Paleomagnetic constraints on Siluro-Devonian Laurentian margin tectonics from northern Appalachian volcanics

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Abstract

Paleomagnetic analyses of Silurian mafic volcanics from the overstep sequence of sedimentary and volcanic rocks deposited over the Central Mobile Belt of the northern Appalachians provide insight into the mid-Paleozoic tectonic history of the Laurentian margin. Stepwise thermal demagnetization of the subaerial mafic volcanics of the Ludlovian Fivemile Brook Formation of northwestern Maine reveals two ancient high-temperature, dual-polarity remanences. A tilt-corrected mean direction yields an inclination of 41° (α1 = 3.9°, N = 4 sites) and the magnetization is interpreted as a near-primary magnetization acquired well before the end of Early Devonian deformation. An in situ mean direction (D = 165°, I = 35°, α95 = 6°, k = 65, N = 10 entries from 8 sites), is interpreted as a secondary overprint with a pole (22°S, 306°E) near the Early Carboniferous segment of the North American apparent polar wander path (APWP). Conglomerate and fold tests of the high-temperature characteristic remanence preserved in Wenlockian subaerial mafic volcanics of the Bryant Point Formation and a red bed of the South Charlo Formation, both of the Chaleur Group of northeastern New Brunswick, constrain paleolatitude and deformational age. The inclination-only fold test peaks at 50% unfolding with a mean inclination of −35° (α1 = 8.5°, n = 148). Synfolding acquisition of magnetization is Wenlockian, based on a negative conglomerate test at the base of the section and a positive conglomerate test at the top of the section. Clockwise streaking of site mean directions away from a predominantly northerly declination is consistent with post-middle Wenlockian dextral shear in the Chaleur Bay region. Comparison of a locus of paleomagnetic pole positions with the North American APWP supports a Silurian age of the magnetization of the Chaleur Group. The age and synfolding nature of this remanence furthermore requires that deformation associated with the Acadian orogeny in New Brunswick began by mid-Silurian times. Moreover, inclinations from these units indicate that, within paleomagnetic resolution, there has been no significant latitudinal displacement with respect to stable North America since the Silurian. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Subduction and collisions along the Laurentian margin associated with closure of the ancient Iapetus and Rheic oceans between Laurentia and Avalon, and Avalon and Gondwana, respectively, resulted in the Appalachian orogen (e.g., Wilson, 1966; Dewey, 1969; Bird and Dewey, 1970; McKerrow and Ziegler, 1972; Van der Voo, 1988, 1993). With subduction of the Iapetan sea-floor, tectonic elements such as island arcs were swept up against the margin of Lau-
rentia, followed by Silurian collision of the Avalon microcontinent (e.g., van der Pluijm et al., 1993a). Late Paleozoic closure of the Rheic ocean culminated in the continent–continent collision of Laurussia and Gondwana. The effects of this late Paleozoic Alleghenian orogeny in the northern Appalachians were minimal, so this region provides an optimal setting for examining mid-Paleozoic tectonics.

In the last decade the northern Appalachians have been intensely studied to unravel the details of the closure of the Iapetus ocean. The northern Appalachians have been subdivided into the autochthonous Laurentian margin, the Humber zone; allochthonous elements compressed into the Central Mobile Belt; and the Avalon zone representing an ancient microcontinent with lower Paleozoic Gondwanide affinity (Williams, 1979; Williams and Hatcher, 1983; van der Pluijm and van Staal, 1988) (Fig. 1).

Silurian closure of Iapetus is indicated by paleomagnetic and tectonostratigraphic studies in Newfoundland, as well as sediment dispersal patterns in Britain (Soper and Woodcock, 1990; van der Pluijm et al., 1993a). Agreement between the apparent polar wander paths (APWP) for Laurentia, Avalon, and Baltica support mid-Silurian closure of both the Iapetus ocean, between Laurentia and Avalon and Baltica, and the Tornquist sea, between Avalon and Baltica, and the Tornquist sea, between Avalon and Baltica (Mac Niocaill and Smethurst, 1994). Upper Ordovician to Middle Devonian units in the northern Appalachians are generally bracketed by Taconic and Acadian unconformities (Malo and Bourque, 1993). The Taconic orogenic pulse is associated with island arc accretion; the Silurian Salinic disturbance is associated with Avalonian collision and Iapetan closure; and the Acadian orogeny correlates with Devonian approach of Gondwana to Laurentia (van der Pluijm et al., 1993a; Van der Voo, 1993).

The Silurian and Devonian rocks of the northern Appalachians form part of an overstep sequence deposited over the Central Mobile Belt. Silurian sedimentary rocks form a southeast thickening wedge of shallow marine sedimentary rocks that grade from platformal carbonates in the northwest to central basinal shales and non-marine sandstones in the southeast (Keppie and Dostal, 1994). Silurian sediments were mainly derived from Laurentia to the northwest, whereas Lower Devonian flysch was derived from Avalon to the southeast. The Piscataquis and Tobique volcanic belts cross-cut the general structural trend of the northern Appalachians (Fig. 1). Geochemical characteristics of the volcanics, including the Fivemile Brook Formation and the Chaleur Group of this study, indicate a continental intraplate environment (Keppie and Dostal, 1994). Bedard (1986) recognized that the Siluro-Devonian volcanics of the Gaspé Peninsula should not be directly related to subduction, and suggested a model incorporating a local tensional environment. A few

Fig. 1. Subdivision of the northern Appalachians showing the Humber Zone (Laurentian margin), Central Mobile Belt (vestiges of the Iapetus) and overstep sequence, Avalon Zone (Avalonian microcontinent), and Meguma Zone. Dark areas indicate volcanics of the Piscataquis and Tobique volcanic belts across Maine and New Brunswick–Quebec respectively. Boxes indicate sampling localities of Silurian volcanics of the Fivemile Brook Formation (Sf) and Chaleur Group (Sc).
recent studies suggest that initiation of volcanic activity coincides with a reversal in shear sense along the Laurentian margin, indicating an origin within a pull-apart setting (Dostal et al., 1993; Keppie and Dostal, 1994).

