The history of meteoritics – overview

G.J.H. McCALL[1], A.J. BOWDEN[2] & R.J. HOWARTH[3]

[1]*44 Robert Franklin Way, South Cerney, Circencester, Gloucestershire GL7 5UD, UK*
(e-mail: joemccall@tiscali.co.uk)
[2]*Earth and Physical Sciences, National Museums Liverpool, William Brown Street,*
Liverpool L3 8EN, UK (e-mail: Alan.Bowden@liverpoolmuseums.org.uk)
[3]*Department of Earth Sciences, University College London, Gower Street,*
London WC1E 6BT, UK (e-mail: r.howarth@ucl.ac.uk)

Abstract: This volume was proposed after Peter Tandy and Joe McCall organized a 1-day meeting of the History of Geology Group, which is affiliated to the Geological Society, at the Natural History Museum in December 2003. This meeting covered the History of Meteoritics up to 1920 and nine presentations were included, the keynote talk being given by Ursula Marvin. There was an enthusiastic audience of about 50, who expressed the view that this meeting should lead to a publication. Dr Cherry Lewis, the chairperson of the group, discussed this with Joe McCall, who said that the material was too small for a Special Publication, but it could be developed by expanding it, taking the history through the 20th century, when there was a revolution and immense expansion both in the scope of meteorite finds and the application of meteoritics to scientific research on a very broad front with the advent of the Space Age. This was agreed and a format of about 24 articles was designed, approaches being made to selected authors.

The sections of this Special Publication relate to the early development of meteoritics as a science; collecting and museum collections; researches establishing the provenance of meteorites; and impact craters and tektites.

Report and recovery after fireballs, disbelief and belated acceptance

This Special Publication has several strands, the four papers that form this first section are devoted to the story of the reports of rock and metal material falling from the sky, the continued disbelief of scientists and how such falls were finally accepted at the end of the age of enlightenment, about 1800. **Marvin**, in an article that is something of a tour-de-force, covers the story from the report of Pliny the Elder of the fall of a brown stone at the Aegos Potamos (River), in Thrace north of the Hellespont in 464 BC, which Diogenes of Apollonia recognized to be of cosmic origin – he wrote 'meteors are invisible stars that die out, like the fiery stone that fell to Earth near the Aegos Potamos'. His solution of the problem took more than two millennia to be scientifically accepted, such accounts being dismissed as products of the fertile minds of ignorant people, but his name would be applied to a meteorite type, the achondrite *diogenite*.

The fall in 861 AD of a heavy black stone near a shrine, close to present day Nogata, in Japan, resulted in the mass being preserved in a monastery there. Studies in 1922, more than a millennium later, showed it to be an L6 chondrite, its age of fall being confirmed by the type of script and ^{13}C dating on the box containing it. This predates Ensisheim (fall, Alsace 1492), which had long been considered to be the earliest fall, material from which is preserved in a collection.

Through ancient times and the middle ages there is a tradition of disbelief by educated people in the reality of fireballs accompanied by iron or stony material falls. However, at the same time meteorites were treated both by the ignorant and the wise as sacred objects or portents – mainly portents of evil, although the Ensisheim fall was taken to be a compliment to the glory of the Emperor Maximilian! Particularly appealing is the reported practice in France of chaining these strange objects up in case they decided to depart as swiftly as they arrived!

The recovery by the conquistadores in 1576 of a large mass of iron from the Campo del Cielo area in Argentina did nothing to change the climate of disbelief, although the local people

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reported that the iron had fallen from the sky. An immense 44 000 metric tonnes (t) of iron has been recovered from an area spanning 75 km here and, with a number of small associated craters, it is one of the great strewn fields of the world.

Despite the Abbé Troili's description of the Albareto fall in Italy in 1766, he concluded that it had been 'hurled aloft from a cleft within the Earth' and cannot, as some claim, be afforded priority over Chladni in publishing the correct rationale for meteorite falls.

The correct answer was arrived at by three separate events: the first of these was the publication of Chladni's book in 1794, arguing for the actuality of falls, linking them with fireballs. He based his conclusions on 18 witnessed falls and the examination of several meteorites including the famous 'Pallas iron' (not an iron but a pallasite) and the Ensisheim stone. The remarkable story of recovery of the 'Pallas iron' and its transport over several years to St Petersburg and incorporation in Peter the Great's collection of oddities is recounted by **Marvin**. Lichtenberg is reported to have told Chladni previously that meteorites were cosmic, but this has never been substantiated. The second event was the fortuitous fall of five stony meteorites, all common chondrites, between 1753 and 1798 (Tabor 1753, Lucé 1768, Siena 1794, Wold Cottage 1794 and Benares 1798). The name of Joseph Banks crops up here for, while he initially sent back the Siena stone sent to him by the wonderfully eccentric 4th Earl of Bristol and Bishop of Derry with the remark that the Bishop was telling tales, it and several samples of the others were later supplied by Banks to Edward Howard who with Louis de Bournon showed that the chemistry and mineralogy was remarkably similar and quite unlike any naturally occurring rocks. Howard, as **McCall** also mentions in 'Chondrules and calcium–aluminium inclusions (CAIs)', was the first to describe the round bodies in these stony meteorites that Gustav Rose, late in the 19th century, named as 'chondrules'. The third event was the fall of 2000–3000 stones at L'Aigle, in France, in 1803. Admirably described by Biot (1803; reprinted Greffe 2003), this convinced even the sceptical French that solid material did indeed fall from the sky (Lucé had been dismissed by Lavoisier earlier as a 'thunderstone'). **Gounelle** describes this fall in detail and its impact on post-revolutionary thinking in France.

The position now was that the fall of stony or metallic masses from the sky was established, but the Aristotelian belief that such masses could form in the atmosphere (as a meteorological process) and the dictum of Newton in 1704 that 'space' must be empty still exerted strong constraints against full enlightenment. The belief was now held that such masses were volcanically ejected from the Moon or that the Aristotelian process was valid. **Jankovic** elegantly describes how the Aristotelian belief was finally eclipsed, a belief that was behind the original use of the term 'meteorology', which has nowadays a meaning quite different to its original one. The eclipse of this belief owed something to Benjamin Franklin's demonstration in 1752 that lightning strikes were an electrical phenomenon. Even Chladni's connection between meteorites and observed fireballs was not fully accepted until the 1830s.

