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Earth and Planetary Science Letters 202 (2002) 541–549

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# Shallow-marine impact origin of the Wetumpka structure (Alabama, USA)

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Received 11 December 2001; received in revised form 27 March 2002; accepted 28 June 2002

**Abstract**

The Wetumpka structure, an arcuate, 7.6 km diameter, rimmed feature of the inner Coastal Plain, Alabama, is a Late Cretaceous shallow-marine impact crater. In this paper, we show unequivocal evidence of Wetumpka's impact origin. Within and about this structure, pre-existing Upper Cretaceous stratigraphy was resedimented and(or) deformed, thus creating distinctive intra-structure and extra-structure terrains. These terrains are located, respectively, within Wetumpka's crystalline-rim terrain and adjacent to the structure on the southern side. Core drilling near the structure's geographic center revealed that Wetumpka's basin-filling sequence has two distinctive units, suggestive of a two-stage filling process consisting of (1) fall-back plus resurge followed by (2) a later secondary seawater resurge event. Wetumpka's lower subsurface unit includes polymict impact breccias, which contain quartz grains displaying shock-characteristic multiple sets of planar deformation features. Selected subsurface samples of this breccia also contain elevated Ir, Co, Ni and Cr concentrations indicative of a minor extraterrestrial component. 

*Keywords:* impact craters; impacts; impact features; marine environment; shallow depth

## 1. Introduction

The Wetumpka structure has been the subject of geological study for over 100 yr. This structure, located in Elmore County, Alabama, USA (centered at 32°31.2′N, 86°10.4′W; Fig. 1), is a topographically prominent, semi-circular, rimmed feature. This structure is composed of relatively highly indurated crystalline rock, forming the rim, and an unconsolidated melange of broken Upper Cretaceous sedimentary formations within and directly outside its crystalline rim on the southern side. During the late 19th century, Wetumpka's unusual and peculiar 'disturbed' geology was recognized by Alabama's first State Geologist, Eugene Allen Smith, who was engaged in

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0012-821X/02/$ – see front matter 
PII: S0012-821X(02)00803-8

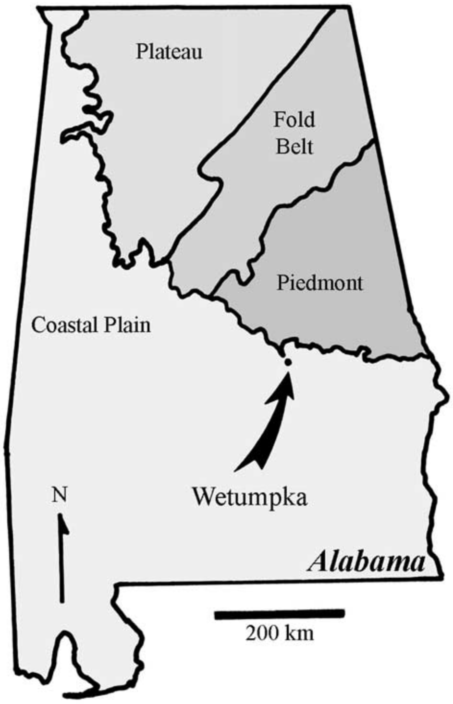


Fig. 1. Location of the Wetumpka structure (dot) in Alabama. Major geological provinces are indicated.

reconnaissance mapping (as recounted in [1]). A subsequent geological mapping effort by the Geological Survey of Alabama, which discovered significant structural and stratigraphic evidence suggestive of an impact origin, was summarized in a later paper [2], wherein this feature was named 'Wetumpka astrobleme' [2]. However, lack of unequivocal evidence for impact left open the question of its origin.

Recent work [3] signaled renewed interest in Wetumpka, but did not confirm its impact origin. In a comprehensive review of impact structures within the United States [4], Wetumpka was recognized only as a 'possible impact structure', based mainly upon evidence presented earlier [2]. In a recent Bouguer gravity survey of the Wetumpka structure [5], it was determined that the structure possesses a total gravity relief of 10 mGal and that the gravity profile is 'consistent in appearance and magnitude' with known meteorite-impact structures [5].

