Geophys. J. Int. (1994) **119**, 1009–1013

Comment on: 'Early Silurian palaeolatitude of the Springdale Group redbeds of central Newfoundland: a palaeomagnetic determination with a remanence anisotropy test for inclination error' by J. P. Hodych and K. L. Buchan

John Stamatakos, Rob Van der Voo, Ben van der Pluijm, Stephen Potts and Trond Torsvik*

Department of Geological Sciences, The University of Michigan, Ann Arbor, Michigan 48109-1063, *USA*

Accepted 1994 August 19. Received 1994 June 3

SUMMARY

Recent palaeomagnetic results from coeval Silurian sedimentary and volcanic rocks of Newfoundland yield contradictory results, with shallow characteristic directions recorded by the redbeds and steeper characteristic directions recorded by the volcanics. In their recent paper on the Springdale Group redbed, Hodych & Buchan (1994a) argue that the redbed magnetization is more reliable based on a fold test, dual-polarity magnetization, conglomerate test and an IRM acquisition experiment specifically designed to test for compaction or inclination error. Accordingly, these authors dismiss the volcanic results as well as the Silurian reference poles for Laurentia, citing possible remagnetization or other complications. However, we argue that the IRM experiments of Hodych & Buchan (1994a) are flawed and do not necessarily resolve the question of inclination error. Moreover, we point out that the conglomerate test is incomplete and that the proposed tectonic reconstruction based solely on the redbed magnetization implies a unique tectonic scenario that is incompatible with out present understanding of Silurian palaeogeography.

Key words: Iapetus, inclination error, IRM anisotropy, palaeomagnetism, redbeds, Silurian palaeogeography.

In their recent paper on the Springdale Group redbeds, Hodych & Buchan (1994a) present palaeomagnetic results that place Newfoundland near equatorial palaeolatitudes during the Silurian. These results are in agreement with palaeomagnetic results from previous studies of the Springdale Group (Potts, van der Pluijm & Van der Voo 1993a) and other Silurian redbeds of Newfoundland (Lapointe 1979; Buchan & Hodych 1989, 1992; Potts, Van der Pluijm & Van der Voo 1993b) but are significantly different from coeval volcanic rocks from Newfoundland (Potts *et al.* 1993a; Gales, van der Pluijm & Van der Voo 1989; Lapointe 1979) as well as volcanics from Nova Scotia (Van der Voo & Johnson 1985; Johnson & Van der Voo 1990), that indicate much higher southerly palaeolatitudes at this time. Discrepancies in palaeolatitudes determined from coeval sedimentary and volcanic rocks are not unique to Newfoundland. Southern Alaska (Coe *et al.* 1985) and southern Britain (Torsvik *et al.* 1993) are also notable examples where sedimentary and igneous rocks yield contradictory palaeolatitudes. These discrepancies have been alternatively explained as deflection of the remanence vectors to shallower directions because of compaction or other techonic strains, preferential remagnetization of one of the rock types or unaveraged secular variation in the volcanic rocks.

Hodych & Buchan (1994a) argue that their mean direction for the Springdale Group is a reliable primary magnetization based on a fold test, dual-polarity magnetization, conglomerate test and an IRM acquisition experiment specifically designed to test for compaction or inclination error. From their results, the authors then infer that the Springdale and Wigwam redbed magnetizations provide the correct palaeogeographic position for Laurentia in the Silurian. Accordingly, these authors not only dismiss steeper directions from the volcanic rocks but also results from other Silurian sedimentary units in the central Appalachians and Indiana on the basis that they are less reliable; either because of inadequate structural control or unaveraged secular variation in the case of the volcanics or unrecognized remagnetizations of the Silurian rocks in the central

* On leave from: Geological Survey of Norway, NGU, P.B. 3006 Lade, N-7002 Trøndheim, Norway.

Appalachians. These conclusions have obvious and important implications for circum-Iapetus palaeogeography, because they suggest that Laurentia stayed in equatorial palaeolatitudes for much of the middle Palaeozoic.

