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PALEOMAGNETIC STUDIES OF ROCK AT THE ORDOVICIAN-SILURIAN BOUNDARY IN WISCONSIN

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ABSTRACT

The paleomagnetism of 64 samples of shale, oolitic iron ore, and dolomite from 10 sites in the Wisconsin area was investigated. The formations studied were the Maquoketa Shale (Late Ordovician), the Neda Iron Ore (latest Ordovician) and the Mayville Dolomite (Early Silurian). The shale and dolomite showed good paleopole directions after thermal demagnetization to 300 °C or AF demagnetization to 50 mT. The Maquoketa Shale produced a reversed pole at 29.3° S., 116° E. (a_{95} = 15.3°). The pole for the Mayville was also reversed and located at 36.7° N., 122.2° E. (a_{95} = 7.60°). Both of these poles are consistent with published Ordovician-Silurian poles of North America.

Thermal demagnetization of the Neda iron ore indicated that its remanence is in the matrix rather than the oolites. The paleopole for the Neda is reversed and located at 45.4° N., 132°E. (a_{95} = 16°). This pole is similar to early Permian poles of North America. This suggests that the hematite in the ore is not original but was produced from the dehydration of goethite through time, possibly during the formation of the Wisconsin Arch. There are no major differences in the magnetic characteristics of the Neda from Iowa, Illinois, and Wisconsin.

INTRODUCTION

This paper is a compilation and review of studies by Kean (1980, 1981) and Voltz (1983) of Ordovician and Silurian age sedimentary rock in Wisconsin and neighboring states. The main objective of these studies was to investigate the paleomagnetism of the Maquoketa Shale (Late Ordovician), Neda Iron Ore (latest Ordovician), and Mayville Dolomite (Early Silurian) (fig. 1). The study is of particular interest for several reasons: (1) Most paleomagnetic results for Ordovician and Silurian time are derived from studies of folded Appalachian rock which contains considerable secondary magnetization. It was considered that a cleaner paleomagnetic record could be obtained from undeformed cratonic rock; (2) If variation in the magnetic characteristics through the Lower Silurian rock could be found, it could be a useful aid in stratigraphic correlation of Lower Silurian rock in eastern Wisconsin; (3) There is a major problem in obtaining original paleopole positions from Ordovician and Silurian age red sedimentary rock. Most results show a pole position of Permian age, or a Permian-age secondary overprint which dominates the magnetization. It was hoped that the Neda Iron Ore would provide some new information for this old problem; and (4) Templeton and Willman (1963) suggested that the Neda ore may be related to the Queenstone Shale of western New York. A comparison of the paleomagnetic directions from the Neda and the Queenstone Shale might add some credence to this idea.

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GEOLOGY

Paleozoic rock of eastern Wisconsin dips gently to the east toward the Michigan Basin. The resistant Silurian dolomite forms a north-northeast trending escarpment which is the result of more rapid erosion of the underlying Maquoketa Shale. Due to its non-resistant nature, exposure of the Maquoketa Shale is of limited thickness in Wisconsin. Samples obtained for this study were limited to the Brainard Shale, the uppermost member of the Maquoketa Formation (Ostrom, 1967). The Brainard is a greenish-gray, fossiliferous, thin-bedded shale interbedded with dolomitic shale.

Lower Silurian rock forms the base of the Silurian escarpment in Wisconsin, and are currently included in one formation, called the Mayville Dolomite (Steiglitz and Allen, 1980). The Mayville is a gray-buff, thick-bedded, cherty, medium-to-coarse-grained dolomite.

The Neda Iron Ore is a hematite-goethite-oolitic formation, which is found locally between the Maquoketa and Mayville. The Neda was originally assigned a Silurian age, but is currently interpreted as having formed during shoaling of the regressing sea in Late Ordovician time (Paull, 1977).

