is a word used in several Aboriginal dialects of the Western Desert and means "dead" or "devil". "Yabu" or "yabbo" refers to a rock or hill (Hamacher 2013).

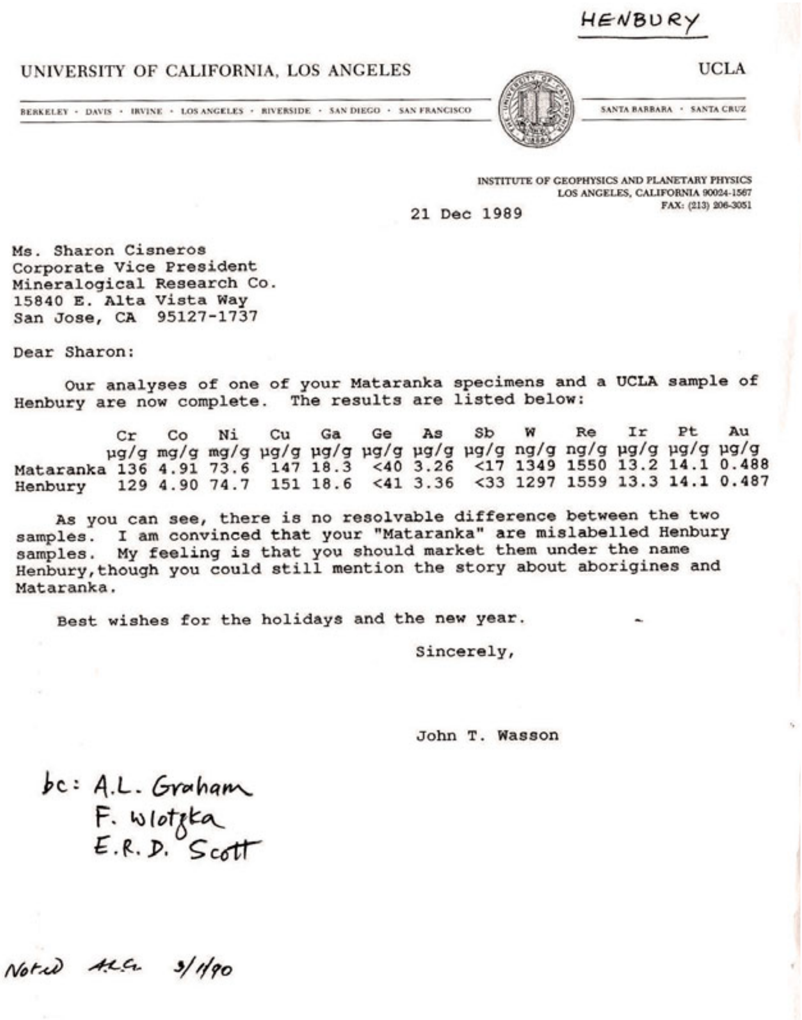
The publications of Alderman and Bedford include very little information on the Aboriginals who accompanied them during fieldwork at Henbury. We know that one gentleman was from Henbury Station, but neither the names nor the families of these men are mentioned and we can only speculate whether they were associated with the Aboriginal custodians of the crater site. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

According to Mitchell he was also told by his Aboriginal guide that they would not drink rainwater that collected in the craters, "fearing the fire-devil ("chinka waroo") that lived in a rock hole would fill them with a piece of iron" (Mitchell 1934). "The man claimed his paternal grandfather had seen the fire-devil and that he came from the sun."

“Kandimalal (Wolfe Creek Crater) and the Rainbow Serpent”. Painting by Aboriginal artist Milner Boxer. The cult of the rainbow serpent is among the most widespread religious beliefs worldwide. In Aboriginal Australia the Rainbow Serpent is believed to have made tracks all over the country, thus creating the rivers, rock holes, and other natural features of the land. It is honored to the present day by the Aboriginal custodians of the site. The anthropologist and leading expert on Aboriginal mythology on Kandimalal, Peggy Reeves Sanday, interviewed Aboriginal elders and recorded their family stories. She reports the following account by Milner Boxer on the creation of the Wolfe Creek Crater:

“Star bin fall down from top and made it. That’s what happened, a big star fell and made Kandimalal (the Crater). We call that star kiki in our language. There was a Rainbow Serpent traveling inside the ground and it came out from the crater. That snake was traveling underground. He came out right in the center of the crater. That’s where the water comes from in the middle of the crater. It comes from Sturt Creek. Sometimes, you can see that snake. In the wet season you can see him. He appears like a big light in the middle of the water. That rainbow — big snake, water snake. The name of the snake is Kalpurtu.”

