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Role of water in the formation of the Late Cretaceous Wetumpka impact structure, inner Gulf Coastal Plain of Alabama, USA

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Abstract–The effect of shallow marine water (~30–100 m deep) in the late excavation and early modification stages of a marine-target crater 5 km in diameter, as exemplified by the Late Cretaceous Wetumpka impact structure in Alabama, USA, is manifest in the early collapse of a weak part of the rim. Excavation flow and connate marine water are interpreted to be factors in this collapse. This partial rim collapse catastrophically emplaced an upper-structure-filling unit of broken and redistributed sedimentary target formations, which presently mantles the deeper fallback breccia deposits within the structure. Furthermore, rim collapse flow facilitated the formation of a structurally modified, extrastructure terrain, which is located outside and adjacent to the collapsed rim segment. This extrastructure terrain appears to be the product of extensive slumping of poorly consolidated target sedimentary formations.

INTRODUCTION

Wetumpka is a Late Cretaceous marine-target impact structure in the inner Coastal Plain of Alabama (Fig. 1) that was originally suggested to be an astrobleme by Neathery et al. (1976), and was later confirmed as an impact structure upon discovery of shocked minerals and a meteoritic chemical signature (King et al. 2002). This impact structure is characterized by 1) a wide, horseshoe-shaped crystalline rim, 2) an interior region of broken and redistributed sedimentary target formations, and 3) an extrastructure terrain on the south-southwestern side composed of structurally disturbed target formations (King et al. 2002, 2003) (Fig. 2). The latter have been faulted, slumped, and in some instances overturned. The extant crater rim spans ~270 degrees of arc and is open on the south-southwest (Fig. 3), the same side as the structurally disturbed terrain just noted. The northwest-southeast diameter of the horseshoe-shaped crystalline rim itself is ~5 km, but impact-related deformation beyond the rim extends the structural diameter to ~7.6 km (King et al. 2003). Wetumpka falls just on the transition between simple, bowl-shaped craters and complex impact structures. As a well-preserved marine-target impact structure that has been mapped and drilled, Wetumpka represents a terrestrial analogue for increasing the understanding of some small wet-target impact structures on Mars.

The present reconstruction of impact effects was undertaken in order to understand the influence of target properties, and especially the role of water (marine water and connate water), on cratering processes. In particular, our focus is on the behavior of water-saturated target sedimentary formations during the late excavation and early modification stages of cratering at Wetumpka. This focus required us first to investigate fully Wetumpka's present state of preservation (i.e., the present erosional level versus the fresh or immediately postimpact crater cross-section). To achieve this, we compared the present geology and topography at the Wetumpka impact structure with standard morphological parameters for fresh impact craters (as discussed in Melosh 1989). In addition, we incorporated recent results from field and laboratory studies of other marine-target craters and structures, especially those strongly affected by the collapse of a thick sequence of poorly consolidated sediments. Recent studies of marine-target structures such as Chesapeake Bay in the U.S. (Poag et al. 1994, 2004; Poag 1997, 2002; Powars et al. 2003; Horton et al. 2005) and Lockne in Sweden (Ormö et al. 2002; Sturkell and Lindström 2004; Lindström et al. 2005; Shuvalov et al. 2005) have brought to light aspects of