The early 1800s had seen the discovery of asteroids (Ceres 1801, Pallas 1802, Juno 1805 and Vesta 1807). Progress was made in meteoritics through to the early–middle 19th century with descriptions of achondrites – the first being the Stannern, Moravia, eucrite fall in 1808 – and carbonaceous chondrites – the first being at Alais, France, in 1808 – also research by Widmanstätten in Vienna on iron meteorites. The fall of the Orgeueil meteorite in France in 1864 was of the most primitive CI class of carbonaceous chondrite yet to be described and is mentioned both by **Marvin** and **McCall** (in 'Chondrules and calcium–aluminium inclusions (CAIs)'). **Howarth** provides an account of the contribution of Daubrée in France to the description of this event and the soft hydrous meteorite mass, and the many other contributions by this ingenious scientist to improving contemporary understanding of the nature of meteorites and their classification. It was Daubrée who founded the Paris collection, described in the second section of this Special Publication by **Caillet Komorowski**.

The Orgueil meteorite was also the subject of an extraordinary hoax perpetrated on samples of it (coal and plant fragments being added to them) that was not discovered for 100 years (McCall 2006).

Although Greg in 1854 suggested that meteorites are minute outliers of asteroids, all pieces of a single planet disrupted by a tremendous cataclysmic event, it was not until the mid-20th century that photographic studies of meteor orbits related to recovered masses (as described by **Bowden** in the third section) conclusively established asteroidal provenance. This was soon to be confirmed by the extreme radiometric ages of approximately 4500 Ma of irons and chondrites (as described by **de Laeter** and **McCall** in the third section), and the complexity of the meteorite chemistry and petrology that showed that a single parent body was untenable, there being a requirement for a large number of such bodies (see **McCall**, again in the third section). In the interim, it was generally accepted that meteorites came from asteroids, comets or interstellar space.

The great museum collections; their origins and histories; and their contribution to research, with particular attention to cold- and hot-desert regions of optimum recovery of finds discovered in the latter half of the 20th century

The great collections in the world's museums are the repository of the greater part of the store of meteorites, which is ever increasing – at a much greater rate since the discovery of the cold- and hot-desert optimum areas of recovery of finds (Antarctica, Nullarbor, North Africa, Oman, etc.), and they are even receiving quite new types of meteorite (brachinites, CH chondrites, the Tagish Lake C1–2 chondrite from Canada and the unique Antarctic find, ALH 84001, from Mars (?)). Their history is surprisingly colourful, including, as it does, the story of falls and finds in many parts of the world. Official collectors went out on arduous journeys to recover them or amateurs made collections, many of which were either donated to museums or purchased by them (the latter case engendering very keen competition between museums). The professional meteorite prospector came to the fore in the last half of the 20th century and has become a major player in making meteorites available for purchase to collections in the last 25 years, being particularly active in the hot deserts (North Africa, Arabia), with rare meteorites fetching huge sums.

Above all, this account is dominated by the curators – meteorites seem to exert a fascination that has drawn a succession of remarkable curators and researchers to the collections: each one of the collections covered here has had one or more renowned personalities involved in its success.

Five of the great European collections (Vienna, Berlin, Moscow, Paris and London) all had their origins in the late 18th and earliest 19th centuries, when the debate about the scientific reality of meteorite falls was at its height. The surprising Vatican collection relates to the interest of Pope Gregory XIII in astronomy and revising the calendar in 1582, but stems directly from three bequests by the Marquis de Mauroy in 1907, 1912 and 1935. The Smithsonian collection in Washington, DC, relates to the remarkable and not fully explained bequest to the USA by James Smithson, an Englishman in 1838, and the American Museum of Natural History collection dates from as late as about 1870. The Japanese collection seems to be entirely related to the amazing find of thousands of meteorites in the Yamato Mountains from 1974 onwards. The surprisingly large Western Australian Museum collection also had its origins in the late 19th century, when a number of large irons were found in the Wheat Belt, east of Perth, but owes its existence to the aridity and immense size of the State (its area is one-third of that of the contiguous United States) and the recognition in the 1960s that the Nullarbor Plain (a limestone desert) must 'be littered with meteorites' (McCall 1967), a prophecy that rapidly was seen to be true.

The museum collections have suffered wars and revolutions but emerged relatively little diminished. They are the fount of research on meteoritics the world over, and never was material so much in demand for research as in the last 50 years of the Space Age, and the demand will continue indefinitely.

The European collections

The history of the Vienna collection is described by **Branstätter**. The collection relates to the founding of the Imperial Natural History Cabinet in 1748, but the first meteorites incorporated were Hrashina (iron, fall 1751, Croatia) and Tabor (stone, chondrite, fall 1753, Bohemia). The geographical extent of the Austro-Hungarian empire was huge at that time, extending to what is now Rumania. The Stannern fall in Moravia in 1808, an eucrite, was added to the collection and subjected to study there. Alexander von Widmanstätten carried out his seminal studies of the iron meteorites at Vienna in 1808, describing the unique etch pattern that now bears his name. The collection increased in size over the years by a combination of gifts and purchases of major private collections. It survived artillery shelling, setting fire to the library in 1848, a revolutionary year. Curators during the late 19th century were Gustav Tschermak and Aristide Brezina, who with Gustav Rose of Berlin and Daubrée in Paris, derived a classification of meteorites that is the basis of that in use today. The collection also survived two world wars, although these did reduce the research and other activities for a number of years. Now, it again it flourishes with the purchase of a large American private collection and two collections from North African desert areas. Research continues apace in Austria, and especially on terrestrial impact processes and tektites. The display in Hall V of 5100 meteorite specimens in cabinets, from more than 1000 localities, probably cannot be matched anywhere else in the world.

The Berlin collection is described by **Greshake**. It had its origins in 1770 with a piece of the 'Pallas iron' in the Gerhard collection, received from the German-born naturalist Peter Simon Pallas. In 1780 this collection became the foundation of the Royal Mineral Cabinet. The original Pallas fragment was lost and was replaced by another presented by Tsar Alexander I to King Frederich Wilhelm III in 1803. Alexander von Humboldt presented a number of meteorites collected during his South American travels (1799–1804). Gustav Rose, the curator from 1821, was closely associated early on with Chladni, who eventually willed his valuable collection of meteorites to the University of Berlin, which had by then taken over the Royal Mineral Cabinet. Rose joined Humboldt on an epic journey to Russia in 1829, exploring the Ural and Altai mountains at the invitation of Tsar Nikolaus I, and returned with two meteorites, Slobodka (ordinary chondrite, fall near Smolensk 1838) and Krasnoi-Ugol (ordinary chondrite, fall, Ryazan 1829). Later in his career Rose put up a number of the names used today, including the terms achondrite and chondrite, and, with Tschermak and Brezina, formulated the classification, the basis of which is still valid in principle. The collections became part of those of the Museum of Natural History, opened in 1890, and soon afterwards several more important collections were added. The meteorite collection survived two world wars without suffering any significant loss. Paul Ramdohr, distinguished for his studies of iron meteorites, became curator in 1934, continuing through the Second World War, but leaving in 1950 for Heidelberg. The collection has lately been enlarged by two purchases of Saharan desert collections, and is today both an exceptional historical heritage and modern research tool.

