BARRINGER METEORITE CRATER, COCONINO COUNTY, ARIZONA

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A one-day field trip will visit Barringer Meteorite Crater. Participants will depart from Tempe in the evening and spend the night in Flagstaff. The field trip will depart from Flagstaff to the Crater and will return to Flagstaff and Phoenix on the same day. At the Crater participants may choose from a number of guided or self-guided options to visit this interesting geologic feature. In addition to the road guide included here participants will be provided with a "Guidebook to the Geology of Meteor Crater, Arizona" prepared for the 37th Annual Meeting of the Meteoritical Society. It has been reprinted and is available from the Center for Meteorite Studies, Arizona State University, Tempe, Arizona 85281.

Access to the Crater is by the courtesy of the Barringer Crater Company and Meteor Crater Enterprises, Inc. Visitors must receive permission to enter nonpublic areas of the Crater.

SYNOPSIS OF THE GEOLOGY OF METEOR CRATER

by Eugene M. Shoemaker

REGIONAL SETTING

Meteor Crater lies in north-central Arizona in the Canyon Diablo region of the southern part of the Colorado Plateau (fig. 1). The climate is arid and the exposures are exceptionally good.

In the vicinity of the crater, the surface of the Plateau has very 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, generally many kilometers in length but with only a few meters to about 30 meters of displacement. Two mutually perpendicular sets of vertical joints of uniform strike occur in the region of the crater. One set is subparallel to the normal faults and the other controls the trend of secondary stream courses (fig. 1).

Basaltic cinder cones and flows of late Tertiary and Quaternary age lie at distances of about 11 to 29 km (7 to 18 miles) to the south, west, and northwest of the crater.

PRE-QUATERNARY STRATIGRAPHY

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 the upper part of the Supai Formation of Pennsylvanian and Permian age, which conformably underlies the Coconino.

The Supai Formation consists of interbedded red and yellow fine-grained argillaceous sandstone and subordinate siltstone. It is more than 300 meters (1,000 feet) thick in this region (Pierce, 1958, p. 84), but not more than 100 meters or so (a few hundred feet) have been penetrated by drill holes at the crater. The Coconino Sandstone (McKee, 1933) consists of about 210 to 240 meters (700 to 800 feet) of fine-grained saccharoidal, white, cross-bedded sandstone. Most of the Coconino sandstone is an unusually clean quartz sandstone; in the lower part of the formation the quartzose sandstone is interbedded with red sandstone beds of Supai lithology. Only the upper part of the Coconino is exposed at the crater. The Coconino is overlain conformably by 2.7-meter- (9-foot-) thick unit of white to yellowish- or reddish-brown, calcareous, medium- to coarse-grained sandstone interbedded with dolomite referred to the Toroweap Formation of Permian age (McKee, 1938).

The Kaibab Formation of Permian age, which rests conformably on the Toroweap Formation, includes 79.5 to 81 meters (265 to 270 feet) of fossiliferous marine sandy dolomite, dolomitic limestone, and minor calcareous sandstone. Three 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 limestone and dolomite with several continuous thin sandstone interbeds. The Kaibab is exposed along the steep upper part of the wall of the crater, and a large area west of Meteor Crater is a stripped surface on the Alpha Member (fig. 1).

