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Paleomagnetism of the Pennington Mountain terrane: A near-Laurentian back arc basin in the Maine Appalachians

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Abstract. Paleomagnetic studies of volcanic terranes in the Appalachians provide quantitative data on the Ordovician paleogeography of the Iapetus ocean. New paleomagnetic results from submarine volcanics of the Middle to Late Ordovician Winterville Formation of Maine further constrain the evolution of Iapetus. Ten sites yield a tilt corrected direction of D/I = 327/-21 (α_{95} = 9.3, k = 27.9); the corresponding paleomagnetic pole calculated for the average site location (46.8°N, 291.3°E) is located at 26°N, 148°E (d_p = 5°, d_m = 10°, A_{95}=7.7). A Silurian conglomerate (Frenchville Formation) test is inconclusive due to a strong present-day field overprint which obscures any primary remanence. The presence of a positive tilt test, however, supports the conclusion that the characteristic magnetization of the Winterville Formation is a prefolding, primary magnetization. An Ordovician paleolatitude of 11 ± 5° for the Pennington Mountain terrane of northern Maine is indistinguishable from that of the Laurentian margin (15-20°) during the Middle to Late Ordovician. The paleolatitude of the Pennington Mountain terrane is also similar to, but slightly more equatorial than that of the previously studied Bluffer Pond Formation of the nearby Munsungun terrane (18 ± 9°). We conclude that the Ordovician Pennington Mountain and Munsungun volcanic terranes of Maine were formed and acquired their characteristic magnetization near the Laurentian margin. The paleolatitudes of these terranes are also similar to that obtained from the Stacyville volcanics of the more outboard Lunksoos terrane (20 ± 8°), but they contrast strongly with the Ordovician Miramichi terrane of northern New Brunswick that yielded a paleolatitude of 51° (+ 21,-16°). These results from Maine support the presence of one or more backarc basins adjacent to the Laurentian margin during the Middle to Late Ordovician.

Introduction

Paleomagnetic evidence supports the model of a wide Iapetus ocean separating Avalon from Laurentia during the Early Ordovician [*Scotese and McKerrow*, 1991; *Channell et al.*, 1992; *McCabe et al.*, 1992; *Van der Voo*, 1993], which had narrowed to within the resolution limit of paleomagnetic data by the Middle Silurian [*Johnson and Van der Voo*, 1990; *van der Pluijm et al.*, 1990]. This is in agreement with biogeographic patterns that are explained by narrowing of the Iapetus Ocean as Avalon approached the Laurentian margin [e.g. *Boucot*, 1993]. This closure resulted in the preservation of exotic terranes within the Central Mobile Belt (CMB) of the northern Appalachians as suggested by *Williams and Hatcher* [1983], *Zen* [1983], and *Keppie* [1985, 1989].

Observations of faunal provinciality within the CMB led *Neuman* [1984] to create a qualitative paleogeographic map of oceanic islands within the Iapetus Ocean. Our study of the Winterville Formation was undertaken to test this paleogeography by determining the paleolatitude of the Pennington Mountain terrane and by comparing it with the paleolatitudes of the Laurentian craton and the Avalon microcontinent, and with paleolatitudes determined from other previously studied Ordovician volcanic terranes within the CMB of the northern Appalachians.

Previous paleomagnetic studies of early Paleozoic terranes in Maine include those of the Jim Pond Formation of the Boil Mountain ophiolite, the Stacyville volcanics of the Lunksoos terrane, and the Bluffer Pond Formation of the Munsungun terrane. The Jim Pond Formation retains no primary magnetization as it appears to have been completely remagnetized [*Lombard et al.*, 1991], while the Stacyville volcanics may retain a primary remanence of Middle Ordovician age or may have been remagnetized during the Late Ordovician [*Wellensiek et al.*, 1990]. The Bluffer Pond Formation retains a primary magnetization of early-Late Ordovician age as demonstrated by a positive tilt test [*Potts et al.*, 1993].

Geologic Setting

Three major tectonostratigraphic zones may be distinguished in the northern Appalachians of Maine [e.g., *Osberg*, 1978; *Ayuso*, 1986; *Ludman*, 1986; *Unger et al.*, 1987; *van der Pluijm and van Staal*, 1988; *Zartman*, 1988; *Boone and Boudette*, 1989; *Spencer et al.*, 1989; *Stewart*, 1989; *Ayuso and Bevier*, 1991]. Although the basement is most likely decoupled from the cover of the orogen, most geophysical, geochemical, structural, and stratigraphic observations support this threefold subdivision for the basement blocks as well as the supracrustal rocks. In this paper we will use the following three major tectonostratigraphic subdivisions for the Appalachians in Maine: the North American

