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# Palaeomagnetism of the *ca.* 440 Ma Cape St Mary's sills of the Avalon Peninsula of Newfoundland: implications for Iapetus Ocean closure

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## SUMMARY

We report on the palaeomagnetism of the gabbroic Cape St Mary's sills of the Avalon Peninsula of Newfoundland, which have previously yielded a 441 ± 2 Ma U–Pb baddeleyite age (latest Ordovician or earliest Silurian). At 12 of 19 sites, stepwise alternating-field or thermal demagnetization isolated a stable characteristic remanence carried by magnetite. This remanence is shown to pre-date Early Devonian folding of the sills. Although a baked-contact test was inconclusive, the positive fold test and the low grade of metamorphism of the sills (prehnite–pumpellyite facies) make it likely that the characteristic remanence is primary. The tilt-corrected site-mean characteristic remanence has a declination of 343° and an inclination of −51° ($k=25$, $\alpha_{95}=9°$), yielding a ∼440 Ma palaeopole at 10°N, 140°E ($dm=12°$, $dp=8°$) for West (North American) Avalonia. The corresponding ∼440 Ma palaeolatitude for the Avalon Peninsula is 32°S ± 8°. The only other West Avalonian palaeolatitude determination from rocks that could be of similar age is from the Dunn Point volcanics of Nova Scotia; their more southerly palaeolatitude of 41°S ± 5° suggests that they are significantly older than 440 Ma, a possibility that we recommend testing with U–Pb dating. Although no ∼440 Ma palaeolatitude determinations are available for East Avalonia (parts of southern Britain and Ireland), interpolating between mid-Ordovician and mid-Silurian determinations gives an estimate of ∼25°S. This is consistent with our Cape St Mary's result and, if the Iapetus Ocean closed orthogonally, with a narrow (∼1000 km) Iapetus Ocean of approximately east–west orientation between Avalonia and Laurentia by 440 Ma.

**Key words:** Ordovician, palaeogeography, palaeolatitude, palaeomagnetism, Silurian.

## 1 INTRODUCTION

We attempt to understand better how the Iapetus Ocean closed by studying the palaeomagnetism of the Cape St Mary's sills of the Avalon Peninsula of Newfoundland. These gabbroic sills have recently yielded a U–Pb baddeleyite age of 441 ± 2 Ma (Greenough, Kamo & Krogh 1993), placing them in the latest Ordovician or earliest Silurian (Tucker & McKerrow 1995). Previous palaeomagnetic study of these sills was only published in abstracts (Hodych & Patzold 1980; Hodych & Buchan 1994a).

Wilson (1996) was the first to suggest that an ocean (the Iapetus) lay between Laurentia and Avalonia in the Early Palaeozoic, explaining their Cambro-Ordovician faunal differences (known since Walcott 1889). Avalonia was perhaps the first accreted terrane to be identified, and the Iapetus Ocean was a prototype for the Wilson cycle of opening and closing of ocean basins, yet the history of the Iapetus Ocean remains contentious (e.g. Keppie *et al.* 1996).

In the northern Appalachians, closure of the Iapetus Ocean was completed when the Avalon Terrane docked with the Gander Terrane (Williams & Hatcher 1983). This had occurred by the mid-Devonian (Williams 1993; Dallmeyer & Keppie 1993). However, the earlier history of Iapetus closure is still debated. Wilson (1966) pictured the Avalon Terrane as originally part of North Africa or southern Europe with a simple orthogonal (head-on) closing of the Iapetus. Recent models (reviewed by Keppie *et al.* 1996) often picture a more complex closure. For example, Dalziel (1997) pictures Laurentia breaking away from South America in the late Precambrian and moving eastwards relative to Gondwana, introducing a large dextral shear component to the closing of the Iapetus.

Palaeomagnetism helps to constrain such models by providing palaeolatitude estimates for Laurentia and Avalonia (although it is unable to provide palaeolongitudes).

Palaeomagnetism suggests that during the Ordovician and Early Silurian, the Laurentian margin of the Iapetus was oriented approximately east–west and was stationed some 20° south of the equator (e.g. van der Pluijm, Van der Voo & Torsvik 1995; Torsvik *et al.* 1996; MacNiocaill, van der Pluijm & Van der Voo 1997). Most Avalonian palaeomagnetic results for this period are from East Avalonia (parts of southern Britain and Ireland). In the Early Ordovician, East Avalonia was far to the south of Laurentia, at ~60°S latitude as shown by palaeomagnetic results from the Treffgarne volcanics of Wales (Trench *et al.* 1992). By the Middle Ordovician, East Avalonia had moved northwards to ~40°S as shown for example by palaeomagnetic results from the Builth volcanics of Wales (Trench *et al.* 1991). By the middle Silurian, East Avalonia had moved farther north to ~15°S as shown by palaeomagnetic results from the East Mendips volcanics of southern England (Trench & Torsvik 1992). The above three palaeomagnetic studies have conglomerate tests that prove remanence is primary (i.e. acquired when the rocks formed).

Hence, from Early Ordovician to mid-Silurian, Avalonia seems to have drifted steadily northwards towards a Laurentia of relatively fixed palaeolatitude (but perhaps changing palaeolongitude). Palaeomagnetic results from terranes between Avalonia and Laurentia (van der Pluijm *et al.* 1995) are generally consistent with this conclusion and support closure of the Iapetus by the Late Silurian (although the palaeolatitude at closure is debated; Hodych & Buchan 1994b; Stamatakos *et al.* 1995). Recently, however, Piper (1995) used palaeomagnetic evidence to suggest that Avalonia made a large rapid southwards excursion to ~57°S in the Late Ordovician. We help test this suggestion with palaeomagnetic results from West (North American) Avalonia for the latest Ordovician–earliest Silurian, a time period unrepresented in the East Avalonian palaeomagnetic literature. This time period (~440 Ma) is also of interest because it includes a short-lived glaciation in Gondwana that may have been caused by its palaeogeography (Crowley & Baum 1995).

From West (North American) Avalonia, the only Ordovician or Silurian palaeomagnetic results that are published in full and that have been interpreted to pre-date folding are those from the steeply dipping Dunn Point Formation volcanics of Nova Scotia. Early studies by Van der Voo & Johnson (1985) and Seguin, Rao & Deutsch (1987) yielded conflicting fold tests, with the former reporting a positive test and the latter an inconclusive test. In a later more detailed re-study of the Dunn Point volcanics, Johnson & Van der Voo (1990) obtained a positive fold test, suggesting that the remanence pre-dates Devonian folding. Unfortunately, as discussed below, the age of the Dunn Point flows is poorly constrained (Hodych & Buchan 1994b). On the other hand, the Cape St Mary's sills of West Avalonia have both an accurate radiometric age (Greenough *et al.* 1993) and a pre-folding remanence (preliminary study by Hodych & Patzold 1980).

## 2 GEOLOGY AND SAMPLING OF THE CAPE ST MARY'S SILLS

The Cape St Mary's sills are gabbroic. They concordantly intrude Middle and Upper Cambrian sediments (mostly black shales) in the southwest of the Avalon Peninsula of Newfoundland, as shown in Fig. 1. The sediments contain well-preserved Avalonian trilobite fossils (Fletcher 1972). The sills yield a 441 ± 2 Ma U–Pb baddeleyite age (Greenough *et al.* 1993) at the site marked by a triangle in Fig. 1. The sills and Cambrian sediments were deformed into open folds with subhorizontal northerly trending axes, probably in the Early Devonian during the Acadian Orogeny (Williams 1993; Hibbard 1994). Metamorphism of the sills was only to prehnite–pumpellyite facies (Greenough *et al.* 1993).