## 2. Target stratigraphy and paleogeography

In this region of the inner Gulf Coastal Plain, three relatively soft, essentially unconsolidated Upper Cretaceous stratigraphic units lie unconformably upon harder crystalline, pre-Cretaceous Appalachian bedrock and thus constitute a monocline that dips south at approximately 8.5 m/km. In age order, the Upper Cretaceous stratigraphic units are: Tuscaloosa Group (thickness = 60 m); Eutaw Formation (30 m); and Mooreville Chalk (30 m) [2,6]. Tuscaloosa is a Cenomanian fluvial and alluvial plain deposit, comprised of numerous 2–4 m thick, fining-upward sequences of clayey sands and sandy clays [7]. Eutaw comprises Santonian–Campanian linear shoreline deposits of quartz-rich sands with small amounts of intercalated sandy marine clays [8]. Finally, Mooreville is comprised of Campanian marine marly clays and clayey marls [8], a sediment type locally referred to as 'chalk'.

An early Campanian relative age date for the Wetumpka structure has been proposed for the Wetumpka structure, because the youngest layers involved in its formation were from the lower part of the Mooreville Chalk, which contains early Campanian guide fossils [9]. At time of formation, Wetumpka's target area was part of the Late Cretaceous continental shelf of southern Alabama and the target site was likely shallow water within a few tens of kilometers of the nearest shoreline [9,10]. Judging from depth-sensitive ostracode eye morphology [11] and supportive ichnosedimentologic evidence from Campanian target strata [12], the seawater depth at the target area was probably about 35–100 m.

## 3. Present surficial geology

Present surficial geology of the Wetumpka structure (Fig. 2) consists of two main domains: (1) a heavily weathered, semi-circular crystalline-rim terrain, composed of post-orogenically deformed Appalachian Piedmont bedrock, which has up to 87 m of present relief; and (2) a relatively low-relief, stream-dissected intra-structure terrain and related extra-structure terrain com-

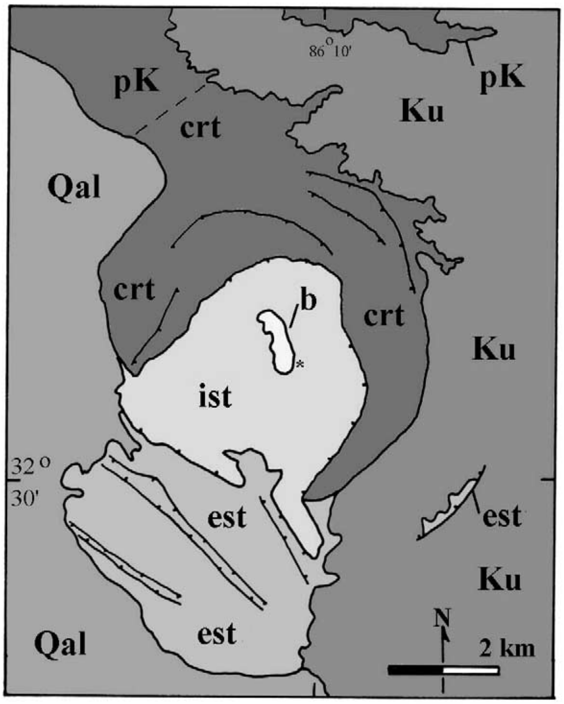


Fig. 2. Generalized geological map of Wetumpka structure showing main terrains (discussed in text) and adjacent geology. Crystalline-rim terrain (crt); intra-structure terrain (ist); extra-structure terrain (est); Upper Cretaceous undeformed units (Ku); pre-Cretaceous crystalline units unaffected by Wetumpka structure (pK). Faults are tick-marked on down side. Star (*) marks drilling location for two wells discussed in text. Map compiled from [2,15].

posed, respectively, of contiguous tracts of resedimented and(or) deformed target strata and tracts of undisturbed to highly disturbed target strata (Fig. 2). The arcuate outcrop of crystalline-rim terrain has a northwest–southeast diameter of 6.1 km. However, the diameter of the entire Wetumpka structure is determined more properly by extending this diameter to an outer concentric fault and associated small outlier of extra-structure terrain located on the southeastern side of the rim (Fig. 2) [13]. Thus, a structural diameter of 7.6 km is obtained.

