Impact fracturing and structural modification of sedimentary rocks at Meteor Crater, Arizona

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1. Introduction

One of the most important characteristics of meteorite impact is the deformation of target rocks, which produces an excavated cavity, uplifted rim, and stratigraphically overturned ejecta blanket. The deformation occurs in a catastrophic burst of energy that fractures, melts, and vaporizes material in a few seconds to a few minutes, depending on the size of the impact event. Deformational stresses are at least 10⁶ to 10⁸ greater than material strength and strain rates are often 10⁹ to 10¹³/s, which are 7 to 12 orders of magnitude greater than that of other geologic processes [Gault et al., 1968; French, 1998]. When an asteroid or comet hits a planetary surface, a shock wave radiates into the crust, compressing target lithologies in an expanding semihemispherical volume of rock. With increasing distance from the point of impact the shock wave weakens. A rarefaction or release wave follows the shock wave. The combined effect of these waves is to create a flow of material that initially moves downward, then outward and upward, excavating and ejecting material to form the crater cavity. The crater wall represents the limit where the flow is unable to eject material, although wall rock is still uplifted to produce a ring syncline with an axial trace beyond the crater rim. Furthermore, some of the ejected components remain stratigraphically coherent and are structurally overturned and redeposited on the uplifted crater rim. Deformation is not limited to excavated components, but also occurs at greater radial distances from the point of impact where shock waves permeate the crater walls and surrounding bedrock. Rock is displaced to a depth about 3 times greater than the excavated depth, defining a transient crater that is partially filled with deformed rock, impact breccias, and, in large events, impact melt [Dence et al., 1977; Grieve et al., 1977]. Although the energy of the impact event is accommodated by or dissipated within a large volume of fractured rock beyond the crater walls, this deformation is still poorly understood.

Few simple craters on Earth are sufficiently well preserved to lend themselves to a structural analysis of deformation within crater walls. One of the most interesting examples is the ~220 ka Tswaing impact crater. Formerly known as the Pretoria Saltpan crater, this structure is ~1 km in diameter and carved from granite and a thin veneer of
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Kumar [1963] mapped as three units (Figure 2): authigenic breccia, allogenic breccia, and mixed debris. The authigenic breccia is basically the fault gauge materials that occur along crater wall faults, whereas the allogenic breccias are composed of shocked rock fragments and meteoritic materials, which are well exposed on the middle to lower parts of the western and northern walls. Mixed breccias are composed of rock fragments derived from the crater wall and meteorite fragments; these are interpreted to be fallback ejecta materials.

[5] In this study, we present the results of a detailed structural analysis of the rock exposures far outside the crater, which are considered to be a proxy of preimpact target rocks, and bedrocks on the crater wall that preserve impact-generated structures. Both outside and inside the crater we have measured the geometries of the bedding planes of Moenkopi and Kaibab formations, the fracture systems, and where ever possible, the geometry of faults and worked out their kinematics. Over 2500 measurements were made in June 2007. The strike/dip data have been imported into digitized equal-area plots (Schmidt net) and evaluated using computer techniques (e.g., RockWorks-2006 software) in order to separate the unique features generated by the impact event from regional tectonic features [e.g., Kumar, 2005]. In section 3, we present the results of the structural geological mapping that will allow a comparison of the nature of target rocks before and after the impact event.

3. Preimpact Structures

[5] Preimpact structures include topography, geometry of rock formations, and weak zones (e.g., faults and fractures)
in them. These preexisting structures can be studied beyond the region affected by crater formation to determine if they influenced the formation of impact deformational features and final crater morphology. A ~1070-m-thick horizontally bedded set of Paleozoic to Mesozoic sedimentary strata and underlying granite-gneiss basement provide the structural context for Meteor Crater. The sedimentary sequence is composed of an ~100 m thick Martin Formation, ~23-m-thick Redwall Formation, ~85-m-thick Naco Formation, ~550-m-thick Supai Formation, ~220-m-thick Coconino Formation, ~3-m-thick Toroweap Formation, ~80-m-thick Kaibab Formation and ~9-m-thick Moenkopi Formation.

