CHAPTER FOUR

Meteorite Craters

Nobody has ever witnessed the formation of a meteorite crater. Interpretations must therefore be based upon measurement and comparison with artificial craters, caused by known magnitudes and depths of explosives. Excellent studies have been performed by Baldwin (1949; 1963; 1970) who was particularly interested in the puzzling problems associated with the lunar craters but, as a basis for his speculations, thoroughly examined several terrestrial craters and presented extensive bibliographies. Results from nuclear test sites have been presented by Hansen (1968) and Short (1968a, b). Krinov (1960b; 1966a, b) has discussed several craters and impact holes associated with meteorites and also devoted a large chapter to the Tunguska comet, which did *not* produce craters at all. See page 9. Stanyukovich & Fedynski (1947), Nininger (1952a; 1956), Shoemaker (1963) and Gault et al. (1968) have made many pioneering studies of cratering and discussed the associated problems from widely varying standpoints. Critical lists of terrestrial meteorite craters and recent bibliographies may be found in Hey (1966: 538), Short & Bunch (1968) and U.S. Geological Survey, Bulletin No. 1320 (1969).

On the Moon and planetary bodies without an atmosphere, even very small particles will, upon impact, create craters. The surfaces of lunar material from the first Apollo 11 mission in 1969 could thus be shown to be sputtered with small pits or craters, probably caused by micrometeorites (Neukum et al. 1970). Examination of lunar surface material recovered by the Apollo missions – a total of 380 kg was secured by Apollo 11, 12, 14, 15, 16 and 17 – has already revealed much meteoritic debris, processed by repeated cratering, "gardening." According to structural and chemical studies, the recognizable debris consists mainly of (i) meteoritic material which was metamorphosed while incorporated in the lunar rocks, (ii) shock-altered fragments of chondrites and iron meteorites, and (iii) rapidly solidified metallic droplets, analogous to the spheroids encountered in the vicinity of Meteor Crater, Arizona (Goldstein et al. 1972; Anders et al. 1973); see page 397.

The bulk of the typical large lunar craters were formed when the kinetic energy $\frac{1}{2}mv^2$ of the impacting body was converted into thermal energy within a fraction of a second, resulting in an explosion. There is a very high probability that the impacting body was thereby itself totally destroyed, melted or vaporized (Hartman & Wood 1971; Ahrens & O'Keefe 1972). Fortunately, for the science of meteoritics and for the inhabitants of Earth, our atmosphere will alleviate the impact of celestial bodies and through a gradual deceleration cause an important proportion to survive as meteorites. However, large and dense bodies, page 22, will penetrate the atmosphere and impact the Earth with a significant fraction of their initial energy still intact. Öpik (1951; 1958a) has examined the statistical probability that Earth is impacted by asteroidal and cometary bodies, Table 16, and has also calculated the lethal effect of the collisions on land life. Öpik even speculated that the development of land life during the Pre-Cambrian period may have been handicapped by catastrophic collisions as well as by other causes.

For the sake of clarity it should be noted here that giant meteorites can form two types of craters. The smaller crater is more properly called a large impact hole and is generated by relatively small meteorites (< 50 ton) with relatively low velocities not exceeding 5 km/sec. Such meteorites cause mechanical destruction of the ground and are themselves usually broken into a number of fragments upon impact. The major part of the meteoritic fragments will remain in the impact hole mixed with shattered rock and soil. Typical examples are the 100-1,700 kg iron

Table 16. Collision Frequencies and Destructive effects

Diameter of Impacting Body, km.		0.13	0.52	4.2	34
Collisions per year with	Comets	$1.8 \cdot 10^{-5}$	$9.8 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$	$1.6 \cdot 10^{-10}$
	Mars Asteroids	$4.0 \cdot 10^{-7}$	$4.5 \cdot 10^{-8}$	$1.6 \cdot 10^{-9}$	$6.1 \cdot 10^{-11}$
	Apollo Asteroids	$2.8 \cdot 10^{-5}$	$6.6 \cdot 10^{-7}$	$2.4 \cdot 10^{-9}$	$8.0 \cdot 10^{-11}$
Total collisions per year		$4.6 \cdot 10^{-5}$	$1.7 \cdot 10^{-6}$	$1.6 \cdot 10^{-8}$	$2.3 \cdot 10^{-10}$
Interval between collisions, years		$2.2 \cdot 10^{4}$	$5.9 \cdot 10^{5}$	$6.1 \cdot 10^{7}$	$4.4 \cdot 10^{9}$
Lethal area, km^2, at v_∞ = 20 km/sec		20	1300	$5.6 \cdot 10^{5}$	$9.6 \cdot 10^{7}$

meteorites of the Sikhote-Alin shower that produced impact holes 6-27 m in diameter and buried themselves to depths of 2-8 m (page 1123).