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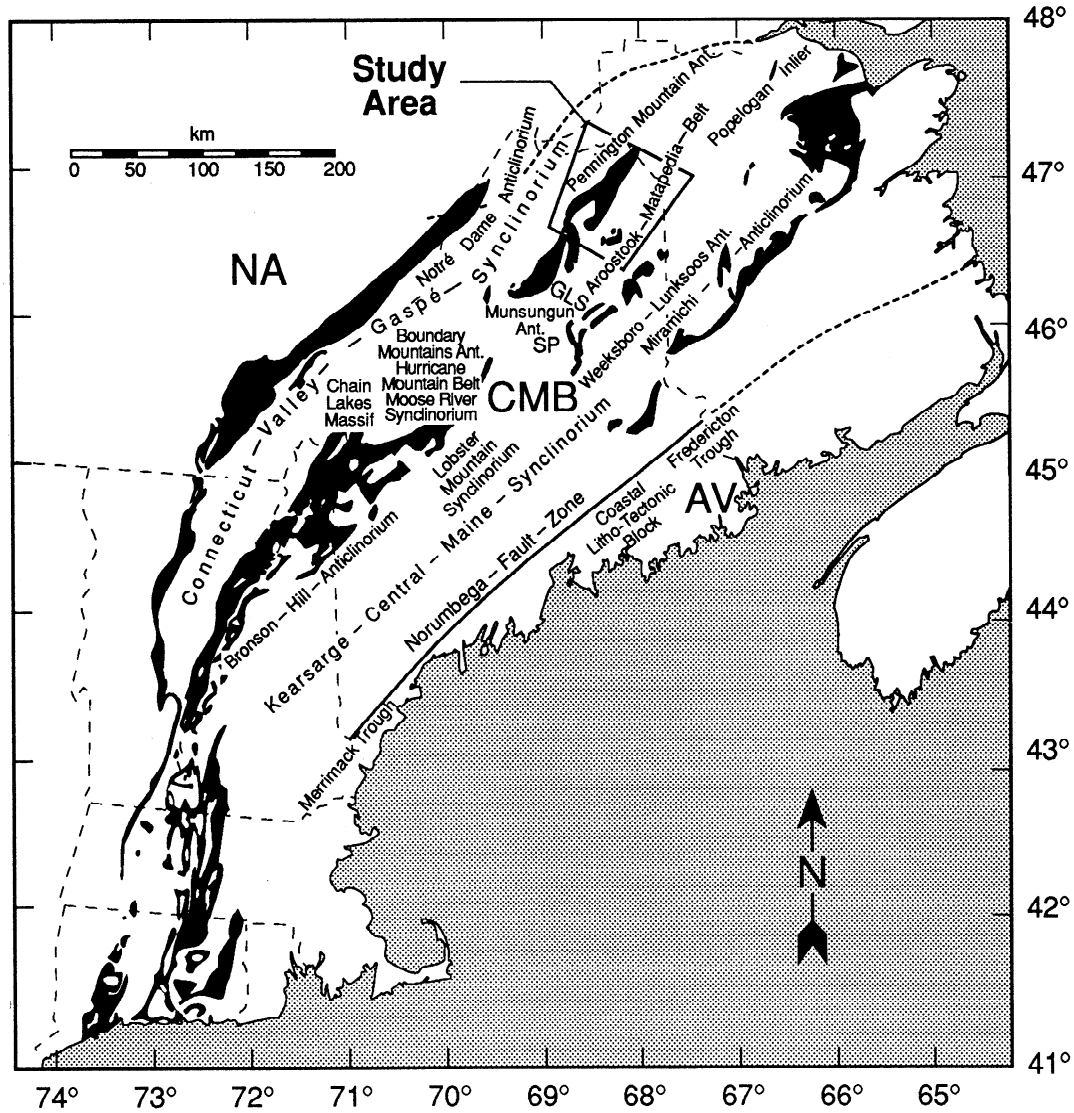

Figure 1. Major tectonostratigraphic subdivisions and terranes of the northern mainland Appalachian Mountains, including early Paleozoic volcanic rocks and associated marine sediments within the Central Mobile Belt (solid) [after *Williams*, 1978; *Osberg et al.*, 1985]. Abbreviations are: NA, North American Margin (Humber Zone); CMB, Central Mobile Belt; AV, Avalon Terrane; and SP and GLS are Saddle Pond and Grand Lake Seboeis inliers, respectively.

margin (Humber Zone), the coastal lithotectonic volcanic zone (Avalon/Acadia), and the intervening Central Mobile Belt (CMB) as shown in Figure 1. The Humber Zone was the Laurentian (northern) margin of Iapetus, the Avalon Zone was part of the Avalonian microcontinent (southern) margin, and a variety of tectonic elements, inferred to be the remains of Iapetus, are preserved within the Central Mobile Belt.

The CMB of Maine includes several major structural elements (Figure 1); these include the Connecticut Valley-Gaspe Synclinorium, the Boundary Mountains anticlinorium and Chain Lakes massif which are adjoined to the Hurricane Mountain belt [*Boone and Boudette*, 1989], the Munsungun and Pennington Mountain anticlinoria [*Roy and Mencher*, 1976], the Moose River synclinorium, the Lobster Mountain anticlinorium, the Aroostook Matapedia belt [*Roy and Mencher*, 1976], the Weeksboro-Lunksoos terrane, the northern extension of the Bronson Hill anticlinorium, the Kearsarge-Central Maine synclinorium (Merrimack synclinorium/trough), the Miramichi terrane, and the Fredericton trough [*Ludman et al.*, 1993]. Many additional names for these elements have been proposed [e.g.: *Boone and Boudette*, 1989; *Ludman et al.*, 1993; *Rast and Skehan*, 1993]. For instance, the coastal lithotectonic volcanic zone (Avalon/Acadia) is itself a composite terrane and has been subdivided into the Ellsworth, Isleboro-Rockport, Benner Hill, and Saint Croix belts [e.g., *Berry and Osberg*, 1989; *Rast and Skehan*, 1993]. Avalon also encompasses a portion of the Fredericton trough [*Ludman et al.*, 1993]. The CMB has also been referred to as the north central Maine belt (NCMB) [*Rast and Skehan*, 1993], which encompasses the Ordovician volcanic terranes of Maine, including the Munsungun and Pennington Mountain anticlinoria.

