Vol. 5, No. 10 October 1995

GSA TODAY

A Publication of the Geological Society of America

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The Record of Terrestrial Impact Cratering

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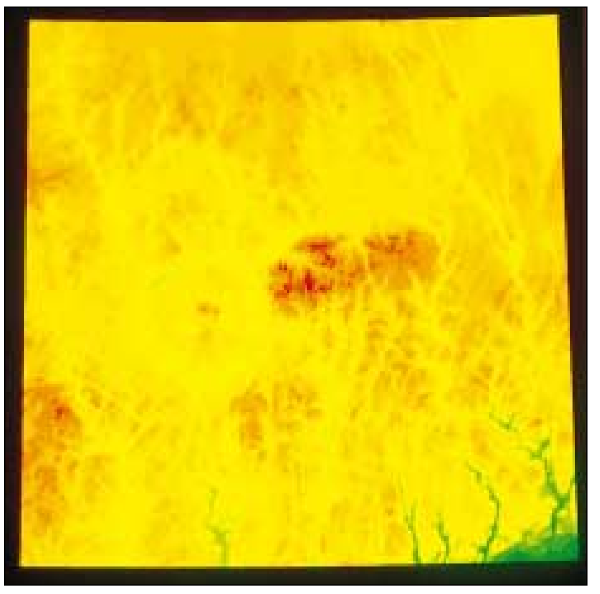

Figure 2. Topography of the Manicouagan complex impact structure, Quebec, Canada. The original diameter of this 214 ± 1 Ma structure is estimated to have been 100 km. Erosion, however, has removed the rim, and the structure appears as a series of circular features with positive and negative relief, beginning with a 150-km-diameter outer fracture zone, seen most easily in the western and southern sectors, and culminating in slightly off-center topographic peaks. The annular Manicouagan reservoir (dark green area slightly left of center) is ~65 km in diameter and at ~360 m elevation. Elevations in the center are as much as ~1100 m (brown).

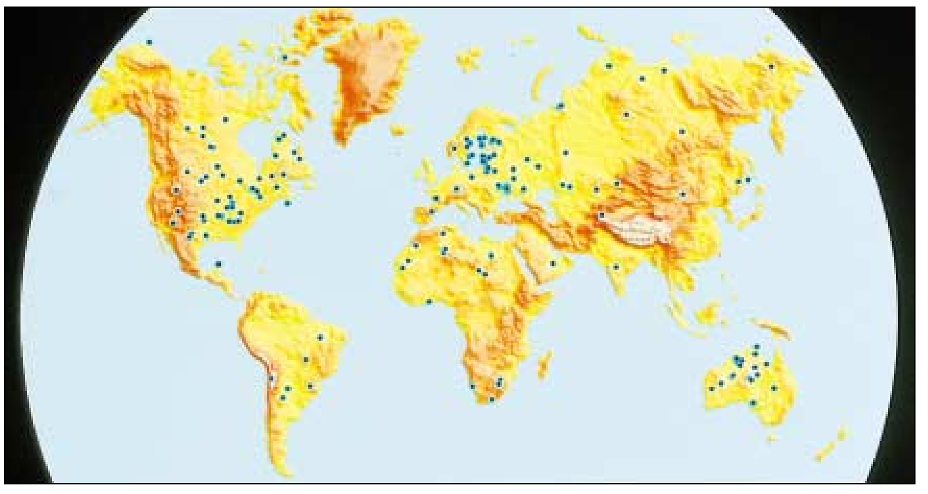

Figure 3. World map indicating locations of currently known terrestrial impact structures. Note concentrations of impact structures in Australia, North America, and northern Europe–western Russia.

ABSTRACT

Approximately 150 terrestrial impact structures are currently known, representing a small, biased sample of a much larger population. The spatial distribution indicates concentrations in cratonic areas—in particular, ones where there have been active search programs. The majority of the known impact structures are <200 m.y. old, reflecting the increasing likelihood of removal by terrestrial geologic processes with increasing geologic age. There is also a deficit of structures <20 km in diameter, due to the greater ease with which smaller features can be removed. Their form is similar to impact craters on other planetary bodies, although comparisons must be made with caution, because of the modifying effects of erosion. Erosion and burial by postimpact sediments can affect estimates of the most fundamental parameters, such as diameter. The contents of compilations of terrestrial impact structures such as presented here, therefore, vary in reliability, with respect to the principal characteristics of individual structures, and are subject to ongoing revision. Nevertheless, it is possible to estimate a cratering rate similar to independently derived rates, based on astronomical observations.