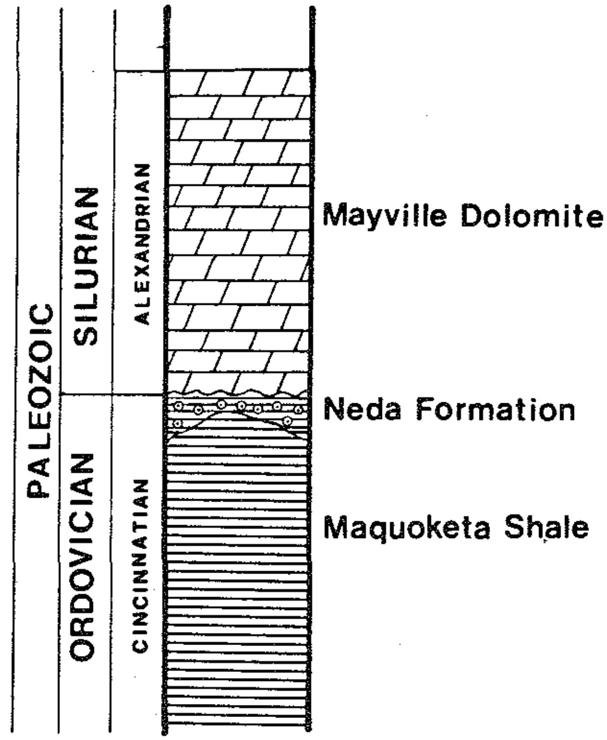


Figure 1. Stratigraphic relationships of Upper Ordovician and Lower Silurian rock in eastern Wisconsin (modified from Nelson and Lasca, 1970).

RESULTS - MAQUOKETA SHALE AND MAYVILLE DOLOMITE

Samples were collected from the Upper Ordovician Maquoketa Shale and Lower Silurian Mayville Dolomite at ten sites in eastern Wisconsin (fig. 2). Sample and specimen totals for each location are given in table 1. A greater number of sampling sites would have been desirable, but good exposures are very limited, particularly for the Maquoketa Shale.

Pilot samples from each location were subjected to detailed alternating field (AF) and thermal demagnetization (McElhinny, 1973). A two axis SCT Cryogenic magnetometer was used to measure the magnetization. Most samples contain a secondary component which could be removed by AF demagnetization at 35-50 mT or by thermal demagnetization at 250 ^{o}C. The optimum method and level of demagnetization for each site was determined by studying Zijderveld diagrams for each pilot sample.

A Zijderveld diagram (1967) depicts the change in magnetic inclination and declination as a function of progressive demagnetization. When the curve shows a linear trend toward the origin, the magnetization is decreasing in intensity, but it is maintaining a consistent direction. This direction is considered to be the stable direction and may represent the original magnetization of the sample. Figures 3 and 4 are Zijderveld diagrams for AF-demagnetized samples of Maquoketa Shale and Mayville Dolomite. Linear trends, depicting stable magnetization, are seen at demagnetization levels above 20 mT. The method and level of demagnetization which results in stable magnetization is used to demagnetize the remaining suite of samples for each site. The optimum demagnetization levels are given in table 2. Samples which are located in close proximity to the Neda Formation generally yield inconsistent results, and were not used in the analysis.

Magnetic directions for all samples are statistically combined (Fisher, 1953) to obtain formation mean directions of magnetization andvirtual geomagnetic poles (McElhinny, 1973).

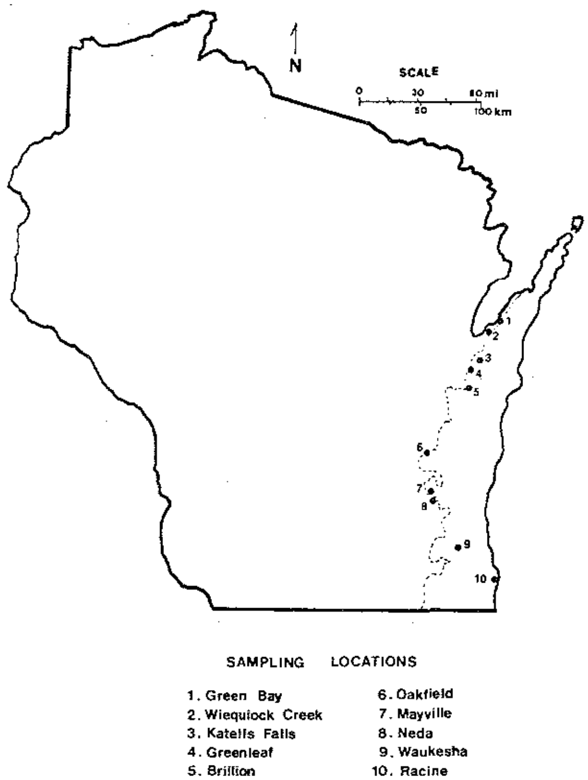


Figure 2. Map of Wisconsin showing sampling locations 1. Green Bay, 2. Wiequiock Creek, 3. Katells Falls, 4. Greenleaf, 5. Brillion, 6. Oakfield, 7. Mayville, 8. Neda, 9. Waukesha, 10. Racine. Dashed line is the Ordovician-Silurian boundary