Origin within a pull-apart rift can cause rotation, and transpression can cause translation. Oblique convergence and transpressional motion associated with closure of the Iapetus has the potential for producing large latitudinal displacements along the Laurentian margin: therefore, paleomagnetic study of Silurian units of the northern Appalachians can be used to document the nature and timing of such displacements and rotations. In this context, previous paleomagnetic studies of Newfoundland’s Silurian units have produced conflicting results for coeval units, generating a Silurian paleolatitude controversy. Intermediate inclinations are reported for volcanics from both the Botwood and Springdale groups (Lapointe, 1979; Gales et al., 1989; Potts et al., 1993). Shallow paleomagnetic inclinations are reported for Newfoundland’s King George IV Lake area, and Botwood and Springdale red beds (Buchan and Hodych, 1989, 1992; Potts et al., 1993). Although consistently shallower remanence directions reported for red beds could reflect inclination shallowing (Buchan and Hodych, 1993; Potts et al., 1993; van der Pluijm et al., 1993b), this has been attributed more recently to incompletely isolated characteristic directions incorporated into the mean (Stamatakos et al., 1995). The tectonic significance of these discrepancies prompted us to investigate other northern Appalachian Silurian units. This study examines the paleomagnetism of the Fivemile Brook Formation of northwestern Maine and the Chaleur Group of northeastern New Brunswick.

2. Geologic setting

The Ludlovian Fivemile Brook Formation in northwestern Maine is part of the Piscataquis volcanic belt of the sedimentary and volcanic overstep sequence. Exposed in the northwestern portion of the Connecticut Valley–Gaspé Synclinorium, the Fivemile Brook Formation is structurally part of a homoclinal younging to the southeast (Fig. 2).

Northeast structural trends dominate in northwestern Maine. The northeast–southwest trend of the Connecticut Valley–Gaspé Synclinorium and the Notre Dame Anticlinorium is mimicked by the strike of major structural lines such as the Baie Verte–Brompton Line and the Rocky Mountain Fault. The bedding parallel Rocky Mountain Fault was active during the Middle Devonian and is marked by Devonian flysch thrust over the Upper Silurian Fivemile Brook Formation, connecting with the LaGuadaloupe fault to the southwest (Roy, 1989).

The Upper Silurian Fivemile Brook Formation is part of a package of southeasterly-younging units between the Dead Brook Fault, which was active in the Late Ordovician, and the Middle Devonian Rocky Mountain Fault (Roy, 1989). The lower contact, with Middle Ordovician to Lower Silurian Depot Mountain Formation flysch, is inferred to be disconformable (Roy, 1989) and is associated with a mid-Silurian hiatus from the Salinic disturbance that is well documented above the upper Llandoveryian Point-aux-Trembles Formation to the northeast (Lajoie et al., 1968). The upper contact with Lower to Middle Devonian Seboomook Formation flysch may be gradational (Dubois, 1986; Roy, 1989). The Ludlovian age of the Fivemile Brook Formation is based on corals in crinoidal–coralline limestone at the base of the type section (Boudette et al., 1976).

The Fivemile Brook Formation is 300 to 1800 m thick and composed of interlayered volcanics and shallow water sediments. The majority of flows is subaerial although a few with pillow structures have been reported (Roy, 1982). The igneous members are up to 1000 m thick and include alkali basalt flows and sills as well as pyroclastic rocks and rhyolites interlayered with the basalt. The stratigraphic sequence suggests that Late Silurian volcanism died out while this shallow–water basin evolved into a deep-water basin in the Devonian (Roy, 1989).

Occurring within the Chaleur Bay Synclinorium, the Chaleur Group is part of the Tobique volcanic belt of the overstep sequence deposited over the Central Mobile Belt (Fig. 1). Chaleur Group formation names differ across the bay between Quebec and New Brunswick and have evolved as workers have studied the stratigraphy in greater detail (Alcock, 1935; Greiner, 1966, 1967; Noble, 1976; Lee and Noble, 1977; Irrinki, 1990; Walker and McCutcheon, 1995). This paper follows the recent nomenclature of Walker and McCutcheon (1995) (Fig. 3). In the...
central and western study region (Fig. 4) the Upper Ordovician Matapedia Group underlies the Chaleur Group. In this heavily sampled region, the Chaleur Group includes the Upsalquitch, LaVieille, South Charlo, Bryant Point, New Mills, and Benjamin formations (Fig. 3). In the southeast study region (Fig. 4) a basal unconformity underlies the Chaleur Group; here the Chaleur Group includes the Weir, LaVieille, South Charlo, Bryant Point, and Simpsons Field formations (Fig. 3). The two formations within the Chaleur Group sampled for this study are the Bryant Point and South Charlo formations.

Previous studies have documented the structural complexity of the Chaleur Group including evidence for at least three generations of folding in the area, a region of dominantly transcurrent dextral shear (van Staal, 1988). Within the Chaleur Group the subaerial mafic volcanics of the Bryant Point Formation and clastic sediments of the South Charlo Formation are middle Wenlockian lateral equivalents (Walker and McCutcheon, 1995). The underlying LaVieille limestone provides the lower time constraint: fossils are dated as Llandovery C6 (Costistricklandia gaspensis and Paleocyclus) to lower or middle Wenlockian (Cyrtia exporrecta at the top of the formation) (Noble, 1976; Lee and Noble, 1977). The upper age constraint is provided by a U-Pb age of 423 ± 3 Ma in the overlying Benjamin Formation felsic volcanics (Walker et al., 1993, via M. Bevier, written communication, 1992). The low metamorphic grade is shown by rocks in the prehnite–pumpellyite facies (Bedard, 1986).