INTRODUCTION

The first studies of a terrestrial impact structure, of the now famous Meteor or Barringer Crater, Arizona, in the early 1900s by D. M. Barringer and colleagues, produced more controversy than acceptance. There was, however, a gradual increase in the number of recognized small craters with meteorite fragments until the 1960s, when so-called shock metamorphic effects became reliable criteria for assigning an impact origin to specific enigmatic terrestrial structures (e.g., see papers in French and Short, 1968). This resulted in a major increase in the number of recognized impact structures. The results of the planetary exploration programs of the 1970s demonstrated the ubiquitous nature of impact in the solar system, and studies of terrestrial impact structures provided a source of ground truth data for the interpretation of the planetary cratering record. These led to a more general acceptance of terrestrial impact structures by the geoscience community, but impact was regarded largely as a "planetary" process, with little relevance to Earth history.

This began to change in the early 1980s, following the discoveries of evidence of impact at the Cretaceous-Tertiary (K-T) boundary. Originally hotly debated, the discoveries at the K-T boundary and of the Chicxulub structure in Yucatán, Mexico, have led to increasing consensus that, at least in this case, large-scale impact can result in sufficient deterioration to the environment to result in a mass extinction. The progress of the debate regarding the involvement of large-scale impact at the K-T boundary can be gauged from papers in Silver and Schultz (1982) and Sharpton and Ward (1990). Currently, there is considerable activity in the area of the hazard to human civilization posed by impact (e.g., papers in Gehrels, 1994).

The presence of impact structures, however, still does not figure highly in general descriptions of the terrestrial geologic environment. The highly active geologic environment of Earth has served to remove, mask, and modify the terrestrial impact record throughout geologic time, making it less obvious and harder to read than that of the other terrestrial planets. The known impact record is a biased sample of a larger population and is the result of the combination of impact and endogenic terrestrial geologic processes. About 150 terrestrial impact craters or crater fields, consisting of clusters of relatively small craters, are currently known, and about three to five new ones are discovered each year. The last widely circulated listing of terrestrial impact craters by Grieve and Robertson (1987) is a world map, sponsored by the International Union of Geological Sciences Commission on Comparative Planetology, which lists 116 features. Here, we update that listing and review the basic character of the terrestrial impact record. We pay particular attention to the inherent biases in the record, as they must be accommodated when drawing inferences from the known record.

Figure 1. Oblique aerial photograph of the 1.2-km-diameter Barringer or Meteor Crater. This relatively well preserved example of a simple impact structure still retains some of its ejecta blanket, seen here as the hummocky deposits exterior to the rim.

THE KNOWN RECORD

Planetary impact craters are recognized by their morphology. Terrestrial impact craters are recognized not only by their morphology but also by their geologic structure. In the most highly eroded examples, terrestrial impact craters no longer have an obvious crater form and are recognized by their geologic characteristics. They are no longer craters, by definition, and are best referred to as impact structures. To avoid confusion and arbitrary definitions, we refer to all terrestrial impact craters as impact structures, regardless of their state of erosion.

All known terrestrial impact structures (Table 1) have evidence of an impact origin, through the documented occurrence of meteoritic material and/or shock metamorphic features. To various degrees they also have several other aspects in common, such as form, structure, and geophysical characteristics. Some of the known terrestrial structures have some of these aspects but lack documented shock metamorphic features. Although some of these are more than likely impact-origin features, they are not included in Table 1, for consistency. Events

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associated with such phenomena as the 1908 Tunguska explosion, the late Pliocene meteorite debris found over ~300,000 km^2 of the South Pacific (Kyte et al., 1988), the North American microtektite strewn field, and others are also not included in Table 1.

In compiling Table 1, we used the literature, supplemented by our own observations, on (most commonly) the presence of shock metamorphic effects at a particular structure. There is, however, a judgmental component in that the documentation of shock metamorphic effects must be convincing. For some cases for which there have been claims of shock metamorphism, we have not included the structure. For example, we do not include the Sevetin structure in the former Czechoslovakia, although there was a report of shock metamorphism in quartz (Vrána, 1987). Our own observations and recent transmission electron microscope studies have indicated that this deformation is not shock produced (Cordier et. al., 1994). In a few cases of reports of shock metamorphism, it is not clear with what structure they are associated. For example, for Bee Bluff, Texas, sometimes known as Uvalde, there are two separate reports of shock metamorphism, but it has been suggested that the shocked materials are detrital and not specific to Bee Bluff (Sharpton and Nielsen, 1988). Until this issue is resolved, we do not list Bee Bluff. Given the discovery rate and the time lag between initial discovery and publication, Table 1 is already out of date.

Any listing of the diameters of terrestrial impact structures is a mix of interpretations from topographical, geological, and geophysical data. Individual diameter estimates can differ. As more data become available for individual impact structures, estimates of their original diameter are revised. The most controversial estimate of diameter is probably for the buried Chicxulub structure (Table 1), which is the source crater for the K-T boundary deposits. We list ~170–180 km (Pilkington et al., 1994); but it has been suggested that Chicxulub may be as large as ~300 km (Sharpton et al., 1993). Additional data acquisition, including reflection seismic, planned for the near future should resolve the issue. Data compilations of rim diameters of terrestrial impact craters, such as Table 1, should be used with some caution. They are dynamic in nature and subject to revision.