The sills were sampled palaeomagnetically at the 19 sites shown in Fig. 1, each site being in a separate sill. Most of the sills sampled are 1–3 m thick, while the rest (sites 2, 3, 7, 12, 13, 17) are much thicker (up to 60 m). The strike and dip of the sediments that the sills intrude were measured at each site and are recorded in Table 1. The thick sill that was radiometrically dated (Greenough *et al.* 1993) was not sampled because we could not reliably establish the palaeohorizontal. A dyke that may have been a feeder to the sills was sampled at site D. Sampling of volcanogenic sediments for baked-contact tests was carried out at this dyke and at the site 14 sill (sites DS and 14S respectively).

Oriented block samples were collected at each site with the aid of a sun compass or by sighting on distant headlands. Oriented cylindrical rock specimens of 2.4 cm diameter and 2.2 cm length were cut from each block in the laboratory.

## 3 PALAEOMAGNETIC PROCEDURE AND RESULTS

Specimens from all 19 sill sites were demagnetized in steps using a Schonstedt GSD-1 alternating-field (AF) demagnetizer. A majority of these specimens were measured using a Schonstedt SSM-1 magnetometer at the Memorial University of Newfoundland. At some of the sill sites, specimens were also thermally demagnetized in steps, usually after partial AF demagnetization. The thermal experiments were mostly performed at the Geological Survey of Canada in Ottawa using a remodelled Schonstedt TSD-1 demagnetizer, with a peak temperature control of ±5 °C, and a Schonstedt DSM magnetometer. The thermal demagnetization experiments were carried out in a magnetically shielded room with a residual magnetic field <3000 nT. Whether AF or thermal demagnetization results were used in the final analysis is shown by A or T, respectively, in Table 1. Volcanogenic sediments collected for baked-contact tests (sites DS and 14S) were stepwise AF demagnetized. Because of their very weak remanence, the sediment specimens were measured using a superconducting magnetometer (CTF Systems Inc.) at the Memorial University of Newfoundland.

After removal of a soft viscous remanence during demagnetization to peak fields of about 15 mT or peak temperatures of about 400 °C, the remanence direction of some sill specimens remained stable during further demagnetization. Examples are shown on orthogonal vector plots in Fig. 2. The stable remanence directions of such specimens were calculated using the least-squares fitting method of Kirschvink (1980) and the number of these specimens per site used in the statistical calculations is indicated under K in Table 1. At seven sites (2, 4, 6, 7, 15, 17 and 19) a mean direction was calculated solely on the basis of these stable endpoints.

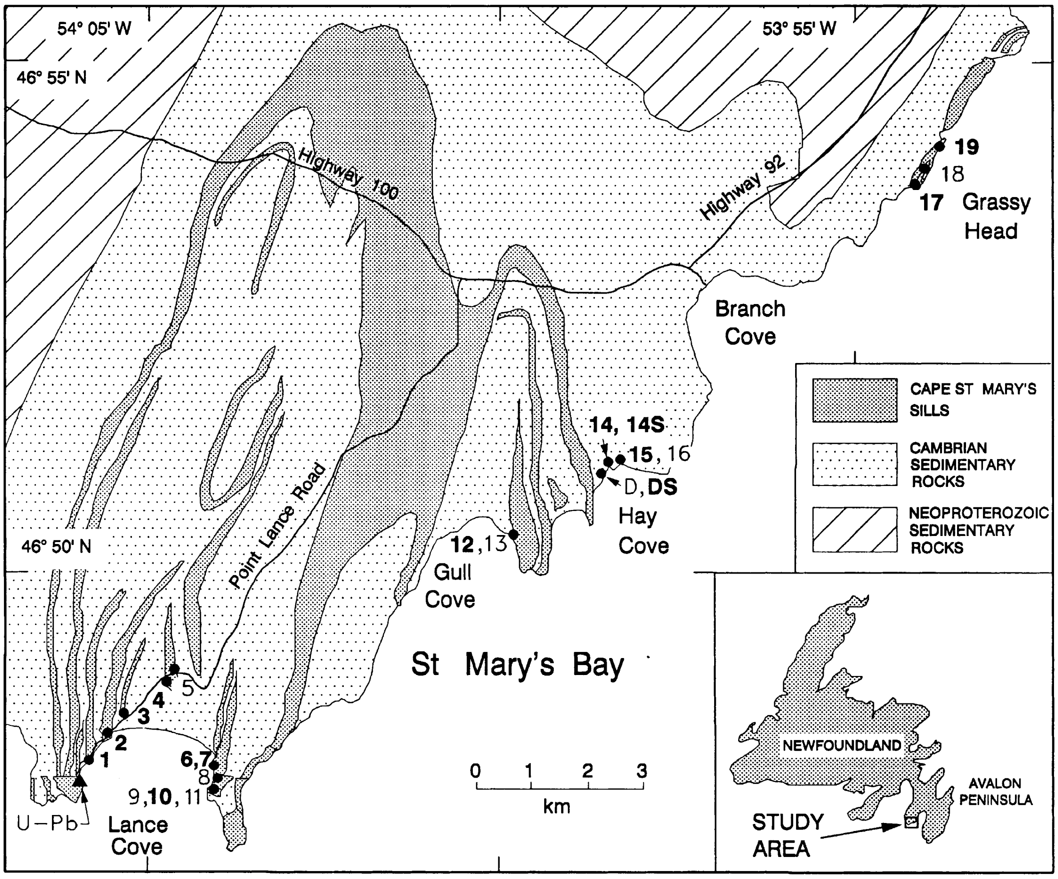


**Figure 1.** Sampling sites (1–19) in the Cape St Mary's sills of the Avalon Peninsula of Newfoundland are shown with closed circles. All sites are in gabbroic sills except for 14S (which is in sediment baked by sill 14), D (in a gabbroic dyke) and DS (in sediment baked by the dyke). Sites that yielded palaeomagnetically useable remanence directions are shown in bolder type. The U–Pb dating site of Greenough *et al.* (1993) is shown by a filled triangle. The geology is after Fletcher (1972).

At other sill sites (1, 3, 10, 12 and 14), most specimens continued to change remanence direction as demagnetization progressed. Great circles (remagnetization circles) were fitted to the data on stereographic plots and their intersections were used to determine the characteristic remanence direction for a site following the method of Bailey & Halls (1984). Examples of such sites are shown in Fig. 3. The number of specimens per site whose remagnetization circles were used is shown under R in Table 1.

At sill sites 5, 8, 9, 11, 13, 16 and 18, demagnetization scattered the remanence directions of all (or all but one) of the specimens due to the low coercivity of the remanence (in the case of AF demagnetization) or to the low unblocking temperatures of the remanence (in the case of thermal demagnetization). These sites were not used in the final analysis of remanence directions and are not listed in Table 1.

The site mean remanence directions for all useable sill sites are shown in Table 1 and plotted in Fig. 4 before and after tilt correction. (The folds are large and open and they plunge less than 10°, allowing simple tilt correction.) Each of these sites is normally polarized. At all the sites of Table 1, magnetite with a low Ti content is the dominant mineral carrying the stable remanence, as demonstrated by unblocking temperatures that are typically in the 400–550 °C range. Unstable site 18 may be dominated by pyrrhotite judging by the 300–350 °C unblocking temperatures. There was no sign of remanence carried by haematite in any of the specimens measured in this study.