Composed of subaerial green to maroon basaltic flows and a few intraformational conglomerates, the Bryant Point Formation was heavily sampled at the type section along the coast of Chaleur Bay. Some flows are massive; others are highly porphyritic with up to 40% phenocrysts. The intraformational conglomerates are clast-supported pebble to boulder conglomerates with an occasionally calcareous matrix. The clasts are lithologically identical to those within the South Charlo Formation conglomerates. One conglomerate site (Sc16) sampled for this study is to the west near Pointe LaRoche, where it is

Fig. 3. Stratigraphy of the Chaleur Group, northeastern New Brunswick (Walker and McCutcheon, 1995; ages from Palmer, 1983).
hematitic with less well-rounded clasts and a brecciated matrix. The second conglomerate site (Sc2) is to the east near Belledune where it contains well-rounded clasts in a sandy quartzose matrix. The clasts in this site are predominantly mafic volcanics, likely derived from the underlying flows, but a few limestone clasts have also been observed. This conglomerate is thought to be syntectonic, deposited while deformation proceeded (J.A. Walker, pers. commun., 1993).

3. Field and laboratory methods

The forests of northern Maine limit suitable outcrop to stream sections and roadcuts. After visiting all probable outcrops (Roy, 1988; Roy et al., 1991), drilling sites for paleomagnetic study of the Fivemile Brook Formation were selected (Fig. 2). Paleohorizontal was determined from contacts with, and bedding within, the limestones and tuffs.

In northeastern New Brunswick exposure is excellent along the coast, and a recent roadcut for TransCanada Highway 11 provides some inland site locations (Fig. 4). The dense cluster of sites at approximately 47°57′N, 66°10′W is in the type section of the Bryant Point Formation. Paleohorizontal of the Bryant Point Formation volcanics was determined from vesicular and oxidized flow tops, intraformational conglomerates, South Charlo red beds, and inferred contact with the LaVieille limestone. Younging was determined from flow tops, intraformational conglomerates and the relationship with stratigraphically adjacent units.

Customary drilling and orientation techniques were used. Standard 2.5 cm paleomagnetic cores were bored with a portable drill. The lack of deflection of the magnetic compass needle by the basalts demonstrated that magnetic intensities did not significantly affect the compass readings. Cores were oriented with an inclinometer and a Brunton compass. In northwestern Maine, 135 cores were collected from 10 sites in the Fivemile Brook Formation (Sm);
in northeastern New Brunswick, 224 cores were collected from 21 sites in the Chaleur Group (Sc).

All laboratory work was performed in the University of Michigan Paleomagnetic Laboratory. Samples were trimmed to standard length (21 to 22 mm) paleomagnetic specimens and stored in a magnetically shielded room with a rest field of less than 200 nT. Anisotropy of magnetic susceptibility (AMS) measurements were made using a Kappabridge KLY-2 susceptibility bridge with each specimen being measured in 15 orientations. Comparisons of the intensity of the susceptibility at room temperature with that at 77 K were made for four representative samples to examine the source of susceptibility in Fivemile Brook specimens (Richter and van der Pluijm, 1993). Natural remanent magnetization (NRM) directions and intensities were measured with a triple-axis 2G superconducting magnetometer. Alternating field demagnetization of a few specimens revealed a high coercivity and, therefore, did not successfully separate the components. The majority of the specimens were thermally demagnetized in an ASC TD-48 thermal demagnetizer, using typically one specimen per sample, but occasionally two. Both demagnetization and measurement were done in the magnetically shielded room. After visual inspection of orthogonal vector endpoint diagrams (Zijderveld, 1967), principal component analysis was used to calculate component directions (Kirschvink, 1980) and the results are summarized in Tables 1–3.

4. Results

4.1. Anisotropy of magnetic susceptibility

AMS measurements showed that bulk susceptibility ranged from $2 \times 10^{-4}$ to $28 \times 10^{-4}$ (SI units) in Fivemile Brook specimens, and from $1 \times 10^{-4}$ to $1133 \times 10^{-4}$ SI in Chaleur Group specimens. The specimens generally revealed a low degree of anisotropy. In the Fivemile Brook specimens, AMS revealed weakly oblate susceptibility ellipsoids with minimum axes nearly perpendicular to cleavage. The preferred orientation of the minimum axis of the susceptibility ellipsoid displays a mean direction of $D = 104^\circ$, $I = 12^\circ$ with an $\alpha_95 = 4^\circ$ (Fig. 5); however, this fabric is not present in all sites. The ratio of bulk susceptibility at 77 K to that at room temperature (293 K) in the Fivemile Brook specimens ranged from 3.1 to 3.9, indicating a paramagnetic contribution. In the Chaleur Group specimens, AMS revealed a very low anisotropy with no apparent magnetic fabric.

4.2. Demagnetization

NRM intensities ranged from 0.3 to 501 mA/m in the Fivemile Brook specimens, from 3 to 103 mA/m in Chaleur Group red bed specimens (Sc1), and from 3 to 9736 mA/m in the Chaleur Group volcanic specimens. In general the demagnetization trajectories were well behaved (Figs. 6 and 7). Mean angular deviations typically ranged from 2° to 10°. Site mean directions and their associated radii of 95% confidence and precision parameters are listed in Tables 1–3.

