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Discovery of microscopic evidence for shock metamorphism at the Serpent Mound structure, south-central Ohio: confirmation of an origin by impact

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Abstract

The origin of the Serpent Mound structure in south-central Ohio has been disputed for many years. Clearly, more evidence was needed to resolve the confusion concerning the origin of the Serpent Mound feature either by endogenic processes or by hypervelocity impact. A petrographic study of 21 samples taken from a core 903 m long drilled in the central uplift of the structure provides evidence of shock metamorphism in the form of multiple sets of planar deformation features in quartz grains, as well as the presence of clasts of altered impact-melt rock. Crystallographic orientations of the planar deformation features show maxima at the shock-characteristic planes of $\{10\bar{1}3\}$ and $\{10\bar{1}2\}$ and additional maxima at $\{10\bar{1}1\}$, $\{21\bar{3}1\}$, and $\{51\bar{6}1\}$. Geochemical analyses of impact breccias show minor enrichments in the abundances of the siderophile elements Cr, Co, Ni, and Ir, indicating the presence of a minor meteoritic component.

Keywords: shock metamorphism; Adams County Ohio; impact craters

1. Introduction

The Serpent Mound structure is a circular area, about 8 km in diameter, of intensely faulted and folded Paleozoic rocks exposed at the surface in south-central Ohio (Fig. 1) [1]. The surface geology of this structure has been well documented by numerous studies over more than a century [2].

The Serpent Mound structure closely resembles many features found throughout the world, that have been identified as craters created by the impact of an extraterrestrial body [3,4]. Dietz [5], after finding shatter cones associated with the Serpent Mound structure, suggested a meteorite impact origin. Later, Cohen et al. [6,7] reported coesite in the Lilley Formation, within the Serpent Mound structure, and used this mineral as unequivocal evidence for a meteorite impact.

Reidel et al. [2] discounted Cohen's coesite discovery as a probable misidentification of a diffuse X-ray line and concluded that their own evidence of multiple deformations over an extended period of time, although not conclusive, strongly suggested

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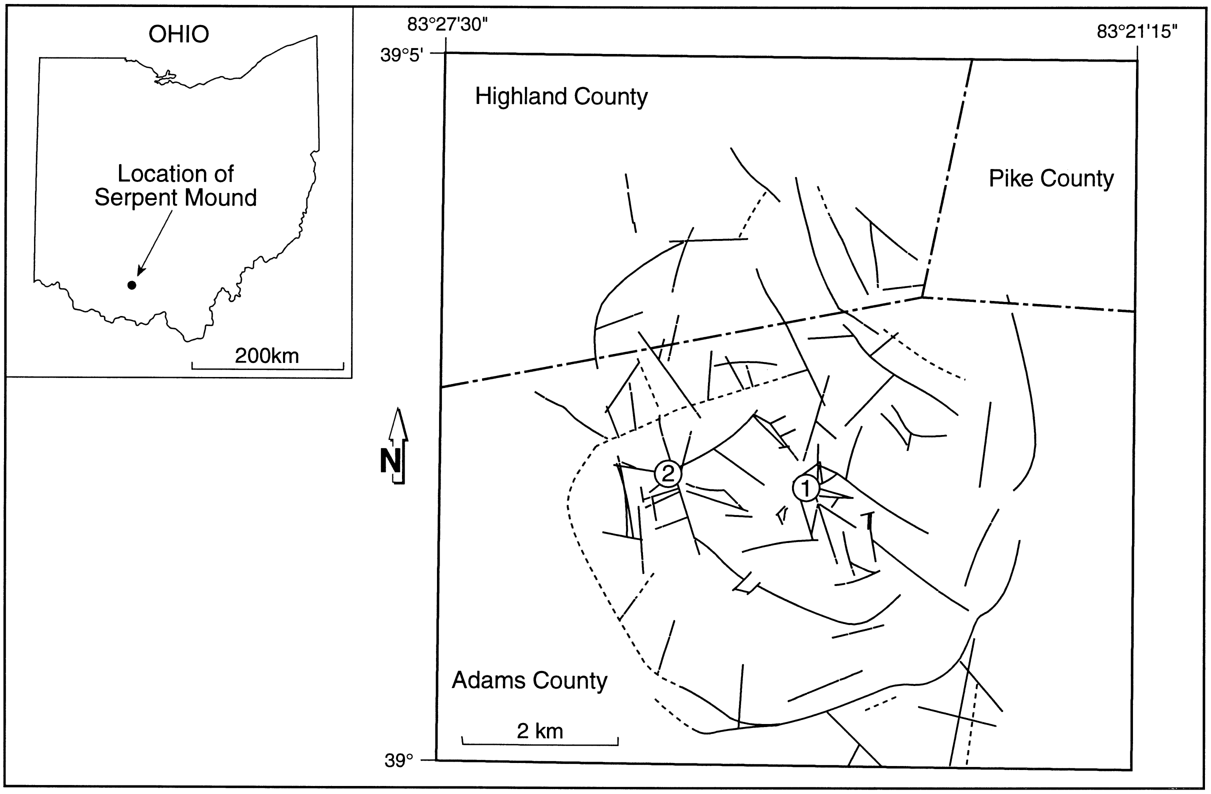

