Meteor Crater, Arizona

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LOCATION

The location of Meteor Crater is shown on nearly all highway maps of Arizona. It lies 6 mi (9.7 km) south of 1-40 between Flagstaff and Winslow in northern Arizona; the turnoff from 1-40, 34 mi (55 km) east of Flagstaff, is well marked by signs along the highway. Access to the crater is by a paved road that leads directly to a visitor center and museum on the rim of the crater. Qualified scientists may obtain permission to hike to various parts of the crater by writing or calling in advance to Meteor Crater Enterprises, 121 East Birch Avenue, Flagstaff, Arizona 86001.

SIGNIFICANCE

Meteor Crater was the first recognized impact crater on Earth; it remains the largest known crater with associated meteorites. It is the most thoroughly investigated and one of the least eroded and best exposed impact craters in the world. Study of Meteor Crater provided clues for the recognition of impact craters on other solid bodies in the solar system, as well as on Earth, and stimulated the search for other terrestrial impact structures.

STRUCTURAL AND STRATIGRAPHIC SETTING

Meteor Crater lies in the Canyon Diablo region of the southern part of the Colorado Plateau. In the vicinity of the crater, the surface of the plateau has low relief and is underlain by nearly flat-lying beds of Permian and Triassic age. The crater lies near the anticlinal bend of a gentle monoclinal fold, a type of structure characteristic of this region. The strata are broken by wide-spaced, northwest-trending normal faults, which generally are many miles (kilometers) in length but have displacements of only a few feet (meters) to about 100 ft (30 m).

Rocks exposed at Meteor Crater range from the Coconino Sandstone of Permian age to the Moenkopi Formation of Triassic age. Drill holes in and around the crater have intersected red beds in the upper part of the Supai Formation of Pennsylvanian and Permian age, which conformably underlies the Coconino. The Coconino Sandstone consists of about 700 to 800 ft (210 to 240 m) of fine-grained, saccharoidal, white, cross-bedded, quartzose sandstone of eolian origin. Only the upper half of the formation is exposed at the crater. The Coconino is overlain conformably by a unit 10 ft (3 m) thick of white to yellowish-to reddish-brown, calcareous, medium- to coarse-grained sandstone interbedded with dolomite, which is referred here to the Toroweap Formation of Permian age.

The Kaibab Formation of Permian age, which rests conformably on the Toroweap, includes 260 to 265 ft (79-81 m) of fossiliferous marine sandy dolomite, dolomitic limestone, and minor calcareous sandstone. Three informal members are recognized (McKee, 1938). The lower two members, the gamma and beta members, are chiefly massive, dense dolomite; the upper or alpha member is composed of well-bedded dolomite and limestone with several sandstone interbeds. The Kaibab is exposed along the steep upper part of the crater wall.

Beds of the Moenkopi Formation (McKee, 1954) of Triassic age form a thin patchy veneer resting disconformably on the Kaibab in the vicinity of the crater. Two members of the Moenkopi are present. A 7- to 20-ft (2- to 6-m) bed of pale reddish brown, very-fine-grained sandstone (McKee's lower massive sandstone), which lies virtually at the base, constitutes the Wupatki Member. Above the Wupatki are dark, reddish brown, fissile siltstone beds of the Moqui Member. About 7 to 30 ft (2 to 10 m) of Moenkopi strata are exposed in the wall of the crater.

QUATERNARY STRATIGRAPHY AND STRUCTURE OF THE CRATER

Meteor Crater is a bowl-shaped depression 600 ft (180 m) deep and about 0.75 mi (1.2 km) in diameter encompassed by a ridge or rim that rises 100 to 200 ft (30 to 60 m) above the surrounding plain. The rim is underlain by a complex sequence of Quaternary debris and alluvium resting on deformed and uplifted Moenkopi and Kaibab strata (Figs. 1 and 2).

The debris units on the crater rim consist of angular fragments ranging from splinters less than 1 μ in size to blocks up to 100 ft (30 m) long. Because of the striking lithologic contrast between the formations from which the debris is derived, it is easy to distinguish and map units or layers in the debris by the lithic composition and stratigraphic source of the component fragments.

