LATE PALEOZOIC MOTIONS OF THE MEGUMA TERRANE, NOVA SCOTIA: NEW PALEOMAGNETIC EVIDENCE

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Abstract. Three rock units from southern Nova Scotia were sampled for a paleomagnetic study of the relationship of the Meguma terrane to the Atlantic-bordering continents during the Paleozoic. These include the Siluro-Ordovician White Rock Formation volcanics, sandstones of the Lower Devonian Torbrook Formation and red beds of the Lower Carboniferous Cheverie Formation. Progressive thermal and alternating field demagnetization of the White Rock basalts and rhyolites reveal a single component magnetization with a mean direction of D = 149.1°, I = 24.3°, α_{95} = 10°, for N = 13 sites. Rotation of the site mean directions about the axis of the Torbrook Syncline suggest a post-folding (post Middle Devonian) age for this magnetization, which corresponds to a pole at 21.9° N Lat., 147.7° E Long. after correction for post-Triassic regional tilting. The magnetization of the Torbrook Formation (D = 15.8°, I = 29.6°, α_{95} = 11.7°) is clearly a secondary magnetization whose pole (55.5° N Lat., 90.7° E. Long.) lies near Triassic poles from both North America and southern Nova Scotia. The age of the Cheverie Formation magnetization (D = 146°, I = 25°, α_{95} = 6°, tilt corrected) appears to pre-date folding in the area (pre-Westphalian) and the corresponding pole (24° N Lat., 152° E Long.) lies near to the White Rock pole, suggesting a similar age of magnetization. The White Rock and Cheverie poles, which are constrained to have Early Carboniferous ages, are 30° or more away from the North American APW path over the same age range, a discrepancy which can be explained by a 15 - 19° northward motion of Meguma with respect to the North American craton along with a 20 - 25° counter - clockwise rotation. There is no paleolatitude discrepancy between these results and paleomagnetic results from the adjacent Avalon Zone although a similar rotational discrepancy is evident. These inferred motions of the Meguma terrane most likely took place during the Carboniferous, prior to the formation of Pangea.

Introduction

Differing paleomagnetic signatures of adjacent geologic provinces have provided evidence for the existence of terranes in the northern Appalachians that were exotic to cratonic North America for portions of Paleozoic time, including Acadia [Kent and Opdyke, 1978, 1979, 1980], Armorica [Van der Voo, 1982], and the Traveler terrane [Spariosu and Kent, 1981, in press, 1983]. Recently, plate tectonic models of the Appalachians have been constructed with the incorporation of the concept of "exotic" or "suspect" terranes in the Paleozoic evolution of the orogen [Williams and Hatcher, 1982; Keppie, in press, 1983]. Such terranes have been defined by as "areas characterized by an internal continuity of geologic record, with features that contrast sharply with those of nearby provinces." To date, however, no paleomagnetic data have been published for the Paleozoic of the Meguma terrane of southern Nova Scotia, a terrane long viewed as exotic to pre-Mesozoic North America on the basis of its lithostratigraphic character [Schenk, 1978; Keppie, 1977b, 1982a,b, in press, 1983; Williams and Hatcher, 1982]. This study presents paleomagnetic evidence that the Meguma terrane did indeed move independently of North America for at least part of Carboniferous time.

Geologic Setting

The Meguma is the outermost terrane of the northern Appalachians, lying farthest from the early Paleozoic cratonic margin of North America [Williams and Hatcher, 1982; Keppie, in press, 1983], (Fig. 1). The Meguma Zone is juxtaposed against the adjacent Avalon composite terrane of northern Nova Scotia and New Brunswick along the Minas Geofracture (Chedabucto-Cobequid fault system) [Keppie, 1982a] and presumably forms the basement beneath the present day continental margin to the South and East. The name is de-

Fig. 1. Map of the northern Appalachians adapted from Williams and Hatcher [1982], showing major terranes.

rived from the Meguma Group, a thick (up to 13km) succession of Cambrian - Ordovician graywackes and shales thought to be derived from a low-lying metamorphic terrane to its southeast; a succession with a distinctly different lithology than the Cambro-Ordovician sections of any of the other northern Appalachian terranes. The Meguma Group is disconformably and unconformably overlain by the White Rock Formation, an undated succession of sandstones and shales locally containing thick piles of mafic and felsic volcanic rocks. Locally, the sediments of the Kentville and New Canaan formations conformably overlie the White Rock; these contain fossils of probable Late Silurian (Ludlovian) age [Keppie, 1977a]. Conformably above these Silurian units more than 1300m of the Torbrook Formation sandstones, siltstones and shales are exposed along the southern edge of the Annapolis Valley. These paralic marine sediments contain an abundant shelly fauna of Rhenish-Bohemian affinity, ranging in age from early Gedinnian to possibly early Emsian (Early Devonian), [Boucot, 1960]. The Torbrook Formation marks the end of a long period of seemingly continuous deposition in a marine environment.

A Middle Devonian orogeny affected all of the above described rock units. The deformation produced northeasterly trending folds associated with an axial plane cleavage and was followed closely by regional metamorphism grading from lower greenschist facies in the north through amphibolite facies in the southwestern corner of Nova Scotia. Subsequently the deformed pile was intruded by the granitoid rocks of the Meguma Batholith, a composite intrusion with radiometric ages ranging from 371±2 ma to 361±1 ma [Keppie and Smith, 1978]. Regional structures and metamorphic isograds are truncated by the granitoid plutons. The age relationships between the uppermost Torbrook Formation and the intrusions thus constrain the age of deformation to be post-early Emsian, pre-360ma, close in time to the Acadian orogeny in the rest of the northern Appalachians.

The Meguma terrane contains no strata of Middle and Late Devonian age. Early Carboniferous (Tournaisian) red beds of the Horton Group rest unconformably on the pre-Carboniferous rocks. The Horton Group contains 1500m of conglomerate, arkose, sandstone, siltstone, shale and coal [Hacquebard, 1972] deposited in subaerial, fluviatile and lacustrine environments. Conformably overlying the Horton sediments are Visean supratidal to shallow marine clastics and carbonates of the Windsor Group. The Horton and Windsor Groups are thought to have been deposited in pull-apart basins formed in a broad region of transcurrent faulting in the Maritimes [Bradley, 1982; Fralick and Schenk, 1981; LeFort and Van der Voo, 1981; Keppie, 1982a,b]. The fluviatile clastics of the Scotch Village Formation of late Westphalian age [Hacquebard, 1972] disconformably overlie the Horton-Windsor succession. A paleomagnetic study of some of these Windsor to Westphalian age rocks is reported by Scotese et al. [this volume].

The Carboniferous rocks of southern Nova Scotia were deformed during the Hercynian orogeny which is generally correlative with the Alleghanian orogeny in the United States Appalachians. Deformation ocurred mainly during Westphalian and Permian times [Keppie, 1982b] with the most intense deformation along the northern margin of the terrane [Keppie, 1982a].

A regional unconformity separates the underlying Paleozoic section from Late Triassic to Early Jurassic continental red beds and plateau basalts exposed along the Bay of Fundy. [Crosby, 1962]. The age of these rocks has been inferred from Upper Triassic fossils in the lowermost and uppermost sediments and from a K-Ar whole rock age of 198ma for the North Mountain plateau basalt [Keppie and Smith, 1978]. The syn-rift deposits of this Triassic - Jurassic graben are similar in many respects to those in other basins of the Newark Series in eastern North America.

