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THE ROLE OF DEBRIS FLOWS IN THE ORIGIN AND EVOLUTION OF GULLY SYSTEMS ON CRATER WALLS: MARTIAN ANALOGS IN METEOR CRATER, ARIZONA (USA)

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ABSTRACT

In 1999, the Mars Global Surveyor acquired images of young gully features on the walls of impact craters. From these and subsequent images, numerous theoretical and physical models have been developed based primarily on three competing theories about the origin of the gullies: 1) scour and deposition by dry granular flows, 2) debris flow driven gully incision due to the sudden release of gases or fluid from the subsurface, or 3) fluid incision via debris flows due to the release of surface volatiles or the melting of ice. To contribute insights and possible constraints on these competing mechanisms, we are performing an intensive investigation of the origin and evolution of the gullies in Meteor Crater, a well-preserved terrestrial analogue. The location of the gullies along radial fractures in the crater wall and the presence of lake sediments on the crater floor have lead researchers to conclude that groundwater seepage and fluvial incision formed the gullies. However, from initial field observations and inspection of high-resolution LiDAR data, we have observed that the gullies: 1) show evidence of multiple events, 2) do not cross the crater floor, 3) have modest size levees, and 4) terminate on an ~8-15° slope. As an alternative to current interpretations, we suggest that gully incision was caused by debris flows driven by periodic snowmelt during the cooler and wetter Pleistocene.

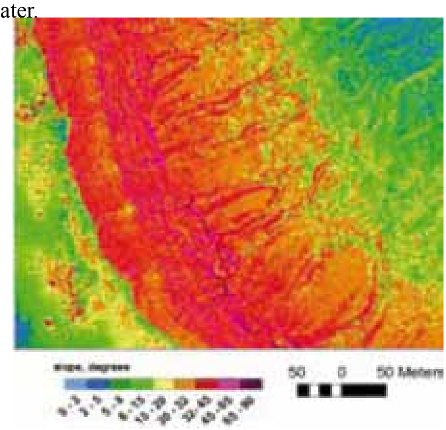
KEY WORDS: Meteor Crater, Mars, Gully erosion

INTRODUCTION

The discovery of geologically-recent gullies on Mars by MALIN & EDGETT (2000) has lead to numerous studies on gullies across Mars (e.g. TREIMAN, 2003; MARQUEZ *et alii*, 2005; HEAD *et alii*, 2008; LANZA *et alii*, 2010) and on terrestrial analogues (e.g. COSTARD *et alii*, 2002; HARTMANN *et alii*, 2003; HUGENHOLTZ, 2008). The morphology of these gully systems varies, but most commonly they have a well-defined source alcove, channels or chutes, and a depositional apron. Despite the abundance of high-resolution imaging and morphometric characterization that has occurred over the last decade, the processes creating these features remains unknown.

Proposed mechanisms for flow generation on Martian gullies span a wide range of processes. TREIMAN (2003) pointed to the similarity between Martian gullies and terrestrial snow avalanches and suggested that they could have formed similarly, from dry granular flows. Experiments performed by SHINBROT *et alii* (2004) showed that dry granular material could produce weakly channelized flows if the settling velocity of the grains is less than the flow velocity. The lower Martian gravity coupled with partially mantled slopes of superposed material, thought to be mainly fine sediment and ice, may encourage dry flows, but thus far it has not been shown that such flows can produce deep channels, natural levees or hummocky terminal deposits.

A second set of hypotheses involves the emergence of gas or fluid from the subsurface. Mellon & Phillips (2001) hypothesize that oscillations in the Martian orbit can lead to freeze-thaw cycles at depth, potentially forcing water to the surface under freezing pressure, similar to springs that emerge from terrestrial pingos, a periglacial landform in which rock and soil cover a large mound of ice. Musselwhite *et alii* (2001) suggest a similar mechanism to Mellon & Phillips (2001), only under the action of liquid CO2. Groundwater seepage has been proposed as a transporting agent by several authors (e.g. Malin & Edgett, 2000; Gilmore & Phillips, 2002; Heldman & Mellon, 2004; MarqueZ *et alii*, 2005) based on observations of similar elevations of alcoves on crater walls, exposure of layered rock in alcoves, and the fact that the present day climate on Mars does not allow for mobilizing appreciable quantities of surface water.



