Paleomagnetism of the Upper Silurian and Lower Devonian carbonates of New York State: evidence for secondary magnetizations residing in magnetite

Christopher R. Scotese¹, Rob Van der Voo² and Chad McCabe²

¹ Department of Geophysical Sciences, University of Chicago, Chicago, IL 60637 (U.S.A.)
² Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109 (U.S.A.)

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Paleomagnetic directions for the Upper Silurian and Lower Devonian carbonates of the Helderberg escarpment (New York State) differ from expected Late Silurian and Early Devonian directions for cratonic North America. The mean direction ($D = 165°$, $I = -10°$; paleopole at $50°$N 129°E) is similar to Late Carboniferous and Early Permian results. Negative fold tests, and a lack of reversals, suggest that the magnetization is secondary. However, low coercivities, low blocking temperatures, the thermomagnetic curves ($T_c$ near 570°C) and the acquisition of isothermal remanent magnetizations all suggest that the remanence is carried by magnetite. If a detrital origin of these magnetites is assumed, the secondary nature of the remanence would argue for thermal resetting as a result of deep burial of the rocks. However, no evidence for such thermal resetting is seen in the alteration of conodonts. More likely perhaps is a chemical or thermochemical origin of the remanence; this would require the magnetites to be authigenic.

1. Introduction

The Siluro—Devonian portion of the North American apparent polar wander path is not well known. The polar wander path is presently defined by a few Middle Silurian poles (French and Van der Voo, 1979; Wilkinson et al., 1981), a single late Silurian pole (Roy et al., 1967), a recently described Early Devonian pole from the Canadian Arctic (Dankers, 1982) and several Late Devonian poles, tabulated by Van der Voo (1981). A pole has been determined for the Middle Devonian Onondaga limestone (Kent, 1979); however, a negative fold test indicates that the magnetization was acquired later in the Paleozoic. Additional Late Silurian or Devonian poles have been published from maritime Canada and New England, as well as from the Alexander terrane of southeastern Alaska (e.g., Kent and Opdyke, 1980; Van der Voo et al., 1980); however, these results are certainly from allochthonous terranes and should not be included with the results from the craton.

Paleomagnetic evidence for cratonic North America suggests that from the Late Silurian to the Late Devonian, North America moved from a subtropical to an equatorial position. The timing of this transition, especially in relation to the positions of Gondwana and Baltica, has important biogeographic and paleoclimatic implications (Ziegler et al., 1980). In order to resolve the time of this movement better, a paleomagnetic study of Upper Silurian and Lower Devonian carbonates of the Helderberg escarpment was undertaken.

Another important aspect of this study is that
the results are obtained entirely from carbonate rocks. Although numerous paleomagnetism investigators have studied carbonates in the past, the nature and acquisition of the remanence is still not well understood (Lowrie and Heller, 1982).

2. Geological setting and sampling

During the Early Devonian, the seas retreated from North America and the resulting emergence and erosion stripped much of the Upper Silurian and lowermost Devonian rock record from the central areas of the craton. Much of what remains is now preserved in the marginal basins of the Appalachians, Ouachitas, and western Cordillera, as well as in the Franklinian basin of the Canadian Arctic. One of the best exposures of Upper Silurian and Lower Devonian rock occurs along the northern margin of the Appalachian basin in upstate New York. Carbonate units crop out along a continuous belt which stretches east from Lake