TABLE 1. KNOWN TERRESTRIAL IMPACT STRUCTURES

Crater name	Location	Lat	Long	Age (Ma)	Diam. (km)
Acraman	South Australia, Australia	32°1′S	135°27′E	>450	90
Ames	Oklahoma, USA	36°15′N	98°12′W	470 ± 30	16
Amguid	Algeria	26°5′N	4°23′E	<0.1	0.45
Aorounga	Chad, Africa	19°6′N	19°15′E	<0.004	12.6
Aouelloul	Mauritania	20°15′N	12°41′W	3.1 ± 0.3	0.39
Araguainha Dome	Brazil	16°47′S	52°59′W	247.0 ± 5.5	40
Avak	Alaska, USA	71°15′N	156°38′W	>95	12
Azuara	Spain	41°10′N	0°55′W	<130	30
B.P. Structure	Libya	25°19′N	24°20′E	<120	2.8
Barringer	Arizona, USA	35°2′N	111°1′W	0.049 ± 0.003	1.19
Beaverhead	Montana, USA	44°36′N	113°0′W	~600	60
Beyenchime-Salaatin	Russia	71°50′N	123°30′E	<65	8
Bigach	Kazakhstan	48°30′N	82°0′E	6 ± 3	7
Boltysh	Ukraine	48°45′N	32°10′E	88 ± 3	24
Bosumtwi	Ghana	6°30′N	1°25′W	1.03 ± 0.02	10.5
Boxhole	Northern Territory, Australia	22°37′S	135°12′E	0.0300 ± 0.0005	0.17
Brent	Ontario, Canada	46°5′N	78°29′W	450 ± 30	3.8
Campo Del Cielo*	Argentina	27°38′S	61°42′W	<0.004	0.05
Carswell	Saskatchewan, Canada	58°27′N	109°30′W	115 ± 10	39
Charlevoix	Quebec, Canada	47°32′N	70°18′W	357 ± 15	54
Chesapeake Bay	Virginia, USA	37°15′N	76°5′W	35.5 ± 0.6	85
Chicxulub	Yucatán, Mexico	21°20′N	89°30′W	64.98 ± 0.05	170
Chiyli	Kazakhstan	49°10′N	57°51′E	46 ± 7	5.5
Chukcha	Russia	75°42′N	97°48′E	<70	6
Clearwater East	Quebec, Canada	56°5′N	74°7′W	290 ± 20	26
Clearwater West	Quebec, Canada	56°13′N	74°30′W	290 ± 20	36
Connolly Basin	Western Australia, Australia	23°32′S	124°45′E	<60	9
Couture	Quebec, Canada	60°8′N	75°20′W	430 ± 25	8
Crooked Creek	Missouri, USA	37°50′N	91°23′W	320 ± 80	7
Dalgaranga	Western Australia, Australia	27°43′S	117°15′E	0.027	0.02
Decaturville	Missouri, USA	37°54′N	92°43′W	<300	6
Deep Bay	Saskatchewan, Canada	56°24′N	102°59′W	100 ± 50	13
Dellen	Sweden	61°55′N	16°39′E	89.0 ± 2.7	19
Des Plaines	Illinois, USA	42°3′N	87°52′W	<280	8
Dobele	Latvia	56°35′N	23°15′E	300 ± 35	4.5
Eagle Butte	Alberta, Canada	49°42′N	110°30′W	<65	10
El′gygytgyn	Russia	67°30′N	172°0′E	3.5 ± 0.5	18
Flynn Creek	Tennessee, USA	36°17′N	85°40′W	360 ± 20	3.55
Gardnos	Norway	60°39′N	9°0′E	500 ± 10	5
Glasford	Illinois, USA	40°36′N	89°47′W	<430	4
Glover Bluff	Wisconsin, USA	43°58′N	89°32′W	<500	8
Goat Paddock	Western Australia, Australia	18°20′S	126°40′E	<50	5.1
Gosses Bluff	Northern Territory, Australia	23°50′S	132°19′E	142.5 ± 0.5	22
Gow	Saskatchewan, Canada	56°27′N	104°29′W	<250	5
Granby	Sweden	58°25′N	15°56′E	470	3
Gusev	Russia	48°21′N	40°14′E	65 ± 2	3.5
Gweni-Fada	Chad, Africa	17°25′N	21°45′E	<345	14
Haughton	Northwest Territories, Canada	75°22′N	89°41′W	23 ± 1	24
Haviland	Kansas, USA	37°35′N	99°10′W	<0.001	0.02
Henbury*	Northern Territory, Australia	24°35′S	133°9′E	<0.005	0.16
Holleford	Ontario, Canada	44°28′N	76°38′W	550 ± 100	2.35
Ile Rouleau	Quebec, Canada	50°41′N	73°53′W	<300	4
Ilumetsa	Estonia	57°58′N	25°25′E	>0.002	0.08
Ilyinets	Ukraine	49°6′N	29°12′E	395 ± 5	4.5
Iso-Naakkima	Finland	62°11′N	27°9′E	>1000	3
Jänisjärvi	Russia	61°58′N	30°55′E	698 ± 22	14
Kaalijärvi*	Estonia	58°24′N	22°40′E	0.004 ± 0.001	0.11
Kalkkop	South Africa	32°43′S	24°34′E	<1.8	0.64
Kaluga	Russia	54°30′N	36°15′E	380 ± 10	15
Kamensk	Russia	48°20′N	40°15′E	49 ± 18	25
Kara	Russia	69°12′N	65°0′E	73 ± 3	65
Kara-Kul	Tajikistan	39°1′N	73°27′E	<5	52
Kärdla	Estonia	58°59′N	22°40′E	455	4
Karla	Russia	54°54′N	48°0′E	<10	12
Kelly West	Northern Territory, Australia	19°56′S	133°57′E	>550	10
Kentland	Indiana, USA	40°45′N	87°24′W	<97	13
Kursk	Russia	51°40′N	36°0′E	250 ± 80	5.5
La Moinerie	Quebec, Canada	57°26′N	66°37′W	400 ± 50	8
Lappajärvi	Finland	63°12′N	23°42′E	77.3 ± 0.4	23
Lawn Hill	Queensland, Australia	18°40′S	138°39′E	>515	18
Liverpool	Northern Territory, Australia	12°24′S	134°3′E	150 ± 70	1.6
Lockne	Sweden	63°0′N	14°48′E	>455	7
Logancha	Russia	65°30′N	95°50′E	25 ± 20	20
Logoisk	Belarus	54°12′N	27°48′E	40 ± 5	17