Lastly, surficial fluid sources have been proposed from the release of seasonal or epochal accumulations of volatiles, or from the melting of ice collected in alcoves or mixed in with fine material that has been atmospherically deposited on crater slopes (Costard *et alii*, 2002; Hecht, 2002; Christensen, 2003; Mangold *et alii*, 2003; Dickson and Head, 2009). Based on the model of Parsons & Nimmo (2010), solar insolation cannot melt ice at rates fast enough to produce the discharges estimated to have flowed through the gully systems. Observations of repeated erosional and depositional activity in Martian gullies over the past two years may suggest that seasonal CO2 frost accumulations can fail and flow through the gully networks, perhaps with sufficient force to entrain debris (Dundas *et alii*, 2010). It has also been proposed that debris flows could be generated by the saturation of surface layers by slow melting or in the generation of excess pore water pressures beneath a frozen surface layer, thereby creating a slushflow (Coleman *et alii*, 2010; Dixon *et alii*, 2010).

Careful analysis of terrestrial analogues, where specific mechanisms can be identified or tested in-situ, is required to provide insight and possible constraints to the proposed mechanisms for Martian gully formation. Meteor Crater, also known as Barringer Meteorite Crater, is an ideal place to perform such a study. While one of the best-preserved craters on Earth, its interior walls are etched with gullies that closely resemble the widely investigated "typical" gully systems on Mars (i.e. those that involve source

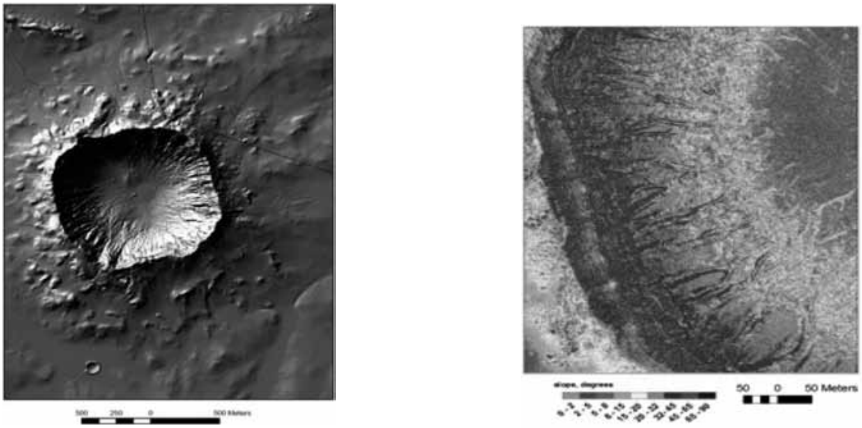


Fig. 1 - (left) Shaded relief map (left) of Meteor Crater derived from lidar provided by the National Center for Airborne Laser Mapping and (right) slope map (on 0.25 m gridded data) (North up). Note access trail is visible in northern part of slope map

alcoves, chutes, and depositional aprons), as shown in Fig. 1. In addition to sharing morphologic similarities to Martian craters, Meteor Crater also has an apparent history of an elevated water table hosting a lake, which raises the issue of groundwater seepage influences. Also, it is a well-studied crater in regards to its basic geology (Shoemaker, 1960; Shoemaker & Kieffer, 1974), post-impact geophysical characteristics (Kumar & Kring, 2008), and recently, even its erosional features been described in some detail (Kumar *et alii*, 2008; Kumar *et alii*, 2010).

Currently, the key issue at Meteor Crater regarding post-impact erosional processes is the role of groundwater in forming the gully networks. Kumar *et alii* (2010) suggest that groundwater seepage and fluvial processes may have dominated, but our observations, based both on an initial field campaign and more importantly, high-resolution topographic data recently obtained from the National Center for Airborne Laser Mapping (NCALM), now suggest an alternative hypothesis. In what follows, we argue that the gullies may be the result of repeated debris flows that have no clear connection to groundwater seepage. Furthermore, essential to the formation of these mass flows is not just the occurrence of water (either from surface runoff or groundwater seepage), but also the presence of fine material from the impact, which when mixed with water serves to mobilize and sustain debris flow motion.

