**FOLD HINGE IN OVERTURNED COCONINO SANDSTONE AND ITS STRUCTURAL DISPLACEMENT DURING THE FORMATION OF BARRINGER METEORITE CRATER (a k a METEOR CRATER).** D. A. Kring[1,2], J. Balcerski[3], D. M. Blair[4], M. Chojnacki[5], P. H. Donohue[6], S. A. Drummond[5], J. M. Garber[7], M. Hopkins[8], M. S. Huber[9], S. J. Jaret[10], A. Losiak[9], A. Maier[8], J. Mitchell[11], L. Ong[12], L. R. Ostrach[13], K. M. O'Sullivan[6], R. W. K. Potter[14], S. Robbins[8], B. Shankar[15], E. K. Shea[16], K. N. Singer[17], M. Sori[16], S. Sturm[18], M. Willmes[18], M. Zanetti[17], and A. Wittmann[1,2], [1]Center for Lunar Science and Exploration, USRA-Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, kring@lpi.usra.edu), [2]NASA Lunar Science Institute, [3]Case Western Reserve Univ., [4]Purdue Univ., [5]Univ. Tennessee, [6]Univ. Notre Dame, [7]Univ. California - Davis, [8]Univ. Colorado-Boulder, [9]Univ. Vienna, [10]Harvard Univ., [11]Univ. Houston-Clear Lake, [12]Univ. Arizona, [13]Arizona State Univ., [14]Imperial College London, [15]Univ. Western Ontario, [16]Massachusetts Institute of Technology, [17]Washington Univ., [18]Westfälische Wilhelms-Univ. Münster.

**Introduction:** Impact crater rims are produced by uplifting and overturning target units. In structural terms, the overturned rim is a compound syncline, because there are actually two folds involved (*e.g.*, Chapter 6 of [1]). Uplift of the target produces a ring syncline that lies buried beyond the crater rim and is either inferred from changes of dip or imaged using geophysical techniques. At the 1.2 km diameter Barringer Meteorite Crater, the axial trace of the ring syncline is located ~0.4 km beyond the crater rim [2,3]. The other syncline occurs in the rim of the crater and can be seen as an overturned stratigraphic sequence (*e.g.*, [4,5]). In rare cases, fold hinges in the overturned sequence are exposed. Thus far, fold hinges have been documented (see Chapters 6 and 14 of [1]) in the Kaibab Formation, of intermediate target depth, and in the Moenkopi Formation, which was the surface unit at the time of impact. In this study, we provide the first description of a hinge within the Coconino and Toroweap sandstones, which were the basal target units affected by this impact event. We further show how that fold was dramatically displaced by the growth of the transient crater and integrated with structural thinning of the ejecta blanket.

**Study Site:** The hinge in the Coconino-Toroweap sandstone is located in the southwest corner of the crater (Fig. 1 and 2), slightly east of a tear fault that defines that corner. The outcrop is exposed along a road that was blasted from the crater wall by early 20$^{th}$ century miners.

**Description of Section:** We rooted our measured section in the Kaibab-Moenkopi contact. Above the contact are the Wupatki and Moqui Members of the Moenkopi Formation, which are the red units along the road on the left edge of Fig. 2. As one begins to walk along the road towards the right as seen in Fig. 2, those units are overlain by an overturned sequence, with the fold axis hidden within the shaly Moqui. The top of the overturned Moenkopi is composed of an unconsolidated breccia of shaly and massive siltstone blocks (either a mixture of both Moqui and Wupatki Members or a mixture entirely of Wupatki, where the shaly clasts are derived from its basal component). That red-rock breccia is overlain by an unconsolidated breccia of Kaibab and Moenkopi. This sequence is similar to that measured on the south rim of the crater 300 m farther east [6]. The sequence is then cross-cut with a fault that juxtaposes those units with a hinge of overturned Coconino-Toroweap. The sandstone units are thinly bedded and similar to those at the top of the sandstone formation exposed in the lower crater walls. Within the fold hinge is an abbreviated sequence of Kaibab sandy dolomite (see Fig. 1 for closeup view). That sequence of sandy dolomite is repeated five times in exposures along the road parallel to the crater wall and along the road where it cuts through the crater rim towards the southwest (Fig. 2).

**Structural Displacement of Hinge:** Hinges in the overturned Coconino-Toroweap are not normally preserved, because they either collapsed to the crater floor during the impact or eroded from the upper crater walls soon thereafter. The loss of that hinge material exposed Kaibab and Moenkopi units in most portions of the upper crater walls around the crater. The Coconino-Toroweap hinge at our study site must have been closer to the crater center during the excavation phase and then faulted radially outward during the emplacement of the ejecta blanket. That motion requires up to 100 m of outward displacement of the hinge. It was displaced along a fault that parallels the road, except towards the east where the fault cuts up across the upper crater wall (Fig. 2). Towards the west, the fault approaches (and is probably buried in) a tear fault that shapes the southwest corner of the crater. Interestingly, this outcrop captures a dramatic change in the physical properties of the rock during the excavation phase of crater formation: The units behaved plastically when folded under the influence of shock and rarefaction waves and rapidly regained their brittle nature to accommodate the faulting. Another small fold occurs in the Coconino on the outward-facing slope of the crater rim that is shown in Fig. 2.

**Structural Thinning of Ejecta:** The Kaibab that lies within the Coconino-Toroweap fold hinge was faulted multiple times and effectively thinned in a radial direction from the crater center. That type of thinning is necessary throughout the continuous ejecta blanket, as that material now covers 9 times more surface area than it did before the impact (*e.g.*, [1]). This is the first location, however, where a mechanism responsible for that thinning is visible in outcrop. In this case, extension was accomodated by a series of five normal faults. Evidence of extension is also visible in the Coconino-Toroweap at this study site. A series of conjugate fractures in the sandstone indicates maximum compression was perpendicular to the overturned bedding and that maximum extension was parallel to bedding, effectively stretching the overturned bed to greater radial distances.