Upon closer examination of the methods and results in the paper of Hodych & Buchan (1994a) we argue that the rock magnetic study is flawed and does not resolve the question of possible inclination shallowing. We also point out that the conglomerate test is incomplete and that the proposed tectonic reconstruction based solely on the Springdale and Wigwam results implies a unique tectonic scenario that is incompatible with out present understanding of Silurian palaeogeography. Therefore, although the palaeomagnetic directions from the Hodych & Buchan (1994a) study appear to be well determined and agree with other recently published observations from the Springdale redbeds (Potts *et al.* 1993a), the question of **why** sedimentary and volcanic rocks yield different directions remains unanswered and awaits further investigation.

IRM EXPERIMENTS

To test for possible inclination shallowing or compaction error, Hodych & Buchan (1994a) used a simple IRM experiment in which they applied an isothermal DC field to selected samples at 45° to bedding in increasing field strengths between 10 and 800 mT. The resulting IRMs were then measured and plotted as the vertical component (IRM_z) against the horizontal component in the direction of the applied field (IRM_x). The samples are then thermally demagnetized and the same ratio is again plotted. There are several important limitations to this method.

(1) The applied fields are too small to magnetize most of the haematite fraction. This can be seen in their Figs 8(a) and 9(a), in which the IRM acquisition curves are still increasing at 800 mT; haematite does not reach saturation until applied fields in excess of 3000 mT (e.g. Dunlop 1970) and may not reach saturation in fields up to 8000 mT (Nagata 1961). The authors argue that this is not a significant problem because thermal demagnetization of the IRM shows unblocking temperatures near 680 °C, similar to the unblocking of the natural remanent magnetization (NRM). However, in haematite, coercivity and unblocking temperature are not strongly coupled. Unblocking temperature is primarily a function of grain size (Néel 1949; Dodson & McClelland-Brown 1980) such that larger grains have a higher unblocking temperature. Coercivity is a function of crystalline anisotropy (Stacey & Banerjee 1974), although coercivity may also be strongly influenced by defects in the crystal lattice. In fact, the role of lattice defects is poorly understood (*cf.* Dunlop 1970, 1971), which itself makes interpretation of the IRM results problematic.

We suggest that the low applied fields in this experiment preferentially magnetized the unstable fraction of haematite (probably the multidomain grains) that do not contribute to the characteristic remanent magnetization. Because these grains may be relatively large, it is not surprising that they unblocked at temperatures near 680 °C despite their low coercivities. The higher coercivity haematite, those grains that most likely carry the Silurian remanence in these rocks were never remagnetized by the applied IRM fields and thus, any preferential orientation of these grains relative to bedding was not directly tested. In fact if the graph in Fig. 8(a) is extrapolated to higher fields, in the range near haematite saturation, it appears that the increasing difference between the intensity of the IRM_x compared to IRM_z would lead to the opposite conclusion, i.e. that significant deflection of the remanence within bedding has occurred.

(2) The approach of using only one direction of induced magnetization does not adequately describe the fabric of the constituent haematite grains. The essential idea is to determine the preferred orientation of the haematite basal planes relative to bedding, because, as noted by the authors, remanence in haematite lies within its basal plane. Similar to the anisotropy of magnetic susceptibility, the anisotropy of remanence can be completely described by a symmetric second-order tensor. Such a tensor quantity requires a minimum of six independent orientations of IRM acquisition, five more than used in the Hodych & Buchan (1994a) experiment. This problem is compounded by the fact that an IRM is an inadequate substitute for NRM or CRM, especially because of the higher stability of IRM in multidomain grains (Lowrie & Fuller 1971; Nagata 1961).

(3) Recent work of Deamer & Kodama (1990) and Sun & Kodama (1992) show that significant shallowing of the NRM can occur during the initial consolidation of the sediments matrix grains. Inclination shallowing during this initial consolidation phase is not accounted for by the theoretical relation of Jackson *et al.* (1991).

CONGLOMERATE TEST

The authors present a positive conglomerate test as evidence that the magnetization in the redbeds has not been thermally reset and by inference that it is primary in the sense that it was acquired at or near the time of deposition. This conclusion would also be reached by considering the fact that maximum temperatures experienced by most redbeds in mildly deformed terranes (generally lower greenschist facies) are not nearly high enough to thermally reset the magnetization (Kent & Miller 1988). It seems much more likely that if these redbeds are remagnetized, then this secondary magnetization would be a CRM.