Fig. 1. Generalized map of the Serpent Mound structure, showing major faults and core locations (modified from Reidel [1]). *1* = DGS core 3274 at 39º01′59″ N, 83º24′11″ W and *2* = DGS core 3275 at 39º02′02″ N, 83º25′26″ W.

an endogenetic process created the Serpent Mound structure. On the other hand, many published lists of impact sites include the Serpent Mound disturbance [3,4]. Clearly, more evidence was needed to resolve the confusion concerning the origin of the Serpent Mound structure.

2. Stratigraphy and structure

In 1993 two continuous cores, drilled in 1979 by John L. Carroll Mineral Exploration Company, were made available to the Ohio Division of Geological Survey (DGS). An Ohio Division of Geological Survey report [8] describes these two cores in detail. The two cores, DGS 3274 and DGS 3275, reach depths of 903 and 629 m total depth, respectively. The disturbed nature of the rock in the cores is in sharp contrast to the gently inclined strata outside the disturbed area. The two cores and new geophysical data [8] provide important new subsurface information about the origin of the Serpent Mound structure.

The undeformed bedrock sequence surrounding the Serpent Mound structure consists of about 1128 m of Paleozoic sedimentary rocks unconformably overlying Precambrian basement rocks. Rocks ranging in age from Early Mississippian to at least Late(?) Cambrian have been structurally disturbed (Fig. 2) and consist of about 1000 m of dolomite, limestone, shale, sandstone, and minor siltstone and chert [8]. Recent paleomagnetic studies on core samples from 3275, and several other nearby cores strongly suggest the Serpent Mound structure is older than Early Triassic (D. Watts, 1998, personal commun.). Thick outcrops of Mississippian and Pennsylvanian sediments 60 km east of Serpent Mound, when extrapolated westward, indicate that the Serpent Mound structure once may have been covered by a minimum of 300 m of sediment younger than Early Mississippian [9].

SYSTEM/ PERIOD	GENERALIZED GEOLOGIC COLUMN		THICK-NESS (METERS)
MISSISSIPPIAN	CUYAHOGA FORMATION SUNBURY SHALE BEREA SANDSTONE BEDFORD SHALE		36
DEVONIAN	OHIO SHALE OLENTANGY SHALE		95
SILURIAN	TYMOCHTEE DOLOMITE GREENFIELD DOLOMITE PEEBLES DOLOMITE LILLEY FORMATION BISHER FORMATION ESTILL SHALE NOLAND FORMATION BRASSFIELD FORMATION		100
ORDOVICIAN	DRAKES FORMATION WAYNESVILLE FORMATION ARNHEIM FORMATION GRANT LAKE LIMESTONE FAIRVIEW FORMATION KOPE FORMATION POINT PLEASANT FORMATION		490
	LEXINGTON LIMESTONE		
	BLACK RIVER GROUP WELLS CREEK FORMATION		
	KNOX DOLOMITE	"BEEKMANTOWN" DOLOMITE	256
		ROSE RUN SANDSTONE	
– – –?– – – CAMBRIAN		"COPPER RIDGE" DOLOMITE	

Fig. 2. Generalized geologic column of stratigraphic units to the base of the Knox Dolomite (after Baranoski et al. [8]).

