Paleomagnetic Determination of the Age of the Serpent Mound Structure[1]

D. R. WATTS, Department of Geological Sciences, Wright State University, Dayton, OH 45435

ABSTRACT. The Serpent Mound structure is a deeply eroded ancient impact in south central Ohio, about 8.0 km across. The age of the structure is poorly constrained by the geology. It post-dates the Lower Mississippian (ca.330 Ma) Cuyahoga Formation and predates Illinoisian glacial deposits. We analyzed the directions of magnetization of 60 rock samples taken from borehole cores drilled within and in the vicinity of the structure using thermal and alternating field demagnetization. The samples were not oriented in azimuth but bedding planes were prominent allowing magnetic inclinations to be determined before and after a tilt correction. Silurian and Ordovician carbonates yielded random results. Lower Silurian Brassfield Formation samples typically have two components of magnetization. A low temperature magnetization with steep inclination that is likely a recent magnetization parallel to the present field is removed from a subset of samples at the earliest stages of treatment. Assuming the low temperature magnetization is parallel to the present field, we can show for these samples that the high temperature magnetization is of reversed polarity. A high unblocking temperature, reversed polarity magnetization has lowest dispersion (k = 138, mean inclination = -1° ± 6.3°) prior to tilt correction, and greatest dispersion (k = 35) after tilt correction, indicating that it was acquired after the structure was formed. From the inclination alone, we estimate the age of magnetization as 256 + 15/-12 Ma. This means the impact responsible for the Serpent Mound structure most likely occurred prior to 256 Ma and after 330 Ma.

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INTRODUCTION

The Serpent Mound structure is perhaps the most unique surface geological feature exposed in Ohio. It is a roughly circular area of intense deformation situated in otherwise flat lying Silurian platform sediments in the southwestern part of the state (Bucher 1921). The structure is named for the spectacular effigy mound in the shape of a serpent constructed by Native Americans on its western flank. Reidel and others (1982) mapped the geology of the structure in detail. The structure has three distinct zones (Fig. 1). The intensely deformed central uplift is about 2.0 km in diameter. The rocks in this zone are uplifted some 300 m from their normal stratigraphic position to expose Ordovician rocks at the core of the structure. The ring graben is a zone in which the rocks are displaced downward approximately 300 m from their normal stratigraphic position and marks the outer boundary of the structure on the surface. The area between the central uplift and the ring graben is the transition zone.

The Serpent Mound structure is one of a number of areas of anomalous, intense deformation, many of which have been identified as impact structures produced by the collision of asteroids or comets with the earth. Carlton and others (1998) report the discovery of planar deformation features in quartz grains collected from deep cores taken from the Serpent Mound structure. This mineral fabric is related to shock metamorphism and supports an impact origin for the structure. There are about 150 known impact structures on earth (Koeberl and Anderson 1996). We are only just beginning to understand how impacts have affected the surface of planet earth. It is important to date the Serpent Mound structure, and other such features, as accurately as possible to determine the bombardment history of planet earth in as much detail as possible. Because the surface of the Earth is constantly shifting due to plate tectonics, the age of an impact is vital in determining its actual paleolatitude and ancient proximity to other impacts on now widely separate continental masses.

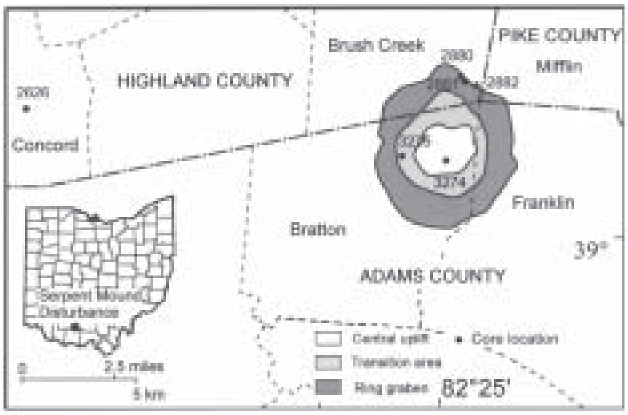

FIGURE 1. Map of Serpent Mound structure showing major structural features and borehole locations from which deep core was collected.

The youngest geological unit involved in the deformation, the Cuyahoga Formation, is found in the outer graben. The Cuyahoga Formation is Lower Mississippian in age (ca. 330 Ma) and provides a lower limit for the age of the structure. The structure is overlain by comparatively recent Pleistocene glacial sediments of Illinoisian age that give an upper limit to the age. It is clear that the geology only poorly constrains the age of the structure.

