SYNFOLDING AND PREFOLDING MAGNETIZATIONS IN THE UPPER DEVONIAN CATSKILL FORMATION OF EASTERN PENNSYLVANIA: IMPLICATIONS FOR THE TECTONIC HISTORY OF ACADIA

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Abstract. The Upper Devonian Catskill Formation was sampled for paleomagnetic study in east-central Pennsylvania (41°N, 76°W). In one area the dominant component of magnetization (SE) is revealed over a broad spectrum of demagnetization temperatures ranging to at least 660°C. A conventional fold test is positive at the 99% confidence level. However, statistical analysis of dispersion with incremental bedding tilt correction shows a significant peak in the precision parameter after about 3/4 unfolding. The magnetization is therefore secondary, with a mean direction of D = 166.6°, I = -1.8°. The corresponding pole position (48.1°N, 124.1°E, a95 = 4.0°) is indistinguishable from paleopoles from earlier studies of the Catskill, which therefore can also be regarded as representing Permo-Carboniferous remagnetizations. A second component of magnetization (SW, pole position 32.8°N, 90.0°E, a95 = 7.2°) with discrete unblocking temperature spectra and southwesterly declination was isolated in a few samples from the first area and in most samples from a second area. A prefolding origin of this magnetization is supported by a positive fold test on five samples from the first area. If this magnetization does represent a Devonian magnetization then the true paleolatitude for east-central Pennsylvania is 16° +/- 7.2°S, which is consistent with the paleolatitude observed in many of the Upper Devonian rock units in the Acadia region, although inconsistent with others. The question of the position of Acadia relative to North America in the Upper Devonian is therefore still open.

Introduction

Until recently, most paleomagnetic results from Permian, Carboniferous, and Devonian cratonic rock units of North America have been interpreted to indicate low paleolatitudes. In contrast, results from the Acadia region (coastal New England-Maritime Canada) for the Devonian and lower Carboniferous consistently place this area some 20° south of cratonic North America. These observations have led to two basic hypotheses. The first is that Acadia was in fact located to the south of North America in the Devonian and Early Carboniferous and then moved to its present location with respect to the continent by the Late Carboniferous [Kent and Opdyke, 1978, 1979; Van der Voo et al., 1979; Irving, 1979]. The second hypothesis is that the similarity in Devonian through Permian cratonic pole positions resulted from remagnetization in the Permian

during the long, reversed polarity Kiaman superchron [Roy and Morris, 1983; Irving and Strong, 1984, 1985]. According to this hypothesis, the relative position of Acadia with respect to North America could not be determined for the Carboniferous or the Devonian because the relevant cratonic pole positions are masked by the Permian overprint.

Two critical studies of cratonic units were on the lower Carboniferous Mauch Chunk [Knowles and Opdyke, 1968] and on the Upper Devonian Catskill [Van der Voo et al., 1979] formations. Both of these studies reported near-equatorial paleolatitudes, normal and reversed polarity directions, and positive fold tests. Other studies of rock units with lower Carboniferous and Upper Devonian ages generally report similar near equatorial paleolatitudes but lack normal polarity samples and/or field stability tests. The Mauch Chunk Formation has recently been restudied from the same outcrop area as the earlier study [Kent and Opdyke, 1985]. It was shown that the earlier study failed to isolate all of the components of magnetization. The magnetization of the Mauch Chunk is actually a composite of an intermediate to high unblocking temperature synfolding magnetization and a very high unblocking temperature prefolding magnetization. The dominant synfolding magnetization is late Carboniferous to Early Permian in age. The prefolding or characteristic magnetization reveals a more southerly paleolatitude and is in agreement with lower Carboniferous results from Acadia.

The results from the Mauch Chunk make it imperative that all the components of magnetization in the Catskill be isolated. The present study was designed to test whether the magnetization of the Catskill is a single component as reported by Kent and Opdyke [1978] and Van der Voo et al. [1979] or if multiple components of magnetization representing a Permian remagnetization and an older, possibly primary, magnetization exist in the Catskill, as was found in the Mauch Chunk.

Geologic Setting

We chose to investigate the Catskill Formation in eastern central Pennsylvania because of the favorable fold geometry for a fold test and because the study of the Upper Silurian Bloomsburg Formation [Roy et al., 1967] suggests that remagnetization problems may be less severe in this part of the Appalachians. The expected declination for a Kiaman or Permian overprint is between 160° and 170° with a very shallow inclination (Figure 1). The bedding strikes of the sampled sites in this study are at a high angle to the expected Kiaman overprint and as such allow for a fold test that is very sensitive
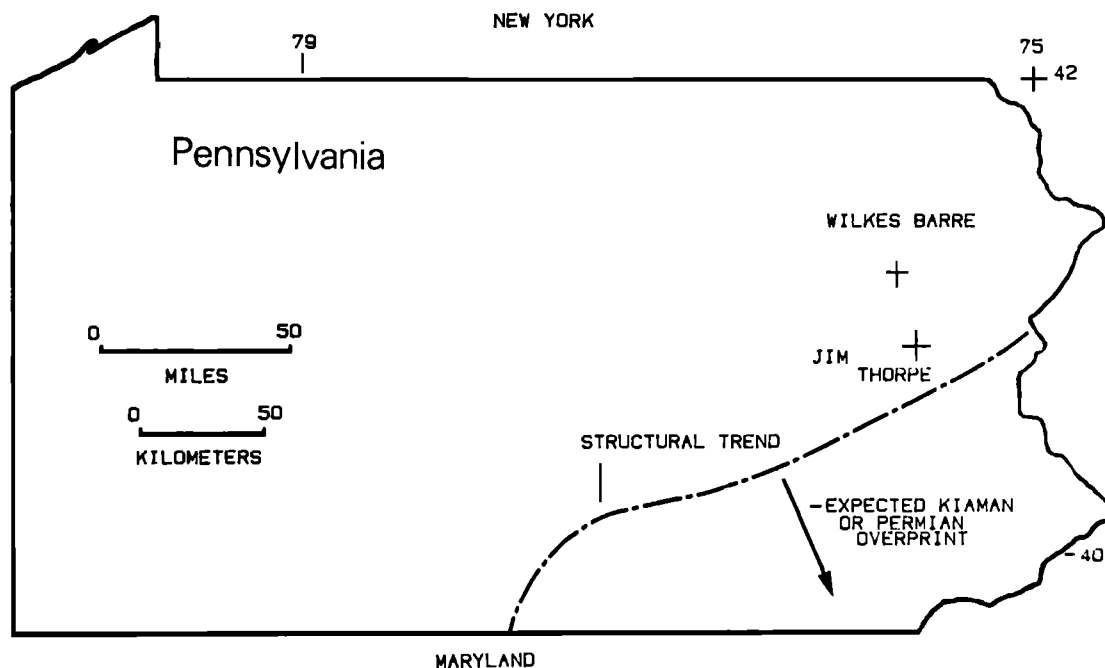
Fig. 1. Location map showing sampling areas. The dashed line is the late Paleozoic
structural trend. The arrow shows the magnetic declination that is characteristic of
a late Paleozoic remagnetization (the inclination of which should be less than 10°).

to any remagnetization. In southern Pennsylvania,
Maryland, and West Virginia, where Van der Voo et
al. [1979] sampled, the structural trend is more
north-south and therefore provides a less
sensitive fold test. In New York State, the study
area of Kent and Opdyke [1978], the Catskill is
flat lying with no possibility for a fold test.

