BRIEF NOTE

Evidence of Maximum Age of the Serpent Mound Impact Event from Shatter Cones

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Initial investigations of the 7-8 km diameter Serpent Mound impact crater, a complex crater formed exclusively in sedimentary rock in southwestern Ohio (39.0356° N, 83.4039° W), suggested that the impact event occurred during the Early Mississippian – Late Permian interval (Bucher 1933; Reidel 1975; Watts 2004; Schedl 2006). Indications of a post-Mississippian event emerged after geologic mapping (Bucher 1933; Reidel 1975; Reidel and others 1982) suggested that the Lower Mississippian Cuyahoga Formation was the youngest geologic unit to have been deformed by the impact event. While Upper Devonian-Lower Mississippian strata appear to be displaced down below normal stratigraphic positions (Bucher 1933; Reidel and others 1982), recent observations of new drill cores and exposures outside of the limit of the disturbance (as proposed by Reidel 1975) indicate that the base of the Upper Devonian inside of the crater is also above, or not displaced from undisturbed elevations (Gabreski and Milam 2010). Non-displacement of this boundary would suggest that Devonian-Mississippian sediments buried the crater following impact. This is consistent with most (but not all) of the structural data by Reidel (1975), which reports beds of Devonian-Mississippian strata dipping within the angle of repose (<30°). The few strata dipping at steeper angles may have been re-oriented by mass wasting, similar to that observed outside of the crater. Even if intracrater Devonian-Mississippian strata are displaced from their initial elevations, it is possible that what appears to be structural offset may relate to post-impact deposition on an uplifted crater rim (higher elevation) and excavated crater floor (lower elevation), leaving open the possibility of a Late Silurian-Early Devonian impact event. Here, we offer additional observations and data which clarify whether or not the Serpent Mound impact event occurred prior to or following the Late Devonian.

Shock metamorphism of rock present at the time of impact provides a more definitive means of constraining the age of an impact event. When a collision occurs, target strata are shocked at pressures (~2-100 GPa) exceeding those at the surface of the Earth (e.g. Stöffler and Langenhorst 1994; Grieve and others 1996; French 1998). At the highest pressures (generally exceeding 35 GPa) rock can be vaporized or partially/completely melted, whereas at lower pressures mechanical deformation occurs. Planar deformation features (PDFs) that are only visible with a petrographic microscopic are commonly formed in shocked minerals (French 1998; Stöffler and Langenhorst 1994). Carlton and others (1998) observed shocked quartz in shale clasts from polymict breccias collected from a core from the Serpent Mound central uplift, indicating peak shock pressures >10 GPa (Koeberl and others, 1998). The authors, basing an interpretation solely on the size and shape of the grains in those shale clasts, suggest that the clasts belong to the Upper Devonian Ohio Shale or Lower Mississippian sandstones of the Cuyahoga Series. This interpretation is called into question by the presence of *only* Ordovician carbonate and shale bedrock in the core studied.

At pressures >2-3 GPa, conical fractures characteristic of impact, known as *shatter cones*, form as target rock fails (e.g. Dietz 1968; French 1998; Sagy and others 2002; Baratoux and Melosh 2003). Only rock present at the time of impact will contain these definitive macro-scale indicators of shock metamorphism. Shatter cones were first discovered by Dietz (1960) in residual boulders in the central peak of the Serpent Mound crater. Others have since observed them in Cambrian-Middle Silurian strata (Reidel 1975; Reidel and Koucky 1981; Reidel and others 1982; Baranoski and others 2003). Figures 1a and 1b show examples of shatter cones

