Meteorite cratering: Hooke, Gilbert, Barringer and beyond

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Abstract: Robert Hooke in the 17th century was the first scientist to consider the possibility of meteorite impact cratering, when looking at the lunar craters. Gilbert in the late 19th century considered it again when studying 'Coon Butte' (now known as 'Meteor Crater'), Arizona, but attributed it to cryptovolcanism. Barringer early in the 20th century attributed the same crater to meteorite impact, as did Shoemaker in 1960–1963, the latter drawing on the results of recent nuclear cratering experiments. This crater and Wolfe Creek Crater in Western Australia are nowadays taken as type examples of the largest (1 km scale) terrestrial craters associated with actual meteorite fragments. A number of smaller impact craters associated with fragments were recognized in the 1930s in Estonia, Arabia, Australia and the USA; and, in 1949, 100 were formed by a shower of iron meteorites in Sikhote-Alin, Siberia. The dawn of the Space Age in the late 1950s saw an extensive search for larger craters and structures, and, because the many craters and structures of more than 1 km diameter so revealed on land had no meteoritic material accompaniment, a number of high-pressure shock indicators were defined – shatter cones, lamellations in quartz, high-pressure polymorphs of quartz (coesite, stishovite), amorphous silica (lechatelierite), diamonds and fullerenes, and impactite breccias with melt glass (suevite, Bunte breccia). About 170 such structures are now recorded, and they include structures more than 100 km across. Tektites, glassy bodies with splash forms and, in some cases, ablation flanges, found in strewn fields up to thousands of kilometres from the source structures are associated with a handful of such structures, but such associations are not the norm. One or two such structures have been located under the sea, and the Pliocene Eltanin structure, not truly craterform and situated beneath the Southern Pacific Ocean, has mesosiderite meteorite specks in the breccias. Isotopic methods have in many other cases indicated a trace extraterrestrial component. The global distribution is extremely uneven, with large populations recorded in Canada and the USA, Fennoscandia and Australia, and extensive blank regions in mid-Africa, Asia and South America. Despite this anomaly, not really satisfactorily explained, it is unlikely that the attribution of these terrestrial craters and structures will be overturned, although some may have been misinterpreted. It is suggested that the attribution of craters and the Maria on the Moon and craters on other bodies of the solar system to impact rather than volcanic agencies is less firmly founded, although entrenched.

This account covers the history of cratering caused by the impact on the surface of the Earth by extraterrestrial objects, mostly meteorites but in the case of very large-scale events possibly asteroids or comets. The meteorites that fall on the Earth are predominantly fragments derived from the break-up of asteroidal parent bodies, but in the late 20th century products of spallation of fragments of the Moon were recognized among meteorite finds (first in Antartica, then in Australia, North Africa and Oman) and the SNC (Shergotty, Nakhla and Chassigny) meteorites were attributed confidently to similar spallation from Mars, although neither of these has, as far as is known, produced a crater on the surface of the Earth.

Robert Hooke

In 1663 the English scientist Robert Hooke (1635–1703), Curator of Experiments of the then newly founded Royal Society, was 'solicited to prosecute his microscope studies'. Having some spare unfilled space on his last plate illustration for his book *Micrographia* (Hooke 1665), he somewhat inconsequentially filled it with drawings of parts of the Moon's surface as seen through a telescope (Fig. 1). This was really the first detailed study of that surface, for no particular reason taking the crater Hipparchus as the subject. Hooke noted that it had the figure of a pear, being elongated rather than circular. His enquiring mind was

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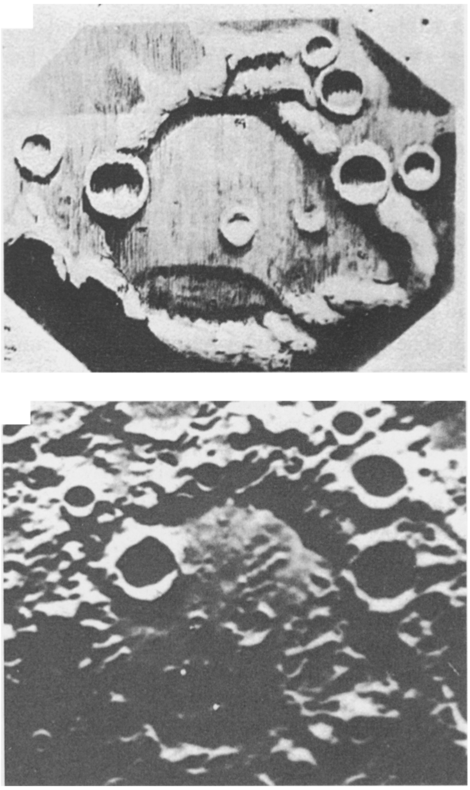

Fig. 1. Robert Hooke's (1665) drawing of lunar crater Hipparchus compared with a modern telescopic image (below). From Green (1965).

led to experiments to determine how it was formed. However, he did not use the term 'crater', writing of 'holes':

- With 'soft well-tempered tobacco pipe clay and water', into which he let fall a 'bullet', representing a heavenly body;
- 'boyling alabaster', and after the eruption of vapours, producing a surface riddled with small bubble cavities.

He concluded that the latter were exactly like the craters of the lunar surface. He did not reject the first experimental result on account of the experimental product, but rather by an argument that he could not conceive what sort of 'bullet' or heavenly body could fall on the lunar surface (despite at least 90 documented falls before 1665, the nature and extraterrestrial provenance of meteorites was not then accepted by Science), so he plumped for an analogy between the lunar craters and 'Vulcans' (volcanoes) known in several places on Earth.

Hooke was thus swayed by the lack of any known agencies for cratering by extraterrestrial bodies. Diogenes of Apollonia had, in fact, long ago in 465 BC solved the riddle of meteorites, postulating a connection between meteorites and stars and placing their source outside the solar system (Krinov 1963), but Science had not listened. The site of meteorite craters, later described, had indeed been visited by conquistadors in northern Argentina – guided there in 1576 by natives to see numerous masses of nickel iron that those natives said had fallen from the sky – but they did not apparently notice the associated craters at Campo del Cielo (Alvarez 1926).

Hooke's observations were followed by an interval of more than 200 years before Science returned to the question of the reality of impact cratering, on the Moon or on the Earth.

G.K. Gilbert

The chemist and mineral dealer Albert E. Foote (1846–1895) visited the crater then known as Coon Butte, Arizona, in 1891 and collected 137 specimens of iron, ranging from few grammes to 91 kg. He pronounced the iron to be meteoritic and this has been generally accepted ever since. Small black and white diamonds were found in a cavity in a cut section of the meteoritic iron. Foote concluded that 'an extraordinarily large mass of 500–600 lbs' (226–272 kg) had 'become oxidised when passing through the air and was so weakened in its internal structure that it had burst into pieces not long before reaching the Earth'.

In 1896 Grove Karl Gilbert (1843–1918), a distinguished American geologist (Fig. 2), published results of his investigations of Coon Butte (also known as Cañon Diablo Crater, Arizona, and now also known as Meteor Crater), approximately 1220 m in diameter (Fig. 3). Gilbert was interested in the philosophy of scientific enquiry and believed in describing the progressive development of his ideas as he went along. He learnt first that shepherds camped on the outer slopes in 1866 had found pieces of iron: Mathias Armijo and his fellow shepherds had concluded that 'The crater was produced by an explosion, the material of the rim being thrown out from the same cavity at the same time'. Gilbert (1896) remarked that this was a comprehensive explanation, accounting for the crater, the iron and their association together. He then noted that Foote had pronounced the iron (Figs 4 & 5) to be meteoritic. The planetesimal theory of the origin of the Earth had lately been propounded by the

Fig. 2. Portrait of Grove K. Gilbert (1843–1918), (from Geological Society, London, archive).

American geologist Thomas C. Chamberlin (1843–1928) and astronomer Forest R. Moulton (1872–1952), and, influenced by this, Gilbert suggested that:

> another small star should now be added to the Earth . . . a raindrop falling on the Earth produces a miniature crater, so does a pebble thrown into a pool of pasty mud. A large crater is made when steel projectile is fired against armor plate; and analogy easily bridged the interval from raindrop to asteroid.

Gilbert now sent W.D. Johnson out to inspect the crater (Seddon 1970) and he plumped for an explanation invoking a laccolith, an igneous intrusion of a type that Gilbert himself was renowned for describing in the literature – in the Henry Mountains, Utah (Gilbert 1880). Laccoliths were in fashion, and Johnson saw an eroded dome rather than a rimmed crater. He could find no trace of igneous rocks, the expectation of a laccolith, so he then turned to cryptovolcanism. Gilbert followed this idea:

> A body of steam was produced at depths of some hundreds or thousands of feet. And the explosion of this steam produced the crater. The fall of iron was independent and the association of the two occurrences at the same locality is accidental.

Thus, Gilbert now had two alternatives: impact of an extraterrestrial body and steam explosion from inside the Earth. He then concluded that a 'stellar body', if such had fallen,

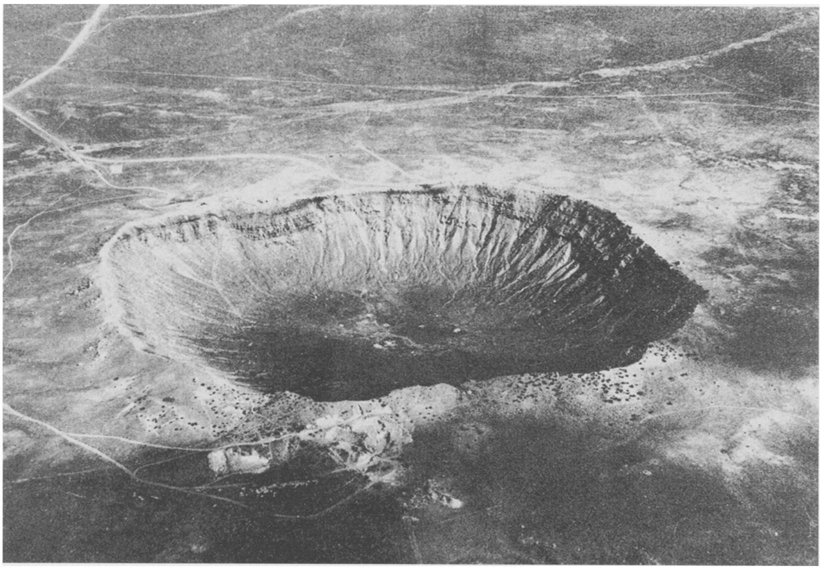

Fig. 3. Photograph from the air of the 1.186 km-diameter Meteor Crater, Arizona. From McCall (1977).