The Serpent Mound structure is a significant surface structural anomaly in a generally undeformed region at the western edge of the Appalachian Escarpment. Eroded and locally faulted Ordovician- to Mississippian-age rocks are exposed at the surface in this region and gently dip to the east at about 6 to 8 m per km [10]. Reidel et al. [2] divided the disturbed area into three zones based upon surface mapping of the area. These zones are the central uplift, the transition zone, and the outer ring graben. Strata in the central uplift is characterized by highly disturbed, faulted, and folded rocks which have been uplifted a minimum of 122 m [2]. Moderately resistant Ordovician and Silurian rocks exposed in the central uplift form a topographic high. The transition area is characterized by both radially and concentrically folded and faulted strata at or near their undisturbed structural position. This area is a topographic low having mostly Silurian rocks at the surface. The ring graben is characterized by fault-bounded strata, that have been displaced below their undisturbed structural positions by as much as 245 m. The ring graben forms a topographic high of resistant Mississippian and Devonian rocks, which are preserved in the down-dropped area [2].

Core 3274, located in the central uplift zone, penetrates 903 m of Ordovician carbonate rocks, shales, and minor sandstones, and chert. (Fig. 3). Bedding inclinations vary widely from overturned beds to beds dipping approximately 30° or less. The drill core penetrates large blocks of sedimentary rocks, on the order of 50 m or more thick with various breccia layers ranging from less than 1 cm to more than 80 m in thickness (Fig. 3).

Core 3275 (Fig. 1), located in the transition area has not been examined petrographically, but has been logged and described megascopically [8]. This core penetrates 629 m of Middle Silurian to Upper Cambrian limestone, shale, dolomite, and sandstone that have been fractured, faulted and brecciated. In the upper two-thirds of this core, beds are displaced 92 to 122 m below their undisturbed structural position and dip from 15° to 90°. In the lower one-third,