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The direction of the magnetization recorded by rocks can be used to date various geological events. The position of North America with respect to the geomagnetic pole, assumed to coincide with the geographic pole, is well known for the past 330 Ma. North American slowly drifted northward across the equator from the Mississippian to Early Triassic. At the equator, the average magnetic field is horizontal with respect to the surface of the earth. In middle latitudes, the average magnetic field is inclined with respect to the surface of the earth. The further north it is, the steeper the inclination is. The age of the magnetization of an *in situ* North American rock may be inferred from the inclination of its magnetization by comparison with the inclinations expected from the published North America paleomagnetic results.

The polarity changes of the geomagnetic field provide an additional age constraint. A very useful event for dating Late Paleozoic magnetization is the end of the Kiaman Reversed Epoch at 262 Ma (Opdyke and others 2000).

Geological events such as thermal heating and chemical alterations often reset the direction(s) of magnetization recorded by rocks. A rock can record more than one direction of magnetization. Any event in the history of the rock that alters the iron oxide chemistry may potentially impart a magnetization to a rock. Many Paleozoic carbonate and hematite rich sedimentary rocks across North America have a reversed magnetization due to remagnetization during the Late Carboniferous and Permian Kiaman Epoch. The present day magnetic field also imparts a component of magnetization to many rocks. The secondary magnetization is removed by stepwise demagnetization in an alternating magnetic field or in a magnetic field free oven to reveal the ancient components of magnetization acquired during the geological history of the rock.

Impact sites such as the Kentland structure (Jackson and Van der Voo 1986), Meteor Crater in Arizona (Cisowski and Fuller 1978) and the Slate Islands structure (Halls 1979) have magnetization that is impact related. We will not provide a comprehensive review of impact magnetization because we did not identify a magnetization generated by such a mechanism. Instead we show that more mundane remagnetization processes erased any previously existing record in the rocks we examined from the Serpent Mound structure. The age of the remagnetization does provide a new upper limit to the age of the structure.

It is important to date the Serpent Mound structure, and other such features, as accurately as possible so that we map the impact history of planet earth with as much detail as possible. Only then will the effect of impacts on geological history and the evolution of life be properly assessed. The absence of suitable minerals that can be dated by radiometric methods from the Serpent Mound structure means our age determination is likely to remain the best possible using the material available.

Istok (1978) studied the paleomagnetism of rocks involved in the Serpent Mound structure. He measured the magnetization of carbonate units in the Silurian Brassfield and Tymochtee Formations exposed in surface quarries. He reports magnetization that appears to be of Late Triassic age. These results are based on 60 specimens drilled out of 8 hand samples collected from surface exposures and analyzed only by alternating field demagnetization. No details of the behavior of the response of the specimens during demagnetization are given.

The present study is based on the systematic logging of deep drill cores (Baranoski and others 2003), which were drilled out at the locations shown in Figure 1 relative to the major structural components of the feature. Core 3274 (903 m deep), was drilled in the middle of the central uplift. Core 3275 (629 m deep) was drilled in the transition zone separating the uplift and the outer graben. Cores 2880 (84 m deep), 2881 (95 m deep), and 2882 (88 m deep) are from the periphery of the graben. Core 2626 (574 m deep) was drilled 16 km west of the center of the structure in rock not affected by the disturbance.

We collected samples from the cores in order to search for a magnetization that could be associated with an impact. The cores are not oriented in azimuth but the axis of the core is an indication of vertical. However, we can determine magnetic inclinations with respect to bedding planes. Inclination data are useful for dating the time of magnetization. The bedding planes were easily identified in the cores and we could determine the dispersion of magnetic inclinations before and after tilt correction, using the procedure described by Parés and others (1994). If the dispersion of the magnetic inclinations is greater after the tilt correction, the age of magnetization must be younger than the tilting of the rocks.

This investigation is divided into two parts. We studied the magnetization of hematite rich layers of the Silurian Brassfield Formation, collected from cores 3275 (8 samples), 2880 (10 samples), 2881 (6 samples), 2882 (9 samples) and 2626 (3 samples). We also examined older Silurian and Ordovician carbonates in cores 3274 (14 samples) and 3275 (10 samples). We concentrate on the results from the Brassfield Formation as they are of greater diagnostic interest than the carbonates.