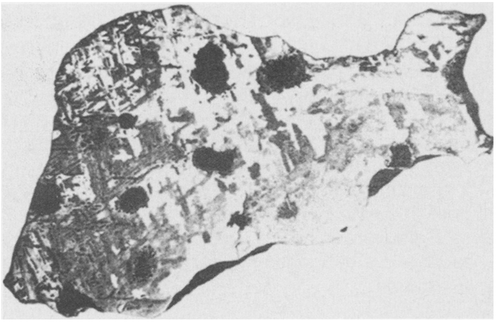

Fig. 4. An iron fragment from outside Meteor Crater showing the etch pattern. This is an octahedrite in the Prior classification, now classified as IAB. From McCall (1977).

should be beneath the 'bowl' and the volume of material excavated by an explosion should be left in the rim. He seems to have ignored the possible effects of erosion in the second case. As the stellar body was apparently of magnetic metal it should be detectable with the magnetic needle. He noted that an explanation which relates the crater to the nickel–iron fragments was 800 times more probable than one that regards the association as fortuitous, but warned against the danger of assuming that this excludes completely the less likely answer. He also considered the possibility of oblique incidence of the impactor; thus removing the need for it to be present beneath the crater if it ricochetted off. A useful let-out as it turned out, for fieldwork revealed no magnetic anomaly. The crater also showed radial symmetry, which Gilbert took to be against oblique impact (although modern experiments indicate that, whatever the angle of incidence, impact craters are likely to approximate to radial symmetry). The total weight of the impacting mass, if there was one, was estimated at approximately 10 tons (widely varying figures have since emerged) and a rather crude volumetric calculation suggested to him that there was no extra mass under the crater.

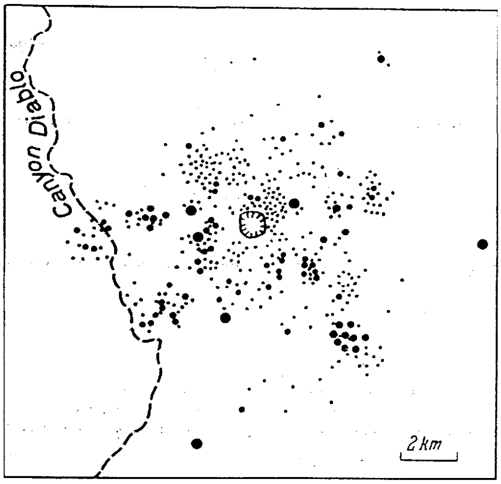

Fig. 5. A plot of the distribution of the irons around Meteor Crater. (after Mason 1962, reproduced by McCall 1977).

In the state of knowledge at the time of Gilbert's researches, the only way to accommodate cryptovolcanic origin was to say that the iron was not related to the crater, as Gilbert did. So he was persuaded to accept the survivor from his ruthless wielding of Occam's Razor, the steam explosion explanation. In doing so he noted that experimental evidence did not discount impact, but that: The excess of matter required by a buried star was not found.

He found that steam explosion 'had its like elsewhere' in Vesuvius, Bandai-San, Krakatoa, the Rhine valley 'maars' (craters formed by explosion involving groundwater and not accompanied by igneous extrusion, also not uncommonly occupied by a small crater lake). He also cited Lonar Lake, India, then believed to be a maar, although it is now listed as an impact crater (Table 1).

Gilbert felt that his work was not finished and, indeed, later entertained the possibility that a combination of the two explanations could be the answer: A falling star ... in some way ... had touched the volcanic button.

This idea is, of course, at the root of many recent interpretations of the 200 km-diameter Sudbury, Ontario, structure as an impact structure, for there is far too much nickel in the associated sulphide ore to come from the impactor.

Gilbert also considered the possibility of the impactor being a stony-iron meteorite or a combination of iron and sulphur: 'The iron being like stones in an astral pudding'.

Gilbert was undoubtedly the first scientific explorer of the possibility of terrestrial impact cratering, now accepted as the process responsible for some 170 terrestrial examples (R.A.F. Grieve, list of terrestrial impact craters and structures as at 3 November 2004: Table 1), that is widely accepted by geologists, although in the end he came out against it: Yochelson (1980) concluded that his basic error was to overestimate the size of the impactor and neglect the possibility of its fusion, evaporation and ejection. In his rejection of impact origin he did invoke cryptovolcanic steam explosion, a process still accepted by geologists, of which a type-example is 'Hole-in-the Ground', Oregon (McCall 1977).

Table 1. *The list of craters and structures worldwide attributed to impact and widely accepted as such, as at 3 November 2004 (from Grieve 2004) (source: http.//www.unb.ca/passc/ImpactDatabase/CINameSort.html)*

Name	Country	Latitude	Longitude	Diameter (km)	Age (Ma)*	Exposed	Drilled
Acraman	South Australia, Australia	S 32°1′	E 135°27′	90	*c.* 590	Y	N
Ames	Oklahoma, USA	N 36°15′	W 98°12′	16	470 ± 30	N	Y
Amguid	Algeria	N 26°5′	E 4°23′	0.45	<0.1	Y	N
Aorounga	Chad, Africa	N 19°6′	E 19°15′	12.6	<345	Y	N
Aouelloul	Mauritania	N 20°15′	W 12°41′	0.39	3.0 ± 0.3	Y	N
Araguainha	Brazil	S 16°47′	W 52°59′	40	244.40 ± 3.25	Y	N
Arkenu 1	Libya	N 22°4′	E 23°45′	6.8	<140	Y	N
Arkenu 2	Libya	N 22°4′	E 23°45′	10	<140	Y	N
Avak	Alaska, USA	N 71°15′	W 156°38′	12	>95	N	Y
B.P. Structure	Libya	N 25°19′	E 24°20′	2	<120	Y	N
Barringer	Arizona, USA	N 35°2′	W 111°1′	1.186	0.049 ± 0.003	Y	Y
Beaverhead	Montana, USA	N 44°36′	W 113°0′	60	*c.* 600	Y	N
Beyenchime-Salaatin	Russia	N 71°0′	E 121°40′	8	40 ± 20	Y	N
Bigach	Kazakhstan	N 48°34′	E 82°1′	8	5 ± 3	Y	Y
Boltysh	Ukraine	N 48°45′	E 32°10′	24	65.17 ± 0.64	N	Y
Bosumtwi	Ghana	N 6°30′	W 1°25′	10.5	1.07	Y	N
Boxhole	Northern Territory, Australia	S 22°37′	E 135°12′	0.17	0.0540 ± 0.0015	Y	N
Brent	Ontario, Canada	N 46°5′	W 78°29′	3.8	396 ± 20*	N	Y
Calvin	Michigan, USA	N 41°50′	W 85°57′	8.5	450 ± 10	N	Y
Campo Del Cielo	Argentina	S 27°38′	W 61°42′	0.05	<0.004	Y	Y
Carswell	Saskatchewan, Canada	N 58°27′	W 109°30′	39	115 ± 10	Y	Y
Charlevoix	Quebec, Canada	N 47°32′	W 70°18′	54	342 ± 15*	Y	Y
Chesapeake Bay	Virginia, USA	N 37°17′	W 76°1′	90	35.5 ± 0.3	N	Y
Chicxulub	Yucatan, Mexico	N 21°20′	W 89°30′	170	64.98 ± 0.05	N	Y
Chiyli	Kazakhstan	N 49°10′	E 57°51′	5.5	46 ± 7	Y	Y
Chukcha	Russia	N 75°42′	E 97°48′	6	<70	Y	Y
Clearwater East	Quebec, Canada	N 56°5′	W 74°7′	26	290 ± 20	Y	Y
Clearwater West	Quebec, Canada	N 56°13′	W 74°30′	36	290 ± 20	Y	Y
Cloud Creek	Wyoming, USA	N 43°7′	W 106°45′	7	190 ± 30	N	Y
Connolly Basin	Western Australia, Australia	S 23°32′	E 124°45′	9	<60	Y	N
Couture	Quebec, Canada	N 60°8′	W 75°20′	8	430 ± 25	Y	N
Crawford	Australia	S 34°43′	E 139°2′	8.5	>35	Y	N
Crooked Creek	Missouri, USA	N 37°50′	W 91°23′	7	320 ± 80	Y	N
Dalgaranga	Western Australia, Australia	S 27°38′	E 117°17′	0.024	*c.* 0.27	Y	N
Decaturville	Missouri, USA	N 37°54′	W 92°43′	6	<300	Y	Y
Deep Bay	Saskatchewan, Canada	N 56°24′	W 102°59′	13	99 ± 4	N	Y

(Continued)

Table 1. Continued

Name	Country	Latitude	Longitude	Diameter (km)	Age (Ma)*	Exposed	Drilled
Dellen	Sweden	N 61°48′	E 16°48′	19	89.0 ± 2.7	Y	N
Des Plaines	Illinois, USA	N 42°3′	W 87°52′	8	<280	N	Y
Dobele	Latvia	N 56°35′	E 23°15′	4.5	290 ± 35	N	Y
Eagle Butte	Alberta, Canada	N 49°42′	W 110°30′	10	<65	N	Y
Elbow	Saskatchewan, Canada	N 50°59′	W 106°43′	8	395 ± 25	N	Y
El'gygytgyn	Russia	N 67°30′	E 172°5′	18	3.5 ± 0.5	Y	N
Flaxman	Australia	S 34°37′	E 139°4′	10	>35	Y	N
Foelsche	Northern Territory, Australia	S 16°40′	E 136°47′	6	>545	N	N
Flynn Creek	Tennessee, USA	N 36°17′	W 85°40′	3.8	360 ± 20	Y	Y
Gardnos	Norway	N 60°39′	E 9°0′	5	500 ± 10	Y	N
Glasford	Illinois, USA	N 40°36′	W 89°47′	4	<430	N	Y
Glover Bluff	Wisconsin, USA	N 43°58′	W 89°32′	8	<500	Y	Y
Goat Paddock	Western Australia, Australia	S 18°20′	E 126°40′	5.1	<50	Y	Y
Gosses Bluff	Northern Territory, Australia	S 23°49′	E 132°19′	22	142.5 ± 0.8	Y	Y
Gow	Saskatchewan, Canada	N 56°27′	W 104°29′	5	<250	Y	N
Goyder	Northern Territory, Australia	S 13°9′	E 135°2′	3	<1400	Y	N
Granby	Sweden	N 58°25′	E 14°56′	3	*c.* 470	N	Y
Gusev	Russia	N 48°26′	E 40°32′	3	49.0±0.2	N	Y
Gweni-Fada	Chad, Africa	N 17°25′	E 21°45′	14	<345	Y	N
Haughton	Nunavut, Canada	N 75°22′	W 89°41′	24	23 ± 1	Y	N
Haviland	Kansas, USA	N 37°35′	W 99°10′	0.015	<0.001	Y	N
Henbury	Northern Territory, Australia	S 24°34′	E 133°8′	0.157	0.0042 ± 0.0019	Y	N
Holleford	Ontario, Canada	N 44°28′	W 76°38′	2.35	550 ± 100	N	Y
Ile Rouleau	Quebec, Canada	N 50°41′	W 73°53′	4	<300	Y	N
Ilumetsä	Estonia	N 57°58′	E 27°25′	0.08	>0.002	Y	Y
Ilyinets	Ukraine	N 49°7′	E 29°6′	8.5	378 ± 5*	N	Y
Iso-Naakkima	Finland	N 62°11′	E 27°9′	3	>1000	N	Y
Jänisjärvi	Russia	N 61°58′	E 30°55′	14	700 ± 5	Y	N
Kaalijärv	Estonia	N 58°24′	E 22°40′	0.11	0.004 ± 0.001	Y	N
Kalkkop	South Africa	S 32°43′	E 24°34′	0.64	<1.8	Y	Y
Kaluga	Russia	N 54°30′	E 36°12′	15	380 ± 5	N	Y
Kamensk	Russia	N 48°21′	E 40°30′	25	49.0 ± 0.2	N	Y
Kara	Russia	N 69°6′	E 64°9′	65	70.3 ± 2.2	N	Y
Kara-Kul	Tajikistan	N 39°1′	E 73°27′	52	<5	Y	N
Kärdla	Estonia	N 59°1′	E 22°46′	4	*c.* 455	N	Y
Karikkoselkä	Finland	N 62°13′	E 25°15′	1.5	<1.88	Y	
Karla	Russia	N 54°55′	E 48°2′	10	5 ± 1	Y	Y
Kelly West	Northern Territory, Australia	S 19°56′	E 133°57′	10	>550	N	N
Kentland	Indiana, USA	N 40°45′	W 87°24′	13	<97	Y	Y