*Crater fields. Diameter given is of largest of the multiple structures.

MORPHOLOGY

Relatively uneroded terrestrial impact structures display the basic progression, from simple to complex forms with increasing diameter, that is observed on other terrestrial planets. Simple craters have the form of a bowl-shaped depression with a structurally upraised rim. The rim area is overlain by ejecta deposits, and the crater floor represents the top of a subsurface breccia lens. The canonical example is Barringer or Meteor Crater (Fig. 1). Because of its young age, Barringer has a partially preserved exterior ejecta deposit. Most simple craters, however, are considerably more degraded than Barringer; in some cases, the rim area has been completely removed by erosion and the interior filled with postimpact sediments.

Simple structures on Earth have diameters of as much as 4 km. Terrestrial impact structures with diameters >4 km generally have a complex form. As with craters on other planetary bodies, however, there is some overlap of forms near the transition diameter. Some of this can be ascribed to differences in target rock properties, complex craters occurring in sedimentary targets at diameters >2 km. Complex crater forms are characterized by structurally complex and faulted rim areas, a flat annular trough, and uplifted topographically high central structures (Fig. 2). Studies at terrestrial impact structures indicate that the central structures contain rocks uplifted from deeper levels (e.g., Grieve and Pesonen, 1992). Various lines of evidence indicate that complex structures result from changes in the nature of the later stages of the cratering process with respect to simple craters. Although some details are not well understood, the basic principles of cratering mechanics in the formation of simple and complex craters have been established (e.g., Melosh, 1989).

Terrestrial complex impact structures also show the second-order forms observed on other planetary bodies, such as central peak craters, peak-ring craters, and ring basins. Care must be exercised, however, when comparing morphologic elements of individual terrestrial impact structures and, in particular, when comparing terrestrial and planetary craters (Pike, 1985). Original morphologic elements can be enhanced, modified, or removed by erosional processes on Earth, processes that affect the relative dimensional relations between morphologic elements. Some of the basic relations, such as depth/diameter, for relatively pristine terrestrial impact structures are given in Grieve and Pesonen (1992).

It is not known if there are examples of true multiring basins on Earth. The largest known terrestrial impact structures are Chicxulub, Sudbury, and Vredefort (Table 1). Chicxulub is buried by ~1 km of platform sediments (Hildebrand et al., 1991). Sudbury is eroded and highly tectonized but may have had an interior ring (Stöffler et al., 1994). Vredefort is also highly eroded—only the crater floor preserved—and there is no direct indication of its original morphology (Therriault et al., 1993). The lack of definitive evidence for multiring impact structures on Earth illustrates that caution is necessary when appraising the form of terrestrial impact structures. All exposed terrestrial impact structures have been modified by erosion. Some buried structures, which formed in areas of continuous postimpact sedimentation, presumably have preserved their original morphology. They are, however, poorly known, because their form can be reconstructed only from spot information, such as from drill holes, and from geophysical interpretations.