MATERIALS AND METHODS

Samples were selected on the basis of magnetic susceptibility measurements carried out using a hand held Kappa Meter. The Brassfield Formation hematite rich beds had susceptibilities ranging from 0.7×10^{-3} to 0.3×10^{-3} SI units, and the carbonates ranged from 0.1×10^{-3} SI units to values that were below the sensitivity of the meter. We selected carbonates that had susceptibilities in the upper part of this range. The cores were drilled and cut to standard 2.3 cm × 2.54 cm cylinders. The reference mark was placed on the core, starting at the top and drawn along the vertices of the ‘V’s formed by the intersection of the bedding planes with the core. A structural or tilt correction is applied by rotating the paleomagnetic vector about the strike of the bedding plane to determine the inclination of the magnetization with respect to bedding. Every effort was made to ensure the core was right side up. The lithological continuity was monitored during the logging process and core depth markers were checked for consistency. The locations of each of the paleomagnetic samples are shown on detailed lithological logs of each of the cores in Baranoski and others (2003).

Samples were measured using a 2-G cryogenic magnetometer at the University of Michigan, and a JR5A spinner magnetometer at The Ohio State University. The measurements done at the University of Michigan were carried out in a magnetically shielded room that reduced the ambient field to levels of 200 nT (nanoTesla). Two carbonate samples and one Brassfield sample were subjected to alternating field demagnetization using a Schonstedt SM-1 A.F. demagnetizer. Step-wise thermal demagnetization using an MMTD60 magnetically shielded oven was applied to the remaining Brassfield and carbonate samples. We used orthogonal projections (Zijderveld 1967) of the demagnetization results during the process, examples of which are given in Figures 2, 3, and 4. For each measurement step, open characters denote the projection of the total magnetization vector into a vertical plane and closed characters denote the projection into a horizontal plane. Components of the natural magnetization are revealed by straight-line trajectories during stepwise demagnetization on these plots, and were isolated using the regression methods outlined in Kent and others (1983).

The statistical method of McFadden and Reid (1982) was used to determine the maximum likelihood estimate of the magnetic inclination of the respective components, and to estimate the precision parameter (k) and associated confidence limits. The precision parameter (k) provides a measure of the dispersion of the results. A value of k less than 3 denotes a random distribution. The greater the value of k, the less random the distribution. The associated confidence limits provide the error of the estimate of the magnetic inclination. We estimated these values for the Brassfield data before and after the application of tilt correction.

RESULTS

Figure 2 shows the result of typical stepwise thermal demagnetization of the Silurian and Ordovician carbonates from cores 3274 and 3275. The magnetization is thermally distributed, rapidly decaying towards or near the origin of the orthogonal projection with multi-vector or curved trajectories before alteration of the magnetic mineral causes an abrupt increase in the magnetization at 400^{o} C. Alternating field demagnetization at 500 nT reduced the intensity of the magnetization by 95%.

The magnetic inclinations of the carbonates were highly variable with a mix of steeply positive (down) and negative (up) inclinations. The high dispersion of inclinations, combined with the presence of reversed directions, implies the magnetization found in the carbonates was acquired over a time interval that is not geologically instantaneous and therefore could not be directly attributed to an impact. The random distribution of the magnetic inclinations that were determined from these rocks precluded further analysis of these results.