The stratigraphically lowest debris unit of the rim is composed almost entirely of fragments derived from the Moenkopi Formation. Within the crater this unit rests on the edge of upturned Moenkopi beds (Fig. 2) or very locally grades into the Moenkopi Formation; away from the crater wall the debris rests on the eroded surface of the Moenkopi. A unit composed of Kaibab debris rests on the Moenkopi debris. The contact is sharp where exposed within the crater, but at distances of 0.5 mi (0.8 km) from the crater, there is slight mixing of fragments at the contact. Patches of a third debris unit, composed of sandstone fragments from the Coconino and Toroweap, rest with sharp contact on the Kaibab debris. No fragments from the Supai are represented in any of the debris.

The bedrock stratigraphy is crudely preserved, inverted, in the debris units. Not only is the gross stratigraphy preserved, but even the relative position of fragments from different beds tends to be preserved. Thus, most sandstone fragments from the basal sandstone bed of the Moenkopi occur near the top of the Moen-

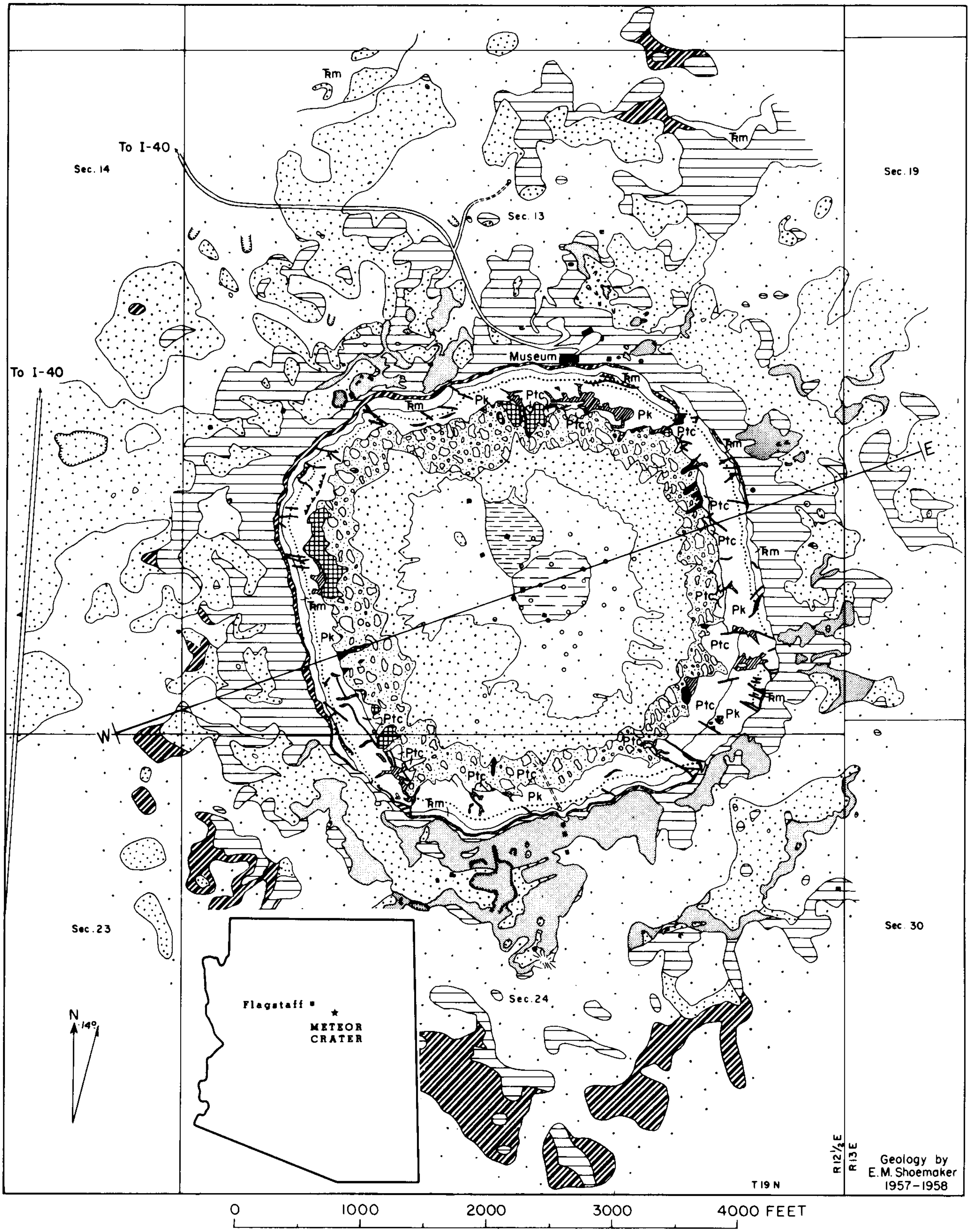
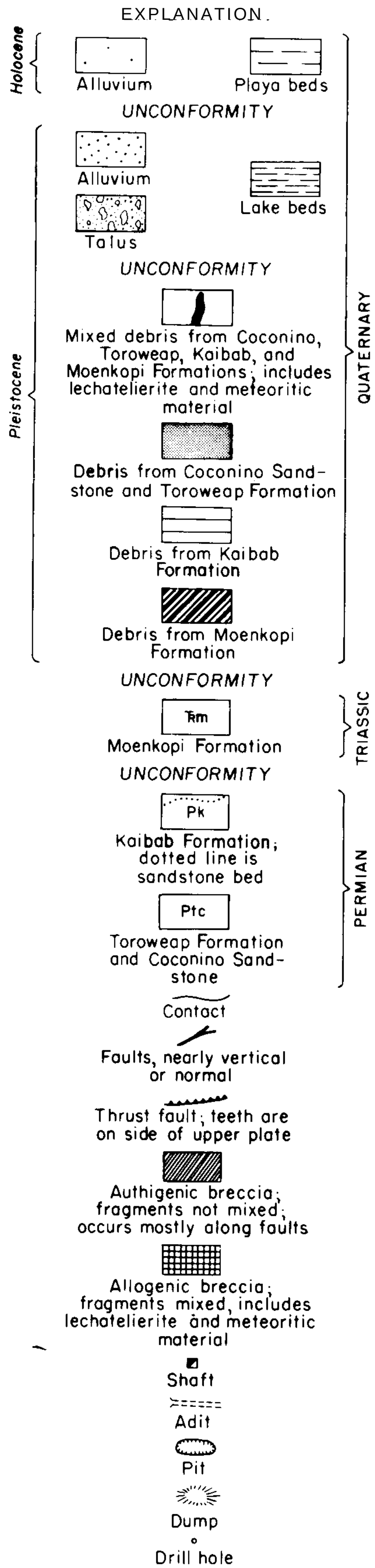