The Moscow Academy (now Vernadsky Institute) collection is described by **Ivanova & Nazarov**. This is one of the greatest collections, representing as it does the geographical immensity of Russia, and, even with the areal reduction resulting from the secession of a number of satellite states in the early 1990s, Russia remains vast. The record of meteorites in Russia goes back to a Scythian burial tumulus of the 7th–3rd centuries BC at Berdyansk. This was known in 1843 and the 2.5 kg ordinary chondrite mass found there is held at the Institute. Presumably, it had some religious significance to the Scythians. There is also mention of a shower of meteorites near Kiev in the *Lavrenty Chronicles* of 1091 and this should probably be equated with the discovery of a number of pallasite masses at Bragin, near Kiev, in 1810. Two masses are in the collection.

The Great Ustyug fall in 1290, Great Novgorod fall in 1421 and New Erga fall in 1662 are all well documented. Such falls in medieval times were regarded as evil omens and frequently chapels were erected above the sites of fall.

The find in 1749 of the 'Pallas iron' near Krasnojarsk in Siberia stimulated interest in the reality or otherwise of meteorite falls. However, despite it being transported to St Petersburg and being cited by Chladni in his book of 1794, the Academy of Sciences was sceptical about his conclusions and lukewarm about meteorite collection, although by 1811 there were two meteorites in their collection. The first fall of a meteorite to be represented in the collection was Zhigaylovka (Kharkov), 1787, Ukraine, an LL6 chondrite that fell in Ukraine in 1787.

In 1898, the tsar passed a law making all meteorites government property. Vernadsky, the outstanding curator of the collection, encouraged ordinary people throughout Russia to report falls and finds.

The meteorites within the collection include many rare types and the Novo Urei fall near Nizhni Novgorod in 1886 was of a quite new type of achondrite, composed of olivine and pigeonite, the first ureilite. This was also the first recorded meteorite to yield minute diamonds formed by shock.

The Tunguska event in Siberia in 1908 is unique and, despite many search parties (led by Kulik, another outstanding curator), no material has ever been recovered from the swamp amidst the vast area of felled trees. It has never been fully explained, although it appears to have been an explosion high in the atmosphere.

The Sikhote-Alin fall in 1947 of a number of jagged iron masses, accompanied by extreme fireball effects, is another unique occurrence, again in forested terrain, but in the far east of Siberia. It produced more than 100 small craters. This fall has been immortalized in the painting by local Russian artist P.I. Medvedev (see Fig. 12 in **Ivanova & Nazarov**). The painting was used on a 40-kopeck commerative stamp issue on the 10th anniversary of the fall in 1957 (Fig. 1).

There are several impact structures in Russia and its recently seceded territories that have

Fig. 1. 40-kopeck stamp commemorating the 10th anniversary of the Sikhote-Alin meteorite fall based on a painting by P.I. Medvedev.

been studied intensively in the late 20th century, the largest being the Popigay structure (100 km in diameter and of late Eocene age) in northern Siberia. The Zhamanshin structure in Kazakhstan (13 km in diameter, Pleistocene) is also very important in the study of impactites and tektites.

Russia has missed out in the case of Antarctic meteorite finds in the late 20th century, despite having a large area of exploration in Antarctica, and its hot deserts in Central Asia have also so far not provided any optimum area for finds.

The French National meteorite collection is described by **Caillet Komorowski**. The origin goes back to the mid-19th century and it was significantly expanded and enriched by Auguste Daubrée and Alfred Lacroix. However, René Häuy, a mineralogist at the Musée National d'Histoire Naturelle, had collected meteorites as early as the late 18th century, prior to the widely observed fall at L'Aigle in 1803. France was the site of the fall of several very important meteorites (Ensisheim, Lucé, L'Aigle, Chassigny, Alais, Orgueil and Ornans come to mind) and the efforts of Jean-Baptiste Biot after the L'Aigle fall officially promoted the science of meteoritics. Another distinguished curator, Stanislas Etienne Meunier, obtained a remarkable insight into the true origin of meteorites in the solar system, and the collection has been further built up in recent years. France is the country with the greatest number of falls per unit area, with 70 discovered meteorites numbered today (discounting those that have been lost).

The London collection is described by **Russell & Grady**. The British Museum originated with the bequest of Sir Hans Sloane's extensive natural history, archaeological and anthropological collections to King George II in 1753. The first meteorites in the collection, formerly that of the British Museum (Natural History) but now of the Natural History Museum, were acquired in 1802–1803, at the time of general acceptance of their extraterrestrial origin by the scientific community. These were three ordinary chondrites: Wold Cottage, Siena and Benares presented by Sir Joseph Banks. The interest at that time in meteorites in England is well illustrated by excellent paintings by Paul Sandby and Samuel Scott of the 1783 fireball meteor from Windsor and the Thames, respectively (Olson & Pasachoff 1998). The latter displays the typical break-up of a number of small bright masses behind the larger fireball (Fig. 2). The London collection had a number of passionate curators, including Maskelyne, Fletcher and Prior – the latter contributing to the classification of stony

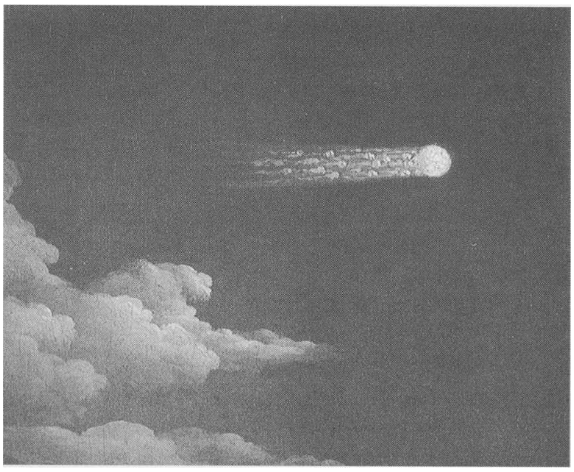

Fig. 2. Detail of a painting attributed to Samuel Scott of the fireball of 18 August 1783 over the Thames, showing the break up of the bolide into a number of smaller bright objects behind the fireball (from Olson & Pasachoff 1998).

meteorites. It is the largest collection of meteorite falls in the world. The museum also has a special role in preparing supplements in *Meteoritics and Planetary Science* to the original Prior catalogue of 1923, which was updated most recently by Grady (2000). This is the accepted world catalogue of meteorites.