Photo published with permission of Peggy Reeves Sanday, originally published in: Peggy Reeves Sanday: Aboriginal Paintings of the Wolfe Creek Crater: Track of the Rainbow Serpent. Philadelphia: University of Pennsylvania, Museum of Anthropology and Archaeology Press 2007



HENBURY

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21 Dec 1989

Ms. Sharon Cisneros
Corporate Vice President
Mineralogical Research Co.
15840 E. Alta Vista Way
San Jose, CA 95127-1737

Dear Sharon:

Our analyses of one of your Mataranka specimens and a UCLA sample of Henbury are now complete. The results are listed below:

	Cr μg/g	Co mg/g	Ni mg/g	Cu μg/g	Ga μg/g	Ge μg/g	As μg/g	Sb μg/g	W ng/g	Re ng/g	Ir μg/g	Pt μg/g	Au μg/g
Mataranka	136	4.91	73.6	147	18.3	<40	3.26	<17	1349	1550	13.2	14.1	0.488
Henbury	129	4.90	74.7	151	18.6	<41	3.36	<33	1297	1559	13.3	14.1	0.487

As you can see, there is no resolvable difference between the two samples. I am convinced that your "Mataranka" are mislabelled Henbury samples. My feeling is that you should market them under the name Henbury,though you could still mention the story about aborigines and Mataranka.

Best wishes for the holidays and the new year.