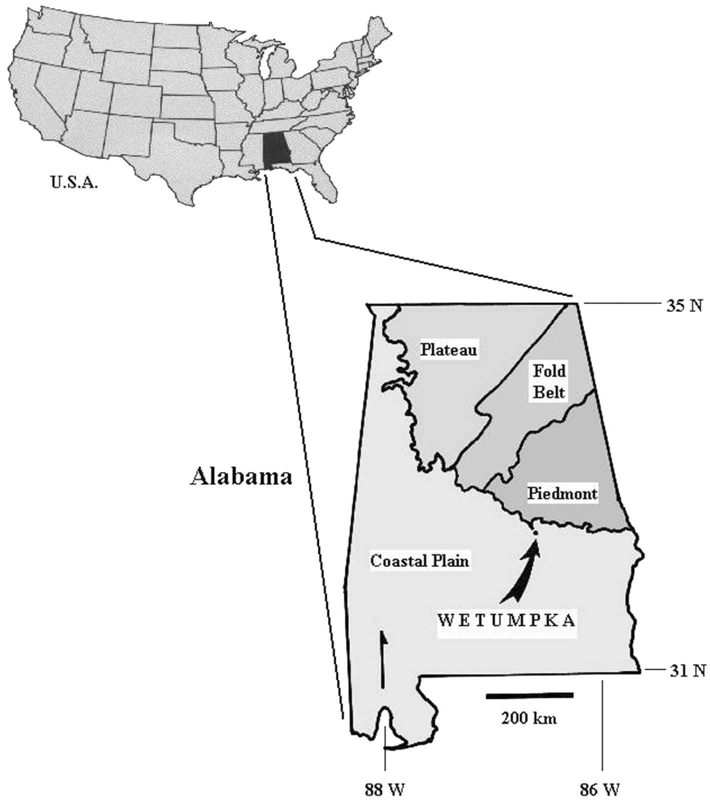

Fig. 1. A map showing the location of Wetumpka impact structure in the inner coastal plain of Alabama, USA (after King et al. 2003).

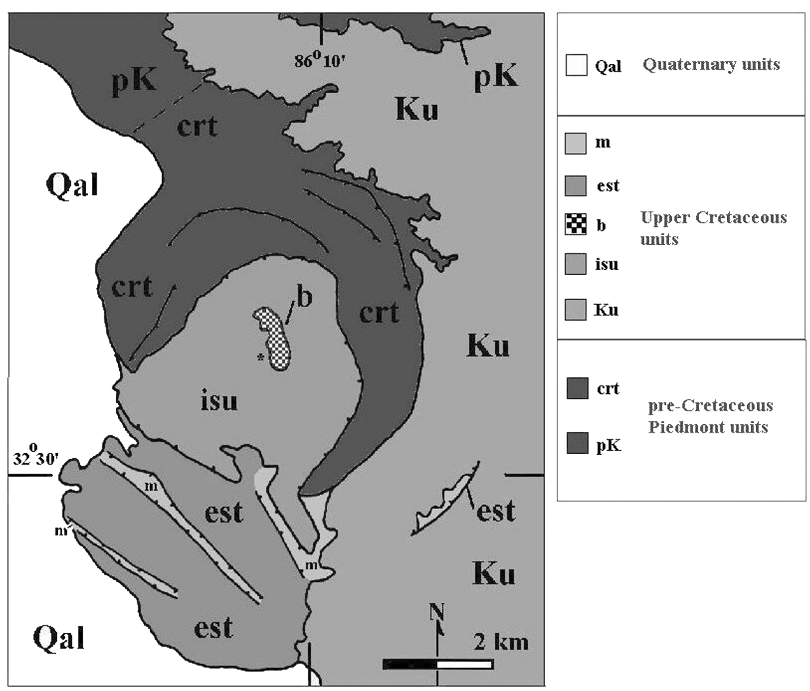

Fig. 2. A simplified geological map of the Wetumpka impact structure (after King et al. 2002). Units: pK = pre-Cretaceous metamorphic rocks; crt = crystalline rim terrain; Ku = Upper Cretaceous target strata; isu = interior sedimentary unit; b = surficial breccia unit; est = extrastructure terrain; m = Mooreville chalk inliers within extrastructure terrain; Qal = Quaternary alluvium. The location of two core holes 200 meters in depth is marked by an asterisk (*).

the marine-target cratering process that are peculiar to such a water-rich target setting. Among these aspects are washback deposition within the fresh crater bowl, impact-structure development in relation to marine water depth, and the destabilizing effects of water saturation of unconsolidated target sedimentary formations. It was pertinent to consider these effects at Wetumpka, because all these water-rich target effects, especially the latter, are displayed there.

PALEOGEOGRAPHIC SETTING AND TARGET PROPERTIES

Preexisting paleogeographic studies of the eastern U.S. Gulf Coastal region during Late Cretaceous (as compiled by King et al. 2002) showed that the Wetumpka impact occurred in shallow marine water ~30–100 m in depth (King et al. 2002, 2003) (Fig. 4). Because the impact occurred in a continental shelf setting and near shore, paleowater depths across a distance equal to the Wetumpka rim diameter (~5 km), i.e., the target area, likely became slightly more shallow toward the north, i.e., in the direction of the coeval shoreline. If the paleoslope of the near-shore shelf was like the average slope of a shallow, passive-margin continental shelf today (~0°07′ or ~2 m/km, per Sheppard 1963), the difference in water depth from the northern rim to the southern rim, across 5 km, would have been ~10 m. As we will show, it seems likely that even this slight difference in water depth across the target area may have been important in the events that transpired during late excavation and early modification stages of this impact structure.