The last of the European collections is the Vatican collection located at the Vatican Observatory, close to Rome. Italy, like France, was the site of very important early falls (Albareto 1766, Siena 1794 and Renazzo 1824), Renazzo and Vigarano (1910) being important carbonaceous chondrite prototypes. The main central collection is at the Vatican, as described here by **Consolmagno**, although there are representations in university collections, especially Bologna. The Vatican collection owes its existence to bequests by the Marquis de Mauroy early in the 20th century, but has been added to since. It was the site of research on Mars by Fr Secchi in the mid-19th century and of later pioneering spectrochemical research by Frs Gatterer and Stein, and Br Treusch.

The great American collections and the Japanese–American Antarctic ice recoveries from 1969 onwards

The first initiated of the two great American collections was that of the Smithsonian Institution, Washington, DC, which is described by **Clarke *et al.*** The institution itself had its origins in a last-resort legacy by the English scientist James Smithson of his mineral and meteorite collection to the United States government in 1835. This led to the receipt of his fortune in gold and manuscripts, as well personal effects, and instigated the setting up by Congress of the Smithsonian Institution in 1846. The first meteorites in the collection were Smithson's acquisitions, largely European, but they were apparently lost in a fire in 1865. The early acquisitions included the famous Tucson, Arizona, Ring iron, found by US troops in 1853. By 1884 a total of 13 different meteorites were represented in the collection; at that time meteorites were valued when they came in, but were not considered to be high-priority items for acquisition. With the addition of the Shepard collection (officially incorporated in 1915) there were 250 specimens by 1888, a spectacular increase. The Canfield and Roebling collections were also added with endowments, and, in the mid-1940s, the important Perry collection. The collection continued to grow and the scientific staff was increased in 1964, prior to the lunar landing; although this development was, in the event, applied more to the discovery of numerous meteorites in Antarctica, rather than to lunar sample studies. Two important aspects of the Smithsonian collection's history covered are: (i) its role in the studies of Meteor Crater at the end of the 19th century (see **McCall**) – Gilbert clearly had second thoughts about his rejection of impact, which unfortunately he did not publish; and (ii) the find of the Old Woman meteorite in California in 1976 on US government land, as a result of which the ownership of meteorites in the United States being with the owner of the land was legally established. The accession of the Allende, Mexico, meteorite specimens due to the alertness of Brian Mason, and the purchase of the Murchison, Victoria, Australia meteorite specimens, both from falls, added two of the most important carbonaceous chondrites to the collection for scientific research.

The American Museum of Natural History Collection, described by **Ebel**, was founded in 1869. The Searsmont, Maine, fall of an ordinary chondrite in 1871 provided the first meteorite catalogued: although not found in today's collection, it is represented in London and elsewhere (Hey 1966). The Museum obtained the Berment collection of minerals in 1900, funded by J. Pierpoint Morgan, a philanthropist and trustee who more than once assisted the growth of the collection. The Ward–Coonley collection of meteorites was added in 1901. The acquisition of the Great Irons: Cape York, Greenland, and Willamette, Oregon – the former as a result of Robert E. Peary's Arctic expeditions – made the Museum justifiably famous. No one can fail to be impressed by these huge masses on display. Ebel's observation about the 'utter contempt and disregard of all attempts to control these masses of extraterrestrial metal and the remorseless way they destroyed everything opposed to it' is a tribute to Peary's tenacity. The new Arthur Ross Hall of Meteorites was opened in 2003: 'The focus on what meteorites tell us about solar system origins, planet formation including the Earth, and the history of the solar system' reflects the move away from simply display in cabinets with labels to an imaginative, informative, teaching approach which has also been adopted by the Natural History Museum in London, and the Western Australian Museum in Perth.

Ebel traces the progress and changes from the early days in the 19th century when meteorites came in from rare falls, such as the Estherville fall in Iowa of mesosiderite masses in 1879. Meteorites were then given, bequeathed or purchased as part of mineral specimen collections. The acquisition of large collections entirely of meteorites became common in the 20th century. A revolutionary change took place in the 1950s from a largely 'ancilliary to minerals' curatorial concern, with some ongoing research on meteorites, to meteorite collections becoming (with the advent of the Space Age interest in planetary science and the consequent increase in research activity as exemplified by the hi-tech instrument research now being carried out at the museum) of extreme scientific importance in their own right.

Kojima describes the amazing events in the Austral summer of 1969, when a field party engaged on glaciological studies in the Yamato Mountains, Antarctica, encountered nine meteorites on the ice, which on examination proved to be of diverse types. Subsequent parties recovered hundreds or even thousands of meteorites and parties were sent out purely for meteorite recovery. This discovery set in motion the ANSMET programmes of the USA on the other side of Antarctica with comparable results. It became clear that the meteorites were concentrated where the ice movement is arrested by nunataks or ridges of rock, buried meteorites travelling in the ice mass towards the coast being re-exposed by ablation. Wind movement is a contributory process to concentration. The processes are very complicated and, a year or so later, the Japanese parties found new occurrences where earlier parties had searched, with meteorites even lying on vehicle tracks. Both the Japanese and American meteorite searches were greatly enhanced in their accuracy of geographical plotting by the timely appearance of GIS systems. The statistics reveal that almost every known type of meteorite was included in the 15 741 meteorites collected, of which 14 643 (93%) were ordinary chondrites. It is noteworthy that it also includes three CI chondrites (the most primitive type of which only five are known from outside Antarctica), nine lunar meteorites and five martian meteorites. The interplay between the Japanese and Americans was a model in scientific co-operation.

Clarke *et al.* describe how, as a result of the chance discovery in 1974 of prolific occurrences of meteorites in the Yamato Mountains, described by Kojima, the Smithsonian Institution became the principal player in the description and classification of the finds subsequently discovered in the parts of Antarctica under American exploration. In the ANSMET programme, Brian Mason is reported to have petrographically examined and initially classified every meteorite received there, more than 10 000, including some Japanese finds. These included the first lunar meteorite to be described, ALH 81005 (Fig. 3). Ursula Marvin also played a major role in this programme. By the end of 2004 more than 11 300 individual specimens had been transferred to the museum.