The test used by Hodych & Buchan (1994a) is incomplete because the clasts in the conglomerate are volcanic and not composed of the same material as the remanence yielding redbeds. It is possible that the redbeds were chemically remagnetized after the deposition of the conglomerate and that this chemical remagnetization did not alter the rhyolite clasts in the conglomerate. There are examples in both southern Britain (Torsvik *et al.* 1993) and Alaska (Coe *et al.* 1985) where the more stable volcanic rocks avoided chemical remagnetization while the surrounding sediments were reset. Viewed in this light, the conglomerate test presented by Hodych & Buchan (1944a) does not add to the reliability of the remanent magnetization of the Springdale Group.

IMPLICATIONS FOR APPARENT POLAR WANDER

(1) Hodych & Buchan (1944a) argue that the Rose Hill Formation is not reliable because the age of the

magnetization is only known to predate the late Palaeozoic Alleghanian folding. Yet, the authors overlook several other Silurian–Devonian results that agree with the Rose Hill results (French & Van der Voo 1977), namely the Wabash Reef (McCabe *et al.* 1985), Bloomsburg Formation (Stamatakos & Kodama 1991) and Andreas redbeds (Miller & Kent 1988), all of which defined a Silurian–Devonian APW path track that moves Laurentia into middle Southern Hemisphere latitudes during Silurian/Lower Devonian time. From this position, North America moves steadily northward, crossing the equator in Permian time. This Palaeozoic motion for North America is also supported by numerous results from Europe, Great Britain, and Baltica (Van der Voo 1990), as well as by palaeofacies and palaeoclimate considerations (e.g. Witzke 1990). While the implication by Hodych & Buchan (1994a) that the other palaeomagnetic results lack a stability test (such as a complete conglomerate test) that definitively proves a Silurian age of magnetization is essentially correct, it seems unlikely that all these results from widely separated areas are remagnetized. The Bloomsburg, Wabash Reef, Andreas and Rose Hill results yield both polarity magnetizations and positive fold tests. While folding of the Appalachian rocks is Permian, folding of the Wabash Reef is Devonian or older. Moreover, after the Silurian, North America never again reached the southerly palaeolatitudes needed to produce the rather steep directions characteristic of the Rose Hill, Bloomsburg, Wabash Reef and Andreas rocks. This lack of similarity to younger palaeomagnetic poles is an important criterion overlooked in Hodych & Buchan's (1994a) discussion of possible remagnetizations.

(2) The suggestion that results from the Dunn Point Formation volcanics are unreliable because of a 'controversial age of magnetization' relative to folding is misleading. Johnson & Van der Voo (1990) show that bedding corrections used by Seguin, Rao & Deutsch (1987) to argue for an inconclusive fold test and hence, unconstrained age of magnetization, were incorrect. When the correct values for bedding are used, the magnetization predates folding. The matter can only be considered controversial if it is shown that the actual bedding attitudes are different from those so carefully measured by Johnson & Van der Voo (1990). To our knowledge such 'errors' have not been demonstrated. The relatively high southerly palaeolatitudes indicated by the Dunn Point are in agreement with results of Hodych & Buchan (1994b) for Newfoundland and these further support the conclusion of relatively high southerly palaeolatitudes for North America in the latest Ordovician and Silurian.

(3) Hodych & Buchan (1994a) state that the temporal constraints on their central Newfoundland closure model (early Silurian) are comparable with that of Torsvik *et al.* (1993) for the British Sector of the Iapetus Ocean. This statement seems curious since the model of Torsvik *et al.* (1993) was, to a large extent, based on palaeomagnetic data from Laurentia that Hodych & Buchan (1994a) rejected in their analysis.

The palaeotectonic scenario of Torsvik *et al.* (1993) during mid-Silurian times (circa 425 Ma) is illustrated in Fig. 1(a). The palaeoposition of Laurentia is based on an average of the Scottish Newer Granites (415–435 Ma) using a Bullard *et al.* (1965) fit, and on the North American Rose Hill Formation and the Wabash Reef limestone. When compared with Silurian palaeomagnetic data from Baltica (e.g. the Ringerike Sandstone) and palaeolatitude estimates from southern Britain, i.e. Mendips and Tortworth (L. Trap and U. Trap in Fig. 1c), the data collectively suggest closure of the Iapetus Ocean across the British sector during early–mid Silurian times (Llandovery–Wenlock) as well as Scandian convergence (circa 425 Ma) between Laurentia and Baltica (Fig. 1a).