In reverse stratigraphic order, the Wetumpka target consisted of 1) ~30–100 m of marine water; 2) poorly consolidated sediment (comprising three Upper Cretaceous stratigraphic units: 30 m of chalky ooze, 30 m of paralic marine sand, and 60 m of terrestrial clayey sand and gravels), and, at base, 3) a weathered crystalline basement. The target stratigraphic units, in the order mentioned above, are the Mooreville Chalk, Eutaw Formation, and Tuscaloosa Group. The Tuscaloosa originally rested disconformably on crystalline lithodemic units of the Appalachian piedmont (King et al. 2002, 2003), and still rests outside the target area.

The crystalline piedmont basement has a modern south-southwesterly dip of ~10 m/km. Although it is subtle, like the slight difference in water depth, this structural dip is thought to have had an important effect on the cratering process at Wetumpka, particularly in the late excavation and early modification stages being discussed. In particular, this dip of basement likely contributed to a significantly greater component of sedimentary material ultimately residing in the southern part (i.e., the down-dip part) of the structure's rim (King et al. 2004). The rim's lithic heterogeneity caused the sedimentary southern and southwestern part to be more porous and thus less stable than other parts. For this reason, we think that this part of the rim was especially susceptible to an early collapse.

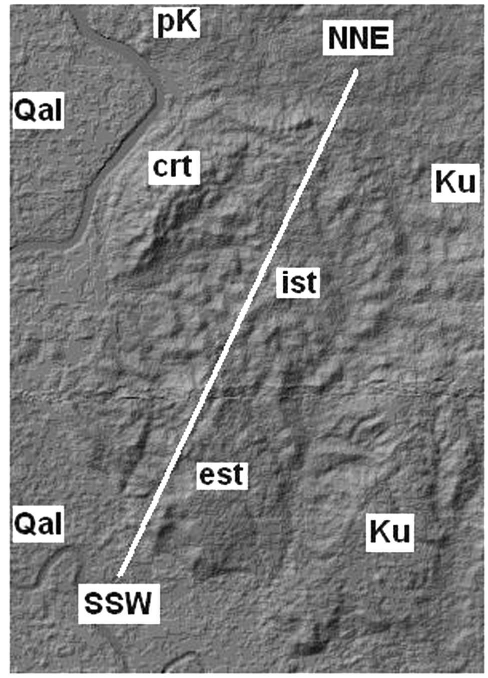

Fig. 3. A digital elevation model (DEM) of the Wetumpka impact structure (USGS data) showing the location of SSW-NNE profile line for the cross-sections shown in Figs. 5–7. Crt = crystalline rim terrain; ist = intrastructure terrain; est = extrastructure terrain; pK = pre-Cretaceous rocks; Ku = undisturbed Upper Cretaceous strata; Qal = Quaternary alluvium of the river basin area The DEM covers approximately the same area as Fig. 2.

RECONSTRUCTION OF IMPACT EFFECTS

To begin reconstructing the Wetumpka impact scenario, we envisioned a hypothetical fresh crater of sufficient size and shape to help us explain present topography as well as surface and subsurface geology (i.e., as originally mapped and diagrammed by Neathery et al. 1976 and as remapped and reinterpreted by Nelson 2000 and King et al. 2002, 2003). In making this reconstruction, the present topography and geology along a SSW-NNE profile (Fig. 3) was compared to the hypothetical subsurface morphology of the structure (King et al. 2003, 2006). Based on standard parameters for impact craters and information from similar marine-target craters and structures (Grieve et al. 1981; Melosh 1989; Ormö et al. 2002; Shuvalov et al. 2005), we reconstructed the dimensions of the Wetumpka "fresh" crater. The best fit was achieved using a fresh crater possessing a diameter slightly <5 km. Based on the relations between fresh-crater diameter and transient cavity given by Melosh (1989), the diameter of the transient cavity at target surface would have been ~4 km.