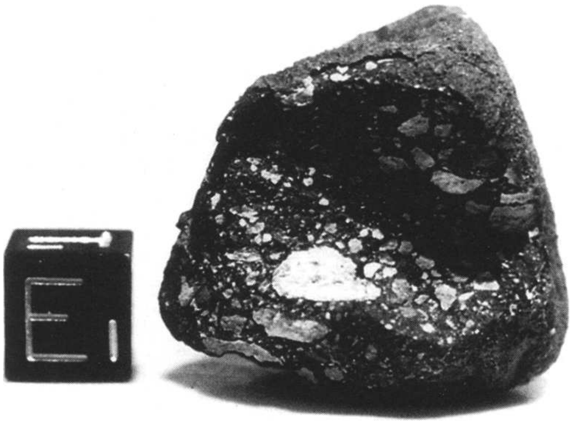

Fig. 3. The meteorite ALH 81005 from the Allan Hills, Antarctica, the first lunar-sourced meteorite to be identified. The cube has sides of 1 cm.

The Western Australian Museum collection and desert meteorite finds from the 1960s onwards

The Western Australian Museum collection, described by **Bevan**, had its origins in the discovery of some large iron meteorites near the settlement of York in the Wheat Belt, east of Perth. The first octahedrite mass was recovered in 1884, although the main mass was not discovered until 1954. Despite a sparse population in this huge state and comparatively recent settlement by Europeans in 1829, meteorite recovery here is not uncommon mainly due to the aridity of the climate and the thin savannah or desert-type vegetation, which favour slow weathering and the likelihood of a find. From 1897 to 1939, E.S. Simpson of the Government Chemical Laboratory curated the collection with great zeal and efficiency in recording, describing and analysing the meteorites. The collection then lapsed and was stored away in a dusty cupboard, until the fall in 1960 of a spectacularly oriented ordinary chondrite mass at Woolgorong Sheep Station revived interest. As a result of this revival, Joe McCall, a geologist, and John de Laeter, a physicist, both working part-time unpaid, were persuaded to rescue it, catalogue it, carry out research on new discoveries and encourage the public to bring in meteorites, with surprising success. Rabbit-trappers on the

Nullarbor Plain led by John Carlisle, and the enthusiastic searches by Bill Cleverly of the Kalgoorlie School of Mines, contributed to a successful group effort. New finds included a second mass of the unique Bencubbin meteorite (found as a door-stop in East Perth!) and the large, almost unique Mundrabilla ataxite irons that surrounded innumerable finger-sized shed masses on the Nullarbor Plain: the irons were spread in a remarkable ellipse of dispersion 125 km long (Fig. 4). Much smaller dispersion ellipses on the Nullabor were found in the case of Mulga North (find, 1964, common (ordinary) chondrite) and Camel Donga (find, 1984,

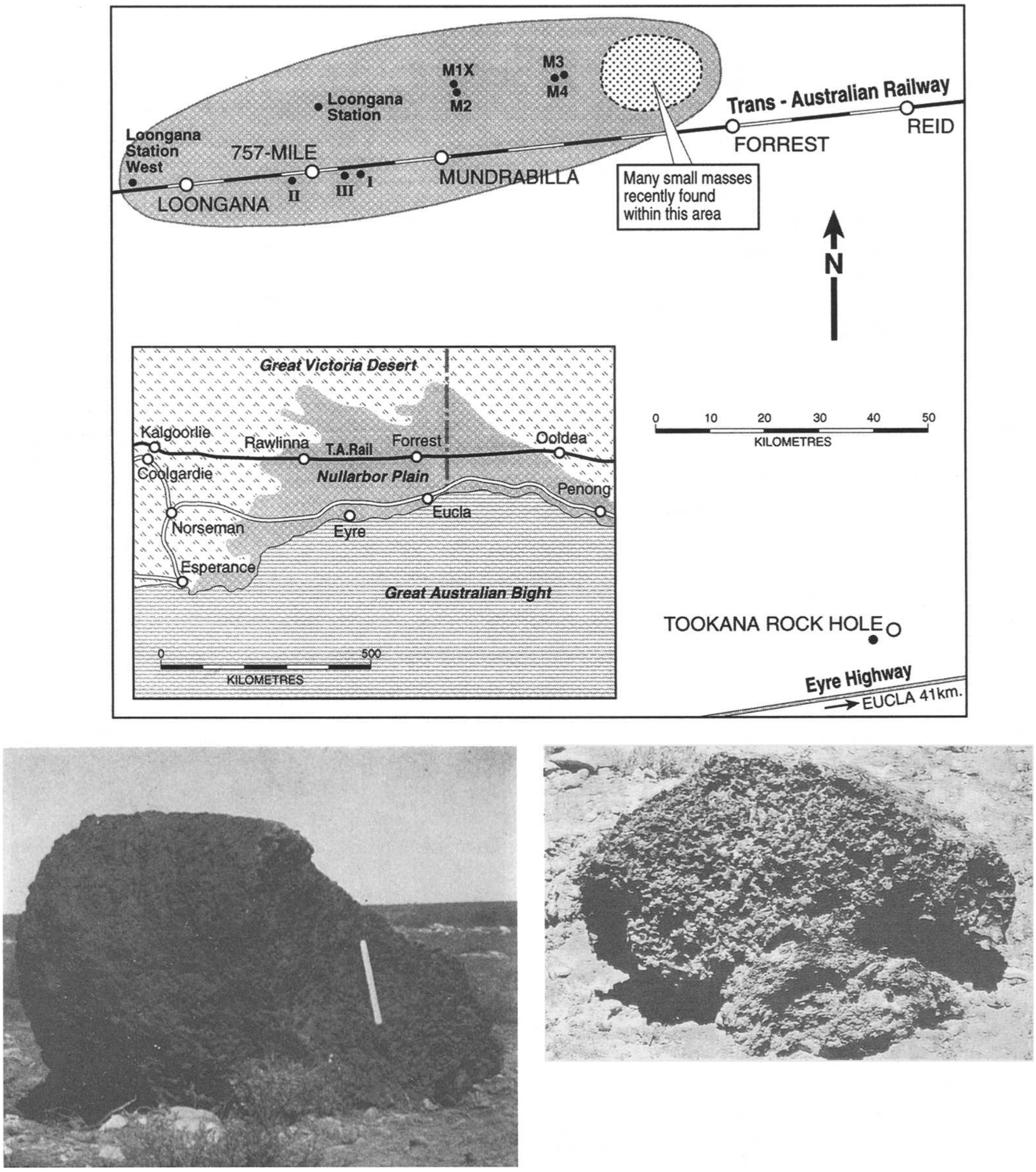

Fig. 4. The ellipse of dispersion of the approximately 1 Ma old Mundrabilla shower of iron meteorites on the Nullarbor Plain, Western Australia. Below, left: the main mass of the Mundrabilla meteorite, weighing *c.* 12 t. The mass displays a shape like that of a space capsule, with an irregular concave face where the second large mass of *c.* 5 t, found 100 m away, separated from it. Below, right: the second mass, with a pad of iron-shale beneath, due to weathering. (Photographs G.J.H. McCall: reproduced with permission from Elsevier, U.K.)

