CAVERNOUS OPENINGS IN THE TARGET ROCKS AND CRATER WALLS OF METEOR CRATER, ARIZONA.
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Introduction: Meteor Crater is a relatively young, well-preserved impact site with good exposure, both within the crater and in the surrounding target terrain. Thus, it is a good site for assessing the types of cavernous features that are associated with impact craters. These types of features can be influenced by the types of target rocks (in this case Permian Coconino Sandstone, Permian Toroweap Formation, Permian Kaibab Formation, and Triassic Moenkopi Formation), pre-impact tectonic and diagenetic conditions that affected the target rocks, regional climatic conditions, and their influence on weathering agents after the crater was excavated. While some of the cavernous features described here will be unique to Meteor Crater, some insights can be derived for cavernous structures elsewhere (e.g., the Moon and Mars).

Cavernous Openings: There are several types of cavernous openings within the crater and in nearby examples of the target rocks: (a) pre-impact openings along joints and faults that cross-cut all of the target rocks, (b) karst in pre-impact target Kaibab, (c) possible dissolution of pre-impact subsurface Toroweap, (d) dissolution in post-impact exposures of Toroweap in the crater wall, (e) karst in crater wall Kaibab in at least two stratigraphic intervals, (f) cavernous weathering of Toroweap, Kaibab, and Moenkopi in crater walls, (g) cavernous weathering in blocks of Kaibab and Moenkopi in the ejecta blanket, (h) cavernous weathering in gouge along near-vertical faults created by differential uplift of the crater walls, (i) cavernous weathering in impact breccia deposits along crater walls, (j) cavities in the breccia lens that fills the lower portion of the crater, (k) cavities created by blocks that have eroded from the crater rim and upper crater walls and rolled onto lower slopes or been transported in debris flows, and (l) cavities created by the erosion of smaller ejected debris between larger blocks of debris in the impact ejecta blanket. Some of these openings provide niches for flora and fauna; in some cases, the openings have been enlarged by the flora and, in particular, by burrowing fauna.

Examples: Pre-impact features in the target rocks include openings created by tectonic joints and faults (Fig. 1). The principal effect is seen in Kaibab, where those openings are enhanced by dissolution and roof and wall collapse. One of these fissures is ~15 m wide and over 25 m deep. The orientation of the tectonic joints in the target area can be deduced from measurements in the crater wall [1,2], and by measurements in

Fig. 1. A joint in Kaibab west of Meteor Crater that has a significant opening.

Fig. 2. Cavernous karst opening at the base of a dolomite bed within the Kaibab on the south crater wall.

the target sequence immediately beyond the impact ejecta blanket [1,3]. These features had an effect on the excavation flow during the impact, producing a square, rather than circular, crater in plan view [1,4]. Fault structures in the target rocks have a more diverse range of bearings.

Cavernous karst can also be seen in the crater walls (Fig. 2). The karst appears to pre-date crater excavation in some cases, as it is deformed in the uplifted crater walls. These features occur in the dolomitic Kaibab in at least two intervals: a stratum near the base of the Kaibab alpha member and at the top of the Kaibab alpha member. The uppermost layer contains significant evidence of dissolution and is characterized by a karst-collapse breccia texture that sometimes involves the overlying Moenkopi [5].

Cavernous weathering is common in the crater walls and surrounding ejecta deposits. Multi-meter-wide openings have been produced in the crater walls, including the uppermost Kaibab member described

Fig. 3. A cavernous opening in the uppermost Kaibab unit in the north crater wall. This unit was affected by karst prior to impact as indicated by the dissolution features and collapse-breccia structure seen in the outcrop.

Fig. 4. Cavernous weathering produces niches in Moenkopi siltstone, as shown here on the south crater wall.

Fig. 5. Cavernous opening in fault gouge in the southeast corner of the crater. As is often the case with openings in the crater walls, this one is currently used and was probably enlarged for shelter by local fauna.

above (Fig. 3). The largest openings of this type occur in Moenkopi and can be found on all sides of the crater (Fig. 4).

Cavernous weathering and/or burrowing by fauna also exists in the relatively soft fault gouge that exists along near-vertical faults around the crater (Fig. 5).

Discussion: Openings associated with pre-impact tectonic structures is possible on both the Moon and Mars, particularly in areas where impact craters for polygonal outlines in plan view [6,7]. Karst enhancement of those openings is not likely, at least on the Moon where carbonate strata do not exist. Skylights have been observed in impact melt and impact breccia fill in lunar craters (e.g., [8]). Those sites are akin to the voids seen between blocks of debris in Meteor Crater's breccia lens, which are currently buried by post-impact lake, playa, and eolian deposits.

Cavernous openings on the crater walls are often large enough to shelter a human. Those openings are, however, on very steep slopes. Thus, while they may be accessible to a geologist on Earth, similar structures on the Moon or Mars would be difficult to access in a spacesuit.

The cavernous openings at Meteor Crater are microniches that are occupied by a variety of flora and fauna, providing cooler and more humid environments. Similar features are potential microniches on Mars, although conditions will be affected by exposure to sunlight and atmospheric processes. Experiments at Meteor Crater [9] indicate cold air may pond on crater floors at night, producing thermal inversions. Those experiments also indicate that variations in daily temperatures are greater on crater floors than on crater rims; thus, cavities at different elevations in a crater may experience different thermal conditions. The experiments also suggest downslope winds can enhance ablation of volatiles from crater wall bedrock, caves, and colluvium debris, particularly where channeled through gullies. Condensation of volatiles is more likely on shadowed slopes and where large-scale nighttime drainage flows spill over a crater rim.

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