## 4 TIMING OF REMANENCE ACQUISITION

We tested whether the characteristic remanence of the Cape St Mary's sills was acquired before probable Early Devonian folding. The *in situ* site mean remanence directions at the 12 stable sites (Fig. 4a) are quite scattered, giving an overall mean direction with declination $D=347.8°$, inclination $I=-48.2°$, precision parameter $k=6.9$ and radius of the circle of 95 per cent confidence $\alpha_{95}=17.9°$. After tilt correction (Fig. 4b), the scatter is significantly reduced, giving a mean direction with $D=343.8°$, $I=-50.8°$, $k=24.9$ and $\alpha_{95}=8.9°$. According to the criteria of McElhinny (1964), the data for the Cape St Mary's sills pass the fold test at the 99 per cent confidence level. (The ratio of the precision parameter after tilt correction to that before tilt correction is 3.6.) Likewise, the alternative correlation test of McFadden (1990) indicates that the remanence of the sills is pre-fold. (Test statistic $\xi_1=9.72$ *in situ* and reaches a minimum of 0.13 at 93 per cent unfolding, which is not significantly lower than $\xi_1=2.18$ at 100 per cent unfolding.)

Baked-contact tests were attempted for a sill and for a dyke, both of which intrude Cambrian volcanogenic sedimentary rocks. At sill site 14, six sediment samples were collected

**Table 1.** Palaeomagnetism of the Cape St Mary's sills.

| Location | Site | St (°) | Di (°) | K/R | A/T | D (°) | I (°) | D′ (°) | I′ (°) | $\alpha_{95}$ (°) | k |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lance Cove | 1 | 10 | 53 | 7R | A | 85.3 | −56.5 | 302.1 | −68.2 | 15/16 | 48 |
| Lance Cove | 2 | 26 | 4 | 4K | T | 344.1 | −66.9 | 337.9 | −64.1 | 6 | 205 |
| Lance Cove | 3 | 27 | 8 | 4R | A | 310.9 | −55.4 | 301.1 | −47.4 | 8/22 | 600 |
| Lance Cove | 4 | 180 | 40 | 3K | A | 319.9 | −31.4 | 357.3 | −49.0 | 16 | 64 |
| Lance Cove | 6 | 188 | 30 | 5K | T | 318.2 | −35.9 | 343.1 | −54.8 | 12 | 44 |
| Lance Cove | 7 | 196 | 30 | 3K | A | 315.8 | −37.1 | 331.6 | −58.4 | 19 | 42 |
| Lance Cove | 10 | 210 | 24 | 3K, 4R | A&T | 347.1 | −24.6 | 359.2 | −39.2 | 8/13 | 61 |
| Gull Cove | 12 | 168 | 30 | 4K, 5R | A&T | 320.8 | −42.2 | 351.7 | −48.7 | 7/9 | 68 |
| Hay Cove | 14 | 342 | 41 | 7R | A | 12.5 | −32.0 | 340.2 | −43.0 | 8/16 | 100 |
| Hay Cove[1] | 14S | 342 | 41 | 5K | A | 20.6 | −31.1 | 346.1 | −49.2 | 12 | 39 |
| Hay Cove[2] | DS | 350 | 50 | 3[3] | T | 16.0 | −45.2 | 321.4 | −43.8 | 17 | 53 |
| Hay Cove | 15 | 241 | 15 | 5K | T | 350.0 | −22.3 | 353.0 | −36.3 | 8 | 94 |
| Grassy Head | 17 | 20 | 40 | 5K | A | 36.5 | −53.2 | 346.2 | −46.3 | 7 | 128 |
| Grassy Head | 19 | 30 | 44 | 5K | A&T | 43.4 | −41.1 | 5.7 | −36.4 | 12 | 43 |
| Mean of 12 sill sites before untilting | | | | | | 347.8 | −48.2 | | | 18 | 7 |
| Mean of 12 sill sites after tilt correction[4] | | | | | | | | 343.8 | −50.8 | 9 | 25 |

[1] Sediment site adjacent to site 14; not used in mean statistical calculation.
[2] Sediment site adjacent to dyke D; not used in mean statistical calculation.
[3] Two specimen directions were determined using Kirschvink analysis; the third by averaging reasonably well-grouped directions obtained during the stepwise heating run.
[4] Paleomagnetic pole after tilt correction: 10°N, 140°E; dm = 12.0°; dp = 8.1° (dm and dp are the semiaxes of the oval of 95 per cent confidence about the mean palaeopole).
St = strike of the bed; Di = dip of the bed; K/R = number of Kirschvink/remagnetization circle analyses; A/T = AF/thermal demagnetization; D = mean declination *in situ*; I = mean inclination *in situ*; D′ = mean declination after tilt correction; I′ = mean inclination after tilt correction; $\alpha_{95}$ = radius of circle of 95 per cent confidence about mean direction for Kirschvink analyses, or semi-axes of oval of 95 per cent confidence for remagnetization circle analyses; k = precision parameter.

5–30 cm below the base of the 2.5 m thick sill (site 14S) and another six samples 11–15 m below the sill. Unfortunately the test proved inconclusive. Five of the samples close to the sill carried a stable remanence direction indistinguishable from the direction determined from great-circle analysis for the sill itself (whilst the sixth sample was unstably magnetized). The samples collected far from the sill were less stably magnetized than most of those sampled close to the sill, so it was not possible to calculate directions using Kirschvink analysis. Nevertheless, the directions from these samples before tilt correction tend to scatter between a steep down northerly direction (perhaps a present Earth's field magnetization) and shallow northerly directions, suggesting partial overprinting in a sill-like direction.

A second baked-contact test using an ESE-trending diabase dyke (site D) that cuts volcanogenic sedimentary rocks near site 14 also proved inconclusive. In this case, the sedimentary rocks were collected near (within 1 m at site DS) and far (6.5–9 m) from the 3 m wide dyke. For each of the dyke samples, the remanence swung to a direction similar to that observed in the Cape St Mary's sills upon AF or combined AF–thermal demagnetization, but the endpoint was not sufficiently stable to allow Kirschvink analysis. As was the case for the sills, unblocking temperatures of the characteristic component of the dyke samples were in the 400–550 °C range. Three of the six sediment samples collected close to the dyke (site DS) carry a stable sill-like remanence direction, with the remaining three samples being unstably magnetized. Far from the sill, remanence directions were either scattered or directed steeply down to the north (before tilt correction), probably carrying a present Earth's field magnetization.

In conclusion, we interpret the baked-contact tests as inconclusive. However, the stable remanence in the sills was acquired before Early Devonian folding and resides in low-Ti magnetite possessing unblocking temperatures between 400 and 550 °C. This is not likely to be a thermoviscous remagnetization since prehnite–pumpellyite metamorphism should involve heating to less than 300 °C (Beiersdorfer & Day 1995). Even if applied for 1 Myr, 300 °C should not have remagnetized magnetite with unblocking temperatures above ~400 °C according to single-domain theory (Pullaiah *et al.* 1975). Even the nomograms of Middleton & Schmidt (1982) predict that 300 °C applied for 1 Myr should not have remagnetized magnetite with unblocking temperatures above 500 °C, and 500 °C is probably an overestimate since it is based on the theory of Walton (1980), which was criticized by Enkin & Dunlop (1988), Worm & Jackson (1988) and Dunlop & Özdemir (1993). Dunlop, Özdemir & Schmidt (1997) show that samples that are inherently single-domain-like or have their multidomain remanence erased by prior low-temperature demagnetization behave as predicted by single-domain theory. Since our thermal demagnetization was usually preceded by partial AF demagnetization to remove multidomain remanence, unblocking temperatures above ~400 °C should not have been thermoviscously remagnetized by the prehnite–pumpellyite metamorphism. The stable remanence in the Cape St Mary's sills is probably a primary thermal remanence acquired when the sills cooled below ~550 °C at 441 ± 2 Ma.