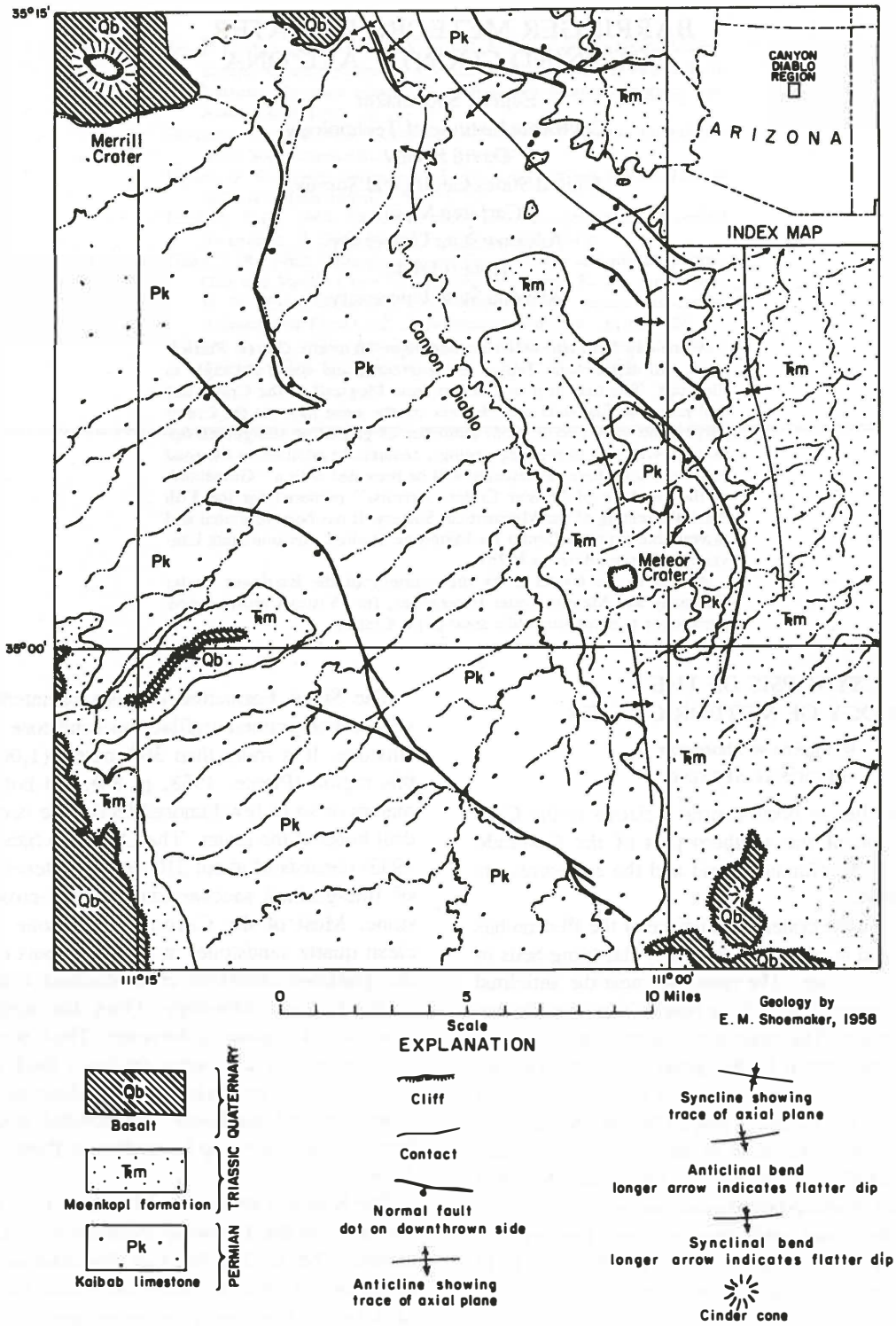


Figure 1. Sketch geologic map of Canyon Diablo region, Arizona.

In the vicinity of the crater, and to the east, beds of the Moenkopi Formation (McKee, 1954) of Triassic age form a thin patchy veneer resting disconformably on the Kaibab. Two members of the Moenkopi are present in the vicinity of the crater. A 3- to 6-meter (10- to 20-foot) bed of pale reddish-brown, very fine-grained sandstone (McKee's lower massive sandstone), which lies from 0.3 to 1 meter (1 to 3 feet) above the base, constitutes the Wupatki Member. Above the Wupatki are dark, reddish-brown fissile siltstone beds of the Moqui Member. About 9 to 15 meters (30 to 50 feet) 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 180 meters (600 feet) deep, about 1.2 km (¾ mile) in diameter, encompassed by a ridge or rim that rises 30 to 60 meters (100 to 200 feet) above the surrounding plain. The rim is underlain by a complex sequence of Quaternary debris and alluvium resting on disturbed Moenkopi and Kaibab strata (fig. 2).

The debris consists of unsorted angular fragments ranging from splinters less than 1μ in size to great blocks more than 30 meters across. Because of the striking lithologic contrast among the older formations from which the debris is derived, it is possible 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. 3) 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 0.8 km (half a mile) 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 Formations, rest with sharp contact on the Kaibab debris. No fragments from the Supai Formation are represented in any of the debris.

The bedrock stratigraphy is 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 Formation occur near the top of the Moenkopi debris unit, fragments from the Alpha Member of the Kaibab limestone occur at the base of the Kaibab debris unit, and brown sandstone fragments from the 3-meter- (9-foot-) thick Toroweap Formation 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 Jeddito Formation of Hack (1942, pp. 48–54) of Pleistocene age (Leopold and Miller, 1954, pp. 57–60; Shoemaker, Roach, and Byers, 1962) in the Hopi Buttes region, some 80 km (50 miles) to the northeast. Holocene alluvium blankets about half the area within the first 0.8 km (half-mile) of the crater and extends along the floors of minor stream courses (fig. 2). It includes modern alluvium and correlatives of the Tsegi and Naha Formations of Hack (1942) of Holocene age (Shoemaker, Roach, and Byers, 1962) 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 (Merrill, 1907, 1908, pp. 472–478; Rogers, 1928, pp. 82–84, and 1930), other kinds of fused rock (Nininger, 1954, 1956, p. 117–134), and less strongly shocked rocks with coesite and stishovite (Chao, Shoemaker and Madsen, 1960; Chao and others, 1962). 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. Unoxidized meteoritic material occurs in two principal forms: (a) large crystalline fragments composed mainly of two nickel-iron minerals, kamacite and taenite (Merrill and Tassin, 1907), and (b) minute spherical particles of nickel-iron (Tilghman, 1906, pp. 898–899, 907; Nininger, 1949, 1951a, b, pp. 80–81). The bulk of the meteoritic material distributed about the crater is apparently in the form of small particles. The total quantity of fine-grained meteoritic debris about the crater, which occurs not only in the Pleistocene and Holocene alluvium but also as lag and dispersed in colluvium, has been estimated by Rinehart (1958, p. 150) as about 12,000 tons.

Beds ranging from the Coconino Sandstone to the Moenkopi Formation are exposed in the crater walls. Low in the crater the beds dip gently outward. The dips are generally steeper close to the contact with the debris on the rim, and beds are overturned along various stretches totalling about one-third the perimeter of the crater. Along the north and east walls of the crater, the Moenkopi can locally 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. 3). 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