The crystalline-rim terrain consists mainly of metamorphic pre-Cretaceous Appalachian Piedmont units (e.g., Kowaliga Gneiss and Emuckfaw Group schists [14]), which crop out in a crescent-shaped (~270°) arc (Fig. 2). In contrast to exposures of the same and related Piedmont units outside the Wetumpka structure, this terrain displays realigned (i.e., radially oriented) dips of foliation [2,15].

The intra-structure terrain consists mainly of resedimented and(or) deformed Tuscaloosa Group sediments, which enclose irregularly shaped and internally deformed palimpsest outliers of younger target units (i.e., Eutaw Formation and Mooreville Chalk; see figure 2A in [2] or figures in [15]), as well as blocks of deformed and undeformed Tuscaloosa Group strata. However, other peculiar features also characterize this terrain, including outcrop-scale soft-sediment folding and clastic dike injection [2,16]. In addition, at the inner margin of the structure's western rim, this terrain is comprised of variously oriented, medium- to coarse-size lithic blocks [17] (diameter = 10–18 m) composed of mildly deformed Tuscaloosa Group and Eutaw Formation strata. These lithic blocks (i.e., 'megablocks' of [9]) exhibit marginal deformation that apparently developed due to compression against one another [9]. In outcrop, iron-oxide seams, 1–5 cm thick, characterize marginal boundaries of these lithic blocks.

Within a small (~0.75 $km^2$), central outcrop area, a rare breccia facies, which may be part of the intra-structure terrain, crops out (unit b in Fig. 2) [15,18]. This breccia contains numerous subrounded to subangular fragments, 5 cm to 30 m across, consisting of schists and gneisses similar to those present in the crystalline-rim terrain and sandstone clasts (from the Tuscaloosa Group and/or Eutaw Formation) supported by a fine sandy matrix. Within this breccia facies, several lithic blocks (15–25 m across) composed of schist (Emuckfaw schist?) also crop out at the surface. The origin and mode of emplacement of these blocks so far from the nearest rim outcrops of this schist are currently unknown.

Core drilling (see Section 4) directly adjacent to this central outcrop area has recovered relatively abundant, similar breccia at depths greater than 64 m below the surface, but did not reveal the physical relationship, if any, between this surface breccia outcrop and similar subsurface breccias.

The intra-structure terrain grades laterally toward the south into the extra-structure terrain, which consists mainly of undisturbed to highly disturbed Tuscaloosa Group sediments. Some of these strata have experienced structural deformation of a probable tensional nature. For example, in several places, Mooreville Chalk fills what we interpret to be northeast-trending, graben-like features developed within Tuscaloosa Group and Eutaw Formation strata (Fig. 2) [2,15].

At Wetumpka, the intra-structure terrain and related extra-structure terrain probably represent a special type of 'broken formation' (a term modified from [19]) resulting from a poorly understood and potentially very complex set of formative processes. In the absence of potentially more appropriate terminology, these terrains have been referred to previously as 'Wetumpka melange' [16] and as 'Wetumpka interior broken unit' [15].

## 4. Subsurface geology

In 1998, core drilling near Wetumpka's geographic center produced samples from two wells, named Schroeder and Reeves, located 300 m apart (located at the star in Fig. 2). These drill cores display a structure-filling stratigraphy that includes: (1) an upper layer, up to approximately 64 m thick, comprised of resedimented and(or) deformed target strata (i.e., the intra-structure terrain described above) and (2) a lower breccia zone consisting of over 130 m of diverse breccia facies [18]. In the subsurface structure-filling unit, the lower breccia zone includes, in order of abundance: (1) angular clast-bearing, matrix-supported sandy breccias and sand units and (2) monomict and polymict clast-supported breccias. In the lower breccia zone, these breccia units are intercalated with 1–10 m thick, deformed and undeformed blocks of target strata and crystalline basement (Fig. 3) [18]. Petrologic description of cores indicates that all three stratigraphic units mentioned above, plus crystalline bedrock, contributed clastic material to the structure-filling breccia unit [18]. In the sandy breccias and sand units, an unusually high percentage of finely comminuted plant matter and lignite clasts was noted that apparently was not derived from the local sedimentary section, which is generally not rich in plant matter. This material may represent part of the extant flora of the region that was entombed during the Wetumpka formative event.