Keurusselkä	Finland	N 62°8′	E 24°36′	30	<1800	Y	N
Kgagodi	Botswana	S 22°29′	E 27°35′	3.5	<180	Y	Y
Kursk	Russia	N 51°42′	E 36°0′	6	250 ± 80	N	Y
La Moinerie	Quebec, Canada	N 57°26′	W 66°37′	8	400 ± 50	Y	N
Lappajärvi	Finland	N 63°12′	E 23°42′	23	73.3 ± 5.3	Y	Y
Lawn Hill	Queensland, Australia	S 18°40′	E 138°39′	18	<515	Y	N
Liverpool	Northern Territory, Australia	S 12°24′	E 134°3′	1.6	150 ± 70	Y	N
Lockne	Sweden	N 63°0′	E 14°49′	7.5	455	Y	Y
Logancha	Russia	N 65°31′	E 95°56′	20	40 ± 20	N	N
Logoisk	Belarus	N 54°12′	E 27°48′	15	42.3 ± 1.1	N	Y
Lonar	India	N 19°58′	E 76°31′	1.83	0.052 ± 0.006	Y	Y
Lumparn	Finland	N 60°9′	E 20°6′	9	*c.* 1000	N	Y
Macha	Russia	N 60°6′	E 117°35′	0.3	<0.007	Y	N
Manicouagan	Quebec, Canada	N 51°23′	W 68°42′	100	214 ± 1	Y	Y
Manson	Iowa, USA	N 42°35′	W 94°33′	35	73.8 ± 0.3	N	Y
Maple Creek	Saskatchewan, Canada	N 49°48′	W 109°6′	6	<75	N	Y
Marquez	Texas, USA	N 31°17′	W 96°18′	12.7	58 ± 2	N	Y
Middlesboro	Kentucky, USA	N 36°37′	W 83°44′	6	<300	Y	Y
Mien	Sweden	N 56°25′	E 14°52′	9	121.0 ± 2.3	Y	Y
Mishina Gora	Russia	N 58°43′	E 28°3′	4	300 ± 50	Y	Y
Mistastin	Newfoundland/Labrador, Canada	N 55°53′	W 63°18′	28	36.4 ± 4*	Y	N
Mizarai	Lithuania	N 54°1′	E 23°54′	5	500 ± 20	N	Y
Mjølnir	Norway	N 73°48′	E 29°40′	40	142.0 ± 2.6	N	Y
Montagnais	Nova Scotia, Canada	N 42°53′	W 64°13′	45	50.50 ± 0.76	N	Y
Monturaqui	Chile	S 23°56′	W 68°17′	0.46	<1	Y	N
Morasko	Poland	N 52°29′	E 16°54′	0.1	<0.01	Y	N
Morokweng	South Africa	S 26°28′	E 23°32′	70	145.0 ± 0.8	N	Y
Mount Toondina	South Australia, Australia	S 27°57′	E 135°22′	4	<110	Y	N
Neugrund	Estonia	N 59°20′	E 23°40′	8	*c.* 470	N	
New Quebec	Quebec, Canada	N 61°17′	W 73°40′	3.44	1.4±0.1	Y	N
Newporte	North Dakota, USA	N 48°58′	W 101°58′	3.2	<500	N	Y
Nicholson	Northwest Territories, Canada	N 62°40′	W 102°41′	12.5	<400	N	N
Oasis	Libya	N 24°35′	E 24°24′	18	<120	Y	N
Obolon’	Ukraine	N 49°35′	E 32°55′	20	169 ± 7	N	Y
Odessa	Texas, USA	N 31°45′	W 102°29′	0.168	<0.05	Y	Y
Ouarkziz	Algeria	N 29°0′	W 7°33′	3.5	<70	Y	N
Paasselkä	Finland	N 62°2′	E 29°5′	10	<1800	Y	Y
Piccaninny	Western Australia, Australia	S 17°32′	E 128°25′	7	<360	Y	N
Pilot	Northwest Territories, Canada	N 60°17′	W 111°1′	6	445 ± 2	Y	N
Popigai	Russia	N 71°39′	E 111°11′	100	35.7 ± 0.2	Y	Y

(Continued)

Table 1. Continued

Name	Country	Latitude	Longitude	Diameter (km)	Age (Ma)*	Exposed	Drilled
Presqu'ile	Quebec, Canada	N 49°43′	W 74°48′	24	<500	Y	N
Puchezh-Katunki	Russia	N 56°58′	E 43°43′	80	167 ± 3	N	Y
Ragozinka	Russia	N 58°44′	E 61°48′	9	46 ± 3	N	Y
Red Wing	North Dakota, USA	N 47°36′	W 103°33′	9	200 ± 25	N	Y
Riachao Ring	Brazil	S 7°43′	W 46°39′	4.5	<200	Y	N
Ries	Germany	N 48°53′	E 10°37′	24	15.1 ± 0.1	Y	Y
Rio Cuarto	Argentina	S 32°52′	W 64°14′	1 by 4.5	<0.1	Y	N
Rochechouart	France	N 45°50′	E 0°56′	23	214 ± 8	Y	N
Rock Elm	Wisconsin, USA	N 44°43′	W 92°14′	6	<505		
Roter Kamm	Namibia	S 27°46′	E 16°18′	2.5	3.7 ± 0.3	Y	N
Rotmistrovka	Ukraine	N 49°0′	E 32°0′	2.7	120 ± 10	N	Y
Sääksjärvi	Finland	N 61°24′	E 22°24′	6	*c.* 560	Y	Y
Saarijärvi	Finland	N 65°17′	E 28°23′	1.5	>600		Y
Saint Martin	Manitoba, Canada	N 51°47′	W 98°32′	40	220 ± 32	N	Y
Serpent Mound	Ohio, USA	N 39°2′	W 83°24′	8	<320	Y	Y
Serra da Cangalha	Brazil	S 8°5′	W 46°52′	12	<300	Y	Y
Shoemaker (formerly Teague)	Western Australia, Australia	S 25°52′	E 120°53′	30	1630 ± 5	Y	N
Shunak	Kazakhstan	N 47°12′	E 72°42′	2.8	45 ± 10	Y	Y
Sierra Madera	Texas, USA	N 30°36′	W 102°55′	13	<100	Y	Y
Sikhote Alin	Russia	N 46°7′	E 134°40′	0.027	0.000055	Y	N
Siljan	Sweden	N 61°2′	E 14°52′	52	361.0 ± 1.1	Y	Y
Slate Islands	Ontario, Canada	N 48°40′	W 87°0′	30	*c.* 450	Y	N
Sobolev	Russia	N 46°18′	E 137°52′	0.053	<0.001	Y	Y
Söderfjärden	Finland	N 63°2′	E 21°35′	5.5	*c.* 600	N	Y
Spider	Western Australia, Australia	S 16°44′	E 126°5′	13	>570	Y	N
Steen River	Alberta, Canada	N 59°30′	W 117°38′	25	91 ± 7*	N	Y
Steinheim	Germany	N 48°41′	E 10°4′	3.8	15 ± 1	Y	Y
Strangways	Northern Territory, Australia	S 15°12′	E 133°35′	25	646 ± 42	Y	N
Suavjärvi	Russia	N 63°7′	E 33°23′	16	*c.* 2400		
Sudbury	Ontario, Canada	N 46°36′	W 81°11′	250	1850 ± 3	Y	Y
Suvasvesi N	Finland	N 62°42′	E 28°10′	4	<1000	N	Y

Tabun-Khara-Obo	Mongolia	N 44°6′	E 109°36′	1.3	150 ± 20	Y	N
Talemzane	Algeria	N 33°19′	E 4°2′	1.75	<3	N	Y
Tenoumer	Mauritania	N 22°55′	W 10°24′	1.9	0.0214 ± 0.0097	Y	N
Ternovka	Ukraine	N 48°08′	E 33°31′	11	280 ± 10	N	Y
Tin Bider	Algeria	N 27°36′	E 5°7′	6	<70	Y	N
Tookoonooka	Queensland, Australia	S 27°7′	E 142°50′	55	128 ± 5	N	Y
Tswaing (formerly Pretoria Saltpan)	South Africa	S 25°24′	E 28°5′	1.13	0.220 ± 0.052	Y	Y
Tvären	Sweden	N 58°46′	E 17°25′	2	*c*. 455	N	Y
Upheaval Dome	Utah, USA	N 38°26′	W 109°54′	10	<170	Y	Y
Vargeao Dome	Brazil	S 26°50′	W 52°7′	12	<70	Y	N
Veevers	Western Australia, Australia	S 22°58′	E 125°22′	0.08	<1	Y	N
Vepriai	Lithuania	N 55°5′	E 24°35′	8	>160 ± 10	N	Y
Viewfield	Saskatchewan, Canada	N 49°35′	W 103°4′	2.5	190 ± 20	N	Y
Vredefort	South Africa	S 27°0′	E 27°30′	300	2023 ± 4	Y	Y
Wabar	Saudi Arabia	N 21°30′	E 50°28′	0.116	0.00014	Y	N
Wanapitei	Ontario, Canada	N 46°45′	W 80°45′	7.5	37.2 ± 1.2	N	N
Wells Creek	Tennessee, USA	N 36°23′	W 87°40′	12	200 ± 100	Y	Y
West Hawk	Manitoba, Canada	N 49°46′	W 95°11′	2.44	351 ± 20	N	Y
Wetumpka	Alabama, USA	N 32°31′	W 86°10′	6.5	81.0 ± 1.5	Y	Y
Wolfe Creek	Western Australia, Australia	S 19°10′	E 127°48′	0.875	<0.3	Y	N
Woodleigh	Australia	S 26°3′	E 114°39′	40	364 ± 8	N	Y
Vista Alegre	Brazil	S 25°57′	W 52°41′	9.5	<65	Y	N
Yarrabubba	Western Australia	S 27°10′	E 118°50′	30.00	*c*. 2000	Y	N
Zapadnaya	Ukraine	N 49°44′	E 29°0′	3.2	165 ± 5	N	Y
Zeleny Gai	Ukraine	N 48°4′	E 32°45′	2.5	80 ± 20	N	Y
Zhamanshin	Kazakhstan	N 48°24′	E 60°58′	14	0.9 ± 0.1	Y	Y

*Pre-1977 K–Ar, Ar–Ar and Rb–Sr ages recalculated using the decay constants cited by Steiger and Jaegar in 1977. Ages in millions of years (Ma) before present.

Notes: (1) One structure is listed by Henkel & Pesonen (1992) which is not on Grieve's list of 2004: it has shock indicators. Sortland, Norway: latitude 68°8′, longitude 15°0′ (no other details given).

(2) The Yallalie structure also not on the list, is described by Dentith *et al.* (1999): Yallalie, W. Australia: latitude 30°40′3″S, longitude 115°46′16.4″E; 12 km diameter, buried. Age: late Cretaceous or younger.

