

## 8. Projectile



Meteoritic remnants of the impacting asteroid that produced Barringer Crater littered the landscape when exploration began ~115 years ago. As described in Chapter 1, meteoritic irons are what initially captured Foote's interest and spurred Barringer's interest in a possibly rich natural source of native metal. After Foote's description was published, samples were collected by F. W. Volz at a nearby trading post and sold widely. Gilbert (1896) estimated that 10 tons of meteoritic debris had already been recovered by the time of his visit. Similarly, Barringer (1905) estimated that 10 to 15 tons of it were circulating around the world by the time his exploration work began. Fortunately, he tried to document the geographic and mass distribution of that debris in a detailed map, which is reproduced in Fig. 8.1. The map indicates that meteoritic irons were recovered from distances approaching 10 km. Gilbert (1896) apparently recovered a sample nearly 13 km beyond the crater rim. A lot of the meteoritic material was oxidized. It is sometimes simply called oxidized iron, but large masses are also called shale balls. A concentrated deposit of small oxidized iron fragments was found northeast of the crater, although those types of fragments are distributed in all directions around the crater. The current estimate of the recovered meteoritic iron mass is 30 tons (Nininger, 1949; Grady, 2000), although this is a highly uncertain number. Specimens were transported in pre-historical times and have been found scattered throughout Arizona (see, for example, Wasson, 1968). Specimens have also been illicitly removed in recent times, without any documentation of the locations or masses recovered.

These iron fragments are collectively called the Canyon Diablo meteorite, whose namesake is a sinuous canyon west of the crater. This meteorite is a coarse octahedrite with a bandwidth of 1.2 to 2.2 mm. It is chemically classified as a Group IA iron (or Group IAB iron). This is a non-magmatic type of iron meteorite. I refer readers to the literature for more details about the petrogenesis of these irons.

The asteroid was dominated by Fe,Ni-alloys, particularly kamacite, reflecting a bulk chemical composition with 6.91 to 7.10 wt% Ni (Moore *et al.*, 1967; Wasson and Ouyang, 1990). The mineralogical diversity, however, is large (Table 8.1). As noted in Chapter 1, diamond is one of the mineralogical components of Canyon Diablo specimens. The interpretation of the diamond-bearing specimens led to a firestorm of controversy. Urey (1956) suggested the diamonds were produced in hydrostatic equilibrium and, thus, came from a planet of sufficient size to produce very high pressures. That implies a planetesimal in excess of 2020 km. Indeed, on the basis of diamonds, Urey postulated a series of Moon-sized bodies as the source of meteoritic material. Lipschutz and Anders (1961a,b) correctly argued that the diamonds were formed from carbon-graphite-troilite nodules by high shock pressures generated by the impact. Not everybody was immediately convinced. Carter and Kennedy (1964) were critical, which generated an interesting exchange (Anders and Lipschutz, 1966).

An analysis of meteorites from the crater rim and surrounding plain indicated the rim samples are much more strongly reheated than the plains samples and saw much higher shock pressures. Thus, the diamond-bearing specimens are concentrated on the crater rim (Nininger, 1956; Moore *et al.*, 1967). Heymann *et al.* (1966) conducted a detailed study of 56 Canyon Diablo specimens distributed from the crater rim to distances of about 4 mi (6 ½ km) and used cosmogenic nuclides to determine their original depth in the parent asteroid. Moderately- to severely-shocked specimens came from greater depths (*e.g.*, a mean of 132 cm vs 72 cm). Diamond-bearing and rim specimens came from greater mean depths (135 and 127 cm, respectively) than plains specimens (81 cm). They noted that the severely shocked specimens were recovered on top of the NE and SE portions of the continuous ejecta blanket, suggesting a ray-like distribution pattern and preferential distribution of material from slightly deeper levels of the asteroid in those directions.