As shown in Fig. 6, Fivemile Brook specimens revealed a number of discrete directions that have been divided into $a$-, $b$-, and $c$-components. In some samples (e.g., Fig. 6a1) a low temperature $a$-component close to the present-day geomagnetic field was revealed, suggesting a viscous remanence overprint. A southerly $b$-component (e.g., Fig. 6a1,b) was typically removed between 200 and 500°C or
Table 1
Characteristic directions from the Chaleur Group of northeastern New Brunswick

<table>
<thead>
<tr>
<th>Site</th>
<th>Nc</th>
<th>S/D</th>
<th>In situ</th>
<th>50% TC</th>
<th>Ns</th>
<th>Nd</th>
<th>k</th>
<th>a95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc1</td>
<td>14</td>
<td>294/93</td>
<td>360/08</td>
<td>355/−34</td>
<td>7</td>
<td>9</td>
<td>56.3</td>
<td>8.1</td>
</tr>
<tr>
<td>Sc2</td>
<td>18</td>
<td>097/79</td>
<td>(Conglomerate test)</td>
<td>(11)</td>
<td>11</td>
<td>1.4</td>
<td>65.8</td>
<td></td>
</tr>
<tr>
<td>Sc3</td>
<td>10</td>
<td>210/82</td>
<td>359/−04</td>
<td>008/−23</td>
<td>5</td>
<td>6</td>
<td>19.1</td>
<td>18.0</td>
</tr>
<tr>
<td>Sc4</td>
<td>11</td>
<td>210/82</td>
<td>345/−14</td>
<td>002/−39</td>
<td>11</td>
<td>15</td>
<td>73.5</td>
<td>5.4</td>
</tr>
<tr>
<td>Sc5</td>
<td>9</td>
<td>030/16</td>
<td>038/−34</td>
<td>033/−35</td>
<td>7</td>
<td>8</td>
<td>16.0</td>
<td>15.6</td>
</tr>
<tr>
<td>Sc6</td>
<td>11</td>
<td>197/79</td>
<td>335/−12</td>
<td>089/−25</td>
<td>10</td>
<td>10</td>
<td>145.4</td>
<td>4.0</td>
</tr>
<tr>
<td>Sc7</td>
<td>10</td>
<td>274/28</td>
<td>Uninterpretable</td>
<td>0</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sc8</td>
<td>10</td>
<td>090/33</td>
<td>097/−24</td>
<td>089/−25</td>
<td>5</td>
<td>5</td>
<td>62.9</td>
<td>9.7</td>
</tr>
<tr>
<td>Sc9</td>
<td>11</td>
<td>120/16</td>
<td>357/−54</td>
<td>002/−47</td>
<td>8</td>
<td>8</td>
<td>56.1</td>
<td>7.5</td>
</tr>
<tr>
<td>Sc10</td>
<td>10</td>
<td>330/65</td>
<td>065/11</td>
<td>065/−21</td>
<td>10</td>
<td>11</td>
<td>35.8</td>
<td>8.2</td>
</tr>
<tr>
<td>Sc11</td>
<td>4</td>
<td>296/115</td>
<td>359/16</td>
<td>354/−35</td>
<td>4</td>
<td>4</td>
<td>28.9</td>
<td>17.4</td>
</tr>
<tr>
<td>Sc12</td>
<td>10</td>
<td>296/115</td>
<td>007/07</td>
<td>358/−47</td>
<td>6</td>
<td>8</td>
<td>55.3</td>
<td>9.1</td>
</tr>
<tr>
<td>Sc13</td>
<td>10</td>
<td>196/79</td>
<td>037/−48</td>
<td>063/−25</td>
<td>11</td>
<td>11</td>
<td>50.1</td>
<td>6.5</td>
</tr>
<tr>
<td>Sc14</td>
<td>11</td>
<td>018/06</td>
<td>006/−34</td>
<td>004/−33</td>
<td>10</td>
<td>10</td>
<td>71.0</td>
<td>5.8</td>
</tr>
<tr>
<td>Sc15</td>
<td>10</td>
<td>018/06</td>
<td>358/−34</td>
<td>356/−33</td>
<td>10</td>
<td>10</td>
<td>109.3</td>
<td>4.6</td>
</tr>
<tr>
<td>Sc16</td>
<td>15</td>
<td>091/37</td>
<td>127/−37</td>
<td>113/−46</td>
<td>8</td>
<td>10</td>
<td>39.7</td>
<td>8.9</td>
</tr>
<tr>
<td>Sc17</td>
<td>12</td>
<td>099/38</td>
<td>137/−19</td>
<td>130/−30</td>
<td>6</td>
<td>9</td>
<td>12.9</td>
<td>19.4</td>
</tr>
<tr>
<td>Sc18</td>
<td>11</td>
<td>098/67</td>
<td>106/−40</td>
<td>079/−37</td>
<td>8</td>
<td>8</td>
<td>53.0</td>
<td>7.7</td>
</tr>
<tr>
<td>Sc19</td>
<td>9</td>
<td>091/32</td>
<td>301/−53</td>
<td>315/−30</td>
<td>7</td>
<td>7</td>
<td>55.4</td>
<td>8.2</td>
</tr>
<tr>
<td>Sc20</td>
<td>10</td>
<td>118/42</td>
<td>357/−49</td>
<td>005/−30</td>
<td>8</td>
<td>8</td>
<td>113.6</td>
<td>5.2</td>
</tr>
<tr>
<td>Sc21</td>
<td>8</td>
<td>209/101</td>
<td>347/−29</td>
<td>029/−50</td>
<td>7</td>
<td>8</td>
<td>18.7</td>
<td>14.3</td>
</tr>
</tbody>
</table>