Figure 1. (a) An overlay of the schematic geologic map of the region around Meteor Crater and a Columbia space shuttle image [Kring, 2007]. Anticlinal and synclinal bends and the fault traces have been drawn on the basis of the work by Shoemaker [1960]; contacts between the Permian Kaibab (Pk), Triassic Moenkopi (Tm), and Quaternary basalt (Qb) are drawn approximately. (b) An overhead aerial view of Meteor Crater. Rim-to-rim distance is ~1.2 km.
These formations represent the well-known Grand Canyon sequence. The crater occurs in an area that is variously capped by Moenkopi and Kaibab formations (Figure 1). For more details of the target lithologies, see Kring [2007].

Drilling studies that penetrated the ejecta blanket indicate the preimpact ground surface of Moenkopi was nearly flat and similar to present-day topography [Roddy et al., 1975]. The rock formations also have near-horizontal bedding planes. However, in some places these rock formations have been affected by gentle folding in the form of N-S to NNW-SSE oriented very broad open folds (Figure 1). It has also been suggested that the crater was emplaced on an anticlinal axis of a gentle monoclinal fold [Shoemaker, 1960]. However, according to Roddy et al. [1975], local dips of the strata are only on the order of a degree or less. Shoemaker [1960] observed two mutually perpendicular sets of preimpact vertical joints of uniform strike (NE-SW and NW-SE). Furthermore, Roddy [1978] reported two
more joint systems in the Moenkopi Formation: NNW-SSE and ENE-WSW oriented subvertical joints. All these joint systems are well preserved in the exposures of Moenkopi and Kaibab formations, and are thought to have been formed as a result of tectonic deformation affecting the Colorado Plateau well before the impact event [e.g., Kelley and Clinton, 1960]. These joint systems also control the regional fluvial drainage development of the plateau [Shoemaker, 1963]. In addition to these fracture systems, faults subparallel to the NNW-SSE to NW-SE oriented fracture systems occur in the area and extend for more than a kilometer. However, according to Roddy [1978], none of these faults occurred at the point of impact and they were at least 5 km from the point of impact (Figure 1).

[10] Although preimpact fracture systems have been reported previously [Shoemaker, 1960; Roddy, 1978], the data are sparse and no longer available for analysis. Also, many of the previous data were collected from stereophotographic measurements [see Roddy, 1978]. Therefore, we have collected a new set of data containing the strike/dip measurements of the Moenkopi and Kaibab bedding planes and the fractures present in them. The data are presented in Figure 3. Our measurements illustrate that the bedding planes of sedimentary rocks are nearly horizontal (mean dip: $4^\circ \pm 1^\circ)$ (Figure 3), confirming the earlier drilling results and outcrop measurements. The new measurements also reveal a few additional details. We find that the majority of the fractures in the Kaibab Formation are oriented in ENE-WSW direction with subvertical dips. As previously suggested by Shoemaker [1963], these fractures probably control the regional drainage patterns around the crater. Interestingly, this dominant fracture set is also approximately parallel to the ENE-WSW crater walls (Figure 3). Therefore, the data indicate the preexisting fractures do not strictly bisect the crater corners, and most of them are, indeed, parallel to the crater long walls.

4. Impact-Generated Structures

[11] Impact deformational structures include folds, faults, fractures, and rim uplift that changes the attitude of the rock formations in and around the crater. Unlike preimpact tectonic structures, these are formed within a few seconds or less. The best place to observe these impact structures in a simple crater are in the bedrocks exposed on the inner crater walls [e.g., Kumar, 2005] and along a cross section of the crater rim [e.g., Brandt and Reimold, 1995]. Although the morphology of Meteor Crater has been said to be influenced by the preimpact joint systems [Shoemaker, 1963], there has been no detailed study that relates how the preimpact fractures affected the impact deformational features exposed on the crater wall. The previous studies apparently lack documentation of impact related joint or fracture systems along the entire crater inner wall. Therefore, we have conducted a structural analysis of the Moqui and Wupatki members of the Moenkopi Formation and the Alpha Member of the Kaibab Formation; these rock formations are more or less continuously exposed below the ejecta, whereas the underlying rock formations are only intermittently exposed on steep slopes where they are largely covered by talus and alluvium near the present-day crater floor. Hence, structural mapping was restricted to the upper crater wall. It involved documentation of the geometry of bedding planes, various fracture systems, faults and slump units. The inner crater wall can be divided into twelve angular zones or tectonic blocks (Figure 2) that are bounded by prominent faults with near-vertical, scissor-like faults [e.g., Shoemaker, 1960; Kring, 2007]. Technically, however, they may be better described as high-angle, dip-slip faults. The largest fault occurring in the southeast corner has generated ~45 m of displacement [Shoemaker and Kieffer, 1974]. Structural measurements within the blocks were collected and then compared with adjacent blocks.