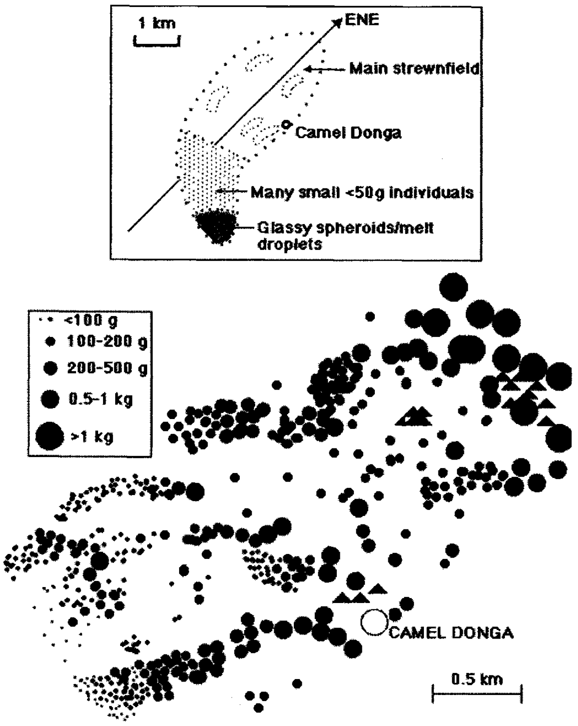

Fig. 5. The ellipse of dispersion of the Camel Donga eucrite, found in 1984, on the Nullarbor Plain, Western Australia. The shower clearly consisted of a number of masses that split off after entry into the atmosphere, and these suffered further fragmentation, giving a pattern of about 10 clusters, each with the larger pieces towards the front as they hit the ground. Triangles indicate broken fragments. (Figure supplied by Alex Bevan.)

eucrite) (Fig. 5). The Mundrabilla meteorite shower is now known from isotopic evidence to have occurred approximately 1 Ma ago. Both main masses were recovered from the Nullarbor and the larger *c.* 12 tonne (t) mass (Fig. 4) is in the museum. The smaller *c.* 5 t mass (Fig. 4) went to South Australia and was later cut into a number of huge polished slices by Paul Ramdohr (one of which now graces the Earth Gallery at the Natural History Museum, South Kensington, London).

The Wolfe Creek Crater, near Halls Creek in the NE of the state, was mapped in detail during the 1960s and a large collection of iron shale balls were collected there (McCall 1965).

In the 1960s, meteorites were made State property by law, although there were provisions to compensate finders. With the realization that the Nullabor Plain was an optimum search region, a EUROMET programme of systematic search was mounted under the new curator, Alex Bevan, in four expeditions in 1992–1994. This resulted in hundreds of recoveries, and the plain, which extends into South Australia, has not been fully searched systematically as yet. The Western Australian Museum collection, which includes many unique or rare types, is now a world-class collection. Lately some of the meteorites have been exhibited in a spectacular new gallery devoted to Earth and Planetary Science (McNamara & Bevan 2002).

The second article by **Bevan** covers the extensive collections from hot-desert areas. Collection from these areas only escalated in the late 1980s. During the last 35 years, the number of meteorites available for study worldwide has increased from about 2000 to nearly 30 000, and, whereas about 20 000 of these come from the Antarctic cold deserts, since the late 1980s 8000–9000 have come from the hot deserts. The most notable of these regions are the Nullarbor Plain, the wider Sahara (Algeria, Libya, Niger, Morocco), the Arabian Peninsula (Saudi Arabia, Oman) and Roosevelt County, New Mexico. Just as only restricted areas of the Antarctic Ice have proved fertile and Greenland has so far proved negative, the hot-desert areas are all different in character and only very special conditions favour proliferation of finds. The Nullarbor is a limestone desert and the Miocene limestone is greyish white, so that meteorites show up dark against it: rainfall is extremely scarce and decay by weathering extremely slow. The Saharan deserts are dominantly sandy and there meteorites may be concentrated by wind deflation. The climatic histories of the two are quite different. Some deserts, for example the Gobi and the Central Asian deserts, have to date proved quite infertile for meteorite finds. The Iranian Kavirs and Jaz Murian Depression could be fertile, for there are similarities both to the Nullarbor and the Oman. These hot deserts have extended our knowledge of early solar system materials by providing samples of meteorites hitherto unknown to science, have provided the basis for new groupings, and have yielded quite a number of lunar and martian meteorites. Important studies of the flux of meteorites with time and regional climate change have been based on these desert finds.

Research establishing the provenance of meteorites

The 7 articles that comprise the third section of this Special Publication are closely interrelated. The article on chondrules and CAIs by **McCall** takes the reader back to the description and analysis by Edward Howard in 1802 of four stony meteorites (all now classified as ordinary chondrites, all falls – Benares, Bohemia

(Tabor), Wold Cottage and Siena). Not only did he establish that they were all alike and collectively unlike any terrestrial rock material, he also described a dark coating (fusion crust) and 'rounded globules'. Henry Sorby, in 1864, published a masterly microscopic description, and attributed these round objects to 'a fiery rain' and 'a time when the Sun extended further out in the Solar System'. Gustav Rose in 1863 coined the terms *chondrule* and *chondrite.*

In the second half of the 20th century, the provenance of chondrites and most other meteorites in asteroids was established by camera tracking of the orbits of the brilliant fireballs of the Pribram, Czechoslovakia (1959), Lost City, Oklahoma (1970), and Innisfree, Alberta (1977), meteorites, all chondrites. The article by **Bowden**, describes in detail more recent developments of this procedure and the results of attempts to match the various classes of meteorites to the spectrographic characteristics of individual asteroids and asteroid groups. Ernst Öpik originally raised dynamical questions concerning the type of mechanism necessary for delivering asteroidal fragments to Earth within a timescale and flux that matched known meteorite falls. Since his original questioning, several workers have risen to the challenge and today the dynamical conditions and potential delivery mechanism are better understood. It was hoped that work on the reflectance spectral characteristics of asteroids would provide suitable asteroid analogues to meteorites held in our collections. However, there are a number of complicating factors that mask true meteorite/asteroid analogues, not least of which are the effects of space weathering. The advent of space missions to asteroids has helped in our understanding of asteroid surface morphologies and geological histories, although a suitable match still has to be found for the ordinary chondrites that make up 86% of known meteorite falls.