Figure 1. Geologic map of Meteor Crater, Arizona, with explanation at right.



kopi debris unit, fragments from the alpha member of the Kaibab occur at the base of the Kaibab debris unit, and brown sandstone fragments from the Toroweap occur just above the Kaibab debris unit.

Pleistocene and Holocene alluvium rests unconformably on all the debris units, as well as on bedrock. The Pleistocene alluvium forms a series of small, partly dissected pediments extending out from the crater rim and also occurs as isolated patches of pediment or terrace deposits on the interstream divides. It is correlated on the basis of well-developed pedocal paleosols with the Pleistocene Jeddito Formation of Hack (1942, p. 48-54) in the Hopi Buttes region, some 50 mi (80 km) to the northeast. Holocene alluvium blankets about half the area within the first 0.5 mi (0.8 km of the crater and extends along the floors of minor stream courses (Fig. 2). It includes modern alluvium and correlative of the Holocene Tsegi and Naha formations of Hack (1942) in the Hopi Buttes region.

Both the Pleistocene and the Holocene alluvium are composed of material derived from all formations represented in the debris and also contain meteorite fragments, lechatelierite (silica glass derived from the Coconino Sandstone), other kinds of fused rock (Nininger, 1956), and less strongly shocked rocks containing coesite and stishovite (Chao and others, 1960, 1962; Kieffer, 1971). Oxidized meteoritic material and fragments of relatively strongly shocked Coconino Sandstone are locally abundant in the Pleistocene alluvium where it occurs fairly high on the crater rim. Sparse unoxidized meteoritic material occurs in two principal forms: (a) large crystalline fragments composed mainly of two nickel-iron minerals, kamacite and taenite; and (b) minute spherical particles of nickel-iron. The bulk of the meteoritic material distributed about the crater apparently is in the form of small particles. The total quantity of fine-grained meteoritic debris about the crater, which occurs in the Pleistocene and Holocene alluvium and also as lag and dispersed in colluvium, has been estimated by Rinehart (1958) as about 12,000 tons.

Low on the crater wall, the bedrock generally dips gently outward. The dips generally are steeper close to the contact with the debris on the rim, and beds are overturned along various stretches totaling about one-third the perimeter of the crater. Along the north and east walls of the crater, the Moenkopi locally can be seen to be folded back on itself, the upper limb of the fold consisting of a flap that has been rotated in places more than 180° away from the crater (Fig. 2). At one place in the southeast corner of the crater, the flap grades outward into disaggregated debris, but in most places there is a distinct break between the debris and the coherent flap.