The Pennington Mountain terrane is bounded on the northwest by the Connecticut Valley-Gaspe synclinorium and on the east and south by the Aroostook-Matapedia belt; both are dominantly composed of sedimentary rocks belonging to the Devonian Seboomook Group. The Winterville Formation may be a lithological correlative of the Bluffer Pond Formation to the southwest and the Stacyville volcanics of the Lunksoos terrane as

well as the Ireland Pond volcanics of the Saddle Pond and Scraggly Lake inliers to the south (see Figure 1). In a possible collage of exotic terranes, such lithotectonic correlations may be misleading, however, as pointed out by *Hibbard and Hall* [1993].

The volcanics of the Munsungun and Pennington Mountain anticlinoria as well as the Stacyville volcanics all appear to be of Middle to early Late Ordovician age [*Hall*, 1970; *Neuman*, 1984; *Riva and Malo*, 1988; *Berry and Osberg*, 1989]. These age estimates are based upon graptolites and brachiopods in associated sedimentary rocks. The age constraints for these volcanics, however, lack precision. Of these, the Stacyville volcanics (Lunksoos terrane) have the best age control. Assuming they are not in tectonic contact with the overlying unit, they are no younger than Late Ordovician (Caradocian) which is the age of the graptolites and conodonts in the overlying Wassataquoik chert [*Neuman*, 1984]. The volcanics of the Lobster Mountain Terrane are also of similar age and, although no paleomagnetic data exist, their geochemical signature is similar to that of the aforementioned volcanics [*Winchester and van Staal*, 1994].

The Winterville Formation is located within the Pennington Mountain terrane (Figure 2). It is of Middle to early-Late Ordovician age (graptolite zones 11 - 15) [*Pavlides*, 1976; *Roy and Mencher*, 1976; *Neuman*, 1984; *Riva and Malo*, 1988]. The Pennington Mountain terrane consists of three Ordovician units. From west to east these units are the Winterville Formation, the Madawaska Lake Formation, and the Lower Carys Mills Formation. The Winterville Formation is composed of volcanic, graywacke and slate facies, while the Madawaska Lake Formation is composed of slates and graywackes. The Lower Carys Mills Formation consists of slate, limestone and graywacke facies [*Roy and Mencher*, 1976]. These Ordovician units are in turn overlain by the Frenchville Formation, which is an early Silurian (late Llandoverian to early Ludlovian) sedimentary unit with a thickness of between 1050 and 1150 m. It is composed of a sandstone member, a slate facies, and a conglomerate member. The conglomerate member is at least 200 m thick and is of late Llandoverian age [*Roy and Mencher*, 1976]. This member shows no penetrative deformation; its only fabric is that of elongate pebbles within bedding.

The Winterville Formation comprises at least 1500 m of mafic pillow lavas interlayered with graptolitic shales/slates, cherts, and water-laid tuffs [*Roy and Mencher*, 1976]. It has been observed by us as well as by others [*Hall*, 1969; *Coombs et al.*, 1970; *Richter and Roy*, 1976] that the regional cleavage does not cut the Winterville Formation, most likely owing to its more massive nature relative to the surrounding units of the Pennington Mountain terrane. This regional cleavage is probably of Devonian age because it is subparallel to the axial surfaces of major folds in both Silurian and Devonian units [*Hall*, 1970]. There is only one mesoscopic cleavage present in the area, and this is parallel to the widely observed northeasterly trending "Acadian" deformation in Maine [*Hall*, 1970]. Thus it is most likely that the folding in the Pennington Mountain terrane also occurred in the Devonian [*Coombs et al.*, 1970]. The only evidence for younger deformational events consists of minor northwesterly trending folds in some Siluro-Devonian rocks that postdate early Acadian structures and are most likely late Acadian features [*Hall*, 1970]. In northern Maine there is little evidence for widespread late Paleozoic (Alleghanian) or younger deformation, although the folding of the Devonian Mapleton Formation could be Alleghanian (*J. Hibbard*, personal communication, 1994).

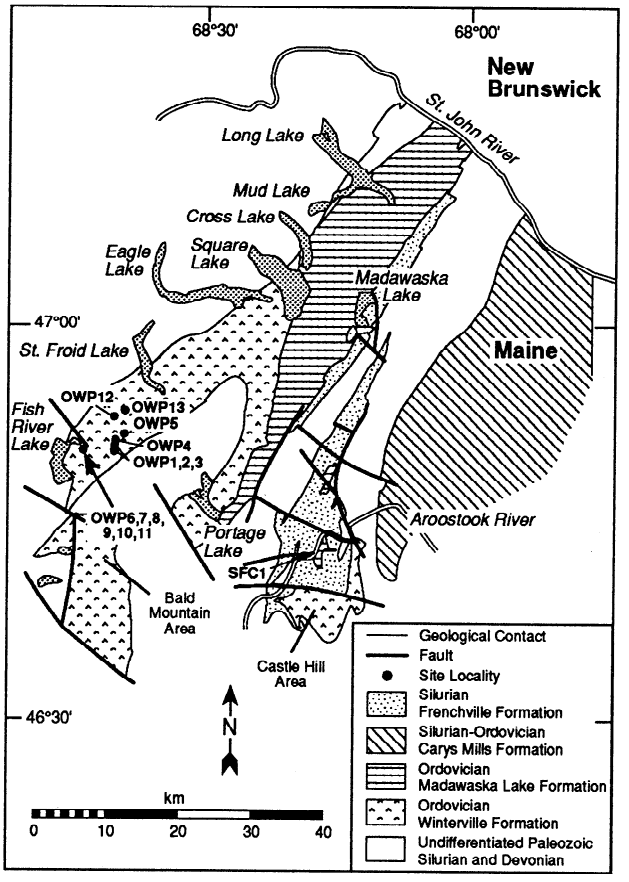

Figure 2. Simplified geologic map of the Pennington Mountain terrane and location of the paleomagnetic sampling sites within the Ordovician age Winterville Formation and Silurian age Frenchville Formation. The site locality numbers correspond to those in Table 1. Map is modified from *Osberg et al.* [1985] and *Roy and Mencher* [1976].