The Catskill Formation in eastern central
Pennsylvania is well described by Epstein et al.
[1974]. Its facies range from prodelta in the
lowest members to meandering and braided river
systems in the upper members. The sediments range
from mudstone to conglomerate. Color varies from
gray to green and red. In the area of Jim Thorpe
(Figure 1) the formation has been subdivided into
nine members. The lowermost member is the
Towamensing, which is overlain by the
Walcksville, Beaverdam Run, Long Run, Packerton,
Sawmill Run, Berry Run, Clark's Ferry, and
Duncannon members. The main red bed units are the
Duncannon, Long Run, and Walcksville members.
Both the Duncannon and the Long Run (or
equivalent) members were sampled in this study.

The Catskill Formation spans most of the Late
Devonian in time of deposition [Epstein et al.,
1974], about 14 m.y. [Harland et al., 1982]. The
total thickness of the Catskill in this area is
2395m. The Duncannon and Long Run members of
which we obtained good stratigraphic coverage are
295m and 720m thick respectively.

The folding in eastern central Pennsylvania is
thought to be Early Permian in age, although a
younger age is permissible on stratigraphic
grounds [Dennison, 1982]. The youngest formation
involved in folding in our study area is the
Pottsville Formation, which is Pennsylvanian in
age [Epstein et al., 1974]. The upper
Pennsylvanian to Lower Permian Dunkard Formation,
which outcrops farther to the southwest, is the

youngest formation in the central Appalachians
involved in Alleghenian folding. Continental
rifting began in the Late Triassic (mid-Carnian)
and is marked by the deposition of the Newark
Supergroup [Olsen et al., 1982].

Since thermal history has implications for the
magnetization of a rock unit, it is worth noting
that the maximum conodont alteration index for
underlying Silurian to mid-Devonian carbonates in
this area is 4.5 [Harris et al., 1978]. This
suggests that the Catskill could have experienced
temperatures of no more than 200°C to 250°C for
time spans of tens of millions of years [Epstein
et al., 1977].

Field Work

Samples from all sites were drilled in the
field with a hand-held gasoline powered drill and
were oriented in place with a Brunton compass and
inclinometer. The 2.5-cm-diameter cores were cut
into from one to three specimens for laboratory
analysis.

Two general areas were sampled in this study
(Figure 1; see Table 1 for site latitudes and
longitudes). The first area (sites A-H) was near
the town of Jim Thorpe where only the Long Run
member was sampled. The sites, each three to six
samples distributed over 30 to 90 m of strata,
were drilled in the road and railroad cut (no
rails) along U. S. 209 just to the south of Jim
Thorpe. The sampled section was in one nearly
continuous outcrop with essentially uniform
bedding attitude (nearly vertical dip to the
northwest). The majority of the samples were
taken from the red beds, with a few samples from
the interbedded green and gray sediments.

The second area sampled [sites K-T, three to
five samples each) was located in an outcrop belt

TABLE 1.   Site Locations and Bedding Orientations

Site	Latitude, °N	Longitude, °W	Strike	Dip
A-H	40.84	75.69	24	82
I	40.84	75.51	54	14
J	40.83	75.51	240	10
K	41.09	76.33	78	36
L	41.09	76.28	74	35
M	41.11	76.12	256	40
N	41.13	76.00	257	40
O-P	40.99	76.16	66	18
Q	40.99	76.16	65	24
R	40.99	76.16	74	53
S	41.06	75.95	63	17
T	41.15	75.92	259	41

Dip direction is 90° clockwise from strike.

between the towns of Bloomsburg and Wilkes-Barre. Sites L, M, N, S, and T were drilled in the Duncannon member. Sites K, O, P, Q, and R were drilled in the Sherman Creek member, which is correlatable to the Long Run member [Berg et al., 1980]. Sites were occupied with both northwest and southeast dip directions, allowing for application of fold tests.

Laboratory Procedures

Measurements were made on both a two-axis cryogenic [Goree and Fuller, 1976] magnetometer and a computerized flux gate spinner [Molyneaux, 1972] magnetometer. Most samples were thermally demagnetized in a minimum of 10 steps, and the susceptibility was measured after each step. Alternating field (AF) demagnetization proved ineffective in decomposing the natural remanent magnetization (NRM) of the red bed samples and so was little used. Chemical demagnetization through acid leaching (6N or 12N HCl in a low field space) was also performed in a minimum of 10 steps. Local mu-metal shielding was used throughout the demagnetization procedures to minimize ambient field contamination.

Demagnetization paths were plotted on Zijderveld [1967] diagrams, and magnetization directions were computed using principal component analysis [Kirschvink, 1980]. Unless otherwise specified, lines were not anchored to the origin. Mean directions and poles were calculated using standard Fisher [1953] statistics.

Experimental Results

Properties Common to Both Areas

Samples from the few green and gray beds that were sampled typically have low unblocking temperatures (below 300°C) and were easily demagnetized by alternating field treatment to 30mT. The magnetic direction is northwest in declination and steeply down in inclination, which is consistent with a present-day or Cretaceous remagnetization. Results from these beds will not be discussed further.

Thermal demagnetization of the red bed samples

shows that in most samples, unblocking of the NRM does not begin until between 300°C and 400°C, and some fraction of the NRM remains to above 650°C. The resistance to AF demagnetization and the high unblocking temperatures clearly suggest hematite as the principal magnetic carrier.

The main problem in thermal demagnetization of samples from the Catskill Formation is that most samples undergo magnetochemical alteration at high temperatures. The alteration is best expressed by up to order of magnitude increases in magnetic susceptibility after heating between 600°C and 680°C (also noted by Kent and Opdyke [1978]. The alteration makes the samples highly susceptible to contamination by stray laboratory fields. The effects of the contamination are quite apparent in the higher temperature portion of some of the demagnetization paths despite the use of local mu-metal shielding around the samples. For this reason, only the data points from demagnetization steps below the temperature where the susceptibility had increased by a factor of 2 tended to be used in the principal component analysis.

Sites A-H

The main component in samples from sites A-H has a southwesterly declination, with moderately negative inclinations before bedding tilt correction and moderately positive inclinations after tilt correction. This component we refer to as magnetization SWa. Component SWa is characterized by a very discrete unblocking temperature spectra. Often a large portion of the NRM is unblocked only in a narrow temperature band near 680°C (Figure 2a). For roughly half of the samples the NRM decays clearly to the origin. The remainder of the sample NRM's appear to have an additional very high unblocking temperature component which is poorly defined. In the sample demagnetization trajectories that appear to trend to a point slightly removed from the origin, any final component is difficult if not impossible to isolate because of the discrete nature of the unblocking temperature spectra and because of the magnetochemical alteration. There is no significant difference between the mean sample directions defined by trajectories that clearly trend to the origin and those that do not.

Only two samples from sites A-H have thermal demagnetization paths that trend away from the origin and into the northern hemisphere. In neither sample is the final northerly component isolated directly. In one sample (Figure 2b) the final component appears to be essentially antiparallel to the SWa magnetization. In the other sample the two magnetizations are clearly not antiparallel.