Several plate tectonic models have been developed to explain the relationships between the Meguma terrane, the adjacent parts of the Appalachian orogen and cratonic North America. Schenk [1978] envisions the Meguma terrane as an Early Paleozoic eugeoclinal sequence marginal to the Morroccan Meseta, emplaced in its present position following the Late Paleozoic collision of Gondwana - North America and separated from Morrocco by subsequent Mesozoic rifting. Reconstructions by McKerrow and Ziegler [1972] and Smith et al. [1973] place Meguma against Colombia, South America, off "northwestern" Gondwana. Subsequent collision between this part of Gondwana and the northern Appalachians during the Devonian, followed by opening of a Carboniferous ocean, left the Meguma terrane in its present location relative to North America. Similarly, Keppie [1977] places Early Paleozoic Meguma off Gondwana adjacent to cratonic basement of Colombia - Central America previous to collision with Avalon and North American terranes in the Devonian. In his model, however, Late Paleozoic dextral transcurrent motion follows between Euramerica and Gondwana. In contrast, Williams [1979] and Bird and Dewey [1970] cite the similarity between Meguma Group graywackes and Cambrian deposits of the Welsh Basin [Rast et al., 1976], speculating that the Meguma terrane could represent a "faulted trough that developed within the Avalon Zone." This interpretation implies that the current geographic relationship between the zones of the Appalachian orogen was established by the end of the Ordovician and has not changed significantly since. Van der Voo [1982] incorporates the Meguma Zone as part of an Armorica plate, which includes the Avalon Zone, Great Britain south of the Great Glen fault, and the Armorican Massif of France. In his model, Armorica first rifts away from Gondwana in the Late Precambrian - Early Paleozoic, collides with North America adjacent to the southern Appalachians in the Ordovician, and moves northward to its present position during Carboniferous sinistral transcurrent motion between North America and an assemblage of Armorica and the Baltic shield.

Paleomagnetism offers the opportunity to constrain models of the motions of suspect terranes by either comparison of segments of apparent polar wander (APW) paths of geologic terranes over the same time period or by comparison of paleolatitudes with those inferred for other terranes or continental blocks. This paleomagnetic study of Paleozoic rocks from the Meguma Zone was conceived with the hope of finding constraints on plate tectonic models involving the Meguma terrane.

Sampling

Siluro-Devonian sections (White Rock and Torbrook Formations) were examined in two localities along the southern slope of the Annapolis Valley prior to sampling. Deformation of the rocks in the Bear River area was observed to be much more penetrative in character than that to the east in the Nictaux Falls - Torbrook area. Here, the White Rock and Torbrook Formations are exposed in the core of the Torbrook Syncline, a northeasterly trending structure intruded by Devonian granites to the South and onlapped by Late Triassic sediments on its northern edge (Fig. 2). The syncline is a large amplitude isoclinal fold with subvertical to slightly overturned limbs, of large enough extent to be apparent on the scale of the geologic map of Nova Scotia [1:500,000; Keppie, 1979]. Small scale folding associated with the major structure has been observed only in the core of the syncline and not on the limbs in the Torbrook - Nictaux Falls area. While a "pencil" cleavage is present in shaly layers of the Torbrook Formation, coarser grained sandstones and the volcanics of the White Rock Formation show relatively little penetrative deformation.

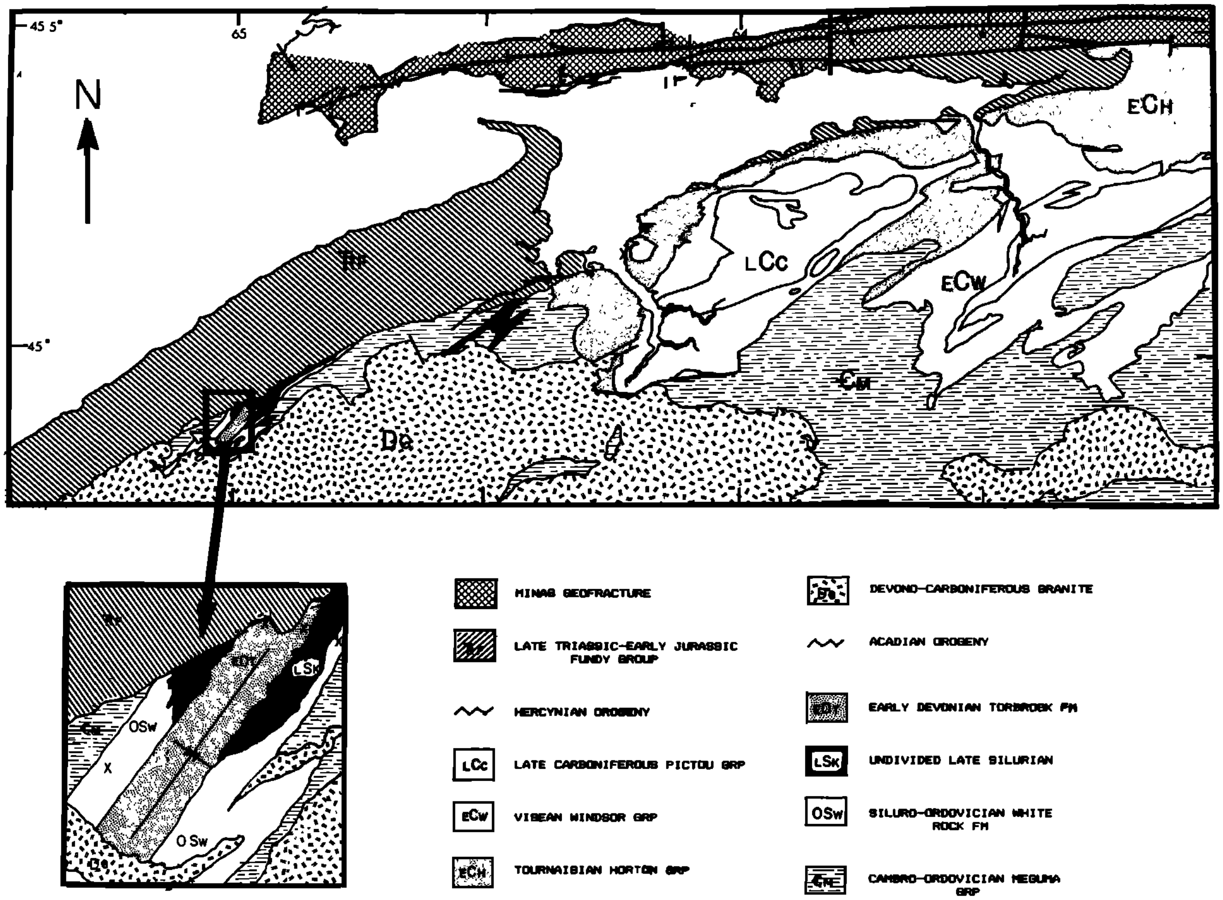

Fig. 2. Simplified geologic map of the northwestern portion of the Meguma Zone, Nova Scotia [modified from Keppie, 1979]. Inset shows detail of the Torbrook Syncline area. "X"s mark sampling localities for the Torbrook and White Rock Fms. (inset) and the Cheverie Fm. (large map).

Samples were collected using a portable diamond-bit coring drill and oriented with a magnetic compass according to standard paleomagnetic practice. Nine sites consisting of six or more oriented cores each were collected in the White Rock Formation on the south limb of the Torbrook Syncline along Fales River, 4 in rhyolites (rhyodacitic ignimbrites) and 5 in basalt flows. On the north limb, 11 sites were sampled along the Nictaux Canal, 6 in the rhyolite and 5 in the overlying basalts. Sandstones of the Torbrook Formation were sampled along Spinney Brook at 4 sites on the north limb of the syncline and at 6 sites upstream on the south limb. Sampling sites were well north of the contact metamorphic zone adjacent to the Meguma Batholith, except those along the Nictaux Canal which were near, although outside of the aureole.

Red sandstones of the Early Carboniferous Cheverie Formation were collected at 11 sampling sites along the shore of the Minas Basin in the Walton-Cheverie area (Fig. 2). This locality was chosen because it appeared that enough structure was present to allow application of a fold test [McElhinny, 1964] although it is still south of the zone of penetrative deformation of this formation [Boyle, 1963].

Rock Magnetic Studies

Procedures

Oriented drill core samples were sliced into 2.4 cm specimens, yielding one to three specimens per core. Natural remanent magnetizations (NRM) were measured on either a fluxgate spinner magnetometer [Molyneaux, 1972] or a cryogenic magnetometer [Goree and Fuller, 1974]. Representative specimens were then selected for pilot alternating field (AF) and thermal demagnetization experiments. During stepwise thermal demagnetization procedures, bulk susceptibilities (K) were measured following each heating/cooling cycle for the purpose of detecting magnetochemical changes due to the heating/cooling process [Dunlop, 1972].