Table 8.1. Minerals in the Canyon Diablo Meteorite

Mineral Name	Chemical Formula	Type of Mineral
kamacite	Fe,Ni-alloy	metal
taenite	Fe,Ni-alloy	metal
troilite	FeS	sulfide
daubreelite	FeCr <sub>2</sub> S <sub>4</sub>	sulfide
sphalerite	(Fe,Zn)S	sulfide
mackinawite	(Fe,Ni)S <sub>0.9</sub>	sulfide
chalcopyrrhotite	(Cu,Fe)S	sulfide
schreibersite	(Fe,Ni) <sub>3</sub> P	phosphide
cohenite	(Fe,Ni,Co) <sub>3</sub> C	carbide
haxonite	(Fe,Ni) <sub>23</sub> C <sub>6</sub>	carbide
graphite	C	carbon
diamond	C	carbon
lonsdaleite	C	carbon
olivine	(Mg,Fe) <sub>2</sub> SiO <sub>4</sub>	silicate
pyroxene	(Mg,Fe,Ca) <sub>2</sub> Si <sub>2</sub> O <sub>6</sub>	silicate
plagioclase	(Ca,Na)(Si,Al) <sub>4</sub> O <sub>8</sub>	silicate
ureyite	NaCrSi <sub>2</sub> O <sub>6</sub>	silicate
krinovite	NaMg <sub>2</sub> Cr <sub>2</sub> Si <sub>3</sub> O <sub>10</sub>	silicate
chromite	FeCr <sub>2</sub> O <sub>4</sub>	oxide
rutile	TiO <sub>2</sub>	oxide

Additional details about the Canyon Diablo meteorite appear in V.F. Buchwald's volumes about iron meteorites (1975).

In addition to meteoritic fragments, isolated opaque melt droplets were showered around the crater, either as a direct impact melt product or as a molten condensate from an impact-generated vapor cloud. In an early survey, Nininger (1951) reported a recovery rate of 100 g/ft<sup>3</sup> of ejecta and/or alluvium derived from ejecta, which is 3,000 tons of spherules per square mile. He says the total area covered by the spherules is unclear, although there is a "sparse sprinkling...over 100 sq mi." Nininger (1956) later amended these estimates, reporting that 4,000 to 8,000 tons of spherules exist in the upper 4 inches of soil, based on measurements in 60 locations. From these data, he suggests the original asteroid had a mass of 100,000 to 200,000 tons. Most of the spherules are found within 1 ½ mi (2.4 km), although they have been found as far away as 5 mi (8 km) from the crater rim.

The spherules do not have the same composition as Canyon Diablo meteorites and were, thus, somehow fractionated during their formation. The compositional disparity was detected by Nininger (1951), who reported spherules with 17% Ni. Blau *et al.* (1973) found that the spherules are also enriched in S and P. They suggested the spherules formed by preferential shock melting of sulfide-rich portions of the asteroid, rather than oxidation of Fe. Using the dimensions of dendritic crystalline texture in the spherules, they calculated that the 1 mm spherules cooled between 500 and 30,000 °C/sec. They further argued that unshocked "plains" specimens spalled off the asteroid as it approached the surface, that shocked "rim" specimens were blasted off the trailing edge or backside of the asteroid, and that the remainder of the asteroid was dispersed in vapor cloud.

More recently, cosmogenic nuclides have been used to determine the source depths of the spherules on the asteroid. Surprisingly, this signature is preserved, despite the fractionation of the principal siderophile elements. Xue *et al.* (1995) examined the cosmogenic nuclides <sup>10</sup>Be and <sup>26</sup>Al in 17 spherules

and compared them to meteorite fragments. They concluded that the spherules come from a greater depth than meteorites (or that Al and Be is lost during the spherule-forming process). Leya *et al.* (2002) pursued more cosmogenic noble gases. They also concluded that the spheroids come from a deeper depth than meteorites, but still from within a distance of 2.3 m from the pre-atmospheric asteroid surface.

Other isotope systems were employed to independently assess the relative depths of meteorite and spherule production. Schnabel *et al.* (1999) found that a group of spherules contains 7 times less  $^{59}\text{Ni}$  than meteorite specimens, implying the spherules came from a depth that is 0.5 to 1.0 m deeper in the impactor than the meteorites. In absolute terms, their results suggest the spherules came from a region that was 1.3 to 1.6 m beneath the pre-atmospheric surface. A model simulation of the impact event in that same study suggested that 1.5 to 2 m of the backside of asteroid (assuming spherical symmetry, 30 m diameter asteroid, and a 20 km/s impact velocity) survives as solid material. This represents 16% of asteroid. The remainder was obliterated and these authors suggest that the bulk of that material was dispersed in a spray of fine molten material and did not involve a significant vapor component. They also argued that the Ni isotope data are consistent with 20 km/s impact simulation, not a slower, 15 km/s simulation; I refer the reader to their paper for details of that discussion.