The sample NRM's were stable in acid (Figure 2c), decaying only slowly. After over 2000 hours in acid, all samples were still easily measurable. The magnetizations revealed by chemical demagnetization are statistically indistinguishable from those found through thermal demagnetization. However, for reasons to be discussed later, the directions isolated through chemical demagnetization were excluded from calculation of the mean SWa magnetization direction.
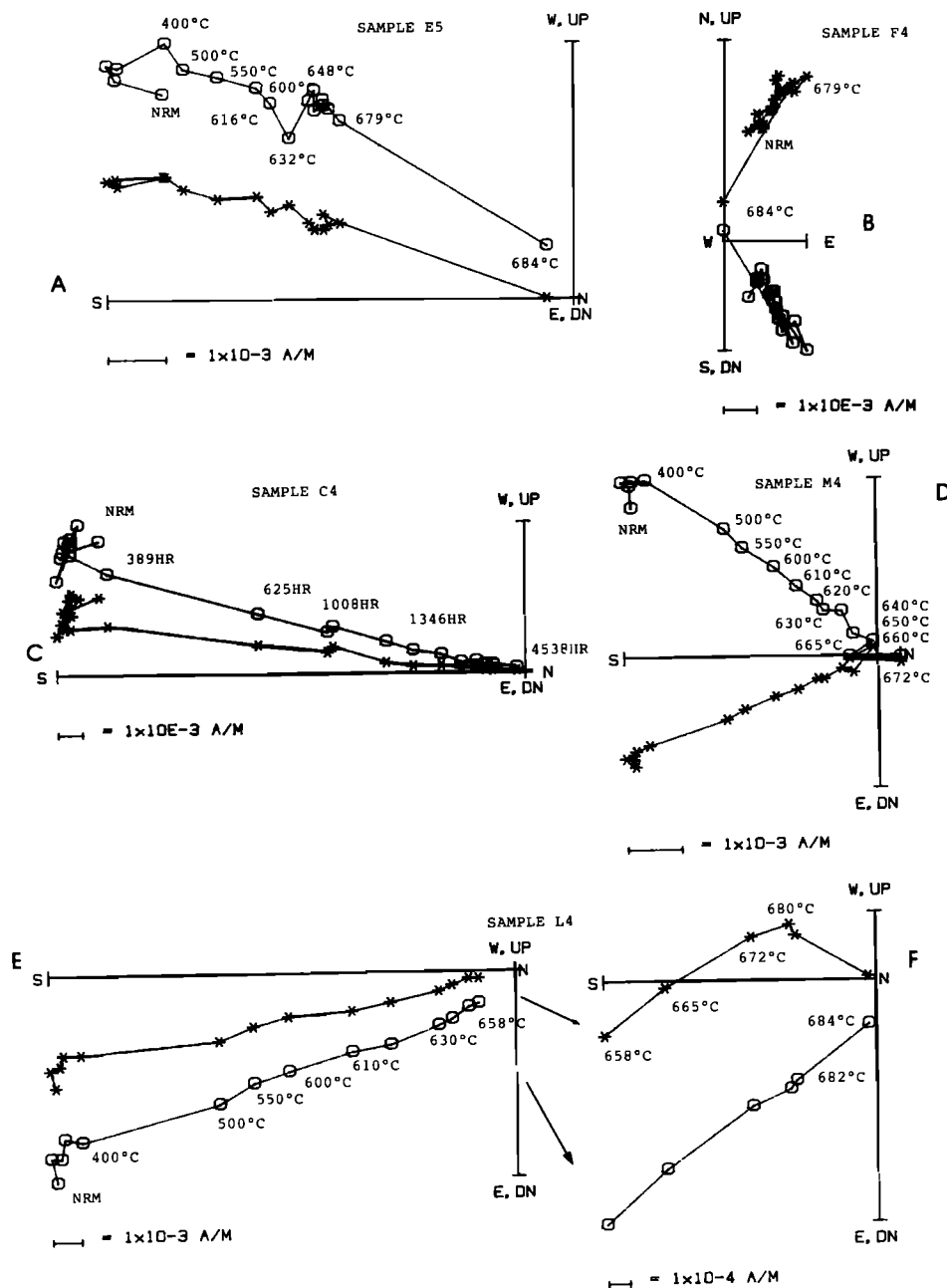
Fig. 2. Typical thermal (°C) and chemical (HR) demagnetization Zijderveld diagrams. All plots are in in situ coordinates. Open (star) symbols represent vertical (horizontal) components of vector end points. All other Zijderveld diagrams are plotted in this manner. (a) Typical thermal demagnetization for magnetization SWa (Jim Thorpe area). (b) The only sample to have present an obvious normal component that appears to be antiparallel to SWa (note the change in axes). (c) Typical chemical demagnetization for a sample from the Jim Thorpe area. (d) Demagnetization of a sample with magnetization SE (Wilkes-Barre area). (e and f) Samples with both magnetization SE (below 680°C) and magnetization SWb (Wilkes-Barre area).

Sites K-T

In contrast to magnetization SWa, the dominant component in sites K-T (magnetization SE) is to the southeast, is removed over a broad demagnetization temperature range, and in most samples appears to decay univectorially to the origin, by 660°C (Figure 2d). Some of the samples do have demagnetization paths that do not converge to the origin but viscous effects clearly associated with enhanced susceptibility after demagnetization to high temperatures usually precluded isolation of any possible final component. The exceptions were five samples from sites K-T in which the susceptibility did not change appreciably during thermal treatment and the main SE magnetization trajectory misses the origin. A final discrete, high unblocking
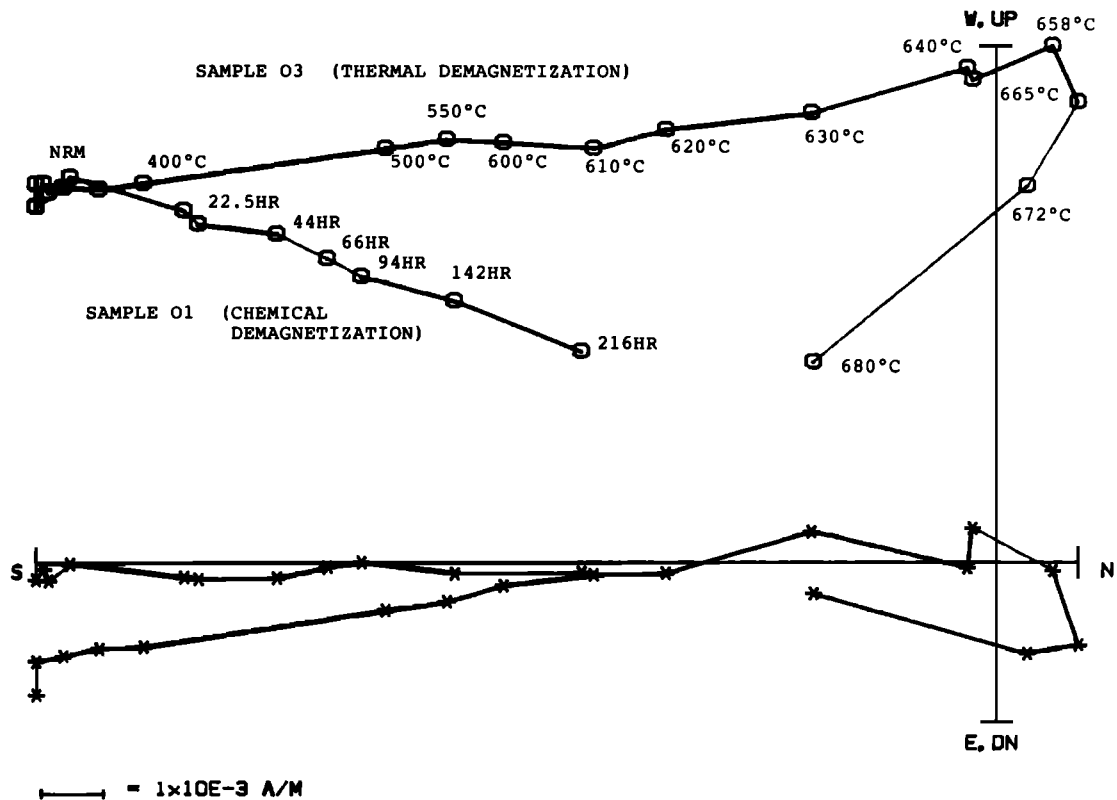
Fig. 3. Zijderveld diagrams comparing effectiveness of thermal versus
ineffectiveness of chemical demagnetization techniques on two samples from site O.