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GEOLOGICAL SETTING

GEOLOGY

Meteor Crater is located in the Colorado Plateau in north central Arizona (35°03´N, 111°02´E). The crater is a bowl-shaped depression, about 180 m deep and 1.2 km in diameter, and is encompassed by a rim of ejecta that rises 30 to 60 m above the surrounding plain (Shoemaker, 1960). Independent dating using ^{10}Be-^{26}Al measurements (Nishiizumi *et alii*, 1991), cosmogenic ^{36}Cl measurements (Phillips *et alii*, 1991) and thermoluminescence dating of shock-metamorphosed dolomite and quartz (Sutton, 1985), places the age of the impact at about 50,000 years. In the vicinity of the crater, the Colorado Plateau is underlain by nearly flat-lying beds of Permian and Triassic age (FOOS, 1999). The crater lies near the anticlinal bend of a gentle monoclinal fold and the strata are broken by wide-spaced, north-west trending normal faults, which are typically kilometers in length but have displacements of only several meters (Shoemaker, 1960; Conley, 1977). A majority of these faults are parallel with a north-westerly regional joint set, and these joints may have led to the 'squarish' shape of the crater, as mapped by Shoemaker (1960). Roddy (1978), and subsequently Kumar & Kring (2008), measured the azumuthal bearings of the joints surrounding the crater and the faults in the crater wall.

Shoemaker (1960, 1987), Shoemaker & Kieffer (1974), Kring (2007), and Kumar *et alii*, (2010) provide a detailed description of the bedrock, ejecta and surface deposits at Meteor Crater, which we only briefly summarize here. The rocks exposed in the crater range from the Coconino Sandstone of the Permian age to the Moenkopi formation of the Triassic age, which are units in the upper portion of the Grand Canyon Sequence (Grotzinger *et alii*, 2007). A cross-section is shown in Fig. 3. The lowest exposed unit in the crater is the Coconino sandstone, composed of well-sorted quartz eolian sands (McKee, 1945). This is overlain by 3 m of Toroweap Formation, composed of sandstone and dolomite. The Kaibab Formation, an ~80 m thick unit, is composed of dolomite, dolomitic limestone, and thin calcareous sandstone horizons, and overlies the Toroweap. The Kaibab is exposed along the steep upper wall of the crater. Two beds of the Moenkopi Formation rest disconformably on the Kaibab. The bottom bed is the Wupatki Member, which is 2-6 m thick and composed of very-fine sandstone. Atop the Wupatki is the Moqui Member, which is 2-10 m and is composed of siltstone. The crater rim is underlain by a sequence of Quaternary debris and alluvium, resting on the previously described strata. The ejecta debris units in the rim consist of angular fragments ranging from 1 micron to 30 m (Shoemaker, 1987). Beneath the crater floor lies about 1.6 m of Holocene sediments resting on ~30 m of Pleistocene lake sediment that overlie 10.5 m of thoroughly mixed (by source) bedrock debris, which is most likely fallout debris (Fig. 3). Beneath this mix layer is brecciated bedrock, locally over 150 m thick.

Breccia produced by the impact consists of three units: authigenic (breccias produced by shattering approximately in situ), allogenic (breccias formed by major displacement), and mixed debris. Kring (2007) notes that the authigenic breccias at Meteor Crater are located along the faults that cross-cut the crater walls and rim, and the allogenic breccias, which are com-