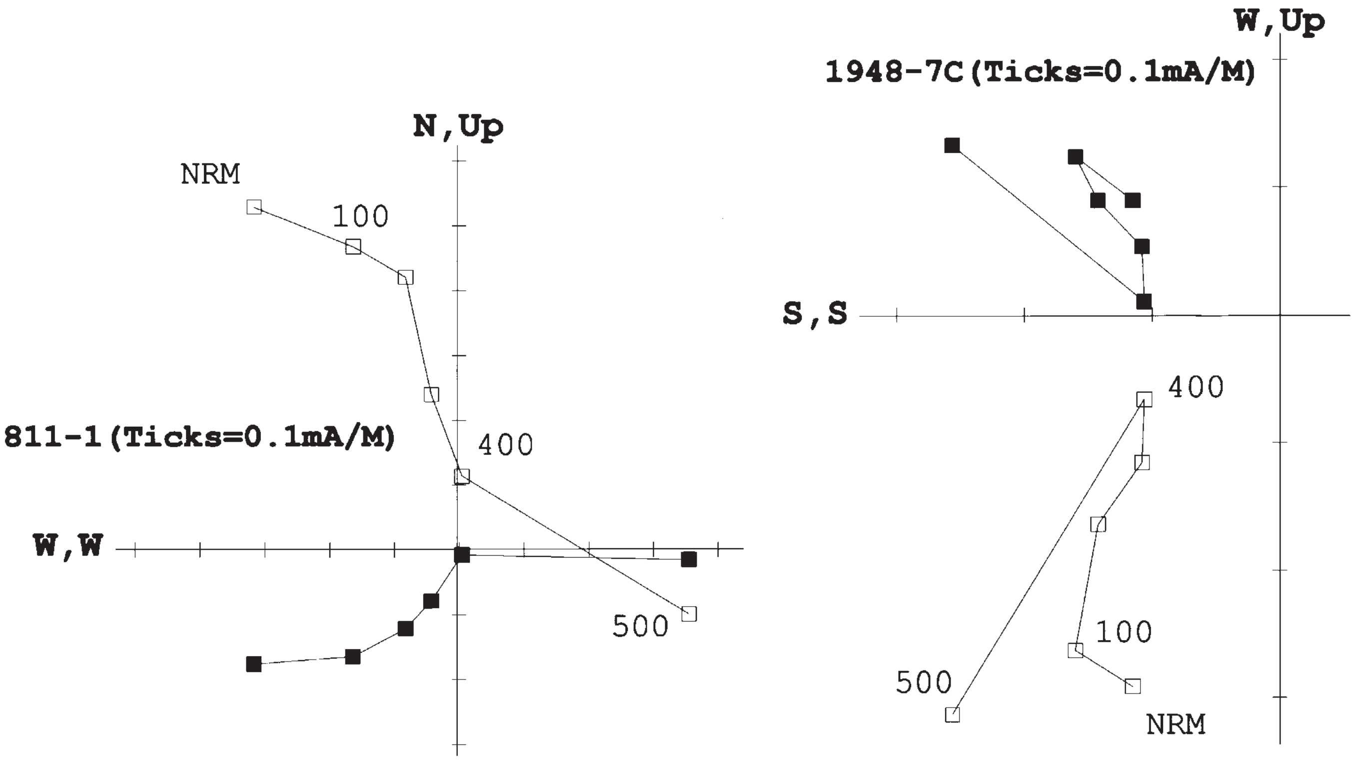

FIGURE 2. Orthogonal projections of demagnetization results from Silurian and Ordovician carbonates in boreholes 3274 and 3275. Open symbols denote projection on the vertical plane. Closed symbols denote projection on the horizontal plane. Sample 811-1 is from borehole 3275 and sample 1948-7C is from borehole 3274.