We assume that the water layer was excavated along with the sediment and crystalline rocks at Wetumpka, owing to a paleowater depth that was significantly less than the diameter of the impactor (see Ormö et al. 2002). However, it is possible that the thick pile of poorly consolidated sediments allowed some shallow excavation flow similar to that interpreted for

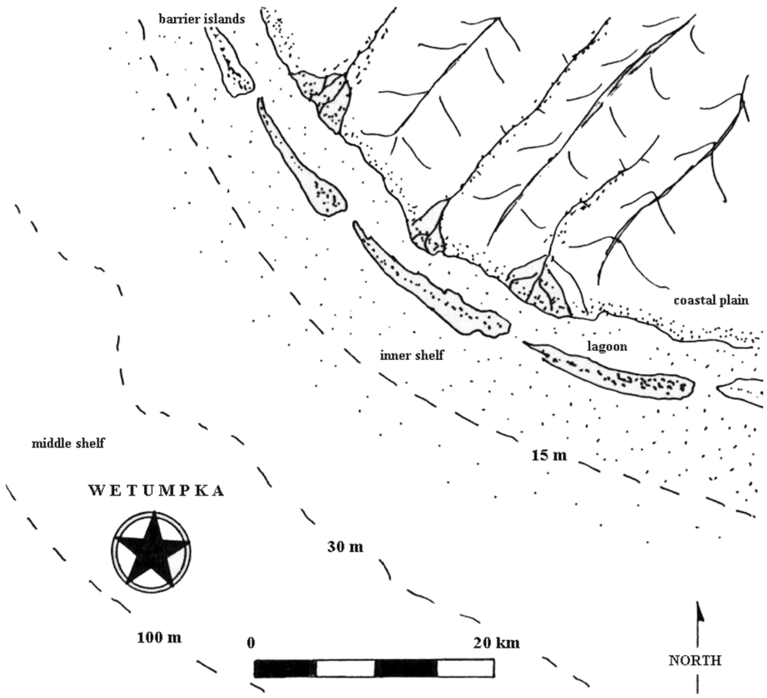

Fig. 4. A paleogeographic map, including hypothetical paleobathymetric contours, showing the interpreted setting for the Late Cretaceous Wetumpka impact event (after King et al. 2003).

marine impact craters that formed in water deeper than Wetumpka (e.g., Lockne crater) (Ormö and Lindström 2000). This shallow excavation flow likely resulted in an "inverted sombrero" morphology of the fresh crater (cf. Melosh 1989). Similar morphology has been observed in craters with a thick, relatively weak surface layer (e.g., Red Wing crater) (Grieve et al. 1981). In addition to forming as a result of a shallow excavation flow, inverted sombrero morphology can form during crater modification from extensive collapse of a thick surface layer of poorly consolidated sediments (e.g., the Chesapeake Bay crater) (Horton et al. 2005).

In the marine environment, a fresh crater's rim is ephemeral and would be rapidly reduced by the removal of the water layer under the overturned flap, and by dewatering and compaction of sediments. The envisioned situation at Wetumpka, which formed at a very shallow target water depth (i.e., much less than the impactor diameter), is depicted in the cross-section shown in Fig. 5. Shallow excavation flow prior to crystalline flap deposition would also generate a slightly lower fresh crater rim than would be expected with a dry target. Onset of central uplift (as indicated in Fig. 5) and slight downfaulting (terracing) of the rim (Fig. 7) are inferred from exemplar craters in crystalline rock that are >4 km (although not yet observed in the field or in drill core at Wetumpka; see examples in Grieve et al. 1981).

The rim height of a fresh crater 5 km in diameter in solid rock and measured from the target surface should be 203 m, based on an equation valid for simple craters on all terrestrial planets (Pike 1977; Melosh 1989). Half of the rim height is assumed to be due to structural uplift; this decreases to zero at a distance of ~1.3–1.7 crater radii (based on examples in Melosh 1989). The structural uplift of the basement should have been slightly less on the southern side than on the northern side due to the previously mentioned structural dip of the basement. Figure 6 shows the return of marine water, which was not sufficiently deep to overcome the rim, except perhaps in some places on the southern rim, which would have been the side of the structure with the deeper water.

Due to the great influence of marine water, including connate water, on rim formation (particularly on the southern side), greater sedimentary content of the southern rim, and lower structural uplift of the basement on this end, this southern sector of the fresh crater rim would have collapsed almost immediately. Large detached blocks of crystalline rock (with diameters equaling hundreds of meters) occur today near the crater center and are interpreted to be fragments of the southern rim that slumped or were catastrophically rafted into this position (King et al. 2002) (blocks occur within unit b, see Fig. 2).