For the Maquoketa Shale, 22 specimens from 10 samples from six horizons yield a mean inclination and declination of 18.8 and 158.1 respectively ($K = 20$, $a_{95} = 15.3^{o}$); the paleomagnetic pole is located at 29.3^{o} S., 63.2^{o} W. (North pole at 29.3^{o} N., 116.8^{o} E.).

For the Mayville Dolomite, 137 specimens from 29 samples from 11 horizons yield a formation mean direction of $I = 9.8^{o}$, $D = 156.1$ ($K = 38.5$, $a_{95} = 7.5^{o}$); the paleomagnetic pole is located at 36.7^{o} S., 57.8^{o} W. (North Pole at 36.7^{o} N., 122.2^{o} E.). These results are in general agreement with those of other Ordovician-Silurian studies (fig. 5). Further discussion is presented later.

As was mentioned earlier, stratigraphic correlation of members of Lower Silurian rock in Wisconsin is difficult because of relatively few thick exposures. The most extensive exposure of the Mayville Dolomite which starts at the contact with the Brainard Shale (uppermost member of the Maquoketa Formation) is located at the Waukesha Lime and Stone Company Quarry (location 9, fig. 2). A cursory study through the 30 m exposure was made to see if there were any significant variations in magnetic characteristics or magnetic directions, which could be used as stratigraphic markers.

Table 1. Sample and specimen totals for each sampling location.

Sampling location hand samples	Number of hand samples	Number of
Maquoketa Shale		
Wiequiock Creek	16	29
Katells Falls	6	8
Oakfield	6	18
Total	28	55
Lower Silurian Dolomite		
Wiequiock Creek	4	14
Green Bay	4	21
Katells Falls	2	16
Greenleaf	4	25
Brillion	4	13
Mayville	4	19
Neda	6	20
Waukesha	16	101
Racine	15	10
Total	59	239

One hundred one specimens from 16 hand samples were measured for demagnetization characteristics and magnetic directions. The optimum demagnetization levels did not change much (table 2), nor were the variations in magnetic directions statistically significant (fig. 6).

AF and thermal demagnetization characteristics are not always sufficient to determine the magnetic mineralogy of rock samples. Therefore, saturation magnetization studies and remanence coercivities studies were also performed.

The remanence acquisition for the Maquoketa Shale shows saturation at 100-200 mT. The remanence coercivity value is approximately 50 mT (Voltz, 1983). Both of these values indicate a spinel phase mineral such as magnetite. The Mayville Dolomite shows a two component remanent acquisition curve; saturation of a spinel phase mineral is indicated at 100-200 mT and the acquisition of significant remanence at 200-1000 mT suggests the presence of hematite. The remanence coercivity study also shows a two component remanence. One value at 38 mT and the other at 453 mt (Voltz, 1983). The results are reasonable for a spinel phase such as magnetite and for hematite respectively.

From these results and AF and thermal demagnetization studies, we conclude that the magnetic carrier for both the Maquoketa Shale and the Mayville Dolomite is a spinel phase iron oxide such as magnetite. We have assumed this to be primary, although recent studies by McCabe and others. (1983) indicate that magnetite can be produced by diagenetic processes as well.

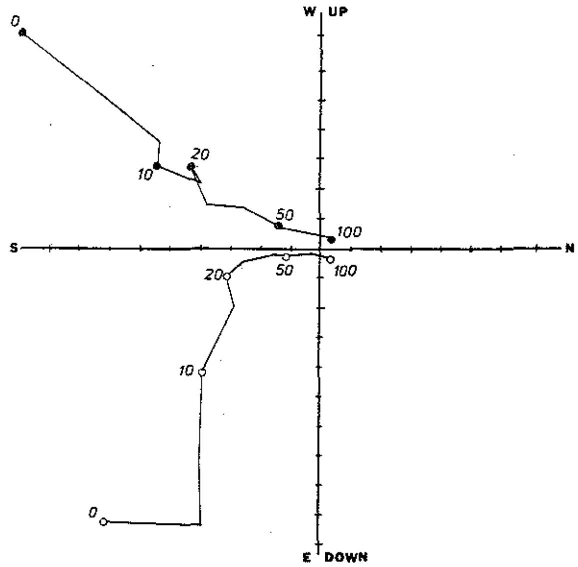


Figure 3. Zijderveld diagram for AF demagnetization of Maquoketa Shale. Numbers along the curve indicate the level of demagnetization in mT. Solid circles are declination, open circles are inclinations. Units along the axes are 10^{-5} Am^{-1}.