Mineralogical observations suggest that the Winterville Formation underwent common seafloor alteration (spilitization) and then later low grade (zeolite facies) regional metamorphism [*Walker*, 1991; *Murphy*, 1992]. Seafloor alteration does not necessarily result in remagnetization as it is likely to create a chemical remanent magnetization (CRM) that has the same direction as the original thermoremanent magnetization (TRM) [*Smith and Banerjee*, 1986; *Beske-Diehl*, 1990]. Seafloor alteration is most intense near ancient hydrothermal vents [*Giovannini and Walker*, 1994], where the presence of massive sulfide deposition is ubiquitous [*Fyffe et al.*, 1990]. Paleomagnetic sampling sites were, therefore, chosen so as to avoid these areas. Because the Winterville Formation has not experienced metamorphism higher than subgreenschist facies (prehnite-pumpellyite facies) [*Coombs et al.*, 1970; *Richter and Roy*, 1976], the primary remanence is unlikely to have been thermally reset [*Pullaiah et al.*, 1975].

Field Methods

Paleohorizontal was determined from both pillows and interbedded and overlying sediments. Most sites are steeply dipping, but sites with differing strike and dip angles could be obtained in order to perform a fold test. The elongation of

pillows is parallel to bedding, and the attitudes of multiple pillows averaged over a single site yield a mean strike and dip for that specific site. The typical tucked bottoms and rounded tops of pillows provide younging directions. Where bedding is obtained from both the pillows and overlying sediments, it agrees closely, and it is estimated that these methods are accurate well within 10° of paleohorizontal. Errors in estimating strike and dip for individual sites are random, and given sufficient sites, they should average out in the calculation of the tilt-corrected formation mean. Structural attitude is determined independently at each site, and therefore there should be no systematic error.

During the summers of 1989, 1990, and 1991, over 100 samples from 13 sites within the Ordovician Winterville Formation and one site within conglomerate of the Silurian Frenchville Formation were collected for paleomagnetic study. At least seven samples were collected per site and generally, at least two samples were collected from each pillow. Samples were spread throughout the pillows from both rims and centers. Most samples were drilled and oriented in the field with a portable gas-powered core drill, magnetic compass, and clinometer. Additional samples were collected as oriented blocks and drilled in the laboratory. The low magnetic intensities of these rocks do not significantly affect the magnetic compass readings, as demonstrated in the field by the lack of deflection of a magnetic compass needle.

Laboratory Methods

The cores were cut into standard size paleomagnetic samples (2.25 cm x 2.5 cm) and stored within a magnetically shielded room at the University of Michigan Paleomagnetic Laboratory. Natural remanent magnetization (NRM) directions were measured on either a ScT two-axis superconducting rock magnetometer or a Schonstedt SSM-1A spinner magnetometer. Alternating field (AF) demagnetizations of the NRM were performed with either a Schonstedt GSD-1 single-axis AF demagnetizer or a Sapphire Instruments SI-4 AF demagnetizer. Thermal demagnetization was conducted using a Schonstedt TSD-1 furnace, and temperatures have been recalculated based upon a 1991 recalibration. Alternating field demagnetization of pilot samples failed to resolve multiple components of remanence and left a significant high-coercivity portion of the NRM intensity even after applied fields of ~100 mT. Therefore we have primarily used thermal demagnetization in this study. Thermal demagnetization from room temperature (NRM) to approximately 600°C included between 15 and 20 steps.

Principal component analysis [*Kirschvink*, 1980] was used to fit lines and planes (great circles) to the components identified by inspection of orthogonal vector diagrams [*Zijderveld*, 1967]. At least three, and on average four, points were used to calculate each segment, and only lines and planes with mean angular deviations (MADs) of 15° or less were used. In addition the method of *Bailey and Halls* [1984] was used to calculate a site mean for site Owp10 by combining stable end point and great circle data [*Halls*, 1976, 1978] from individual samples within a single site. Site means and a formation mean are presented with their respective α_{95} cones of confidence and precision parameter *k* [*Fisher*, 1953].

Rock magnetic experiments involved additional equipment, including a water-cooled Varian electromagnet with a peak field of 1.4 T for saturation isothermal remanent magnetization (SIRM) acquisition experiments and a Sapphire Instruments SI-4 AF demagnetizer for anhysteretic remanent magnetization (ARM) field acquisition (0.05 mT d.c. bias field applied over an AF window between 110 mT and 10 mT) and for AF demagnetization of SIRM and ARM. Thermal demagnetization experiments of three axis isothermal remanent magnetization (IRM) [*Lowrie*, 1990] were conducted on samples using field strengths of 1.4 T, 0.4 T, and 0.1 T along three mutually orthogonal axes.