[12] These measurements reveal radial, concentric, and conical sets of fractures, which are illustrated in outcrop view (Figure 4) and schematically (Figure 5). Figures 6, 7, and 8 show the measured geometries of these radial, concentric, and conical fracture systems in the upper crater wall, respectively. The radial fractures have subvertical dips and strike approximately perpendicular to the bedding...
Figure 3. Preimpact structures seen far outside the Meteor Crater deformation zone. (a and b) Great circles and pole density contours representing the geometry of bedding planes in the Moqui Member of the Moenkopi Formation and Alpha Member of the Kaibab Formation; The Wupatki Member is not included here because bedding orientations were sometimes difficult to isolate from strong cross-bedded laminae in the unit. (c) A field photograph showing horizontal bedding surfaces of the Kaibab Formation. (d, e, and f) Great circles, pole density contours, and bidirectional rose diagram showing the orientation of fractures in both Moqui and Wupatki members of the Moenkopi Formation. (g, h, and i) Great circles, pole density contours, and bidirectional rose diagram showing the orientation of fractures in the Kaibab Formation, respectively. Equal-area (or Schmidt) net is used to show the great circles and pole density contours throughout the paper. Pole density range (in percent) and contour interval (in percent) are shown inside the equal-area plots of Figures 3a, 3b, 3e, and 3h; n represents a number of strike/dip measurements. Throughout the paper, the strikes are shown with reference to the geographic north considering the magnetic declination value of $\sim 11^\circ$ east for June 2007 [National Geophysical Data Center, 2007].
Figure 4. Crater wall pictures showing (a) outward dipping bedding planes of the Kaibab dolomite that expose traces of fractures; (b) radial fractures in the Kaibab dolomite; (c) a trace of steeply dipping concentric fracture in the Moenkopi sandstone showing slumping; and (d) a conical fracture in the Kaibab dolomite cutting the bedding planes.

Figure 5. A schematic diagram showing the crater wall fractures.
planes, although some of them are oriented obliquely. In
general, the radial fractures have preferred orientations, in
the directions of NNW-SSE and ENE-WSW, approximately
parallel to the crater long walls (Figure 6). The radial
fractures occur as single, conjugate pairs, and branching
types. Most of them are straight to curvilinear on map view.
The concentric fractures strike more or less parallel to the
bedding planes and dip away from the dip directions of the
bedding planes (Figure 7). That is, the concentric fractures
dip toward the center of the crater except where affected by
lateral tilting (e.g., drag folding near a tear fault). The
amount of dip of these fractures is also highly variable.
The concentric fractures also have preferred orientation in
the direction of the dominant preimpact fractures, i.e.,
ENW-ESE, while the other sets are less dominant. The
conical fractures are similar to the concentric fractures in
their strikes, but have highly variable dips that are roughly
in the direction of the bedding planes (Figure 8). Interest-
ingly, the conical fractures have a preferred orientation with
a NW-SE bearing and a less dominant NE-SW bearing.
Faulting may have also been accommodated along bedding planes, but that type of fault slip and/or fracturing is still poorly documented [e.g., Kring, 2007] and is not included in our population of conical fractures. In general, the radial, concentric and conical fractures show mutual crosscutting relationships.