## 5 DISCUSSION

We have argued that the stable remanence of the Cape St Mary's sills was acquired before Early Devonian folding

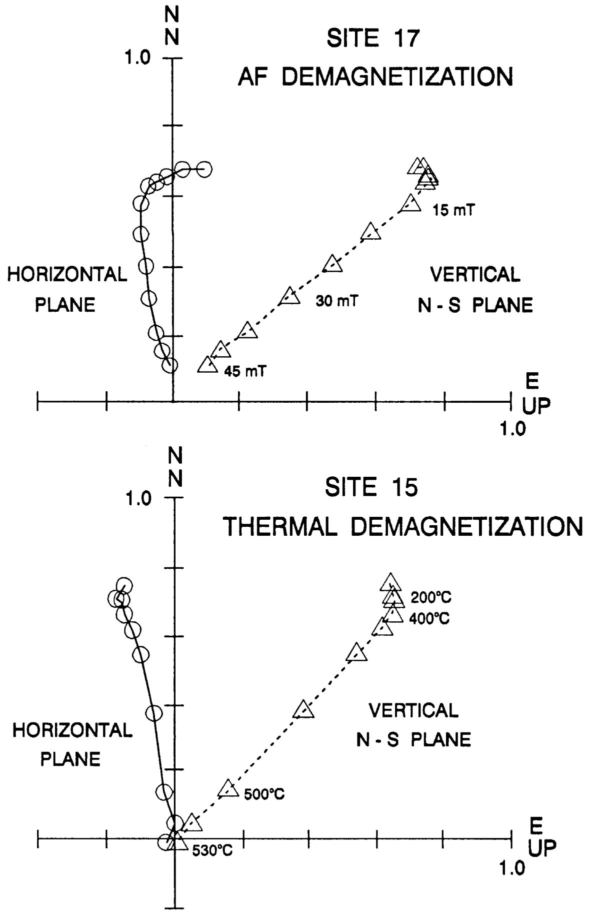


**Figure 2.** Examples of specimens from the Cape St Mary's sills that show little change in remanence direction after a soft viscous component is removed by demagnetization with ~15 mT alternating field or ~400 °C heating in field-free space. On these orthogonal component plots, circles represent projection of the end of the remanence vector onto the horizontal plane and triangles represent projection onto the vertical north–south plane. The results have been tilt-corrected.

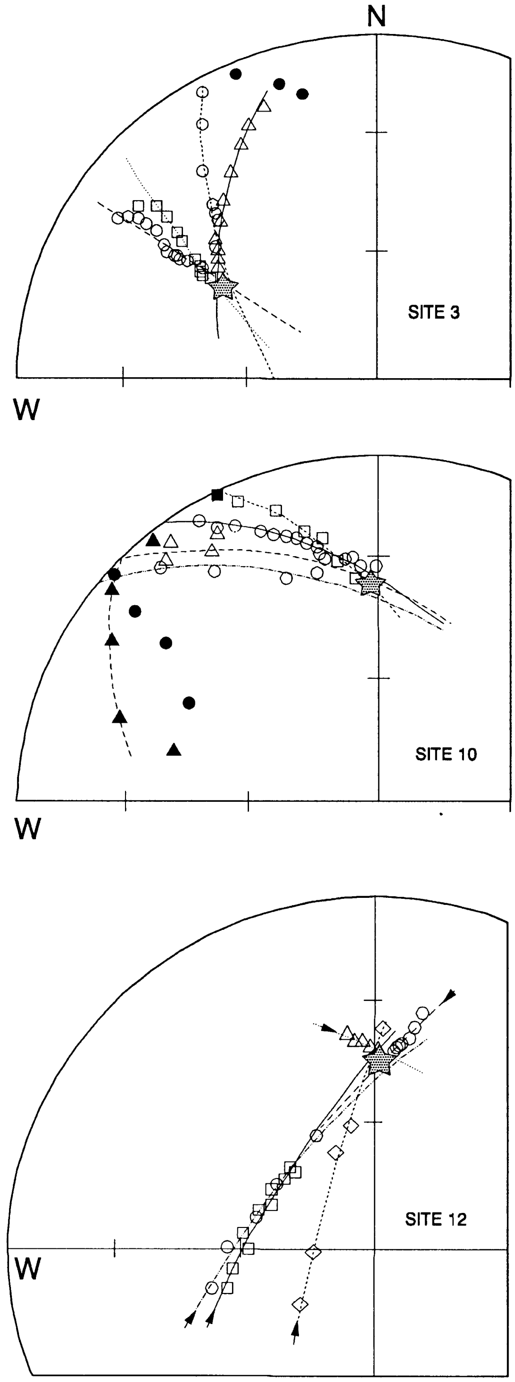


**Figure 3.** Examples of converging remagnetization circles from three sites in the Cape St Mary's sills. Open symbols indicate up directions on an equal-area stereographic projection, after tilt correction. The stars show the mean directions to which the remagnetization circles converge.

and that it probably records the magnetic field direction when the sills were intruded at 441 ± 2 Ma. (We quote $2\sigma$ errors for radiometric dates and 95 per cent confidence limits for palaeolatitude estimates throughout this paper.) Assuming that the sills represent a long enough time interval to average out palaeosecular variation, the average inclination of stable remanence relative to bedding provides a palaeolatitude estimate of 32°S ± 8° for the Avalon Peninsula in the latest Ordovician–earliest Silurian. As discussed above, a positive fold test has also been reported for the Dunn Point volcanics of the Avalon Zone of Nova Scotia (Johnson & Van der Voo 1990), yielding a palaeolatitude estimate, after unfolding, of 41°S ± 5° (Johnson & Van der Voo 1990).

The Dunn Point volcanics may be of latest Ordovician or earliest Silurian age, like the Cape St Mary's sills, since the Dunn Point volcanics are overlain with only slight unconformity by sediments containing earliest Silurian fossils (Boucot *et al.* 1974). If so, the palaeolatitude difference between the Dunn Point volcanics and the Cape St Mary's sills might be due to insufficient averaging out of palaeosecular variation or to latitudinal separation of these two parts of West Avalonia at 440 Ma. Separation might help to explain why the Avalon Peninsula of Newfoundland escaped the Ordovician deformation that affected the Avalonian of Nova Scotia, indicated by deformed Early Ordovician rocks unconformably overlain by the Dunn Point volcanics (Boucot *et al.* 1974).

