10. Trajectory ❖ ❖ ❖

The trajectory of the impacting asteroid is another issue of considerable debate and still unresolved. Historically, circular plan views of impact craters confounded many investigators who assumed a circular crater requires a vertical impact. They wondered why more craters are not elliptical. Gilbert and Barringer both realized that 45° impacts are the most probable trajectories for meteoritic material. Yet Gilbert, like many of his contemporaries, mistakenly thought a 45° impact produces an oval crater (Hoyt, 1987). Barringer, on the other hand, realized that a 45° impact will produce a round crater (Hoyt, 1987). Despite this insight, Barringer, like Gilbert, initially assumed that the northern Arizona impact had been vertical or nearly vertical and that the asteroid was buried beneath the center of the crater floor.

When extensive drilling did not locate a main mass beneath the crater floor and instead only produced traces of the projectile, Barringer began to consider other options. He had already noted several features that seem to have a directional symmetry. In his 1905 paper, he observed that clusters of immense Kaibab boulders were deposited on the east and west sides of the crater. In his 1910 paper, he argued that the lowermost section of the Coconino only appears in the south-east section of the ejecta blanket and, thus, that the deepest units excavated by the impacting object were ejected in that direction. In that same paper, he also observed that the southern cliffs were uplifted as a single entity by 105 ft. He then suggested that the uplift was caused by a meteoritic mass moving from the north to the south and that the mass remained wedged beneath the cliffs along with a vast amount of shattered rock and Variety A and B shock-metamorphosed Coconino sandstone. He felt vindicated when drilling in 1920-1922 produced a 1,376 ft deep borehole on the southern crater rim that encountered ~30 ft of oxidized meteoritic material, Variety A and B shock-metamorphosed sandstone, and became stuck in what was interpreted to be the main asteroid mass. (See Table 4.2 for the driller's log of that hole.) He published a report (Barringer, 1924), concluding the "mass seems to have approached the earth at an angle of approximately 45°, and from a direction slightly west of north, and to have made a slight curve to the west in its slanting flight through more than 2500 feet or one half-mile of solid rock...."

Shoemaker, on the other hand, was impressed with thrust faults in the crater walls. (See Chapter 6 for more details about the faults.) These faults outlined wedges of rock that are thrust into crater walls, forming anticlines and enhancing crater rim uplift. He and Kieffer (1974) argued that they only occur on the north and west sides of the crater and that they were especially well-developed in the northwest corner. They suggested the features were produced by a bolide moving from the southeast to the northwest.

I agree that the thrust faults are impressive and seem to point to a flow of material through the transient crater margin into the surrounding crater wall in a rough south-to-north direction that encompasses flow towards the northwest and northeast. I have observed a few additional thrust faults along the east margin of the crater, so a purely southeast to northwest flow no longer seems plausible. Taken at face value, the thrusts seem to imply a trajectory roughly from the south to north, with variations to both the northwest and northeast possible. However, I can also imagine the same thrusts produced in reaction to an impact with a projectile trajectory in the opposite direction. I also worry that we are biased by what we can observe. If thrust-faulting occurs low on the hidden portions of the crater walls, we are unable to factor that information into our analysis. The observations only seem truly inconsistent with an east to west or west to east trajectory. Thus, the thrust faults can possibly be reconciled with Barringer's proposed trajectory and the impressive amount of material that may have been injected beneath the rim along the south side of the crater. (See discussion of injected material in Chapter 4.) The uplift of the southern crater wall is a less convincing indicator, because the amount of uplift along the southern crater wall is much less than that in the east-southeast corner of the crater, as shown in Fig. 17.6 and 17.9 in the trail guide chapters. If uplift is an indicator of trajectory, then the east-southeast corner seems to be at the end of the trajectory. Alternatively, crater wall uplift may be influenced as much by preferential movement along tear faults as trajectory and, thus, not a diagnostic indicator of trajectory.

That was the status of the issue of trajectory when the first edition of the guidebook was published. Since that time, other potential structural indicators of trajectory were measured. In one study, the relative uplift of target strata and the strike of those units were measured along the Kaibab-Moenkopi contact (Poelchau *et al.*, 2009). It was thought that deviations from a perfectly concentric distribution of bedding might indicate the path of the impacting asteroid. The results were ambiguous, but the study concluded a trajectory from the north-northwest to the south-southeast was more likely.