temperature component with southwesterly
direction (magnetization SWb) was isolated. SWb
was only defined by a few points in the
Zijderveld plots, even at demagnetization steps
of 2°C (Figures 2e and 2f). Because of the small
number of data points, the sample directions for
magnetization SWb were estimated by anchoring the
data to the origin in the principal component
analysis.

Chemical demagnetization was also performed on
samples from sites K-T but did not appear to
provide as clean a component separation as did
thermal treatment. The failure to separate
components is best illustrated in the comparison
of two specimen demagnetizations from site O
(Figure 3). The clear trend to a point removed
from the origin during initial and intermediate
stages of thermal demagnetization signifies the
presence of at least one additional component,
which in this case does not appear to be
attributable to laboratory fields. The chemical
demagnetization of a sample from the same site
with a similar NRM shows only an apparently
univectorial decay to the origin with a D, I of
178.9°, -19.3° before (and 182.8°, -35.6° after)
tilt correction. The chemically "isolated"
component is not consistent with any directions
isolated from other sites and clearly must
represent a resultant of the thermally
distributed magnetization and a remaining high-
temperature component. Given this clear failure
of acid leaching to separate the magnetic
components in this site the remainder of the
chemically isolated components were excluded from
statistical analysis and pole position

calculations. However, for most sites the mean
direction for the chemically isolated components
is not significantly different from the site mean
directions isolated through thermal treatment
because of the essentially univectorial NRM's in
most of the samples.

Age Constraints on Magnetizations

Standard Fold Tests

Two treated samples from sites A-H were
excluded from statistical calculations for lack
of linear demagnetization segments. Seven
specimen magnetizations were rejected because of
the poor chemical demagnetization results. For
the 20 accepted samples, the mean direction of
magnetization SWa (Figure 4a and 4b; Table 2) is
D, I of 194.2°, -31.7° (a95 = 7.5°); after tilt
correction, the mean is D, I = 196.1°, 35.0° with
the same dispersion because all the samples from
sites A-H are from the same limb of the
structure. Two sites sampled near sites A-H were
intended to provide a local fold test, but poor
demagnetization results from these sites
precluded any meaningful test.

One treated sample from sites K-T was rejected
because of questionable orientation. The
remainder of the 18 specimens not used were
excluded because of the poor chemical
demagnetization results as discussed above. The
sample directions of magnetization SE (Figures 4c
and 4d) show better grouping after tilt
correction than before. Before tilt correction,
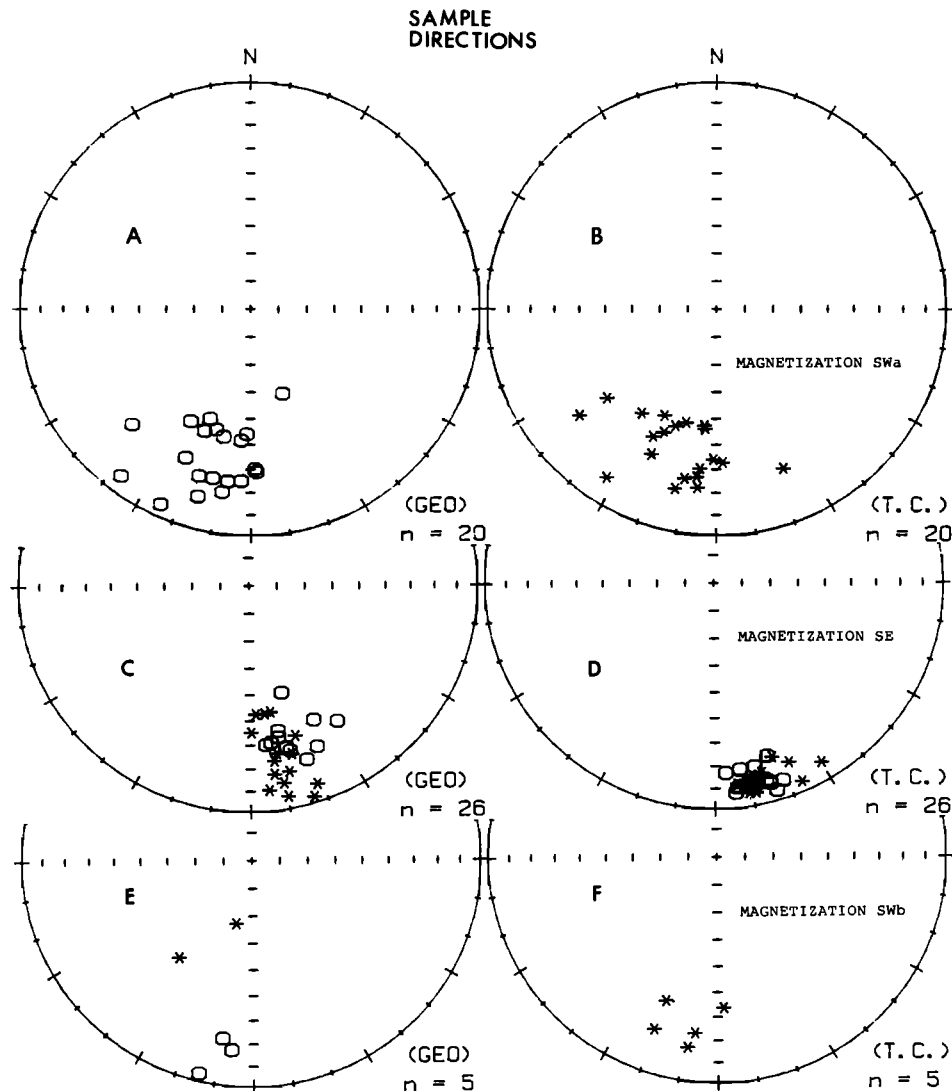the site mean D, I (Table 3) is 166.9°, 3.5° with

SAMPLE
DIRECTIONS

Fig. 4. Equal-area stereo net plots of best fit sample directions for
magnetizations SWa (top), SE (center) and SWb (bottom). Left hand plots are before
tilt correction; right-hand plots are after full tilt correction. Open symbols
represent negative (upward) inclinations, star symbols represent positive (downward)
inclinations.

k = 8.5, and after tilt correction the site mean
D, I is 166.7°, -3.6° with k = 44.8 (a95 = 7.8°).
The fivefold increase in k, for N = 9 sites,
gives a statistically valid fold test at the 99%
confidence level [Watson, 1956; McElhinny, 1964].