The Wetumpka structure's basin-filling stratigraphy is remarkable in that two distinct units are present. Although further work is needed to specify the exact origins of these units, their division clearly suggests two separate and successive stages in Wetumpka's structure-filling process.

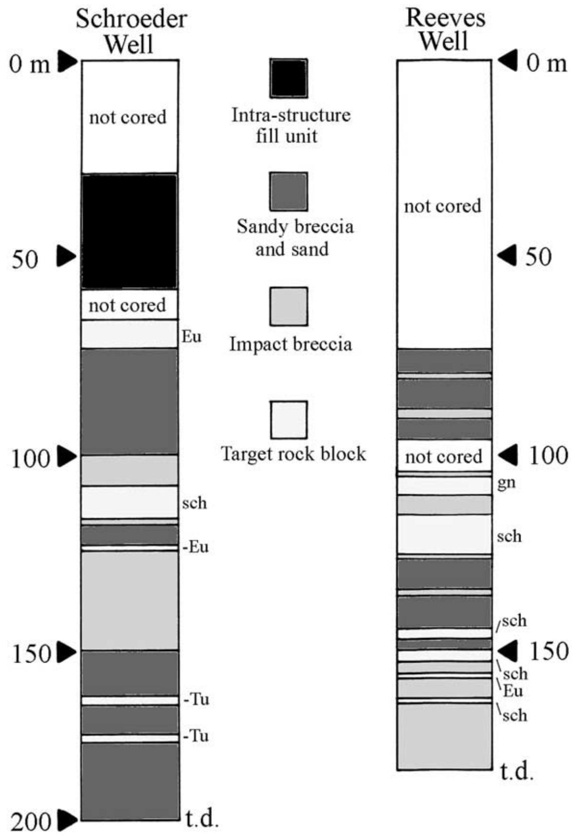


Fig. 3. Stratigraphic sequence of structure-filling rocks, derived from Wetumpka core-drilling logs for the Schroeder and Reeves wells. Intra-structure fill unit (discussed in text) is same as intra-structure terrain (ist) on Fig. 2. Lower breccia zone, described in text, encompasses the three other units (sandy breccia and sand; impact breccia; and target rock blocks) shown in these sections. Impact breccia includes both monomict and polymict breccia. Eu = Eutaw Formation; Tu = Tuscaloose Group; gn = gnesis; sch = schist.