The southern rim collapse at Wetumpka (Fig. 7) was probably aided further by the onset of a resurge of marine water. As evidence, we note polymict breccias at Wetumpka, which resemble the polymict resurge deposits at Lockne crater (cf. Lindström et al. 2005) and which occur near crystalline slabs in the vicinity of the structure's center (King et al. 2002). These polymict breccias are in a stratigraphic position above the broken and redistributed sedimentary target formations that characterize the structure's present

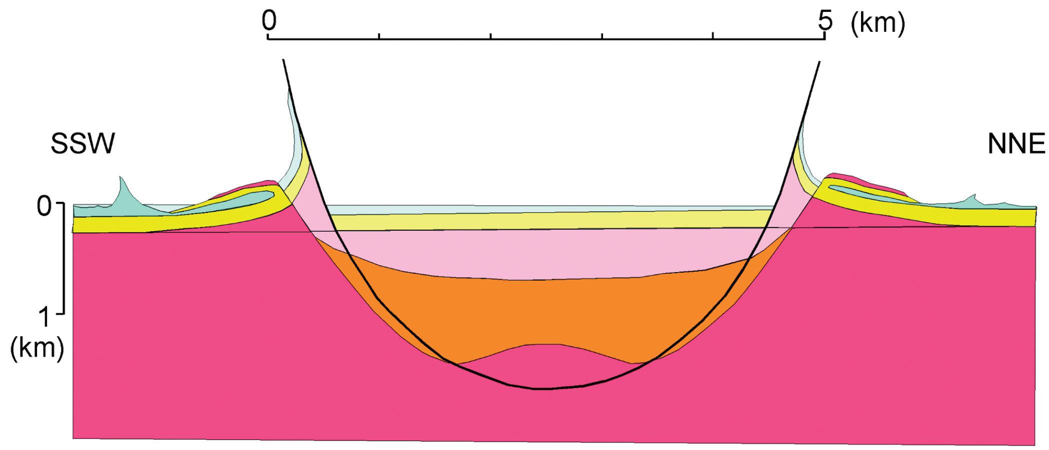

Fig. 5. An interpretive cross-section showing the late excavation stage, including onset of central uplift at Wetumpka. Blue = water; yellow = sediments; pink = crystalline; orange = the autochthonous breccia lens. Within the transient crater, shades of the same units are lighter. The effect of the basement's structural dip (~10 m/km) and deepening of marine water (~2 m/km) both increase towards the SSW. The throughgoing datum line is the top of the crystalline piedmont basement.

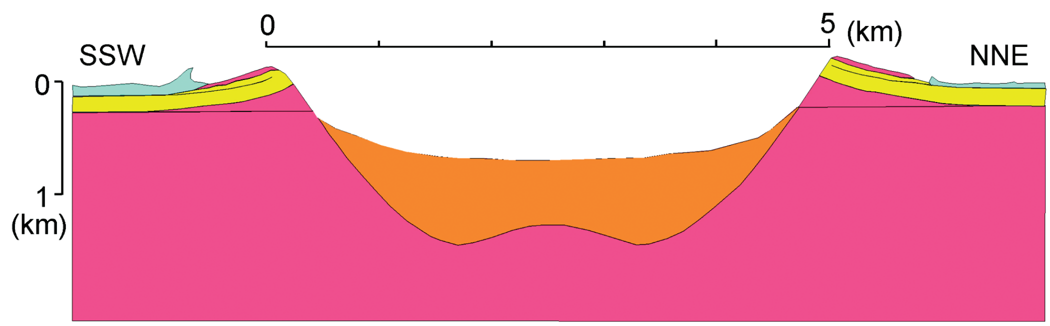

Fig. 6. An interpretive cross-section showing the early modification stage return of marine water to the fresh crater rim at Wetumpka. Due to factors noted in the text, the southern rim is slightly lower than other parts. The southern rim is not stable and will immediately collapse (see Fig. 7). Blue = water; yellow = sediments; pink = crystalline; orange = the autochthonous breccia lens.