SPATIAL DISTRIBUTION

All known terrestrial impact structures (Fig. 3) are entirely on land, with the exceptions of Montagnais, Chesapeake Bay, Chicxulub, and Ust-Kara (Table 1). The status of Ust-Kara has also been questioned. It is poorly exposed, and Nazarov et al. (1991)

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TABLE 1. *(continued)*

Crater name	Location	Lat.	Long.	Age (Ma)	Diam. (km)
Lonar	India	19°58′N	76°31′E	0.052 ± 0.006	1.83
Lumparn	Finland	60°12′N	20°6′E	~1000	9
Macha*	Russia	59°59′N	118°0′E	<0.007	0.3
Manicouagan	Quebec, Canada	51°23′N	68°42′W	214 ± 1	100
Manson	Iowa, USA	42°35′N	94°33′W	73.8 ± 0.3	35
Marquez	Texas, USA	31°17′N	96°18′W	58 ± 2	13
Middlesboro	Kentucky, USA	36°37′N	83°44′W	<300	6
Mien	Sweden	56°25′N	14°52′E	121.0 ± 2.3	9
Mishina Gora	Russia	58°40′N	28°0′E	<360	4
Mistastin	Newfoundland-Labrador, Canada	55°53′N	63°18′W	38 ± 4	28
Mizarai	Lithuania	54°1′N	24°34′E	570 ± 50	5
Montagnais	Nova Scotia, Canada	42°53′N	64°13′W	50.50 ± 0.76	45
Monturaqui	Chile	23°56′S	68°17′W	<1	0.46
Morasko*	Poland	52°29′N	16°54′ E	0.01	0.1
New Quebec	Quebec, Canada	61°17′N	73°40′W	1.4 ± 0.1	3.44
Newporte	North Dakota, USA	48°58′N	101°58′W	<500	3
Nicholson	Northwest Territories, Canada	62°40′N	102°41′W	<400	12.5
Oasis	Libya	24°35′N	24°24′E	<120	11.5
Obolon′	Ukraine	49°30′N	32°55′E	215 ± 25	15
Odessa*	Texas, USA	31°45′N	102°29′W	<0.05	0.17
Ouarkziz	Algeria	29°0′N	7°33′W	<70	3.5
Piccaninny	Western Australia, Australia	17°32′S	128°25′E	<360	7
Pilot	Northwest Territories, Canada	60°17′N	111°1′W	445 ± 2	6
Popigai	Russia	71°30′N	111°0′E	35 ± 5	100
Presqu′île	Quebec, Canada	49°43′N	74°48′W	<500	24
Pretoria Saltpan	South Africa	25°24′S	28°5′E	0.220 ± 0.052	1.13
Puchezh-Katunki	Russia	57°6′N	43°35′E	175 ± 3	80
Ragozinka	Russia	58°18′N	62°0′E	55 ± 5	9
Red Wing	North Dakota, USA	47°36′N	103°33′W	200 ± 25	9
Riachao Ring	Brazil	7°43′S	46°39′W	<200	4.5
Ries	Germany	48°53′ N	10°37′E	15 ± 1	24
Rio Cuarto*	Argentina	30°52′S	64°14′W	<0.1	4.5
Rochechouart	France	45°50′N	0°56′E	186 ± 8	23
Roter Kamm	Namibia	27°46′S	16°18′E	3.7 ± 0.3	2.5
Rotmistrovka	Ukraine	49°0′N	32°0′E	140 ± 20	2.7
Sääksjärvi	Finland	61°24′N	22°24′E	~560	6
Saint Martin	Manitoba, Canada	51°47′N	98°32′W	220 ± 32	40
Serpent Mound	Ohio, USA	39°2′N	83°24′W	<320	8
Serra da Cangalha	Brazil	8°5′S	46°52′W	<300	12
Shunak	Kazakhstan	47°12′N	72°42′E	12 ± 5	3.1
Sierra Madera	Texas, USA	30°36′N	102°55′W	<100	13
Sikhote Alin	Russia	46°7′N	134°40′E	0	0.03
Siljan	Sweden	61°2′N	14°52′E	368.0 ± 1.1	52
Slate Islands	Ontario, Canada	48°40′N	87°0′W	<350	30
Sobolev	Russia	46°18′N	138°52′E	<0.001	0.05
Söderfjärden	Finland	62°54′N	21°42′E	~600	5.5
Spider	Western Australia, Australia	16°44′S	126°5′E	>570	13
Steen River	Alberta, Canada	59°30′N	117°38′W	95 ± 7	25
Steinheim	Germany	48°2′N	10°4′E	15 ± 1	3.8
Strangways	Northern Territory, Australia	15°12′S	133°35′E	<470	25
Sudbury	Ontario, Canada	46°36′N	81°11′W	1850 ± 3	250
Suvasvesi N	Finland	62°42′N	28°0′E	<1000	4
Tabun-Khara-Obo	Mongolia	44°6′N	109°36′E	>1.8	1.3
Talemzane	Algeria	33°19′N	4°2′E	<3	1.75
Teague	Western Australia, Australia	25°52′S	120°53′E	1630 ± 5	30
Tenoumer	Mauritania	22°55′N	10°24′W	2.5 ± 0.5	1.9
Ternovka	Ukraine	48°1′N	33°5′E	350 ± 00	15
Tin Bider	Algeria	27°36′N	5 7′E	<70	6
Tookoonooka	Queensland, Australia	27°0′S	143°0′E	128 ± 5	55
Tvären	Sweden	58°46′N	17°25′E	>455	2
Upheaval Dome	Utah, USA	38°26′N	109°54′W	<65	10
Ust-Kara	Russia	69°18′N	65°18′E	73 ± 3	25
Vargeao Dome	Brazil	26°50′S	52°7′W	<70	12
Veevers	Western Australia, Australia	22°58′S	125°22′E	<1	0.08
Vepriai	Lithuania	54°1′N	24°34′E	>160 ± 30	8
Vredefort	South Africa	27°0′S	27°30′E	2006 ± 9	300
Wabar*	Saudi Arabia	21°30′N	50°28′E	0.006 ± 0.002	0.1
Wanapitei	Ontario, Canada	46°45′N	80°45′W	37 ± 2	7.5
Wells Creek	Tennessee, USA	36°23′N	87°40′W	200 ± 100	12
West Hawk	Manitoba, Canada	49°46′N	95°11′W	100 ± 50	2.44
Wolfe Creek	Western Australia, Australia	19°18′S	127°46′E	<0.3	0.88
Zapadnaya	Ukraine	49°44′N	29°0′E	115 ± 10	4
Zeleny Gai	Ukraine	48°42′N	32°54′E	120 ± 20	2.5
Zhamanshin	Kazakhstan	48°20′N	60°58′E	0.9 ± 0.1	13.5