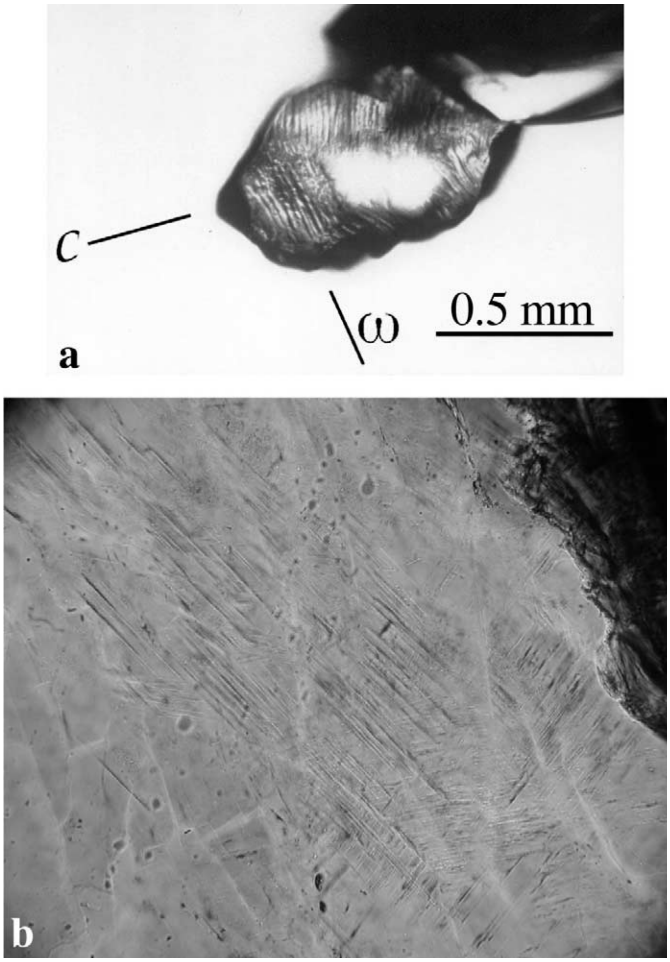


Fig. 4. (a) Wetumpka shocked quartz grain, slightly etched and mounted on a needle, showing two directions of PDFs. *c*-axis and main PDF orientation ω are indicated. Scale = 0.5 mm. (b) Different Wetumpka shocked quartz grain in thin section, showing three directions of PDFs. Crossed polarizers. Width of field of view is 0.1 mm. Both a and b are from Schroeder well sample number 385.5 (depth = 117.5 m).

## 5. Petrography of shocked materials

Disaggregation and microscopic sorting of polymict breccia matrix revealed shocked quartz with a density of approximately 10 grains/cm$^3$ within the matrix. Etching of quartz grains with dilute HF revealed planar deformation features (PDFs) clearly, especially the ω{10$\bar{1}$3} plane (Fig. 4a). Two thin sections from Wetumpka's polymict breccia contained abundant PDFs in quartz (Fig. 4b). These PDF-bearing grains were situated within the fine sandy matrix of the polymict breccia. Thin sections of other rock types from Wetumpka showed no PDFs.

In both of the polymict breccia thin sections noted above, crystallographic orientations of PDFs were measured on an optical microscope fitted with a four-axis universal stage. In sample 385.5 from the Schroeder well, the orientations of 98 planes were measured within 34 grains, which included 16, 6, 5, and 4 grains having two, three, four, and one sets of PDFs, respectively. A maximum of seven sets of PDFs per grain was observed in two grains within this sample. In sample

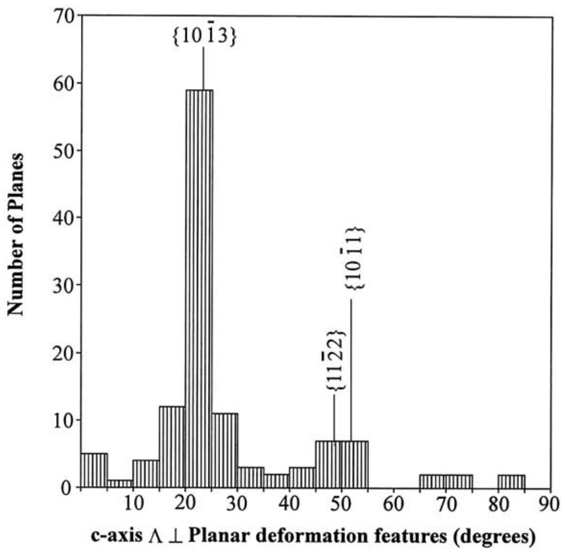


Fig. 5. Histogram plot of PDF orientations in thin sections of sample 447.3 from the Reeves well and sample 385.5 from the Schroeder well, which are binned in 5° increments of angle between *c*-axis and poles of the planes of PDFs. Total grains measured, 45; total planes measured, 122. Dominant PDF orientations are indicated.