Sum Nc = 224 Ns = 148 Nd = 185

Mean of 19 sites
In situ: (019/−34) 2.8 24.6
Mean of 19 sites
(026/−43) 4.9 16.9
Mean inclination −35

The S/D column indicates strike and dip of bedding and primary surfaces (down dip to the right of strike). D/I are the declination and inclination in degrees of the site mean direction. TC indicates degree (%) of tilt-correction. Brackets about a site mean direction indicate exclusion from the computation of the formation mean. The Nc column indicates the numbers of samples (cores) collected, Ns indicates the number of specimens used in the statistical analysis for site-means and the formation mean, and Nd is the number of specimens demagnetized. k and a95 are the precision parameter and the radius of the 95% confidence cone about the mean direction in degrees (Fisher, 1953). Standard deviation of tilt-corrected inclination = 8.5°.

occasionally between 300 and 600°C. As observed in specimen Sm1J (Fig. 6a1), many specimens displaying the southerly b-component became spurious after 500 or 600°C, and some did not decay to the origin suggesting the presence of an unresolvable high temperature component in those specimens. In some of these specimens successive demagnetization datapoints show trajectories on a stereonet heading to a north and up direction (e.g., Fig. 6a2). A northerly b-component was typically removed between 600 and 680°C (e.g., Fig. 6c) but between 200 and 580°C in a few specimens. In specimen Sm2Ca (Fig. 6d) both a southerly and a northerly direction were preserved. As shown in Fig. 6b,e, a westerly c-component was revealed at high temperatures, typically between 600 and 680°C, although occasionally it began to decay by 450 or 500°C. A high temperature easterly c-component was preserved as a single.
Table 2
Characteristic (c-component) directions from the Fivemile Brook Formation in northwestern Maine

<table>
<thead>
<tr>
<th>Site</th>
<th>Nc</th>
<th>SID</th>
<th>In situ D/I</th>
<th>100% TC D/I</th>
<th>Nd</th>
<th>Na</th>
<th>k</th>
<th>a95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sm1</td>
<td>14</td>
<td>033/85</td>
<td>264/39</td>
<td>173/42</td>
<td>5</td>
<td>15</td>
<td>39.2</td>
<td>12.4</td>
</tr>
<tr>
<td>Sm2</td>
<td>36</td>
<td>033/69</td>
<td>260/19</td>
<td>201/44</td>
<td>8</td>
<td>8</td>
<td>82.4</td>
<td>6.1</td>
</tr>
<tr>
<td>Sm3</td>
<td>8</td>
<td>033/69</td>
<td>258/29</td>
<td>182/34</td>
<td>4</td>
<td>5</td>
<td>18.5</td>
<td>21.9</td>
</tr>
<tr>
<td>Sm4</td>
<td>14</td>
<td>034/33</td>
<td>079/-28</td>
<td>009/-43</td>
<td>6</td>
<td>6</td>
<td>317.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Sm5</td>
<td>13</td>
<td>033/85</td>
<td>079/-28</td>
<td>009/-43</td>
<td>6</td>
<td>6</td>
<td>317.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Sm6</td>
<td>14</td>
<td>034/33</td>
<td>079/-28</td>
<td>009/-43</td>
<td>6</td>
<td>6</td>
<td>317.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Sm7</td>
<td>9</td>
<td>037/93</td>
<td>129/32</td>
<td>213/42</td>
<td>8</td>
<td>8</td>
<td>82.4</td>
<td>6.1</td>
</tr>
<tr>
<td>Sm8</td>
<td>5</td>
<td>038/39</td>
<td>258/29</td>
<td>182/34</td>
<td>4</td>
<td>5</td>
<td>18.5</td>
<td>21.9</td>
</tr>
<tr>
<td>Sm9</td>
<td>10</td>
<td>037/79</td>
<td>079/-28</td>
<td>009/-43</td>
<td>6</td>
<td>6</td>
<td>317.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Sm10</td>
<td>12</td>
<td>037/79</td>
<td>079/-28</td>
<td>009/-43</td>
<td>6</td>
<td>6</td>
<td>317.7</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Sum Nc = 135 Nd = 23 Nl = 121

Mean of 4 sites (260/27) 211.7 6.3
Mean of 4 sites 186/41 69.5 11.1
Mean of 23 specimens (260/26) 46.2 4.5
Mean of 23 specimens 189/42 36.2 5.1

Conventions as in Table 1. The precise locations of the four sites that preserve the c-component are: Sm6 at 47°02′08″N, 69°28′47″W; Sm7 at 47°01′56″N, 69°29′23″W; Sm8 at 47°02′10″N, 69°28′45″W; and Sm10 at 47°00′30″N, 69°31′52″W. Standard deviation of tilt-corrected inclination =3.9°.

component in all specimens from site Sm10 that was removed between 600 and 680°C (Fig. 6f). Directions revealed in tuffs were consistent with those revealed in the basalts.

The Chaleur Group specimens were well behaved, revealing one or two components. A low temperature component observed in some specimens (e.g., Fig. 7a) is close to the present-day geomagnetic field, suggesting a viscous remanence overprint. The high temperature component was removed between 500°C and 680°C with many specimens displaying a double-shouldered intensity decrease (e.g., Fig. 7b,c). Fig. 7 illustrates the wide range of in situ directions observed in Chaleur Group specimens. Site Sc7 specimens were uninterpretable. Directions revealed in the red bed (Sc1) were similar to those revealed in nearby basalts (Sc11 and Sc12) (Table 1).

Unblocking temperatures of 680°C and high coercivity evidenced by alternating field demagnetization of the pilot specimens indicate that the magnetization is carried dominantly by hematite in both the Fivemile Brook Formation and the Chaleur Group.