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attributed its impact lithologies to its twin structure, Kara (Table 1). Several structures now on land were formed under water in epicontinental seas or on continental margins. No impact structures are known from the world's ocean basins. Oceanic structures undoubtedly exist, but the present level of knowledge of the ocean floors is insufficient for identification. Ocean-floor spreading and subduction also play a role in the obliteration of oceanic impact craters. Not all known structures are exposed at the surface. Many contain postimpact sediments and ~30% are completely buried by cover rocks. The latter were generally discovered through geophysical anomalies that are associated with impact structures (Pilkington and Grieve, 1992), and they were subsequently explored through drilling.

The spatial distribution of known impact structures is not random. There are concentrations in North America, Australia, and Northern Europe through to the western part of the former Soviet Union (Fig. 3). These are largely cratonic areas, either exposed Precambrian Shield or platform sediments overlying shield, where there have been programs to identify and study impact craters. We cannot emphasize enough the importance of the influence on the local rate of discovery of programs to identify impact structures. Increased awareness of impact structures and their characteristics in Fennoscandia led to the confirmation, since 1992, of an impact origin for Gardnos, Lockne, Iso-Naakkima, Lumparn, and Suvasvesi (Table 1). There has been a similar recent upsurge in identification of impact structures in southern Africa. Few impact structures have been found outside cratonic areas, which are the most suitable surfaces for the preservation of such structures in the terrestrial geologic environment. A few structures have been heavily tectonized—e.g., Beaverhead and Sudbury (Table 1)—or occur in mountainous areas—e.g., Gardnos and Kara-Kul (Table 1), where they were formed after the mountain belts formed.

TEMPORAL DISTRIBUTION

Approximately 40% of known terrestrial impact structures have been dated isotopically, generally from the analysis of impact melt rocks. Most of the materials (~90%) affected by impact in a cratering event, however, are subjected to insufficient shock pressures and postshock temperatures to significantly disturb isotopic dating systems (Deutsch and Schärer, 1994). The bulk of isotopic dates are K-Ar or, more recently, $^{40}Ar/^{39}Ar$ plateau dates. Fine-grained, commonly clast-rich, impact melt rocks are not particularly easy to date isotopically, because of inherited Ar from the clasts. In only a few cases is the grain size or compositional variation of impact melt rocks sufficient to permit use of such dating techniques as Rb-Sr isochrons (Deutsch and Schärer, 1994). In a few cases, precise U-Pb dates have been obtained from shocked zircons (Krogh et al., 1993) and from new zircons crystallized from impact melts (Hodych and Dunning, 1992).