Results

Characteristic Directions

A partial viscous overprint of recent origin (present-day Earth field direction) is removed at low temperatures in many of the samples. The high temperature characteristic direction is then removed between 490° and 595°C (Figure 3). Most samples carry the characteristic magnetization between 520° and 570°C (Figure 3). Representative orthogonal vector end point diagrams of thermal demagnetization (in stratigraphic coordinates) are presented in Figure 3 (sites Owp2, Owp6, Owp8, and Owp9). The characteristic direction has been isolated in 12 of 13 sites, but in two of the sites (Owp12 and Owp13; excluded from the mean) only a few samples exhibit the characteristic direction (Table 1). The rejected samples display only the present-day field direction. In general, the rock magnetic properties of the Winterville Formation are very similar to those previously presented for the Bluffer Pond formation of the Munsungun terrane [*Potts et al.*, 1993]. We conclude that magnetite is the carrier of the characteristic remanent magnetization as demonstrated by unblocking temperature spectra and IRM acquisition experiments as well as AF demagnetization of SIRM (Figure 4).

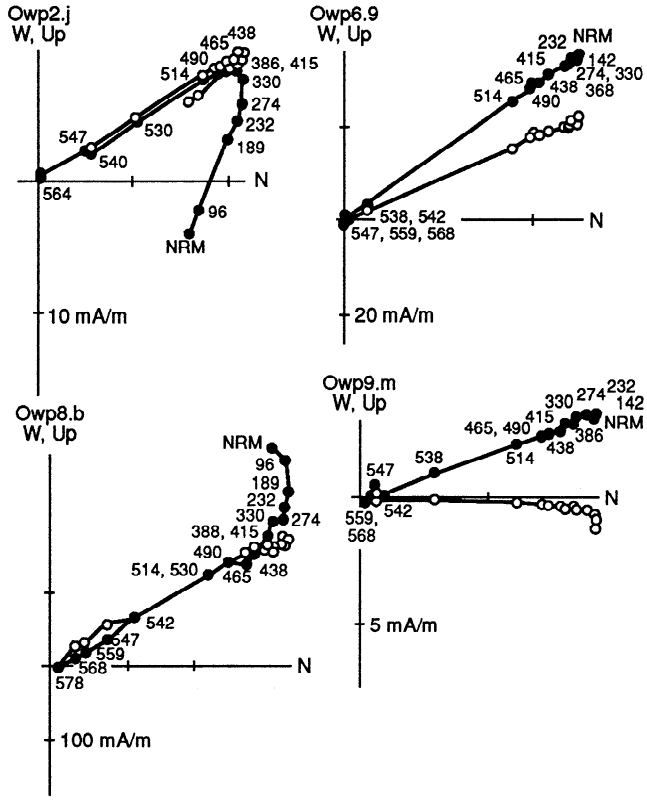

Figure 3. Orthogonal vector end point diagrams for thermal demagnetization of samples from sites Owp2, Owp6, Owp8, and Owp9 in tilt-corrected coordinates. Solid (open) symbols are projections of the horizontal (vertical) component.

Table 1. Site Mean Directions of the Characteristic Component for the Winterville Formation, Maine

Site	Strike/Dip (deg)	nd/ng/N	D/I (In Situ)	D/I (Tilt Corrected)	k	α_{95}
OWP1	35/90	8/0/10	86/-53	329/-27	42.1	8.6
OWP2	35/90	6/0/8	93/-62	320/-23	77.8	7.6
OWP3	40/90	13/0/13	107/-56	324/-31	42.1	6.5
OWP4	40/90	12/0/12	110/-60	320/-27	81.9	4.8
OWP5*	40/90	0/0/10				
OWP6	215/90	9/0/9	332/71	313/-16	37.4	8.5
OWP7	215/90	8/0/8	4/69	323/-15	3.9	32.1
OWP8	215/75	9/0/9	337/46	328/-21	94.8	5.3
OWP9	10/30	4/0/11	343/-18	338/-3	108.2	8.9
OWP10	330/15	4/2/14	353/2	353/-3	16.2	20.1
OWP11	215/90	7/0/7	328/51	320/-35	3.0	42.6
OWP12*	260/20	2/0/9	315/-3	312/-19		
OWP13*	260/20	1/0/11	339/2	338/-17		
SFC1+	15/51	8/0/8	89/79	101/28	6.0	25.0
Formation mean						
In situ		10	16/-5		1.4	74.0
Tilt corrected		10		327/-21	27.9	9.3

When looking in the direction of strike, the dip is to the right; nd is, number of stable endpoint directions; ng is, number of great circles; N is number of samples thermally demagnetized; D/I is, declination and inclination of site mean directions; k is estimate of precision parameter [*Fisher*, 1953]; α_{95} is radius of cone of confidence [*Fisher*, 1953].

* Sites were not used to calculate the Winterville Formation mean direction due to an inadequate number of acceptable samples.

+ Site SFC1 (Silurian Frenchville Conglomerate) is not used to calculate the Winterville Formation mean direction.