Conversely, Hodych & Buchan (1944a) discard the North American palaeomagnetic data, and by implication the Scottish palaeomagnetic data, because the latter terranes formed a coherent part of Laurentia prior to the break-up of the North Atlantic in the late Mesozoic; hence invalidating the reconstructions of Torsvik *et al.* (1993). A reconstruction that relies solely on the Springdale, Wigwam, and King George IV redbeds places Laurentia in a lower latitudinal position (Fig. 1b), and implies that the Iapetus across the British sector is wide open (1000–1500 km; Fig. 1c) during early-mid Silurian times as opposed to Iapetus closure across Central Newfoundland. It also suggests that Western Avalonia (including eastern Newfoundland) and Eastern Avalonia (including southern Britain) formed separate terranes during Upper Ordovician and Silurian times. Their model also fails to explain the well-established Scandian collision (425 Ma) between Laurentia and Baltica, although this could be accommodated by colliding the Scottish Terranes with SW Norway (*cf.* Figs 1a and b) because longitude is unconstrained from palaeomagnetic data.

CONCLUSIONS

After close examination of the experimental method and results presented in Hodych & Buchan (1994a), we conclude that their results simply do not support the contention that Springdale and Wigwam results are the most reliable Silurian directions for North America. The IRM tests used to detect inclination shallowing are problematic and may not be applicable to this problem. The conglomerate test used to argue for a primary or near primary magnetization only reinforces the already established conclusion that these redbeds were not thermally remagnetized. It does not prove a DRM or a pDRM origin nor does it prove a Silurian age for the magnetization. Finally, the authors omit or dismiss other important Silurian results that directly relate to questions of North American palaeography. These other data contradict their contention of an equatorial palaeolatitude for Newfoundland in the Silurian, a palaeogeographic position that appears difficult to reconcile within the framework of established continental reconstructions. We suggest that the shallow inclinations from the Springdale and Wigwam redbeds relative to coeval volcanic units remain enigmatic and future study is needed before remagnetization, compaction or other strain-related modifications of remanence can be ruled out. Until this enigma is resolved and given the palaeogeographic considerations outlined above, we submit that the steeper directions from the volcanic units represent the more reliable estimate of the Silurian palaeofield for Newfoundland.