**Conclusions:** Meteor Crater is one of very few impact sites where the geologic details of crater excavation and ejecta emplacement are preserved. Previous work at the site has shown that those processes folded and overturned the excavated units. As shown here, they also created local shear in the ejecta blanket, displacing material radially outward, and producing extension of that material over a larger area around the crater. Shear is more likely to occur in the uprange or downrange rim of a crater (*e.g.*, [7,8]), so the structural displacement described here and that seen elsewhere on the south side of the crater [6] suggest an impact trajectory from the N to S or S to N. For a 45º impact angle (the most probable impact angle and consistent with the symmetrical shape of the crater), shear is more likely to occur in the downrange rim of a crater, suggesting an impact trajectory from the N to the S.

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**References:** [1] Kring D. A. (2007) *Guidebook to the Geology of Barringer Meteorite Crater, Arizona*, LPI Contrib. #1355. [2] Roddy D. J. et al. (1975) *Proc. Lunar Sci. Conf. 6th*, 2621-2644. [3] Pilon J. A. et al. (1991) *JGR*, *96*, 15563-15576. [4] Barringer D. M. (1910) *Meteor Crater (formerly called Coon Mountain or Coon Butte) in northern Arizona* (1910) self published. [5] Shoemaker E. M. (1960) *Int. Geol. Cong. 21st*, 418-434. [6] Kring D. A. et al. (2011) this conference volume. [7] Fechtig H. et al. (1972) Naturwissenschaften 59(4), 151-157. [8] Gault D. E. (1974) in *A Primer in Lunar Geology*, NASA TMX 62359, 137-175.

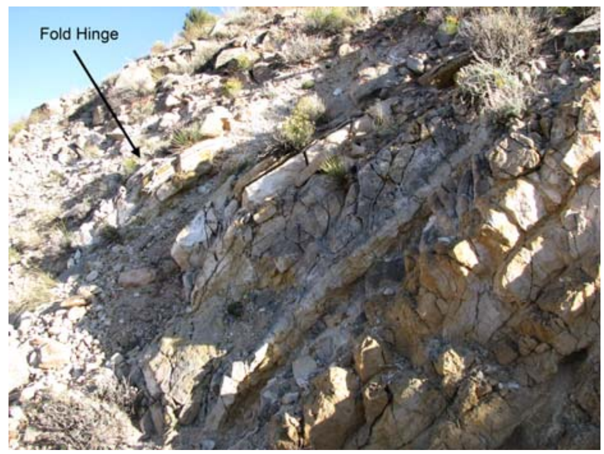


**Fig 1.** View of hinge in Coconino-Toroweap sandstone (upper left) and transition to sandy dolomite within the fold (lower right).

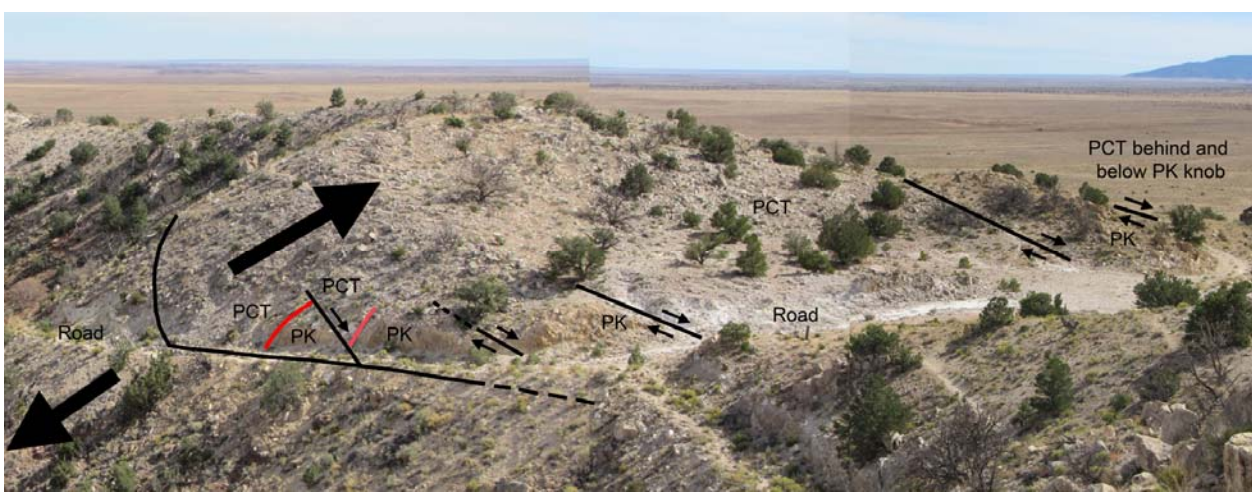


**Fig. 2.** A hinge (red curves) in the Coconino-Toroweap (PCT) is exposed in contact with the Kaibab (PK) in the southwest portion of the crater. The hinge was faulted outward from the crater center by up to 100 meters (with relative motion indicated by large black arrows), although that motion may also have had a lateral (west-directed) component that carried it towards a tear fault (not labeled) that cut through the crater rim in the lower right corner of the view shown. The overturned PK, below the overturned PCT, was thinned in a series of outward-dipping normal faults (with relative motion indicated by small black arrows), one of which cut through the hinge, producing a duplication of the hinged PCT-PK contact. Apparent displacements along the faults (from left to right) are ≤100 m, 3 m, 6 m, 30 m, 2 m, and ~20 m. The viewer is looking towards the southeast.