Additionally, thin (0.6 to 1.2 cm) disks of samples from the Torbrook and Cheverie sandstones were cut and radially slotted for stepwise chemical demagnetization. These were soaked in 8N HCl while kept in field-attenuated space for periods totalling up to greater than 500 hours. Procedures followed were generally similar to those described by Henry [1979] and Roy and Park [1974].

Following analysis of pilot demagnetization experiments, specimens from all remaining samples were subjected to thermal, AF or the combination thereof deemed likely to isolate and establish the stability of all significant magnetization components. All specimens used in the final analyses have been subjected to a minimum of three demagnetization steps. Statistical procedures used in data reduction include linear regression component analysis [Kent, 1981], spherical dispersion analysis [Fisher, 1953], as well as three level averaging techniques [Irving, 1964].

Results

White Rock Formation. The rhyolites at the Nictaux Canal locality are typically weakly magnetized, on the order of 10^{-4} Am^{-1} compared to remanent intensities of about 10^{-1} for the basalts. More pertinent is that linear demagnetization trajectories are either not apparent in many of the rhyolite samples (11 of 35) or else the directions isolated are often not consistent from sample to sample within a site (3 sites of 6 have sample direction distributions that cannot be excluded as random at the 95% confidence level; Table 1). These magnetic characteristics may be attributable to the proximity of the rhyolite to the contact metamorphic zone of the Meguma Batholith at the Nictaux Canal locality, which may have resulted in complex thermochemical alteration of the original carriers of magnetization. Vector end-point demagnetization diagrams of well-behaved rhyolite samples from the Nictaux Canal locality are shown in Figure 3. Note that the magnetization directions revealed by both AF and thermal demagnetization in companion specimens from a sample (Fig. 3a) are virtually identical. Magnetite appears to be the dominant carrier of magnetization. Consequently, AF treatment was used for progresive demagnetization in the majority of White Rock samples. Figure 3b shows an example from a site where individual samples display a linear demagnetization trajectory but the isolated directions appear to be randomly distributed (Table 1).

The basalts at Nictaux Canal gave marginally better results. The dominant direction (18 samples from 3 sites) is toward the southeast with moderate inclination (Fig. 3c) and is carried by a magnetic phase of moderate to high coercivity and blocking temperatures less than 550°C. Figure 3d shows an example of a univectorial sample magnetization whose direction however is removed from both the present field and the dominant southeasterly direction but which may correspond to a Triassic overprint; the distribution of sample directions at this (SWH) and another (SWG) basalt site are random.

Magnetization intensities of rhyolites and basalts at the Fales River locality are more comparable, $5x10^{-2}$ Am^{-1} and 10^{-1}, respectively, and in general a much higher proportion of the samples provided usable data. The dominant direction is southeasterly with moderate positive inclination, as at Nictaux Canal, and typically is revealed over a moderate coercivity range (Fig. 3e). In one rhyolite site (SWN), all but a single sample showed unstable demagnetization behavior; in that sample the southeasterly component is observed over intermediate stages of AF demagnetization but is followed by what may be a present-day field direction at higher demagnetization levels (Fig. 3f). Finally, one basalt site (SWQ; Table 1) was characterized by an anomalously high Koenigsberger ratio (>30) which may have resulted from lightening effects. On this basis, and also because the directions although well grouped are aberrant, results from site SWQ are rejected from further consideration.

Site mean directions for the White Rock Formation are listed in Table 1 and plotted in Figure 6a. In situ directions group in the southeast quadrant, primarily about a moderate (25°) inclination although some streaking of directions toward the present field direction is noted (Fig. 6a). The in situ mean directions for Nictaux Canal and Fales River are nevertheless almost identical, less than 5° apart. Following correction for bedding tilt (finite rotation about bedding strike) the Nictaux Canal and Fales River site groupings diverge and the overall dispersion increases significantly. Although there is some suggestion that the resulting pattern (Fig. 6a) constitutes a dual polarity set, observe that all of the northwesterly directions come from sites on the south limb of the syncline while the southeasterly site means are from sites on the north limb. Consideration of the fold geometry reveals that the structural correction involves near 90° rotations in opposite senses for the two limbs of the syncline since the in situ site mean directions are nearly perpendicular to bedding strike. Also note that the two post-correction groupings do not form an antiparallel pair, but in fact are only 148° apart. It is thus appropriate to conclude that the pattern observed in the corrected directions is an artifact of the structural geometry and that the age of magnetization for the Silurian White Rock Formation is of post-folding (post Early Devonian) origin. Other evidence relevant to the possible age of this secondary magnetization will be discussed in a later section.

Torbrook Formation. One pilot specimen from each site in the Torbrook Formation was selected for stepwise AF demagnetization and at least one

TABLE 1. Site mean directions for the White Rock Formation

Site	Lithology	N/n^a	In situ Decl. (°)	Incl. (°)	k	α_{95}	
1. Nictaux Canal (Bedding strike/dip = 32°/71°SE)							
SWA	Felsic	4/6	144.5	60.5	193.	6.6	
SWB	Felsic	4/6	(87.4	60.7	2.2	83.	)^b
SWC	Felsic	4/6	(350.5	26.6	1.8	104.	)^b
SWD	Felsic	5/6	153.0	12.5	72.	9.1	
SWE	Felsic	3/6	(150.7	-35.3	2.4	111.	)^b
SWF	Felsic	4/5	158.5	-12.5	17.	23.	
SWG	Mafic	6/6	(180.6	65.6	1.9	68.	)^b
SWH	Mafic	6/6	(285.1	74.0	1.5	89.	)^b
SWI	Mafic	6/6	147.2	28.7	27.	13.	
SWJ	Mafic	6/6	148.7	32.9	33.	12.	
SWK	Mafic	6/6	141.4	9.6	107.	6.5	
Mean (6/11 sites):			**149.3**	**21.9**	**10**	**22**	
(after tilt correction			156.4	-41.1	)		
2. Fales River (Bedding strike/dip = 229°/88°NW)							
SWL	Felsic	6/6	158.9	17.1	21.	15.	
SWM	Felsic	4/6	167.6	23.3	24.	19.	
SWN	Felsic	1/6	(				)^c
SWO	Felsic	5/6	145.9	45.8	65.	9.6	
SWP	Mafic	4/6	146.9	20.7	58.	12.	
SWQ	Mafic	5/5	(289.0	71.8	103.	7.6	)^d
SWR	Mafic	6/6	146.7	18.5	48.	9.8	
SWS	Mafic	4/4	132.2	27.5	19.	22.	
SWT	Mafic	6/6	142.4	28.4	138.	5.7	
Mean (7/9 sites):			**148.9**	**26.2**	**33**	**11**	
(after tilt correction			298.4	64.0	)		

Formation mean (13/20 sites, in situ):

D= 149.1° I= 24.3° k= 18 α_{95}= 10°

corrected for post-Triassic tilt (strike, dip = 250°/7°N):

148.4° 31.2°

Pole position: 21.9° N Lat., 147.7° E Long., dp,dm = 6.2, 11.2

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[a] Number of samples used in mean calculation/total number of samples.

[b] Site excluded because random distribution hypothesis could not be rejected at the 95% confidence level.

[c] only one sample gives an interpretable demagnetization trajectory.