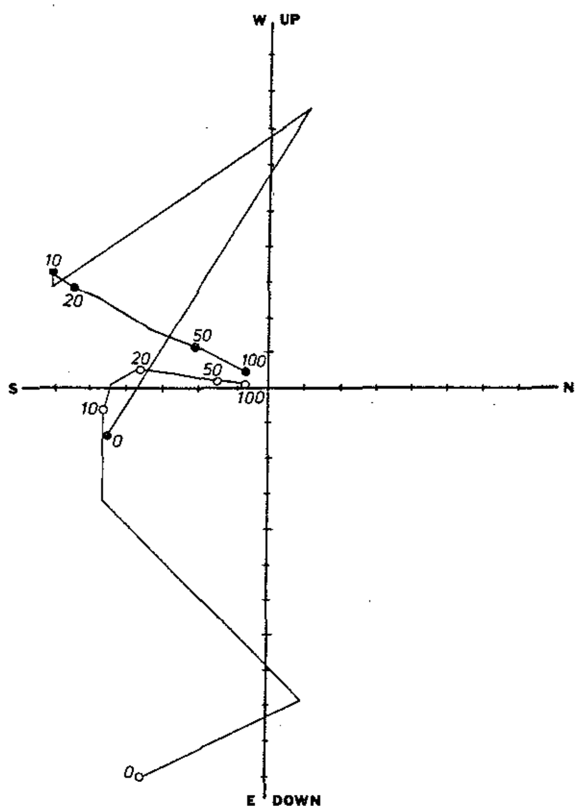


Figure 4. Zijderveld diagram for AF demagnetization of Mayville Dolomite. Numbers along curve are demagnetization level in mT. Solid circles are declination, open circles are inclination. Units along the axes are 10^{-5} Am^{-1}.

RESULTS - NEDA FORMATION

Samples of Neda Iron Ore were collected from locations at Neda, Wisconsin, Dubuque, Iowa, and Kankakee, Illinois (fig. 7). These three sites represent almost all the exposures in the midwest. All samples are from the soft ore or areas rich in oolites.

AF demagnetization of samples from each site show no changes in magnetization direction or intensity. Thermal demagnetization results (figure 8) indicate the dominant magnetic carrier is hematite.

Chemical demagnetization was performed on several samples from Illinois. This is a process in which a sample is placed in an HCl solution for progressively longer periods of time; magnetization is measured after each interval. Chemical demagnetization is effective in removing chemical remanence, which is carried by coatings on grains or secondary pore deposits. Chemical demagnetization of the Neda results in removal of the matrix; eventually

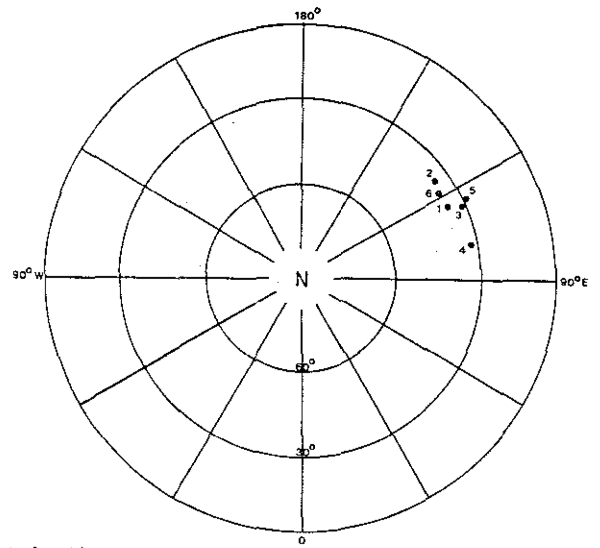
Table 2. Demagnetization scheme chosen for each site based on results of graphic analyses.