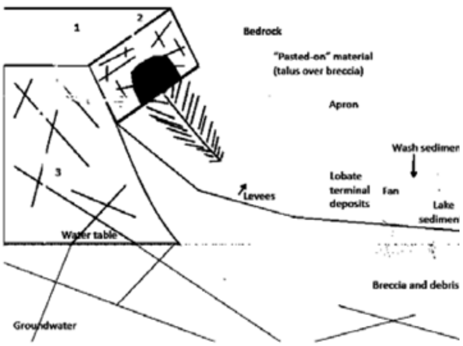

Fig. 2 - (above) Conceptual sketch of materials and surface features in crater. Note the covariation in slope gradient, materials and process. Bedrock is exposed in the upper wall (slopes >~32°). Deep canyons are cut through the equivalent of "pasted-on" materials (~20 - 32°) found on Mars and the channels terminate in lobate or tongue-shaped deposits, which through successive events cross each other (corresponding mostly to the 8 to 15° slopes in Figure 1). Water sorted sediments (wash and lake deposits) occupy the lowest regions. The fan is the cartoon is based on comments found in Kumar *et alii (2010) and has not yet been detected from the LIDAR images or the brief initial field work. The numbers refer to three general sources of water: 1) local recharge and crater wall discharge associated with impact fractures [based on* Kumar *et alii (2010)], 2) surface moisture runoff (snow melt or rain), and 3) regional groundwater rise and discharge to crater wall (not shown). Compare cartoon with Figure 3*

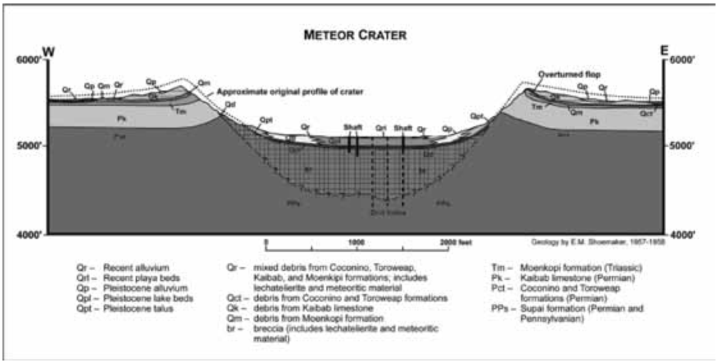

*Fig. 3 - Lithologic cross-section of Meteor crater (*Shoemaker*, 1960)*

posed of material from multiple formations as well as shock-melted Coconino and meteoritic debris, are located on the upper crater walls and in a thick lens on the crater floor.

The steepest and highest part of the crater wall consists of exposed bedrock with local patches of breccia. This is bordered by material mapped as talus by Shoemaker & Kieffer (1974), downslope of which lies sediment referred to as Pleistocene and Holocene alluvium and lake deposits (and Holocene playa beds) (Figs. 2 and 3). The talus is located in a similar position to the "pasted-on" deposits in Martian gullies (Mustard *et alii*, 2001; Christensen, 2003) and the older alluvium is similar to the "apron" deposits on Mars. The 30 m of lake sediments in the crater apparently began deposition immediately after impact (Shoemaker & Kieffer, 1974).

CURRENT AND PALEO-CLIMATE

Precipitation at Meteor Crater is 300 to 450 mm annually, with approximately equal amounts of rain and snow. Kumar *et alii* (2010) report mean annual rainfall of 200 mm and snowfall of 290 mm at the Winslow station (about 30 km away) for the past 100 years.

At Meteor Crater, grasslands dominate the vegetation. To the east of the crater, at lower elevations, there is a sagebrush ecosystem and to the west, at higher elevations, the grassland turns to woodland, dominated by juniper and pinyon (some of which is observed on the south rim of Meteor Crater) and pine (Anderson *et* *alii*, 2000; Kring, 2007). Packrat middens have been observed in the crater wall and burrowing animals are still present at the crater, as indicated by the burrow system on the crater floor (Kring, 2007).

Coats *et alii* (2008) collected sixty packrat middens across the Colorado Plateau that ranged from >48,000 years BP to present and found that differences in elevation distributions for trees and shrubs ranged from 1200 m to no change. This study also found that at some times Wisconsinan climates must have had greater monsoon precipitation than today in order to support certain conifer populations north of their current distributions. Kring (2007) found pollen deposited in the lake sediments at Meteor Crater, suggesting that woodlands might have been established near or at the impact site. However, the diversity and concentration of pollen is low, indicating it travelled from long-distances and supporting the hypothesis that sagebrush may have dominated during the late Pleistocene.