4.3. Fivemile Brook in situ and tilt-corrected means

In situ stereoplots of site mean directions show four distinct groups of directions. These four directions are illustrated in Fig. 8a,b: westerly shallow to intermediate down direction, an easterly intermediate up direction, a south-southeasterly intermediate down direction, and a northerly up direction. The east-west directions correspond to the bipolar c-component, and the north-south directions correspond to the bipolar b-component. The direction (D = 57°, I = -61°) preserved in an oxidized zone of site Sm2 (labelled Sm2a in Table 3) cannot be unambiguously assigned to any one of these four groups; the direction does, however, fall near the great circle between the b-component and c-component and may be an unresolvable mixture of the two. The mean in situ direction of the c-component site means is D = 260°, I = 27° (α95 = 6°, k = 212, based on the mean of 4 site-means) and the tilt-corrected mean is D = 186°, I = 41° (α95 = 11°, k = 70; standard deviation of inclination αI = 3.9°) (Fig. 8c). The b-component site means yield a mean direction in situ of D = 165°, I = 35° (α95 = 8°, k = 65, based on ten entries; see Table 3) and tilt-corrected of D = 164°, I = -31° (α95 = 10°, k = 23).

4.4. Fivemile Brook reversal test

The approximately antipodal directions suggest preservation of reversals. The c-component passes
Fig. 7. Representative in situ orthogonal vector endpoint diagrams of thermal demagnetizations that display characteristic directions from the Chaleur Group. Conventions as given in Fig. 6.

Fig. 8. (a) In situ Fivemile Brook c-component site means. The overall formation mean is $D = 260^\circ$, $I = 27^\circ$, $\alpha_{95} = 6^\circ$, $k = 212$. (b) In situ Fivemile Brook b-component site means. The overall formation mean is $D = 165^\circ$, $I = 35^\circ$, $\alpha_{95} = 6^\circ$, $k = 65$. (c) Fivemile Brook c-component site means in tilt-corrected coordinates. The overall formation mean is $D = 186^\circ$, $I = 41^\circ$, $\alpha_{95} = 11^\circ$, $k = 70$. Closed/open symbols represent projections onto the lower/upper hemisphere.
McFadden and McElhinny (1990) common kappa reversal test and is assigned an A-I classification. In tilt-corrected coordinates the means \((D = 009°, I = -43°)\) and \((D = 185°, I = 41°)\) display a deviation \(\gamma = 4°\) (Fig. 9a). The \(b\)-component is a bit more complex. The northerly and up in situ mean site-mean direction \((D = 355°, I = -40°)\) is about antipodal to the south-southeasterly and down mean direction \((D = 161°, I = 32°)\) (Fig. 9b). With deviation \(\gamma = 16°\), this passes the common kappa test, giving a \(\text{C}\) classification; however, when a simulation is run, the null hypothesis of a common mean direction is rejected.

### 4.5. Chaleur Group conglomerate tests

Results of the two conglomerate tests (Watson, 1956) for the Chaleur Group have important implications. As shown in Fig. 10 the conglomerate test at the base of the section \((S_{c16})\) is negative. If all ten samples are used, the results \((N = 10, R = 8.845, R_0 = 5.03; R > R_0)\) imply rejection of the null hy-

---

**Table 3**

<table>
<thead>
<tr>
<th>Site</th>
<th>(N_c)</th>
<th>(S/D)</th>
<th>In situ (D/I)</th>
<th>100% TC (D/I)</th>
<th>(N_a)</th>
<th>(N_d)</th>
<th>(k)</th>
<th>(\text{ang.})</th>
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<tbody>
<tr>
<td>Sm1</td>
<td>14</td>
<td>033/85</td>
<td>171/39</td>
<td>164/-27</td>
<td>18</td>
<td>19</td>
<td>128.2</td>
<td>3.1</td>
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<tr>
<td>Sm2a</td>
<td>36</td>
<td>033/69</td>
<td>(057/-61)</td>
<td>(334/-30)</td>
<td>(7)</td>
<td>16</td>
<td>114.8</td>
<td>5.7</td>
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<tr>
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<td>–</td>
<td>033/69</td>
<td>004/-40</td>
<td>346/07</td>
<td>5</td>
<td>–</td>
<td>8.9</td>
<td>21.1</td>
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<td>033/69</td>
<td>165/36</td>
<td>159/-21</td>
<td>2</td>
<td>–</td>
<td>126</td>
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<td>Sm3</td>
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<td>356/-45</td>
<td>338/08</td>
<td>8</td>
<td>9</td>
<td>84.1</td>
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<td>14</td>
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<td>347/-34</td>
<td>346/32</td>
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<td>17</td>
<td>38.6</td>
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<tr>
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<td>167/-37</td>
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<td>038/89</td>
<td>164/31</td>
<td>182/-34</td>
<td>4</td>
<td>5</td>
<td>26.3</td>
<td>18.2</td>
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<tr>
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<td>037/79</td>
<td>150/29</td>
<td>148/-48</td>
<td>5</td>
<td>6</td>
<td>31.6</td>
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<tr>
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<td>12</td>
<td>037/79</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>–</td>
<td>6.6</td>
</tr>
</tbody>
</table>

| Sum  | \(N_c = 135\) | \(N_a = 77\) | \(N_d = 121\) |
| Mean of 10 entries (without 2a) | 165/35 | 65 | 6.1 |
| Mean of 10 entries (without 2a) | (164/-31) | 23 | 10.2 |

Conventions as in Table 1. Samples from the same site that show similar directions (for instance, either normal or reversed) have been grouped together as sub-sites (e.g., sites Sm2a, 2b or 2c); for additional sub-sites, dashes are placed in the \(N_c\) and \(N_d\) columns.
4.6. Chaleur Group tilt-correction

In situ site mean directions for the Chaleur Group are widely scattered (Fig. 11a), indicating the need for structural corrections to find a meaningful magnetic direction. The inclination-only fold test (Fig. 11b) shows a seven fold increase in $k$, peaking at 50% unfolding to yield a mean inclination of $-35^\circ$ with a standard deviation ($\sigma_I$) of 8.5°. Site means at 50% unfolding show significant streaking in declination (Table 1, Fig. 11c) that cannot be caused by tilt. Although map patterns are suggestive of plunging folds, bedding plane intersections, where we could measure them, are within a few degrees of horizontal.