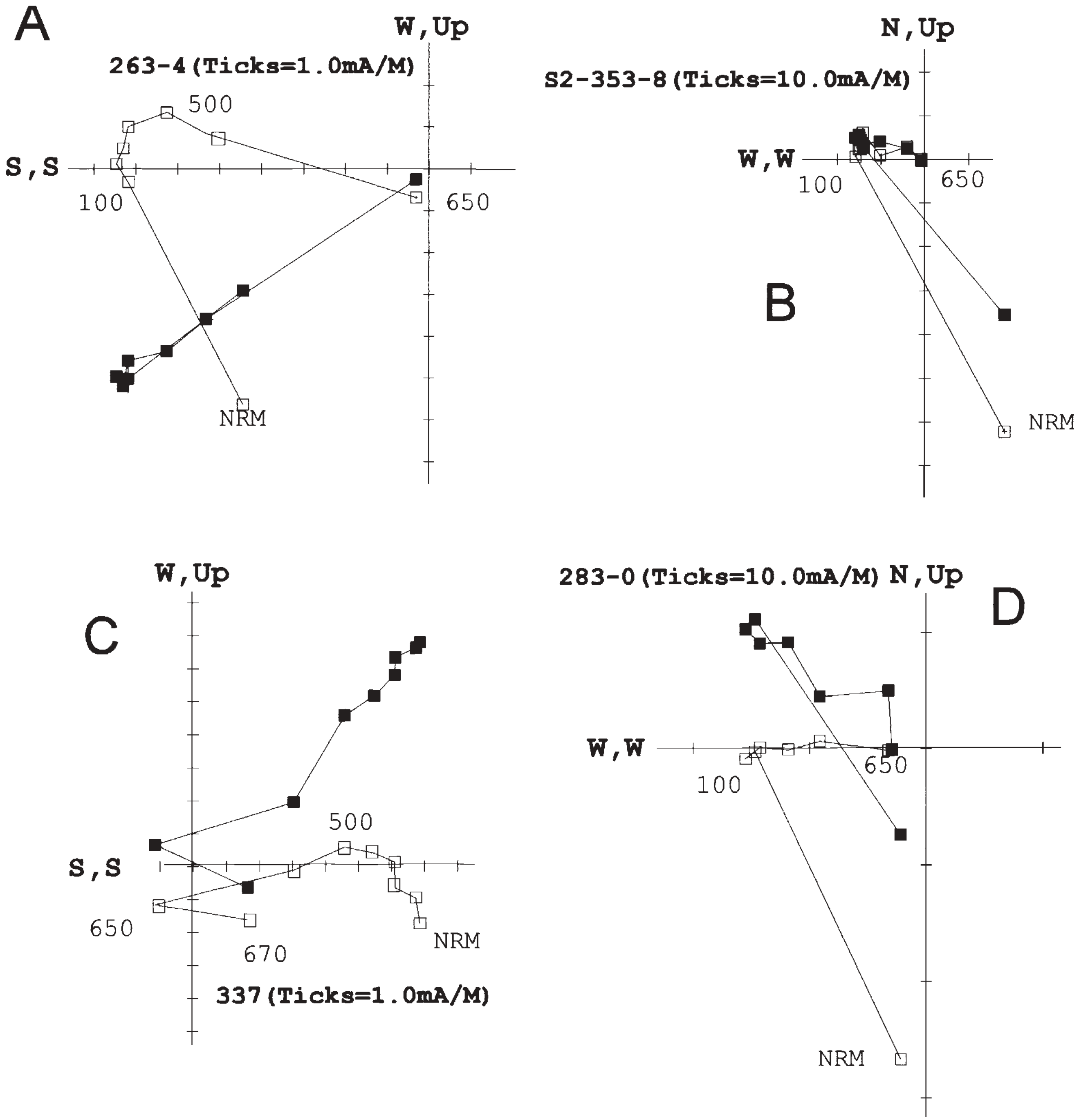

FIGURE 3. Orthogonal projections of demagnetization results from the Brassfield Formation. Convention of projection as in Figure 2. Sample 263-4 (Fig. 3A) is from borehole 2881. Samples S2-353-8 (Fig. 3B) and 337 (Fig. 3C) are from borehole 3275. Sample 283-0 (Fig. 3D) is from borehole 2882.

Figure 3 shows orthogonal projections of thermal demagnetization results from the hematite rich beds of the Brassfield Formation. A steep, positive inclination secondary magnetization was removed from many samples during the early stages of thermal demagnetization to reveal a high unblocking temperature thermally discrete magnetization. The high unblocking temperature magnetization did not always decay towards the origin of the demagnetization plot, and it was impossible to extract any further information due to acquisition of laboratory-induced magnetization at this level of treatment.

Assuming the low temperature magnetization is a present day overprint, we assume that its projection into a horizontal plane points to magnetic north. We can estimate the declination of the high temperature magnetization by the angle its horizontal projection (declination) makes with respect to that of the low temperature magnetization. Examination of the horizontal projections (closed symbols) in Figure 3A,B,D shows that the declination of the secondary magnetization is nearly opposite (~180°) that of the high temperature magnetization. Of the 36 samples examined from the

Brassfield Formation, 24 had both low and high temperature magnetization. The others yielded results depicted by Figure 3C, which does not show a low temperature magnetization. Figure 4 is an equal area projection of the high temperature magnetization with the declination estimated by rotating the low temperature magnetization declination to north. The diagram shows the high temperature magnetization to be of reversed polarity. There is no clear evidence for normal polarity, antipodal magnetization from this population. The results exhibited in Figure 4 are sufficiently accurate to show that no normal polarity magnetization is present in this subset of samples. Although we are convinced that the magnetization is of reversed polarity, we do not regard the estimates of the declinations to be sufficiently accurate to calculate a mean direction of magnetization. We use only the inclination data of the high temperature magnetization, combined with the evidence that it is of reversed polarity, to estimate the age of the magnetization.