Sampling location	Demagnetization technique	Demagnetization level
Maquoketa Shale		
Wiequiock Creek	thermal	300 °C
Katells Falls	----	---
Oakfield	AF	50.0 mT
Lower Silurian Dolomite		
Green Bay	AF	35.0 mT
Wiequiock Creek	----	---
Katells Falls	thermal	250 °C
Greenleaf	thermal	250 °C
Brillion	----	---
Mayville	AF	35.0 mT
Neda	thermal	300 °C
Racine	----	---
Waukesha		
(level above shale in meters)		
3.05	AF	30.0 mT
6.10	AF	30.0 mT
9.14	AF	75.0 mT
12.19	AF	30.0 mT
15.24	AF	20.0 mT
18.29	AF	30.0 mT
21.34	thermal	300 °C
24.38	AF	50.0 mT
30.48	AF	50.0 mT
32.00	AF	50.0 mT

only loose sediment and oolites remain. A Zijderveld plot of the results (fig. 9) shows a linear trend toward the origin, which indicates the magnetization is carried by the matrix material rather than by the oolites (Kean, 1981). X-ray diffraction analysis (Synowiec, 1980) shows that the dominant iron ore in the Neda Formation is goethite.

Paleomagnetic results for the Neda Formation (table 3) are as follows: I = -12°, D = 152°, K = 200, a_{95} = 16°. The reversed paleomagnetic pole is located at 45.5 °S., 48° W. (North pole at 45.4° N., 132° E.).

A comparison of results for the Maquoketa Shale, Neda Formation, and Mayville Dolomite shows that, with 95 percent confidence, the magnetization of the Neda is significantly different than that of the Maquoketa or Mayville (fig. 10). The paleomagnetic pole for the Neda is consistent with published results for Permian time. In addition, the paleopole is similar to results obtained from the Queenstone Shale, that is inclination = -10°, declination = 160°, a_{95} = 10°. The paleomagnetic pole is located at 42°S, 44°W (North pole at 42°N, 136°E) (Kean, 1980).



Explanation

Pole	Age	Source
1.	Middle Ordovician	McElhinny and Opdyke, 1973
2.	Late Ordovician	Proko and Hargraves, 1973
3.	Late Ordovician	Van der Voo and French, 1977
4.	Late Silurian	Roy, et al., 1967
5.	Late Ordovician	this study
6.	Early Silurian	this study

Figure 5. Polar stereographic projection comparing paleomagnetic North pole positions of this study with published Ordovician-Silurian paleomagnetic poles.

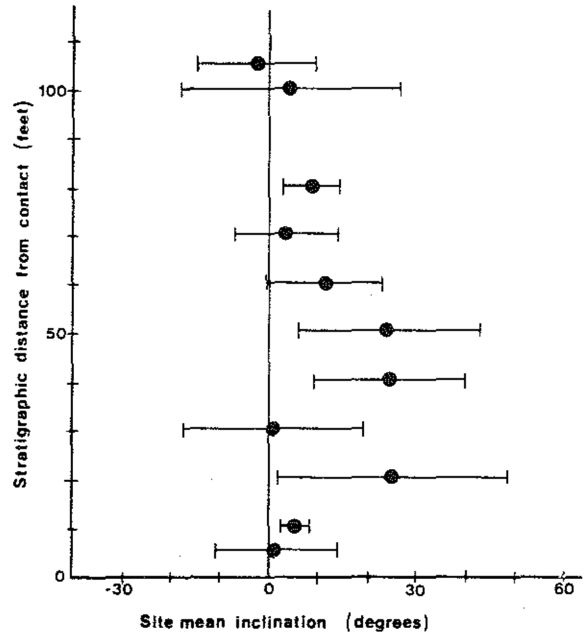


Figure 6. Site mean inclination versus stratigraphic position for Lower Silurian Dolomite. Brackets indicate limits of 95 percent confidence.

DISCUSSION

Obtaining reliable paleopole positions from undeformed sedimentary rock is a tenuous business from the very beginning, because there is never a guarantee that the magnetic minerals are primary or that the magnetism is primary. The usual criteria for the reliability of directions from undeformed sedimentary rock has been, the composition of the magnetic minerals, the internal consistency of the results, and the agreement or near agreement with published paleopoles from similar aged igneous rock or from folded sedimentary strata in which the magnetism exhibit a positive fold test (Graham, 1949).