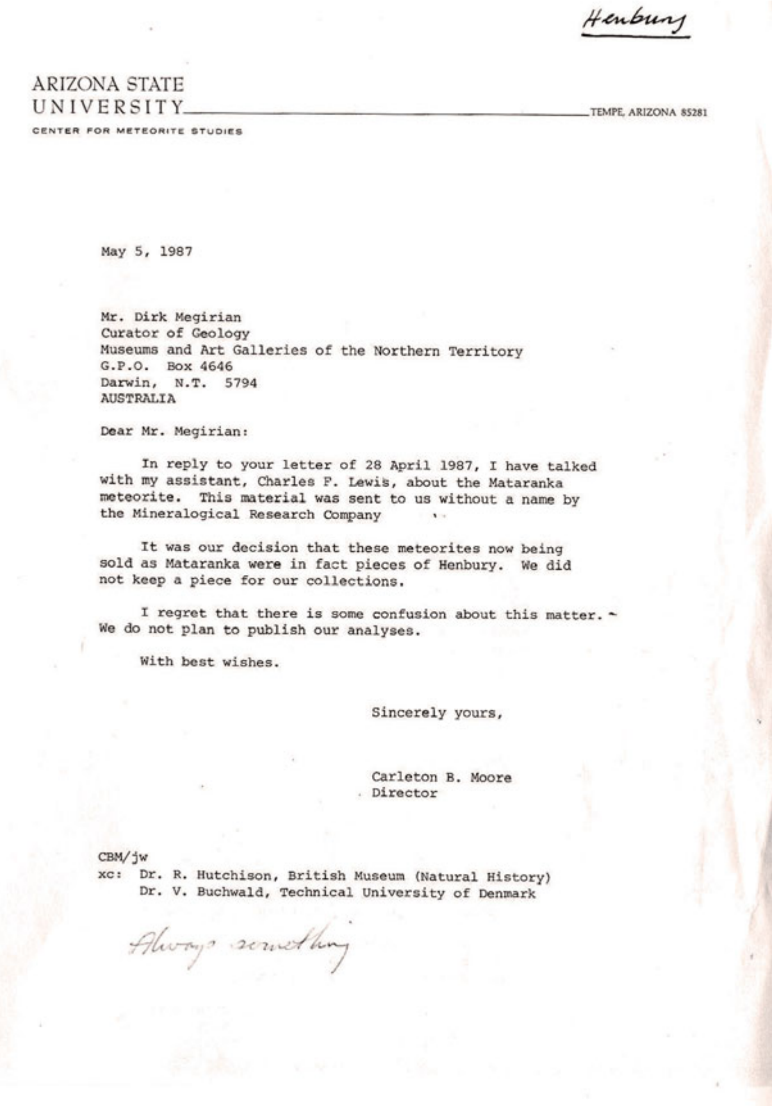
Sincerely,

John T. Wasson

bc: A.L. Graham
F. Wlotzka
E.R.D. Scott

Noted A.L.G. 3/1/90

Letter by J.T. Wasson to Sharon Cisneros on the analyses of specimens from the Mataranka meteorite. The Mataranka mass which was originally believed to represent a different meteorite turned out to be a mislabeled Henbury specimen. One of the possible explanations of the remote find location is the transport of the meteorite to Mataranka from the 1,075 km distant Henbury craters by Aboriginals. Natural History Museum London, British Museum Inventory, Henbury Register



Henbury

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May 5, 1987

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G.P.O. Box 4646
Darwin, N.T. 5794
AUSTRALIA

Dear Mr. Megirian:

In reply to your letter of 28 April 1987, I have talked with my assistant, Charles F. Lewis, about the Mataranka meteorite. This material was sent to us without a name by the Mineralogical Research Company

It was our decision that these meteorites now being sold as Mataranka were in fact pieces of Henbury. We did not keep a piece for our collections.

I regret that there is some confusion about this matter. We do not plan to publish our analyses.

With best wishes.

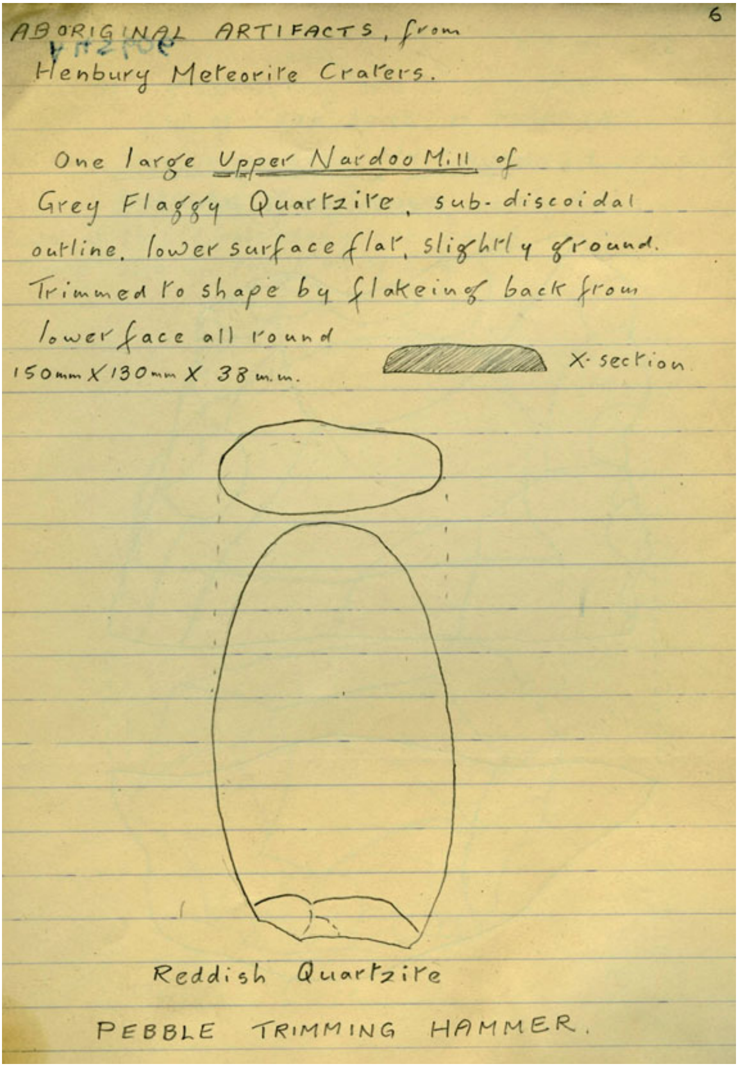
Sincerely yours,

Carleton B. Moore
Director

CBM/jw
xc: Dr. R. Hutchison, British Museum (Natural History)
Dr. V. Buchwald, Technical University of Denmark