5. Discussion of paleomagnetic results and tectonic implications

5.1. Fivemile Brook results

AMS results indicate a low degree of anisotropy, indicating minimal probability of remanence deflection. The ratios of bulk susceptibilities at 77 K to those at room temperature (293 K) indicate involvement of a paramagnetic mineral phase that is probably chlorite. Moreover, the magnetic fabric observed in a number of Fivemile Brook sites is roughly cleavage parallel.

Based on high unblocking temperatures it is inferred that both the c- and b-components are carried by hematite. In view of the extremely high temperatures required to thermally reset hematite grains (Pullaiah et al., 1976), both the c- and b-components are presumably chemical remanent magnetizations (CRMs) resulting from hematite replacement of original magnetite. Subaerial weathering may account for initial oxidation of the magnetite in these volcanics; a later CRM may be associated with fluid circulation (Dorobek, 1989).

The approximately antipodal directions are interpreted as a record of geomagnetic field reversals. The c-component clearly passes the common kappa reversal test. Although the b-component reversal shows a deviation $\gamma = 16^\circ$, the evidence suggests that this represents a field reversal. Plotted on a stereonet, successive directions with treatment above 300°C in many specimens from sites Sm1 and Sm12 appear to lie along a great circle path trending towards a north and up direction (e.g., Fig. 6a2). The b-component magnetization in the Fivemile Brook Formation is similar to dual-polarity, post-depositional red bed magnetizations observed elsewhere (e.g., Roy and Park, 1974; Channell et al., 1982) and

Fig. 10. Chaleur Group conglomerate tests. (a) Negative conglomerate test at the base of the section (Sc 16). (b) Positive conglomerate test at the top of the section (Sc 2).
Fig. 11. (a) Scattered Chaleur Group in situ mean directions. (b) Chaleur Group inclination-only fold test peaks at 50%, corresponding to an inclination of $-35^\circ$. (c) Clockwise streaking of Chaleur Group site mean directions observed at 50% tilt-correction.

The magnetic directions in the Fivemile Brook samples clearly suggest two diachronous components. Although the $\alpha_{95}$ of the c-component increases after unfolding, this is not statistically significant at the 95% confidence level, because of the low number (4) of site means. If we compare the statistical parameters based on the means of the 23 specimen directions, the corresponding $\alpha_{95}$ values are 4.5° and 5.1° before and after tilt correction, respectively, with a $k_1/k_2$ ratio of 1.27, which is also not statistically significant (Table 2). The in situ c-component direction is unlike any North American direction since the Silurian, so its magnetization must be older than much of the folding which is Early Devonian in Maine. When an early syn-tilting origin is considered for the c-magnetization, the possible range of inclination values is between $+41^\circ$ and $+50^\circ$. The tilt-corrected inclination of $41^\circ$ ($\alpha_1 = 3.9^\circ$) corresponds to a paleolatitude of $24^\circ \pm 3^\circ$ which fits the North American reference path values for either the Middle to Late Silurian or the Early Devonian (Fig. 12). An early syn-tilting origin of the magnetization would typically yield a steeper inclination (around $+50^\circ$) and, hence, an even higher paleolat-
Fig. 12. Paleolatitude plot illustrating agreement of Fivemile Brook c-component (Sm) and Chaleur Group (Sc) results with North American reference values. Flagging about data points represents potential error.

Fig. 13. Paleomagnetic pole positions corresponding to an inclination of 41° crosses the North American APWP along the Early Devonian segment and near the Middle to Late Silurian reference pole. (a) In tilt-corrected coordinates the c-component mean direction \((D = 186°, I = 41°)\) yields a pole at 19°S, 285°E near the Early Devonian segment of the North American APWP. (b) The pole calculated from the in situ b-component mean direction \((D = 165°, I = 35°)\) is at 22°S, 306°E or near the Early Carboniferous corner of the North American APWP. Although the α95 error circle surrounding the in situ b-component pole includes the mid-upper Silurian reference pole, this magnetization could not have been acquired in the Silurian because a Silurian magnetization would predate deformation. We interpret the b-component to be a post-deformational direction acquired during the Early Carboniferous as a CRM remagnetization event.

5.2. Chaleur Group results

The Chaleur Group results indicate a single ancient magnetization with its age constrained by the ages of the two conglomerates. Chaleur Group conglomerate tests indicate that magnetization must postdate deposition of the conglomerate at the base of the section (Sc16) and predate deposition of the syntectonic conglomerate at the top of the section (Sc2). Furthermore, the inclination-only fold test indicates a syneformational magnetization, and the wide range of declinations suggests that substantial rotations occurred during later deformation, as will be discussed below. The sequence of events therefore must be: the initial extrusion of subaerial volcanics and early deposition of the lower conglomerate (Sc16), partial deformation, acquisition of magnetization, followed by deposition of conglomerate (Sc2) during protracted deformation that includes folding or tilting, as well as in age, then these results support tectonic models with little or no rotation of northwestern Maine (e.g., Malo et al., 1995). We interpret the Fivemile Brook Formation c-component magnetization to be an ancient magnetization that is older than Early Devonian tilting which may have been acquired during subaerial weathering of magnetite to hematite during either the Late Silurian or Early Devonian.