Confirmation of the asteroid source of meteorites was obtained from isotope-based methods of age dating of meteorites, establishing formation *ages*, covered here by **de Laeter**: the first determination on a meteorite was made in 1953 by Clair Patterson on an iron from Meteor Crater, Arizona, with an age of approximately 4550 Ma being obtained. Chondrites initially gave ages of about 4555 Ma. These extreme ages are consistent with an origin of meteorites in asteroids. Ages obtained on achondrites, which are clearly magmatic and formed by processes within the asteroid parent body, are slightly less than those for chondrites, which is as expected. There is no evidence at all to link the HED (howardite, eucrite, diogenite) achondrites with chondrites; we simply do not know what their parent material was, but rare achondrites such as brachinites and acupulcoites do appear to be achondrites derived from chondrites. However, the HED achondrites do appear to be attributable to one known asteroid parent body namely (4) Vesta, so called as it was the fourth to be discovered (in 1807), as described in the article by **Bowden**.

Chondrites with unaltered chondrules are less common than chondrites showing varying degrees of thermal recystallization due to subsequent metamorphism and/or shock effects related to collisions in space. A classificatory system has been derived to denote the progressive development of the metamorphic process (which in its extreme development produced the brachinite and acupulcoite achondrites), and another to denote the degree of shock.

The carbonaceous chondrites are more primitive than the common chondrites, and both the extremely hydrous CI class (Orgueil, Ivuna) and the CM class (Murchison) contain amino acids (the latter 74), the former a very restricted number (these meteorites may come from comets). The CI chondrites actually contain no chondrules. The amino acids are different, both isotopically and optically, from those in terrestrial life forms and are considered to be abiogenic (Glover 2003). The CI chondrite composition has provided the basis for the 'Chondritic Earth Model', it being considered to approach closely that of the solar nebula.

The fall of the Allende (CV) meteorite in Mexico in 1969 gave rise to the recognition of the CAIs (refractory calcium and aluminium-rich inclusions), which are abundant in this class. They were originally thought to be older than the chondrules, but refined age dating has pushed the age of some chondrules back, and both CAIs and some chondrules seem to have formed at about 4366.7 Ma, although the Allende meteorite does contain some presolar grains (nanodiamonds, SiC).

Recent research has suggested that, although ordinary chondrites are the most common to fall to Earth, this may be because this natural sample derives from only the near-Earth asteroids, and this may not be a representative statistic for the asteroids as a whole. **Bowden** describes some of the attempts made to solve the chondrite paradox when searching for asteroidal analogues and their distribution.

A general consensus seems to have been reached that chondrules and the CAIs formed in the outer regions of the non-homogenous solar disk very early on where shock pressures raised the temperature, but research on this is continuing and there is no single universally accepted model.

The article by **de Laeter** is focused on age dating, and it must be emphasized that a vast amount of other research is nowadays ongoing on isotopic relationships in meteorites. Articles regularly appear in journals such as *Meteoritics and Planetary Science* on applications to exposure to cosmic rays while on Earth after fall (thus giving the age on Earth for finds), exposure to cosmic rays while a meteoroid is in space (cosmic-ray exposure ages) and, even, looking back into presolar system history.

There are two non-asteroidal provenances of meteorites, represented by a very small minority of the world meteorite count. Since the first Antarctic discovery we continue to find lunar-sourced meteorites, (clearly identifiable from our knowledge of *Apollo* samples) and more than 20 are now known. These mainly stem from finds in Antarctic or hot-desert regions, although one has been found in Western Australia outside the Nullabor Plain. These are invaluable as they sample parts of the lunar surface not previously sampled by the *Apollo* and *Luna* missions, and, all being breccias, may include fragments from levels beneath the lunar surface. These have apparently been spalled-off the lunar surface by impacts during the last few thousand years. There remains an unanswered question: 'Where has all the much greater volume of material, spalled-off our satellite in the "great bombardment" at *c.* 4000 Ma, gone?'. Some of it should surely have collided with asteroidal meteorites, but there is no record whatsoever of asteroidal–lunar mixed breccias. This is a major problem waiting to be solved.

There is a second set of about 34 meteorites, the SNC meteorites (Shergotty, Nakhla, Chassigny). These are planetary sourced, and are described here by **Grady**. It is now 25 years since they were widely accepted as coming from Mars – it was initially difficult to accept spallation by impact from Mars as a physical process, but this problem has been resolved. Gases preserved in a shocked meteorite from Antarctica and others match isotopically those in the martian atmosphere as established by the Viking probes in the 1970s. Formation ages from these meteorites differ from those of asteroidal meteorites (e.g. Shergottites *c.* 180 Ma, i.e. Jurassic; Nakhlite and Chassignite *c.* 1300 Ma, i.e. Proterozoic). These ages indicate a source in a planet with igneous rock-forming processes occurring at widely different times in its history, not an asteroid. By a process of elimination, Mars is arrived at as the source: (i) Mercury is so like the Moon that it seems almost certain that here also surface activity ceased around 4000 Ma: the formation ages are thus unlikely to relate to Mercury; (ii) it is almost impossible for material to be spalled-off Venus by impact, considering its thick atmosphere; and (iii) the outer planets are not rocky, but are 'gas' or 'ice giants'. The SNC meteorites are all igneous, most are shocked and many show evidence of hydrous activity. This restriction to igneous rocks of a narrow range of composition is puzzling; surely one would expect a wider range from a complex-surfaced planet such as Mars? These meteorites have been used to build up a picture of the martian surface and planetary development, complementing spacecraft observations, but these are early days of martian exploration and, as yet, no coherent lava flow has been recorded in close-up imagery by any of the Mars landers, with only boulder-strewn loose 'sand' terrains being encountered. However, one of the rocky outcrops examined by the Mars Rover *Opportunity* showed a layered formation that may have a sedimentary rather than igneous origin. This marks a change in martian petrology from the ubiquitous basalts sampled by the other rovers.

The article by **Brush** provides an account of the theories of origin of the solar system, strongly influenced by observation, evidence and theorizing about meteorites. The meteoritic–planetesimal theory of planet formation, as developed in Russia by Schmidt and Safronov, has been established by Wetherill as the preferred theory of the origin of the terrestrial planets.