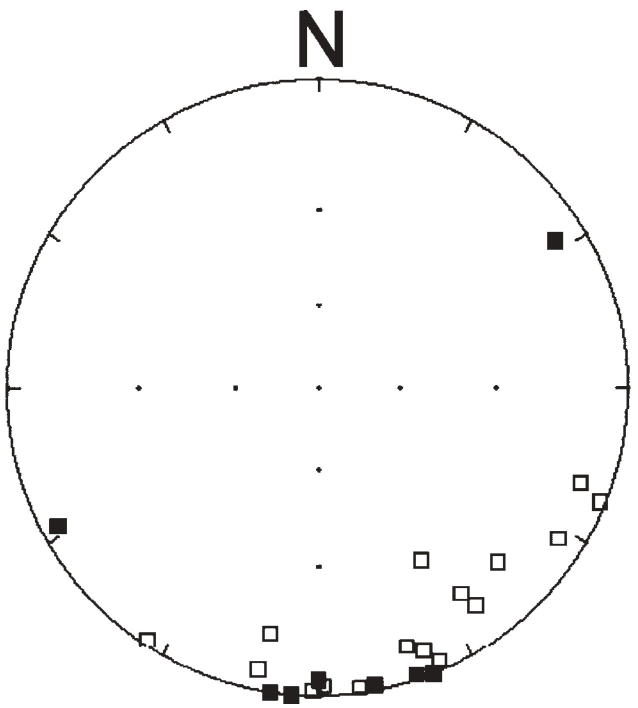

FIGURE 4. Equal area projection of high temperature magnetizations of the Brassfield Formation with declinations estimated assuming low temperature magnetizations are parallel to the present day magnetic field and therefore an indication of geographic north. Open symbols denote negative (up) inclination. Closed symbols denote positive (down) inclination.

The data for each specimen are given in Table 1. Listed are the core number (Fig. 1) and depth of the sample, and the estimated paleomagnetic inclination before and after correction for the dip of the beds. Note that the declinations given in Table 1 refer to the dip direction exhibited by each individual specimen and not to geographic north. Using the procedure of McFadden and Reid (1982) we calculate the average inclination before and after the correction for the tilt of the beds. We organize the data into groups or ‘sites’ such that the

TABLE 1

Results from the Brassfield formation showing the core number as located in Figure 6, depth of the sample in meters, the magnetic declination/inclination of the high temperature component prior to rotation about the sample bedding plane, and magnetic declination/inclination after rotation about the sample bedding plane. Note that the declinations are not referred to geographic north, as the core was not oriented in azimuth. The declinations are referred to the dip direction of the bedding observed in the specimens.

Core	Depth Meters	Declination/Inclination Before tilt correction	Declination/Inclination After tilt correction
3275	103.7	315°/-5°	309°/-26°
3275	104.4	334°/3°	330°/-28°
3275	105.2	319°/-8°	314°/-26°
3275	105.8	328°/-12°	317°/-41°
3275	105.85	239°/-7°	241°/11°
3275	106.7	267°/-24°	252°/-16°
3275	107.0	262°/-12°	256°/-4°
3275	107.8	284°/-12°	275°/-18°
2626	51.30	314/10°	314/10°
2626	51.34	197°/2°	197°/2°
2626	51.38	7°/2°	7°/2°
2880a	75.5	118°/-3°	118°/2°
2880a	75.9	74°/-6°	75°/-9°
2880a	76.0	163°/7°	162°/16°
2880a	76.2	209°/-1°	210°/8°
2880a	76.3	131°/5°	129°/11°
2880a	76.4	238°/-1°	238°/4°
2880b	80.3	146°/-1°	146°/8°
2880b	80.7	110°/-4°	111°/-1°
2880b	81.8	225°/1°	225°/6°
2880b	83.2	26°/3°	26°/-6°
2881	79.0	1°/-5°	1°/-20°
2881	79.05	275°/-1°	274°/-2°
2881	80.3	346°/-1°	346°/-16°
2881	80.5	9°/-1°	9°/-16°
2881	80.6	50°/0°	51°/-10°
2881	80.65	337°/6°	337°/-8°
2882	81.2	317°/1°	316°/-10°
2882	86.2	330°/-1°	329°/-14°
2882	86.3	305°/1°	305°/-7°
2882	86.35	279°/-6°	278°/-8°
2882	86.4	304°/-5°	302°/-13°
2882	86.5	281°/-6°	279°/-9°
2882	86.6	263°/0°	263°/2°
2882	86.65	301°/-2°	300°/-10°
2882	86.7	308°/-2°	307°/-11°

average inclination from each site is an estimate of the time average paleomagnetic direction. For borehole 2880, there is a clear break in the sample elevations between 76.4 m and 80.3 m (see Table 1). We therefore divide the results from this borehole into two sites. Site 2880a has samples located between 75.7 and 76.4 m. Site 2880b has samples between 80.3 and 83.2 m. We treat the data from the other boreholes as individual sites, giving 6 independent estimates of the average paleomagnetic field inclination. Table 2 contains the average inclinations calculated for each site. We calculate from these data the site-mean inclinations and associated error, α_{95}, see McFadden and Reid (1982), which are also given in Table 2. The site-mean average inclination is –1º ± 6.3º, k = 138 prior to tilt correction, and -4º ± 12.5º, k = 35 after tilt correction.