Fig. 1. Outcrop belt of Helderberg limestones and location of sites (after Rickard (1962), Fig. 10).
Fig. 2. Stratigraphic relationships (modified after Rickard, (1962), Fig. 27) with sampling localities indicated.
Cayuga, across to Utica and Albany, and south
down the Hudson River valley (Fig. 1).
The Late Silurian (Cayugan) in this area con-
ists of shales and shaly dolomites. The dolomites,
which are often thin-bedded and eurypterid-bear-
ing (Fiddler's green limestone), are succeeded
gradationally by Lower Devonian limestones of
the Helderberg group. The name Helderberg comes
from the Dutch words “helder” meaning bright,
and “berg” meaning mountain, and locally refers
to the hills and escarpments southwest of Albany.
Several facies have been recognized in the lime-
stones of the Helderberg group, from which lagoonal
(Thacher limestone), nearshore neritic
(Dayville and Ravena limestones) and deeper
neritic environments (Kalkberg and New Scotland
formations) have been inferred (Rickard, 1962).
The stratigraphy of Upper Silurian and Lower
Devonian rocks of New York State has been de-
scribed extensively (Oliver et al., 1967; Head, 1969,
1974; Barnett, 1970). A study and correlation of
more than 175 measured sections by Rickard (1962)
provided the stratigraphic framework for the pre-
sent study.
Twenty-five sites were sampled along the
Helderberg escarpment during the summer of 1979
by C.R.S. An additional site was added by C.
McC. in 1980. In total, 120 samples of Upper
Silurian and Lower Devonian carbonates were col-
clected from 18 sites along a 150-mile traverse from
Utica south to Kingston (Fig. 1). Eight additional
sites in Middle Silurian and Middle Devonian
sandstones were also sampled. However, because
these rocks have different (noncarbonate) lithology
and because they did not reveal stable, characteris-
tic directions of magnetization, the results from
these sites will not be described. Figure 2 il-
lustrates the stratigraphic position and di-
achronous relationships of the formations which
were sampled. The vertical bars indicate the strati-
graphic range of the samples collected at each site.
At sites 1–20, the beds are flat-lying, or dip
gently to the S-SW. Only one site exhibits dips
greater than 5°. In contrast, the beds at sites
22–26 along the Hudson River are strongly folded.
The fold axes are aligned nearly N–S, with limbs
dipping 20–45°. The youngest beds affected by
the folding are Middle–Late Devonian in age,
although it is not clear whether the folding was the
result of the Acadian (Middle–Late Devonian) or
Alleghenian (Late Carboniferous–Early Permian)
orogeny (Rodgers, 1970, p. 68).

3. Laboratory techniques
The magnetization of the samples was measured
using the Superconducting Technology (ScT) mag-
etometer at the University of Michigan. All sam-
ple were demagnetized in stepwise fashion using
either thermal or alternating-field (AF) techniques.
The direction of magnetization remaining after
each treatment was plotted using the demagne-
tization diagrams described by Zijderveld (1967).
Directions of magnetization were determined in all
cases by vector subtraction for straight-line de-
magnetization trajectories defined by three or more
points.

Fig. 3. NRM directions (site means) plotted on in situ coordi-
nates: $\Theta =$ mean of site means, $\times =$ mean NRM direction for
Onondaga limestone (Kent, 1979); solid circles indicate posi-
tive (downward) inclinations; open circles, negative (upward)
inclinations. Directions plotted in stereographic polar projec-
tion.
4. Natural remanent magnetization

Upper Ordovician, Upper Silurian and Lower Devonian carbonate rocks from upstate New York were first studied paleomagnetically by Graham (1954). Seven samples were collected from the Cayugan dolomites of upstate New York as part of a broader study of Paleozoic rocks from cratonic North America. His work, based on undemagnetized samples, revealed that Paleozoic rocks ranging in age from Ordovician to Permian were characterized by an extremely stable natural remanent magnetization (NRM). NRM directions, in general, were consistently southerly and very steeply inclined.

Similar NRM directions were obtained from the Cayugan and Helderberg carbonates in this study. The site mean NRM directions plotted in Fig. 3 show the same pattern as obtained by Graham. The mean NRM direction for the Onondaga limestone (Kent, 1979), which lies stratigraphically just above the Helderberg group, is also plotted in Fig. 3.

5. Characteristic directions and viscous magnetizations

Subsequent investigation of some of the same units studied by Graham, namely the Trenton limestone (McElhinny and Opdyke, 1973) and the Onondaga limestone (Kent, 1979), have demonstrated that the steep NRM direction is actually a composite of two directions. These directions are revealed by stepwise thermal or AF demagnetization.