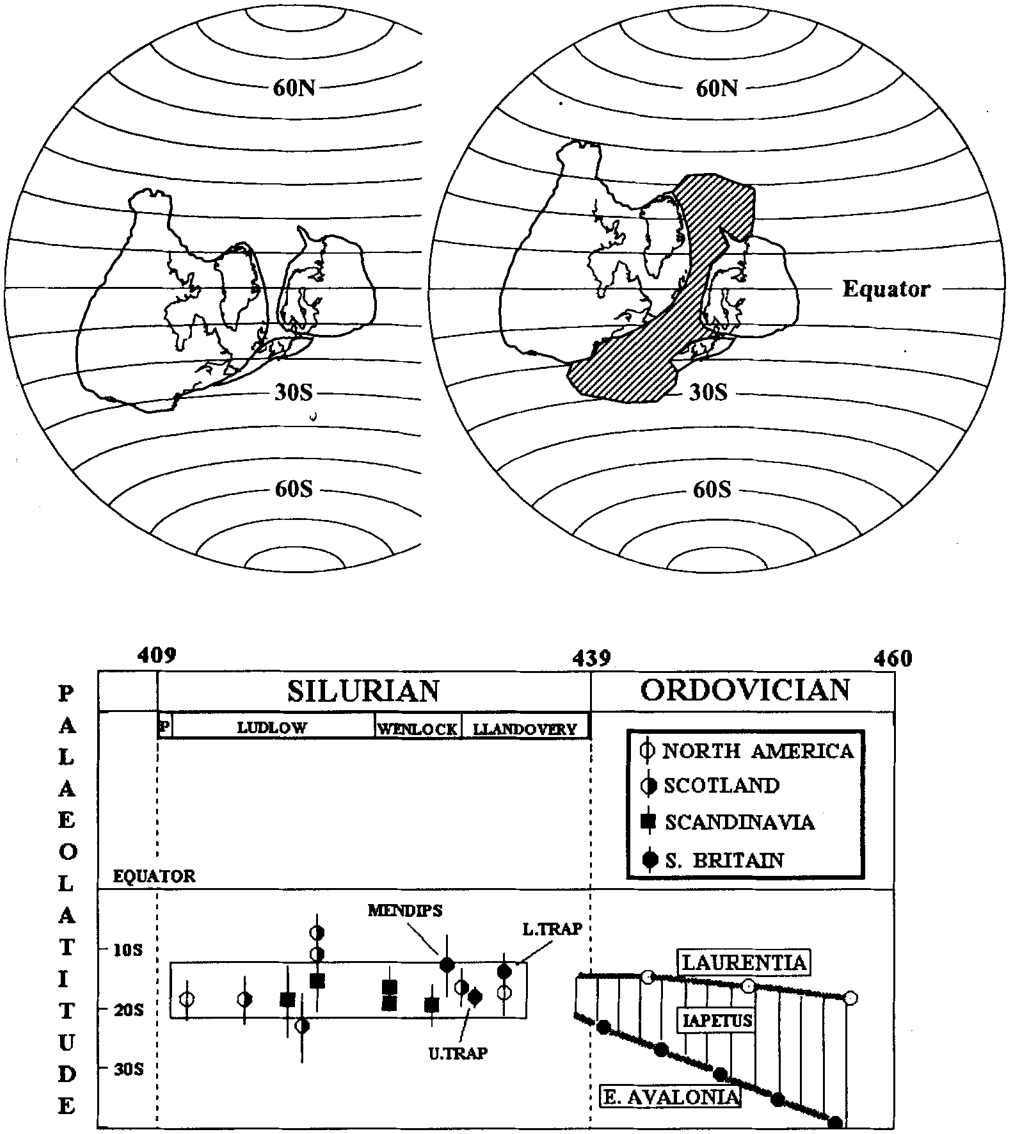

Figure 1. (a) Palaeogeographic reconstruction for Laurentia, Eastern Avalonia and Baltica in Mid-Silurian times (circa 425 Ma). Adapted from Torsvik *et al.* (1993). (b) Alternative Mid-Silurian reconstruction; rejecting the existing palaeomagnetic data from North America and Scotland (both part of Laurentia) and positioning Laurentia according to palaeomagnetic data from Western and Central Newfoundland (Hodych & Buchan 1994a), *cf.* text. (c) Comparison of Silurian palaeolatitudes (with errorbars) based on palaeomagnetic data from North America & Scotland (Laurentia), Scandinavia (Baltica) and southern Britain (Eastern Avalonia). Note the broad agreement, mostly within 10° of latitude, from Upper Llandovery times. Palaeolatitude estimates are according to an European (S. Britain) reference location of 51.5°N and 2.5°W. Adapted from Torsvik *et al.* (1994).

REFERENCES

Buchan, K.L. Hodych, J.P., 1989. Early Silurian paleopole for redbeds and volcanics of the King George IV Lake area, Newfoundland, *Can. J. Earth Sci.*, **26,** 1904–1917.

Buchan, K.L. & Hodych, J.P., 1992. Early Silurian paleolatitude for central Newfoundland from paleomagnetism of the Wigwam Formation, *Can. J. Earth Sci.*, **29,** 1652–1661.

Coe, R.S., Globerman, B.R., Plumley, P.W. & Thrupp, G.A., 1985. Paleomagnetic results from Alaska and their tectonic implications, in *Tectonostratigraphic Terranes, Pacific Northeast Quadrant,* pp. 85–108, ed. Howell, D.G., Circum-Pacific Council for Energy and Mineral Resources, Houston, TX.

Deamer, G.A. & Kodama, K.P., 1990. Compaction-induced inclination shallowing in synthetic and natural clay-rich sediments, *J. geophys. Res.*, **95,** 4511–1529.

Dodson, M.H. & McClelland-Brown, E., 1980. Magnetic blocking temperatures of single-domain grains during slow cooling, *J. geophys. Res.*, **85,** 2625–263.

Dunlop, D.J., 1970. Hematite: Intrinsic and defect ferromagnetism, *Science*, **169,** 858–860.

Dunlop, D.J., 1971. Magnetic Properties of fine-particle Hematite, *Ann. Géophys.*, **27,** 269–293.

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.*, **84,** 7688–7696.

Gales, J.E., van der Pluijm, B. & Van der Voo, R., 1989. Paleomagnetism of the Lawrenceton Formation volcanic rocks, Silurian Botwood Group, Change Island, Newfoundland, *Can. J. Earth Sci.*, **26,** 296–304.