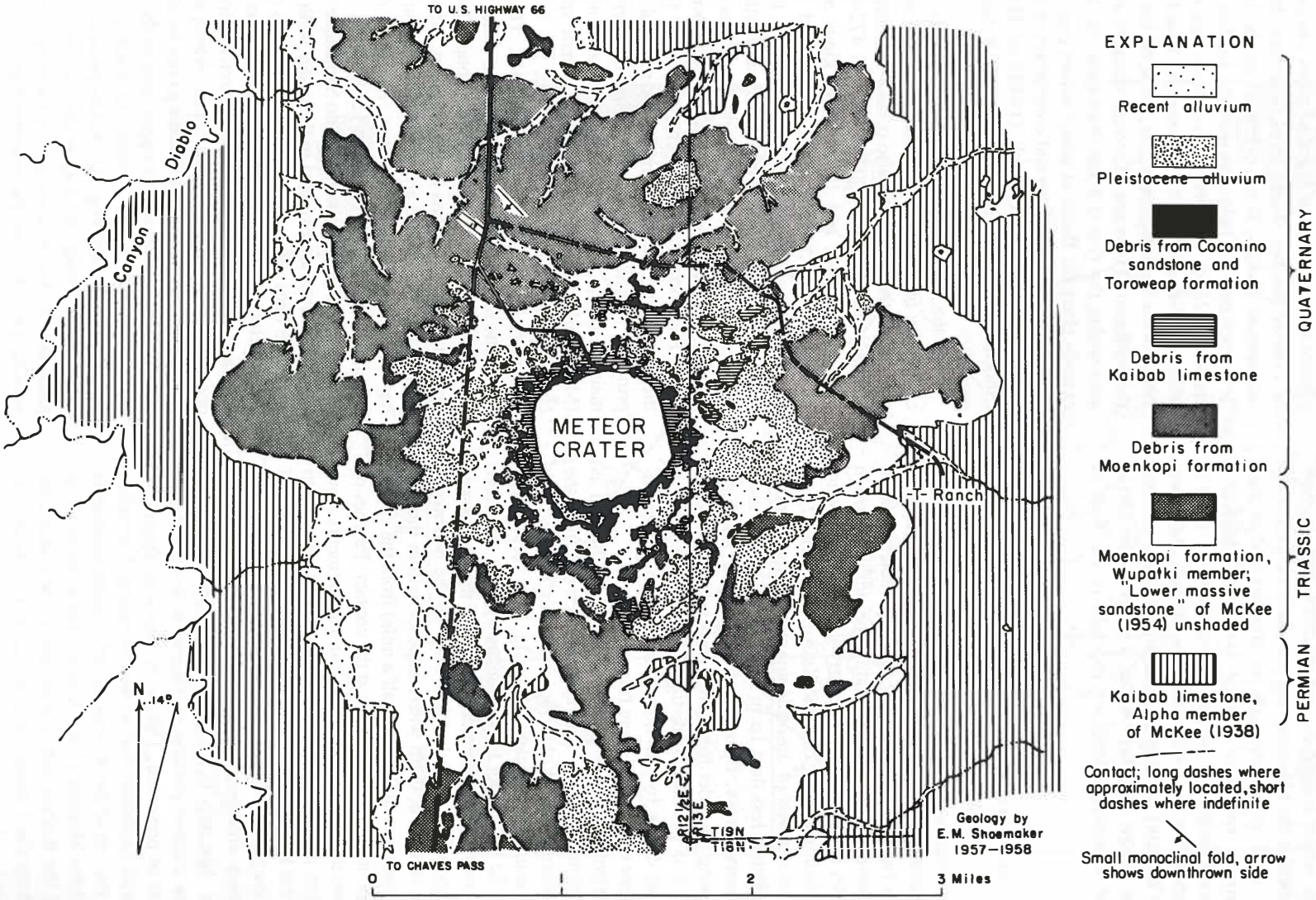


Figure 2. Geologic map of area around Meteor Crater, Arizona.

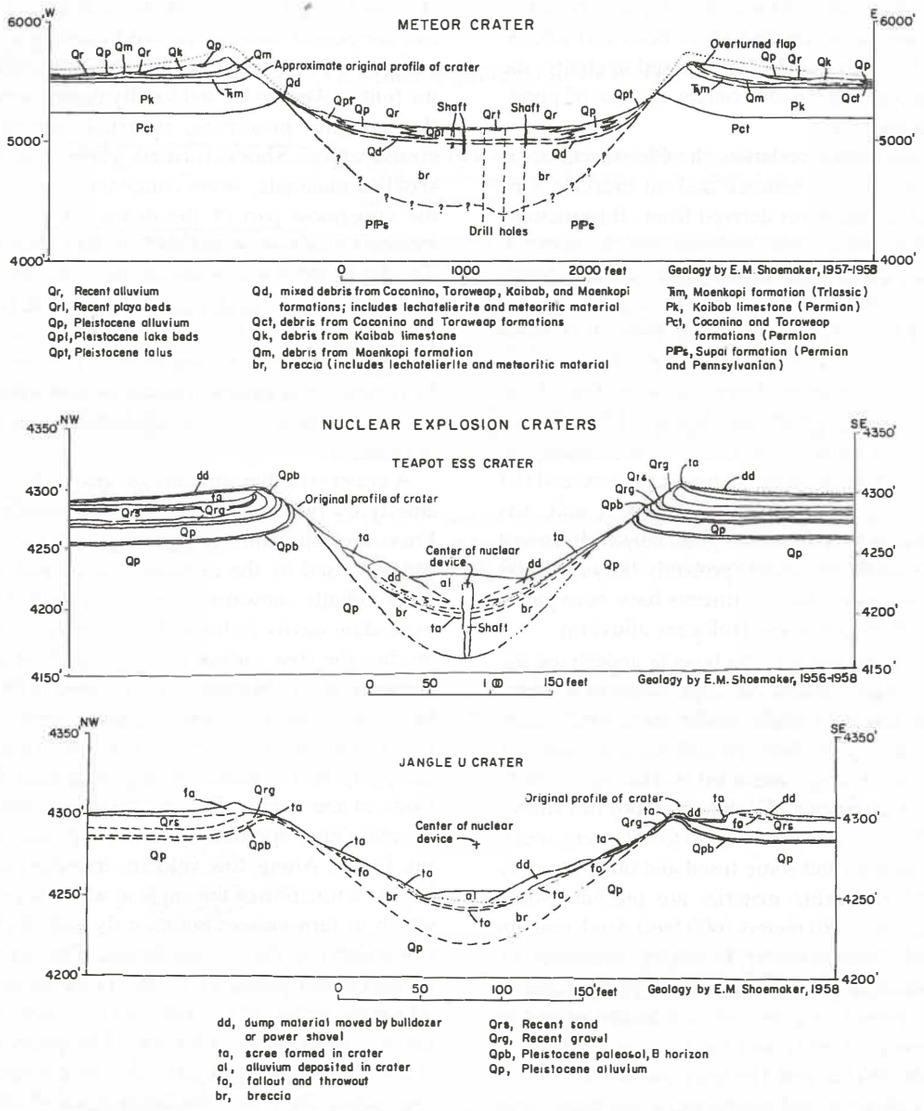


Figure 3. Cross sections of Meteor Crater, Arizona, and nuclear explosion craters.

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 by a number of small, nearly vertical faults with scissors-type displacement. A majority of these tears are parallel with the northwesterly regional joint set, and a subordinate number are parallel with the northeasterly set. Regional jointing has controlled the shape of the crater, which is somewhat squarish in outline; 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 corner of the crater a torn end of the overturned flap of the east wall forms a projection suspended in debris. A few normal faults, concentric with the crater wall, occur on the southwest side. A number of 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 is locally present along all types of faults; it has been designated authigenic breccia, to distinguish it from another type of breccia under the crater floor.