More specific paleo-climate inferences have been made for the nearby Black Mesa basin (Zhu *et alii*, 1998; Zhu *et alii*, 2010). Direct dating, numerical modelling and tracing of noble gases suggest that 14,000 to 17,000 years ago the recharge rates increased by three times relative to today. Rainfall intensity may have also been higher. Zhu *et alii* (1998) propose the pulse of high recharge was due to a northward migration of the southern branch of the split jet stream and that water level fluctuations rose by as much as 60 m relative to current levels. Recently, Wagner *et alii* (2010), reported the results of a high-resolution analysis of a speleothem from a cave in Arizona. They demonstrate that the record tracks the pattern of millennial variability seen in diverse locations throughout the Northern Hemisphere between 54 and 30 kyr BP. The record continues to about 11, 000 BP. Taken together, these studies show that a systematic wetter and cooler climate existed in the late Pleistocene, but significant climatic oscillations occurred during the period of active gully development in Meteor Crater. Snow may have been a greater proportion of the total precipitation, potentially generating snowmelt, or more intense rain may have occurred, leading to surface runoff.

CURRENT AND PALEO-HYDROLOGY

In 1978, Roddy (1978) reported that the water level in the Meteor Crater well, located 1050 m north of the point of impact, was 186 m below the ground surface (or 1500 m MSL), putting the water table about 60 m below the current crater floor. Pilon *et alii* (1991) used ground-penetrating radar to locate the water table, and found it to be ~65m below the crater bottom (or 1440 m MSL), in good agreement with the well reading. Based on the immediate formation of lake deposits post impact, Shoemaker & Kieffer (1974) proposed that at the time of impact, the water table was 30-40 m higher (1536-1546 m MSL) than the current water level. Roddy (1978), however, pointed out that shock compression of the Coconino sandstone could have induced high pore pressures which forced water to flow upward into the crater, allowing for a lake to form without the crater floor intersecting the local groundwater table.

In the Black Mesa basin in northeast Arizona, Zhu *et alii* (1998) used ^{14}C dating of groundwater in combination with numerical simulations of groundwater flow to look at groundwater levels from 40,000 years ago to present, and found that around 15,000 years ago the groundwater levels reached a maximum (55 m higher than present) and then steadily declined. Though Meteor Crater is not in the Black Mesa basin, it does share a similar climate and geology, and perhaps experienced similar groundwater levels. If so, at the time of impact, assuming the impact occurred 50,000 years ago, the groundwater levels may have been 35-40 m higher than present. Kring (2007) summarizes studies of the fossil record in the lake sediments, which suggest sustained lake levels (not seasonally dry) that may have been supported by springs.

The intensive fracturing associated with the meteorite impact may also have created "enhanced permeabilities on the crater wall rocks" (Kumar *et alii*, 2010). As illustrated in Fig. 2, if such fracturing were to lead to water directed to the walls, then perhaps very local seepage could occur there. Given that the bedrock was already relatively permeable before impact, it is not clear if a perched water table within the fractured rock and above the regional water table would occur, or if it would drain to the crater walls.

.OBSERVATIONS AND DISCUSSION

Meteor Crater serves as an analogue to Martian gullies for several reasons. Firstly, it shares morphological similarities to Martian gullies. In addition to having erosional features with the classic "alcovechannel-apron" shape, the crater also has thick talus deposits that the gullies have eroded into, similar to the "pasted-on" terrain into which Martian gullies have eroded. Secondly, it is a well-studied crater, from its formation mechanism to its geology to its past hydrology and ecology, data which are almost impossible to obtain about any crater on Mars. Thirdly, it has evidence of a paleo-lake that may have been supported by an elevated water table. This fairly raises the question about groundwater influences, which is a central question concerning Martian gullies, since many craters on Mars also show signs of past lake deposits. And lastly, it is young enough that its full erosional history can be deciphered.

For these reasons, we have obtained a high-resolution topographic data set from the National Center for Airborne Laser Mapping (NCALM), which allows us to detect detailed morphology of the gullies, including their levees. With this dataset and an initial field campaign we have observed that the Meteor Crater gullies: 1) cut through talus, 2) show evidence of multiple events, 3) do not cross the crater floor, 4) mostly terminate on an apron that has a slope between 8 to 15 degrees, 5) are 1 to 10 m wide across the top of the alcove, and 6) have modest-sized, but distinctive, levees.