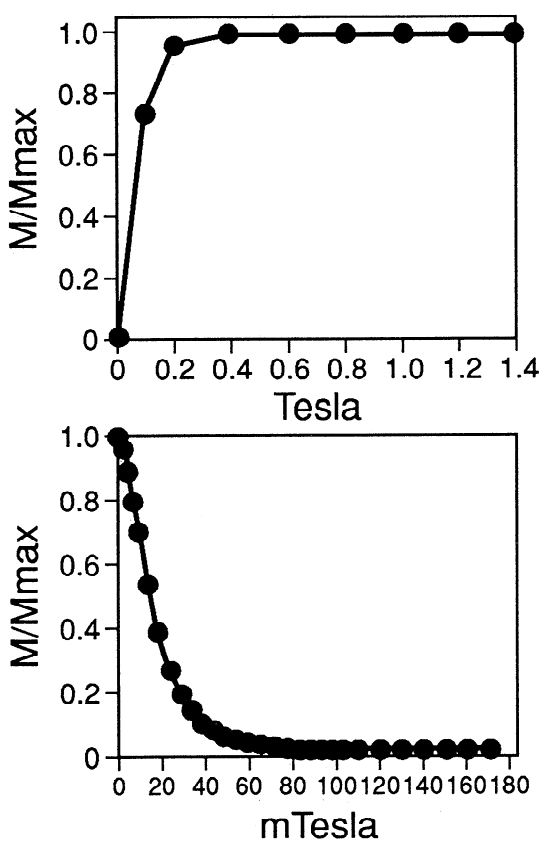

Figure 4. Saturation isothermal remanent magnetization (IRM) acquisition and AF demagnetization of saturation IRM for sample Owp6.4, showing characteristics of magnetite.

Conglomerate Test

The conglomerate test, obtained on pebbles derived from the Winterville Formation and deposited in the Silurian Frenchville Formation, is inconclusive. The equal-area stereograms (Figure 5) show high-temperature directions between 440° and 560°C, above which the directional behavior becomes unstable. The mean direction in geographic coordinates is D/I = 089/79, (α_{95} = 25, k = 6), while the mean direction after tilt correction is D/I = 101/28. Because the in situ direction is similar to the NRM direction (steep and down) (Figure 5a) it appears that a strong present-day field overprint dominates the remanence removed during thermal demagnetization. The distribution of characteristic directions is not random as it fails the conglomerate test of *Watson* [1956] and *Irving* [1964], ($R = 6.84 > R_O$ = 4.48). The mean direction of the conglomerate, however, does differ from the stable direction observed in the underlying Ordovician volcanics of the Winterville Formation, and the corresponding paleomagnetic pole (10°N, 6°E) does not resemble younger North American paleomagnetic poles. So, although the test is not positive, evidence for a consistent widespread regional remagnetization affecting both Ordovician and Silurian units is lacking.

Tilt Test

Upon tilt correction the site mean directions cluster significantly better. The mean direction in geographic coordinates is D/I = 16/-5 (α_{95} = 74.0, k = 1.4), while the mean direction after tilt correction is D/I = 327/-21 (α_{95} = 9.3, k = 27.9); site means are shown in equal area projections (Figure 6). This characteristic magnetization direction passes the tectonic

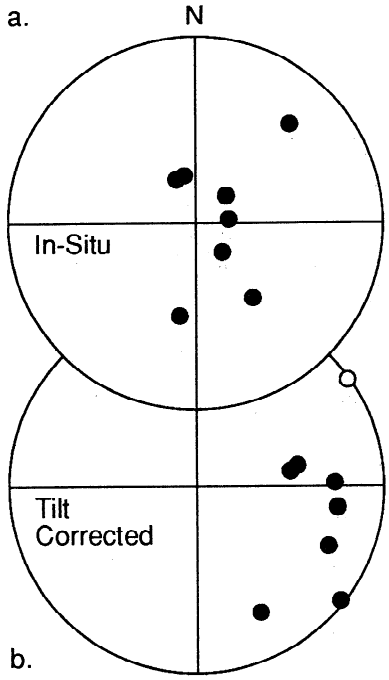

Figure 5. Equal-area stereograms of (a) in situ and (b) tilt corrected sample directions from the conglomerate of the Silurian Frenchville Formation. Solid (open) symbols are projections on the lower (upper) hemisphere.

correlation fold test at the 99% confidence level [*McFadden*, 1990] (SCOS = 7.005 > $SCOS_{99\%}$ = 5.120). The large decrease in the confidence ellipse (α_{95}) and the large increase in the estimate of the precision parameter (k) also indicate that this is a prefolding magnetization. The characteristic magnetization does

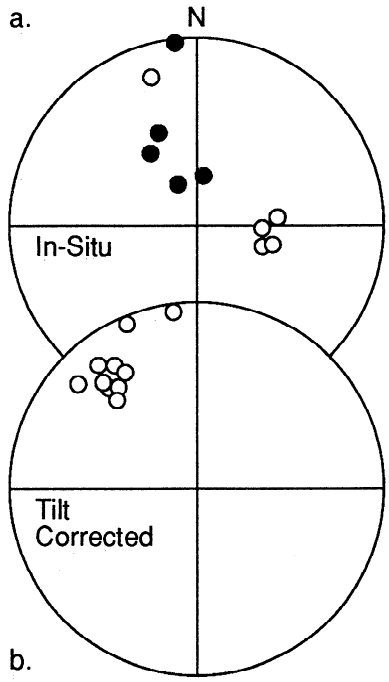

Figure 6. Equal-area stereograms of (a) in situ and (b) tilt corrected site mean directions from the Ordovician Winterville Formation of northern Maine. Solid (open) symbols are projections on the lower (upper) hemisphere.