The remainder of known terrestrial impact structures have biostratigraphic or stratigraphic dates. Some postimpact biostratigraphic dates are minimum age estimates—e.g., Lockne (Table 1; Grahn and Nolvak, 1993). Most stratigraphic dates, however, are maximum age estimates, the age being listed only as less than the age of the target rocks; e.g., Eagle Butte is formed in Cretaceous rocks and listed as <65 Ma (Table 1). In the worst cases, a crude constraint on the age is provided by the degree of erosion. For example, the age of the Slate Islands is based on the similarity of its erosional level to that of Charlevoix, which has been isotopically dated (Table 1). They are similar in size and occur in areas of broadly similar geologic history. Erosional rates, however, can vary considerably, particularly in areas that have been glaciated. In addition, some craters have been buried, preserved, and only recently exhumed—e.g., the old, but relatively small Brent, Janisjärvi, and Sääksjärvi structures (Table 1).

Impact age estimates, therefore, are a mixture of determinations that vary in accuracy and precision. Caution must be exercised when using these ages to calculate parameters such as cratering rate estimates and as input into time-series analyses for searches for periodicities and links to other geologic processes (e.g., Stothers and Rampino, 1990). Some broad trends, however, are clear. The temporal distribution of known terrestrial impact structures is biased toward younger ages; over 60% are younger than 200 Ma (Fig. 4). This is a function of erosion. As surface features in a highly active geologic environment, terrestrial impact structures can be removed relatively rapidly. The rate at which this occurs varies with the geologic history of the area. For example, it has been estimated that structures with diameters ≤20 km can be effectively removed in as little as 120 m.y. in exposed shield areas that have been glaciated (Grieve, 1984). Conversely, the interior of Australia, which has had a remarkably stable geologic history, has a relatively high number of Proterozoic-aged impact structures (~30% of the known structures in Australia; Table 1), and the Russian platform has a relatively high number of impact structures of Mesozoic age (Table 1), because of postimpact burial by platform sediments.

SIZE DISTRIBUTION

Terrestrial impact structures are as much as ~300 km in diameter (Table 1). As noted earlier, there is considerable uncertainty in some diameter estimates. In some cases, erosion has removed all topographic expression, and what remains is a geologic anomaly, with a roughly circular shape. In a few cases, the original negative topographic expression of the crater has been replaced by positive topography. For example, Gosses Bluff (Table 1) is a 5-km-diameter, topographically high ring of erosionally resistant sandstones. Other data indicate that the original diameter of the structure was 22 km and that what remains is the erosional remnant of the interior of a central uplift.

There is a bias in the size-frequency distribution of terrestrial impact structures. In the Phanerozoic impact record, the cumulative size frequency of terrestrial impact structures at large

Cratering *continued on p. 196*

Cratering *continued from p. 195*

diameters is similar to that on other terrestrial planets (Fig. 5). At diameters less than ~20 km, however, the cumulative size-frequency distribution falls off, indicating the increasing effects of removal and, to a lesser extent, burial of smaller structures. At simple structures the geological effects of impact are visible to a depth of about one-third the final rim diameter (Grieve and Pesonen, 1992). Thus, the geologic evidence for the largest terrestrial simple impact structures can be removed by <1.5 km of erosion. At larger complex structures, the depth:diameter ratio is shallower, but the absolute depths are often greater. The uplift of originally deeper rocks in the center of complex structures provides an additional geologic manifestation of the event. The amount of stratigraphic uplift undergone by the deepest lithologies exposed in the central structures of complex impact structures is about one-tenth the final rim diameter. Thus, even when the topography and interior impact lithology at a complex impact structure have been completely removed by erosion, it will still be recognizable as a roughly circular geologic anomaly. The shape of the cumulative size-frequency distribution in Figure 5 appears to be an inherent property of the terrestrial record. It has persisted as more impact structures have been added to the known sample over the years.

CRATERING RATE

The most complete record of impact cratering is that of relatively large, geologically young impact structures in cratonic areas, such as North America and northern Europe–western Russia, that have been studied intensively. Therefore, rate estimates are based on a relatively small number of impact structures. Earlier estimates of the terrestrial cratering rate can be found in Shoemaker (1977) and Grieve and Dence (1979). On reexamination, Grieve (1984) concluded that the original sample of 15 impact structures used by Grieve and Dence (1979) may have been affected by erosion and was incomplete. From a reanalysis of the original data, the estimate of the cratering rate was revised upward to 5.5 $\pm$ 2.7 $\times$ 10^{-15} km^2/yr for diameters ≥20 km and impact structures dated at ≤120 Ma. This rate estimate is comparable to the earlier estimate of Shoemaker (1977) and is very similar to an estimate based on astronomical observations of Earth-crossing asteroids and comets of 4.9 $\pm$ 2.9 $\times$ 10^{-15} km^2/yr (Shoemaker et al., 1990). The uncertainties attached to all these estimates are large, ± 50%, reflecting concerns about completeness of search and small number of statistics.