As mentioned previously, most Martian gullies occur on slopes that are partially mantled with material that has most likely been atmospherically deposited.. The scarcity of large boulders in HiRISE images of the depositional region and the abundance of large boulders in the wall rock exposed in alcoves seems to indicate that gully forming processes entrain and transport pasted-on material, not material derived from wall rock. Also, it is likely that the pasted-on material is largely composed of fine material, ranging from sand to dust-sized particles, and it is this size range that is important for forming flows capable of deep channels, natural levees or hummocky terminal deposits. Many of the gullies on Meteor crater, which cut through deposited terrain (i.e. talus), may work in the same way.

Kumar *et alii* (2010) describe in detail the "alcove-like" headwater areas to the gullies. They note that the alcoves occur on the bedrock exposures on the upper to middle crater walls, either originating from the rim crest or below the contact of the Kaibab dolomite and Coconino sandstone. The alcoves in the Coconino sandstone tend to be wider and deeper than those in the Kaibab, most likely due to the differences in weathering between the hard Kaibab dolomites and the soft Coconino sandstone. Kumar *et alii* (2010) also note that the larger gullies incise down into the bedrock and the smaller gullies incise only talus and alluvial deposits. The crater also has an extensive network of fractures, which have been grouped into three categories by Kumar & Kring (2008): radial, concentric, and conical. Based on the observations of Kumar *et alii* (2010), most of the gullies occur preferentially along the radial fractures, which strike more or less perpendicularly to the bedding planes. Based on our inspection of one alcove area, there was no evidence that seepage had occurred. There was no staining, or coarse lag deposits, and the channels below showed no sign of sustained fluvial wash.

We observed at our site (and it has been observed on Mars) that portions of the aprons are not connected to their chutes and are generally smoother in appear-

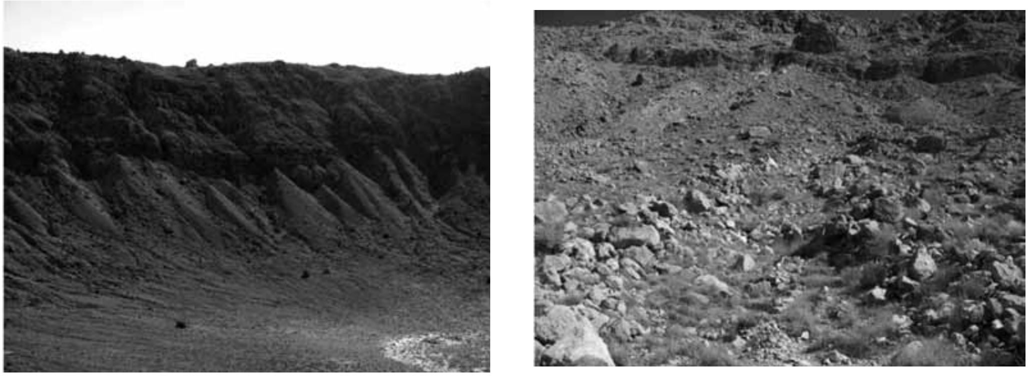

Fig. 4 - A. Photograph (above left) of Meteor Crater showing upper bedrock, lowered mantled (pasted-on) slope followed by hummocky apron of crossing levee deposits down to white playa lake area. B. Photograph (above right) looking upslope in apron area showing boulder levees

ance. In addition, chutes disconnected from source alcoves, degraded chutes, terraces along chutes, and apron-head trenching indicate multiple flow events. It is plausible that the formation of the Meteor Crater alcoves, chutes, and aprons (as well as the Martian ones) requires many flow events to form.

Another feature that both Meteor Crater and Martian gullies share is the abrupt termination of chutes and hummocky deposits. Photogrammetric measurement of depositional aprons on Mars indicates that most exhibit nearly linear profiles inclined 8 to 15 degrees (Howard *et alii*, 2008a; Parsons & Nimmo, 2010). At Meteor Crater, we observed that the channels do not form an integrated network, and commonly they either terminate abruptly without a fan or end in a lobate, or tongue-like, deposit of debris. This apron transition from the talus incision to the termination point, lying in the ~8 to 15 degree slope range (the same as on Mars), corresponds to an elevation drop from 1580 m to 1570 m. The lower elevation is about the height of the highest mapped lake sediments in the crater [the bottom of crater is at about 1561 m above mean sea level (MSL)].