The b-component is observed in 77 specimens from 8 sites in the Fivemile Brook Formation. The mean is based on 10 entries, counting normal- and reversed-polarity mean directions separately. The tilt-corrected b-component direction \((D = 164°, I = -31°)\) corresponds to a typical Jurassic direction for North America, but this is nonsensical because tilting occurred much earlier, that is, during the Early Devonian Acadian orogeny in Maine. We interpret the Fivemile Brook Formation c-component magnetization to be an ancient magnetization that is older than Early Devonian tilting, possibly implying a latest Silurian to earliest Devonian age for the magnetization. As already discussed, the deviating in situ westerly direction makes it very unlikely that we are dealing with a post-tilting or late syn-tilting magnetization.
rotations. In fact, structural features such as fiber patterns traced elsewhere are continuous through sharp bends in rocks from southern Gaspé and provide evidence for continuous deformation rather than discrete deformational stages (Kirkwood et al., 1995; Kirkwood and Malo, 1993).

We have examined the large spread in declinations at all levels of unfolding. Regardless of the application of partial or full tilt-corrections, the declination distribution persists. Corrections for estimated plunges of some of the folds are minor and do not result in significantly better grouped declinations. Given the results of the inclination-only fold test, we analyze the spread in declinations of the site means at 50% unfolding only. The observed pattern indicates vertical axis rotations, an interpretation that is also suggested by structural map patterns. A detailed analysis of the rotations implied by these directions and comparisons with the geometry of the structures is not possible without much further work, not in the least because it requires more accurate mapping than is now available, or even possible, due to limited exposure in the area. Clearly, the region has undergone complex polyphase deformation, including the effects of anastomosing shear zones.

A mid-Silurian inclination of $-35^\circ$ ($\sigma_1 = 8.5^\circ$) corresponds to a paleolatitude of $19^\circ+ 5^\circ/ -4^\circ$ in agreement with North American reference values (Fig. 12). Because the inclination indicates a paleolatitude closely matching North American reference...
values for mid-Silurian times, this is evidence that these rocks have been a part of North America since early acquisition of the magnetization, and that they have not undergone significant latitudinal displacement within paleomagnetic resolution. Note that fault displacements reported in the Gaspé Peninsula, such as the 155 km total displacement reported by Malo and Bélanger (1989) or even the 300–400 km dextral offset of equivalent tectono-stratigraphic zones of the northern Appalachians (van Staal and Williams, 1988), are not within paleomagnetic resolution.

The clockwise streaking of site mean directions away from a dominantly northerly declination (Fig. 11c) is consistent with post-middle Wenlockian dextral shearing. Deformation of the Chaleur Group has been interpreted as a polyphase deformation including dominantly transcurrent dextral shear (van Staal, 1988, F3-related deformation). The reversal from sinistral to dextral transpression in the northern Appalachians is not well understood because structural complexities obscure reliable indicators that could constrain the timing of this shear-sense reversal. Many recent studies suggest that, most likely, Silurian transpression was due to sinistral shear, which changed abruptly to early Devonian dextral faulting (e.g., de Roo and van Staal, 1994; Hibbard, 1994).

Given the uncertain effects of rotations, a formation-mean declination for the Chaleur Group remains uncertain so that only a small circle about the sampling site can be used to determine the locus of paleomagnetic pole positions (Fig. 13c). The locus of poles corresponding to an inclination of −35° crosses the south APWP for North America near the Middle to Late Silurian reference pole, consistent with a Silurian age of the magnetization for the Bryant Point volcanics. Whereas this locus could suggest that an Early to Middle Devonian age of the magnetization is also possible (Fig. 13), the positive conglomerate test and U–Pb age from the overlying felsic volcanics constrain the age of magnetization to be older than 423 ± 3 Ma. Thus a Devonian age can be excluded, and the age of the Chaleur Group magnetization is considered to be middle Wenlockian.

6. Conclusions

New paleomagnetic results for Silurian volcanics presented here provide further constraints on the mid-Paleozoic tectonic evolution of the Laurentian margin. Previous studies indicate that subduction of Iapetan crust and collision of island arcs and other vestiges of the Iapetus with North America during the Ordovician and Silurian provided a northwesterly source for sediments of the ensuing Siluro-Devonian overstep sequence. This study indicates that Early Devonian Acadian deformation in northwestern Maine largely postdates the Late Silurian or Early Devonian acquisition of the c-component by the Five mile Brook Formation. Chaleur Group results indicate that the age of the magnetization of the Bryant Point Formation is mid-Wenlockian. Given that its inclination indicates a paleolatitude closely matching the North American reference values for mid-Silurian, we conclude that these rocks have been a part of North America since their formation, and have not undergone paleomagnetically significant latitudinal displacement. Some sites in the Chaleur Bay region have undergone large local rotations, consistent with post-middle Wenlockian dextral shear. If the inclinations from these northern Appalachian units indeed do represent the Silurian geomagnetic field, then they make an important contribution to the Silurian paleolatitude controversy because they do not show a large discrepancy in inclination with Laurentian reference poles. Hence, we conclude that, within paleomagnetic resolution, there have been no significant latitudinal displacements of the Siluro-Devonian overstep sequences or underlying Ordovician units with respect to stable Laurentia since the Middle Silurian.

In addition to contributing to the Silurian paleolatitude controversy, paleomagnetic results from the Chaleur Group provide constraints on the timing of mid-Paleozoic deformation in the northern Appalachians. A middle Wenlockian synfolding magnetization in the Chaleur Group requires that deformation associated with the Acadian orogeny in northern New Brunswick began no later than mid-Silurian times.

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