A crude schematic of the asteroid that summarizes these data is shown in Fig. 8.2. The schematic diagram illustrates a perfectly spherical asteroid. In reality, the asteroid probably had an irregular surface and may have been significantly elongated. To illustrate a possible morphology, model images based on radar data are also included in Fig. 8.2 courtesy of Steve Ostro. The model images are of near-Earth asteroid (29075) 1950 DA, which is a suspected metallic asteroid. These images were selected rather than those of metallic main belt asteroids, because the Canyon Diablo asteroid was truly a near-Earth asteroid. The other candidate near-Earth metallic asteroid that has been imaged with radar is 1986 DA (Ostro *et al.*, 1991). Two previously imaged metallic asteroids in the main asteroid belt are 216 Kleopatra and 16 Psyche.

As the model images suggest, metallic asteroids can have irregular surfaces that reflect their collisional evolution. In the case of the Canyon Diablo asteroid, cosmic ray exposure ages suggest the object was liberated in a planetesimal breakup event ~540 million years ago and was subsequently involved in a secondary collision ~170 million years ago (Heymann *et al.*, 1966; Michlovich *et al.*, 1994).

It is not yet clear how surface irregularities or the shape of the asteroid may have affected the excavation of the crater and distribution of debris around the crater (including the distribution of projectile components). This is an area of study that has become approachable only recently with the advent of new computational codes that permit 3-D simulations with asymmetrical components.

The size of (29075) 1950 DA is ~1 km in diameter, which is far larger than the Canyon Diablo asteroid. Previous estimates of its diameter generally fall within the range of 10 to 50 m, but the exact size is still uncertain. To help readers link a discussion of proposed masses with asteroid diameters, I built a table (Table 8.2) of hypothetical spherical projectiles with radii from 5 to 25 m (and, thus, diameters of 10 to 50 m). As noted above, a recent simulation of the impact event assumed a 30 m diameter object, which corresponds to a mass of  $1.1 \times 10^8$  kg or 110,000 metric tons assuming a density of 7.8 g/cm<sup>3</sup>. Other mass estimates include 400,000 tons (Magie, 1910); 10,000,000 tons (Barringer, 1914); 5,000 to 3,000,000 tons (Moulton, 1931; per Hoyt, 1987); 15,000 tons (Wylie, 1943a,b); 5,000,000 tons (Öpik, 1936; Rostoker, 1953); 100,000 to 200,000 tons (Nininger, 1956); 2,600,000 tons (Öpik, 1958); 30,000 to 194,000 tons (Bjork, 1961); 63,000 tons (corresponding to 25 m sphere; Shoemaker, 1963); and 500,000 to 1,000,000 tons (Shoemaker in Elston, 1990), as discussed in greater detail by Buchwald (1975) and Hoyt (1987). Only a small fraction of this mass survives. As described above, the current estimate of surviving meteoritic material is 30 tons. In addition, Rinehart (1958) estimates 8,000 tons survives as dispersed metallic particles.