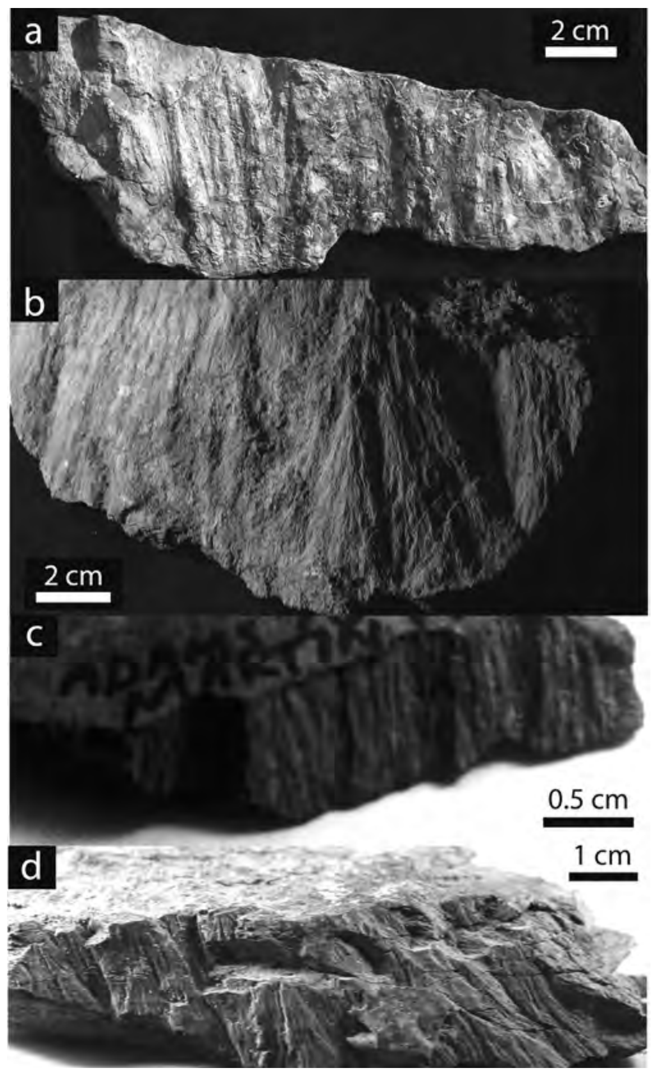

Figure 1. Images of selected shatter cones in (a) limestone from the Lower Silurian Brassfield Formation, (b) limestone of the Middle Silurian Lilley Formation, and (c and d) black fissile shale from the eastern flank of the central uplift, samples SC-1 and SC-2 respectively.

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Table 1

Major element (oxide) chemistry of fissle black shales from X-ray flourescence analyses.

Oxide	SC-1 (M. Baranoski)	SC-2 (D. Miller)
SiO_2	60.46	64.65
Al_2O_3	13.29	9.98
Fe_2O_3	4.84	6.33
MnO	0.017	0.007
MgO	1.24	0.72
CaO	0.48	0.27
Na_2O	0.29	0.3
K_2O	3.53	2.92
TiO_2	0.75	0.6
P_2O_5	0.05	0.13
Cr_2O_3	0.01	0.01
LOI	14.74	14.15
Total	99.69	100.1

in the Lower Silurian Brassfield Limestone and Middle Silurian Lilley Formation respectively. Shatter cones in these geologic units support an impact event sometime following the Middle Silurian.

Recent field excursions along the eastern flank of the Serpent Mound central uplift have uncovered shatter cones in structurally-deformed, fissile black shale exposed along the southern side of an eastward-flowing stream (at 39° 2' 4.3" N; 83° 23' 48.4" W). This outcrop was mapped as Upper Devonian Ohio Shale by Reidel (1975) and lies stratigraphically above (immediately downstream of) a Middle Silurian dolostone. Two samples were collected: SC-1 (Figure 1c) was collected *in situ*, while SC-2 is a cobble (Figure 1d) collected from the stream itself adjacent to the exposure. Both samples contain approximately five to eight unidirectional shatter cones ranging from 1.25-2.5 cm in length with apical angles ranging from approximately 35-40°. X-ray diffraction spectra (with the most intense peaks near $2\theta = 26.7°$ and 20.9°) from the two samples collected reveal that the shale is dominated by quartz, the most common mineral in Upper Devonian-Lower Mississippian strata exposed near Serpent Mound. Similarly, the bulk chemistry of each shatter-coned shale (Table 1) is comparable to those measured for both the Middle Silurian Estill Shale and the Upper Devonian-Lower Mississippian shales (for comparison, please see Milam and others 2011 this issue). However, the apparent lack of the dolomite (indicated by low CaO and MgO, Table 1 and analysis of XRD spectra) in the shale clasts precludes their identification as Lower Silurian Estill Shale.

Based on the general appearance, stratigraphic position of the source outcrop, dominance of quartz, and the bulk chemistry of each fragment, we interpret the shatter-coned fragments to represent Upper Devonian-Lower Mississippian shale, such as the Olentangy, Ohio, Sunbury, or Bedford Shales. This is the first time that shatter cones have been identified in Upper Devonian strata. Our results indicate that Upper Devonian-Lower Mississippian detrital sedimentary rocks were present at the time of impact and therefore, the Serpent Mound impact event occurred sometime following the Late Devonian-Early Mississippian.

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