However, the Dunn Point volcanics may be considerably older than the Cape St Mary's sills, because the time interval represented by the unconformity between the subaerial Dunn Point volcanics and the overlying earliest Silurian marine

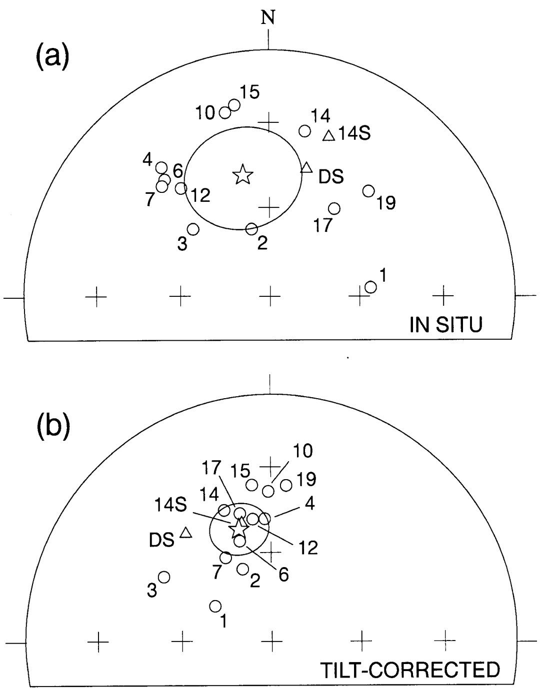


**Figure 4.** Fold test for stably magnetized sites in the Cape St Mary's sills. Sill directions (circles) and their mean (shown as a star) with its circle of 95 per cent confidence are illustrated (a) before and (b) after tilt correction. Open symbols indicate up directions. Triangles indicate sites 14S and DS (in sediments adjacent to sill site 14 and dyke D, respectively), which were used for baked-contact tests but are not used in calculating the mean sill direction.

sediments may have been 'considerable' (Boucot *et al.* 1974). We suggest that the Dunn Point volcanics may be approximately 10 Myr older than the Cape St Mary's sills, and that their palaeolatitude difference reflects northward drift of Avalonia (at a rate of $\sim 0.7^\circ$ Myr$^{-1}$, judging by the palaeolatitudes for East Avalonia in Fig. 5).

To test our suggestion, we recommend that precise U–Pb zircon dating be attempted for the Dunn Point volcanics. Zircons should be present in some of the ignimbrites since Zr contents as high as 1643 ppm are reported by Keppie, Dostal & Zentilli (1978). We consider the Rb–Sr date available for the Dunn Point volcanics (Fullagar & Bottino 1968) unreliable. With modern decay constants (Harland *et al.* 1990, p. 191), the date becomes $397 \pm 20$ Ma or, if the most discordant data point is omitted, $419 \pm 10$ Ma. Even the latter age is too young because the volcanics are unconformably overlain by sediments containing early Llandovery (Rhuddanian) fossils (Boucot *et al.* 1974) whose age should lie between 443 and 439 Ma according to the U–Pb zircon-based timescale of Tucker & McKerrow (1995). Greenschist facies metamorphism of the Dunn Point volcanics in the Devonian has affected Rb and Sr abundances (Keppie *et al.* 1978), which has probably caused the unreliability of Rb–Sr dating.

Early Ordovician to mid-Silurian palaeolatitude determinations for East Avalonia (parts of southern Britain and Ireland) are plotted versus time in Fig. 5. They are based only on palaeomagnetic results that have passed field tests for primary or pre-folding remanence. The late Tremadoc–early Arenig Treffgarne Volcanic Formation of Wales carries a primary remanence, as shown by a positive intraformational conglomerate test, and yields a $62^\circ$S$\pm 10^\circ$ palaeolatitude

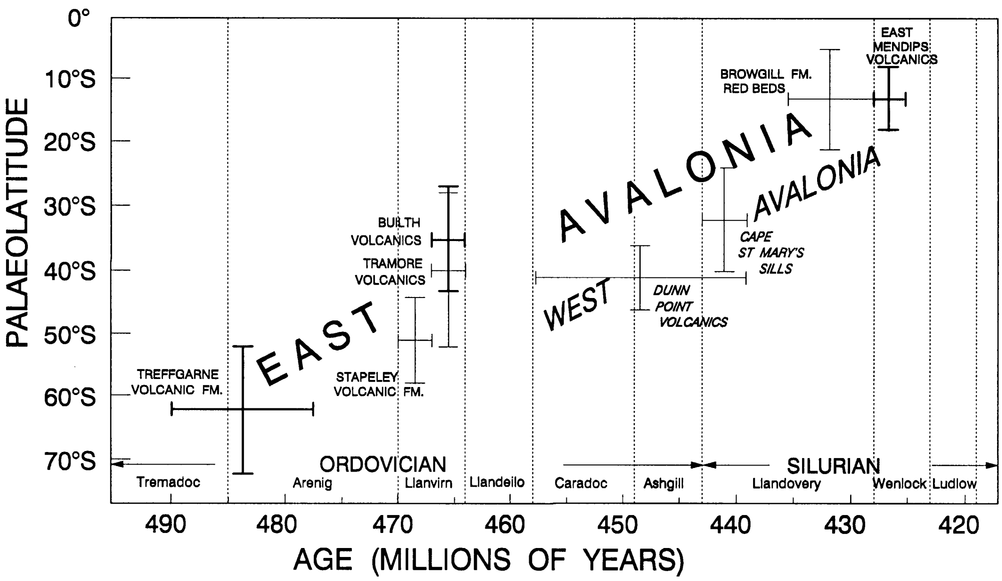


**Figure 5.** Early Ordovician to mid-Silurian palaeolatitudes estimated palaeomagnetically for Avalonia are plotted against age. References for the palaeolatitude determinations are given in the text. The 95 per cent confidence limits for palaeolatitudes are shown and primary remanence is assumed. (Results that pass tests for primary remanence are shown as bolder lines than results that have only passed tests for pre-folding remanence.) Except for the Cape St Mary's sills for which there is a U–Pb date, formation ages are based upon fossils and the age estimates of Tucker & McKerrow (1995) for epochs of the Ordovician and Silurian (shown by vertical dotted lines). Results from West (North American) Avalonia are shown in italic type to distinguish them from results from East Avalonia (parts of southern Britain and Ireland).

(Torsvik & Trench 1991; Trench *et al.* 1992). The early Llanvirn Stapeley Volcanic Formation of the Shelve Inlier of Wales carries a remanence that pre-dates Ashgill folding (Trench & Torsvik 1991; McCabe & Channell 1991; Channell *et al.* 1992) and yields a palaeolatitude of 51°S±7° (McCabe & Channell 1990; Channell *et al.* 1992). The late Llanvirn volcanics and related intrusives of the southern part of the Builth Inlier of Wales carry a primary remanence, judging by a positive conglomerate test, and yield a palaeolatitude of 35°S±8° (Trench *et al.* 1991), with similar results from the combined north and south Builth results of McCabe, Channell & Woodcock (1992), although Channell *et al.* (1992) argued that the south Builth results are anomalous. The late Llanvirn volcanics of Tramore, southeast Ireland, carry a remanence that pre-dates Devonian folding and yields a palaeolatitude of 40°S±12° (Deutsch 1980). The early Wenlock volcanics from the East Mendips Inlier of southern England carry a primary remanence as shown by a positive agglomerate test, and yield a palaeolatitude of 13°S±5° (Trench & Torsvik 1992; Torsvik *et al.* 1993). The late Llandovery Browgill Formation red beds of the English Lake District carry a remanence that pre-dates Devonian folding and yields a palaeolatitude estimate of 13°S±7° (Channell, McCabe & Woodcock 1993).

Note that no *late* Ordovician results for East Avalonia are plotted in Fig. 5. The early Caradocian Borrowdale Volcanic Group of the English Lake District was omitted because it carries a *post*-folding remanence whose age is uncertain (Channell & McCabe 1992). Although the Caradocian Moel-y-Golfa Andesite of Wales may carry a primary remanence, judging by a conglomerate test, and its palaeolatitude estimate is consistent with those in Fig. 5, it was omitted because only one site was studied (Piper 1995).