(3) There is also the Eltanin Structure in the southern Pacific Ocean (Gersonde *et al.* 1997): Eltanin: latitude 57°47′S, longitude 90°47′W (position of drill core); *c*. 25′km diameter. Age: 2.3 Ma (Pliocene). This is not craterform, but has extensive disturbance and brecciation of the sea-floor sediments and is associated with minute mesosiderite specks.

These additions make the grand total of impact craters and structures widely accepted as 170.

The presence of nickel–iron scattered around the crater was not in itself proof of extra-terrestrial impact origin – native nickel–iron occurs in basalt lavas in both Greenland (Disko Island) (McCall 1973) and Siberia (Norilsk) where it takes the place of accessory sulphide. In Siberia there is a lively market (Treiman *et al.* 2002) in false 'mesosiderite meteorites' and the resemblance of these basalt fakes to the stony-iron meteorites is striking. However, such terrestrial native nickel–iron never displays Widmanstätten etch patterns, unlike the octahedrite meteorites found in Arizona. The difference is due to the slow cooling from high temperatures in the core of the meteorite parent body. The Widmanstätten pattern produced by etching in the laboratory establishes the extraterrestrial provenance of the nickel–iron.

Successors to Gilbert

An American mining entrepreneur, Daniel M. Barringer (1860–1929), revived the impact hypothesis (the crater is not uncommonly referred to as the 'Barringer Crater': Table 1). He spent a long time searching for the missing buried iron meteorite, putting down a number of diamond drill holes, one to a depth of more than 1000 ft (Barringer 1905*a*, *b*, 1906*a*, *b*). He cited the character of the nickel–iron, the distribution of the nickel–iron masses found, the large amount of minutely pulverized silica and limestone within the crater, and the absence of volcanic rocks. However, his more prosaic arguments in favour of meteoritic origin took years to influence scientific thinking, and it is Gilbert's colourful arguments that are chiefly remembered to this day.

By 1932 more than 35 scientific papers had been published on Meteor Crater. Ives (1919), following on from experience in the first World War, studied explosion pits made by bombs, and rejected oblique impact ricochetting off because of the radial symmetry of the crater. Gifford (1924), on the basis of comparisons with dynamite and TNT explosions, demonstrated that whatever the angle of impactor approached, the crater would be roughly circular; also that with an explosion one would not expect to find the impactor buried under the crater. Hager (1953) kept alive the cryptovolcanic argument, arguing that the crater was exactly on an anticlinal nose, and was a graben-like sink in its apex, the two features being separate but related. The American geologist Eugene ('Gene') Shoemaker (1928–1997) advanced the study of the crater further after the advent of the Space Age (see below).

Small craters with associated iron or stony-iron material

It was not until the late 1920s and 1930s that there were any significant new finds of impact craters outside the Arizona crater (McCall 1977). There were a number of descriptions of small craters – Haviland, Kansas, 1925; Kaalijarv, Estonia (1928) (Fig. 6a); Henbury and Boxhole, Australia (1931, 1937); Wabar, Arabia 1933 (Fig. 6b); Campo del Cielo, Argentina, 1933; Dalgaranga, Australia, 1938; Odessa, Texas, 1939; the largest of these, one of the Henbury craters, measures only 220 × 110 m. All are associated with iron meteorite fragments except Dalgaranga, which has an association with stony-iron, mesosiderite, fragments (Gilbert's 'astral pudding'!). These craters are listed in Table 1. In 1947, more than 100 such craters were formed by a meteoritic event accompanied by a spectacular

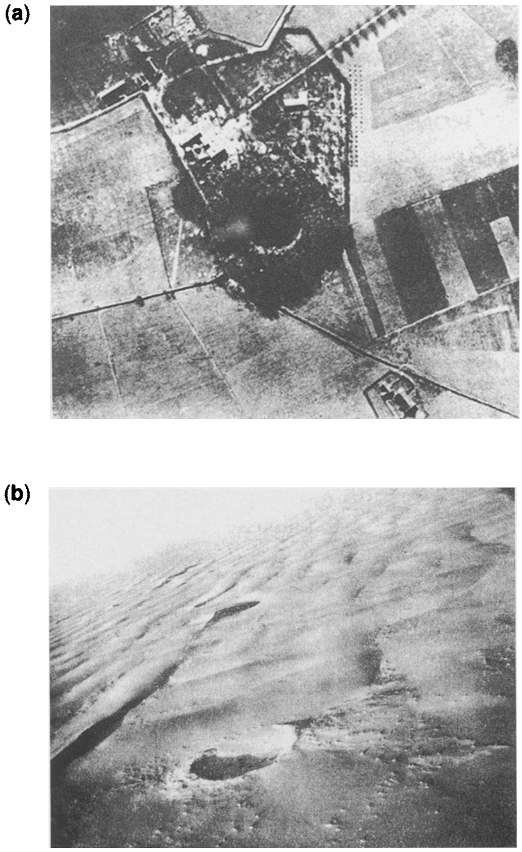

Fig. 6. (**a**) The largest, 0.110 km-diameter, of the Kaalijarv, Estonia, craters from the air (from Krinov 1963, reproduced in McCall 1977). (**b**) The 0.116 km-diameter Wabar crater from the air (photograph from D.A. Holm, Aramco, reproduced in McCall 1977).

display in the sky (Fig. 7) in a remote area of Sikhote-Alin, Siberia, and many jagged pieces of octahedrite meteoritic iron were collected. Kaalijarv, Henbury, Wabar, Campo del Cielo and Sikhote-Alin are all crater fields, where the impactor has broken up due to shock while driving down through the atmosphere and the several pieces have produced a pattern of craters.

Also, during this period, a suggestion was published proposing that certain cryptic structures in the United States were meteorite impact scars (Boon & Albritton 1937).

The onset of the Space Age

The Soviet cosmonaut Yuri Gagarin (1934–1968) squeezed himself into a tiny football-like spacecraft *Vostok 1* and orbited the Earth in 1 h 48 min in 1961 and ushered in the Space Age. Almost at once studies of all things extraterrestrial escalated. Gene Shoemaker (Fig. 8) now (Shoemaker 1960,

Fig. 7. Painting of the fireball and trail accompanying fall of the Sikhote-Alin meteorite shower in 1947, which produced more than 100 craters (the original is at the offices of the Meteorite Committee of the Russian Academy of Sciences; it was reproduced in McCall 1977).

1963) produced a seminal detailed study of the Arizona crater, relating Hager's anomalous features to the impact explosion process – by this time the Second World War and its aftermath had provided Science with nuclear explosions and all the experimental nuclear explosion craters with names such as 'Teapot Ess' and 'Jangle U', which could be scaled to apply to the impact explosion process. The high-pressure polymorphs of silica – coesite and stishovite – were recognized there at that time. Diamond, a shock product of graphite in the iron meteorite fragments, had already been recorded by Foote (1891). Fusion of quartz in quartzite was also recognized: later, in 1963, Dietz reported poorly formed shatter cones in the sandstone (Fig. 10a).

Meteor Crater is today the type-example of a kilometre-scale terrestrial impact-explosion crater (Fig. 3); Wolfe Creek, Australia (McCall 1965) (Fig. 9) can also be taken as the perfect geological expression of the process at this scale, although it lacks the various indicators of impact shock pressures – shatter cones (Fig. 10a), lamellations in quartz, impactites, coesite and stishovite, and nano diamonds – that have now been found at Meteor Crater.

Physical studies of impact shock processes have indicated that a process of interference between shock waves radiating out upwards

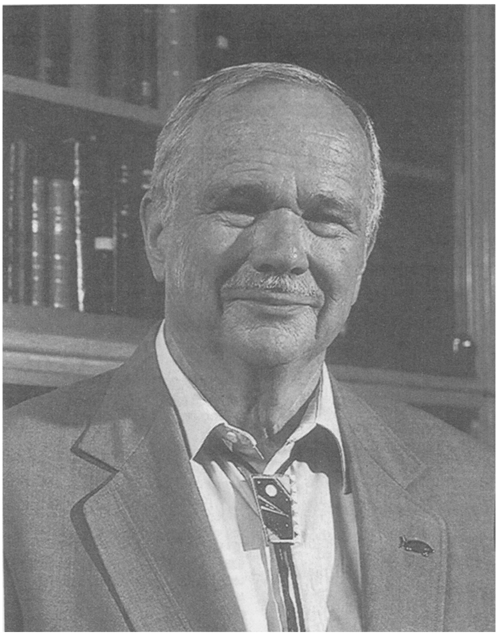

Fig. 8. Photograph of Eugene M. Shoemaker (1928–1997) (from Grady *et al.* 1998).

Fig. 9. Photograph from the air of the 0.876 km-diameter Wolfe Creek Crater, Western Australia (photograph from Australia News and Information Bureau).

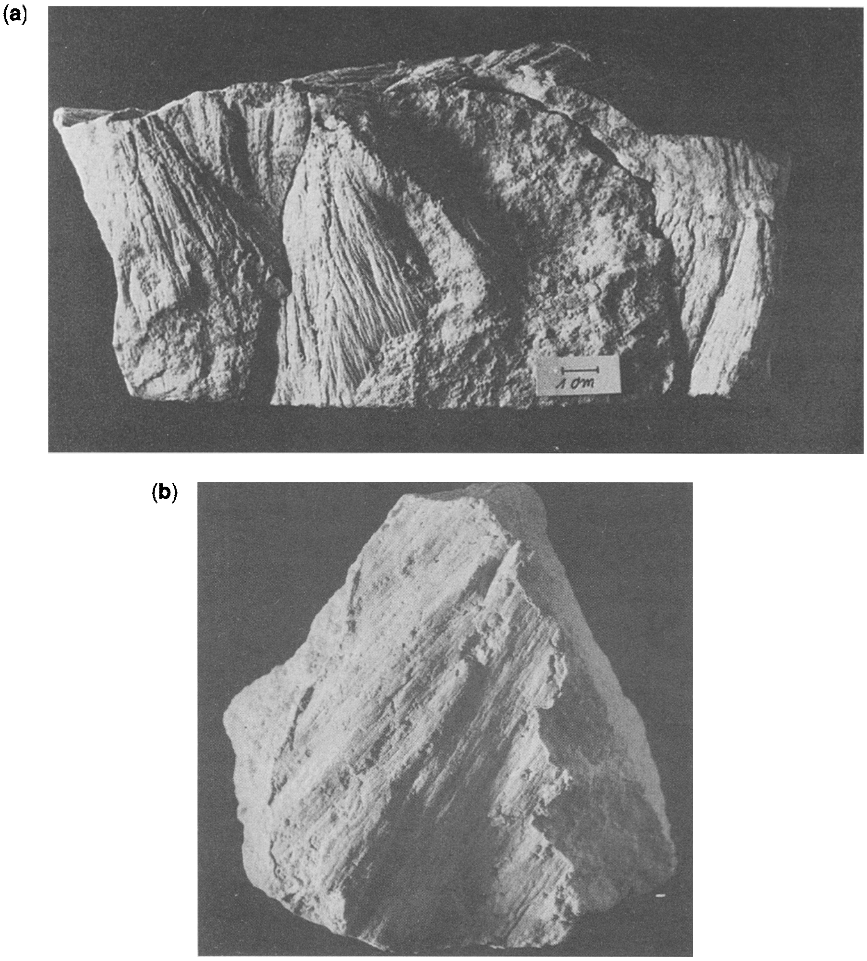

Fig. 10. (**a**) Shatter cones in the Coconino Sandstone at Meteor Crater (from Dietz 1963). (**b**) Shatter cones at the Steinheim Basin, Germany, among the earliest of such structures to be recorded by Rohleder in 1933 (from Dietz 1963).

from a shallow zone below the point of impact and their reflections downwards can result in the preservation of unmelted fragments from the rear part of the impactor, as preserved around both Meteor Crater (Fig. 5) and Wolfe Creek Crater, even if the greater part of the impactor was vaporized, as suggested by George P. Merrill (1954–1989) in 1908.