The two demagnetization plots shown in Fig. 4 are typical thermal-demagnetization diagrams. Two components of magnetization can be clearly identified. The first component has a relatively low blocking temperature and is completely removed at 350°C. This component is steeply inclined to

Fig. 4. Thermal demagnetization diagrams for (A) Cayugan dolomite (site 26-A) and (B) Helderberg limestone (site 26-E) plotted on in situ coordinates: solid circles represent vector endpoints projected onto the horizontal plane; open circles, vector endpoints projected onto the N–S vertical plane.
the north, and is nearly coincident with the present-day field direction for upstate New York. Similar behavior was observed by Kent (1979) for the Onondaga limestone. In that study, viscous remanent magnetization (VRM) experiments demonstrated the presence of a viscous component aligned with the present-day magnetic field.

The second component, which is revealed at temperatures above 350°C, decays linearly to the origin and is completely eliminated at \( \approx 500°C \). Its southerly direction and shallow negative inclination are characteristic of Middle–Late Paleo-

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**Table I**

<table>
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<tr>
<th>Site</th>
<th>Section</th>
<th>Site</th>
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<td></td>
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<td>Longitude (deg.)</td>
<td>( D ) (deg.)</td>
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</table>

Means: 117/120 165 - 10 200 2.4 -50.1 -50.8 (50.1 129.2)

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* a Treesh (1972).
* b Waines (1967). All other sections, Rickard (1962).
* c \( k = 395, \alpha_{95} = 1.7 \).
affected. Because of this disparity in inclination, samples that had been AF-demagnetized were not included in the calculation of the site means.

6. Evidence of secondary nature of remanence

The characteristic directions listed in Table I were obtained from beds spanning ~15 My and covering 140 m of section. If the results for the Onondaga limestone are included, these ranges are nearly doubled. Yet, from formation to formation the direction of magnetization is remarkably constant. Furthermore, there is no record of magnetic reversals. Both of these observations suggest that the remanence of the Late Silurian and Early Devonian carbonates may be secondary.

In order to determine conclusively whether this magnetization is primary or the result of a secondary overprint, a fold test was carried out at five sites in the tectonically disturbed areas along the west bank of the Hudson River (sites 22–26). Four of these sites are located in road cuts along Route 199, 0.5 miles west of the Kingston–Rhinebeck bridge (Waines, 1967). There, a continuous section of Helderberg limestones and younger strata is exposed in a series of N–S-trending synclines and anticlines.

Although the limbs of the folds are steeply dipping, the directions of the fold axes are, unfortunately, nearly coincident with the characteristic direction. As a result, within-site dispersion does not significantly change after tilt corrections have been applied.

In each case, however, after unfolding, the inclination of the site means becomes more positive, moving away from the tight cluster of directions obtained from the flat-lying beds (Fig. 7). An argument may be made that the remanence is secondary because the characteristic directions from the folded sites without tilt correction cluster better with the directions from the flat-lying sites. This argument is strengthened by the observations that the directions are uniform throughout the section, that there are no reversals, and that the Onondaga limestone, which stratigraphically overlies the Helderberg group, fails the fold test (Kent, 1979).
If the remanence is secondary, when was it acquired? The folding in the Hudson River valley has been attributed to the Acadian or the Alleghenian orogeny (Rodgers, 1970). At present, neither alternative can be eliminated.

7. Rock magnetism: magnetite as the carrier of remanence

Several rock magnetic experiments were carried out to ascertain the nature and mode of occurrence of the remanence carrier(s). All these experiments indicated fine-grained, relatively pure magnetite in the limestones as the only carrier of NRM. It is of interest to note that these findings are entirely similar to those of Kent (1979) for the Onondaga limestone.