[d] Site SWQ excluded because of anomalously high Koenigsberger ratio (>30), possibly a result of lightning strike.

for detailed thermal demagnetization. Stepwise thermal demagnetizations of the samples already AF demagnetized were also carried out. Vector end-point diagrams of typical demagnetization curves are shown in Figure 4. Initial demagnetization steps of 10mT or 200°C remove low coercivity/blocking temperature magnetization components, but they appear to be of minor significance in terms of the magnitude of their contribution to the NRM and possess no significant directional grouping. Subsequent thermal demagnetization to 660° reveals three main clas-

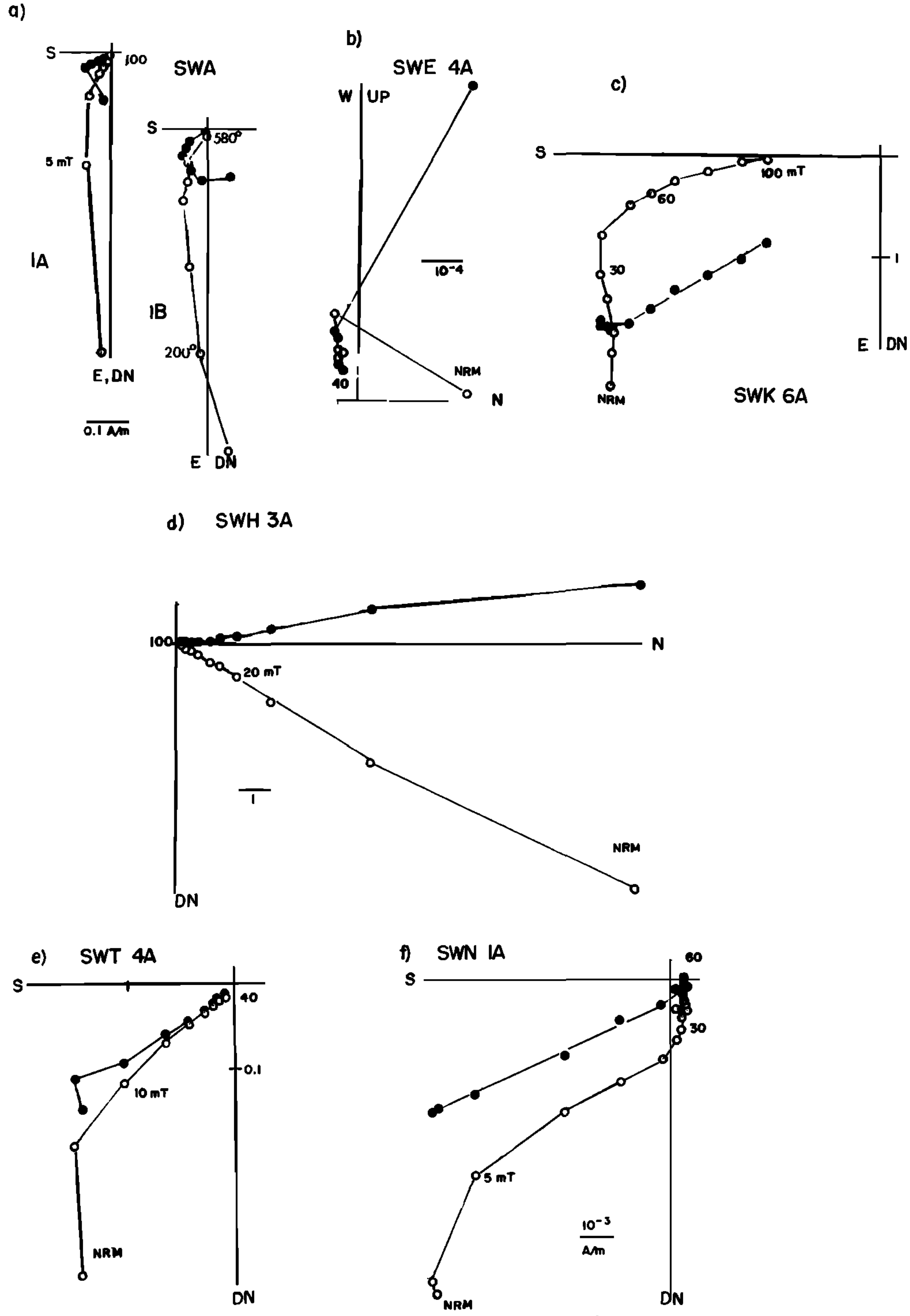

Fig. 3. Orthogonal demagnetization diagrams [Zijderveld, 1967] of specimens from the White Rock Formation. Open circles represent projections on the vertical, North-South plane, closed circles projections on the horizontal plane. Demagnetization fields in millitesla (mT), temperatures in degrees Celsius. Magnetization intensity units (scale bars or axes units) all in amperes per meter (Am^{-1}). (a) AF and thermal demagnetization of two specimens from the same core sample of a basaltic flow. (b) Example of a linear demagnetization trajectory in a specimen from a site with a random distribution of directions. (c) AF demagnetization of a basalt specimen from the Fales River section. (d) A stable direction which is thought to represent a Triassic overprint. (e) Single component magnetization in a basalt from Fales River. (f) Multicomponent magnetization in a rhyolite from Fales River.

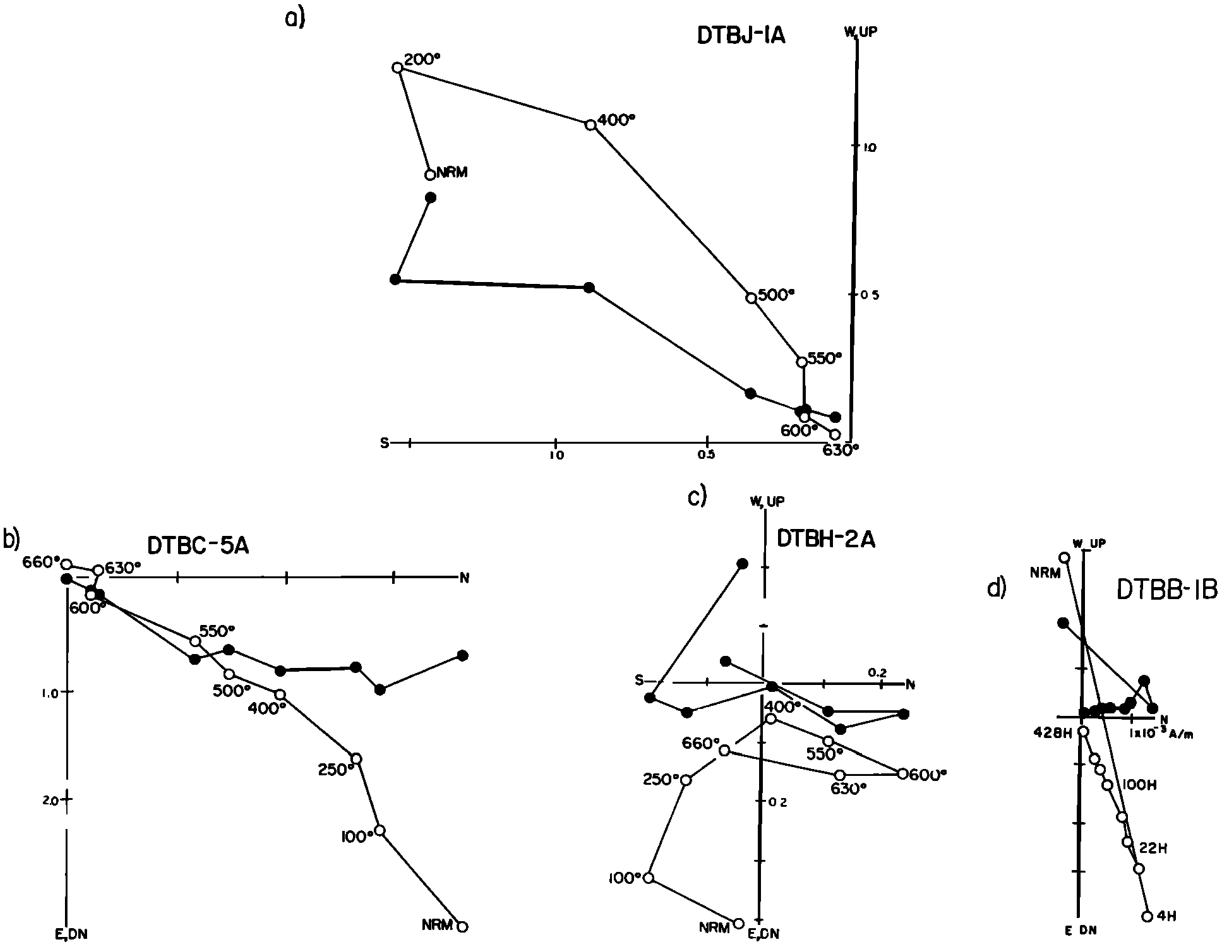

Fig. 4. Demagnetization plots for specimens from the Torbrook Formation. Symbols and units are the same as in Figure 3, all are plotted in in situ coordinates. (a) A specimen illustrating typical behavior of "normal" polarity magnetized samples. (b) Example of a reversely magnetized specimen. (c) Specimen showing evidence of components of both polarities, normal from 400°C to 600°C, reversed from 600° to 660°. (d) An example of predominant behavior observed during chemical demagnetization. Note the difference in direction compared to thermal demagnetization.

ses of directional behavior: 1) generally linear decay to the origin of a south to southwesterly component with shallow negative inclinations (Fig. 4a), 2) similar behavior of a component directed north to northeasterly with 20-30° positive inclinations (Fig. 4b), and 3) removal of either the northerly or southerly component, although missing the origin, followed either by removal of the other or unresolvable directional behavior. Figure 4c illustrates the removal of the northerly, down component between 400 and 600°, followed by removal of the southerly component from 600°. AF demagnetization to 100mT most often results in stable directional behavior in either the northerly or southerly directions noted above but is ineffective in substantially reducing magnetization intensities, hence stepwise thermal demagnetization was selected as the most effective cleaning procedure for the bulk of the remaining samples, which were demagnetized with a minimum of four temperature steps to 640-660°.