Proliferation of large terrestrial impact craters and structures

The first great advances in attribution of large terrestrial craters and structures to extraterrestrial impact accompanied by explosion came in the USA and Canada: the American geologist Robert S. Dietz (1963, 1965), who seems to have coined the term 'astrobleme', cited Talemzane Crater, Algeria; New Quebec Crater, Labrador; Lonar Lake, India; Bosumtwi Crater, Ghana; and Steinheim, Basin, Germany, all much larger then the Arizona, Crater, and none with associated meteorite material. He also cited structures of the same size range without good crater form, such as the Wells Creek Basin, Tennessee; the Crooked Creek and Decaturville structures in Missouri; Serpent Mound, Ohio; Kentland Structure, Indiana; and the Sierra Madera Structure, Texas The largest of these, Wells Creek Basin, has a diameter of 14 km. He also cited the much larger, 140 km-diameter Vredefort Dome in South Africa. Dietz based his arguments mainly on the presence of shatter cones (distinctly striated conical structures in rocks, generally nested or in composite groups, and attributed to the passage of shock waves) (Fig. 10a, b), and shock lamellations in quartz, feldspar, olivine and zircon, planar deformation features (PDFs: sets of extremely straight, sharply defined parallel lamellae, usually in multiple sets with differing specific crystallographic orientation) (Fig. 11), such as had been produced in the Hardhat nuclear explosion experiment. Somewhat later Dietz predicted that he would find shatter cones at the Sudbury Structure, Canada, and did so. Indeed, they are widely developed there.

Shatter cones are the only megascopic indicator of impact shock, other than the presence of evidence of melt in impactites. These conical striated fracture surfaces can develop at pressures as low as 2–6 GPa, but have been found in rocks subjected to approximately 25 GPa. They are characteristically developed in the parautochthonous rocks flooring impact structures and in central uplifts in large, complex structures. When beds containing shatter cones are rotated back to their pre-impact position, most apices point to the central impact location (Manton 1965). They tend to form early and so may be found in breccias. Shatter cones form best in fine-grained homogenous rocks such as quartzites and limestones, and, although they form in coarser crystalline rocks, such as granites, they are less well formed there.

According to Grieve (1998), the shock metamorphic effects used as indicators of impact origin are mostly developed at pressures and temperatures well beyond those encountered in terrestrial metamorphism caused by igneous or tectonic activity. However, coesite is also found in high-pressure tectonic and metamorphic situations (e.g. see Bolin Cong & Quingchen Wang 1996).

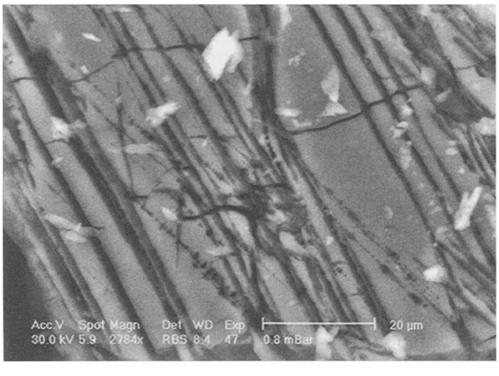

Fig. 11. Shock lamellation in a quartz grain under the microscope, from the Woodleigh Structure, Western Australia (back-scattered electron image from SEM) (from Hough *et al.* 2003).

In Canada, Beals *et al.* (1963) and Dence (1965) recognized the quite small (3 km-diameter) buried Brent and Holleford structures, a similar sized structure at West Hawk Lake, and also much larger structures at Carswell Lake, Clearwater Lake (two contiguous), Deep Bay, Lac Couture and Manicouagan, the latter 100 km in diameter (Figs 12 & 13). Many more structures in Europe and Africa, Asia and Australia followed, and by 1977 the present author was able to publish two Benchmark sets of readings from the literature on *Meteorite Craters* (McCall 1977) and *Astroblemes and Cryptoexplosion Structures* (McCall 1979).

These attributions to impact were not without controversy and the extraterrestrial impact attribution was vigorously contested by Bucher (1963, 1965), particularly in the case of the Ries and Steinheim Basin in South Germany, and Currie (1965, 1972), the former invoking cryptovolcanism and the latter resurgent calderas. The present author, then in Australia after a decade of experience mapping in volcanic terrains of the rift valleys in East Africa, was also doubtful (McCall 1965), especially as the Wolfe Creek crater, which he was the first geologist to map comprehensively (McCall 1965), was situated in a province characterized by lamproites and sparse diamond finds (the Kimberleys region is now a diamondiferous province with something like 100 pipes). Later, the discovery of schreibersite (Fe,Ni_3P, a platy mineral peculiar to meteorites) and iron meteorite fragments (displaying the most common, octahedrite etch pattern) adjacent to the crater, confirmed meteoritic origin.

Nicolaysen *et al.* (1963) and Nicolaysen (1972) proposed an endogenous (derived from within, by a geological process) origin for certain structures in the USA and rejected extraterrestrial impact origin for the Vredefort dome, following Brock (1950). Crawford (1978) found that the craters and structures had a non-random distribution geographically, militating against an impact origin.

von Engelhardt recognised 10 impact structures in western Europe (Engelhardt 1972) (Fig. 14) and Masaytis (1976) recognized 12 in the USSR (Fig. 15), the largest of which, Popigay (100 km diameter), was described by Masaytis *et al.* (1971). French & Short (1968) edited a definitive account of shock metamorphism. The larger structures commonly depart from simple crater form and may have a central uplifted area, as at Manicouagan, or have a nested crater pattern, as at the Ries, which has both an outer and an inner sub circular depression. At the Ries, a complex development of impactites – shock metamorphosed rocks

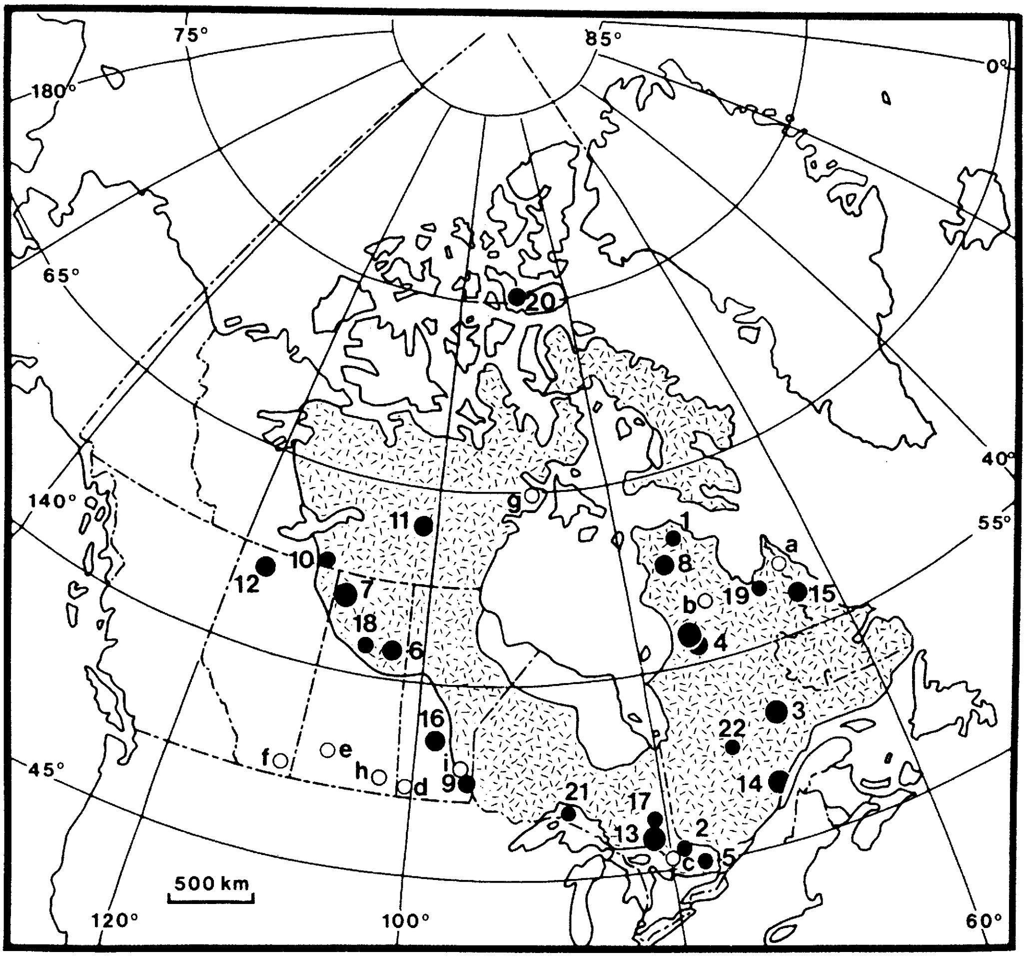

Fig. 12. Plot of craters and structures attributed to impact in Canada Small circles marked f, e, h and d are the Eagle Butte, Maple Creek, Elbow and Viewfield Structures of the Williston Basin, Saskatchewan, shown in Figure 18 (NASA diagram).

including breccia and melt rocks – was recognized (Engelhardt 1972) and the terms 'suevite' and 'Bunte breccia' were introduced, both these terms being nowadays applied to other craters and structures. Suevite contains shocked rock and mineral fragments, glass fragments and glass bombs, in a groundmass of montmorillonite. Bunte breccia is a weakly shocked polymict breccia. Coesite and stishovite in the fragments in these types of impactite testify to extreme shock as do diamonds and fullerenes – complex forms of carbon with a ring structure (Gilmour 1998) – both being formed from graphite. These two impactite types occur both in and outside the crater structure, from which huge blocks have been ejected. Such impactites are recognized widely in other structures, a recent find being the impactite (Bunte breccia type) associated with the buried Yallalie structure in Western Australia (Fig. 16). The Zhamanshin structure in Kazakhstan has an association of two kinds of impactites within the structure, and these have been termed 'zhamanshinites' and 'irghyzites' (Masaytis *et al.* 1984; McCall 2001*a*). Impactites are also associated with the Popigay Structure (Masaytis *et al.* 1971). Rocks that would normally be taken to be lava formations, revealed by drilling, have been attributed to impact melting in the case of the Brent structure, and, in the case of the Sudbury structure, rocks that would normally be taken to be welded tuffs or ignimbrites that form the thick development of the Onaping Formation have been similarly attributed. The heat produced by the impact is believed to have produced melting