Perhaps the most convincing are the thermomagnetic measurements made using a vibrating-sample magnetometer on a sample chip, which yielded a Curie temperature of $\sim 565^\circ$C (Fig. 8). The field applied was 1.8 T, the vacuum was $10^{-4}$ torr, and the weight of the sample chip was $\sim 30$ mg. The smooth, reversible, and convex-upward nature of the curve suggests relatively pure (titanium-free) magnetite, and shows no indication of maghemite inversions or of pyrohstite, despite the presence of abundant pyrite in our samples.

In Fig. 9 the acquisition of isothermal remanent magnetization (IRM) is plotted for several representative samples, versus the applied field produced in a cryogenic solenoidal magnet constructed at the University of Michigan. Almost all samples reach saturation rapidly, well below 0.3 T (3000 gauss), again suggesting that magnetite is the only iron compound capable of carrying remanence.

In order to ascertain whether the magnetites undergo the magnetocrystalline transition at
The dissolution process removed all iron oxides. Further dissolution experiments using different buffered acids are planned for the near future.

Another approach has been to examine thin sections using scanning and transmission electron microscopy (STEM) techniques, but no iron oxides have thus far been unambiguously identified. This is not surprising in view of the magnetic intensities of our samples, which predict iron oxides to constitute ~10 p.p.m. of the total rock.

8. Discussion

The paleomagnetic directions in the Upper Silurian and Lower Devonian rocks from the Helderberg escarpment give a paleopole at 50°N 129°E; this pole is very similar to that of the overlying Onondaga limestone (Kent, 1979) and falls in a group of Late Carboniferous–Early Permian poles for the North American craton (Van der Voo, 1981). The pole does not agree with North American Middle or Late Silurian poles obtained from the Bloomsburg redbeds (Roy et al., 1967), the Rose Hill formation (French and Van der Voo, 1979), the Wabash limestones from Indiana (Wilkinson et al., 1981), or a recently described Early Devonian pole from the Canadian Arctic, located at 25°N 99°E (Dankers, 1982). The position of our Helderberg pole suggests a remagnetization during Late Carboniferous–Early Permian time.

Support for this contention is found in the negative fold test for the Onondaga limestone (Kent, 1979) and the inconclusive fold test for our samples; although the age of the deformation is uncertain and could be related to either the Acadian or the Alleghenian orogeny, the available evidence precludes a primary age of the magnetization. Further study of equivalent strata in the Valley and Ridge Province in Pennsylvania is underway in order to settle the question concerning the age of magnetization, and preliminary fold tests have revealed a post-folding magnetization. It is worth noting that Late Devonian, Silurian and Ordovician formations of the Valley and Ridge Province all appeared to carry secondary (post-folding) Late Paleozoic overprints as well as pre-

![Figure 10. Intensity of IRM, given at liquid-nitrogen temperature, measured quasi-continuously as a function of temperature as sample is allowed to warm up. No magnetic transitions are observed.](image-url)
folding characteristic magnetizations (Roy et al., 1967; French and Van der Voo, 1977; Van der Voo and French, 1977; Van der Voo et al., 1979; Watts and Van der Voo, 1979). Clearly, the whole area of the central Appalachians and adjacent plateaus in New York, Pennsylvania and further south, underwent some Late Carboniferous—Early Permian event that caused large-scale magnetic overprinting.

The interesting question then arises of whether this event was thermal, chemical, or a combination of the two. A purely thermal magnetic resetting, however, seems precluded by a combination of factors, such as the blocking temperatures of the overprints compared with the low paleo-temperatures in central and western New York State as indicated by the alteration of conodonts (Epstein et al., 1977), as well as the relatively low estimates for the depth of burial in that area. Instead, we prefer to argue for a chemical or thermochemical cause of the remagnetization, involving diagenetic growth of new (authigenic) minerals.

In the Helderberg escarpment, our study shows that this involves authigenic magnetites. Until conclusive electron-microscope evidence is obtained concerning the mode of occurrence, the morphology and chemistry of these magnetites, we cannot speculate about the mechanisms for remagnetization. Future work is planned to resolve this.

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References