The results shown in Fig. 5 suggest that East Avalonia was drifting steadily northwards during the Ordovician and early Silurian. Although no East Avalonian results are available for times near the Ordovician–Silurian boundary, interpolation in Fig. 5 would suggest a ~25°S palaeolatitude. This is compatible with the 32°S±8° palaeolatitude yielded by the Cape St Mary's sills for West Avalonia, as can be seen in Fig. 6. This makes it unlikely that Avalonia moved to ~57°S in the Caradoc as suggested by Piper (1995), since this southerly excursion would require Avalonia to move back northwards by ~30° during the ~6 Myr of the Ashgill. Also, Piper's suggestion is mostly based on the palaeomagnetism of the Breidden Dolerite, which does not pass the fold test with 95 per cent confidence.

Fig. 6 shows a possible palaeogeography for ~440 Ma, assuming that subsequent closure of the Iapetus Ocean was orthogonal, and using palaeomagnetically estimated palaeolatitudes and north directions. For West Avalonia, we used the 32°S palaeolatitude and the northerly direction yielded by the Cape St Mary's sills. For East Avalonia, we used a ~25°S palaeolatitude (interpolated from Fig. 5) and assumed that the positions of East and West Avalonia relative to one another were those held just before the opening of the Atlantic (as illustrated by Stevens 1986). For Laurentia, we used the 26°S palaeolatitude and north directions (corrected for oroclinal bending) yielded by the Juniata and Rose Hill formations of

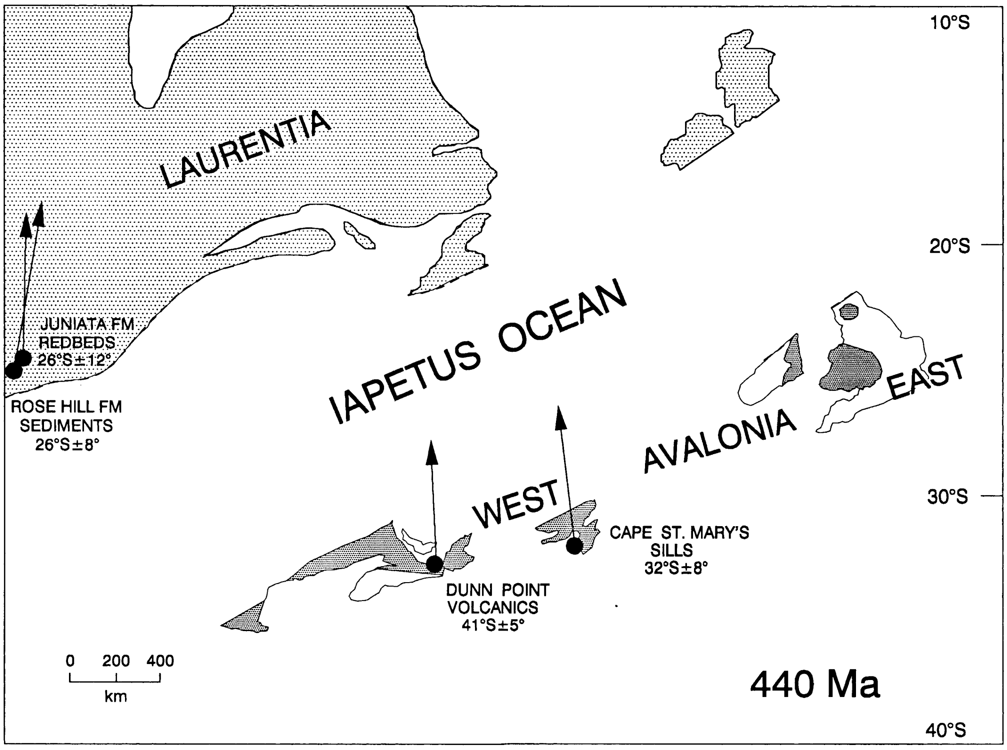


**Figure 6.** A possible continental reconstruction for ~440 Ma (the Ordovician–Silurian boundary) based on palaeomagnetism and the assumption of orthogonal closure of the Iapetus Ocean. Palaeomagnetically determined palaeolatitudes and north arrows are indicated. Laurentia is shown lightly stippled, with northern Britain and Ireland in their pre-Atlantic-opening position relative to North America (following Stevens 1986). West Avalonia (from the Avalon Peninsula of Newfoundland to the Boston area) and East Avalonia (parts of southern Britain and Ireland) are shown darkly stippled and in their pre-Atlantic-opening positions relative to one another. Terranes between Laurentia and Avalonia (such as the Gander Terrane) are omitted.

the central Appalachians. The Ashgill-aged Juniata Formation red beds carry a remanence that pre-dates Late Carboniferous folding and yields a palaeolatitude estimate of 26°S ± 12° (Miller & Kent 1989). The late Llandovery Rose Hill sediments (excluding reversely magnetized red sandstones) carry a remanence that pre-dates Late Carboniferous folding and yields a palaeolatitude estimate of 26°S ± 8° (French & Van der Voo 1979). In the reconstruction of Fig. 6, the Iapetus Ocean has a width of ~1000 km.

Van der Pluijm *et al.* (1995), Torsvik *et al.* (1996) and MacNiocaill *et al.* (1997) show a palaeogeography similar to Fig. 6 for ~440 Ma, but position Avalonia a little further north, hence narrowing the Iapetus Ocean. A narrower Iapetus is supported by Nd isotope studies suggesting that early Llandovery sediments overlying the Dunn Point volcanics of Nova Scotia were derived not from Avalonia but perhaps from Laurentia (Murphy *et al.* 1996). Also, the geochemistry of the Cape St Mary's sills is consistent with formation in a transpressional tectonic environment, perhaps signalling the start of docking between the Avalon and Gander terranes (Greenough *et al.* 1993). On the other hand, MacNiocaill & Smethurst (1994) position Avalonia a little further south than in Fig. 6, widening the Iapetus Ocean. A wider Iapetus is supported by graptolites that retain non-Laurentian affinities at least to middle Llandovery time in central Newfoundland (Williams & O'Brien 1991) and to middle Wenlock time in central Ireland (Lenz & Vaughan 1994). Both narrower and wider Iapetus Ocean models than that of Fig. 6 are permitted by the errors in the palaeolatitude determinations, which are typically ~8° (~900 km).

Dalziel's (1997) model implies that there was a large dextral shear component to the closure of the eastern Iapetus Ocean in the late Ordovician. That is, Laurentia may have been much further west relative to Avalonia than portrayed in Fig. 6, making the Iapetus wider. On the other hand, structural studies (Soper *et al.* 1992; Hibbard 1994; van Staal 1994) provide evidence for sinistral transpression during Silurian closure of the Iapetus. This led Soper *et al.* (1992) to place Laurentia at 440 Ma a little further east relative to Avalonia than in Fig. 6, making the Iapetus narrower. Both more westerly and more easterly positions for Laurentia than shown in Fig. 6 are permitted by the palaeomagnetic data, since they constrain palaeolatitude but not palaeolongitude.

## 6 CONCLUSIONS

The Cape St Mary's sills carry a pre-folding remanence that was probably acquired when they cooled below 550 °C soon after intrusion at 441 ± 2 Ma. This remanence yields a palaeolatitude estimate of 32°S ± 8° for the Avalon Peninsula of West Avalonia at ~440 Ma. The only other palaeomagnetic results from West Avalonia that may be of similar age are from the Dunn Point volcanics of Nova Scotia, which yield a palaeolatitude estimate of 41°S ± 5° (Johnson & Van der Voo 1990). We suggest that the difference in the two palaeolatitude estimates may be due to the Dunn Point volcanics being significantly older than 440 Ma, and recommend U–Pb dating of the volcanics to test this hypothesis. Although no high-quality palaeomagnetic data for ~440 Ma exist for East Avalonia, interpolation between mid-Ordovician and mid-Silurian results suggests a palaeolatitude of ~25°S, consistent with ~32°S for the Cape St Mary's sills. If the Iapetus Ocean closed orthogonally, the palaeomagnetic data suggest a narrow (~1000 km) Iapetus Ocean of approximately east–west orientation between Avalonia and Laurentia by 440 Ma.