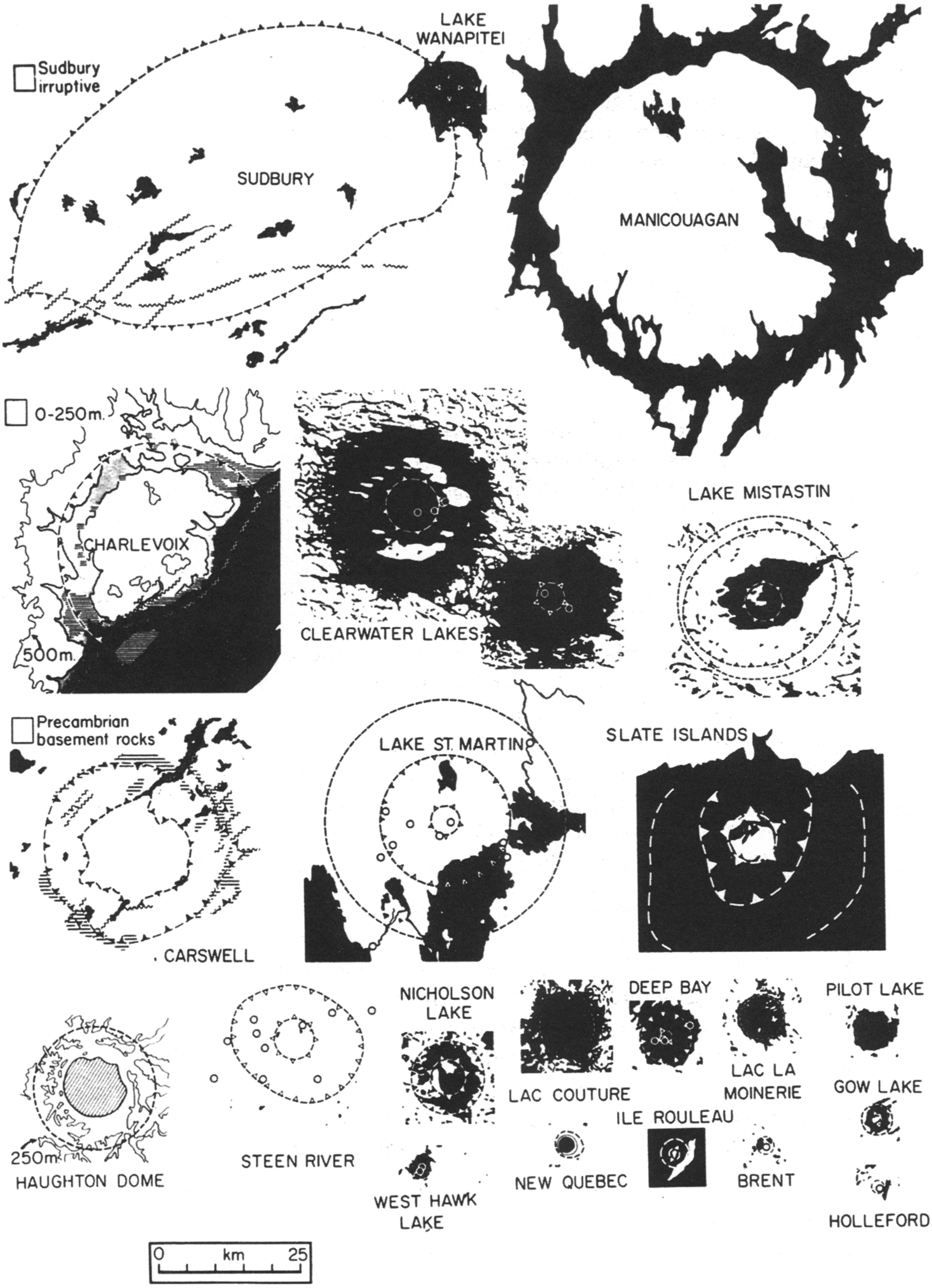

Fig. 13. Drawing of the outlines of craters and structures attributed to impact in Canada (NASA diagram). Black = water.

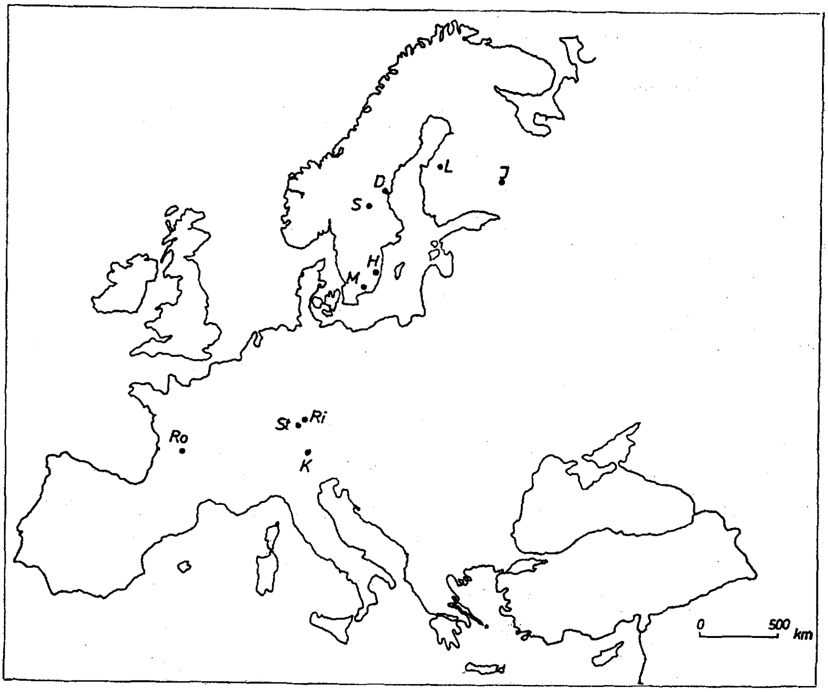

Fig. 14. Distribution of craters and structures attributed to impact in Europe (from Engelhardt 1972, reproduced in McCall 1977).

of country rocks to the extent of producing flows resembling lavas and particulate flows. Pseudotachylite – a dense, fine-grained dark rock produced by extreme mylonitization (pulverization to a compact, chert-like rock, sheared or banded, without cleavage) and/or melting – is associated with the Sudbury and Vredefort structures (Spray 1998), occurring as injection veins with or without exotic fragments: such veins occur up to 80 km outside the Sudbury Igneous Complex.

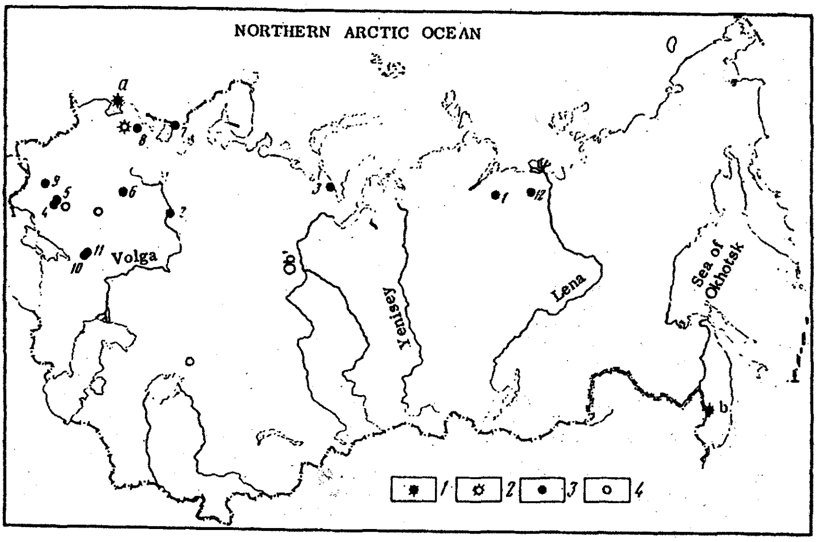

Fig. 15. Distribution of craters and structures attributed to impact in the former USSR (after Masaytis 1976).

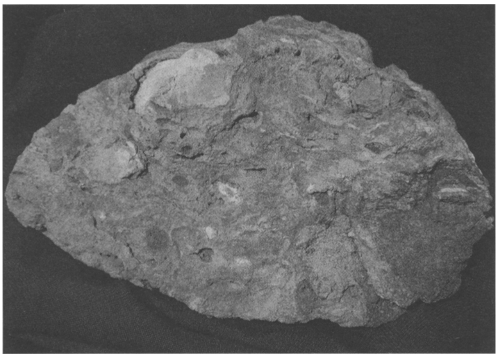

Fig. 16. Impactite (Bunte breccia-type) from the Yallalie Basin Structure in Western Australia: sample 30 cm across (photograph supplied by Alex Bevan, Western Australian Museum).

The last quarter of a century

Many more impact structures have recently been described, in Canada and the USA and southern Africa in particular, and the number recognized in the comparatively small areal extent of Scandinavia is remarkable (Henkel & Pesonen 1992). Grieve (1998) noted that there was bias in the global distribution (Fig. 17) towards North America (USA and Canada), Australia (Bevan & McNamara 1993) and Fennoscandia (Henkel & Pesonen 1992) – these authors listed 62 in Fennoscandia but only 26 of these appear valid on the criterion of displaying shock effects.

The figures from Table 1, and half a dozen more structures with accompanying shock indicators not so listed there, are: Australia 22 (13%), USA 26 (15%), Canada 28 (16%) and Fennoscandia 26 (15%).

Out of the approximately 170 recognized structures, 102 (59%) are in these four regions. This bias could partly be explained by the fact that stable cratonic areas had low rates of erosional and tectonic activity, so that they were optimum regions for preservation of old structures. The number of scientific investigators active in a region may also be a factor. Asia, South America and Africa (except South Africa) had fewer recognized impact structures, and the second factor above could partly explain this, but not entirely. The paucity in China is surprising but could partly be explained by burial under recent loess. The highest concentration in North America is in the Williston Basin straddling the boundary between Saskatchewan, Canada and North Dakota, USA (Grieve *et al.* 1998): here six structures listed in Table 1 occupy an area with a maximum diameter of approximately 500 km (Fig. 18), a remarkable concentration – especially as more than one age of impact is represented.

Grieve showed that about five new discoveries are made per year. There is a paucity in the record of new finds of old craters or structures

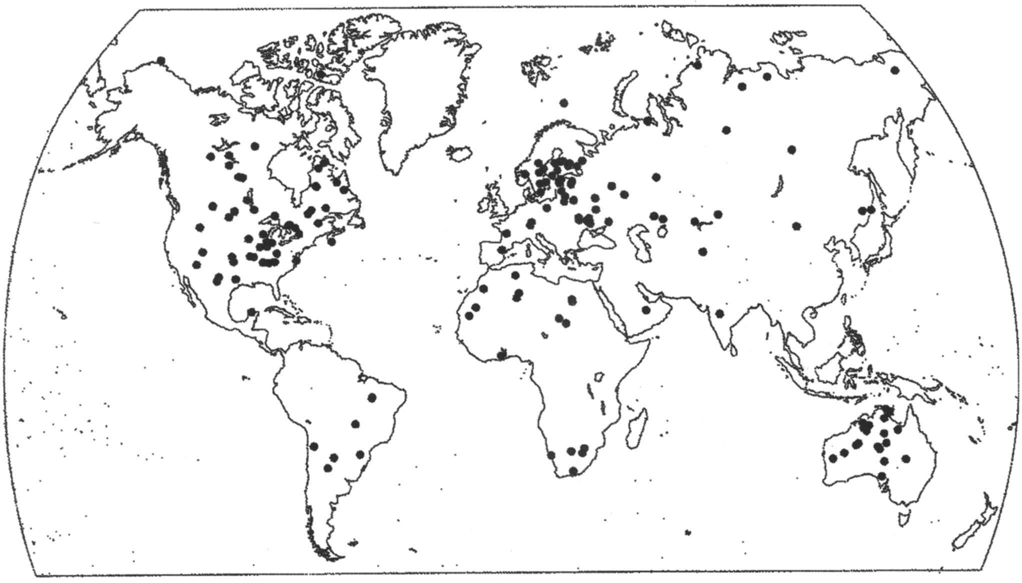

Fig. 17. Plot of the global distribution of craters and impact structures attributed to impact processes (after Grieve 1998).