Table 8.2. Masses of hypothetical iron asteroids

Radius (m)	Volume (m <sup>3</sup> )	Density (g/cm <sup>3</sup> )	Mass (kg)	Mass (metric ton)
5	524	7.8	$4.08 \times 10^6$	$4.08 \times 10^3$
6	905	7.8	$7.06 \times 10^6$	$7.06 \times 10^3$
7	1437	7.8	$1.12 \times 10^7$	$1.12 \times 10^4$
8	2145	7.8	$1.67 \times 10^7$	$1.67 \times 10^4$
9	3054	7.8	$2.38 \times 10^7$	$2.38 \times 10^4$
10	4189	7.8	$3.27 \times 10^7$	$3.27 \times 10^4$
11	5575	7.8	$4.35 \times 10^7$	$4.35 \times 10^4$
12	7238	7.8	$5.65 \times 10^7$	$5.65 \times 10^4$
13	9203	7.8	$7.18 \times 10^7$	$7.18 \times 10^4$
14	11494	7.8	$8.97 \times 10^7$	$8.97 \times 10^4$
15	14137	7.8	$1.10 \times 10^8$	$1.10 \times 10^5$
16	17157	7.8	$1.34 \times 10^8$	$1.34 \times 10^5$
17	20580	7.8	$1.61 \times 10^8$	$1.61 \times 10^5$
18	24429	7.8	$1.91 \times 10^8$	$1.91 \times 10^5$
19	28731	7.8	$2.24 \times 10^8$	$2.24 \times 10^5$
20	33510	7.8	$2.61 \times 10^8$	$2.61 \times 10^5$
21	38792	7.8	$3.03 \times 10^8$	$3.03 \times 10^5$
22	44602	7.8	$3.48 \times 10^8$	$3.48 \times 10^5$
23	50965	7.8	$3.98 \times 10^8$	$3.98 \times 10^5$
24	57906	7.8	$4.52 \times 10^8$	$4.52 \times 10^5$
25	65450	7.8	$5.11 \times 10^8$	$5.11 \times 10^5$

The fate of the missing material has been at the center of considerable debate. Barringer, of course, thought it was buried beneath the crater floor. He considered the alternative possibility that the object was vaporized (Barringer, 1910). In that case, he reasoned, the vaporized projectile and target materials would have re-condensed, producing a mass of material (perhaps similar to rock flour) that was stained with iron and nickel oxides. Since this is not observed, he argued the mass must still exist inside the crater. (At this point in the development of his model, he also thought the asteroid was a cluster of fragments rather than a solid mass.)

Others have argued that a large fraction of the object was obliterated, either in the form of a vapor or finely-dispersed molten mist. A quantitative assessment of that fraction and the amount of obliterated material that was truly ejected is still lacking. Or, rather, a consensus has not developed around one of the proposed answers. Shoemaker, for example, maintained that one-third to one-half of the projectile mass is dispersed in material that remains in the crater (Elston, 1990), consistent with his initial assessment of the impact event (Shoemaker, 1963). In contrast, others have suggested nearly all of the projectile was dispersed beyond the rim of the crater as melted and/or vaporized ejecta (*e.g.*, Blau *et al.*, 1973).

The size and strength of the Canyon Diablo asteroid affected the outcome of the impact event. Smaller and weaker objects are often unable to penetrate the atmosphere without catastrophically fragmenting far above the ground. For example, a 6 to 8 m diameter stony asteroid with L-chondrite affinities fell about ~15,000 years ago in northern Arizona, but fragmented into thousands of stones (the Gold Basin meteorites) that showered more than 225 km<sup>2</sup> of the Earth's surface rather than create a hypervelocity impact crater (Kring *et al.*, 2001). In the case of Barringer Crater, however, the asteroid was able to collide with the Earth's surface while still moving with a large fraction of its cosmic velocity.

As noted briefly above, Barringer wondered whether the impacting asteroid hit as a solid iron mass, a cluster of iron fragments, or as iron fragments within a stony or icy matrix. The impact cratering community continues to debate the first two options. Results are in considerable flux at the moment, so I will not try to capture them here and suggest instead that interested students watch the literature.

With regard to Barringer Crater and the projectile that produced it, there are two other observations worth noting. First, with a diameter of ~1 km, the crater approaches the lower limit of hypervelocity craters on Earth (Table 8.3). The atmosphere screens most objects that make smaller craters. That is, the atmosphere shields the surface from objects that are smaller or weaker. Because most small craters are associated with iron asteroids, they appear to be stronger than stony asteroids. Second, the number of craters produced by type IAB irons, relative to other irons, is higher than the ratio of those objects seen in the smaller meteorite population. At least 14 to 15 of the craters in Table 8.3 were generated by irons and, of these, 6 (or ~40%) were produced by type IAB irons. Also, at least 28% of all the small crater impacts were produced by type IAB iron asteroids. In contrast, only 10% of observed iron meteorite falls are type IAB (Grady, 2000). Even in a combined population of iron meteorite finds and falls, type IAB specimens constitute only 15% of the population. The data suggest one of three conclusions: (1) Type IAB asteroids are stronger than other irons and, thus, better able to penetrate the atmosphere; (2) Type IAB asteroids are less collisionally evolved than other irons and, thus, less populous among meteorite-size objects; or (3) we are falling prey to the vagaries of small number statistics.