TABLE 2

The site-borehole number, the number of samples (N), the mean paleomagnetic inclination (I) and associated error (α_{95}, see McFadden and Reid 1982) prior to tilt correction.

Site/Borehole	N	I	α_{95}
3275	9	-10º	6.6º
2626	3	5º	16.6º
2880a	5	0º	6.5
2880b	4	-1º	6.0º
2881	6	0º	4.6º
2882	9	-2º	3.0º
Site-Meam	6	-1º	6.3º

Parés and others (1994) lament the lack of a statistical significance test for the inclination only fold test, and so do we. We cannot assign a statistical precision to the level of significance of the fold test. However, the increase in dispersion after the structural correction is applied indicates the magnetization was acquired after the tilting. This can be demonstrated graphically by examining histograms (Fig. 5) showing the frequency of results before and after structural correction. Figure 5A shows the distribution of the inclinations prior to correction for the tilt of the beds. Figure 5B shows the distribution after correction for the tilt of the bedding in the core. Clearly, the correction for tilting scatters the results, indicating that the magnetization was acquired after the structural deformation. We use the inclination of –1° ± 6.3°, as the estimate of the average reverse polarity inclination at the time the Brassfield Formation acquired its high temperature magnetization.

DISCUSSION

The high unblocking temperature magnetization of the Brassfield Formation was clearly acquired after the structure was formed. The high unblocking temperature implies that it is a chemical remnant magnetization (CRM) acquired by the chemical alteration of the iron bearing minerals in the rock. The rocks were remagnetized after the deformation that produced the Serpent Mound structure. Therefore the impact happened before the remagnetization, and the age of the high temperature magnetization provides the younger age limit for the Serpent Mound structure.

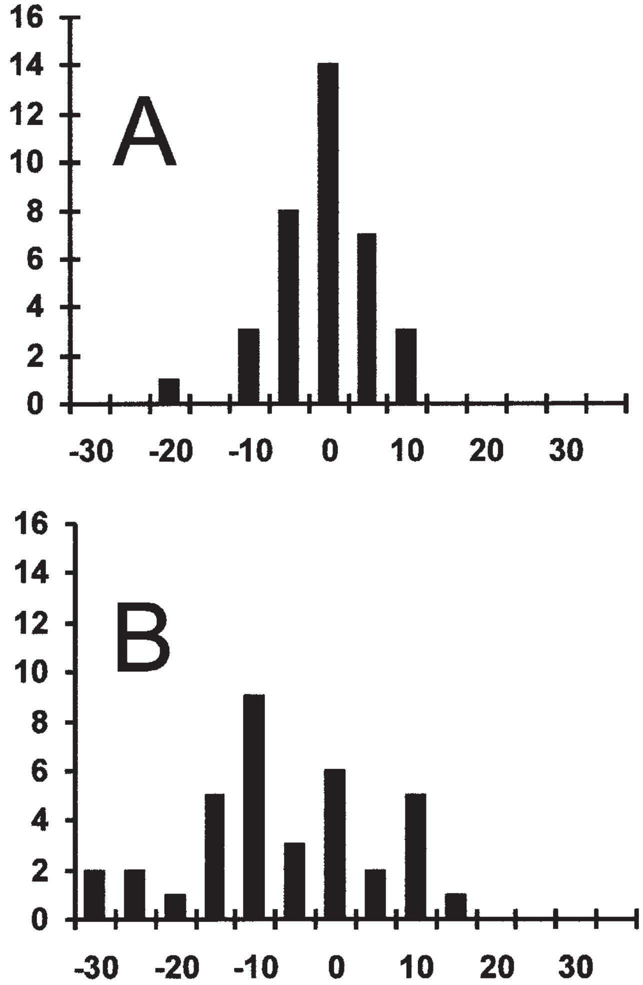

FIGURE 5. Histograms showing the frequency (vertical axis) of different values of the magnetic inclination (horizontal axis) estimated from the Brassfield Formation before tilt correction (A) and after tilt correction (B). Histogram (A) clearly shows the smaller dispersion of the data prior to tilt correction indicating that the magnetization was acquired after the deformation that produced the Serpent Mound structure.