Another structural indicator of trajectory is shearing that has recently been recognized in the crater rim and ejecta blanket (Kring *et al.*, 2011a, 2011b, 2012). In the south crater rim, nearly all (80 m) of the Kaibab ejecta has been sheared radially outward to greater distances from the crater center. (See Chapter 18 for descriptions of the outcrops.) Moreover, in the southwest crater rim, a portion of the ejecta curtain was sheared radially outward, emplacing a rare hinge in the overturned Coconino on top of Moenkopi in the crater wall. That type of shearing is more likely to occur in the uprange or downrange rim of a crater according to cratering experiments (Fechtig *et al.*, 1972; Gault, 1974). For a 45° impact angle, the most probable impact angle and consistent with the symmetrical shape of the crater, shear is more likely to occur in the downrange rim of a crater, suggesting a trajectory from the north to the south.

Other directional indicators have been noted by several investigators: Barringer (1910) pointed to a concentration of iron oxide beyond the northeast corner of the crater; Nininger (1956) and Rinehart (1958) pointed to a concentration of meteoritic soil particles in that same direction; Heymann *et al.* (1966) pointed to a concentration of highly-shocked and diamond-bearing Canyon Diablo meteorite specimens near the northeast and southeast crater rims. Shoemaker and Kieffer (1974) suggested Silica Hill is a small uplift on the crater floor that is offset towards the north. The concentration of meteoritic oxide and iron-rich soil particles in the northeast is the most-often cited evidence beyond the crater rim. Rinehart (1958), for example, wrote that "a highly reasonable hypothesis is that the meteorite approached the earth from a south-westerly direction and, when it struck, pitched forward large quantities of meteoritic material to the position where it now rests." That would seem to be consistent with a numerical model of the impact (Artemieva and Pierazzo, 2011) that suggests at least 50% of the impacting asteroid was ejected and that it would be concentrated in the downrange direction.

A more distant indicator of impact trajectory may be another young impact crater that some investigators speculate was produced at the same time at the Barringer Crater. This story, too, has its origins with a Barringer. In this case, D. Moreau Barringer Jr. had an opportunity to explore another crater-like structure near the West-Texas town of Odessa. Within a few hours, he found iron meteorites and shale balls and concluded that the structure was an impact crater with at least one satellite impact crater. He telegraphed the news to his father immediately. In private correspondence, Daniel Moreau Barringer wondered if his crater and the Odessa crater could have been produced at the same time by a pair of asteroids traveling together. Several years later, he summarized the evidence for trajectory (Barringer, 1958) and conclude the most likely path was from north or northeast to south or southwest.

The possibility that Barringer and Odessa craters were produced by a pair of asteroids was further explored by Brandon Barringer in a paper presented to The Meteoritical Society in 1965 and published in 1967. Several hints seemed to link the two impact events. (1) Both were produced by similar types of iron asteroids. (2) Although the ages of the craters were imprecisely known, they were approximately similar. Estimated ages for Barringer Meteorite Crater and Odessa Crater were 20,000 and 25,000 years, respectively, at the time of Brandon Barringer's report. (3) There were hints that both craters were produced by objects with roughly north to south trajectories.

Brandon Barringer recognized problems with some scenarios linking the two events, noting that it was "unlikely that they were formed by the decomposition of a single natural satellite" in the atmosphere. He left the door open, however, to other possibilities. In general, he recommended further study to resolve these and other issues regarding the origin of the craters.

Additional research and newer technology have shed light on the hypothesis. The chemical compositions of the iron asteroids that produced the craters have been analyzed in greater detail and the ages of the two craters have been better determined.

Wasson (1967, 1968) examined the trace element compositions of the iron meteorites at Barringer Crater and those at Odessa. Although both groups of meteorites are part of the same chemical class, there are subtle differences between the meteorites that led Wasson to suggest they formed from two unrelated iron asteroids.

The second set of studies began in the 1980's, when Sutton (1985) examined the crystalline damage caused by naturally occurring radioactive isotopes in crater rocks. Using the isotopes as a clock, he estimated the Barringer Crater was produced approximately 49,000 years ago. Nishiizumi *et al*. (1991) and Phillips *et al.* (1991) used different types of isotopic clocks in crater rocks. They too estimated the crater formed approximately 49,000 years ago. (See Chapter 12 for more information about estimates of the crater's age.)

More recently, techniques similar to those of Sutton were applied by Holliday *et al.* (2005) to the Odessa impact site. They estimated the Odessa craters were produced approximately 63,000 years ago. Although the ages of Barringer and Odessa craters are still not precisely known, these approximate ages suggest Odessa formed earlier, with the caveat that the Barringer crater may be older than 49,000 yrs. (See discussion in Chapter 12). Thus, the two impact events may not be directly related and may not have any bearing on the issue of trajectory.

Nonetheless, several other potential indicators of trajectory survive (and even the Odessa connection might be revived). Unfortunately, those indicators cannot be reconciled at the present time and I think it fair to conclude that the trajectory of the impacting asteroid that produced Barringer Crater remains uncertain.