447.3 from the Reeves well, 24 planes were measured in 11 grains, which have one to three sets of PDFs. Fig. 5 shows a histogram of total PDF orientations from Wetumpka, which displays clear maxima at the shock-characteristic angles of ω{10$\bar{1}$3}, r, z{10$\bar{1}$1}, and ξ{11$\bar{2}$2} (e.g., see [20,21]). Basal (0001) orientations are rare.

The presence of quartz grains with sets of PDFs with multiple orientations in Wetumpka breccias confirms the impact origin of this feature and suggests that shock levels experienced by these rocks were relatively low (probably ∼10 GPa; for comparison, see [21]). Orientations of the PDFs, especially r, z{10$\bar{1}$1}, are consistent with a porous sedimentary target [20].

## 6. Geochemistry

Major element analyses were performed on powdered samples using standard X-ray fluorescence (XRF) procedures (see [22] for details on procedures and their precision and accuracy). The concentrations of V, Cu, Y and Nb were also determined by XRF analysis. All other trace elements were analyzed by instrumental neutron-activation analysis (INAA; see [23] for analytical procedures, instrumentation, standards, accuracy and precision). Iridium contents were determined by multiparameter γ–γ coincidence spectrometry (see [24] for details of this method, which has detection limits of a few parts-per-trillion (ppt) in carbonate- or sandstone-dominated samples).

Results for the chemical composition of four drill-core samples are given in Table 1. Most pertinent among the results are their iridium values. In two samples (numbers 385.5 and 445.7 from the Schroeder well), the iridium contents are about 200 ppt, which is distinctly higher than average crustal abundances, which commonly range from 10 to 50 ppt [25]. The other two samples, samples 257.2 and 447.3 from the Reeves well, show lower iridium abundances, with one being near crustal background and the other one having an apparently 'intermediate' iridium content (Table 1). The two samples with elevated iridium, as well as the one with 'intermediate' iridium content, also have higher Cr, Ni and Co contents compared to the low-abundance sample (and average crust). Assuming these iridium abundances represent an extraterrestrial component, yields a value of approximately 0.04% of an extraterrestrial component within Wetumpka breccias (assuming a chondritic composition for the impactor [25]). Wetumpka's component is similar to meteoritic contents found at several other impact structures [25]. As noted above, two samples (385.5 from the Schroeder well and 447.3 from the Reeves well) with abundant PDFs in quartz also have elevated Ir, Cr, Ni and Co levels.

## 7. Conclusions

The presence of multiple sets of PDFs in quartz from drill-core samples of breccias from Wetumpka and elevated contents of Ir, Co, Ni and Cr in these breccias provide clear evidence of a meteoritic impact origin of the Wetumpka structure. Wetumpka has a diameter consistent with small, complex impact structures and it displays a partially developed outer 'terrace zone' characteristic

Table 1
Chemical composition of four subsurface samples[a]