[13] The crater wall is cut by several fault systems, whose orientations are also parallel to the preexisting joint systems (Figures 2 and 3). The four corners of the crater have the most prominent tear faults (Figure 9), which are parallel to the preexisting NW-SE and NE-SW fractures and are generally thought to have been activated into tear faults during the excavation phase of the crater forming event [Shoemaker, 1960; Roddy, 1978]. Thrust faults have also been observed [Shoemaker, 1960], which occur subparallel to the bedding surfaces in the sedimentary rocks (Figure 2). The relationship between the thrust faults and fracturing reported here is unclear. Slumping is common on the inner slope and appears to have formed during the crater modi-
Inside Crater: Conical Fractures

Figure 8. Impact structures (conical fractures): great circles, pole density contours, and bidirectional rose diagrams representing the geometry of conical fractures in the Moenkopi (Moqui and Wupatki members) and Kaibab (Alpha and Beta members) formations of the 12 crater wall tectonic blocks. The pole density range (in percent) and contour interval (in percent) are shown inside the equal-area plots; n represents a number of strike/dip measurements. A bidirectional rose diagram representing all measurements indicates preferential orientations of the conical fractures.

5. Link Between the Preimpact and Impact Fractures

[14] Figure 10 summarizes the nature of target rocks before and after the impact. Before the impact, the bedding surfaces are essentially horizontal, while after the impact, they acquire an asymmetric uplift pattern seen in the form of an amoeboid-shaped pole density contour pattern. The impact-related crater wall fractures appear different from the preimpact fracture systems. Although the impact may have generated new fracture orientations, a genetic link may also be masked by a reorganization of preimpact fractures during rim uplift. Crater rim uplift creates average dips of 20° to 56° and even overturns bedrock strata (Figure 11). In order to distinguish new from reoriented fracture orientations, we have recalculated the strikes and dips of the crater wall
fractures by bringing their host sedimentary bedding planes to a preimpact horizontal plane. This calculation was done using the mean strike/dip values of the bedding planes in each tectonic block. When the crater rim is restored to a preimpact condition, the geometries of radial and concentric fractures resemble preimpact fracture populations (Figure 12). For example, the radial fractures maintain their preferred orientations (NNW-SSE and ENE-WSW) after the crater rim restoration. Interestingly, the NNW-SSE set of fractures in the crater walls are similar in orientation to a preimpact set of fracture, but do not reflect the dominant orientation among preimpact fractures. This may be a consequence of an impact parameter, like trajectory, that is not yet understood. Also, after restoration, the concentric fractures do not show any significant variation and the preferred orientation remains in the direction of ESE-WNW, similar to one of the preimpact fracture orientations. Therefore, it appears the preimpact fracture system controlled the radial and concentric fracture systems and the near-squarish shape of Meteor Crater as surmised previously by Shoemaker [1960]. This primary source for the square shape of the crater has been accentuated by preferential erosion along those faults and the authigenic breccia that fill them.

[15] Interestingly, upon rim restoration, the conical fractures acquire a spoke-like geometry, with a slight dominance in NE-SW and NW-SE directions coinciding with the corner zone tear faults (Figure 12). Significantly, the orientations of the conical fractures are dissimilar to those of preimpact fractures and appear to be formed purely by the impact. The near-perfect symmetry of the restored orientations of the conical fractures (Figure 12), compared to the preferred orientations seen in the uplifted crater rim (Figure 8), implies most of the conical fractures formed before the bulk of the structural rim uplift and reactivation of (and potentially the formation of new) radial and concentric fractures.