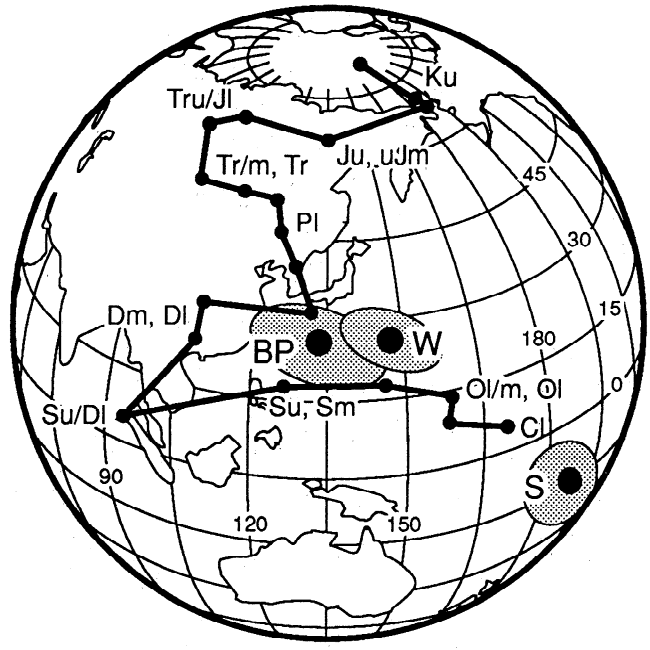

Figure 7. North American apparent polar wander path composed of mean paleomagnetic poles with Q ≥ 3 [after *Van der Voo*, 1990]. Pole from this study is plotted as a solid circle (labeled W) with its respective confidence ellipse. Also plotted are poles from other Ordovician terranes in Maine. BP is Bluffer Pond Formation of the Munsungun terrane [*Potts et al.*, 1993]; S is Stacyville volcanics of the Lunksoos composite terrane [*Wellensiek et al.*, 1990].

not appear to be of synfolding age because the maximum value of k and minimum value of SCOS are not obtained until the beds are completely restored to original horizontality. Thus the magnetization was acquired prior to Siluro-Devonian folding (the Acadian orogeny).

As can be seen in the stereogram (Figure 6), all of the site mean directions are upward. This is a normal polarity direction given the generally accepted southern hemisphere paleogeography of Iapetus and is the expected polarity for this age [*Trench et al.*, 1991]. These directions and this polarity, and thus the resulting paleomagnetic pole position, also agree well with the results previously reported from the correlative Bluffer Pond Formation of the Munsungun terrane [*Potts et al.*, 1993]. The corresponding paleomagnetic pole for the Winterville volcanics is 26°N, 148°E (A_{95}=7.7o, d_p = 5, d_m = 10), which plots close to the expected mean mid-late Ordovician paleomagnetic pole of Laurentia [*Van der Voo*, 1990] (Figure 7).

Although the Winterville Formation is estimated to have a thickness of about 1.5 km, it is not easy to determine how our sampling sites are distributed stratigraphically, because of a lack of continuous outcrop. This is important for the consideration whether secular variation has been sufficiently averaged in our result. At Fish River Falls, where many of our sites are located, we estimate that we have sampled at least 100 m of the volcanic pile, containing several individual flows. The absence of information on the amount of time elapsed between successive eruptions, however, makes claims for adequate sampling impossible.

Finally, the steep tilts for the individual sites may lead, upon tilt correction, to apparent rotations (i.e., declination variation) when folds are plunging. However, inclinations and hence paleolatitudes are not affected by this.

Discussion and Tectonic Interpretation

On the basis of the positive fold test, the observed magnetic polarity, the low metamorphic grade of the Winterville Formation, and the directional agreement with the correlative Bluffer Pond Formation we conclude that the characteristic magnetization is primary. An alternative interpretation involves the possibility of remagnetization at the Laurentian margin after the formation of the volcanics in the Middle to Late Ordovician but before the Siluro-Devonian Acadian folding of these northern Maine units. This interpretation, however, seems unlikely as the Laurentian margin moved farther south (25-30°) during the earliest Silurian thus resulting in an overlap problem with the volcanic units that have the lower paleolatitudes (11-20°) typical of the Middle to Late Ordovician.

Existing paleogeographic interpretations based on the stratigraphy of the Pennington Mountain terrane are qualitative and are no more specific than that these units were deposited in relatively deep water and relatively far from cratonal sources [*Roy and Mencher*, 1976]. Geochemical studies of relict pyroxene compositions, immobile trace elements, and large ion lithophile elements (LILE) indicate a back arc basin/rift environment [*Hynes*, 1976, 1981; *Winchester and van Staal*, 1994]. Paleontologic studies of Scoto-Appalachian shelly fossil faunas with cosmopolitan affinities suggest that Middle to Late Ordovician volcanic terranes of northern Maine have a near-Laurentian location [*Neuman*, 1984]. Our result quantitatively constrains the paleolatitude for this terrane, which we compare with those from Laurentia and the other Iapetan terranes. Contrary to recent claims [*Winchester and van Staal*, 1994], the paleolatitudes determined from paleomagnetic studies are consistent with both geochemical and paleontologic data.