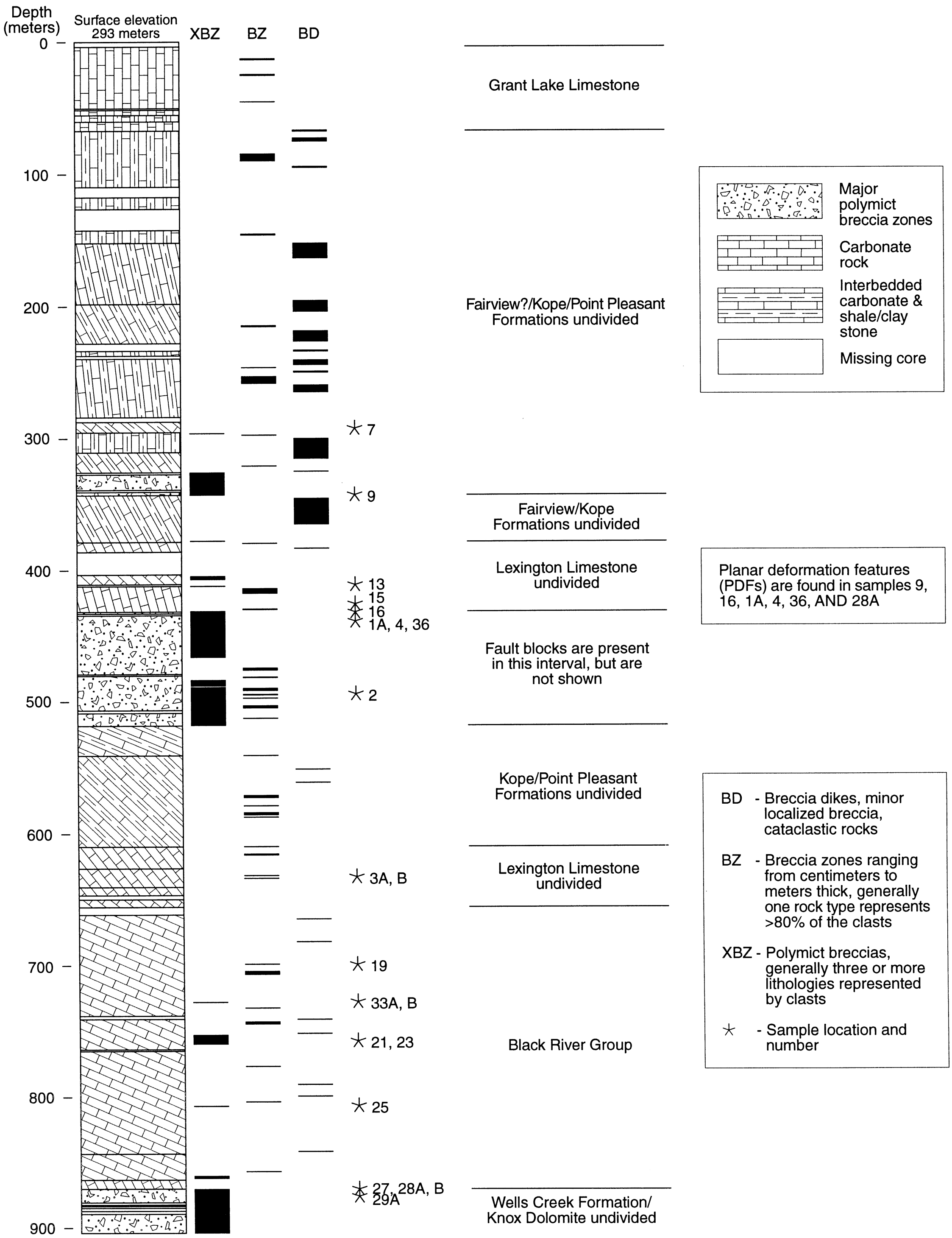

Fig. 3. Generalized graphic core description of DGS 3274. Depths of samples used in the petrographic study and breccia zones are indicated. Bedding dips are schematic. Actual bedding orientations are reported in Baranoski et al. [8].

mildly deformed to undeformed Ordovician rocks dip from 0º to 20º and have 18 to 24 m of downward displacement [8].

3. Methods

Petrographic thin sections of 21 samples from core 3274 (Fig. 3) were examined by optical microscopy. A 15-cm section of polymict breccia (SM1-36) from 438 m was taken for grain-mount studies. The SM1-36 core specimen was gently broken into fragments and placed in 10% (by volume) HCl solution for several days in order to remove the carbonate component of the breccia. After acid treatment, coarse shale and siltstone clasts were removed. The remainder was wet sieved and disaggregated in an ultrasonic bath. The 37 to 350 μm grain-size interval was used to make three grain-mounted thin sections (SM1-36a, b, c).

Crystallographic orientations of planar deformation features were measured on an optical microscope using a universal stage with four axes. In addition, major and trace element analyses were done on three breccia samples by standard X-ray fluorescence (XRF) and instrumental neutron activation analysis (INAA) procedures (see Koeberl and Reimold [11], for procedural details).

4. Results

4.1. Petrography

Core 3274 was chosen for a search for evidence of shock metamorphism because of its position at the central uplift. The breccias examined petrographically are predominantly limestone-clast breccias having subordinate amounts of shale, claystone, sandstone, siltstone, chert, and possibly altered impact-melt clasts. Three of the breccias examined contain more shale or claystone fragments than carbonate rock clasts (SM1-7, SM1-13, and SM1-4 at 293, 411 and 438 m, respectively). Two sandstone samples, SM1-27 and SM1-28B, both from about 871 m, have been tentatively identified as Cambrian Rose Run sandstone. A chert sample, SM1-15, from 425 m was also examined petrographically.

4.2. Planar deformation features

Planar deformation features (PDFs) occur in most rock-forming minerals and are uniquely characteristic of shock metamorphism associated with impact-crater formation (see for example, Ref. [12]). In quartz grains, they commonly form multiple intersecting sets of parallel planes consisting of amorphous silica. The planes are narrow (<1–3 μm thick), straight, extend through the whole grain, and are densely spaced (2–10 μm apart).