[16] The radial, concentric, and conical fractures documented above are visible in the existing crater wall. Erosion has cut back into the original crater wall [e.g., Kring, 2007], suggesting we are seeing features that extended at least several meters beyond the original crater wall. Geophysical studies have delineated fracture systems beneath the ejecta blanket and the crater floor. For example, a ground-penetrating radar study of bedrock beneath ejecta on the crater rim [Pilon et al., 1991] identified two
sets of faults: (1) a few outward dipping reverse faults that are regularly distributed to a radial distance >700 m from the rim crest and (2) a few inward dipping thrust faults across the rim crest. Dips of the reverse faults are comparable to the conical fractures but are much steeper and therefore it is unlikely that the faults are genetically related to the fractures. In contrast, the geometry of the inward dipping thrust faults in the rim crest is similar to the concentric fractures exposed on the crater wall; however, it is unclear whether the concentric fractures have been involved in thrusting prior to crater wall slumping. A model of seismic refraction data [Ackermann et al., 1975] suggests fracturing extends to a depth of 800 m beneath the crater rim, shallowing but extending out to radial distances >900 m. Gravity data [Regan and Hinze, 1975] and drilling studies [Roddy et al., 1975] indicate fracturing beneath the true crater floor, but the actual extent of impact fractures is not yet fully understood. Therefore, it is uncertain whether the types of fracturing and the orientation of fracturing we observe in the upper crater walls are similar to those at depth. Potentially, some insights might be gleaned from studies of complex craters in sedimentary targets whose deeper levels are exposed because of erosion [e.g., Kriens et al., 1999; Scherler et al., 2006; Okubo and Schultz, 2007]. However, in those complex craters the type of fracture systems described at Meteor Crater will be modified by the flow of material to form a central peak and the extensive collapse of transient crater walls.

6. Comparing Simple Craters in Basalt and Sedimentary Rocks

[17] Lonar Crater is a simple, bowl-shaped impact crater that is similar in size (~1.8 km diameter, ~120 m deep) and age (~50 ka) to Meteor Crater [see Fudali et al., 1980; Kumar, 2005]. In contrast, however, it was excavated from a layered sequence of basalt lava flows rather than sedimentary rocks. Significant differences exist in the nature of rim uplift and geometries and distribution of fractures and faults (Figure 13). Unlike Meteor Crater, it has a circular rather than square outline. Unlike Meteor Crater, it also has a circular distribution of impact deformation, instead of the preferred orientations seen at Meteor Crater. The target rocks for these two craters are different, which may partially explain these differences. The basalts of Lonar Crater have a much higher dynamic strength than the sedimentary rocks at Meteor Crater [Ai and Ahrens, 2004]. Also, preexisting tectonic fractures are less abundant at Lonar Crater than at Meteor Crater.

[18] A detailed view of the structural features in the upper crater wall at Lonar is illustrated by Kumar [2005]. The basalt sequence has been turned upward, producing a circular deformation pattern. Mean dips of lava flows vary from 5 to 35°, which are much lower than the dips of sedimentary rocks at Meteor Crater. Indeed, the rim of Lonar Crater is only 20 m higher than the surrounding plain [Fredriksson et al., 1979]. If crater wall slumping during the modification stage is not greater than that at Meteor Crater and if erosion is similar, then there was less rim uplift at Lonar Crater than at Meteor Crater. This is particularly surprising because Lonar is slightly larger than Meteor Crater (~1.8 km versus ~1.2 km) and should, thus, have a correspondingly higher rim. The difference may be due to the target strength and impact parameters. Like Meteor Crater, three fracture systems (radial, concentric, and conical) are exposed on the inner crater wall. Interestingly, the radial fractures have spoke-like arrangement, unlike similar fractures at Meteor Crater that have preferred orientations. The concentric and conical fractures also show circularity in their strike pattern, unlike those at Meteor Crater where they have preferred orientations. Radial tear faults are apparently absent at Lonar Crater. Uplift and tilting of the basalt sequence and formation of the fractures inside the crater are clearly related to the impact event and are different from the preimpact structures such as cooling-related columnar joints and fractures of possible tectonic origin, which are observed outside the crater; however, the preimpact fractures are less abundant in the target basalts. These observations suggest that the shallower dips in the uplifted crater wall strata and
relatively small rim height at Lonar Crater are produced by a combination of the inherent strength of basalt relative to sedimentary rocks and the lack of a preexisting fracture system like that at Meteor Crater. The relative contributions of these two factors, however, still need to be resolved.