As shown in Table 2 all three of the Ordovician volcanic terranes of Maine have similar paleolatitudes (the Munsungun terrane, 18 $\pm$ 9°; the Lunksoos terrane, 20 $\pm$ 8° [*Potts et al.*, 1993; *Wellensiek et al.*, 1990] and the Pennington Mountain terrane, 11 $\pm$ 5°) . They also have similar geochemical signatures [*Winchester and van Staal*, 1994], which suggests that they acquired their characteristic magnetizations in similar environments. Their low paleolatitudes indicate that the Munsungun and Pennington Mountain terranes were most likely formed near the Laurentian margin (15-20°). The Stacyville volcanics of the Lunksoos composite terrane also appear to have acquired their characteristic magnetization near the Laurentian margin, but this magnetization may either be primary (Middle? Ordovician) or a late Ordovician remagnetization as no field tests exist to further constrain the age of the characteristic magnetization. If the Stacyville volcanics are as young as Late Ordovician (Caradocian) [*Neuman*, 1984], their paleolatitude is not inconsistent with a primary age of magnetization. A contrasting history for the Lunksoos terrane, relative to that of the Pennington Mountain and Munsungun terranes, is suggested by the paleomagnetic pole from the Stacyville volcanics which is distinct from those of the Winterville and Bluffer Pond Formations (Figure 7). This difference is due to later relative tectonic rotation of the Lunksoos terrane during final accretion and/or early Acadian shear [*Hibbard and Hall*, 1993].

The paleogeography of northern Maine contrasts with that of northern New Brunswick, where the Tetagouche Group represents a continental rift environment and the Fournier Group the remains of an oceanic back arc basin that are separated by a belt of blueschist [*van Staal*, 1994]. The Tetagouche group of the Miramichi terrane was formed at a considerable distance from the Laurentian margin [*Liss et al.*, 1993], yielding a paleolatitude of 53°S (+ 21, -16°) for the rift and back-arc basin environment of the Miramichi terrane, thus placing it at the Avalonian margin of Iapetus.

Given that the Munsungun and Pennington Mountain terranes may have formed in a back arc basin near Laurentia, we may speculate as to the identity of the associated magmatic arc. Although there are no obvious candidates for the arc in northern Maine [*Zen*, 1983], it may have been discontinuous along strike. Good candidates for the arc are located both to the south and to the north of Maine. The Bronson Hill belt (anticlinorium) is located to the south and slightly outboard, and extends from Long Island Sound through central Massachusetts and New Hampshire into southwestern Maine [*Naylor*, 1968; *Foland and Loiselle*, 1981]. This belt has been proposed as the Taconic arc responsible for the Taconic orogeny [*Robinson and Hall*, 1980; *Rodgers*, 1981] and is composed of the appropriate felsic plutonic core rocks and overlying Ordovician volcanics [*Naylor*, 1968]. Furthermore, the plutonic rocks of this calc-alkaline magmatic arc were formed at least partly on continental crust. The identity of this crust remains unknown, but *Tucker and Robinson* [1990] have suggested it may have been a sliver of continental crust rifted from Laurentia that later rejoined in a collision during the Early Silurian. The metamorphosed plutonic core rocks and overlying felsic volcanics are also of the appropriate age as they have been dated by U-Pb geochronology as Late Ordovician (454-442 +3,-2 Ma); moreover, there is no evidence in New England that the Bronson Hill magmatic arc was active prior to the late Llanvirnian (~465 Ma) [*Tucker and Robinson*, 1990]. The overlying volcanic units (Partridge Formation and Ammonoosuc volcanics), although coeval with the plutonic core rocks, have geochemical signatures that indicate they were most likely formed in a back arc basin and later structurally emplaced upon the rocks of the Bronson Hill anticlinorium [*Hollocher*, 1993]. Thus the volcanics of the Partridge Formation and the Ammonoosuc volcanics are possible along strike equivalents of the volcanics of the Pennington Mountain and Munsungun terranes.

Along strike to the north of the Pennington Mountain and Munsungun terranes, a magmatic arc (Popelogan arc) correlative with the Bronson Hill arc has been identified in northern New

Table 2. Paleolatitudes of Ordovician Terranes in the Central Mobile Belt, Maine and New Brunswick Appalachians

Unit	Paleomagnetic Pole	dp, dm	Paleolatitude	Reference
Winterville Formation	26°N, 148°E	5°, 10°	11 $\pm$ 5°	This study
Bluffer Pond Formation	26°N, 134°E	7°, 13°	18 $\pm$ 7°	*Potts et al.* [1993]
Stacyville volcanics	14°S, 188°E	8°, 14°	20 $\pm$ 8°	*Wellensiek et al.* [1990]
Tetagouche Group	52°S, 172°E	19°, 22°	51 +21, -16°	*Liss et al.* [1993]

All paleolatitudes have been calculated for northern Maine; dp and dm are semiaxes of confidence ellipse about the paleomagnetic pole.

Brunswick and the Gaspe of Quebec [*van Staal et al.*, 1991], which is located to the north of and inboard from the Miramichi terrane. This arc comprises the Duncans Brook and Lincour basalts [*Winchester et al.*, 1992], andesites of the Goulette Brook Formation in the Popelogan inlier of New Brunswick, and the dacite tuffs of the Arsenault Formation in Quebec [*van Staal et al.*, 1991]. In southern New Brunswick remnants of this arc may include the volcanic rocks of the Meductic-Woodstock area [*van Staal et al.*, 1991].

In conclusion, the Ordovician Winterville Formation of the Pennington Mountain terrane of northern Maine probably acquired its characteristic magnetization in a back-arc basin environment that was located at the Laurentian margin. These results are similar to those from the Bluffer Pond Formation of the Munsungun Anticlinorium [*Potts et al.*, 1993] and to those from the Stacyville volcanics of the Weeksboro-Lunksoos Terrane [*Wellensiek et al.*, 1990] and are supported by geochemical and paleontological data.

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