Rocks now represented by the debris of the rim have been peeled back from the area of the crater somewhat like the petals of a flower. The axial plane of the fold in three dimensions is a flat cone, with apex downward and concentric with the crater, that intersects the crater wall. If eroded parts of the wall were restored, more overturned beds would be exposed.

The upturned and overturned strata are broken or torn with scissors-type displacement along a number of small, nearly verti-

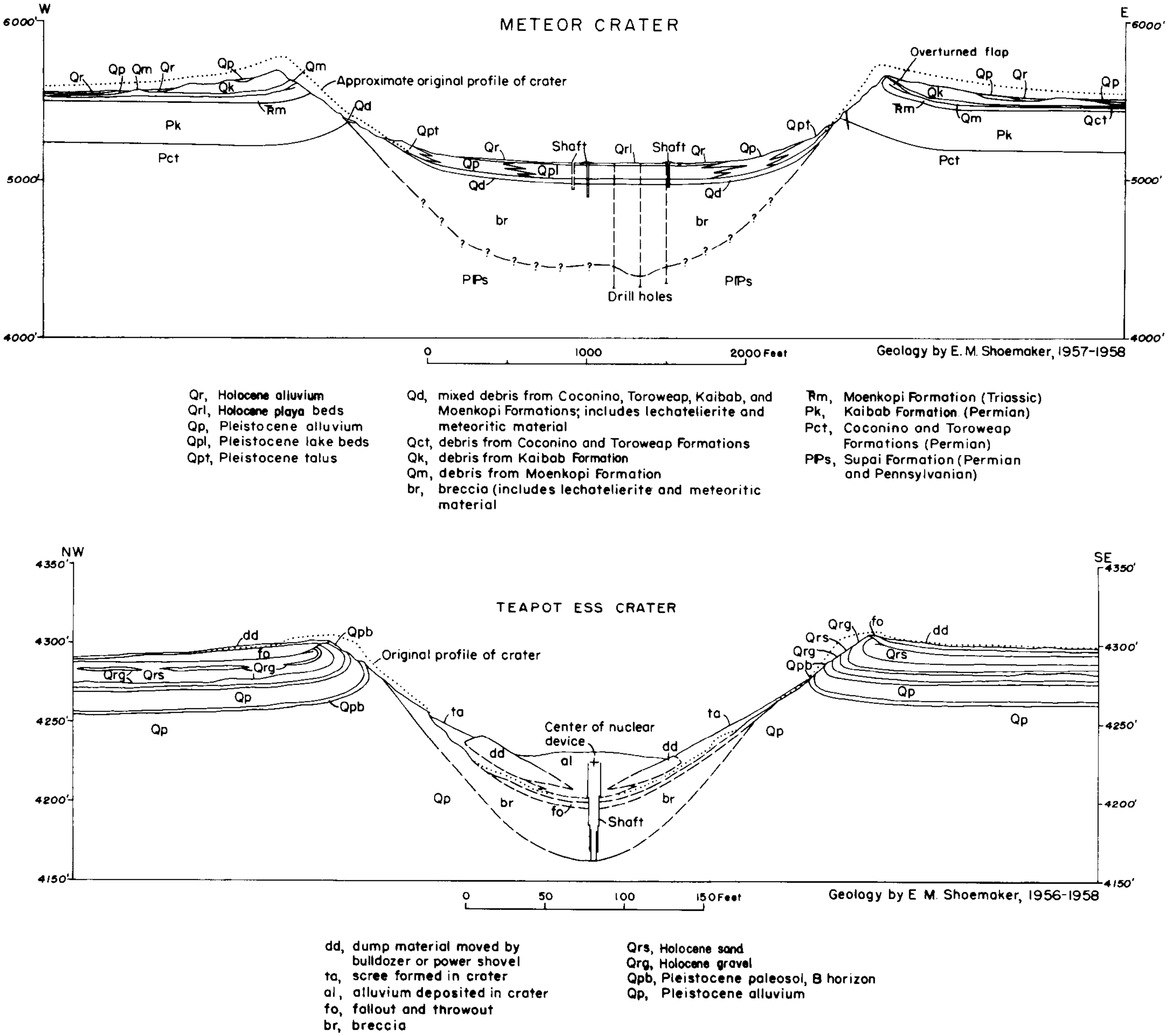


Figure 2. Cross sections of Meteor Crater, Arizona, and the teapot Ess nuclear explosion crater.