The genuine craters discussed here are more than 100 m in diameter and were formed as the result of an explosion at the moment of impact. The projectile itself vaporized almost entirely, and tremendous shock waves raced outward from the focus. The largest explosions produced ring anticlines and synclines surrounding an upraised central dome. On Earth these features have been severely modified by subsequent erosion or glaciation but are observed to perfection on the Moon. At the time of impact the rock was crushed to a rock flour (see Canyon Diablo), and the quartz minerals formed coesite (Chao et al. 1960; Stöffler & Arndt 1969), stishovite (Chao et al. 1962; Ida et al. 1967) or lechatelierite (Rogers 1930). Glasses formed from the desert sand (Wabar, Henbury) and fallout breccias, called suevites, formed as extensive blankets over the crater basin (Ries Kessel; Engelhardt & Stöffler 1968).

Shatter cones (Dietz 1963; 1968) are now known from 20 of the 50 recognized meteorite craters. They are striated cup-and-cone structures which are best developed in dolomite and other carbonate rocks but also occur in shale, sandstone, quartzite and granite. The cones range in size from 1 cm to 2 m and generally seem to have their apex pointed towards the ground zero of the explosion. They evidently formed by the passage of intense shock waves associated with the cratering impact.

Öpik (1958a) estimated the effect of impact upon the terrestrial rocks and found the following equations to be valid for impacting velocities, v, above 15 km/sec:

Volume of vaporized rock: $V_G = 0.284\ v\ d^3\ km^3$
Volume of melted rock: $V_M = 0.224\ v\ d^3\ km^3$
Volume of crushed rock: $V_C = 7.3\ v\ d^3\ km^3$,

where d is the diameter in km of the impacting (stone) meteorite.

Baldwin (1949; 1963; 1971) analyzed the cratering situation somewhat differently, extending his own results from TNT explosives to meteorite impacts on the Earth and Moon. On the assumption that the impacting meteorite only penetrated to shallow depths, equal to twice its own diameter, before it was brought to a full stop, he calculated the required energies and velocities to produce craters of a given size. See Figure 21 and Table 17.

Table 17. Sizes of iron meteorites which could produce certain craters if they exploded in "average soil" at a scaled depth of burst: H cm = 0.04 $\sqrt[3]{E}$ cal. Adapted from Baldwin 1963:165, 175, 447.

Crater Diameter meter	Log Energy, E calories (1 kg TNT ~ 10^6 cal.)	Velocity at impact, v_i 12 km/sec		16 km/sec		Time to Stop, seconds v_i = 16 km/sec
		Log mass ton	Diameter meter	Log mass ton	Diameter meter	
9.5	8.88	-0.21	0.51	-1.61	0.16	0.000045
95	12.13	3.34	6.3	1.64	2.16	0.000545
950	15.55	6.46	87	5.06	29.7	0.00750
9500	19.18	10.09	1410	8.69	483	0.122
95000	23.06	13.97	27750	12.57	9480	2.39

Baldwin's equations and curves will in general indicate that a given crater may be produced by meteorites an order of magnitude smaller than those derived from Öpik's equations.

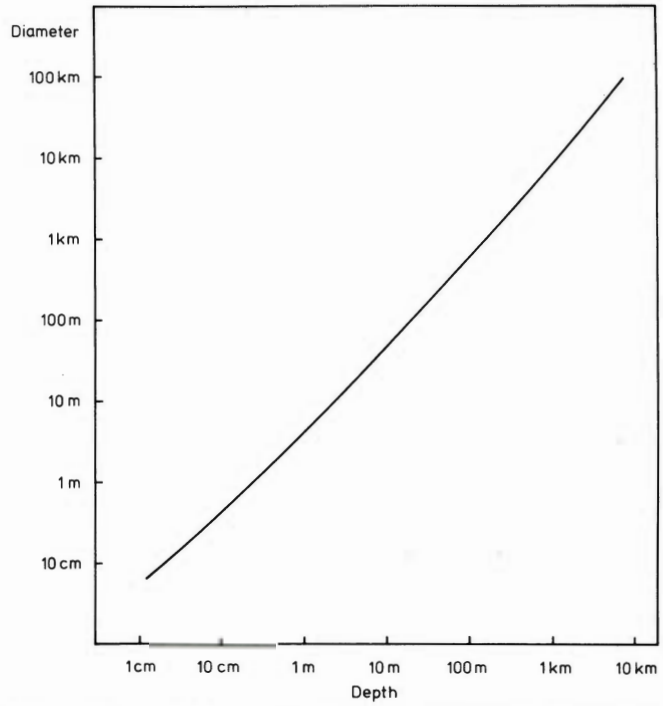

Figure 21. To a first approximation the dimensions of craters vary in proportion to the cube root of the expended energy. The log-log plot shown here indicates for a variety of explosion craters and meteoritic craters on Earth and Moon the diameter versus apparent depth (i.e., distance from rim crest to exposed bottom). (Adapted from Baldwin 1963.)