Site mean results for the thermally demagnetized Torbrook sandstones are listed in Table 2 and plotted in Figure 6b. In situ site mean directions form an apparently dual polarity set and in fact, mean reversed (southerly) and mean normal (northerly) group means do not differ significantly from bipolarity. After correction for bedding tilt, however, dispersion increases dramatically in both normal and reversed polarity groups. Dispersion also increases when the entire group is treated as a dual polarity set of the same paleomagnetic field (reversed directions inverted). We infer from this that the magnetization is post-folding (post-Early Devonian).

TABLE 2. Site Mean Directions for the Torbrook Formation

				In situ			Tilt Corr.	
Site	Bedding	N/n	Pol.[a]	Decl. (°)	Incl. (°)	α_{95}	Decl. (°)	Incl. (°)
DTBA	36/85S	6/7	N	6.5	26.9	4.7	63.8	27.8
DTBB	36/85S	5/6	M	22.9	60.1	21.5	96.4	10.8
DTBC	36/85S	5/5	M	19.2	28.0	13.7	63.8	17.2
DTBD	36/85S	3/4	R	199.1	-18.0	9.0	233.2	-17.6
DTBE	215/94N	5/6	N	42.1	22.7	22.7	11.8	5.0
DTBF	215/94N	6/6	N	26.5	30.3	12.4	4.9	-9.4
DTBG	215/94N	6/6	N	15.2	31.8	11.3	2.7	-18.9
DTBH	233/93N	3/4	M[b]	13.6	30.4	35.3	17.4	-35.0
DTBI	233/93N	5/5	M	350.3	2.5	27.0	53.4	-62.3
DTBJ	233/93N	4/6	M	6.9	38.6	22.9	5.4	-36.5

Formation mean:[c]
in situ D= 15.8°, I= 29.6°, α_{95}= 11.7°, k= 18.1, N= 10 sites
tilt corrected 36.2°, -9.1°, 29.1°, 3.7

Pole (in situ): 58.0° N Lat., 85.3° E Long., dp= 7.1°, dm= 12.9°
Corrected for post-Triassic tilt: (strike= 70°, dip= 7°N)
55.5° N Lat., 90.7° E Long.

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[a] Magnetization polarity; N=normal, R=reversed, M=mixed polarity, some sample directions inverted to dominant site polarity.

[b] All samples from Site DTBH had reversed directions at intermediate temperatures, normal at high temperature (>600°C); only the high temperature component is included in the site mean calculation.

[c] Site DTBD direction inverted.

Although the presence of both polarities was once thought to be an indication of a primary magnetization [McElhinny, 1973], dual-polarity secondary magnetizations have been documented elsewhere [eg., Kent, et al., 1982]. Note that in the case of the Torbrook sandstones, both polarities are observed within single sites and sometimes within single specimens. Also, there is no apparent relationship between structural position in the syncline and polarity nor any obvious stratigraphic control over polarity zonation. The combination of dual polarity and secondary characteristics of this magnetization points, we think, to a long process of magnetization, most likely a slow chemical process spanning at least the time required for a field reversal.

In order to learn more about the magnetization mechanism of these rocks, 6 specimens were subjected to the chemical demagnetization procedures described above. One of the specimens disintegrated during early stages of the process and results are not used further. Of the remaining five, two of the specimens showed scatter and/or unresolvable directional behavior during the demagnetization process, three demagnetized univectorially to the origin following removal of spurious components in the first (4 hour) step (Fig. 4d). The directions of these three lie along the present day field direction for the sampling locality (in situ coordinates). After bedding correction, however, directions from the two specimens sampled on the southern limb of the syncline move away from the direction of the specimen from the northern limb. We believe that the component removed by chemical demagnetization (and not recognized during thermal demagnetization) represents a Tertiary to Recent magnetization that is unstable under AF and high temperature but resistant to dissolution in HCl, although the small number of samples chemically demagnetized makes any such statement equivocal. A possible explanation for the behavior of the sandstones during these different demagnetization procedures is: 1) the recent magnetization is carried by large multidomain (detrital?) magnetite or hematite grains with very low coercivities and blocking temperatures but whose grain size renders them resistant to attack by the acid; and 2) the stable secondary magnetization revealed during thermal demagnetization is carried by fine-grained hematite which was either deposited interstitially long after deposition or