Petrographic examination of samples from core 3274 revealed the presence of PDFs in quartz in seven of the breccias examined: SM1-9 (342 m), SM1-16 (431 m), SM1-1A (437 m), SM1-4 (438 m), SM1-36 a, b, c grain mounts (438 m), SM1-2 (495 m) and SM1-28A (869 m). Most of the PDFs are located in the top 500 m of the core. Nearly all the PDFs identified are found in subangular quartz grains less than 90 μm in diameter. PDFs were found in quartz grains in Devonian shale clasts from a polymict breccia in sample SM1-4 (438 m). In all cases, the quartz grains containing PDFs resemble in size and shape quartz grains from Devonian- and Mississippian-age sandstones, siltstones, and shales found in outcrops near the Serpent Mound structure. Quartz grains containing PDFs are distinctly different from the rounded, medium-to-coarse quartz grains found in the Rose Run sandstone, which has been tentatively identified near the base of the cores DGS 3274 and 3275.

The PDFs were confirmed by determining the orientation of these structures using a universal stage. Quartz grains in grain-mount samples SM1-36a and b contain abundant PDFs; two to three intersecting sets are most abundant (Fig. 4). A maximum of six sets of PDFs per grain was observed. For the measurement of the crystallographic orientations of the PDFs, only quartz grains displaying two or more sets of PDFs were analyzed to allow some confidence in assignment of crystallographic planes relative to the a_1, a_2, and a_3 axes. Ninety-six grains were analyzed, and orientations for 232 sets of PDFs were determined in these grains. Of these, 170 sets of PDFs (73%) could be assigned with confidence to a rational crystallographic plane (Fig. 5) [13]. The results show a clear maximum at the shock-characteristic orientations of $\{10\bar{1}3\}$ and $\{10\bar{1}2\}$. Less pronounced maxima occur

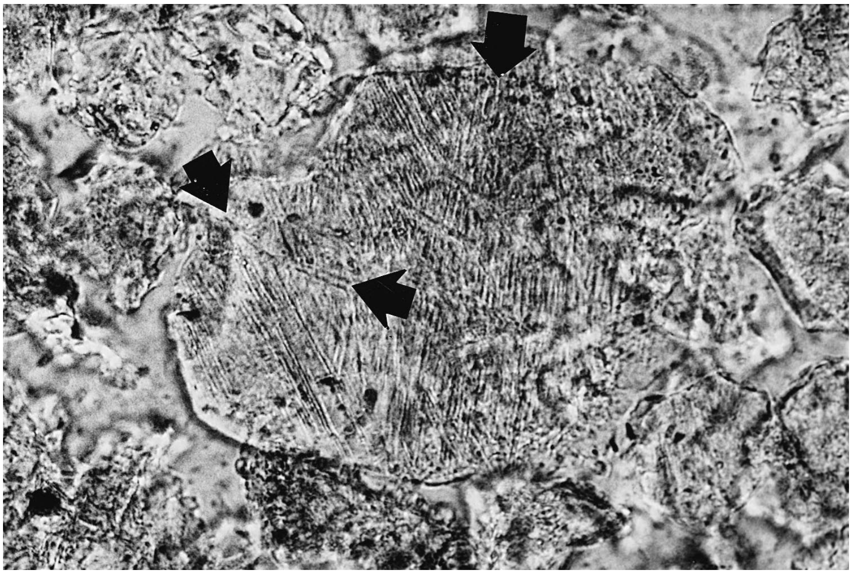

Fig. 4. Photomicrograph of quartz grains from sample SM1-36a displaying three sets of planar deformation features, indicated by arrows. Width of image: 0.30 mm, parallel polars.