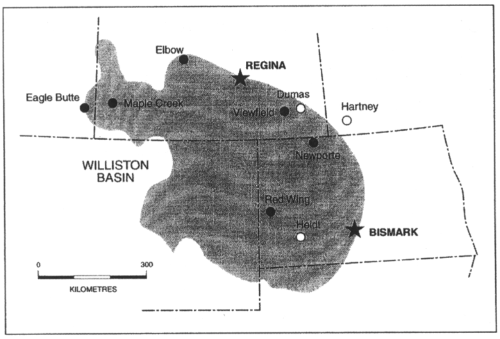

Fig. 18. Six structures attributed to impact processes in the Williston Basin, Saskatchewan and North Dakota (after Grieve *et al.* 1998).

in the smallest size range, because these are readily obliterated by tectonic orerosional processes. The two largest structures, Sudbury and Vredefort, with reconstructed original diameters of 250 and 300 km (Grieve 1998), are also the oldest, being of early Proterozoic age. There are no Archaean structures recognized at all in this roughly 1500 Ma time span and the only possible evidence of impact during this time is in the form of spheroids found in Western Australia and South Africa, and attributed to impact. Although some of these have internal patterns similar to those in microtektites (McCall 2001*a*), the lack of glass preservation makes such an attribution questionable at the best, because there are many other ways microspheroids can form.

The older structures are likely to have been subject to burial, erosion and exhumation. About 35% of the structures in the list (Table 1) are covered by later sediments, and the recognition of such buried structures, of which Chesapeake Bay, USA, Yallalie (Fig. 19), Tookoonooka, Australia and Morokweng, South Africa are examples, is generally first made by geophysical methods. This is followed by drilling. The Russian platform, where the sedimentary cover is unusually thick, has also revealed a number of large buried structures.

Over the last 25 years much more detailed studies have been made of several of the large

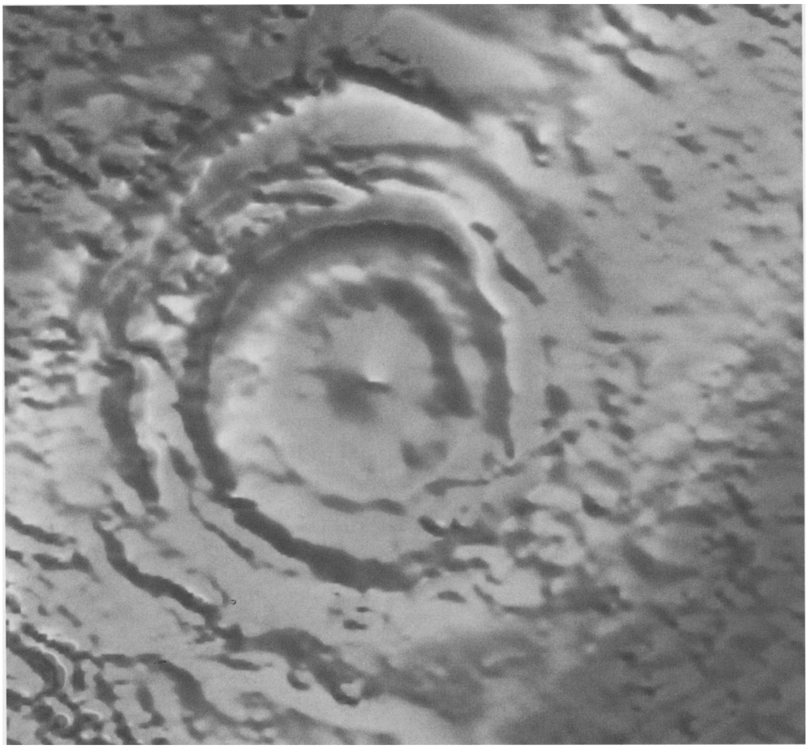

Fig. 19. Magnetic anomaly pattern abiove the buried 12 km-diameter Yallalie Structure, Western Australia (image supplied by Phil Hawke, University of Western Australia Museum).

structures, and high-quality geological maps have been published of Popigay (Whitehead *et al.* 2002) and the Shoemaker (fomerly Teague Ring) structure in Western Australia, the latter (30 km diameter: *c.* 1600 Ma) with its granite core being a smaller analogue of the Vredefort Structure (Pirajno 2002).

Two structures, Mjolnar in the Barents Sea (Gudlaugsson 1993) and Montaignis off Nova Scotia, are entirely covered by the sea, but there is only one known structure within the deep ocean, the Pliocene 25 km-diameter Eltanin Structure in the southern Pacific (Kyte *et al.* 1988; Margolis *et al.* 1991; Gersonde *et al.* 1997). This does not have a crater form, the impactor having apparently failed to make a crater, but there is extensive disturbance of the sea-bed formations extending down to more than 100 m and there are minute fragments of a mesosiderite stony-iron meteorite preserved in the disturbed rock. In this case the impact origin is incontrovertible.

Impact and tektites

Tektites were first mentioned in the literature by Liu Xun, an official of Tang Dynasty in the 10th century AD (Barnes 1969) and constituted an enigma. The many suggested origins are mentioned by McCall (2001*a*). Up to the time of the manned *Apollo* and unmanned *Luna* recovery missions to the Moon, a lunar orgin was strongly championed, but Taylor (1962) had already indicated that tektites have terrestrial geochemistry and the Rare Earth patterns appear to be conclusive. Likewise, the presence of sedimentary heavy mineral suites in Muong Nong-type tektites from Indo-China (Glass & Barlow 1979) – the suite includes zircon, corundum, rutile, monazite, chromite and quartz – and polymorphs of silica, tridymite and cristobalite: the high-pressure polymorph of silica coesite and lechatelierite (naturally fused amorphous silica) had earlier been identified by Walter (1965), These properties indicated formation from terrestrial sedimentary target rocks, accompanied by shock processes.

The widely accepted origin for tektites is explosive expulsion from large-scale impact sites of melt formed at very high temperatures and pressures. Modelling by Melosh (1998) showed both to be extreme and much higher than those involved in glass manufacture. Solidification occurred of splash forms in ballistic flight to Strewn Fields up to thousands of kilometres from the target source. Three of the four strewn fields of Eocene–Pleistocene age are linked to specific craters or structures: Bosumtwi Crater in Ghana (10.5 km diameter) – Ivory Coast Strewn Field; the Ries, Germany (24 km diameter) – Central European Strewn Field; and the Chesapeake Structure, USA (85 km diameter) – North American Strewn Field. The fourth and largest strewn field, the Australasian, has no source structure yet identified. Three of these events, but not the Central European, produced microtektites, in the shape of spheroids found in marine sediments sampled in drill cores.

It is clear that only a minority of large impact craters or structures are associated with tektites, the reason for this restriction being obscure. The Chicxulub, Mexico, structure (*c.* 170 km diameter), at or very close to the Cretaceous–Tertiary (K/T) boundary, has an association with forms of tektite *sensu lato* (smectite-enveloped glass bodies) in Haiti and Mexico; there are also late Devonian microspheroids closely resembling the microtektites associated with the three strewn fields mentioned above, in sediments in Belgium and China. Similar bodies are found actually within the limits of the Eltanin structure of Pliocene age, a proven impact structure (Margolis *et al.* 1991) and microspheroids lie below the horizon of the late Eocene North American microtektites in the Caribbean and Weddell Sea, being attributed to the Popigay impact structure in northern Siberia.

Impact structures and extinctions

Alvarez *et al.* (1979*a*, *b*) reported the discovery of anomalous concentrations of iridium (×30) as a trace element in a 1 cm-thick marine claystone band at the palaeontological K/T boundary near Gubbio, Italy. Further such discoveries were made in the Mexico, New Zealand and Denmark. In the western USA shocked quartz was found at this same horizon at a number of localities (Izett 1990). The story of the search for the 'smoking gun' is well known and eventually the Chicxulub structure, Yucatan, Mexico (Hildebrand *et al.* 1998), was identified following rejection of the like-aged Manson structure, Iowa, of similar age. The attribution of the faunal extinction to large-scale impact was by no means readily accepted by palaeontologists (see MacLeod *et al.* 1997; Hallam 1998, 2004; MacLeod 1998; Milner 1998) and the original ultra-catastrophic 'nuclear winter-like' scenario has required some modification. The effects of impact and of flood basalt eruption (e.g. Deccan, India) at the same time are now widely favoured as an alternative explanation for this extinction. Glasby & Kunzendorf (1996) have noted that the oceans were already stressed by the end of the Cretaceous owing to a long-term drop in atmospheric carbon dioxide and in sea level, and the frequent development of oceanic anoxia. The biota were susceptible to change, as extinction of several marine species was occurring several million years prior to the K/T boundary. The eruption of the Deccan Trap lavas, which began at 66.2 Ma and lasted 0.7 Ma, expelled very large quantities of sulphuric and hydrochloric acid, carbon dioxide, dust and soot into the atmosphere, leading to a sea-level drop and temperature change. Extinction of biological species was graded and appears to have correlated with the main eruptive events. Elements such as iridium were incorporated in the volcanic ash, probably as soot particles. The sharpness of iridium spikes at the K/T boundary (Fig. 20) and a lack of time-spread of the iridium anomaly would seem to rule out a Deccan provenance for it – although recent studies of iridium anomalies in dinosaur egg shells in sections straddling the boundary in China have revealed six iridium spikes covering sediments laid down over 250 ka and extending just up into the Palaocene (Zhao *et al.* 2002). According to Glasby & Kunzendorf (1996) the Chicxulub impact after the onset of the Deccan volcanism may have had a regional rather than global role in the K/T extinctions.