The floor of the crater is underlain by Quaternary strata, debris, and breccia. Pleistocene talus mantles the lowest parts of the crater walls and grades into Pleistocene alluvium along the floor. The Pleistocene alluvium, in turn, interfingers with a series of lake beds about 30 meters (100

feet thick) toward the center of the crater. Up to 1.6 meters (6 feet) 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 bedrock and on breccia. This layer is composed of fragments derived from all formations intersected by the crater and includes much strongly shocked rock and oxidized meteoritic material. The material from all the different sources is thoroughly mixed. Where intersected by a shaft in the crater floor, it is about 10.5 meters (35 feet) thick and almost perfectly massive, but 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 rarely exceed 0.3 meter (1 foot) in diameter. I believe that this unit was formed by fallout of debris thrown to great height. It has not been recognized outside the crater, probably because it has been entirely eroded away. Its constituents have been partly redeposited in the Pleistocene and Holocene alluvium.

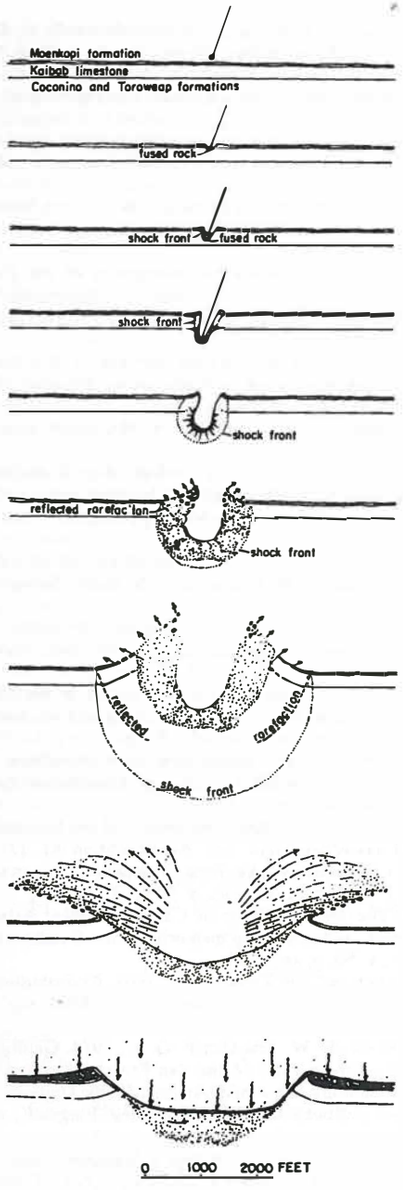
Where exposed at the surface, the breccia underlying the mixed debris is composed chiefly of large blocks of Kaibab, but the breccia exposed in shafts under the central crater floor is made up chiefly of shattered and twisted blocks of Coconino. Extensive drilling conducted by Barringer (1905, 1910, 1914) and his associates (Tilghman, 1906) has shown that, at a depth of 100 to 200 meters (300 to 650 feet), much finely crushed sandstone and some fused and other strongly shocked rock and meteoritic material are present. Some drill cuttings from about 180 meters (600 feet) depth contain fairly abundant meteoritic material. In cuttings examined by the writer the meteoritic material is chiefly in the form of fine spherules dispersed in glass, similar to the impactite described by Nininger (1954) and by Spencer (1933, pp. 394–399) from the Wabar and Henbury meteorite craters. Cores of ordinary siltstone and sandstone of the Supai were obtained at depths of 210 meters (700 feet) and deeper. The lateral dimensions of the breccia are not known because the drilling was concentrated in the center of the crater. Some of the meteorite-bearing or allogenic breccia was evidently encountered in a hole drilled from 1920 to 1922 on the south rim of the crater (Barringer, 1924). (See log of hole in Hager, 1953, pp. 840–841.)

MECHANISM OF CRATER FORMATION

Nearly all the major structural features of Meteor Crater, Arizona, 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. 3), about 90 meters (300 feet) across and originally about 30 meters (100 feet) deep, was produced in 1955 by a 1.2 kiloton device detonated at a depth of 20 meters (67 feet) below the surface (Johnson, 1959, p. 10). 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 alluvium and dispersed glass. Some of the fragments are strongly sheared and compressed. The breccia was formed by complex movement of material within the crater; locally, the original bedding of the alluvium is roughly preserved in the breccia.

A crater with the structure of Teapot Ess crater is formed chiefly by two mechanisms, which operate in succession. First, the alluvium, as it is engulfed by a compressional shock caused by the explosion, is accelerated in all directions radially outward from the detonated device, and an expanding cavity is formed underground. When the shock reaches the free surface of the ground, it is reflected as a tensional wave. Momentum is trapped in the material above the cavity, and it continues to move up and outward, individual fragments following ballistic trajectories. Kinetic energy is also imparted to the fragments from expanding gases in the cavity. Ejected fragments close to the crater maintain their approximate relative positions, inverted during flight. Along low-velocity trajectories, their range is largely a function of the angle at which they are thrown out, which in turn varies continuously with their original position relative to the nuclear device. The margin of the crater is determined primarily by the radial distance, in plan, at which the reflected tensional wave is just strong enough to lift and separate the alluvium. The position at which this occurs is just inside of and concentric with the hinge of the overturned flap, i.e., the intersection of the axial plane of overturning with the surface of the ground. The reflected tensional wave starts a fracture at the surface but does not appreciably change the momentum of most of the material thrown out. Beds are sheared off along a roughly conical surface that starts at the surface slightly inside the hinge and is propagated downward to join tangentially the lower part of the hole expanded behind the shock front. Material brecciated by very strong shock initially has the form of a roughly spherical shell around the hole, but most of the upper hemisphere is thrown out, and the lower hemisphere is sheared out in the form of a concavo-convex lens. Overturning of the beds in the upper crater wall may be looked on as drag along the conical shear zone.