7. Fractures in Artificial Craters: Implications for Impact Fracturing

[19] Laboratory experimental impact craters on rocks and ice, plus small-scale impacts on spacecraft components, generate impact fracture networks that may provide insights to impact fracturing [e.g., Polanskey and Ahrens, 1990; Arakawa et al., 2000; Graham et al., 2004]. It appears that deformational processes of these strength-controlled artificial craters are similar to those of strength-controlled natural simple craters [Ahrens et al., 2002]. The distribution of impact fractures and their relative ages are shown in a plan view of the images of cratered solar panels (Figures 14a and 14b), which are permeated with concentric fractures and/or damage zones and radial fractures. While the radial fractures predate the concentric zones, in some cases they postdate them. For example, the radial fractures have developed from the concentric damage zones (Figure 14a); in other cases, the concentric zones limit the growth of radial ones (Figure 14b). More interestingly, in some instances, many of the radial fractures appear very similar to the branching-type dynamic tensile fractures produced in laboratory experiments. This points to the growth of very high velocity fractures during the impact [see Sagy et al., 2001]. A vertical section across the laboratory impact crater (Figure 14c) on gabbro reveals the sets of radial and concentric fractures below a zone of near-surface fractures, location of which coincides with the theoretical near-surface zone predicted by a spallation model [Polanskey and Ahrens, 1990] (Figure 14c). The relative age relationship between the radial and concentric fractures in vertical section is also the same as those seen on the plan view of spacecraft craters.

[20] The radial and concentric fractures seen on the plan view of Meteor Crater (Figures 6 and 7) appear similar to those of the artificial craters (Figures 14a and 14b), and probably, the conical fractures of the Meteor Crater (Figure 8) are comparable to the radial fractures seen on the vertical section of the artificial crater (Figure 14c). However, it must be remembered that the radial and concentric fractures of Meteor Crater are largely produced by reactivation of preimpact tectonic fractures, and those formed in the artificial craters are purely related to impacts, as the targets of artificial craters do not appear to contain any visible preimpact fracture systems. Therefore, the comparison does not necessarily reflect the same mechanism of fracture formation. It is worth mentioning here that there have been no experimental or numerical studies that describe how impact fractures would form in the presence of closely or regularly spaced preimpact fracture systems in the target rocks. Obviously, preimpact weakness zones would reduce the dynamic strength of the
Figure 12. Equal-area plots of pole density contours and bidirectional rose diagrams displaying the geometry of impact fractures, when the bedding surfaces are restored to the horizontal surface, similar to the preimpact target conditions. (a) Note that the geometry of the radial fractures is more or less parallel to the straight walls of the crater, suggesting their production was affected by the same preimpact fracture system that is responsible for the near-squarish outline of the crater. (b) The concentric fractures have an approximately E-W preferred orientation, similar to one of the dominant orientations of the preimpact fractures. (c) The conical fractures show a radial pattern dissimilar to the preimpact fractures and, therefore, appear to be an independent impact-related product; the NW-SE and NE-SW conical fractures are subparallel to the major tear faults occurring in the crater diagonals.

Figure 13. A comparison between the impact structures of (a) Meteor Crater and (b) Lonar Crater. Number of strike/dip measurements (n); pole density range in percent (r); and contour interval in percent (i).
target materials. In addition, in the presence of such preimpact weakness zones, the target would behave somewhat differently in response to the impact. For example, motions would preferentially occur along these weakness zones when shock waves pass through the target medium; this condition may inhibit the formation of new fractures, rather they would preferentially reactivate the existing ones. For example, Gault et al. [1968] show that crater flow during excavation can be greatly influenced by preexisting weakness zones. Nuclear explosion craters also provide ample evidence in support of the reactivation process. For example, the explosion craters formed in the alluvial flat of Yucca region of Nevada clearly suggest that the development of explosion-related fracture systems around the craters have been greatly influenced by the preexisting weakness zones in the bed rocks (Figure 14d).