Lately there has been a suggestion based on foraminifera from a core there that the Chicxulub impact occurred 300 000 years before the palaeontological K/T boundary (Keller *et al.* 2003): this was vigorously contested by Smit (2004); although there are a handful of impact

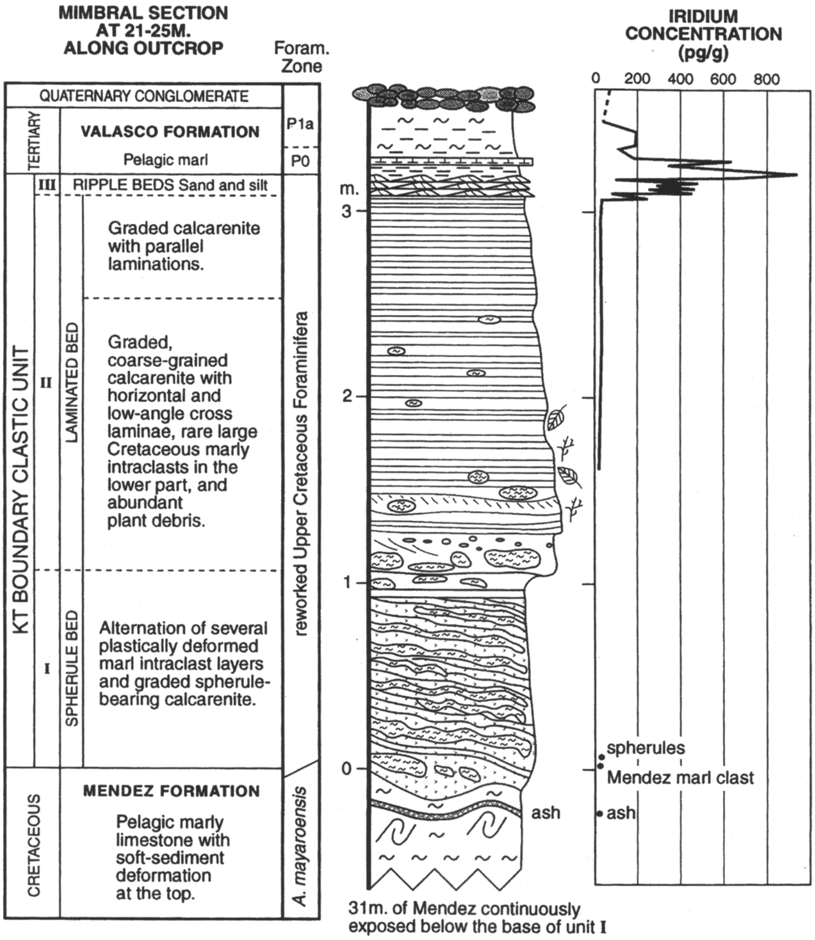

Fig. 20. Geological section at Mimbral, Mexico, covering the K/T boundary. Showing the sharpness of the iridium spike (after Smit *et al.* 1992).

structures recognized of about this age, none appears be of the stature of Chicxulub, capable of producing a global mass extinction.

No other impact event has been conclusively matched with another mass extinction in the geological record (Hallam 2004), although there have been suggestions. The Devonian 'microtektites' are not of the right age.

Proof of impact origin?

The 25 km-diameter Eltanin structure in the South Pacific Ocean, of an order greater of diameter than Meteor Crater and Wolfe Creek Crater, is the only structure larger than them to have an actual association with meteoritic material, there being minute mesosiderite specks in the breccia. This structure is atypical in form, there being no crater, only a roughly circular zone of disturbance. The absence of meteoritic material from the other large craters and structures is explained by complete vaporization in the explosive process. This absence does mean that arguments against impact origin can still be reasonably pursued, and it is, indeed, likely that some of the craters and structures in the list (Table 1) have been misinterpreted. However, the indirect evidence for impact processes is so strong that it seems inconceivable that the general story of large-scale terrestrial impact craters and structures can be overturned.

A further line of indirect evidence has come from studies of impact melt rocks associated with such structures in the form of enrichments in siderophile elements above the levels in the target rocks. For example, Cr may be enriched (Palme 1982). Such enrichments are attributed to admixture of a very small fraction (up to a few per cent) of the actual impactor material in the melt. Elemental analysis has indicated that the East Clearwater Lake structure is likely to have been formed by a carbonaceous chondrite (Palme *et al.* 1979) and a similar result has been obtained from Chicxulub (Shukolynkov *et al.* 1998) – although Kyte *et al.* (1980) had concluded from a study of boundary sediments that the impactor was a metal-sulphide core of an asteroid or weak cometary matter that was slowed down while falling to Earth. However, many structures examined in this way yielded no siderophile element anomaly.

^{187}Os and ^{187}Re isotopes has been studied by Koeberl & Shirey (1993) on Bosumtwi melt glass and Ivory Coast tektites, helping to establish impact origin. This method has been extended to 40 others of the list of structures in Table 1 (Koeberl 1998). At Vredefort 0.2% meteorite material content was detected in this way (Therriault *et al.* 1996). Unfortunately, the method does not discriminate between different meteorite classes. There are lists recording such determinations in the literature (e.g. Grieve & Pesonen 1996), suggesting a domination by chondrite impactors, but this is suspect (Grieve 1998).

Large-scale impact frequency and the threat to humankind

Much has been written on the risk to humans of asteroid or cometary impact (for example, Tate 1998) (Table 2). These rather alarmist statistics have been criticized (McCall 2001*b*). Assessments of the incidence of large impactors have been published by Tate (1998) (Table 3) and Shoemaker (1998). Hughes (1998, 2000) also produced estimates and deduced in the second publication that, for events producing craters of 3, 8, 20, 40 and 100 km in diameter, respectively, the incidence rate was one every 160 ka, 300 ka, 740 ka, 2.8 Ma and 17 Ma. These figures are probably the best so far advanced, but the data on which such calculations are based are by no means exact, especially because the geological ages of many structures in the list in Table 1 are inexact. Tate's incidence values are higher than Hughes' later estimate.

Terrestrial and extraterrestrial impact cratering

Although the Space Age was what triggered the research of the last half century, impetus was also given by the work of Baldwin (1949) on lunar craters.

It seems fair to say that, despite the remarkable degree of geographical bias revealed in Figure 17, the terrestrial impact cratering record

Table 2. *The supposed chance of fatality from asteroid strike (after Tate 1998)*

Cause of Death	Probability
Motor accident	1 in 100
Homicide	1 in 200
Fure	1 in 800
Firearm accident	1 in 2500
Electrocution	1 in 5000
Aircraft accident	1 in 20 000
Asteroid impact	1 in 25 000
Flood	1 in 30 000
Tornado	1 in 60 000
Venomous bite	1 in 100 000
Firework accident	1 in 1 000 000
Food poisoning	1 in 3 000 000

Table 3. *Incidence probability values for a near-Earth object impact on Earth (after Tate 1998)*

Diameter	Impact probability (once per number of years)	Impact energy (megatonnes of TNT)
10 km	100 000 000	100 000 000
1 km	100 000	100 000
100 m	1000	100
1 m	10	0.1

is far better established than that for any extraterrestrial body – this must be so, if only because little direct geological study by humans has been carried out on extraterrestrial bodies and sample return has been restricted to the lunar regolith and a few fragments from deeper levels in the lunar-sourced meteorite breccias (Demidova *et al.* 2003) – there is little, if any, extraterrestrial 'ground truth'.

In this text the author has concentrated on impact of extraterrestrial bodies on this planet, and has avoided so far mention of cratering on other bodies in the solar system, in order to keep the length of the text within reasonable bounds. He has expressed some reservations (McCall 2004*a*, *b*) about the widely accepted ubiquity of lunar or mercurian impact cratering, for two main reasons. First the lunar and mercurian surfaces are supposed to have been pockmarked in the early 'Great Bombardment' approximately 3900 Ma ago. The evidence from the Moon on which this conclusion is based has failed, despite diligent research, to indicate heavy bombardment from approximately 4600 Ma to this date. There is no record of this postulated event on the Earth, but this can readily be explained by obscuration entirely by subsequent geological complications. Much more damagingly, there is no record of the immense amount of material that must have been ejected if craters and structures up to the scale of Mare Imbrium and Mare Orientale (1200 km diameter) are, indeed, impact scars. Products of the quite recent minor impacts on the moon have reached the Earth, as evidenced by lunar-sourced meteorites found in Antarctica, Australia and North Africa (e.g. see McCall 2001*c*). These were spalled off the Moon and fell on the Earth in geologically recent times, as is shown by isotopic determinations on them yielding terrestrial ages (the time that they have spent on Earth after fall) and cosmic-ray exposure ages (measuring the time they spent in space as metre-sized meteorites). Surely part of the immeasurably greater load of ejectamenta from the 'Great Bombardment' would have collided with the asteroidal-sourced meteorites, if they were orbiting at that ancient time (McCall 2001*c*) – we know chondrite meteorites showered down as long ago as the Ordovician (*c.* 480 Ma ago) on Sweden (Schmitz 2003) and there is no reason to suppose that meteorites were not orbiting from very near the beginning of the solar system. Why are there no combined asteroidal–lunar-sourced mixed meteorite breccias? There seems to be too much asteroidally sourced meteoritic material orbiting in space and too little lunar-sourced material. The second doubt is about the philosophy among space scientists of considering impact cratering as the 'default' process – 'everything that is not demonstrably volcanic must be an impact structure'. This thinking is unsound because on Earth far more craters are of volcanic origin than of impact origin; there are crater patterns on Mercury that are difficult to relate to impact and, furthermore, on Mars this thinking may have been even more grossly misapplied.

It is extremely difficult to distinguish from morphology alone which is which, especially with simple craters, as Figures 21a, b surely illustrate.

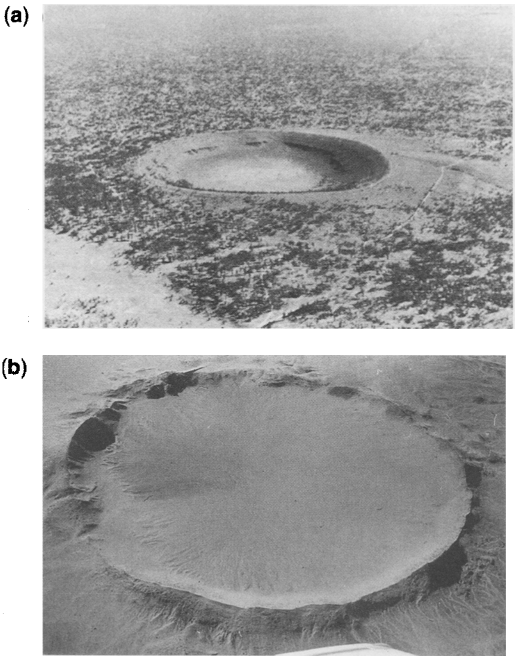

Fig. 21. Two simple terrestrial craters. Imagine that these are on the surface of another planet: could you use physiography alone to differentiate which is a crater formed by volcanic processes and which is believed to be an impact crater? (See the end of the references for a guide to the correct answer.)

The future will undoubtedly reveal many more terrestrial impact structures and increase our knowledge of the processes involved. Sooner or later, much more disciplined approaches to extraterrestrial cratering will surely be adopted. However, studies of terrestrial impact craters and structures have limited use in solving cratering problems of extraterrestrial bodies because the indicators applied here on Earth rely on examination of rock material or minerals, or structures like shatter-cones and pseudotachylite that can be studied in the field. Comparisons of physiographic forms of craters and structures are at the best crude because of the different physical conditions and surface materials at extraterrestrial surfaces and our very hazy knowledge of the nature of their internally generated eruptive processes or even the internal configuration of the body. Obviously, a human being geologizing the surface would be the ideal, but it is suspected that a manned mission, say to Mars, would be little more than a hyperexpensive political stunt, and that the future must lie in unmanned sample recovery missions, however difficult technically: the present author foresees the use of balloon and pogo-stick-like unmanned traversing vehicles and recovery back to Earth of samples from multiple sites. A weakness in the evidence from the lunar maria is the lack of any profiling in depth (e.g. geophysical, seismic) to show whether or not they are deeply excavated, as is required by impact theory.

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Answer to the Fig. 21 question. Hole-in-the-Ground, Oregon, cryptovolcanic, above: Tenoumer, Mauretania, attributed to impact, below (see Table 1). (**a**) Photo: From McCall (1977); (**b**) Photo: R.F. Fudali.