The magnetization SWb found in five samples
also appears to show a positive fold test at the
99% confidence level (Figures 4e and 4f; Table
2). The mean D, I is 190.9°, 25.4° (a95 = 11.0°)
after tilt correction.

We are thus left with the interesting problem
of having two components of magnetization from
sites K-T that appear to pass the fold test and
apparently predate folding: the dominant
thermally distributed, southeasterly component
(SE) and the subordinate thermally discrete,
southwesterly component (SWb).

Incremental Fold Tests

All of the site mean inclinations from
magnetization SE change sign after correction for

bedding tilt (Table 3). This means that the
magnetic directions from opposite limbs pass near
a common point during correction for bedding
tilt. We therefore suspected that this component
might be of synfolding origin. In order to test
this hypothesis, an incremental fold test was
applied. An incremental fold test consists of
correcting the site means by progressively larger
fractions of the measured bedding dips at each
site and calculating the overall precision
parameter, k, at each step. For example, at 50%
of unfolding, all of the bedding dips are reduced
to one half of their original value, and the
group k is calculated. The value of k can then be
plotted versus percentage of unfolding. If there
is a statistically significant peak in k at some
intermediate point in unfolding, then that
magnetization can be interpreted as having
occurred after some amount of folding. This
method represents a mathematical convenience, and
the percentage of unfolding corresponding to a
peak in k cannot be strictly related to the

TABLE 2. Directions and Poles:
Magnetizations SWa and SWb

Site/ Sample	In Situ		Tilt Corrected	
	Dec	Inc	Dec	Inc

Magnetization SWa (Site Mean Data)

A-H*	194.2	-31.7	196.1	35.0
S/N=20/27		k=20.1	a95=7.5	

Magnetization SWb (Sample Data)

L 1A	194.2	66.7	177.7	33.8
L 4	216.9	45.9	200.2	20.4
N 3A	189.7	-21.1	189.0	16.0
T 2A	194.2	-3.3	199.6	33.3
T 4A	186.5	-16.5	187.3	22.6
MEAN	195.2	13.4	190.9	25.4
	k=4.1	a95=43.1	k=49.7	a95=11.0

Pole Positions
(Computed from Sample Pole Positions)

	°E	°N	°E	°N
SWA	74.4	63.0	86.3	25.9
	k=27.2	a95=6.4	k=22.3	a95=7.1
SWB	84.4	36.0	91.1	34.4
	k=8.2	a95=28.4	k=63.7	a95=9.7

Mean SW Pole Position
(Computed from Site Mean Pole Positions)

SW	(Tilt Corrected, four Sites)	90.0	32.8
		k=165.4	a95=7.2

Dec is declination, Inc is inclination; k is
Fisher's precision parameter; and a95 is 95%
circle of confidence. S/N is the ratio of the
number of samples used in calculation to the
number of samples treated.
* Treated as one site.

actual degree of folding that had occurred at the
time of magnetization. The method can, however,
distinguish whether the magnetization was
acquired at some point during the folding
history, rather than simply before or after
folding, as in the conventional fold test.

For component SE, k peaks at 74% unfolding
(Figure 5), and k at this unfolding step is
significantly greater than the 100% tilt
corrected k at the 95% confidence level (Figure
5; Table 3). Hence magnetization SE clearly dates
to some point after folding began. The mean D, I
for magnetization SE at 74% of unfolding is
166.6°, -1.8° (a95 = 4.6°); the corresponding
pole position is 48.1°N, 124.1°E.

For component SWb, k reaches a maximum only
after full tilt correction. This result confirms
the positive fold test on this component and
indicates its age as prefolding.

If we wish to consider the possibility that
the magnetization SWa is of synfolding origin,
then the obvious data set with which to compare
is the clearly synfolding magnetization revealed
by the statistically well grouped SE component.
If both magnetizations were synfolding, then

their ages, hence directions, should be similar.
At no point during incremental rotation do the
circles of 95% confidence for SWa and the SE
component overlap. The mean inclinations of
magnetizations SWa and SE can be made to
correspond at shallow values at partial tilt
correction, but there is still a significant
inconsistency in the mean declinations. Therefore
if both of the magnetizations are synfolding,
then some relative rotation of 15° to 20° of the
two areas must have occurred since the
magnetizations were acquired. There is no
physical evidence for any such tectonic rotation.
Also, the same areas were sampled in the study of
the Mauch Chunk, and no evidence of relative
rotation was found in either the prefolding or
synfolding magnetizations [Kent and Opdyke,
1985]. This suggests that these two
magnetizations (SWa and SE) lack a common origin.

Further Age Constraints on SWa

In the absence of a clear local fold test, the
interpretation of the age of magnetization SWa is
not straightforward. If the magnetization is
conservatively considered to be of postfolding
age then the mean pole position from SWa is
closest to the North American apparent polar
wander path (NAAPWP [Irving and Irving, 1982];

TABLE 3. Directions and Poles: Magnetization SE

		Site Mean Directions					
		In Situ		Tilt Corrected			
Site	S/N	Dec	Inc	Dec	Inc	k	a95
K	2/4	167.3	28.8	167.2	-7.2		
L	4/6	169.5	19.5	169.4	-15.2	340	5.0
M	2/4	151.1	-31.9	153.3	7.1		
N	4/5	162.4	-29.5	163.0	10.6	36	15.5
O-P*	2/6	172.2	8.2	172.3	-9.1		
Q	2/2	166.8	7.9	167.1	-15.7		
R	4/6	175.4	40.8	172.6	-11.5	295	5.4
S	2/3	166.7	15.8	166.2	-0.9		
T	5/9	170.7	-30.8	170.5	10.2	494	3.4
Mean		166.9	3.5	166.7	-3.6		
		k(0%) = 8.5		k(100%) = 44.8			
		a95 = 18.7		a95 = 7.8			

at 74% tilt correction:
Dec = 166.6 Inc = -1.8
k(74%) = 124.5 a95 = 4.6

[k(74%) / k(100%) = 2.8]

Pole Position (Calculated at 74% TC)