Hodych, J.P. & Buchan, K.L., 1994a. 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.*, **117,** 640–652.

Hodych, J.P. & Buchan, K.L., 1994b. Paleomagnetism of the Early Silurian Cape St. Mary's Sills of the Avalon Peninsula of Newfoundland, Canada, *EOS, Trans. Am. geophys. Un.* **75,** (Spring Meeting Supplement), 128.

Jackson, M.J., Banerjee, S.K., Marvin, J.A., Lu, R. & Gruber, W., 1991. Detrital remanence, inclination errors and anhysteretic remanence anisotropy: Quantitative model and experimental results, *Geophys. J. Int.* **104,** 95–103.

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.

Kent, D.V. & Miller, J.D., 1987. Redbeds and thermoviscous magnetization theory, *Geophys. Res. Lett.*, **14,** 327–330.

Lapointe, P.L., 1979. Paleomagnetism and orogenic history of the Botwood Group and Mount Peyton Batholith, Central Mobile Belt, Newfoundland, *Can. J. Earth Sci.*, **16,** 866–876.

Lowrie, W. & Fuller, M., 1971. On the alternating-field demagnetization characteristics of multi-domain thermoremanence in magnetite, *J. geophys. Res.*, **76.**

McCabe, C., Van der Voo, R., Wilkinson, B.H. & Devaney, K., 1985. A Middle/Late Silurian paleomagnetic from limestone reefs on the Wabash Formation (Indiana, USA), *J. geophys. Res.*, **90,** 2959–2965.

Miller, J.D. & D.V. Kent, 1988. Paleomagnetism of the Siluro-Devonian Andreas redbeds: Evidence for an early Devonian Supercontinent?, *Geology,* **16,** 195–198.

Nagata, T., 1961. *Rock Magnetism,* Maruzen Company Ltd, Tokyo, Japan.

Néel, L., 1949. Théorie du trainage magnétique des ferromagnétiques en grains fins avec applications aux terres cuites, *Ann. Géophys.*, **5,** 99–136.

Potts, S.S., van der Pluijm, B. & Van der Voo, R., 1993a. Discordant Silurian paleolatitudes for central Newfoundland: New paleomagnetic evidence from the Springdale Group, *Earth planet. Sci. Lett.,* **120,** 1–12.

Potts, S.S., van der Pluijm, B. & Van der Voo, R., 1993b. Discordant Silurian Paleolatitudes for Central Newfoundland, *EOS, Trans. Am. geophys. Un.*, **74,** (Spring Meeting Supplement), 118.

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.

Stamatakos, J. & Kodama, K.P., 1991. The effect of grain-scale deformation on the Bloomsburg Formation pole, *J. geophys. Res.*, **96,** 17 919–17 933.

Stacey, F.D. & Banerjee, S.K., 1974. *The Physical Principles of Rock Magnetism,* Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.

Sun, W.W. & Kodama, K., 1992. Magnetic anisotropy, scanning electron microscopy, and X-ray pole figure goniometry study of inclination shallowing in a compacting clay-rich sediments, *J. geophys. Res.*, **97,** 19 599–19 616.

Torsvik, T.H., Trench, A. & McKerrow, W.S., 1994. Implications of paleomagnetic data from the Tortworth Silurian Inlier (Southern Britain) to palaeogeography and Hercynian tectonism, *Geophys. J. Int.*, **119,** 91–100.

Torsvik, T.H., Trench, A., Svensson, I. & Walderhaug, H.J., 1993. Palaeogeographic significance of mid-Silurian palaeomagnetic results from southern Britain—major revision of apparent polar wander path for eastern Avalonia, *Geophys. J. Int.*, **113,** 651–688.

Van der Voo, R., 1990. Phanerozoic paleomagnetic poles from Europe and North America and comparisons with continental reconstructions, *Rev. Geophys.*, **28,** 167–206.

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.*, **13,** 337–340.

Witzke, B.J., 1990. Paleoclimatic constraints for Paleozoic paleolatitudes of Laurentia and Euramerica, in *Paleozoic Paleogeography and Biogeography,* ed. McKerrow, W.S. Scotese, C.R., Geol. Soc. Lond. Mem. **12,** 57–73.