Modest sized levees were seen on foot and are detectable with the 25 cm contour-interval LiDAR data, and are characteristic of mass wasting, not fluvial processes. Exposure in the levee walls show that the levees are cored by matrix supported material. However, locally, well-sorted boulder levees do occur. We have not yet detected features that suggest a delta transition into standing water. Also, if sustained seepage occurred due to the intersection of the crater wall with the water table, we would expect that alluvial fans would be present at the mouth of the channels, but inspection of the LiDAR data does not detect such features.

.AN ALTERNATIVE HYPOTHESIS TO GROUNDWATER SEEPAGE

Kumar *et alii* (2010) argue that the gullies at Meteor Crater are associated with the radial fractures and tear faults exposed in the crater walls and suggest this association is due in part to groundwater discharge. This discharge could be derived from local recharge in the fractured rock surrounding the crater. They conclude that "fluvial processes eroded the materials from the crater walls and deposited them as Pleistocene alluvium… inter-fingered with lake sediments". Aside from the observation that the gullies occur preferentially along the fracture-fault system in the crater wall, there is no other quantitative or qualitative data that exists to support the inference that fluvial processes (e.g. surface runoff producing overland flow or small creeks) are the erosive and transporting agent.

Our observations suggest that an alternative explanation to the previously proposed seepage erosion and fluvial incision and deposition scenario may be needed. From the point of view of modeling gully formation processes on Mars, it is important to distinguish river incision and deposition (fluvial processes) from that done by debris flows (mass transport). River transport of coarse sediment on steep slopes is a subject of active research in terrestrial channels (e.g. Yager *et alii*, 2007; Lamb *et alii*, 2008). Field observations suggest that shallow flows on steep slopes often cannot generate sufficient boundary shear stresses to mobilize coarse sediment (i.e. cobbles and boulders) as bedload. Instead, sweeping of coarse sediment downslope and incision into underlying bedrock is driven by periodic debris flows (Stock & Dietrich, 2003 and 2006). This distinction is important: much more water is needed to transport sediment, and erode bedrock, (e.g. Sklar & Dietrich, 2004) at the relatively low concentrations of bedload transport than is necessary to produce a mass flow that can scour and mobilize large particles. Experimental work by Hsu *et alii* (2008) demonstrates the effectiveness of debris flow incision into bedrock. Hence, it is important if the Meteor Crater gullies are to be used to test models like those of Parsons & Nimmo (2010) that we quantify the relative role of fluvial versus debris flow processes in the incision, transport and deposition of sediment.

As an alternative to current interpretations, we propose that debris flows, perhaps driven by periodic snowmelt during the cooler, wetter Pleistocene drove gully incision into the talus and led to interlacing channels downslope (Fig. 2). An essential ingredient was not just water, but the presence of fines, that when mixed with water served to mobilize and sustain the debris flow motion. We hypothesize that the fines are derived in part from the crushed rock and dust that is patchily found around the crater. The talus has some strength so that it can support cuts into it, and yet, through erosion, it may provide the necessary fines for debris flow mobilization. If our future work finds this to be correct, it will provide an additional constraint on the essential elements for debris flow initiation and mobilization on Mars (i.e. fines from impact waste).

CONCLUSIONS AND FUTURE WORK

Key observations and data are still needed to resolve the difference between the previous groundwater seepage model coupled to fluvial incision and our debris flow model from surface water (perhaps from snow melt). Our goal for this paper was merely to add to the observations of Kumar *et alii* (2010) and propose an alternative way of interpreting these observations. It is now necessary to: 1) identify morphologic, sedimentologic and weathering features that would support a seepage versus surface water origin of the channels via field observation and careful analysis of LiDAR data, 2) determine the maximum height of the ground water table during the late Pleistocene through the use of numerical groundwater models, 3) obtain cosmogenic dating of the most recent debris flows to find out if they were active in the Holocene (when the water table was presumably near current levels), and 4) document of the role of crushed rock fines in debris flow generation through large scale experimentation in a vertically rotating drum [similar to the work of Hsu (2010)].

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