Always something

Letter by Carleton B. Moore (R. Hutchison and V.F. Buchwald in copy) to Dirk Megirian informing the latter on the true nature of the mislabeled Mataranka material. Natural History Museum London, British Museum Inventory, Henbury Register



6

ABORIGINAL ARTIFACTS, from
Henbury Meteorite Craters.

One large Upper Nardoo Mill of
Grey Flaggy Quartzite, sub-discoidal
outline. lower surface flat, slightly ground.
Trimmed to shape by flakeing back from
lower face all round
150mm X 130mm X 38 m.m.

Reddish Quartzite

PEBBLE TRIMMING HAMMER.

Drawing of a monofacially retouched Aboriginal stone tool “from Henbury meteorite craters”, collected and described by J.E. Johnson in 1953. While the silcrete rocks from the Bacon Range were used over many generations by Aboriginals as a raw source for stone tools, and despite the abundance of readily available metal for tool fabrication around Henbury craters for the last ~ 5,000 years, no evidence for the Aboriginal use of meteoritic iron has ever been found. Scan: Personal Field Book: Ethnographical and Geological) by J.E. Johnson, page 6, ‘Aboriginal artefacts from Henbury meteorite craters’, 22 August 1953. Inventory # AA 159/1/2, Archive of the South Australian Museum, Adelaide

Another version of this story is reported from a local resident of Kadina who investigated legends concerning the Henbury location in 1932 (Hamacher 2013). The man and a friend had contacted the Aboriginal elders of the region to learn about their perspective of the crater field. The Aboriginals reported that all young men and women were forbidden from approaching the craters. This was explained by the fact that "Schindo waroo chinka yabbo shinna kadicha cooka," meaning "a fiery devil ran down from the sun and made his home in the earth. He will burn and eat any bad blackfellows" (cited after Hamacher 2013). Based on Mitchell's and the Kadina resident's report, Hamacher suggested that such accounts indicate "either a living memory of the event or recognition that the site is related to a catastrophic event in the distant past" (Hamacher 2011). According to Hamacher, events like these were perceived as the acts of higher powers by the Aboriginals: "The destructive event was seen as divine punishment. Such disasters are often attributed to people breaking laws and taboos" (Hamacher 2013).

The Aboriginal Areas Protection Authority gave the Arrernte name of the site as Tatyeye Kepmwere (or Tatjakapara), and advised the Parks and Wildlife Commission of a sacred site centered on the crater area. (Parks and Wildlife Commission 2002). The Commission added that "some of the mythologies for the area are known, but will only be used for interpretation purposes after agreement by the Aboriginal custodians of the site." Hamacher consequently assumed that, "if the site is considered sacred and secret, it may explain Alderman's claim, since his Aboriginal informants may have feigned ignorance or disinterest to prevent him from obtaining secret information" (Hamacher 2011). Hamacher (Hamacher and Norris 2009) also points out that there are more stories concerning Henbury, but that they are not in the public domain and considered sacred and secret by some of the Aboriginal communities, and thus are not shared with Westerners (Hamacher and Norris 2009). (The authors of this book followed this convention and refrained from citing stories considered sacred by the Aboriginal communities.)

A most interesting legend of what obviously was a large crater-forming meteorite event is reported from the Paakaniji (Bakendji) people of western New South Wales (Jones 1989). Although this is far from the Henbury region, according to Bevan the reported site of the event is probably not identical with the site where the event was recorded. Thus it is possible that the legend describes the Henbury meteorite fall (Bevan *et al.* 1996).