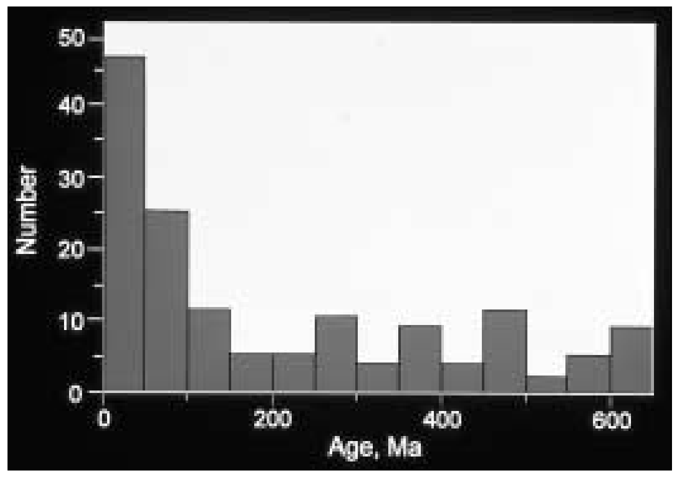

Figure 4. Histogram of age estimates of terrestrial impact structures in the Phanerozoic, binned by 50 m.y. Note that the majority of the known structures are <200 Ma, due to the effects of terrestrial geologic processes on the preserved record.

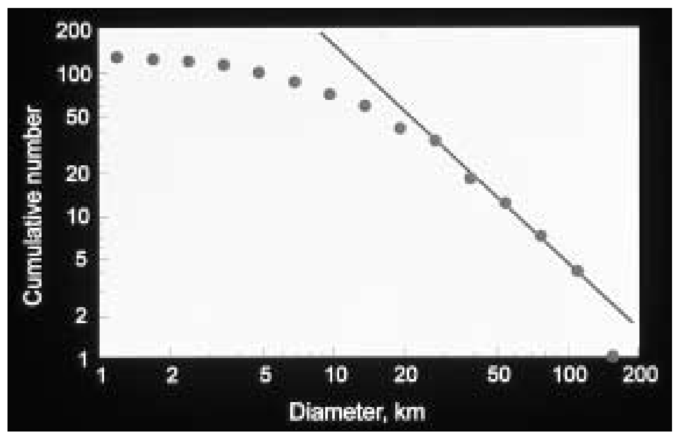

Figure 5. Log-log plot of the cumulative number of Phanerozoic-aged impact structures above a particular diameter, binned by increments of $\sqrt{2}$. Note the power-law distribution down to diameters of ~20 km, below which the size-frequency distribution falls off, indicating a deficit of smaller impact structures.

CONCLUSIONS

Largely because of the K-T debate, there have been attempts to discredit the presence of shock metamorphic effects, particularly in quartz, as a reliable diagnostic criterion for the occurrence of a terrestrial impact event (e.g., Rice, 1987; Carter et al., 1990; Lyons et al., 1993). These have been partially out of context and have attributed the term "shock" to features that are not considered diagnostic of shock metamorphism. This has led to some confusion in nonexperts. Shock metamorphic effects are well defined and diagnostic of impact (see retrospective by French, 1990). In the terrestrial environment, the shock metamorphism of quartz has been particularly useful, because of its ubiquitous nature and the relatively wide range of shock pressures over which diagnostic shock effects are produced. These were extensively reviewed in Stöffler and Langenhorst (1994).

The number and the level of detail of studies of individual terrestrial impact structures vary greatly. In compiling the data for Table 1, we were, therefore, conservative, on the basis of the assumption that it is easier to add a new structure than to remove an old structure from a listing because new data indicate that the identification of shock metamorphism was in error. There is always some risk in compiling such lists as Table 1, particularly with respect to their subsequent use. We have, however, specifically focused here on the inherent biases in the terrestrial impact record that are largely the result of terrestrial geologic activity. Although we have tried to be as accurate as possible with the information in Table 1, the compilation of data involves a wide range of sources, and it is almost inevitable that there will be some errors. Because the data compilation forms the basis of more detailed studies of the character of terrestrial impact structures, we would appreciate hearing of any errors or omissions in Table 1. To report such errors or to receive information on the various details of particular terrestrial impact structures currently in our databases, please contact, by E-mail, crater@gsc.nrcan.gc.ca.

ADDENDUM

Since the original writing of this article, shock metamorphic effects have been observed at two additional structures. They are Goyder, Northern Territory, Australia, 13°29′S, 135°03′E, >136 Ma, 3 km; and Mjølnir, Barents Sea, 73°48′N, 29°40′E, ~135 Ma, 39 km.

ACKNOWLEDGMENTS

We thank M. Pilkington and B. Sharpton for commenting upon an earlier version of the manuscript. Geological Survey of Canada contribution 15395.

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Manuscript received March 10, 1995; revision received June 20, 1995; accepted June 22, 1995 ■

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