There is also a question as to the reliability of pole positions from folded sedimentary strata which have secondary components. The Ordovician-Devonian folded sedimentary rock from the eastern United States are a good example, because most of the sedimentary rock contains a significant secondary magnetization overprint which is usually obtained during or after folding (see Van der Voo and French, 1977 as an example). Although it appears that the secondary magnetization can be removed, there is always a question as to the effect of a small residual secondary component on the final pole positions. Therefore, it would not be improbable to find the pole positions displaced slightly from each other. However, if the two pole positions are statistically similar, then one's confidence in the pole position is enhanced.

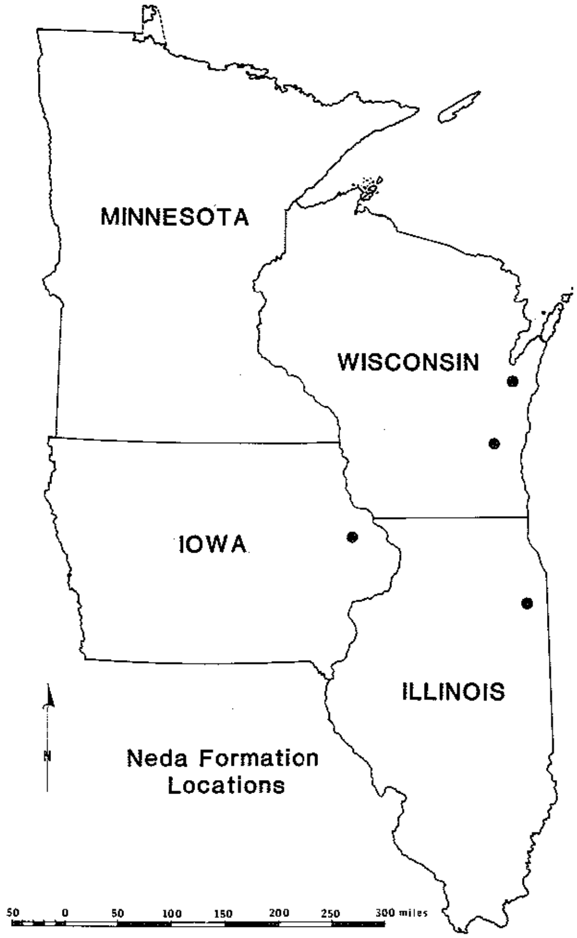


Figure 7. Location map for Neda ore samples: Neda, Wisconsin, (44.16° N, 88.08° W); Dubuque, Iowa (42.5° N, 90.75° W); Kankakee, Illinois, (41.1° N, 87.8° W).

For the formations studied in this report, the results from the Maquoketa Shale are probably the most reliable. The paleolatitude and longitude of the pole position (29.3°N, 116°E) is closer to other published Ordovician poles. In addition, the magnetic mineralogy is a single, spinel phase mineral which is probably magnetite. The Mayville Dolomite is somewhat less reliable because it does contain two phases of magnetic minerals, hematite and probably magnetite. In addition, the pole position is higher in latitude (36.7 °N) than most published Silurian poles. It is tending toward a Permian direction, which is most likely the result of a secondary overprint from the hematite.

Finally, there is little doubt that the magnetic direction for the Neda Iron Ore is a secondary one, and is considered Permian in age, caused by the chemical change of hydrous iron oxides to hematite (Kean, 1981). More recent studies by Perroud and Van der Voo (1983) on the Silurian Red Mountain Formation, Alabama, and by Hodych and others (1983) on the hematite ore of Birmingham, Alabama, have come to the same conclusion for those formations.

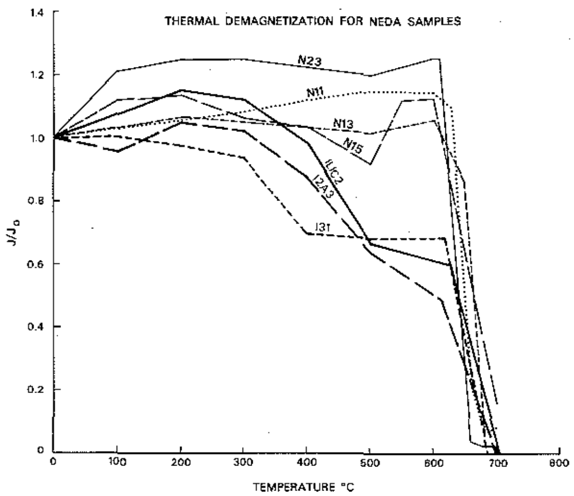


Figure 8. Thermal demagnetization curves for Neda samples from Wisconsin, Iowa and Illinois.