In the legend of the Paakaniji, a group of people camped near a bend of the river when "they heard this rumbling noise from the sky, like thunder... and as it [the falling star] came down there was red streaks, and a great big ball of fire coming down ... and there was smoke.... And where it fell, some of them died there and some of them got burnt.... there was fire in it. The ones that weren't too badly burnt, they got away. The others died there...." (Jones 1989). Hamacher points out that the oral tradition on the Henbury craters is generally supported by an unusually strong awareness of meteoritical phenomena in the "Dreamings of Aboriginal groups in Central Australia, primarily that of the Arrernte and Luritja. These include meteors, meteorites, and impact craters that are uncommon to most cultures in the world" (Hamacher 2011).

Both Bevan and Hamacher cite another story recorded by Mountford that attributes the origin of the largest of the Henbury craters "to a lizard-woman" (Mulumura) that formed the bowl-shape of the crater by picking up handfuls of soil and tossing them away, thus forming the bright rays of debris around the crater (Hamacher 2013). This story is of particular interest, as it is not only proof for an accurate topographic perception of the elongated main crater, but also gives a very vivid explanation for the origin of the ejecta rays. Mountford, however, consequently remarked that this myth showed that the group sharing this tradition had no memory of the initial impact event whatsoever (Bevan *et al.* 1996).

Given the fact that the increasing public interest in the Henbury craters and meteorites after their discovery by Western researchers did affect the Aboriginal's approach to the site, it appears to be likely that their beliefs and myths were altered by outside influences as well. Bevan *et al.* (1996) suggested that the account given by Mitchell was already influenced by Western theories circulating about the craters and Hamacher (2013) reported other cases in which Western knowledge did in fact influence Aboriginal crater traditions. Thus, the inconsistencies in the perspectives of the crater site as held by the Luritja and the Pitjantjatjarra may as well be attributed to the fact that their legends are still evolving under the impression of Western knowledge.

This a general problem that researchers face, when investigating events of the distant past by studying the legends of natives. As Hamacher points out, memories are changed and altered by a variety of memory errors known to psychologists: "An example is transience – the loss of memory as time passes. This affects the quality of a memory, the details of which tend to deteriorate from specific to general. Other forms of memory error include confabulation – the recollection of inaccurate or false memories; unconscious transference – misattribution of the source of a memory, imagination inflation – details of a memory that are exaggerated in the mind; or schematic errors – where a schema (organized pattern of thought) is used to assist in constructing elements of an event that cannot be recalled" (Hamacher 2013). Given such influences it is evident that a realistic account, let alone specific details, of a meteorite impact that occurred 5,000 years ago, cannot have survived in the oral tradition: "General details of an event could remain in memory, although the length of this time is a matter of ongoing debate" (Hamacher 2013).

All this leaves us with the unanswered question why there is hardly any evidence of any Aboriginal use of meteoritic iron from the Henbury site or others such as the Boxhole Crater. Compared to the ceremonial and practical significance of Australian tektites in the Aboriginal culture, there is no indication of a similar acknowledgement of meteoritic iron by Aborigines. In view of the skillful and widespread use of a wide range of natural materials by Aboriginals, the absence of tools or cult objects made from meteorites is quite enigmatic (Bevan *et al.* 1996). Even more so, given the fact that silcrete from the Chandler Range, just 300 meters south of the craters, has been extensively utilized for making Aboriginal tools over a long period of time, which can be deduced from the masses of chipped and broken fragments that can still be found in the area.

There are a number of cases, however, where meteorites shown to be part of the Henbury fall were found at a considerable distance from the crater field, e.g.: Basedow Range, Nutwood Downs, Gallipoli Station (Buchwald 1975) and Mataranka. The transport of these masses can only be explained by human agency, although no proof exists, that any of these meteorites were transported by Aboriginals (Bevan *et al.* 1996).

"Kai Kai, Western Arrernte man, Henbury Station". Herbert Basedow (1881–1933) photographed the native doctor in the Aboriginal camp attached to Henbury station, Northern Territory, in 1920. Photo: Herbert Basedow, National Museum of Australia, public domain

Bevan continues: "Although there is some evidence for Aboriginal selection of meteoritic iron objects as things being out of the ordinary, and that they may have been transported from their original place of fall to other locations, no substantial evidence exists of experimental working of iron meteorites by Aborigines during prehistory." (Bevan *et al.* 1996)

Although a prehistoric artifact that would link Aboriginals and Henbury meteorites is yet to be discovered, it was observed that the local tribes did collect meteorites at Henbury soon after it became known that Western researchers and local residents had an interest in them. In Adelaide's newspaper Chronicle, the author of the popular feature "Out among the people" reports that in 1945 the Aboriginals had clearly recognized the commercial potential of the meteorites: "I asked Wilfred Steele about the famous Henbury meteorite, and he told me that a lot of fragments were brought in a few weeks ago. The blacks have noted the interest white people have taken in these, and they have been selling pieces of 'the star that fell from the sky'" (Vox 1945).