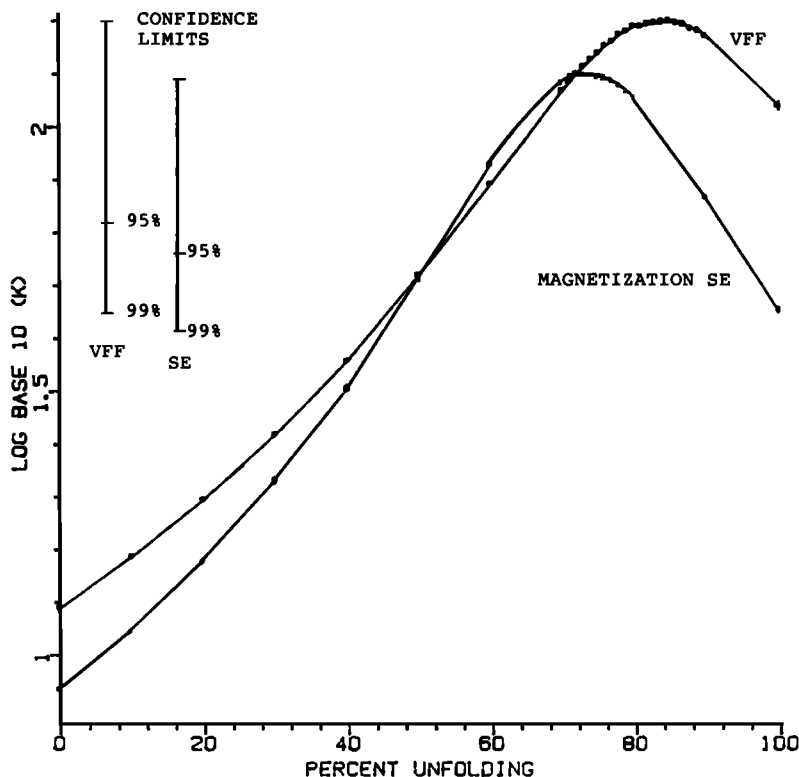| °N	°E	a95
48.1	124.1	4.0

Same notes as Table 2.

Fig. 5. Logarithm of precision parameter k versus percent of unfolding of site
means for magnetization SE. VFF refers to the curve generated by incremental
unfolding of site mean directions as reported by Van der Voo et al. [1979]. Plotting
k on a logarithmic scale allows the confidence limits to be applicable over any
portion of the curves.

Figure 6) in the Late Triassic/Early Jurassic
(200 Ma). These pole positions, with their
associated confidence limits, are likely to be
different at the 99% confidence level [McFadden
and Lowes, 1981]; therefore we do not favor this
interpretation of postfolding remagnetization.

While it is not statistically precluded that
the magnetization SWa does represent a synfolding
remagnetization acquired earlier in the Triassic,
this interpretation also seems unlikely. The pole
position trace for SWa during progressive
unfolding remains close to the NAAPWP back to
about the 230 m.y. reference mean pole. The
closest approach of the trace to the NAAPWP is at
30% of unfolding and near the Late Triassic (200
to 220 Ma) reference paleopoles. Given the
confidence limits of the data, it is
statistically permissible that magnetization SWa
represents a synfolding remagnetization in the
Late Triassic. However, continental rifting and
deposition of the Newark Supergroup began at
least by the middle Carnian (early in the Late
Triassic [Olsen et al., 1982]), so that it is
unlikely that active folding of the orogen also
continued into the Late Triassic.

Finally, the SWa pole position calculated
either before, during, or after bedding tilt
correction does not fall near the prefolding
results from the Mauch Chunk Formation. [Kent and
Opdyke, 1985] or the Deer Lake Group [Irving and
Strong, 1984]. Therefore magnetization SWa is
unlikely to represent a lower Carboniferous
remagnetization.

We are left then with the possibility that the
magnetization SWa represents a prefolding
magnetization, possibly Devonian in age. This
interpretation is supported by the observation
that the tilt-corrected mean pole position for
magnetization SWb (which passes a fold test) is
statistically indistinguishable from the tilt-
corrected mean pole position from magnetization
SWa. The magnetizations SWa and SWb thus appear
to be samples of the same prefolding
magnetization population, SW, with a
corresponding pole position of 32.8°N, 90.0°E,
a95 = 7.2 for N = 4 sites (Table 2; Fig 6).

Magnetizations SE and SW

In the interest of clarity, a brief summary of
the results to this point might be of use. We
have sampled members of the Catskill at two
different geographic localities. There are only
two samples that contain normal polarity
components, but in neither sample is the normal
polarity component well defined. In the area
southwest of Wilkes-Barre (sites K-T), there is a
clearly defined thermally distributed
southeasterly component (SE) that is of
synfolding origin and must therefore be
secondary. In the same sites there is also a
poorly represented high unblocking temperature
southwesterly component (SWb) which passes the
fold test. In the area of Jim Thorpe (sites A-H),
the thermally discrete magnetizations (SWa) tend
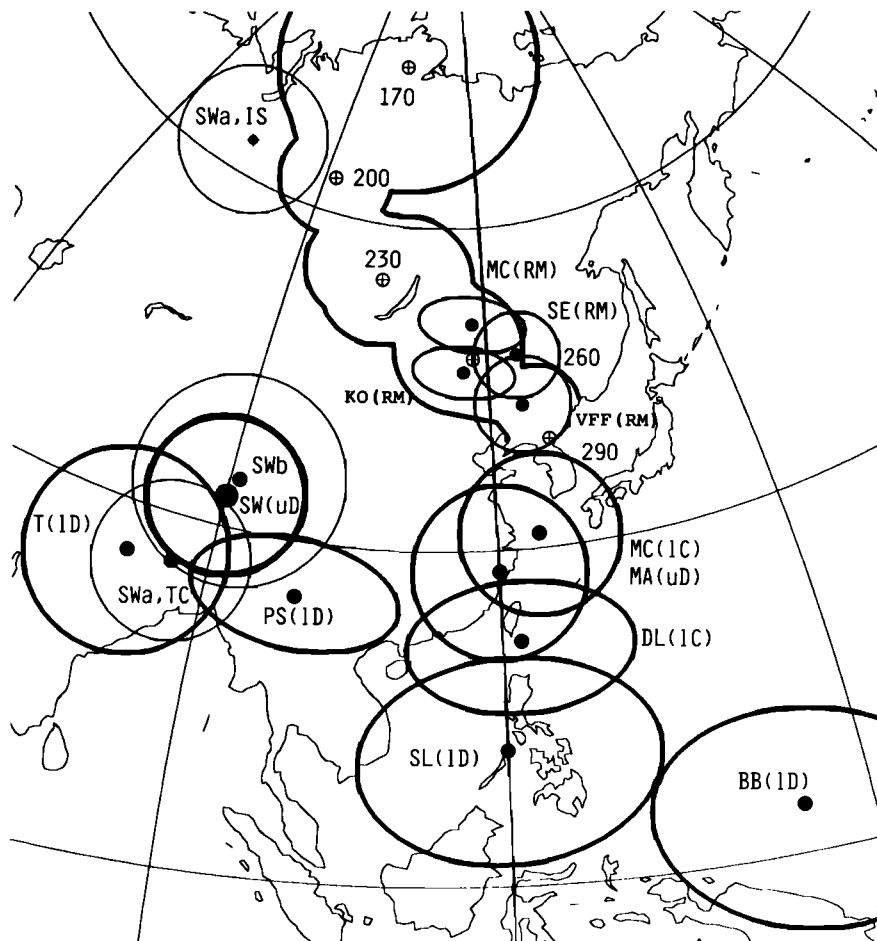to be southwesterly in declination with moderate