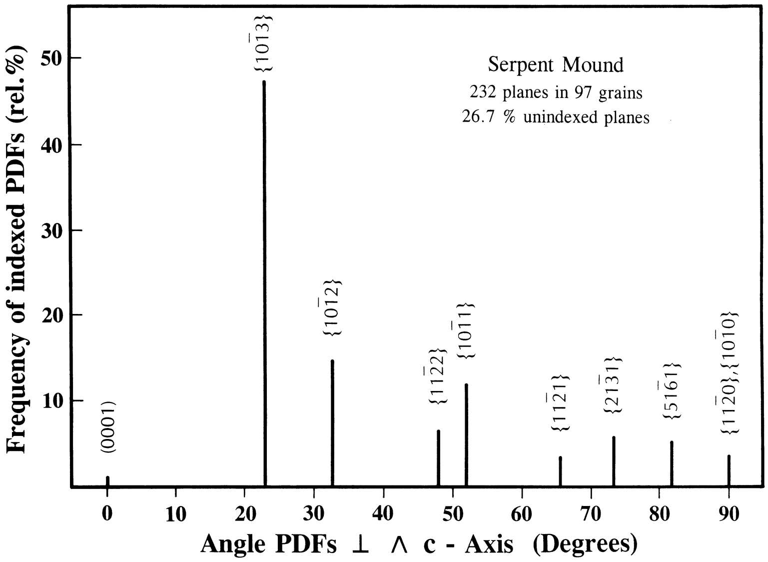

Fig. 5. Crystallographic orientation of PDFs. Histogram showing frequency of indexed PDFs versus angle between *c*-axis and PDFs; only exact angles are plotted (after Grieve et al. [13]; shock-characteristic orientations {10$\bar{1}$3}, {10$\bar{1}$2}, {11$\bar{2}$2}, {10$\bar{1}$1}, (c, ω, π, and ξ, respectively) dominate.

at the {10$\bar{1}$1}, {21$\bar{3}$1}, and {51$\bar{6}$1} orientations. Basal (0001) orientations are rare. The distribution of orientations of PDFs in samples from the Serpent Mound structure suggests that the shock levels experienced by these rocks were relatively low (>10 GPa) [12].

4.3. Impact-melt rock(?)

Six of the 18 breccias examined petrographically (SM1-33A, SM1-33B, SM1-23, SM1-25, SM1-28A, and SM1-29A) contain an estimated 1 to 3% by

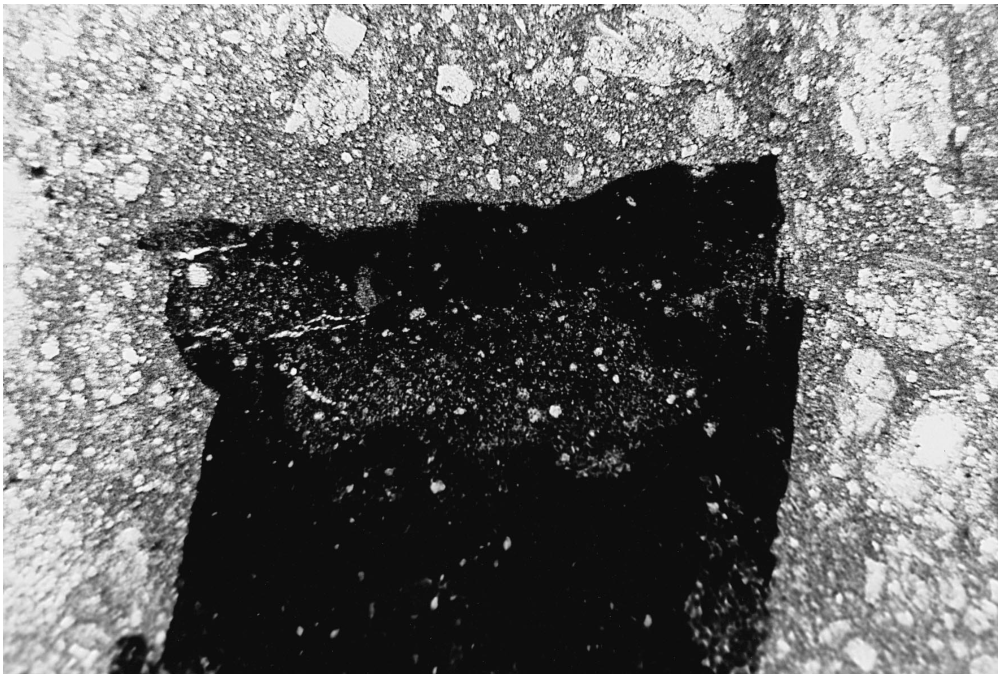

Fig. 6. Photomicrograph of altered impact-melt rock(?) from SM1-3A (633 m). Small inclusions of carbonate and quartz are scattered throughout the black clast. The lighter area within the black clast appears to be a shale fragment. The black clast is set in a groundmass of highly comminuted carbonate rock. Width of black clast is 1.65 mm.

volume of black aphanitic clasts. These clasts range in length from less than 1 mm to more than 1 cm and in shape from equant blocky or rounded fragments to irregularly shaped clasts having possible flow structure (Fig. 6). These clasts probably represent fragments of altered impact-melt rock(?) that have been completely replaced by calcite and pyrite. Under high magnification in transmitted light, the groundmass is dark gray, cloudy, microcrystalline to cryptocrystalline carbonate filled with 1–4 μm pyrite.