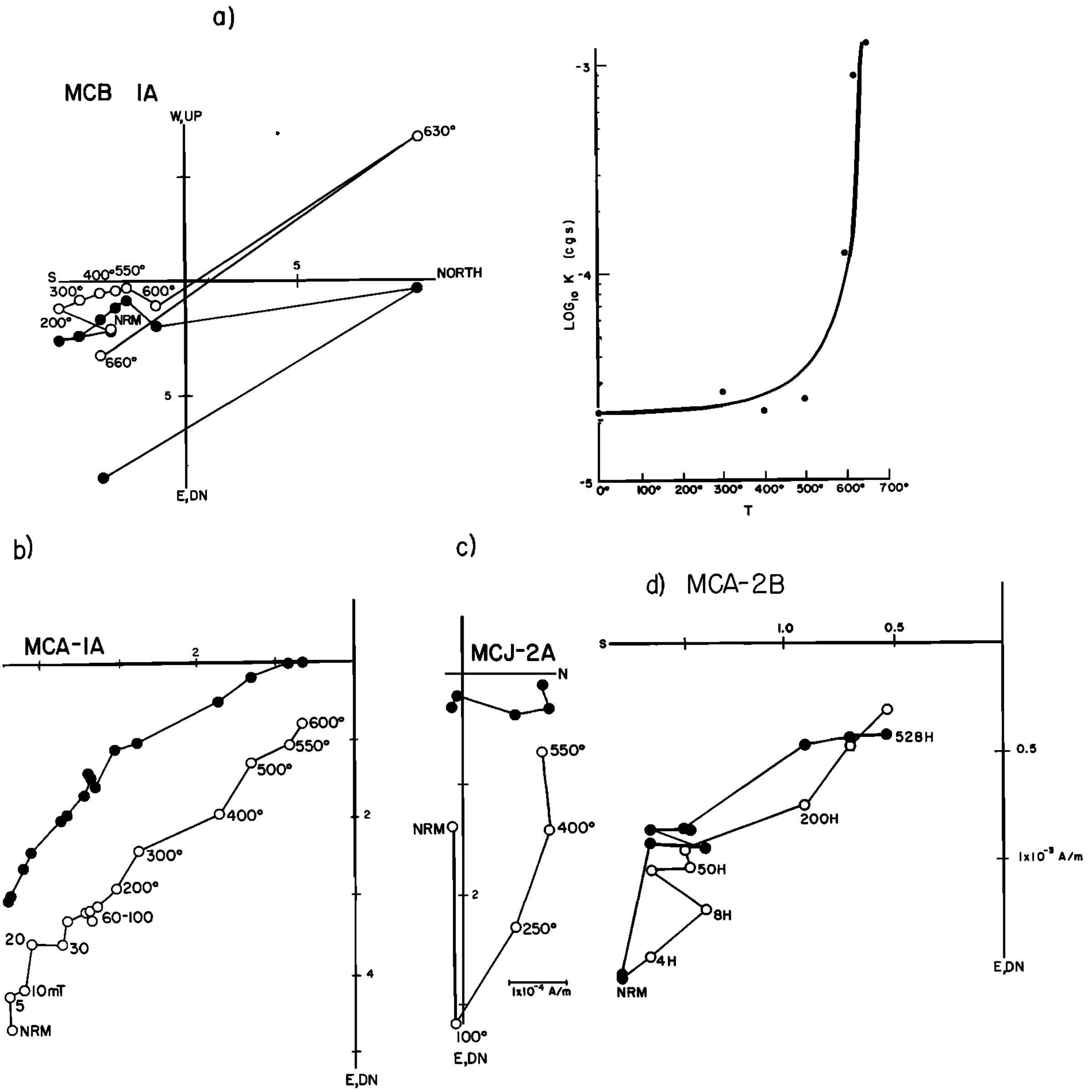

Fig. 5. Typical demagnetization behavior of samples from the Cheverie Formation; symbols and units as in Figure 3. (a) Zijderveld plot alongside temperature vs. bulk susceptibility plot for a typical specimen; note the sudden increase in intensity and the unstable directional behavior associated with the sharp rise in bulk susceptibility beginning around 600°C. (b) Typical behavior during thermal and AF demagnetization of samples from 9 of the 11 sites. (c) Example of behavior noted in samples from two sites. The trajectory initially does not trend toward the origin but at higher temperatures begins to reverse and approach the origin from a direction perhaps antiparallel to that exhibited in (a) and (b). Unstable behavior above 600° prohibits isolation of this component. (d) Chemical demagnetization in 8 Normal HCl. Demagnetization levels are in cumulative hours in the acid solution (H).

formed as an oxidation product from ferrosilicates and/or oxide grains, thus leaving it vulnerable to dissolution in acid. More rock magnetic and petrographic work is needed to better understand the magnetization history of the Torbrook sandstones.

Cheverie Formation. NRM directions of Cheverie Formation samples group predominantly in the southeast quadrant with inclinations varying from steeply positive (down) to -25 to -30°. AF demagnetization to fields up to 100mT generally fails to remove more than 10 to 20% of the

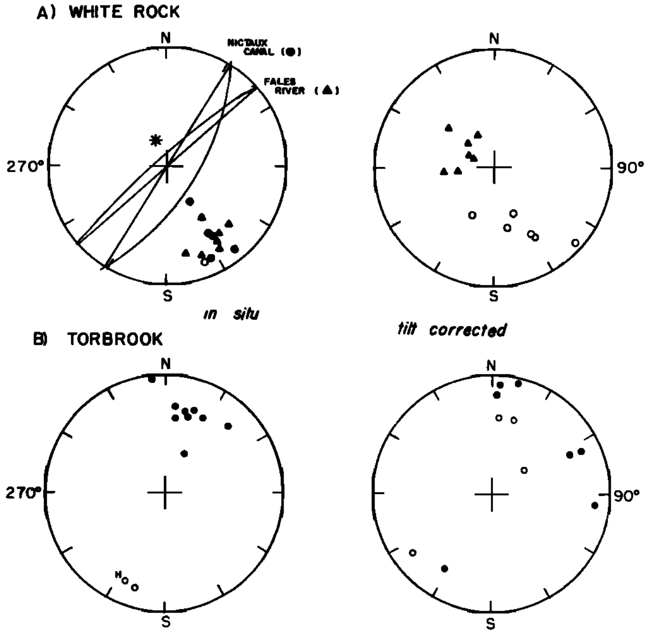

Fig. 6. Equal area projections of site mean directions from the studied rock units. Filled (open) symbols are projected on the lower (upper) hemisphere. (a) White Rock Formation (Table 1); also shown are the direction of the present day field at the locality (*) and the bedding plane orientations at the two sections sampled. (b) Torbrook Formation; point marked "H" represents the intermediate temperature reversed component in site DTBH samples and was not used in the formation mean calculation.

remanence, although demagnetization trends are toward the origin. Decay during thermal demagnetization follows the same trajectories observed during AF in most cases, up to about 550°-600°C, although heating is much more effective in reducing total magnetization intensities; above these temperatures spurious directional behavior is observed, often along with sudden increases in intensity (Fig. 5a). This behavior occurs in conjunction with increases in bulk susceptibility from one to four orders of magnitude above initial values. Such behavior has been associated with the formation of magnetic mineral phases during heating and cooling in air [Dunlop, 1972; Kent and Opdyke, 1978]. This characteristic of these rocks prevents us from isolating any distinct components residing at blocking temperatures above 600°C, a blocking temperature range usually important in redbed magnetizations. Nonetheless, the linear demagnetization trajectories observed at lower temperatures and their direct trends toward the origin lead us to believe that we have effectively isolated the dominant magnetization of the Cheverie Formation.

Exceptions to the behavior described above were some samples from sites MCI and MCJ. The initial component removed by AF demagnetization and thermal demagnetization up to 300°C in these appears to be the same southeast and down magnetization observed in the others, however, the linear trend clearly bypasses the origin (Fig. 5c). Subsequent thermal demagnetization begins to remove a component directed north to northeasterly with intermediate positive inclination. Another example (thermal demagnetization only) shows the northerly component alone. Unfortunately, the spurious magnetizations due to heating precluded isolation of this component in any of the other samples.

Chemical demagnetization experiments reveal no magnetization components not noted above from thermal demagnetization. In fact trajectories of the demagnetization plots look remarkably similar for either thermal or chemical procedures (Fig. 5d). One specimen from site MCJ shows the north - northeasterly, down component observed during heating in site MCI. This component is not isolated during thermal demagnetization of MCJ samples although trajectories of the southeasterly component "miss" the origin, thus suggesting its presence. The principal magnetization components of the Cheverie sandstones, in contrast to those of the Torbrook Formation, show no differences between blocking temperature and grain solubility spectra.

Two magnetization components are observed in samples from site MCD, a southeasterly, down direction removed by AF demagnetization, or, in one instance, below 200°C thermal demagnetization, and a southeasterly, up direction removed by routine thermal demagnetization. Because this was the only site which appeared to possess two distinct, isolatable magnetizations, "b" specimens were halved and one specimen from each sample subjected to stepwise AF and stepwise chemical demagnetization. AF demagnetization revealed the southeast, down component in every sample, while acid leaching removes the southeast, up component observed during thermal demagnetization of the "a" specimens from this site in 4 out of 5 instances, the other revealing the downward component. These two components are significantly different (Table 3). The component removed by AF demagnetization is directionally nearer the single component magnetization observed during both AF and thermal studies of samples from the rest of the sites. While the unique behavior of samples from site MCD remains unexplained, we note that the southeasterly, up directions from the thermal studies more closely matches the secondary magnetization direction obtained by Scotese et al. [this volume] from similar age rocks of the nearby Schubenacadie basin.

Site mean directions of the southeasterly component (interpreted as the characteristic magnetization) of the Cheverie are listed in Table 3 and plotted in Figure 7b. Although a simple correction for bedding tilt (one-stage finite rotation about bedding strike) produces no better grouping of site mean directions, the variations in site mean inclinations seem gene-

TABLE 3. Site Mean Directions for the Cheverie Formation

Site	Bedding	N/n	In Situ Decl. (°)	In Situ Incl. (°)	α_{95}	Unfolded[a] Decl. (°)	Unfolded[a] Incl. (°)
MCA	56/14S	3/3	143.1	36.0	18.3	142	26
MCB	73/14S	5/5	142.6	40.7	24.0	149	32
MCC	43/20S	4/5	157.9	26.5	16.7	153	15
MCD_{Th}[b]	52/11S	6/6	151.7	-18.4	13.2	152	-27
MCD_{AF}	52/11S	5/6	146.9	37.6	16.7	146	27
MCE	272/12N	5/5	144.8	21.3	11.4	142	30
MCF	286/14N	5/5	151.4	29.5	10.0	147	35
MCG	286/14N	5/5	152.1	15.6	13.8	149	25
MCH	23/75E	5/5	166.4	47.3	10.2	133	7
MCI	18/41E	3/5	160.4	42.4	30.5	141	23
MCJ	28/77E	4/4	180.6	56.9	10.9	139	22
MCK	18/07E	6/6	165.1	29.5	11.1	162	27

Formation mean (11 sites):
in situ D= 155°, I= 35°, α_{95}= 8.5°, k= 30
unfolded 146°, 25°, 6.0°, 59