| Sample numbers[b]: | R-257.2 | R-447.3 | S-385.5 | S-445.7 |
|---|---|---|---|---|
| Major element data[c] | | | | |
| $SiO_2$ | 85.9 | 50.1 | 62.96 | 63.06 |
| $TiO_2$ | 0.29 | 1.13 | 0.91 | 0.86 |
| $Al_2O_3$ | 7.31 | 20.41 | 15.92 | 15.22 |
| $Fe_2O_3$ | 0.89 | 10.45 | 6.43 | 6.26 |
| MnO | 0.04 | 0.20 | 0.13 | 0.10 |
| MgO | 0.32 | 2.76 | 1.99 | 1.58 |
| CaO | 0.43 | 3.90 | 1.74 | 2.20 |
| $Na_2O$ | 0.28 | 2.88 | 1.97 | 1.35 |
| $K_2O$ | 1.69 | 3.26 | 3.68 | 3.92 |
| $P_2O_5$ | 0.03 | 0.21 | 0.19 | 0.10 |
| LOI | 2.71 | 5.10 | 3.57 | 4.46 |
| Total | 99.9 | 100.41 | 99.48 | 99.11 |
| Trace element data[d] | | | | |
| Sc | 4.81 | 20.2 | 13.6 | 14.5 |
| Cr | 19.9 | 69.5 | 119 | 55.6 |
| Co | 3.09 | 14.6 | 13.2 | 14.1 |
| Ni | 10 | 63 | 76 | 68 |
| Zn | 20 | 187 | 121 | 116 |
| As | 0.68 | 1.27 | 0.16 | 1.32 |
| Se | 0.21 | 0.57 | 0.34 | 0.3 |
| Br | 0.06 | 0.3 | 0.2 | 0.3 |
| Rb | 46.3 | 150 | 124 | 133 |
| Sr | 61 | 272 | 139 | 210 |
| Zr | 99 | 455 | 371 | 356 |
| Sb | 0.03 | 0.02 | 0.05 | 0.07 |
| Cs | 0.85 | 3.39 | 3.54 | 3.14 |
| Ba | 295 | 440 | 590 | 550 |
| La | 15.2 | 85.1 | 50.5 | 70.3 |
| Ce | 30.2 | 164 | 102 | 144 |
| Nd | 13.5 | 79.5 | 51.1 | 72.3 |
| Sm | 2.66 | 14.9 | 9.41 | 12.1 |
| Eu | 0.54 | 2.64 | 1.64 | 2.23 |
| Gd | 2.5 | 12.1 | 7.16 | 9.9 |
| Tb | 0.31 | 1.71 | 1.19 | 1.57 |
| Tm | 0.21 | 0.83 | 0.62 | 0.69 |
| Yb | 1.51 | 5.06 | 4.29 | 5.39 |
| Lu | 0.22 | 0.73 | 0.67 | 0.69 |
| Hf | 2.63 | 10.7 | 10.8 | 7.93 |
| Ta | 0.89 | 2.24 | 1.74 | 1.54 |
| Ir (ppt) | $58 \pm 15$ | $92 \pm 19$ | $182 \pm 26$ | $208 \pm 28$ |
| Au (ppb) | 0.2 | 0.8 | 0.6 | $< 1$ |
| Th | 5.11 | 23.9 | 14.7 | 16.2 |
| U | 1.02 | 2.69 | 2.92 | 5.37 |

[a] Samples are from polymict impact breccia, except sample R-257.2, which is a sandy breccia.
[b] Sample numbers are assigned by depth measured in feet; R = Reeves well; S = Schroeder well.
[c] Major element data determined by XRF; data in weight %.
[d] Trace elements by INAA and XRF, and Ir by gamma-gamma coincidence spectrometry; trace-element data in ppm, except where indicated otherwise.

of terrestrial complex impact structures (as described by [13]) in its extra-structure terrain.

The two-part crater-filling sequence at Wetumpka is unusual and best explained in terms of the response of a shallow-marine system to impact cratering and crater collapse. Although further work is needed to specify the exact origins of these units, their division clearly suggests two separate and successive stages in the structure-filling process. Perhaps initially, the lower breccia unit was produced by mixing of fall-back ejecta with resurge-deposited material stripped from the surrounding sea floor and maybe also from the adjacent shoreline by rapidly returning seawater [26]. Subsequently, a modification-stage event involving a catastrophic secondary resurge (wall collapse of the southwest quadrant?) may have deposited the overlying intra-structure terrain (cf. aqueous modification processes in several shallow marine craters described by [27]).

## Acknowledgements

Grant support for drilling at Wetumpka was an in-kind gift to Auburn University from Vulcan Materials Company, Birmingham, Alabama. We thank Mr. and Mrs. E.P. Schroeder and Mr. and Mrs. G. Reeves for access to their property during core drilling. Subsequent work was partially supported by an Auburn University Dean's Research Initiative grant. We thank all contributors to Auburn University's 'Wetumpka Impact Crater Fund' for their generous help. We are grateful to Daniel Boamah and Heinz Huber (University of Vienna) for their assistance with, respectively, the universal-stage measurements of PDFs and geochemical analyses. Work in Vienna was supported by the Austrian Science Foundation, project number Y58-GEO. We thank reviewers Richard Grieve and Michael Rampino for their helpful comments.***[BOYLE]***

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