DATING OF THE IMPACT AND TOTAL KNOWN WEIGHT

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Based on his first investigation, Alderman gave a quite accurate estimate of the terrestrial age of the meteorites. “The author is, however, of the opinion that the fall took place a very long time ago and that the age of the craters must be reckoned in terms of thousands of years” (Alderman 1932). Evidence listed by Alderman includes the “complete oxidation and disintegration” of iron fragments, “generations of trees” which have lived and died in the craters and his “inquiries from aborigines” which produced no result on the origin of the craters (Alderman 1932).

Bedford, by contrast, was aware of Aboriginal oral tradition on the crater origin, and he was therefore convinced that the fall occurred much more recently (Spencer 1932 a). Considering the importance of oral tradition among Aboriginal tribes, Hamacher also argues in favor of the Henbury event having probably been witnessed first-hand by Aboriginal people (Hamacher 2011). An opinion which is also shared by Buchwald, who suggests the possibility “that Henbury is a witnessed fall” (Buchwald 1975).

Milton noted that the outer 30 meters of the ejecta ray extending westwards from crater no. 4 is only marked by a number of 15 cm-size sandstone blocks extending across the course of a wet-weather drainage bed. The fact that they have not been transported by seasonal activity suggests a relatively recent formation of the craters (Milton 1968).

Based on the $^{14}C/^{36}Cl$ ratios measured in Henbury iron meteorites, Goel *et al.* (1962) gave a terrestrial age for the Henbury impact craters of ≤ 7,000 years. A year later the authors revised their results to less than 5,000 years. Buchwald accordingly reports the estimated terrestrial age of the meteorite to be less than 5,000 years (Buchwald 1975), while Storzer *et al.* gave an even younger impact age of the Henbury meteorite obtained by the fission track method of 4,200 ± 1,900 years (Storzer *et al.* 1977).

Buchwald gives the total known weight (TKW) of the meteoritic material as approximately 1,200 kg, based on the collections documented in the scientific literature (Buchwald 1975). While Buchwald’s estimate includes at least 25 kg of meteoritic material contained in the spherules distributed around the Henbury craters, it does not include the more than 1,000 kg of specimens recorded by McColl, which were collected by scientists and private prospectors, from the 1940’s to the late 1990’s (McColl 1997). None of these meteorites appeared in any published documentation. The two figures combined appear to be a more realistic estimate, which puts the total recovered weight of the Henbury meteorites at about 2.2 tonnes.

The actual total, however, could still be twice as much, because of the unknown numbers of specimens that were collected over the years and passed into institutional and private collections unrecorded.

Detail of the western wall of crater no. 3, view to the south. In the right center of the photo and overlying the ejecta blanket, the beginning of the westward oriented ejecta ray can be seen. The ray consists of mall sandstone blocks among a layer of grey Pertatataka shale. Despite annual rainfalls and the exposed location on a surface with hydraulic gradient even the fragile components of the ejecta ray are preserved in situ. Photo: T. Brattstrom

THE PRESENT CRATER RESERVE

S. Buhl, D. McColl, *Henbury Craters and Meteorites,* GeoGuide,
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Many of the thousands of tourists who visit Central Australia every year include the Henbury Reserve in their roundtrips to or from the Watarrka (King's Canyon) National Park via the Ernest Giles Road. They see a crater field in which erosion, sedimentation, and to a lesser extent the influence of human presence in the area, has altered the appearance of the craters quite a lot since they were formed.