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## REFERENCES

Bailey, R.C. & Halls, H.C., 1984. Estimate of confidence in directions derived from mixed remagnetization circle and direct observational data, *J. Geophys.,* **54,** 174–182.

Beiersdorfer, R.E. & Day, H.W., 1995. Mineral paragenesis of pumpellyite, in *Low-Grade Metamorphism of Mafic Rocks,* eds Schiffman, P. & Day, H.W., *Geol. Soc. Am., Spec. Pap.,* **296,** 5–27.

Boucot, A.J., Dewey, J.F., Dineley, D.L., Fletcher, R., Fyson, W.K., Griffin, J.G., Hickox, C.F., McKerrow, W.S. & Ziegler, A.M., 1974. Geology of the Arisaig Area, Antigonish County, Nova Scotia, *Geol. Soc. Am. Spec. Paper,* **139**.

Channell, J.E.T. & McCabe, C., 1992. Palaeomagnetic data from the Borrowdale Volcanic Group: volcano-tectonics and Late Ordovician palaeolatitudes, *J. geol. Soc., Lond.,* **149,** 881–888.

Channell, J.E.T., McCabe, C., Torsvik, T.H., Trench, A. & Woodcock, N.H., 1992. Palaeozoic palaeomagnetic studies in the Welsh Basin–recent advances, *Geol. Mag.,* **129,** 533–542.

Channell, J.E.T., McCabe, C. & Woodcock, N.H., 1993. Palaeomagnetic study of Llandovery (Lower Silurian) red beds in north-west England, *Geophys. J. Int.,* **115,** 1085–1094.

Crowley, T.J. & Baum, S.K., 1995. Reconciling Late Ordovician (440 Ma) glaciation with very high (14X) $CO_2$ levels, *J. geophys. Res.,* **100D,** 1093–1101.

Dallmeyer, R.D. & Keppie, J.D., 1993. $^{40}Ar/^{39}Ar$ mineral ages from the southern Cape Breton Highlands and Creignish Hills, Cape Breton Island, Canada: evidence for a polyphase tectonothermal evolution, *J. Geol.,* **101,** 467–482.

Dalziel, I.W.D., 1997. Neoproterozoic–Paleozoic geography and tectonics: review, hypothesis, environmental speculation, *Geol. Soc. Am. Bull.,* **109,** 16–42.

Deutsch, E.R., 1980. Magnetism of the mid-Ordovician Tramore volcanics, SE Ireland, and the question of a wide Proto-Atlantic Ocean, *J. Geomagn. Geoelectr.,* **32,** S111, 77–78.

Dunlop, D.J. & Özdemir, Ö., 1993. Thermal demagnetization of VRM and pTRM of single domain magnetite: no evidence for anomalously high unblocking temperatures, *Geophys. Res. Lett.,* **20,** 1939–1942.

Dunlop, D.J., Özdemir, Ö. & Schmidt, P.W., 1997. Paleomagnetism and paleothermometry of the Sydney Basin II. Origin of anomalously high unblocking temperatures, *J. geophys. Res.,* **1028,** 27 285–27 295.

Enkin, R.J. & Dunlop, D.J., 1988. The demagnetization temperature necessary to remove viscous remanent magnetization, *Geophys. Res. Lett.,* **15,** 514–517.

Fletcher, T.P., 1972. Geology and Lower to Middle Cambrian trilobite fauna of the southwest Avalon, Newfoundland, *PhD thesis,* University of Cambridge, Cambridge.

French, A.N. & Van der Voo, R., 1979. The magnetization of the Rose Hill Formation at the classical site of Graham's fold test, *J. geophys. Res.,* **84B,** 7688–7696.

Fullagar, P.D. & Bottino, M.L., 1968. Radiometric age of the volcanics at Arisaig, Nova Scotia, and the Ordovician–Silurian boundary, *Can. J. Earth Sci.,* **5,** 311–317.

Greenough, J.D., Kamo, S.L. & Krogh, T.E., 1993. A Silurian U–Pb age for the Cape St Mary's sills, Avalon Peninsula, Newfoundland, Canada: implications for Silurian orogenesis in the Avalon Zone, *Can. J. Earth Sci.,* **30,** 1607–1612.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G. & Smith, D.G., 1990. *A Geologic Time Scale 1989,* Cambridge University Press, Cambridge.

Hibbard, J., 1994. Kinematics of Acadian deformation in the Northern and Newfoundland Appalachians, *J. Geol.,* **102,** 215–228.

Hodych, J.P. & Buchan, K.L., 1994a. Paleomagnetism of the early Silurian Cape St Mary's sills of the Avalon Peninsula of Newfoundland, Canada, *EOS, Trans. Am. geophys. Un.,* **75,** 128.

Hodych, J.P. & Buchan, K.L., 1994b. Reply to comment by Stamatakos *et al.* on 'Early Silurian palaeolatitude of the Springdale Group redbeds of central Newfoundland: a palaeomagnetic determination with a remanence anisotropy test for inclination error', *Geophys. J. Int.,* **119,** 1014–1015.

Hodych, J.P. & Patzold, R., 1980. Paleomagnetism of folded Lower Paleozoic sills of the Avalon Peninsula, Newfoundland, *EOS, Trans. Am. geophys. Un.,* **61,** 220.

Johnson, R.J.E. & Van der Voo, R., 1990. Pre-folding magnetization reconfirmed for the Late Ordovician–Early Silurian Dunn Point volcanics, Nova Scotia, *Tectonophysics,* **178,** 193–205.

Keppie, J.D., Dostal, J. & Zentilli, M., 1978. Petrology of the Early Silurian Dunn Point and McGillivray Brook Formations, Arisaig, Nova Scotia, *Nova Scotia Department of Mines,* Paper **78–5**.

Keppie, J.D., Dostal, J., Murphy, J.B. & Nance, R.D., 1996. Terrane transfer between eastern Laurentia and western Gondwana in the early Paleozoic: constraints on global reconstruction, in *Avalonian and Related Peri-Gondwanan Terranes of the Circum-North Atlantic,* eds Nance, R.D. & Thompson, M.D., *Geol. Soc. Am. Spec. Paper,* **304,** 369–380.

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of paleomagnetic data, *Geophys. J. R. astr. Soc.,* **62,** 699–718.

Lenz, A.C. & Vaughan, A.P.M., 1994. A late Ordovician to middle Wenlockian graptolite sequence from a borehole within the Rathkenny Tract, eastern Ireland, and its relation to the paleogeography of the Iapetus Ocean, *Can. J. Earth Sci.,* **31,** 608–616.

McCabe, C. & Channell, J.E.T., 1990. Paleomagnetic results from volcanic rocks of the Shelve Inlier, Wales: evidence for a wide late Ordovician Iapetus Ocean in Britain, *Earth planet. Sci. Lett.,* **96,** 458–468.

McCabe, C. & Channell, J.E.T., 1991. Reply to comment of A. Trench and T. H. Torsvik on 'Paleomagnetic results from volcanic rocks of the Shelve Inlier, Wales: evidence for a wide Late Ordovician Iapetus Ocean in Britain', *Earth planet. Sci. Lett.,* **104,** 540–544.

McCabe, C., Channell, J.E.T. & Woodcock, N.H., 1992. Further paleomagnetic results from the Builth Wells Ordovician Inlier, Wales, *J. geophys. Res.,* **97B,** 9357–9370.