It is essential that the shock originate deeper than a certain minimum distance below the surface, relative to the total energy released, in order to produce the overturned



1. Meteorite approaches ground at 15 km/sec.
2. Meteorite enters ground, compressing and fusing rocks ahead and flattening by compression and by lateral flow. Shock into meteorite reaches back side of meteorite.
3. Rarefaction wave is reflected back through meteorite, and meteorite is decompressed, but still moves at about 5 km/sec into ground. Most of energy has been transferred to compressed fused rock ahead of meteorite.
4. Compressed slug of fused rock and trailing meteorite are deflected laterally along the path of penetration. Meteorite becomes liner of transient cavity.
5. Shock propagates away from cavity, cavity expands, and fused and strongly shocked rock and meteoritic material are shot out in the moving mass behind the shock front.
6. Shell of breccia with mixed fragments and dispersed fused rock and meteoritic material is formed around cavity. Shock is reflected as rarefaction wave from surface of ground and momentum is trapped in material above cavity.
7. Shock and reflected rarefaction reach limit at which beds will be overturned. Material behind rarefaction is thrown out along ballistic trajectories.
8. Fragments thrown out of crater maintain approximate relative positions except for material thrown to great height. Shell of breccia with mixed meteoritic material and fused rock is sheared out along walls of crater; upper part of mixed breccia is ejected.
9. Fragments thrown out along low trajectories land and become stacked in an order inverted from the order in which they were ejected. Mixed breccia along walls of crater slumps back toward center of crater. Fragments thrown to great height shower down to form layer of mixed debris.

Figure 4. Diagrammatic sketches showing sequence of events in formation of Meteor Crater, Arizona.

syncline in the rim. A crater formed near the Teapot Ess crater by a nuclear device of the same yield, but detonated at 5.4 meters (18 feet) depth rather than 20 meters (67 feet) (fig. 3, Jangle U crater), has an anticline under the rim, not a syncline. An explosion at such a depth (shallow relative to the yield of the device) produces a crater more through radial expansion of the cavity behind the shock and less by ejection of material than in the case of Teapot Ess crater. The greatest expansion of the hole occurs at the surface because of upward relief of stress at the free surface, which manifests itself in concentric anticlinal buckling.

The structure of Meteor Crater would be produced by a very strong shock originating about at the level of the present crater floor (120 meters (400 feet) below the original surface). A minimum scaled depth of penetration of the meteorite or of a major part of the energy associated with the meteorite is indicated by the overturned synclinal structure of the rim. A closer estimate of the depth for the apparent origin of the shock can be obtained from the base of the breccia under the crater floor by scaling from Teapot Ess crater. Some limits may also be set on the mechanics of impact by the fact that the shock was strong enough to fuse

Coconino Sandstone, at a depth of some 90 meters (300 feet) or more below the surface, and that part of the meteorite itself was fused by shock on impact, as shown by the dispersal of spherical particles of meteoritic material in some of the fused rock.

Not all meteorite craters exhibit overturned synclines in the rim, as at Meteor Crater, which indicates that the scaled depth of penetration on impact is not always so great. The rim of the main meteorite crater at Odessa, Texas, for example, is underlain by an anticline similar to that of the Jangle U crater (compare with Hardy, 1953; Sellards and Evans, 1941).

The reconstructed sequence of events in the formation of Meteor Crater, based on theoretical analysis (Shoemaker, 1960), is illustrated in figure 4. The crater was formed by impact of meteoritic iron bolide about 30 meters (100 feet) across. On the basis of scaling from the Sedan Crater in Nevada, the energy released by impact was 4 to 5 megatons TNT equivalent. This event occurred 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.

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ROAD GUIDE FROM FLAGSTAFF TO METEOR CRATER

by
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MILES Interval	Total	
0.0	0.0	Butler Street interchange, U.S. Interstate Highway 40 (I-40), heading east toward Meteor Crater and Winslow. Just north of U.S. Route 66 in Flagstaff, at 9:00 below the horizon, is Switzer Mesa, which is capped by Pliocene basalt flows dated at 5.80 ± 0.34 m.y. (Damon and others, 1974). The relatively straight margins of Switzer Mesa suggest that basaltic lava once flowed down a graben valley and that subsequent erosion produced the present "reverse topography." This filled graben is one of many straight-walled valleys and escarpments formed in the pre Plio-Pleistocene deposits by pervasive normal faulting. Cropping out below the protective lava cap of Switzer Mesa is part of the lower Wupatki Member of the Moenkopi Formation of Early Triassic age (McKee, 1951). San Francisco Mountain, including Humphreys Peak, and Elden Mountain are visible at 10 and 11 o'clock, respectively, on the left. San Francisco Mountain, a largely andesitic strato-volcano, probably attained a total eruptive elevation of more than ~4,500 m (15,000 feet). The volcano may have been modified by either summit collapse or explosive eruption. More recent fluvial and glacial erosion have also modified the form of the volcano. Humphreys Peak, elevation 3,851 m (12,633 feet), is the highest mountain in Arizona. Elden Mountain (2,835 m; 9,299 feet) is a dacite dome, complex in detail because part of it (north) appears to be laccolithic, tilting and exposing pre-Kaibab Paleozoic rocks as old as Devonian, while another part (the south end, visible from the road) was extrusive (Kluth and Kluth, 1974). Large viscous flow lobes with marked jointing can be seen from the highway on the south and east sides of the mountain.
0.6	0.6	The road cut exposes the top of the Alpha Member of the Kaibab Formation of Permian age (McKee, 1938). The top of the Kaibab is an ancient karst surface. The upper 20 to 30 meters (65 to 100 feet) of the Kaibab Formation appear to have been modified by solution.
0.4	1.0	The road crosses a southeast-trending escarpment bordering a small valley ("park") which is probably a graben.
1.9	2.9	Route 89 north toward Page and Grand Canyon exists here. Continue west on I-40.
0.4	3.3	Proceed slowly! About 100 meters ahead of you, a fault-line scarp is visible. The downthrown block is on the west and forms the small depression which you are traversing. On the left at 9:00 o'clock is Sheep Hill, a cinder cone of the Tappan age-group (Moore and others, 1974). As you approach the fault-line scarp, a quick glance to the rear at about 5:00 o'clock will reveal a basalt flow in the depression below I-40. This flow emanated from the base of Sheep Hill. The east margin of this depression is sometimes occupied by an ephemeral lake, Bill Fill Lake.