Today the craters are partly filled with fine grained post crater alluvium. Some, like crater no. 2, are completely leveled, and their presence is only indicated by a pebble free surface and the presence of

Previous pages:

Henbury main crater (no. 7a and 7b) seen from the northwest crater wall. Bowman Hill and Bacon Range in the background. The trees behind the wall of the main crater mark Water Crater (no. 6). Photo: T. Brattstrom

Mulga trees. Understandably the present objective of the Henbury Crater Reserve is focused on the preservation of the craters, their environment, including plant and animal communities in the area, and on the preservation of any remaining meteorites at the site.

In 1934, with this purpose in mind, a first reserve of 1,000 acres was created under section 139 of the Northern Territory Mining Act (NT Government 2002). This "Henbury Meteorite Reserve" was extended in 1964 and 1983 to become the current Henbury Meteorites Conservation Reserve. In 1998 an additional Reservation from Occupation (R.O. 1393) was declared that from there on also included a large part but not all of the meteorite scatter area northeast of the crater field.

Centered on the crater area is a site sacred to the Aboriginals, which underlines the Reserve's Aboriginal cultural significance. Any actions, work within the area or visits of the area requires that the Reserve management obtains an authority clearance under section 20 of the Northern Territory Aboriginal Sacred Sites Act from the Aboriginal representatives in charge. However, as the Reserve management frankly admits, it is unfortunate that there is only little information on the past Aboriginal cultural values and use of this site (Northern Territory Government 2002).

Although the Draft Plan of Management of 2002 particularly stresses the rarity and significance of terrestrial impact craters with associated ejecta rays, it appears that the ray features were of little importance to the early planners of the Reserve. When the first access roads were built in the 1960s, the westward pointing ejecta features fell victim to the bulldozer. This work once and for all removed most of the evidence where Alderman and Milton once investigated the narrow ridges composed of sandstone blocks ejected from craters no. 3 and 4. This access road, which can be seen in the aerial images from the 1970s, was later recultivated and is barely visible on the ground today. In satellite images, however, it can still be clearly seen.

The mistakes of the past cannot be reversed, but the present Reserve management is undertaking considerable efforts not to repeat them. Care is taken to minimize the impact of the visitors on the environment particularly in terms of soil erosion. A crater protection zone has been established covering all 12 craters, also including their walls. This inner zone is surrounded by a Nature Zone in which only limited activities are allowed. By fencing off the main crater area, cattle and horses are prevented from entering the site, which helps to reduce erosion considerably. Camels were common in the area for many years, however, and they were able to simply step over the existing fences and destroy much crater vegetation in the dry seasons. Today, marked walking tracks lead to and around but not through the craters, and carefully placed information signs advise the visitor of the significance of the craters and the need for responsible behavior.

Collecting of meteorites within the boundary of the Reserve is prohibited, as is the collecting of Aboriginal artifacts or firewood. Low impact activities such as bushwalking and photography are allowed in the outer Natural Zone of the Reserve though. The site is monitored by routine patrols of the Parks and Wildlife Commission Ranger staff based at the Alice Springs Telegraph Station Historical Reserve.

Henbury craters nos. 6, 7a and 7b, and 8 during extremely dry weather conditions in summer 2006. Photo taken from Bowman Hill southeast of the craters. Photo: D. McColl

Even today small pieces of meteoritic iron can be found around the Henbury craters. The photo shows a shrapnel (near tip of the stylus) and a piece of meteoritic shale (below stylus) on the pediment surface west of crater no. 4. (specimens were left in situ). Photo: D. McColl

Since the time of their discovery, meteorites from Henbury have been popular among scientists and meteorite curators from all over the world – as well as among the growing community of private meteorite collectors and enthusiasts. Meteorites, including those from Henbury, that were found in the Northern Territory after 15 June 1988, are subject to the 1988 Meteorites Act. This Northern Territory law was consolidated 12 years later, and has been in force since July 12, 2000. The Act is administered by the Museums and Art Galleries Board (MAGB). Its basic implication is that every meteorite that falls under the Act (found after 15 June 1988) is property of the state. In contrast to the legislation of other Australian states, the Northern Territory also includes tektites in the Meteorites Act (Meteorites Act 2000).