Impact craters and tektites

The last two articles in this section by **McCall** are closely related. In the first, on meteorite cratering, he mentions Robert Hooke in the 17th century as experimenting and considering the possibility of impact cratering. Seminal studies of Canyon Diablo Crater in Arizona by Grover Gilbert in the late 19th century resulted in him favouring endogenous steam explosion, whereas Daniel Barringer, who searched for the missing iron mass, favoured impact. Gene Shoemaker in 1960–1963, in a careful study, demonstrated its impact origin. In the 1930s a number of small craters associated with iron fragments in the USA, Estonia, Australia and Arabia were described, and in the 1960s Wolfe Creek Crater in Australia was shown to be a smaller analogue of Canyon Diablo (now renamed Meteor Crater). These two craters are the largest terrestrial craters associated with meteorite fragments. However, as described in two benchmark volumes (McCall 1977, 1979), a number of larger structures, some exceeding 100 km in diameter, were subsequently attributed to impact as a result of Shoemaker's publications, and since then the number has risen to about 175. These are recognized on the basis of certain indicators of extreme shock – including shatter cones, high-pressure silica polymorphs, and various types of impactites including rocks with evidence of shock melting, high-pressure silica polymorphs and shock-produced diamonds.

The ocean crust shows a complete lack of such structures – perhaps not surprising as it is recycled by plate tectonic processes. However, one non-crateroid structure 25 km in diameter is known from the Southern Ocean, the Pliocene Eltanin structure, and breccias carry minute mesosiderite or howardite meteorite specks. Impact under the sea has recently been discussed, together with another little-researched topic, impact on ice surfaces, which has applications to Mars and the outer ice giant planets and many of the outer satellites (Dypvik *et al.* 2004).

Although **McCall** considers that it is extremely unlikely that the attribution of all these craters and structures to large-scale extraterrestrial impact will ever be overturned, the global distribution is unexpectedly heavily weighted to North America, Scandinavia and Australia, and this is a major anomaly that needs explanation. This article concentrates on terrestrial cratering, extraterrestrial cratering not being considered except for the 1665 experiments of Hooke. The original ideas of Wegener (1921), who used experimental data to argue that they must be due to impacts, and Baldwin (1949) on lunar cratering of course contributed to the widespread acceptance of large-scale terrestrial impact cratering.

McCall's second article traces the history of tektites from records in China in the 12th century through to the 18th–20th centuries: the four major strewn fields in North America (Late Eocene), Central Europe (Miocene), Ivory Coast (Pleistocene, *c.* 1 Ma) and Australasia (*c.* 0.78 Ma) were recognized by the mid-1930s. A bewildering number of possible explanations for these aerodynamically shaped siliceous glassy objects were suggested. In the mid-20th century lunar origin was highly favoured, and wind-tunnel experiments reproduced the forms of flanged-button australites perfectly, showing that the original splash forms had been secondarily ablated in descent through the atmosphere. However, *Apollo XI* demolished lunar models instantaneously and it became clear that suggestions previously made that tektite chemistry was terrestrial were correct, leading to acceptance by most scientists of an origin in violent expulsion from sites of large impacts on the Earth, although there remain some dissenters. The Ivory Coast tektites were firmly equated with the Bosumtwi Crater in West Africa, the Central European tektites with the Ries structure in south Germany, and quite recently the North American tektites with a buried 90 km-diameter structure centred under Chesapeake Bay. However, remarkably, no source structure has ever been found for the largest strewn field, the Australasian. Microtektites were found in ocean sediment cores and related to all but the Central European Strewn Field from the 1960s onwards.

Only a handful of the known large terrestrial impact structures have a tektite association: just why is not apparent. There are other ongoing problems yet to be solved, including the source of the Australasian Strewn Field, the manner of dispersion, over hundreds of kilometres of the large irregular layered Muong Nong-type tektites in South-east Asia, the exact geological sources of the tektites at the target structures, and the relationship between microtektites and tektites – including how the microtektites, rarely exceeding 1 mm in maximum dimension, managed to travel many thousands of kilometres from the target (they are not simply shed drops from the larger tektites).

Conclusion

The history of meteoritics is never complete: new events are occurring from day to day. Quite astonishing was the recent discovery (Schmitz 2003) of 12 horizons of ordinary chondrites in a quarry within a 480 Ma old Ordovician 'Orthoceratite' limestone near Göteborg, Sweden (Fig. 6). These represent repeated showers over *c.* 1.75 Ma. For meteorite showers to fall in the same place again and again is extraordinary because of the rotation of our planet, and one can deduce that these showers must have been very widespread geographically (another occurrence is indeed known 500 km away in Sweden). The spread of each shower may even have been right round the global circumference. It can be deduced that at that time the flux of meteorites to Earth was of an order greater than at present.

A fall in Portales Valley, Roosevelt County, New Mexico in 1998 yielded a unique metal melt breccia with silicate meteorite that is transitional between more primitive H chondrite and evolved (achondrite, iron) types, and is best classified as an H7 metallic melt breccia of shock stage 1 (Ruzicka *et al.* 2005). Any day something new may arrive from the sky!

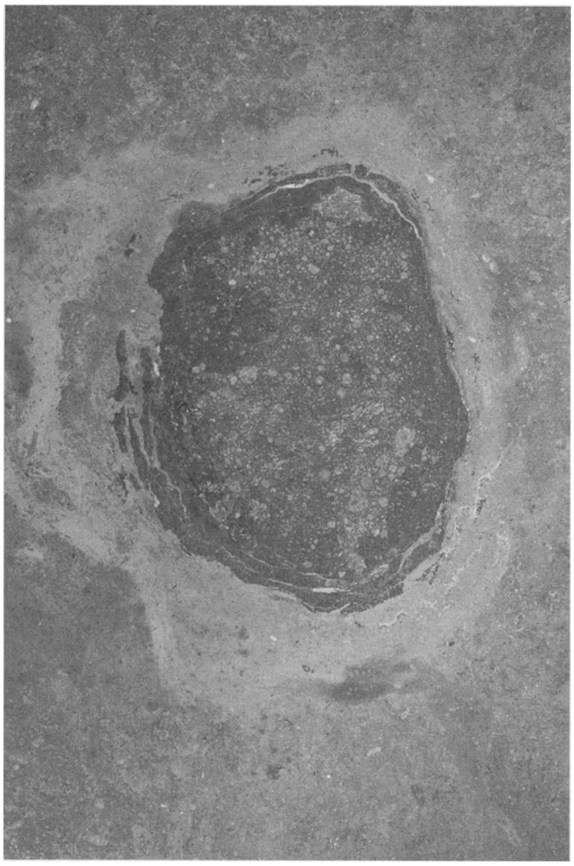

Fig. 6. An ordinary chondrite mass within Ordovician (*c.* 480 Ma) 'Orthoceratite' limestone, in a quarry face near Göteborg, Sweden. (Photograph Birger Schmitz.)

In 2004, the Mars Rover *Opportunity* imaged an iron meteorite resting on the martian surface, the first discovery of a meteorite on an extraterrestrial body. This find raises the whole question of the behaviour of meteorites falling on Mars through its thin atmosphere and impacting its surface (McCall 2005).

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