0.1	3.4	In the escarpment directly east of Big Fill Lake and in the road cut, the jumbled beds of the karst horizon of the Alpha Member of the Kaibab Formation are again exposed. A distinctive red bed sequence may be seen below the top of the Kaibab; this unit thins toward the east and is not present at Meteor Crater. The entire Kaibab Formation pinches out 30 miles beyond Meteor Crater.
0.1	3.5	Many quarries are dug into the cinder cones, such as Sheep Hill (at 9:00 o'clock), Wildcat Hill (11:00 o'clock), and Turkey Hill. The cinders are used in road metal and in cinder blocks. There are more than 400 cinder cones in the San Francisco volcanic field.
2.5	6.0	Turn off to Walnut Canyon National Monument.
0.2	6.2	The red beds in the Alpha Kaibab Formation are again exposed in the road cut north of eastbound I-40.
2.2	8.4	Cosnino road exit.
0.6	9.0	Normal fault, downthrown to the west.
0.7	9.7	From this section of the road, the view to the south is of a stripped surface developed on top of the Kaibab Formation. Topography in this area accurately reflects the bedrock structure, except where it is moderately dissected by gullies.
0.3	10.0	At about 8 o'clock, below the horizon, Sunset Crater is visible as a bright-rimmed cinder cone, devoid of vegetation. It lies just to the right of, and below, O'Leary Peak. The most recent eruption in the volcanic field occurred in 1064 A.D. at Sunset Crater. The date is based on dendrochronology (Smiley, 1958).
1.2	11.2	Along the highway good exposures of thin grey beds within the Alpha Member of the Kaibab Formation are visible beneath 1 to 3 m of the jumbled rocks in the karst horizon. The Kaibab here is mostly silty dolomite and dolomitic sandstone with some chert. Marine fossils (brachiopods such as Derbya; productids; cephalopods; invertebrates; a few fish teeth) are abundant in many beds.
0.1	11.3	At 10:30 o'clock is a large cinder quarry (the Darling pit) at Cinder Mountain, owned by the Santa Fe Railroad.
0.4	11.7	Walnut Canyon
0.3	12.0	A lava flow of the Tappan age-group (Moore and others, 1974), is visible in the road cut. For the next 2.5 miles a cinder blanket of variable thickness covers the land surface. The cinders probably came from four cinder cones just south of the highway.
0.4	12.4	Winona exit. The basaltic cinder cone on the right has a rootless lava flow on its northwestern flank. This cone is probably the source of the lava flow at mile 12.0. A last view of Sunset Crater silhouetted in front of O'Leary Peak may be obtained by looking back to the left (about 8 o'clock?).
1.2	13.6	The road drops back to the stripped surface on the Kaibab, thinly strewn with cinders. To the left, just beyond the Santa Fe railroad tracks, is the margin of a basaltic lava flow.
1.0	14.6	Looking ahead, the road rises over a gentle anticline, reflected as a swell on the stripped surface on top of the Kaibab Formation.
0.4	15.0	Three miles to the north at 9:30 o'clock, Piper Crater, a basaltic cinder cone, is superposed on the south side of Rattlesnake Crater, an older maar-type vent. Merrill Crater is east of Piper Crater at 10 o'clock.
2.1	17.1	Merriam Crater is located in the distance at 9:00 o'clock.
1.2	18.3	The small cinder cone at 3:00 o'clock is the nearest Quaternary volcanic feature to Meteor Crater.
0.7	19.0	The eastward gradient of the highway steepens noticeably as it comes over the crest of the anticline mentioned at mile 14.6. From here, the road descends into Padre Canyon. The Hopi Buttes volcanic field can be seen in the distance (about 80 km; 50 mi) at 10 to 11 o'clock, across the Little Colorado River valley). On the skyline to the right is Anderson Mesa, capped by basalt flows dated at 6.2 ± 1.2 m.y. (Damon, 1965).
0.9	19.9	Padre Canyon and Twin Arrows Trading Post.
1.3	21.2	As one looks out across the broad stripped surface on the Kaibab, it should be kept in mind that in this region of the Colorado Plateau, the topography reflects the structures beneath. A broad anticline is visible in the distance ahead. Normal faults which have been crossed are controlled by a regional pattern of jointing. Two orthogonal sets of joints which trend predominantly northeast and northwest are parallel to important regional structures in this part of the Colorado Plateau (Colton, 1936).
1.7	22.9	The long ridge between about 2 and 3 o'clock is an irregular basalt-capped ridge

which extends toward Meteor Crater and will be seen end on from road to Meteor Crater.

2.4 25.3 For the next 2 miles the highway traverses an anticline where an oil test well was drilled to Precambrian strata in 1962, about half a mile north of the highway (NE¼ NW¼ sec. 12, T. 20N., R.11E.). The well was converted for watering stock. Following are subsurface thicknesses of Paleozoic formations penetrated by this well (Peirce and Scurlock, 1972, p. 159):

	Feet	Meters
Kaibab (Permian)	283	86.3
Coconino (Permian)	890	271.3
Supai (Permo-Pennsylvanian)	1370	417.7
Naco (Pennsylvanian)	515	157.0
Molas (Pennsylvanian)	12	3.7
Redwall-Zones A, B, C (Mississippian)	110	33.5
Martin (Devonian)	380	115.8
Precambrian, depth	3560	1085.4
Precambrian, elevation	2175	663.1
Total depth of well	3630	1106.7

The Toroweap Formation, a marine unit between the Kaibab and the Coconino Formations in the Grand Canyon, was not recognized in this well as it is readily confused with the Coconino (McKee, 1938). Approximately the lower 73 m (240 ft) of Coconino in this well are correlated with the DeChelly Sandstone, which thickens toward the Defiance Plateau (Pierce and Scurlock, 1972).

0.2 25.5 The escarpment crossed by the road is a fault-line scarp on the flank of the anticline. The bedrock is downthrown to the east and exhibits reverse drag.

0.2 25.7 Crest of anticline.

1.5 27.2 A good view is obtained here of the rim of Meteor Crater in the distance at 1:00 o'clock. The Hopi Buttes volcanic field has become more prominent on the left horizon at about 11 o'clock.

1.9 29.1 The road rises over the crest of another anticline. East and West Sunset Buttes are visible in the distance to the right of Meteor Crater.

0.5 29.6 A fault-line scarp bounding the drainage at 1:30 to 3:00 o'clock at a distance of about one half mile is along a normal fault downthrown to the west.