Fig. 6. Paleomagnetic pole plot (stereographic projection) with 95% confidence envelopes. Age notation: RM, remagnetized in late Paleozoic; 1C, lower Carboniferous; uD, Upper Devonian, and 1D, Lower Devonian. Points from this study include SWa in situ (SWa,IS) and after full tilt correction (SWa,TC); the synfolding, thermally distributed component (SE(RM)); the prefolding, thermally discrete component (SWb(uD)); and the composite magnetization SW(uD). Numbered points represent ages of the late Carboniferous to Early Jurassic segment of Irving and Irving's [1982] apparent polar wander path for the 30 ma window. Other remagnetized poles include VFF(RM), Catskill pole reported by Van der Voo, et al. [1979]; KO(RM), Catskill of New York State [Kent and Opdyke, 1978]; and MC(RM), synfolding magnetization of the lower Carboniferous Mauch Chunk Formation [Kent and Opdyke, 1985]. Lower Carboniferous poles are MC(1C), the prefolding magnetization of the Mauch Chunk Formation [Kent and Opdyke, 1985] and DL(1C), prefolding magnetization of the Deer Lake Group [Irving and Strong, 1984]. Upper Devonian poles from Acadia: MA(uD), mean pole taken from Van der Voo and Scotese (1981); SL(uD), the St. Lawerence Granite [Irving and Strong, 1985] and BB(uD), from the Bonavista Bay Dikes [Murthy, 1983]. Lower Devonian poles: T(1D), from the Traveler Terrane (see text) and PS(1D), from the cratonic Peel Sound Formation [Dankers, 1982].

inclinations. Magnetization SWa is similar in direction after tilt correction to magnetization SWb, and a similar prefolding magnetization is inferred for both magnetizations. Magnetizations SWa and SWb both appear to represent the same magnetization, SW.

Implications of Magnetization SE

The pole for component SE (calculated at 74% of unfolding; Table 3) agrees remarkably well with the previous paleomagnetic poles (Figure 6) from the studies of Van der Voo et al. [1979] and

Kent and Opdyke [1978]. The close proximity of these poles suggests that these magnetizations from the Catskill Formation sampled at these different geographic localities have similar secondary origins.

In the study of Van der Voo et al. [1979] the conventional fold test was positive at the 99% confidence level, the same result we initially obtain for SE. Through incremental rotation of their reported site means, however, we calculate a peak in k at 85% of unfolding (Figure 5). Although this peak value of k is not significantly higher than k at full tilt

correction, it does support our contention that both of these magnetizations are secondary. The explanation as to why the southeasterly magnetization of the Catskill in the Van der Voo et al. [1979] study area does not show a statistically significant peak in k through the incremental fold test while the magnetization SE clearly does may lie in the geometrical relationship between magnetic overprinting and folding in the two study areas noted earlier. Another interesting possibility is that the relative ages of the remagnetization and folding in the two study areas are different.

Paleomagnetic results from other cratonic rock units (Columbus and Delaware limestones [Martin, 1975]; Temple Butte and Martin formations [Elston and Bressler, 1977]) have previously been considered to possibly represent primary magnetizations largely because of their similar paleopole positions to those of the Catskill. Since it has now been shown that the magnetization isolated previously in the Catskill is secondary, it seems reasonable to conclude that the results from these other units also represent late Paleozoic remagnetizations.

Implications of Magnetization SW

The pole position from magnetization SW after full tilt correction falls very close to the pole from the cratonic lower Devonian Peel Sound Formation [Dankers, 1982] (Figure 6). There is, however, an age difference between the Catskill and Peel Sound units, as the Peel Sound is Lower Devonian. This agreement may be just coincidence, but it is also possible that the reason these poles agree is that they do in fact collectively represent a good estimate of the Devonian pole position for North America.

The SW pole position is also close to the pole from the Lower Devonian Traveler Terrane (25°N, 99°E, a95 = 9° for N = 3 studies; Figure 6). The Traveler Terrane pole is calculated as the mean pole from the Traveler Felsite (29°N, 82°E [Spariousu and Kent, 1983]), the Compton metasediments (28°N, 77°E [Seguin et al., 1982]), and the Dockendorff Group (20°N, 84°E [Brown and Kelly, 1980]). Particularly interesting is the agreement with the pole from the Compton metasediments [Seguin et al., 1982], as this magnetization passed a fold test on Acadian folding and as such is constrained to be pre-Middle Devonian in age of magnetization. The Traveler is considered a suspect terrane and cannot with confidence be considered cratonic; comparison with the contemporaneous Peel Sound pole position [Dankers, 1982] does allow for some rotation of the Traveler block as proposed by Spariosu and Kent [1983]. Nevertheless, we believe that the close correspondence of the poles for the Catskill, Traveler, and Peel Sound units does suggest similar ages of magnetization.

The new Catskill pole does not coincide with the mean Upper Devonian pole for Acadia [Van der Voo and Scotese, 1981] (Figure 6). However, the nature of the discrepancy is again in the paleoazimuths and not in the paleolatitudinal positions. The paleolatitude calculated for magnetization SW is 16°S +/- 7.2°. This compares with a paleolatitude of 19°S +/- 8.1° predicted

for the eastern Pennsylvania sampling area from the mean Upper Devonian Acadia pole of Van der Voo and Scotese [1981]. Therefore there is no direct evidence for a latitudinal offset between Acadia and cratonic North America in these data (as inferred by Irving and Strong [1984, 1985]), contrary to what was interpreted from the earlier Catskill results [Kent and Opdyke, 1978; Van der Voo et al., 1979; Irving, 1979].

The difference in the paleoazimuths may reflect some amount of post-Late Devonian rotation of Acadia counterclockwise relative to North America and/or of eastern Pennsylvania clockwise relative to both the interior parts of North America and Acadia. In the study of the Mauch Chunk around the curve of the Pennsylvania salient, the prefolding magnetization declinations from sites in eastern Pennsylvania tended to be about 15° clockwise to those from south-central Pennsylvania [Kent and Opdyke, 1985]. We cannot therefore exclude the possibility that the southwesterly declinations in the Catskill of eastern Pennsylvania reflect to some degree regional rotation in this part of the Appalachian orogen.

An alternative interpretation is that the rock units that are summarized as providing the Upper Devonian pole for Acadia were actually magnetized in the Carboniferous (either through remagnetization or poor age control on the rock units themselves). The Upper Devonian pole for Acadia of Van der Voo and Scotese [1981] is indistinguishable from the two cratonic lower Carboniferous poles (Figure 6) and from the prefolding magnetization observed in the Tournaisian [Howie and Barss, 1975] Terrenceville Formation from Acadia (pole position 27.4°N, 123.5°E [Kent, 1982]), which had previously been thought to be Upper Devonian.

If the recently determined paleopoles from the Upper Devonian Saint Lawrence Granite [Irving and Strong, 1985] and Wesleyville dikes [Murthy, 1983] of the Burin Peninsula are a better representation of the Upper Devonian pole for Acadia than the previous studies summarized by Van der Voo and Scotese [1981], then a discrepancy in paleolatitude reappears because the paleolatitudes predicted from these units for eastern Pennsylvania (35°S +/- 9°, St. Lawrence Grantite; 42°S +/- 9°, Wesleyville dikes, sotheasterly magnetization) are significantly more southerly than the paleolatitude observed for the Catskill. It should be noted that the mean declinations from these two studies in Newfoundland differ by some 20°, suggesting some amount of local rotation. Also, Murthy [1983] isolated another magnetization from other dikes in the Bonavista Bay area (originally interpreted as the primary magnetization) which corresponds to a paleolatitude of 74.5°S for Acadia in the Upper Devonian. Further work is clearly needed in both the North American craton and Acadia before any final answer can be given to the question of displacement of Acadia in the Upper Devonian.

