12. Age of the Crater ❖ ❖ ❖

As any visitor can see, the crater is exceptionally well-preserved. Although talus covers the lower slopes of the crater walls and finer-grained sediments cover the crater floor, the crater still has the sharp edges of a relatively unaltered structure. For that reason, a young age has always been assigned to it. Indeed, Barringer (1905) estimated the age to be 2,000 to 3,000 yrs, not much older than the 700 yr-old rim cedars (junipers). Likewise, Tilghman (1905) commented that the crater looked like it formed yesterday and that it must have an age less than 10,000 yrs and probably less than 5,000 yrs.

Measuring a precise age for the crater, however, was difficult. Even using modern techniques, the question of age was difficult to resolve. The impact did not produce huge volumes of impact melt that might be analyzed using the isotopic systems (*e.g.*, ^{40}Ar-^{39}Ar) often applied to other igneous rocks, including impact melts. In addition, the crater is too young for many of those radiometric systems to be applied, because they involve half-lives that are too long. For that reason, many early attempts to determine the age of the crater relied on evaluations of erosion and sedimentation.

In a paper titled "The Age of Meteor Crater," Blackwelder (1932) evaluated the thickness of lake sediments within the crater, the amount of alluvium and finer-grained debris on the crater slopes and crater floor, ravines cut into the crater deposits, and dissolution pitting of ejected limestone blocks. Based on those criteria, he estimated the crater was produced between 40,000 and 75,000 years ago. As described further below, this may be an incredibly accurate estimate.

At about the same time, Jakosky *et al*. (1932) conducted an electrical and magnetic survey of the crater. In the course of that investigation, they evaluated the thickness of lake beds on the crater floor, lag deposits of concretions on Coconino and Kaibab surfaces on the crater rim, and small basins filled with sediment from eroded ejecta. They argued that the "fresh looking cliffs" are not, in fact, fresh, but rather "the products of centuries of erosion." They also pointed out that the thickness of Moenkopi buried beneath Kaibab and Coconino in the crater walls is much greater than the thickness of Moenkopi on the surrounding plains. They required sufficient time to erode up to 40 ft of Moenkopi on the plains. We now understand that this latter argument is flawed, because the Moenkopi is thickened by an overturned component in the crater walls and, thus, the discrepancy is not an erosional one. Nonetheless, based on all of these criteria, they concluded the crater formed tens of thousands of years ago and probably about 50,000 years ago.

Shoemaker (1960, 1974) compared the Pleistocene and Holocene alluvium that covers the ejecta blanket with deposits elsewhere on the Colorado Plateau. Drawing on those comparisons, he estimated (Shoemaker, 1974) the crater was produced "a few tens of thousands of years ago, as shown by the mid-Wisconsin age of the oldest sedimentary deposits on the rim and in the interior of the crater." He quantified those words with estimates of 20,000 to 30,000 yrs and 25,000 ± 5,000 yrs (Shoemaker, 1983), which were numbers he used for over a decade. His estimate may have been influenced by the first radiometric age of material in the crater. Ives *et al.* (1964) obtained a radiocarbon age for shells from a dump around the crater's main shaft. The measured age was 24,000 ± 2,000 yrs. The shells were believed to be from the basal portion of the lake sediments. Assuming the lake sediments were deposited immediately after the crater formed, the value indicated the age of the crater. However, if either the lake did not form immediately or the shells were from a higher level within the lake sediments, the date only represented a minimum age for the crater.

Those shells and other fossils deposited in lake sediments on the crater floor provide additional clues about the crater's age through correlations with fossil assemblages in other localities and climatic events. The results, however, are ambiguous (Reger and Batchelder, 1971; Forester, 1987) and will not be discussed in any detail here. In addition, a preliminary assessment of pollen from the base of the lake sediments (Davis and Kring, 2002) found an assemblage that is similar to those in 50 ka sediments in Walker Lake near Flagstaff. That, however, is more a measure of climatic conditions and not a diagnostic indicator of age.

Efforts to directly measure the age of the crater resumed in the mid-1980's, when Sutton (1985) measured thermoluminescence ages for shock metamorphosed rocks. He estimated an age of 49,000 ± 3,000 yrs for the crater. Similar ages were soon recovered using cosmogenic nuclides that measured the amount of time boulders on the rim of the crater had been exposed. In back-to-back papers, Phillips *et al.* (1991) and Nishiizumi *et al.* (1991) reported 49,700 ± 850 and 49,200 ± 1,700 yr ages, respectively. Based on the extraordinary agreement between these three independent studies, 49 or 50 ka is widely accepted to be the age of the crater.

The ages based on cosmogenic nuclides are being re-evaluated, because estimates of the production constants and scaling factors needed for the calculations have been improved. The recalibration of production rates was an immense consortium project called Cosmic-Ray Produced Nuclide Systematics on Earth or, CRONUS (Borchers *et al.*, 2016). While that effort was underway, we re-examined the ^{36}Cl-based age determinations of Phillips *et al.* (1991). Splits of the original samples were re-analyzed using modern techniques. The measured values were very similar to the original values. However, application of a preliminary version of the revised production rates produced an older age of 56.0 ± 2.4 ka, which we reported at the 2010 Meteoritical Society meeting (Marrero *et al*., 2010).

Unfortunately, the final CRONUS production rates have not yet been applied to the ^{36}Cl data, nor to the ^{10}Be-^{26}Al measurements of Nishiizumi *et al.* (1991). I am told (Kuni Nishiizumi, personal communication, 2017) that the deviation from the original 49 ka age will not be as large for the ^{10}Be-^{26}Al system as it appears to be for ^{36}Cl. Thus, at the present time, I recommend the age of the crater used in public venues remain at 50,000 yrs, but caution that the age could drift to slightly older ages as geochronological techniques are refined.

Plans for other types of age determinations have been made. The first involves pack-rat middens that are scattered among the rocky clefts of the crater walls. Pack-rat middens have been excellent sources of both age and climate information elsewhere on the Colorado Plateau. Appropriate samples will be collected to determine an age for the deposits, which will provide an additional minimum age for the crater. In addition, the fossil sequence within the lake sediments will be resampled. This latter task, however, is delayed until the walls of Main Shaft and/or Shaft #2 (also called the Science Shaft) in the crater floor can be stabilized. Efforts are underway to raise funds so that the shafts can be re-cribbed and converted into permanent research and educational facilities.

I considered using the thickness of carbonate rinds (caliche) around ejected debris to place a constraint on the age of the crater. While that method has been applied in the southwestern United States (Amoroso, 2006), the uncertainty on caliche production rates is too large to sharpen our assessment of the crater's age. I have, for example, measured caliche layers 0.3 to 0.5 mm thick around pebbles and cobbles in the ejecta blanket (*e.g.*, Cernok and Kring, 2009; also Fig. 15.6). When applying the calibration curve of Amoroso (2006) to the thickest caliche layer (0.5 mm), I derive an age of 54^{+10}_{-8} ka. However, I also note that two of the data points used to derive that calibration curve have ages ranging from 20 to 90 ka for rind thicknesses of 0.5 mm. A related technique that cross-correlates variations in carbon and oxygen isotopes with U-Th geochronology in layers of pedothem carbonate (*e.g.*, Oerter *et al*., 2016) is a newly developed option that has yet to be applied.

An effort to determine the age of volcanic ash that fell into the crater is also underway. Deposits of ash fell when a lake filled the crater and after that lake dried up (Chapter 14). If these attempts are successful, they will provide a minimum age for the crater. They will also help calibrate the chronology of geologic events that helped shaped the crater we see today.