1.1 30.7 Canyon Diablo.

0.7 31.4 Weathered outcrops of massive sandstone beds in the Wupatki Member of the Moenkopi sandstone (Triassic) form characteristic knobby or biscuit-like outcrops just above the Kaibab limestone.

2.8 34.2 Meteor Crater exit from I-40.

0.6 34.8 **STOP 1.** The first stop is at Indian Country Road intersection. To the east may be seen an abandoned stone building located just north of the old alignment of U.S. Highway 66. This building once housed H. H. Nininger's meteorite collection. It was operated as a museum, open to the public at a fee, where visitors heard lectures by Nininger and could study the collection and purchase specimens. The operation of this museum was the source of Nininger's livelihood for many years. Visitors could climb the stone tower and look off to the north to get a view of Meteor Crater without deviating from their route on Highway 66.

The museum is built just above a low escarpment which trends northwest-southeast and can be traced by eye for a distance of about two miles. The escarpment is along a small normal fault which offsets the lower beds of the Moenkopi at this place. The throw on the fault is about 9 meters (30 feet). On the upthrown side may be seen outcrops of the lower Massive Sandstone unit of the Wupatki Member of the Moenkopi Formation, which are the lowermost beds of the Moenkopi at this place. Erosional remnants of the Lower Massive Sandstone form a line of small knobs trending off to the southeast. About 3 meters (10 feet) of siltstone and very fine sandstone of the Moqui Member of the Moenkopi Formation are preserved locally above the Lower Massive Sandstone. Nininger's old museum is built of pieces of Moenkopi sandstone from both the Wupatki and Moqui Members. Some of these pieces are beautifully ripplemarked.

A water well, 100 meters (300 feet) away, at 11 o'clock, brings water up from the middle of the Coconino Sandstone at a depth of 200 meters (600 feet). The Coconino Sandstone is the principal aquifer in this part of northern Arizona. Here the water table slopes gently to the north, in the same direction as the average regional dip of the beds. Meteor Crater is located on the southern flank of the Black Mesa basin; the beds dip generally about one degree to the northeast.

0.5 35.3 The road drops into a shallow valley where Wupatki sandstone is well exposed.

Interleaf. Upturned edges of stratified rock on west side of interior of Meteor Crater, Arizona; San Francisco Peaks in distance. (Photograph No. PK 14,092 by Troy L. Péwé, January 2, 1970.)

0.9 36.2 The road drops to the level of the Moenkopi-Kaibab contact. A few scattered blocks of Kaibab Limestone may be seen to the side of the road.

0.9 37.1 **STOP 2.** Here the road comes over the crest of a rise, and the visitor obtains a first good overall view of the crater rim. At this point, the road is on the Moqui Member of the Moenkopi, about 5 meters (15 feet) above the base of the Moqui Member.

To the left and behind the rim of Meteor Crater may be seen the lava-capped mesas known as East Sunset Butte and West Sunset Butte. Both buttes are capped by basalt, which rests on the Chinle Formation of Upper Triassic age. The flanks of the buttes visible from the vantage point along the road are mantled with landslide debris which supports a pygmy forest of pinyon and juniper. In places along the flanks of the buttes, not visible from this point, a complete section of the Moenkopi Formation and a partial section of the Chinle Formation are exposed. Three cinder cones are visible on the buttes which mark the vents from which the basaltic lavas were erupted.

To the right of Meteor Crater, from about 12 o'clock to about 3 o'clock, the skyline is formed by basalt-capped mesas of the Mormon Mountain volcanic field. The basalts in this field are Miocene and Pliocene in age. One of the basalts capping Anderson Mesa, at 3 o'clock, is dated at 6.2 ± 1.2 m.y. (Damon, 1965). The two highest points visible in the volcanic field are Hutch Mountain, at about 1:30, and Mormon Mountain, at about 2 o'clock.

The high point between Hutch Mountain and Mormon Mountain is the end of a long, northeast-trending ridge that extends directly toward the viewer from the more distant part of the volcanic field. The ridge is capped by a single lava flow, most of which has now been destroyed by landsliding on both sides of the ridge. Red beds of the Chinle Formation and Moenkopi Formation may be seen exposed in parts of the landslide blocks on the near end of the ridge.

Between 3 o'clock and 5 o'clock lie the volcanoes of the San Francisco volcanic field. The largest volcano is San Francisco Mountain. A circle of peaks surround the eroded core of this volcano, the highest of which is Mt. Humphreys. At 3,851 meters (12,633 feet), Mt. Humphreys is the highest point in Arizona. The San Francisco stratovolcano is composed mainly of andesite lava flows and ashes. Rhyolites and dacites occur as domes perches on the flank of the older stratovolcano. The largest of these domes forms Mount Elden, which is the prominent toe extending to the left of the main mountains. Domes which have been dated range in age from 2.71 ± 0.13 m.y. to 0.212 ± 0.011 m.y. (Damon and others, 1974).

To the right of the San Francisco peaks is an extensive field of Pleistocene basaltic cinder cones. This is the main locus of basaltic activity, at the present time, in the San Francisco volcanic field. The youngest cinder cone in this field, not visible from this vantage point, is Sunset Crater, which has been dated by dendrochronological methods at A.D. 1064 (Smiley, 1958). The nearest prominent reddish colored cinder cone is Merrill Butte, which lies about 27 km (17 miles) airline distance. At the extreme right of the volcanic field is a large symmetrical cinder cone called Merriam Crater. The cinders on the side road, extending to the west, and also used as aggregate in the asphalt capping of the Meteor Crater road, have been excavated from basaltic cinder cones.

1.9 39.0 **STOP 3.** AT JUNCTION OF BAR-T-BAR RANCH ROAD. Low buttes on each side of the road are formed by beds of the Moqui Member of the Moenkopi Formation. An excavation around the flank of the butte, on the right side of the road, is a fossil quarry excavated by the University of California. Materials recovered from this quarry include an extensive collection of footprints and fossils of ganoid fishes and amphibians. On the basis of regional studies of the stratigraphy of the Moenkopi Formation and on fossils obtained from this and other nearby quarries, the beds at this horizon can be placed near the base of the Middle Triassic. The fossils were found in freshwater dolomite and siltstone beds in the floor of the quarry. These beds are no longer exposed.