Pole position (unfolded directions):
24° N Lat, 152° E Long, dp = 3°, dm = 6°

[a] Corrected for flexural slip distortion and bedding tilt (see text)

[b] Th = thermal demagnetization result, AF = alternating field demagnetization result; Th not included in formation mean calculation (see text)

rally related to the dip of the beds. Examination of the minor folds in the area suggests that flexural-slip or flexural-flow were the main fold mechanisms, which would modify the site mean directions as shown in Figure 7a. Ramsay [1967] describes the geometry of this type of deformation and a method for removing its effects. Unfolding of the Cheverie site mean directions was accomplished by first rotating them to bring the fold axes to the horizontal, and then rotating them along small circles about the appropriate fold axis (031/12NE or 077/5NE) through the angle $[\theta-(\beta-\beta'')]$ or $[\theta-(\beta'-\beta)]$. This produces a much tighter grouping of site mean directions (Fig. 7b). The ratio of the precision parameters after/before these corrections increases to 2.0, barely short of the 2.1 required for a positive fold test at the 95% confidence level for 11 site means [McElhinny, 1964]. This suggests that the Cheverie Formation magnetization was acquired prior to folding which is post-Windsor Group (Visean) and pre-Scotch Village Formation (late Westphalian).

Paleopoles and Implications

The White Rock Formation magnetization is clearly post folding in age (post-Middle Devonian) and its mean in situ direction yields a paleomagnetic pole at 24.7° N. Lat., 147.2° E. Long. While there are no constraints on the minimum age of this magnetization, the pole does not fall near any post Devonian segment of the North American apparent polar wander path and thus may be considered anomalous in that respect.

The mean direction of the Torbrook Formation (D=15.8°, I=29.6°, α_{95}=11.7°) corresponds to a post-folding (post Early Devonian) magnetization with a pole at 58.0° N. Lat., 85.3° E. Long., far removed from the White Rock pole. Unlike the White Rock pole, however, the Torbrook pole lies in the general vicinity of a younger segment of the North American apparent polar wander path, the Triassic (Fig. 8). This pole is also in close proximity to poles from Triassic rocks within the Meguma Zone, including two results from the North Mountain Basalt [Larochelle, 1969; Carmichael and Palmer, 1968] and one from a Late Triassic dike in southern Nova Scotia [Larochelle and Wanless, 1966], as well as to other poles from Newark Series rocks in eastern North America [Beck, 1972; de Boer, 1968; Opdyke, 1961].

If the Torbrook and White Rock magnetizations are Late Triassic - Early Jurassic or older, then the mean directions should be corrected for the sloping of the pre-Late Triassic peneplane and

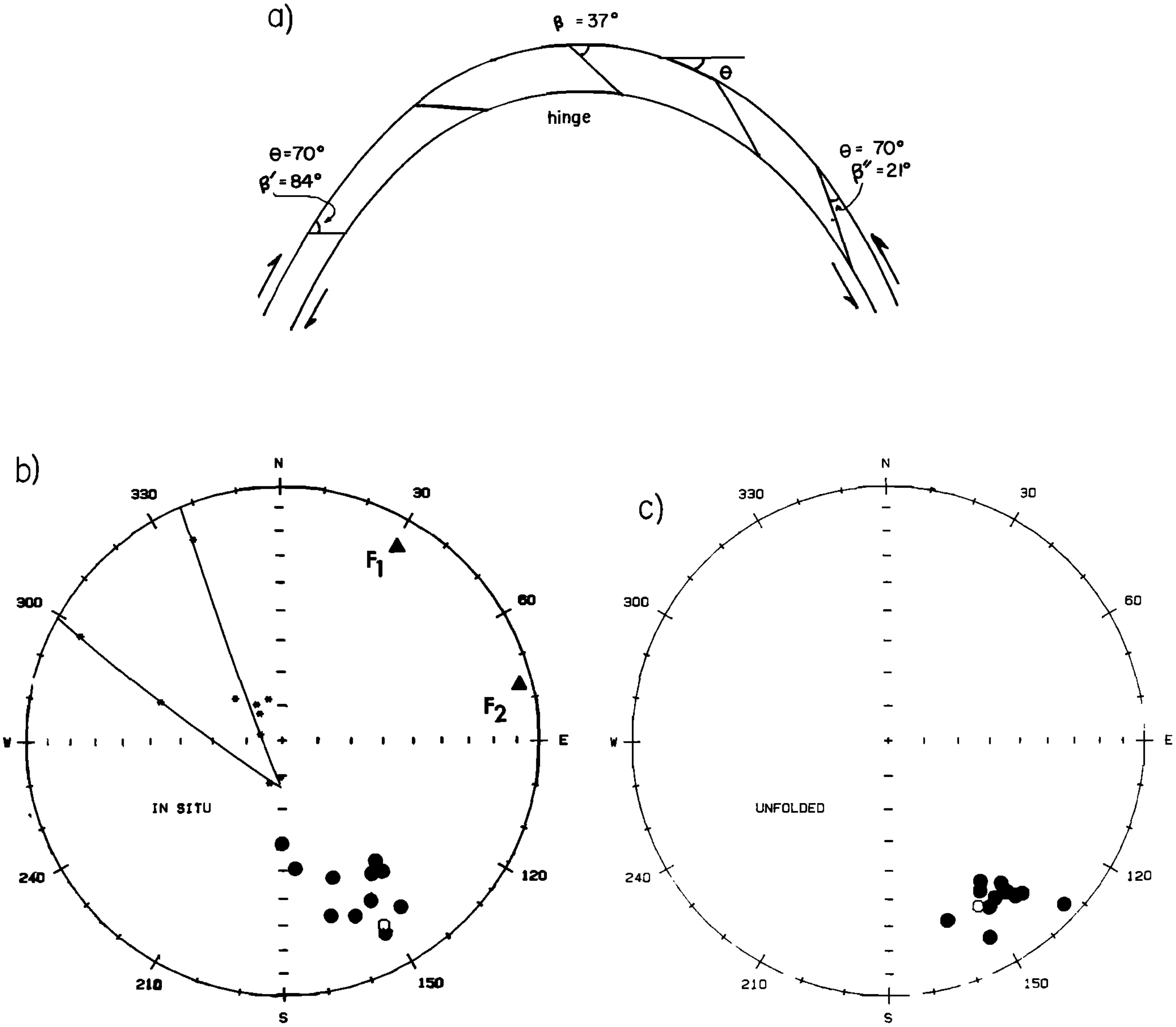

Fig. 7. (a) Cross section of a flexural-slip fold showing effect of folding on magnetization vectors or other linear features. The correction for this effect is explained in the text. (b) Equal area plot showing in situ site mean directions, poles to bedding planes with fold axes and unfolded site mean directions. The only direction not included in the formation mean calculations is the one shown on the upper hemisphere and represents thermal demagnetization results from site D.

overlying strata, which in the Annapolis Valley strike 70° and dips approximately 7° to the North. This rotation yields a direction of D=13.8°, I=23.8° for the Torbrook, corresponding to a pole at 55.5° N. Lat., 90.7° E. Long. in close proximity to poles from the Middle Triassic Manicouagan impact site, Quebec [Larochelle and Currie, 1966; Robertson, 1967]. The same rotation on the White Rock gives a direction of D=148.4°, I=31.2°, with a pole at 21.9N, 147.7E. The Torbrook direction is not similar to results reported in abstract by Seguin et al. [1981], who found two magnetization components in Torbrook sandstones with directions of D=320°, I=-10° (in situ), and D=230°, I=30° (tilt corrected, in situ unknown). Details of this work are not yet known, although most of their samples came from a different locality than in this study [Seguin, personal communication, 1982]. It is interesting, however, that their secondary direction from the Torbrook is roughly antiparallel to the secondary direction in the White Rock Formation.