4.4. Polymict breccias and dikes

Of the 21 samples examined petrographically, 18 are polymict breccias having clasts ranging from 7 cm in diameter (SM1-7, 293 m) to coarse silt (matrix material is considered <30 μm). Clasts are mostly shale, claystone, limestone, dolomite, chert, sandstone, and altered melt-rock(?). Sand- and silt-size mineral grains of quartz, feldspar, and glauconite make up a small percentage of the breccia framework. Matrix material is finely comminuted material similar in composition to the framework clasts and grains. Carbonate cement is generally present, creating a hard, compact rock. Some samples (e.g. SM1-7, SM1-1A) with high percentages of shale and claystone clasts are friable and readily break down in water. Many of the samples (e.g., SM1-23, SM1-25) have a superficial resemblance to volcanic tuff.

4.5. Cataclastic structure

Cataclastic texture is not necessarily indicative of impact, but has been reported from many impact sites [14–16]. Cataclastic texture is developed in carbonate, chert, shale, and sandstone clasts throughout both cores. In SM1-28B (869 m), conjugate fractures occur in a large Rose Run sandstone clast. The fractures are filled with calcite and clay. No PDFs were found in any quartz grains from the Rose Run sandstone, but planar fractures (PFs) and shatter cones are present in the highly fractured rock.

4.6. Shatter cones

Dietz [5] recognized shatter cones at Serpent Mound, and until now, they were the only shock-metamorphic feature reported and confirmed to be present at Serpent Mound. Reidel et al. [2] reported shatter cones in float from Ordovician carbonate rocks within the central uplift, but apparently concluded they were insufficient evidence for meteorite impact.

Shatter cones are common throughout core 3274. They occur in large blocks of indurated carbonate rock and shale, as well as in shale and carbonate-rock clasts within the breccias. Observed shatter cones range in height from a few cm to 17 cm.

4.7. Elemental analysis

The major element abundances of breccias SM1-4 and SM1-16a confirm that they are composed of carbonate-dominated sedimentary rock having high CaO (15–61 wt%) and loss on ignition values (26–42 wt%). The trace element compositions are typical of sedimentary rocks having a major dolomite or limestone component. The host rock for the breccia in SM1-16b is limestone that has minor silica and high Sr contents. The chondrite-normalized, rare-earth element patterns also are typical for upper crustal rocks; La_N/Yb_N ratios are about 5 to 8 and Eu anomalies are minor to moderately negative. Siderophile element contents were determined to assess the possible presence of an extraterrestrial component. Because of the carbonate-dominated composition of the breccias, detection limits for Ir were quite favorable by INAA. Compared to the limestone-dominated host rock (SM1-16b), the two breccia samples show enrichments in Cr, Co, Ni, and Ir. This enrichment is especially obvious in the case of the breccia-host rock pair (SM1-16a/b); Cr, Co, and Ni values are about 10 times higher in the breccia than in the host rock, and Ir is significantly enriched as well (to about 0.2 ppb). Taken at face value, these data indicate the presence of about 0.2% of an extraterrestrial component with chondritic composition.

5. Summary and conclusions

Rocks from two cores, DGS 3274 and 3275, drilled into the Serpent Mound structure, in south-central Ohio were studied for their petrographic and geochemical characteristics. The cores were drilled near the central uplift and in the transition zone and reached depths of 903 and 629 m, respectively. Samples of the core from various depths in the central uplift showed abundant evidence for shock metamorphism in the form of multiple sets of PDFs in quartz grains.

The presence of shatter cones in bedrock and PDFs in quartz grains from the Serpent Mound structure indicates a variety of shock pressures in the rocks of core 3274, ranging from low pressures of $\sim$2 GPa (shatter cones) to $>$10 GPa (higher crystallographic orientations of PDFs). Devonian and Mississippian rocks, which are likely to have been close to the surface at the time of the impact, seem to contain evidence for the highest shock pressures.