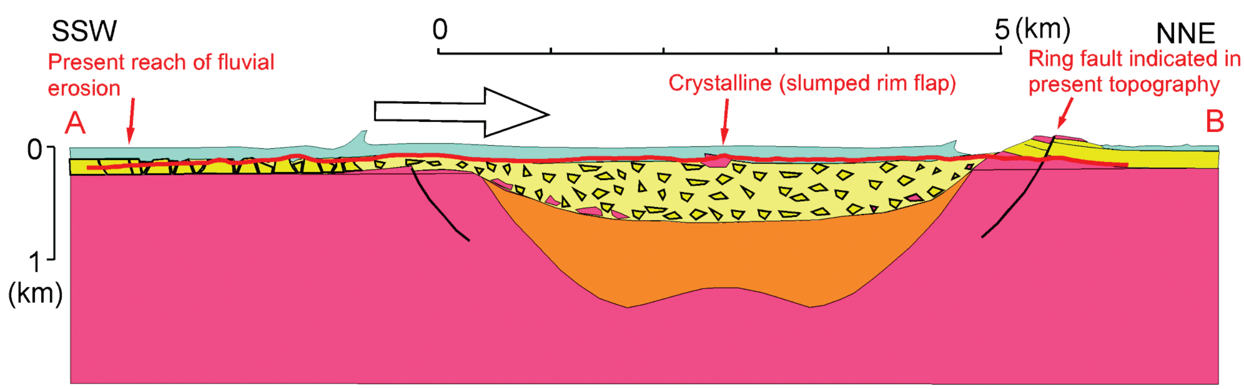

Fig. 7. An interpretive cross-section showing the southern rim collapse at Wetumpka and associated collapse of large-scale blocks of poorly consolidated, fluidized sediments in the extrastructure terrain. As noted in the text, rim collapse is localized in the southern sector, resulting in a horseshoe-shaped rim. Broken and redistributed deposits of sedimentary target formations inside the fresh crater are colored yellow and marked by fragment symbols. The thin red line delineates present topography. Present reach of fluvial erosion refers to the edge of Quaternary alluvium within the Tallapoosa River basin (see the river basin in Fig. 3). Crystalline (slumped rim flap) refers to rafted blocks of schist and polymict breccia from the southern rim (mapped as unit b in Fig. 2). The ring fault was mapped by Neathery et al. (1976). Blue = water; yellow = sediments; pink = crystalline; orange = the autochthonous breccia lens.

floor (King et al. 2003). In contrast, the other sides of the crater rim, where marine water was less deep, did not collapse. As noted earlier, the strength of the other sides of the crater rim was aided by structural uplift of the basement, forming a stronger, crystalline barrier.

Because no coherent rim on the down-dip side of the crater that might have held back the partially fluidized sediments of the target existed for any significant amount of time, collapse flow from the southern sector affected adjacent areas outside the initial diameter of the fresh crater (Fig. 7). Effects of this collapse flow are noted in a wide zone of faulted (horst-graben), slumped, and overturned stratigraphic section, situated adjacent to the southern and southwestern limit of the structure (i.e., the "extrastructure terrain" of King et al. 2003, as shown in Fig. 2; also known as the "structurally disturbed terrain" of Nelson 2000). In Fig. 2, these faulted zones (grabens) are especially evident as "Mooreville chalk inliers." This zone somewhat resembles the annular trough with slumped and rotated megablocks that surrounds the central basement crater in the Chesapeake Bay impact structure, Virginia, USA (described by Poag et al. 2004 and Horton et al. 2005). At Chesapeake Bay, this zone was similarly interpreted as the product of extensive slumping of poorly consolidated target sedimentary formations.

Recent numerical simulations of an oblique impact for the Lockne crater have showed a much larger flap-formation and an extensive downrange ejecta curtain (Shuvalov et al. 2005). In this simulation, the marine-water resurge was likely stronger from the uprange direction (Shuvalov et al. 2005). If we assume an impact at Wetumpka from the southwest, then the effects on crater collapse that we now infer from the slope of the basement and the deepening of the water would be significantly enhanced. Unfortunately, there is no independent evidence of angle and trajectory for the Wetumpka impactor.

CONCLUSIONS

The reconstructions show that the present erosional level of the crater most likely allows only the extant northern crystalline rim to be part of the structural rim uplift. However, our recent field observations of disturbed Upper Cretaceous sediments in a position topographically below crystalline rim material in the southeastern tip of the extant rim suggest that some sectors of the rim may have preserved parts of a crystalline flap. Further studies are needed to confirm this possibility. The south-southwestern sector of the crater shows indications of an extensive rim collapse, the effects of which seem to reach far outside the location of the original fresh crater rim. Whether selective failure of Wetumpka's rim is due to instability caused by inhomogeneity within the rim, the effects of excavation flow, or a combination of both, the presence of this distinctive morphologic feature—in and of itself—in other marine impact structures on Earth and Mars has great importance for interpreting target composition and preimpact geologic history with regard to the presence of weak sedimentary target layers and overlying marine water and the depth of that water.

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