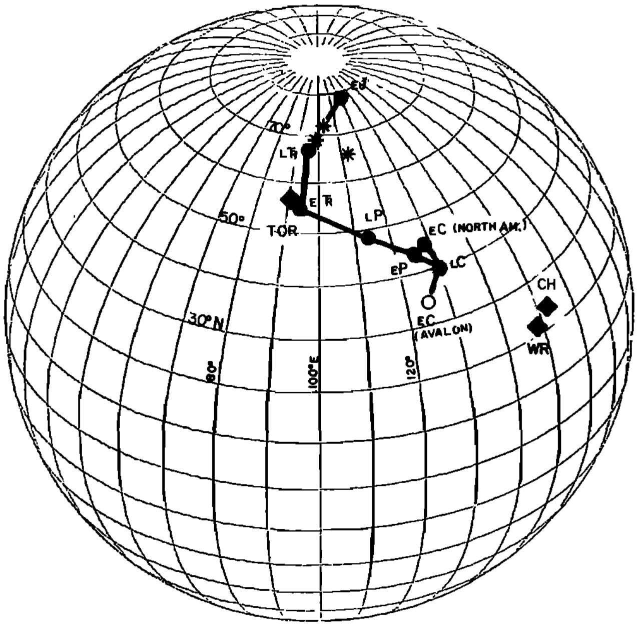

Fig. 8. Paleomagnetic poles from this study (diamonds) plotted against the apparent polar wander path for North America (solid circles). North America APW from Van der Voo and French [1974] with Early and Late Triassic mean poles recalculated to shift Manicouagan poles from early to late Triassic based on K-Ar ages of Wolfe [1971]. The open circle represents the Early Carboniferous pole for Acadia (Avalon Terrane) from Roy and Park [1974]. Asterisks (*) denote Late Triassic to Early Jurassic poles from southern Nova Scotia (see text).

As noted above, the fold test for the Cheverie Formation suggests an Early Carboniferous age of magnetization. This further implies that the unfolded formation mean direction (D=146°, I=25°) and the corresponding pole (24° N. Lat., 152° E. Long.) are representative of the Early Carboniferous paleomagnetic field with respect to the Meguma terrane. A noteworthy aspect of this paleopole is its proximity to the White Rock Formation secondary pole (Fig. 8), suggesting either similar magnetization ages for the two rock units or slow polar wander rates with respect to Meguma between the times of their magnetization. Indeed, if the White Rock remagnetization is due to a thermal resetting caused by the intrusion of nearby plutons, its age (361-371ma) may not be much older than the depositional age of the Cheverie Formation (Tournaisian). If this is true, then these poles, from rock units affected by different deformation events and sampled in localities separated by 50 km, must represent the position of the Meguma Zone for some time near the Early Carboniferous.

Discussion

The paleomagnetic poles from the White Rock and Cheverie formations can provide useful constraints on the relationships between the Meguma Zone and adjacent terranes in the northern Appalachians. Figure 8 shows these poles plotted relative to the APW paths for North America and the Acadia (Avalon) terrane for Late Paleozoic to Early Mesozoic time. Comparing them first with the APW for cratonic North America, we note that the Meguma poles are about 30° away from North American mean poles for either early or late Carboniferous time (Fig. 8). This implies a 20 to 25° counter-clockwise rotation of Meguma with respect to North America. Also implied is a northward translation of Meguma with respect to North America, considering the 13-17° South paleolatitude inferred from the Meguma poles and the near equatorial paleolatitude of North America at this time. These motions must both occur at some time between the Tournaisian and late Westphalian, sometime before the Westphalian assembly of Pangea [Van der Voo et al., this volume]. There is no room for Meguma to translate northwards at any other time prior to the opening of the present Atlantic Ocean.

The White Rock - Cheverie poles are also about 30° away from Acadia mean poles for the early to late Carboniferous. This can be accounted for a similar 20 to 25° counter-clockwise rotation of Meguma with respect to Acadia. There does not appear to be a significant paleolatitude difference (paleolatitude=17° S. for the White Rock, 13° S. for the Cheverie, and 9° S. for Acadia; Fig 9) within the range of statistical error and possible age differences of these magnetizations. The degree of rotation inferred from comparison to older results from the Avalon terrane [eg., Roy and Park, 1974] is substantiated by new results from the Nova Scotia Avalon terrane (North of the Chedabucto - Cobequid fault) presented in this volume by Scotese et al. This rotation is consistent with Keppie's [1982a] hypothesis of a collision of the Meguma terrane with southern New Brunswick following transcurrent displacement along the Minas geofracture during the Hercynian Orogeny. Although the Triassic opening of the Fundy Basin could be associated with a counter-clockwise rotation, its width is far too narrow (¼100km) to account for the implied twenty degree rotation. We infer from these results that independent motion of the Meguma terrane relative to both North America and the Avalon terrane during the Carboniferous, although Meguma and Avalon may have already been in close association [Keppie, 1983].

Unfortunately, these data do not permit a test of the hypothesis that the Meguma Zone was once closely associated with Gondwanaland. As noted above, the oldest that the White Rock and Cheverie magnetizations can be is Early Carboniferous. During the Early Carboniferous, paleola-

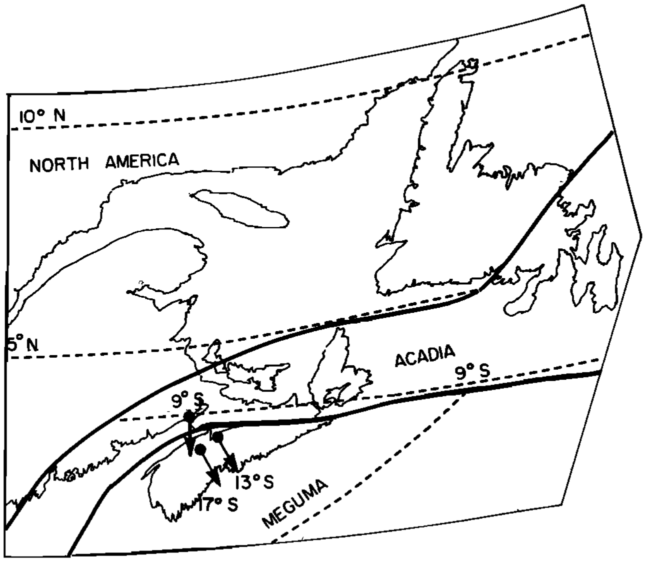

Fig. 9. Results from the Meguma Terrane [this study] plotted on a paleolatitude grid of North America and Acadia for the Early Carboniferous. North America paleolatitudes from Kent and Opdyke [1979]. Acadia result is the Hopewell Group pole [Roy and Park, 1974]. Arrows denote declination, numbers alongside signify paleolatitude. Note the declination (rotational) discrepancy between the White Rock and Cheverie directions and those from both Acadia and North America.

titudes for Gondwana [Kent et al., this volume] are not different enough from Meguma or the Avalon terrane to conclude any major separation exists. A paleomagnetic test of whether Meguma was more closely associated with the northern or southern continents requires poles of Devonian or older age for the Meguma terrane.

In summary, we can consider the Early Carboniferous configuration of the Atlantic-bordering continents and terranes, remembering that paleomagnetic data provide no longitudinal constraint. The Avalon terrane was south of its present position with respect to North America, although it is unlikely that an ocean existed between them. The Meguma terrane was located at about the same latitude as the Avalon terrane, perhaps quite nearby as suggested by sedimentological data [Keppie, 1982a], but not necessarily moving together with Avalon as a single plate. The northern margin of Gondwana (including Meguma?) was at a similar latitude and moving northward. During late-early to early-late Carboniferous time, Avalon and Meguma moved northward with respect to North America, probably in response to the impingement of Gondwana as suggested by Lefort and Van der Voo [1981]. During the final throes of the Alleghanian - Hercynian collision, the Meguma terrane rotated some twenty degrees counter-clockwise with respect to Avalonia and North America. The Carboniferous basins of the Maritime provinces may have formed and deformed in response to these tectonic motions. It seems unlikely that the Meguma terrane was internal to a larger Armorica plate as proposed by Van der Voo and Scotese [1981] considering this evidence for its independent motion, although it may yet prove to have an origin in close association with some part of Gondwanaland.

Acknowledgments. This study was funded by National Science Foundation grant EAR 80-07748. The manuscript was reviewed by G. Bond, C. Scotese, and L. Tauxe. Field assistance provided by S. Coughlin and C. Kent, laboratory assistance by D. Lafferty. Lamont-Doherty Geological Observatory contribution #3509.

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