cal faults. A majority of these tears are parallel with a northwesterly regional joint set, and a subordinate number are parallel with a northeasterly set. Regional jointing has controlled the shape of the crater, which is somewhat squarish in outline (Fig. 1] the diagonals of the "square" coincide with the trend of the two main sets of joints. The largest tears occur in the "corners" of the crater. In the northeast comer of the crater a tom end of the overturned flap on the east wall forms a projection suspended in debris. A few normal faults, concentric with the crater wall and along which displacement is down toward the crater, occur on the southwest side. Small thrust faults occur on the north and west sides of the crater; relative displacement of the lower plate is invariably away from the center of the crater. Crushed rock (authigenic breccia) is locally present along all types of faults.

The floor of the crater is underlain by Quaternary surficial deposits, debris, and breccia. Pleistocene talus mantles the lowest parts of the crater walls and grades into and is overlain by Pleistocene alluvium along the floor. The Pleistocene alluvium, in turn, interfingers with a series of lake beds about 100 ft (30 m) thick toward the center of the crater. Up to 6 ft (1.8 m) of Holocene alluvium and playa beds rest unconformably on the Pleistocene. Where exposed in shafts, the lowermost Pleistocene lake beds contain chunks of pumiceous, frothy lechatelierite.

A layer of mixed debris underlies the Pleistocene talus and lake beds and rests on breccia and on bedrock. This layer is composed of fragments derived from all formations intersected by the crater and includes much strongly shocked rock and oxidized meteoritic material. Material from the different stratigraphic horizons is thoroughly mixed. Where intersected by a shaft in the crater floor, the mixed debris is about 35 ft (10.5 m) thick and almost perfectly massive, but it exhibits a distinct grading, from coarse to fine, from base to top. The average grain size, about 2 cm, is much less than in the debris units of the rim or in the underlying breccia; the coarsest fragments at the base of the mixed debris rarely exceed 1 ft (0.3 m) in diameter. Evidently this unit was formed by fallout of material thrown to considerable height. It has not been recognized outside the crater and apparently has been entirely eroded away. However, its constituents have been partly redeposited in the Pleistocene and Holocene alluvium on the crater rim.

Where exposed at the surface, the breccia underlying the mixed debris is composed chiefly of large blocks of Kaibab, but the breccia exposed in shafts under the central crater floor is made up chiefly of shattered and twisted blocks of Coconino. Extensive drilling conducted by Barringer (1906) and his associates (Tilghman, 1906) has shown that, at a depth of 300 to 650 ft (100 to 200 m), much finely crushed sandstone and some fused and other strongly shocked rock and meteoritic material are present. Some drill cuttings from about 600 ft (180 m) depth contain fairly abundant meteoritic material, chiefly in the form of fine metallic spherules dispersed in glass. Cores of ordinary siltstone and sandstone of the Supai were obtained at depths of 700 ft (210 m) and deeper. The lateral dimensions of the breccia are not known because the drilling was concentrated in the center of the crater. The age of the breccia, and hence the crater, has been determined by thermoluminescence techniques as 49,000 ± 3,000 years (Sutton, 1985).

MECHANISM OF CRATER FORMATION

Most of the major structural features of Meteor Crater are reproduced in a crater in the alluvium of Yucca Flat, Nevada, formed by the underground explosion of a nuclear device. The Teapot Ess crater (Fig. 2), about 300 ft (90 m) across and originally about 100 ft (30 m) deep, was produced in 1955 by a 1.2-kiloton device detonated at a depth of 67 ft (20 m) below the surface. Beds of alluvium exposed in the rim are peeled back in an overturned syncline, just as the bedrock is peeled back at Meteor Crater. The upper limb of the fold is overlain by and locally passes outward into debris that roughly preserves, inverted, the original alluvial stratigraphy. Shock-formed glass and other strongly shocked materials, some containing coesite, are present in the uppermost part of the debris. A thin layer of debris formed by fallout or fall-back is also present in the crater. The floor and lower walls of the crater are underlain by a thick lens of breccia containing mixed fragments of shock-compressed alluvium and dispersed glass.