Figure 6 shows estimates of the average paleomagnetic inclinations for the North American location of the Serpent Mound structure as a function of geologic age. These were calculated using the same North American reference data that Stamatakos and others (1996) used to date the timing of folding in the Appalachian Mountains. We convert our reversed polarity inclination to normal polarity for comparison with the reference by changing the sign from negative to positive. The reference magnetic inclination at the site slowly changed in time from negative to positive, representing the slow northward drift of the site across the equator into the northern hemisphere. If the average normal polarity

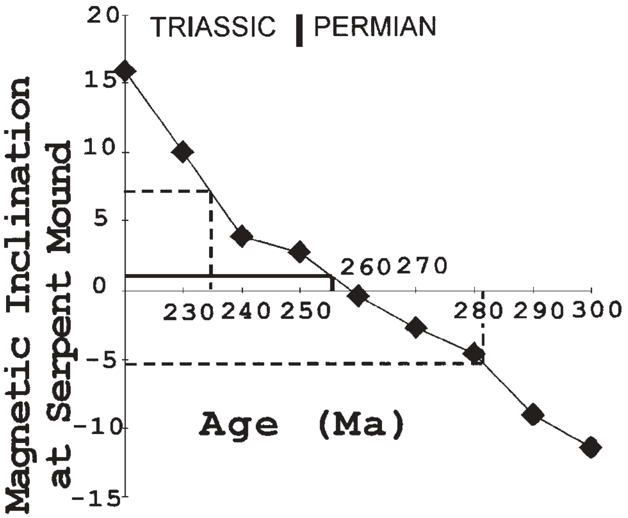

FIGURE 6. Magnetic inclination plotted against geological age at the site of the Serpent Mound structure. The estimate of the age is shown as a solid line, and the error limits are shown as dashed lines. The normal polarity inclination increased as North America drifted northward during the Late Paleozoic.

inclination is 1° ± 6.3°, the age of magnetization inferred from Figure 6 is 256 Ma. Because of the different rate of change of the site magnetic inclination with time, the upper bound of the uncertainty is 234 Ma and the lower bound is 281 Ma as illustrated in Figure 6. This is the best estimate of the age of the magnetization using only the inclination measurement.

However, if the magnetization was acquired during the widespread remagnetization that affected much of the North American craton during the Kiaman reversed epoch, the lower end of the age estimate may be more appropriate. The Kiaman reversed epoch spanned a period of time from Late Pennsylvanian to Late Permian or about 316 to 262 Ma (Opdyke and others 2000). During this time the earth's magnetic field was locked in a reversed polarity. Considering both the magnetic inclination and the reversed polarity, we suggest the age of the Brassfield magnetization to be Late Permian, possibly acquired during the Kiaman interval. If the Brassfield magnetization was indeed acquired during the Kiaman interval, it is older than 262 Ma. However, it is impossible to prove this hypothesis at this point because other reversed polarity periods doubtless occurred within the error range of the age estimated from the paleomagnetic inclination.

The age estimate from the paleomagnetic data is not likely to be improved by radiometric methods because no suitable material has been found associated with the structure. The paleomagnetic age estimate provides a much better upper age constraint than afforded by the geological relationships. It does raise the possibility that ejecta from the impact may be preserved in Permian or Carboniferous rocks that are closest to the site. The identification of microfossils or lithologies from allocthonous breccias preserved within the structure and the deep core may yield more information diagnostic of the age of formation of the feature.

McFarland and Carlson (1996) suggest a Late Paleozoic age for the Serpent Mound structure based upon the evidence for brine migration through the structure. The timing of the mineralization linked to brine migration likely coincides with the Allegheny Orogeny. It is not possible to give a more accurate age than this, based upon the mineralization alone. The high temperature magnetization found in the Brassfield Formation may be related to the chemical alteration of the iron bearing minerals during this mineralization. This same event is believed to be one of the major mechanisms driving the widespread remagnetization that is found in North America. It is likely that the age constraints we report here are also valid estimates for the age of the regional fluid migration responsible for the mineralization found in the vicinity of the Serpent Mound structure.

When considering the impact history of the Earth, it is important to recall that the present latitudes of the structures are not necessarily the locations where they formed due to plate tectonics. Examining the age ranges of the Serpent Mound structure, Figure 6 shows that the site of the Serpent Mound structure must have been at a low southern to low northern paleolatitude and part of the Pangea super continent when the impact occurred. This may be useful for future comparison with other impact sites to determine whether or not the Serpent Mound structure was one of a number of structures caused by a swarm of impacting objects.

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