Impact fractures form as a result of the passage of shock waves in the target medium [see Sagy et al., 2004, and references therein]. For example, cratering experiments on water ice has indicated the relationship between the passage of shock waves and the initiation of tensile radial fractures, which apparently form immediately after the passage of seismic precursor waves [Arakawa et al., 2000]. Also in rocks, the radial fractures are formed immediately behind the outgoing stress wave, whereas the concentric fractures are initiated at later times and appear to be related to the tensile phase of the stress pulse associated with sudden release of the impulsive force applied at the surface [see Ahrens and Rubin, 1993, and references therein]. The radial cracks are formed perpendicular to the direction of peak tension, and thus normal to the quasi spherical compressive wavefront. These mechanical processes can probably be extended to natural craters. The impact structures documented from Meteor Crater can thus be related to the response of target rocks to the shock wave propagation at the time of crater excavation and crater wall slumping related to the crater modification after excavation. However, the presence of preexisting weakness zones and their geometry significantly affect the interaction between the target bedrock and the expanding shock wave, and, thus, the formation of the transient crater and any subsequent crater wall collapse. For example the excavation flow and the crater collapse should occur preferentially along any preexisting weakness zones.

8. Conclusions

Over 2500 structural measurements reveal that the upper crater walls of Meteor Crater are crosscut by three distinct groups of fractures: radial, concentric, and conical fractures. These are similar to the types of fractures that occur at Lonar Crater [Kumar, 2005]. We also confirm that the target was crosscut by three prominent sets of preimpact tectonic fracture systems. The majority of the preimpact fractures are parallel to the crater long walls, suggesting that either the excavating flow preferentially hinged and overturned material along the fractures or that crater wall slumping preferentially occurred along those fractures (or both).

When the crater rim is restored to preimpact condition, the geometry of the radial and concentric fractures resembles preimpact fracture populations, indicating that crater wall deformation and rim uplift was partly accommodated by activation of preexisting fractures. In contrast, the conical fractures have orientations that are dissimilar to the preimpact fractures and apparently formed as a direct result of impact deformation. Some of the fractures were transformed into tear faults during the impact event. Furthermore, we confirm that a combination of fractured-controlled motion along the crater walls and along the tear faults created the unusual square shape of Meteor Crater in plan view. This feature was subsequently enhanced by preferential erosion along those fractures/fauxts and the authigenic breccia in them. A symmetric distribution of conical fractures appears to have been produced prior to crater rim uplift and complex motion along tear faults. Thus, most conical fractures were produced prior to motion that was activated along radial and concentric fractures during crater rim uplift and subsequent slumping of inner crater walls.

The preimpact fracture system in the Meteor Crater region weakened the target lithologies affected by the impact event. Not only did this entranch and facilitate motion along radial and concentric fractures, it led to greater rim uplift (at least 30 to 60 m) than that seen at Lonar Crater (only 20 m) in a stronger set of basaltic lava flows. These data imply that structural deformation, crater rim uplift, and the morphology of simple craters are influenced by the preimpact structural state of target lithologies. Similar affects may occur on the Moon where some impacts occur in relatively strong crystalline lithologies and others occur in weakened cataclasites or thick regolith. Likewise, similar affects may occur on Mars, where some impacts may occur in relatively strong crystalline lithologies while others occur in relatively weak sedimentary and pyroclastic deposits.

Figure 14. (a and b) Secondary electron micrographs of impact craters formed on the solar panels of spacecrafts by micrometeoroid impacts [Graham et al., 2004] (with permission from the Geological Society of London); box b1 in Figure 14b shows the traces of radial (labeled R) and concentric (labeled C) fractures and the relationship between them. (c) A cross section of an experimentally produced crater on San Marcos gabbro by Polanskey and Ahrens [1990] (with permission from Elsevier); note the occurrence of three types of fractures: radial (RF), concentric (CF), and near-surface fractures (NSF), which all occur below a theoretical near-surface zone (TNSZ). (d) Fractures around a nuclear test site in the Yucca flat region of Nevada [Barosh, 1968] (with permission from the Geological Society of America). This is a classic example for a fracture pattern formed in response to the reactivation of preimpact fractures by a nuclear explosion. The NW-SE (labeled 1) and NE-SW fractures (labeled 3) are subparallel to the preexisting faults/fractures in the basement rocks exposed around Yucca flat. However, a few of them are similar to the radial fractures seen in the meteorite impact craters. The concentric fractures (labeled 2) may be related to the crater collapse.
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