Three samples were analyzed for major and trace element compositions: two breccia samples and one breccia host-rock sample (carbonate-rich). Minor enrichments in siderophile elements (Cr, Co, Ni, Ir) indicate the possible presence of about 0.2% of a meteoritic component in the breccia samples. These observations unequivocally confirm that the Serpent Mound structure is a result of hypervelocity impact, probably during the late Paleozoic (D. Watts, 1997, personal commun.).

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References

[1] S.P. Reidel, Bedrock geology of the Serpent Mound cryptoexplosion structure, Adams, Highland, and Pike Counties, Ohio, Ohio Division of Geological Survey Report of Investigations 95, 1975, color map, scale 1:12 000, one sheet with text.

[2] S.P. Reidel, F.L. Koucky, J.R. Stryker, The Serpent Mound disturbance, southwestern Ohio, Am. J. Sci. 282 (1982) 1343–1377.

[3] R.A.F. Grieve, J. Rupert, J. Smith, A. Therriault, The record of terrestrial impact cratering, GSA Today 5 (1995) 193–196.

[4] C. Koeberl, R.R. Anderson, Manson and company: Impact structures in the United States, in: C. Koeberl, R.R. Anderson (Eds.), The Manson Impact Structure, Iowa: Anatomy of an Impact Crater, Geol. Soc. Am. Spec. Pap. 302 (1996) 1–29.

[5] R.S. Dietz, Meteorite impact suggested by shatter cones in rock, Science 131 (1960) 1781–1784.

[6] A.J. Cohen, T.E. Bunch, A.M. Reid, Coesite discoveries establish cryptovolcanics as fossil meteorite craters, Science 134 (1961) 1624–1625.

[7] A.J. Cohen, A.M. Reid, T.E. Bunch, Central uplifts of terrestrial and lunar craters: Part 1, Kentland and Serpent Mound structures , J. Geophys. Res. 67 (1962) 1632–1633, abstract.

[8] M.T. Baranoski, G.A. Schumacher, D.R. Watts, R.W. Carlton, B. Elsaiti, Report on the geology of the Serpent Mound disturbance based upon new core and geophysical data, Ohio Division of Geological Survey Report of Investigations 146 (in press).

[9] M.C. Hansen, Return to sunken mountain: The Serpent Mound cryptoexplosion structure, Ohio Division of Geological Survey, Ohio Geology, Winter, 1994, pp. 1–6.

[10] E.M. Swinford, Geology of the Peebles quadrangle, Adams County, Ohio, Ohio J. Sci. 85 (1985) 218–230.

[11] C. Koeberl, W.U. Reimold, The Newporte impact structure, North Dakota, USA, Geochim. Cosmochim. Acta 59 (1995) 4747–4767.

[12] D. Stöffler, F. Langenhorst, Shock metamorphism of quartz in nature and experiment: I. Basic observations and theory, Meteoritics 29 (1994) 155–181.

[13] R.A.F. Grieve, F. Langenhorst, D. Stöffler, Shock metamorphism of quartz in nature and experiment: II. Significance in geoscience, , Meteor. Planet. Sci. 31 (1996) 6–35.

[14] B.J. Witzke, R.R. Anderson, Sedimentary-clast breccias of the Manson impact structure, in: C. Koeberl, R.R. Anderson (Eds.), The Manson Impact Structure, Iowa: Anatomy of an Impact Crater, Geol. Soc. Am. Spec. Pap. 302 (1996) 115–144.

[15] W.U. Reimold, W.P. Colliston, Pseudotachylites of the Vredefort Dome and the surrounding Witwatersrand Basin, South Africa, in: B.O. Dressler, R.A.F. Grieve, V.L. Sharpton (Eds.), Large Meteorite Impacts and Planetary Evolution, Geol. Soc. Am. Spec. Pap. 293 (1994) 177–196.

[16] N.M. Short, Anatomy of a meteorite impact crater: West Hawk Lake, Manitoba, Canada, Geol. Soc. Am. Bull. 81 (1970) 609–648.