On the other hand, as the late Dirk Merigian, the former curator, pointed out (Merigian 1998), it must be recognized that there exists a long-established trade in Northern Territory meteorites, mostly involving Henbury, innumerable fragments of which were legally collected prior to 1988. These specimens may be freely traded and/or exported from the Northern Territory, although their export overseas from Australia requires a permit under the Commonwealth Movable Cultural Heritage Act (Merigian 1998).

Within the meteorite community, the Northern Territory legislation on meteorites has inspired frequent discussions on its

The main craters no. 7a and 7b as seen from the east-northeast. The trees growing in Water Crater (no. 6) can be seen on the left. Despite the abundant vegetation, annual erosion, sedimentation and human activity the scars left in the landscape by the catastrophic impact five millennia ago are clearly evident. Photo: T. Brattstrom

pros and cons. In this context it is often argued that the *a priori* declaration of ownership by the state has a negative effect on the disclosure of new meteorite finds, and the discovery of new meteorites in general. While the low recovery rates in the Northern Territory may have various other reasons apart from the restrictive meteorite laws, the figures provide little evidence to counter that kind of criticism. According to the Meteoritical Bulletin database (status April 2012), only one meteorite (Erldunda, 1992) of a total of 325 Australian meteorite recoveries published in the Bulletin after the Northern Territory Meteorite Act came into effect in 1988, was recovered in the Northern Territory during that period.

With the low meteorite recovery rate in the Northern Territory in mind, it is only logical to consider measures that could improve these circumstances. Merigian suggested that tolerating ‘some level of private ownership’, ‘provided the objectives of the Meteorites Act are not compromised or undermined’ might achieve some better results (Merigian 1998).

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“Left to right: Bill Bedford, Ben Peters, Perce Peters”. The Bedford Papers archived in the Barr Smith Library of the University of Adelaide provided invaluable insight into the early research at the Henbury meteorite craters and the pioneer characters involved in their study. Bedford Papers, Barr Smith Library, University of Adelaide, MSS 92 B4113p

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THE AUTHORS

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SVEND BUHL

is a government relations consultant in Hamburg, Germany. To fund his studies of German Philology and Theory of Sciences/ Philosophy at the University of Trier, Buhl worked as a miner in an underground anhydride quarry where he completed training as a demolition specialist. After graduation as a Doctor of Philosophy in 2000, he chose a career in the public relations branch. His occupation with mineralogy and meteoritics in particular began in the 1990s, but it was not until 2002, that he formed an international team of experts and organized their first meteorite expedition into the Ténéré desert in the Republic of Niger. A dozen expeditions followed, the majority to the Central and Western Sahara. His website, Meteorite-Recon.com, includes illustrated field journals covering some of these expeditions. Meanwhile, close to 100 meteorites recovered by Buhl and his team have been analyzed, classified and published, among them several rare achondrites. Apart from reference samples curated by the classifying institutions, meteorites traded and donated by Buhl are today being kept in Natural History Museums and University collections in Europe, Morocco, Russia, Canada and the USA. Svend Buhl is a contributing author of *Lapis* and *Meteorite*, a Harvey Award recipient, fellow of the Meteoritical Society and member of the Confrerie St-Georges des Gardiens de la Meteorite d'Ensisheim.

DON MCCOLL

is a retired geology graduate of Melbourne University. He began his studies with the first two years of geology at Adelaide University where he met and worked with Professor Arthur Alderman, who encouraged him to take up studies in meteoritics.

After graduation, during the years from 1964 to 1970, Don McColl curated the collections at the Tate Museum at Adelaide University. Later he was in charge of the national collections at the Bureau of Mineral Resources in Canberra from 1972 to 1981. As a post retirement job, from 1996 to 1998, he was minerals curator in Mount Isa for the Queensland Museum. McColl has specialized in meteoritics, mineralogy and gemmology, and has published about seventy assorted papers and articles on meteorites, tektites and mineralogical subjects. An avid field worker, he has personally found about 30 stony meteorites, about 500 iron meteorites and about 5,000 tektites, most of which are currently held in Australian museums. Don McColl and his wife Lois lived in Alice Springs for five years in the interval from 1986 to 1991, which gave him ample opportunity to mingle with prospectors and mineral collectors in Central Australia and compile records of where the more recent specimens of Henbury meteorites were actually found.

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