McElhinny, W., 1964. Statistical significance of the fold test in paleomagnetism, *Geophys. J. R. astr. Soc.,* **8,** 338–340.

McFadden, P.L., 1990. A new fold test for palaeomagnetic studies, *Geophys. J. Int.,* **103,** 161–169.

MacNiocaill, C. & Smethurst, M.A., 1994. Paleozoic paleogeography of Laurentia and its margins: a reassessment of palaeomagnetic data, *Geophys. J. Int.,* **116,** 715–725.

MacNiocaill, C., van der Pluijm, B.A. & Van der Voo, R., 1997. Ordovician paleogeography and the evolution of the Iapetus ocean, *Geology,* **25,** 159–162.

Middleton, M.F. & Schmidt, P.W., 1982. Paleothermometry of the Sydney Basin, *J. geophys. Res.,* **87,** 5351–5359.

Miller, J.D. & Kent, D.V., 1989. Paleomagnetism of the Upper Ordovician Juniata Formation of the Central Appalachians revisited again, *J. geophys. Res.,* **94B,** 1843–1849.

Murphy, J.B., Keppie, J.D., Dostal, J., Waldron, J.W.F. & Cude, M.P., 1996. Geochemical and isotopic characteristics of Early Silurian clastic sequences in Antigonish Highlands, Nova Scotia, Canada: constraints on the accretion of Avalonia in the Appalachian–Caledonide Orogen, *Can. J. Earth Sci.,* **33,** 379–388.

Piper, J.D.A., 1995. Palaeomagnetism of Late Ordovician igneous intrusions from the northern Welsh Borderlands: implications to motion of Eastern Avalonia and regional rotations, *Geol. Mag.,* **132,** 65–80.

Pullaiah, G., Irving, E., Buchan, K.L. & Dunlop, D.J., 1975. Magnetization changes caused by burial and uplift, *Earth planet. Sci. Lett.,* **28,** 133–143.

Seguin, M.K., Rao, K.V. & Deutsch, E.R., 1987. Paleomagnetism and rock magnetism of Early Silurian Dunn Point volcanics, Avalon Zone, Nova Scotia, *Phys. Earth planet. Inter.,* **46,** 369–380.

Soper, N.J., Strachan, R.A., Holdsworth, R.E., Gayer, R.A. & Greiling, R.O., 1992. Sinistral transpression and the Silurian closure of Iapetus, *J. geol. Soc. Lond.,* **149,** 871–880.

Stamatakos, J., Lessard, A.M., van der Pluijm, B.A. & Van der Voo, R., 1995. Paleomagnetism and magnetic fabrics from the Springdale and Wigwam redbeds of Newfoundland and their implications for the Silurian paleolatitude controversy, *Earth planet. Sci. Lett.,* **132,** 141–155.

Stevens, M.B., 1986. Stratabound sulphide deposits of the Appalachian–Caledonian Orogen, *Geol. Surv. Can.,* Map 1649A.

Torsvik, T.H. & Trench, A., 1991. The Ordovician history of the Iapetus Ocean in Britain: new palaeomagnetic constraints, *J. geol. Soc. Lond.,* **148,** 423–425.

Torsvik, T.H., Trench, A., Svensson, I. & Walderhaug, H.J., 1993. Palaeogeographic significance of mid-Silurian palaeomagnetic results from southern Britain–major revision of the apparent polar wander path for eastern Avalonia, *Geophys. J. Int.,* **113,** 651–668.

Torsvik, T.H., Smethurst, M.A., Meert, J.G., Van der Voo, R., McKerrow, W.S., Brasier, M.D., Sturt, B.A. & Walderhaug, H.J., 1996. Continental break-up and collision in the Neoproterozoic and Paleozoic–a tale of Baltica and Laurentia, *Earth Sci. Rev.,* **40,** 229–258.

Trench, A. & Torsvik, T.H., 1991. Comment on 'Palaeomagnetic results from volcanic rocks of the Shelve Inlier, Wales: evidence for a wide Late Ordovician Iapetus Ocean in Britain' by C. McCabe & J.E.T. Channell, *Earth planet. Sci. Lett.,* **104,** 535–539.

Trench, A. & Torsvik, T.H., 1992. The closure of the Iapetus Ocean and Tornquist Sea: new palaeomagnetic constraints, *J. geol. Soc. Lond.,* **149,** 867–870.

Trench, A., Torsvik, T.H., Smethurst, M.A., Woodcock, N.H. & Metcalf, R., 1991. A palaeomagnetic study of the Builth Wells–Llandrindod Wells Ordovician inlier, Wales: palaeogeographic and structural implications, *Geophys. J. Int.,* **105,** 477–489.

Trench, A., Torsvik, T.H., Dentith, M.C., Walderhaug, H. & Traynor, J.J., 1992. A high southerly palaeolatitude for Southern Britain in Early Ordovician times: palaeomagnetic data from the Treffgarne Volcanic Formation SW Wales, *Geophys. J. Int.,* **108,** 89–100.

Tucker, R.D. & McKerrow, W.S., 1995. Early Paleozoic chronology: a review in light of new U–Pb zircon ages from Newfoundland and Britain, *Can. J. Earth Sci.,* **32,** 368–379.

van der Pluijm, B.A., Van der Voo, R. & Torsvik, T.H., 1995. Convergence and subduction at the Ordovician margin of Laurentia, in *Current Perspectives in the Appalachian–Caledonian Orogen,* eds Hibbard, J.P., van Staal, C.R. & Cawood, P.A., *Geol. Assc. Can. Spec. Paper,* **41,** 127–136.

Van der Voo, R. & Johnson, R.J.E., 1985. Paleomagnetism of the Dunn Point Formation (Nova Scotia): high paleolatitudes for the Avalon Terrane in the Late Ordovician, *Geophys. Res. Lett.,* **12,** 337–340.

van Staal, C.R., 1994. Brunswick subduction complex in the Canadian Appalachians: record of the Late Ordovician to Late Silurian collision between Laurentia and the Gander margin of Avalon, *Tectonics,* **13,** 946–962.

Walcott, C.D., 1889. Stratigraphic position of the *Olenellus* fauna in North America and Europe: *Am. J. Sci.,* **30,** 29–42.

Walton, D., 1980. Time–temperature relations in the magnetizations of assemblies of single domain grains, *Nature,* **286,** 245–247.

Williams, H., 1993. Acadian orogeny in Newfoundland, in *The Acadian Orogeny: Recent Studies in New England, Maritime Canada and the Autochthonous Foreland,* eds Ray, D.C. & Skehan, J.W., *Geol. Soc. Am., Spec. Paper,* **275,** 123–133.

Williams, H. & Hatcher, R.D., Jr., 1983. Appalachian suspect terranes, in *Contributions to the Tectonics and Geophysics of Mountain Chains,* eds Hatcher, R.D., Jr., Williams, H. & Zietz, I., *Geol. Soc. Am. Memoir,* **158,** 33–53.

Williams, S.H. & O'Brien, B.H., 1991. Silurian (Llandovery) graptolites from the Bay of Exploits, north-central Newfoundland, and their geological significance, *Can. J. Earth Sci,* **28,** 1534–1540.

Wilson, J.T., 1966. Did the Atlantic close and then re-open?, *Nature,* **211,** 676–681.

Worm, H.U. & Jackson, M., 1988. Theoretical time–temperature relationships of magnetization for distributions of single domain magnetite grains, *Geophys. Res. Lett.,* **15,** 1093–1096.