Table 8.3. Small ( $\leq 1$  km) diameter impact pits and impact craters.

Crater	Locality	Diameter (km)	Projectile	Age (Ma)
Haviland	Kansas, USA	0.011	Pallasite	0
Dalgaranga	Western Australia, Australia	0.021	Mesosiderite	0.025
Sikhote Alin	Primorskiy Kray, Russia	0.027	IIB	0
Campo del Cielo*	Gran Chaco Gualamba, Argentina	0.05	IAB	<0.004
Sobolev	Primorye Territory, Russia	0.053	Iron	0
Vevers	Western Australia, Australia	0.08	IIB	<1
Ilumetsa	Estonia	0.08	?	>0.002
Wabar*	Rub' al Khali, Saudi Arabia	0.097	IIIB	$0.006 \pm 0.002$
Morasko*	Poznan, Poland	0.1	IAB	0.01
Kaalijarvi*	Saaremaa, Estonia	0.11	IAB	$0.004 \pm 0.001$
Henbury*	Northern Territory, Australia	0.157	IIIB	<0.005
Odessa*	Texas, USA	0.168	IAB	<0.05
Boxhole	Northern Territory, Australia	0.17	IIIB	0.03
Macha*	Russia	0.3	Iron	<0.007
Aouelloul	Adrar, Mauritania	0.39	Iron or Pallasite	$3.1 \pm 0.3$
Amguid	Algeria	0.45	?	<0.1
Monturaqui	Antofagasta, Chile	0.46	IAB	<1
Kalkkop	South Africa	0.64	?	<1.8
Wolfe Creek	Western Australia, Australia	0.87	IIIB	<0.3
Tswaing	South Africa	1.13	Chondrite	$0.220 \pm 0.052$
Barringer	Arizona, USA	1.19	IAB	$0.049 \pm 0.003$

From Grieve (1991), Grieve *et al.* (1995), Koeberl *et al.* (1994), and Koeberl *et al.* (1998).

\*Crater field; diameter of largest crater listed.

# DISTRIBUTION OF METEORITIC MATERIAL AROUND METEOR CRATER, COCONINO Co., ARIZONA



#### *LEGEND*

- Canyon Diablo iron meteorites from 10 to 547 lbs. Discovered by Standard Iron Company.
  - ★ Canyon Diablo iron meteorites from 10 to 1000 lbs. Discovered by employees of F.W. Volz et al., previous to acquisition of property by S.I.Co.
  - ▲ Small Canyon Diablo iron meteorites. Discovered by S.I.Co. The distribution of specimens is only approximated because thousands were found. Specimens are usually a few grains or ounces in weight; irons weighing from 1 to 10 lbs were only found occasionally.
  - ✿ Large irregular masses of meteoritic iron oxide or large shale balls from 100 to 300 lbs in weight, due to oxidation of meteoritic iron rich in chlorine and sulphur or shale ball iron.
  - Small broken fragments of meteoritic iron oxide or iron shale (a few grains or ounces, rarely a pound in weight). Thousands of such pieces found, hence distribution only approximated.

Reproduced from November 1908 map published by Barringer (1910).