A crater that has the structure of Meteor Crater or Teapot Ess crater is formed by propagation of a shock wave either from the penetration path of a high velocity projectile or from an explosion originating at moderate depth beneath the surface (Shoemaker, 1960, 1963). In the case of impact, a strong shock races ahead of the projectile into the target rocks, and another engulfs the projectile. At projectile speeds corresponding to encounter speeds of asteroids with the Earth (typically in the range 9 to 19 mi/sec; 15 to 30 km/see), initial shock pressures generally exceed the dynamic yield strengths of rocks and meteorites by several orders of magnitude. The target rocks engulfed by shock are initially accelerated more or less radially away from the penetration path of the projectile. An expanding cavity is formed by the divergent flow of the target material. Near the cavity wall, the direction of flow is approximately tangent to the wall, owing to upward acceleration in an expanding rare faction between the shock front and the wall. Part of the target rock and much of the projectile flow up the wall and out of the growing cavity.

As the shock wave expands, pressures at the shock front drop rapidly. A limit for displacement of the target rocks is reached where the stresses in the shock wave drop below the dynamic yield strength of the rocks. This limit defines the outer boundary of deformation and uplift of bedrock beneath the crater rim. The position of the final wall of a structurally simple crater like Meteor Crater or Teapot Ess is located approximately where the outward flow along the wall of the growing cavity is stopped by the combined effects of gravity and the shear strength of the target material. At Meteor Crater, a sheath of fragmented rock that stopped flowing up the cavity wall collapsed back toward the center of the crater to form the thick breccia lens beneath the crater floor.

The kinetic energy of the projectile required to form a crater the size of Meteor Crater can be estimated from computer simulation of the impact process (Roddy and others, 1980) to be about 15 megatons TNT equivalent. This energy is equal to that of a spherical body of meteoritic iron about 130 ft (40 m) in diameter traveling at a speed of 12 mi/see (20 km/sec; the rms encounter speed of Earth-crossing asteroids). Somewhat greater energy was required if the projectile struck at an oblique angle, as suggested by the presence of faults with underthrust displacement on the north and west walls of Meteor Crater.

REFERENCES CITED

Barringer, D. M., 1906, Coon Mountain and its crater: Proceedings of the Academy of Natural Sciences of Philadelphia, v. 57, p. 861-886.

Chao, E. C.T., Shoemaker, E. M., and Madsen, B. M., 1960, First natural occurrence of coesite: Science, v. 132, p. 220-222.

Chao, E. C.T., Fahey, J. J., Littler, J., and Milton, D. J., 1962, Stishovite, $Si0_2$, a very high pressure new mineral from Meteor Crater, Arizona Journal of Geophysical Research, v. 67, p. 419421.

Hack, J. T., 1942, The changing physical environment of the Hopi Indians Peabody Museum of Natural History Papers, v. 35, p. 3-85.

Kieffer, S. W., 1971, Shock metamorphism of the Coconino Sandstone at Meteor Crater, Arizona: Journal of Geophysical Research, v. 76, p. 5449-5473.

McKee, E. D., 1938, The environment and history of the Toroweap and Kaibab formations of northern Arizona and southern Utah Carnegie Institution of Washington Publication 492,221 p.

— ,1954, Stratigraphy and history of the Moenkopi Formation of Triassic age: Geological Society of America Memoir 61, 133p.

Nininger, H. H., 1956, Arizona's meteorite crater: Denver, Colorado, World Press, 232 p.

Rinehart, J. S., 1958, Distribution of meteoritic debris about the Arizona meteorite crater: Smithsonian Institution Contributions to Astrophysics, v. 2, p. 145-160.

Roddy, D. J., Schuster, S. H., Kreyenhagen, K. N., and Orphal, D. L., 1980, Computer code simulations of the formation of Meteor Crater, Arizona; Calculations MC- 1 and MC-2 Proceedings of the Eleventh Lunar and Planetary Science Conference, New York, Pergamon Press, p. 2275-2308.

Shoemaker, E. M., 1960, Penetration mechanics of high velocity meteorites, illustrated by Meteor Crater, Arizona International Geological Congress, 21st, Copenhagen, pt. 8, p. 418434.

— , 1963, Impact mechanics at Meteor Crater, Arizona, *in* Middlehurst, B., and Kuiper, G. P., eds., The moon, meteorites, and comets; The Solar System, Volume 4 Chicago, Illinois, University of Chicago Press, p. 301-336.

Sutton, S. R., 1985, Thermoluminescence measurements on shock-metamorphosed sandstone and dolomite from Meteor Crater, Arizona—2. Thermoluminescence age of Meteor Crater: Journal of Geophysical Research, v. 90, p. 3690-3700.

Tilghman, B. C., 1906, Coon Butte, Arizona: Proceedings of the Academy of Natural of Sciences of Philadelphia, v. 57, p. 887-914.