0.7 39.7 **STOP 4.** This stop is just beyond a broad curve in the road at a point where road heads nearly due east. To the north of the road, at 9

o'clock, the skyline is formed by a ridge of siltstone and sandstone of the Moqui Member of the Moenkopi. The south slope of the ridge is mantled with late Pleistocene colluvium containing abundant fragments of sandy dolomite from the Kaibab Formation. These fragments have been derived by reworking of a blanket of ejecta that surrounds the crater. At one time this ejecta blanket extended beyond the ridge of Moenkopi, but the more distant parts of that blanket have now been eroded away during the time elapsed since the crater was formed. The colluvium extends to the south into a shallow drainage where it is overlain by a thin deposit of Holocene alluvium. The outer eroded edge of the ejecta blanket lies essentially at this position, and is concealed beneath late Pleistocene and Holocene alluvial deposits.

The difference in elevation between the crest of the Moenkopi ridge and the lowest outcrop in the ejecta blanket, near the drainage, provides a minimum estimate of the relief on the precrater surface. It is clear that the ridge of Moenkopi is an erosional feature that predated the crater and had a precrater relief of at least 15 meters (50 feet).

On the near side of the drainage is a surface that climbs gradually toward the crater rim and which is underlain by late Pleistocene alluvium. The road bed is built on this alluvial unit. The age of this and other alluvial deposits at Meteor Crater has been determined by correlation of pedocal paleosols developed on them. A well-defined sequence of Pleistocene and Holocene deposits has been studied in the Hopi Buttes region, about 80 km (50 miles) to the northeast. (The nearest of the Hopi Buttes are just visible on the northeast horizon.) There the deposits have been dated by means of vertebrate fossils, C-14 analysis, and on the basis of artifacts contained in the youngest alluvial units. A well-developed paleosol, corresponding to the youngest Pleistocene soil in the Hopi Buttes, is exposed in a shallow borrow pit in the alluvium 50 meters (170 feet) to the south of the road. This Pleistocene alluvium rests directly on the preserved part of the ejecta blanket.

The ejecta blanket surrounding Meteor Crater is stratified and can be divided into three distinct mappable units:

1) a unit composed of fragments of the Moenkopi Formation at the base,
2) a unit composed of fragmental debris from the Kaibab Formation, and
3) a unit composed of fragments of the Coconino Sandstone at the top.

Exposures of the Kaibab debris unit can be seen between 10 o'clock and 3 o'clock. At 3 o'clock the Kaibab debris rises high on the crater rim. Low mounds with large, light-colored blocks, lying 100 to 300 meters (300 to 1,000 feet) from this vantage point, between 10 o'clock and about 1 o'clock, are exposures of the Kaibab debris unit that protrude through the surrounding Pleistocene alluvium. This part of the crater rim is essentially a stripped surface on the top of the Kaibab debris unit. The gently hummocky topography of the rim reflects the original configuration of the contact between the Kaibab debris unit and the overlying Coconino debris unit, which has been largely stripped away.

At 2 o'clock, on the horizon, is the chimney of a building now destroyed by fire. This building was the headquarters for the exploration activity of the old Standard Iron Company and the latter-day Barringer Crater Company. During the 1930's and 1940's, after exploration had ceased, the building also served as a visitor center and a small museum for the public visiting the crater. This building is constructed on a high-level pediment surface that is cut into the rim units of the crater. The pediment is capped by relatively coarse alluvial and colluvial debris derived from still higher parts of the rim. The pediment can be traced as a cut surface between about 1:30 and 3 o'clock. The easternmost edge of the pediment lies just to the left of a powder magazine, which has been dug in a brilliant white deposit beneath the pediment gravels. This white deposit is a remnant of the Coconino Sandstone debris unit, which is preserved in a pocket beneath the pediment gravels.

The difference in elevation between the highest recognizable pediment on the crater rim and the upper edges of the latest Pleistocene alluvial deposits at this locality provide a minimum estimate for the amount of

Interleaf. Upturned edges of stratified rock on southwest side of interior of Meteor Crater, Arizona. (Photograph No. PK 14,093 by Troy L. Péwé, January 2, 1970.)

dissection of the rim by erosion that has occurred since the crater has formed. On the northeast flank of the crater rim this difference is about 12 meters (40 feet). The total amount of degradation of the rim is, of course, substantially greater than this. A conservative but realistic estimate of the total reduction in rim elevation by erosion would be 15 to 20 m (50 to 75 feet). In places the rim crest may have been eroded down as much as 30 m (100 feet). In most places the Coconino debris unit has been entirely stripped away.

0.2 40.0 **STOP 5.** BY TRAILER INSTRUCTION SIGN AND JUST BEYOND ROAD TO WATER WELL. At approximately 1 o'clock may be seen a tongue-shaped mass of light-colored rocks, extending to the crest of the crater rim. This mass is a remnant of the Coconino Sandstone debris layer preserved in a depression on the top of the Kaibab debris layer. Kaibab debris underlies the grassy slopes surrounding the Coconino debris remnant. A water well at 7:30 extends slightly below the water table at a depth of about 200 meters (600 feet). This well provides the water for the museum and the visitor center on the crater rim and for the residences of the museum staff.

0.2 40.2 **STOP 6.** IN LOWER PARKING LOT. Exposures in cuts at the southeast corner of parking lot provide an excellent introduction into the nature of the rim debris units. A part of the Kaibab debris unit is exposed in this cut. The debris consists of angular to subangular fragments ranging in size from 1 micron or less up to blocks more than a meter across. The size frequency distribution of this material follows a rather well-known fragmentation law. The cumulative mass of the debris is a simple power function of the particle size. The exponent of this power function is such that about 50 percent of the total mass falls in the largest three phi intervals. As one examines the debris in the cut, about 50 percent of the volume of the material consists of easily recognized fairly coarse blocks set in a matrix of finer crushed material. In general, the fines are only recognizable in fresh exposures such as this. The effect of weathering is to wash away the fines, leaving the surface mantled with the coarser debris. When seen on a natural outcrop, the debris unit appears to be composed almost entirely of the coarser blocks.