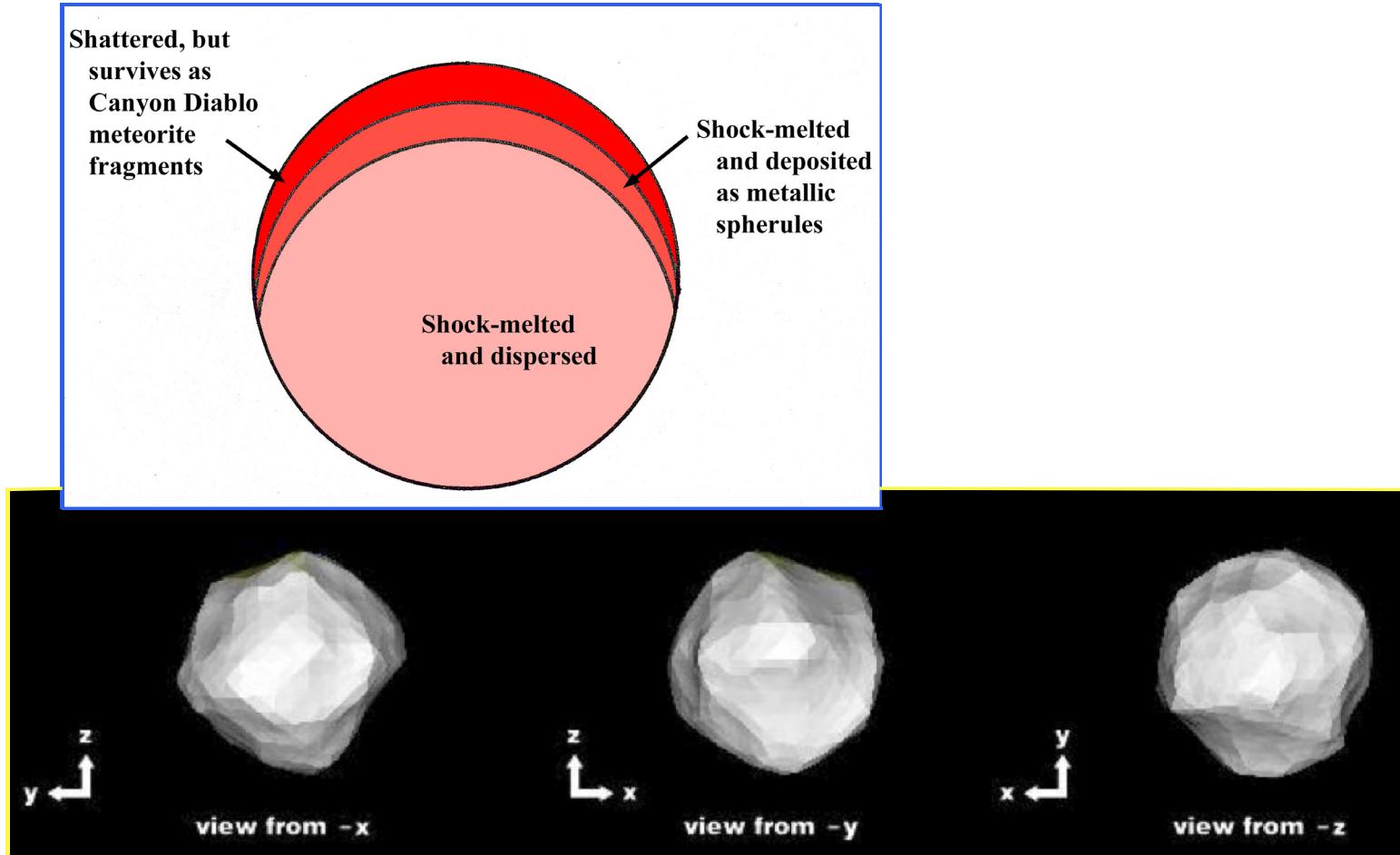


Fig. 8.2 Schematic diagram of the asteroid that produced Barringer Crater (upper left). Cosmogenic nuclides suggest the surviving meteoritic component of the asteroid was derived from a shallower depth (roughly 0.6 to 1.3 m) than molten metallic spherules (roughly 1.3 to 2.0 m depth). Furthermore, lightly-shocked meteorites appear to come from a shallower depth (mean of 0.8 m) than moderately- to heavily-shocked meteorites (mean of 1.3 m depth). The lightly-shocked meteorites are distributed on the plain surrounding the crater, while moderately- to heavily-shocked meteorites are concentrated near the crater rim. Almost all of the diamond-bearing specimens were found on the crater rim. The shape of the asteroid that produced Barringer Crater is unknown, but a suspected metallic near-Earth asteroid is shown (bottom panel) to provide an example of possible morphologies. Three model images based on radar data are shown for (29075) 1950 DA, which were kindly provided by Steve Ostro for our field guide. This object is far larger than the one that produced Barringer Crater (1 km versus 10 to 50 m), but it should help focus our discussion of projectile shape. I refer readers to a paper by Busch *et al.* (submitted to *Icarus*, 2007) for additional details about asteroid (29075) 1950 DA.