The first crater on Earth which was widely – although not universally – accepted as being of meteoritic origin was "Meteor Crater" or "Barringer Crater," around which the Canyon Diablo meteorites were found. From its history which is summarized on page 381. it is quite clear that a wealth of scientific ideas have been tested here since Barringer (1905) first proposed its meteoritic nature. By a curious coincidence the next half a dozen craters were all recognized in the ten years between 1928-1937, since which time only one crater, Wolf Creek, associated with meteoritic debris has been reported.* However, other, more ancient craters without meteorites have been discovered since the 1950s due to a concerted effort particularly by Canadian scientists (see, e.g., Hartmann 1965; Dence et al. 1968; Freeberg 1969). At least 16 craters on the Canadian shield are now well documented, many of them being of Pre-Cambrian age. The Charlevoix (La Malbaie) crater, on the north shore of the St. Lawrence River is 35-40 km in diameter, but it is bisected by the river and deeply eroded, so that it was not recognized until the presence of shatter cones was noted (Rondot 1968; Robertson 1968). The Manicouagan crater in Quebec, which is of Palaeozoic age and now a lake, is, with its

*In the Supplement the author has added one more such crater, Monturaqui.

diameter of 60 km, one of the largest known meteorite craters on Earth. Its nature seems, however, still to be open to discussion (Currie 1972).

The largest crater in Europe is Ries Kessel, east of Tübingen. It is 24 km in diameter and was formed 14.6 million years ago as indicated by several independent studies (Hörz 1965; Preuss & Schmidt-Kaler 1969; Storzer & Gentner 1970). Lake Mien in southern Sweden is 5 km across and has an estimated age of 92±6 million years (Svensson & Wickman 1965; Storzer 1971). The smallest crater on Earth so far recognized is Kaalijärv, page 704. The newest and perhaps largest is the 75 km Popigai Crater in northern Siberia (Masaitis et al. 1972). For the entire Earth a total of about 50 craters over 100 m in diameter can be said to be sufficiently well examined to warrant their meteoritical origin.

If we limit ourselves to the examination of genuine explosion craters with associated meteorites we only have ten examples; see Table 18. These are Canyon Diablo, Odessa, Brenham, Monturaqui, Kaalijärv, Wabar, Wolf Creek, Henbury, Boxhole and Dalgaranga, all of them very young geologically speaking. The meteoritic debris proves unambiguously that the craters were caused by iron or stony iron meteorites. Four of them, Canyon Diablo, Odessa, Monturaqui and Kaalijärv were caused by typical group I irons, while four were caused by typical irons of groups IIIA and IIIB. From Table 27 we will see that group IIIA-B is the most common iron meteorite type, comprising 33.1% by number. Group I comprises 14.4% of all iron meteorites and is the next most common. It is thus no coincidence that the craters were caused by these types. Evidently these two iron meteorite groups consititute both with respect to number and masses the most important iron meteorites of all.

Whether the ancient craters (astroblemes), such as La Malbaie and Ries Kessel, were also caused by iron meteorites is unknown, but it appears likely. Future examinations of the average chemical composition of the impactites may contain a clue to the nature of the impacting body. In the meantime, the Apollo space program has just established instrumented stations for analyzing impact events on the Moon. In May 1972 the first important result was registered on three of the four seismographs. A meteorite impact occurred not far from the Apollo 14 site and the vibrations lasted three hours. Expectations are high that this sort of experimentation will also yield valuable information about the Moon's interior, in addition to data on the cratering phenomena inself.

Table 18. Crater-forming Meteorites

	Class	Group	% Ni	Found	Recovered metallic material kg	Recovered metallic material No.	Largest mass kg	Smallest mass kg	Main Crater diameter m.	Coesite Stishovite Glass Lechatelierite	Estimated Age Years
America											
Canyon Diablo, Arizona	Og	I	7.1	1891	30,000	20,000	639	~ 0.05	1,200	C,S,G,L	20,000
Odessa, Texas	Og	I	7.4	1928	1,000	2,000	135	~ 0.05	165	–	50,000
Brenham, Haviland, Kansas	Pallasite		10.8	(1882)1933	5,000	2,000	210	0.005	17 X 11	–	>5,000
Monturaquí, Chile	Og	I	7.8	1965	Only fully oxidized fragments				375	G	>100,000
Europe											
Kaalijärv, Estonia	Og	I	6.6	1928	0.2	25	0.038	0.002	110	–	5,000
Asia											
Wabar, Arabia	Om	IIIA	7.4	(1887)1932	2,500	25	2,170	0.03	100	C,G	<5,000
Australia											
Wolf Creek	Om	IIIB	9.2	1947	< 1	10	0.1	0.02	900	–	>100,000
Henbury	Om	IIIA	7.6	1931	1,200	2,000	225	0.02	180 X 130	G	<5,000
Boxhole	Om	IIIA	7.7	1937	500	500	167	0.02	170	–	5,000
Dalgaranga	Mesosiderite		8.8	1923	?	300	0.06	0.002	21	–	25,000

The Brenham and Dalgaranga craters are probably not true craters but impact holes similar to the impact holes of the Sikhote-Alin shower. Morasko, page 836, may belong to the crater-forming meteorites but is not yet sufficiently well examined. The preatmospheric mass of all these meteorites was no doubt larger than any of the masses listed in Table 20: Largest Iron Meteorite.