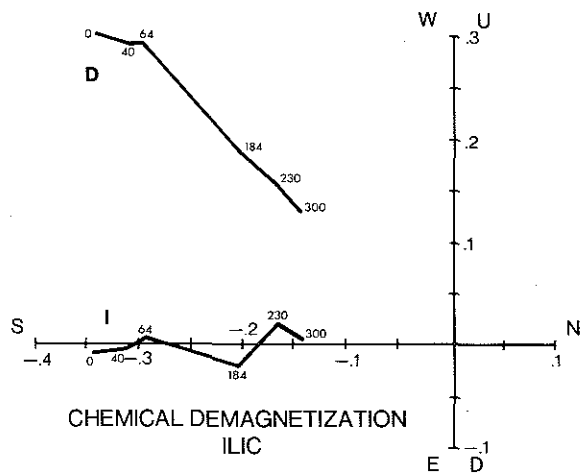


Figure 9. Zijderveld plot of chemical demagnetization for sample ILIC from Kankakee, Illinois.

CONCLUSIONS

The following conclusions may be drawn from the paleomagnetic results.

1. The Maquoketa Shale and Mayville Dolomite appear to record an original Ordovician-Silurian magnetization which is carried by spinel-phase iron oxide. Paleopole results are consistent with published Ordovician-Silurian results.

2. Preliminary studies suggest that neither magnetic characteristics nor magnetic directions can be used for stratigraphic correlation in the Lower Silurian Dolomite of Wisconsin.

3. The magnetization in the Neda is Permian in age, probably produced by dehydration of goethite to hematite as a result of minor uplift during Late Mississippian or Permian time.

4. We cannot determine from the magnetic data whether the Illinois and Wisconsin ooitic ores differ from the Iowa ores, nor can a relationship be drawn between the Neda and the Queenstone Shale. However, data from all areas show chemical magnetization acquired during Permian time, probably by

conversion of goethite or other hydrous iron oxides to hematite. The hematite is not primary at any of the sites.

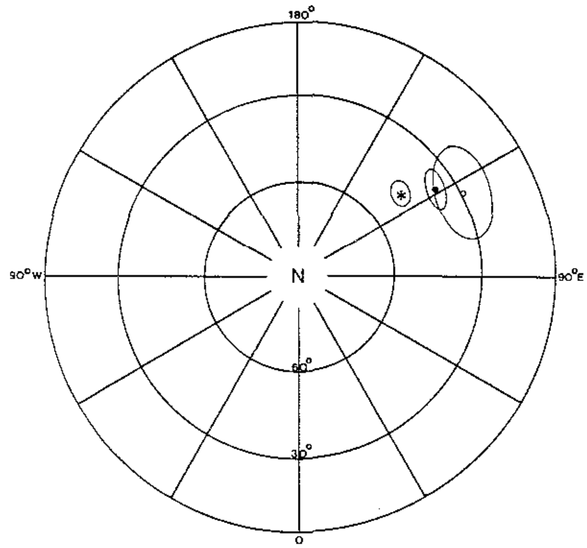


Figure 10. Polar stereographic projection of paleomagnetic north poles for Upper Ordovician Maquoketa Shale (open circle), Neda Formation (Kean, 1981) (asterisk), and Lower Silurian Dolomite (solid circle), including ovals of 95 percent confidence.

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Table 3. Paleopole positions for the three Neda ore sites.

Location	N	Dec	Inc	a_{95}	k	VGP Lat	VGP Long
		in degrees					
Neda, Wisconsin	12	162	-6.7	5.3	67	46.8 S.	52 W.
Dubuque, Iowa	7	146	-18	5.6	120	46 S.	38 W.
Kankakee, Illinois	6	148	-11	20	45	43 S.	34 W.
Average of three sites		152	-12	16°	200	45.4 S.	48 W.

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