Origin of Synfolding Magnetization

The Catskill is not the first rock unit found to possess a synfolding magnetization. Examples of other units in which synfolding magnetizations

have been isolated include the Mauch Chunk red beds [Kent and Opdyke, 1985], the Helderberg limestone [McCabe et al., 1983], the Old Red Sandstone [Chamalaun and Creer, 1964; Chamalaun, 1964; McClelland-Brown, 1983], and various Cretaceous units in western Wyoming [Schwartz and Van der Voo, 1984]. The exact nature of the origin of the synfolding magnetization in the Catskill is as yet unknown, but a few inferences can be made from the data presented in this study.

The Permian, or Kiaman, remagnetization of red beds, which is common in the Appalachians, is most likely to be chemical in origin. If the remagnetization were of thermal origin, then the unblocking temperatures of the synfolding magnetization observed in the Catskill (>650°C) would require that the sediments had been subjected to similarly high (>630°C) temperatures at some point during burial [Pullaiah et al., 1975]. Given the lack of evidence for metamorphism in the Catskill and the data from conodonts, it is therefore unreasonable to ascribe a thermal origin to the remagnetization. This observation leaves chemoremanence, the precipitation or recrystallization of hematite from solution, as the only viable alternative mechanism of remagnetization. However, the remagnetization might have been enhanced by elevated fluid temperature during orogenesis.

If the folding in the central Appalachians is seen as a continuous process, then it is interesting to note that synfolding magnetizations produce such linear trends during demagnetization. One might intuitively expect that if the remagnetization and folding were proceeding simultaneously, curved demagnetization trajectories might be the rule. This expectation arises from the idea that if hematite is being chemically precipitated during folding, then that hematite which was deposited early in the folding process would have a somewhat higher unblocking temperature (because it had more time to attain a larger, more magnetically stable grain size) and a slightly different direction (because of the difference in bedding attitude) than hematite deposited later in the folding process.

The observation that the synfolding magnetizations typically have linear demagnetization paths could mean that the remagnetization occurred concurrently with folding over a very short time period with respect to folding. Another possible explanation for the linear demagnetization paths is that the folding was discontinuous and the remagnetization occurred between two phases of deformation. It has been suggested that the Alleghenian orogeny consisted of two phases of deformation that were not everywhere coaxial [Geiser and Engelder, 1983]. It is possible then that the remagnetization event for the red beds occurred after the first phase of folding and was subsequently reordered by the next phase of deformation.

In any case, an observation that tends to support the idea that the remagnetization of the Catskill (as well as the Mauch Chunk) is in some way related to orogenesis is that the magnetization of these rock units lacks any postfolding magnetization except for the present-day overprint. If the remagnetization were a deep weathering process related to the near-equatorial position of North America in the late Paleozoic [Creer, 1968], then it should have continued past the end of folding, since North America occupied a near-equatorial position into the Late Permian [Irving and Irving, 1982].

Age of Alleghenian Folding

Regardless of the exact mechanism of the remagnetization, the synfolding magnetization provides an estimate of the age of folding in the Alleghenian orogeny. A mean synfolding pole position (47.6°N, 122.3°E, a95 = 6.9 for N = 3 studies) can be calculated by combining the synfolding result from the Mauch Chunk [Kent and Opdyke, 1985] with those of the Catskill (the present study and that of Van der Voo et al. [1979]). Comparison of the mean synfolding pole with the NAAPWP of Irving and Irving [1982] suggests that the folding was in progress in the Early Permian (about 270 Ma) somewhat after the deposition of the Dunkard Group. In a study utilizing postfolding magnetizations from the Ordovician Juniata and Silurian Rose Hill formations, Van der Voo [1979] placed the age of folding as late Carboniferous to Early Permian. These two estimates are consistent and suggest that the age of Alleghenian folding was Early Permian.

Conclusions

A demonstrably secondary magnetization (SE) acquired during late Paleozoic folding was isolated, corresponding to a paleopole position (48.1°N, 124.1°E), which plots on the Early Permian portion of the NAAPWP and near to the paleopole reported for the synfolding magnetization of the Mauch Chunk [Kent and Opdyke, 1985]. This paleopole is indistinguishable from the previous pole positions reported from the Catskill by Van der Voo et al. [1979] and Kent and Opdyke [1978]. It is now clear that these previous studies of the Catskill also isolated secondary late Paleozoic magnetizations and as such should no longer be considered as representative of Devonian age magnetizations. This study confirms the contention of Irving and Strong [1985] that all of the pole positions in addition to the Catskill that had previously been thought to represent the Upper Devonian pole position for North America (Temple Butte and Martin formations [Elston and Bressler, 1977] and Columbus and Delaware limestone [Martin, 1975]) can also be considered late Paleozoic remagnetizations.

Given the results of this study and other studies that have isolated synfolding magnetizations, the application of some form of incremental fold test might be a prudent addition to the standard paleomagnetic NRM stability tests, particulary for rock units folded in the Alleghenian orogeny.

The hypothesis that the synfolding remagnetization actually occurred between two phases of deformation is testable if a suitable location can be found. It will be necessary to sample in an area where the phases of deformation

are well defined structurally, allowing for a multiple phase structural tilt correction. It would then be possible to determine whether the magnetization components were acquired during any given phase or between phases.

Through comparison of the mean synfolding pole position with the NAAPWP [Irving and Irving, 1982], the synfolding magnetization now documented in Devonian and lower Carboniferous rock units in the central Appalachians is thought to have been in progress at about 270 Ma. This suggests an age of Early Permian for Alleghenian folding in the Valley and Ridge Province.

The high unblocking temperature magnetization SW corresponds to a southern hemisphere paleolatitude for eastern central Pennsylvania of about 16°S, which is some 10° to 15° farther south than the paleolatitudes reported from the earlier studies of the Catskill. An early acquisition age for this magnetization is implied by a positive fold test on a small number of samples from the Wilkes-Barre area and by the fact that the corresponding pole position does not fall near to any reported post-Devonian paleopoles for North America.

The paleopole from the prefolding magnetization SW (32.8°N, 90.0°E) is similar to poles from rock units in the Traveler Terrane and from the cratonic Peel Sound Formation, which are, however, Lower Devonian. The paleolatitude from magnetization SW suggests that there was no latitudinal offset between Acadia and North America in the Late Devonian when compared with the paleolatitude predicted for this area from the mean paleopole for Acadia of Van der Voo and Scotese [1981]. A significant latitudinal offset exists, however, with the paleolatitudes observed from eastern Newfoundland Upper Devonian rock units [Murthy, 1983; Irving and Strong, 1985]. The data from eastern Newfoundland leave open the possibility of some latitudinal offset between all, or part, of Acadia and North America in the Late Devonian.

The isolation of prefolding magnetizations from the Catskill over a broader area, especially in south-central Pennsylvania, will be needed to test the hypothesis of relative rotation within this part of the orogen. This, however, would not necessarily solve the problem of an Upper Devonian reference pole for cratonic North America, which must be based on studies from a demonstrably stable area.

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