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The Lower Palaeozoic apparent polar wander path for Baltica: palaeomagnetic data from Silurian limestones of Gotland, Sweden

Allan Trench* and Trond H. Torsvik
Geological Survey of Norway, PB 3006, Lade, Trondheim, N-7002, Norway

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SUMMARY

Well-dated and undeformed Silurian (Lower Wenlock) limestones from Gotland, southern Sweden, yield two stable remanence components following detailed thermal and alternating-field demagnetization studies.

(1) A low blocking-temperature/coercivity magnetization, termed L, delineated below 250 °C/10 mT, is oriented parallel to the present Earth's field (Dec. 001, Inc. +67, $n = 4$ sites, $a_{95} = 16°$).

(2) A higher blocking-temperature/coercivity magnetization, termed H, unblocked between 250–400 °C/10–35 mT, has a NNE declination and shallow negative inclination (Dec. 025, Inc. −19, $n = 5$ sites, $a_{95} = 5°$). This H component direction compares favourably with a previous result from Gotland based upon blanket cleaning.

Given a lack of evidence for subsequent geological heating (Conodont Alteration Index = 1–1.5), or pervasive palaeomagnetic overprinting, the H palaeopole is regarded as reliable and primary/early diagenetic in origin (19°S, 352°E, *dp*/*dm* 3/5). The only other well-constrained Mid-Silurian pole from Baltica, that from the Ringerike Sandstone of the Oslo district, is in excellent agreement with the Gotland data. These combined poles resolve previous problems regarding the shape and time-calibration of Silurian apparent polar wander relative to Baltica.

Key words: Baltica, palaeomagnetism, Silurian, Sweden.

INTRODUCTION

Recently reported palaeomagnetic studies from Baltica have placed new constraints on its Lower Palaeozoic movement history. In particular, reliable data, substantiated by a magnetic-polarity stratigraphy, have been obtained from undeformed Ordovician carbonates of the Swedish platform (Torsvik & Trench 1990, 1991; Perroud, Robardet & Bruton 1991). When combined with results from the Scandinavian Caledonides, these data define a well-constrained Cambrian–Ordovician apparent polar wander path (APWP) for Baltica (Torsvik *et al.* 1990a; Torsvik & Trench 1991). The APWP implies that Baltica occupied temperate southerly latitudes in the Late Cambrian and then moved northward during the Ordovician whilst undergoing counter-clockwise rotation.

Silurian palaeomagnetic data from Baltica are less clear however, and uncertainties remain concerning the relative age of palaeopoles and the definition of the Silurian APW. This problem led Torsvik *et al.* (1990a) to propose two alternative Silurian path segments for Baltica which they termed path-options X and Y (Fig. 1).

The present study was therefore initiated in an attempt to discriminate between paths X and Y and to time-calibrate Silurian APW relative to Baltica. In the latter respect, the rich fauna of the Gotland limestones provides an excellent stratigraphic constraint if one considers that the rock age and magnetization age coincide.

PREVIOUS PALAEOMAGNETIC WORK

A previous palaeomagnetic investigation of the Gotland limestones was undertaken by Claesson (1979) using a Digico spinner magnetometer to measure the natural remanent magnetization (NRM). In an extensive sampling (84 sites), only a subordinate number of specimens were found to retain a *repeatably* measurable NRM after blanket demagnetization at 150 °C (occasionally 250 °C). These data were combined to produce Silurian palaeomagnetic pole

* Now at: Department of Geology, University of Western Australia, Nedlands, Perth, WA 6009, Australia.

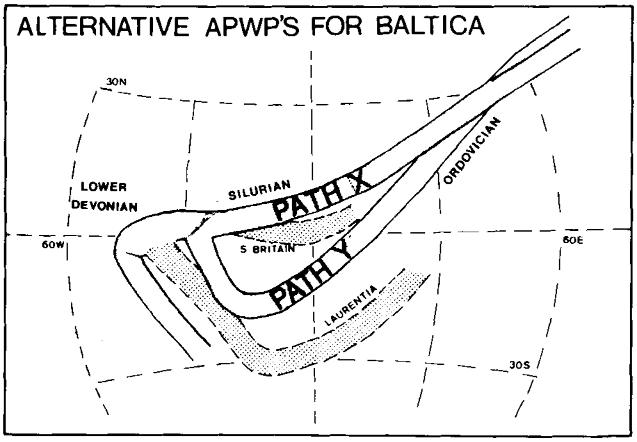

Figure 1. Alternative apparent polar wander path (APWP) segments X and Y for Baltica (after Torsvik *et al.* 1990a). Path segment X is derived by direct interpolation between poles from the Ordovician Platform Carbonates (Torsvik & Trench 1990), and Silurian–Devonian 'corner' poles i.e. high precision results from the Honningsvåg Gabbro and component A from the Kalak Nappe Complex (*c.* 415 Ma, Torsvik *et al.* 1990a). Path X does not include the Ringerike Sandstone pole (Douglass 1988), whereas path Y is anchored to this pole at *c.* 425 Ma. Path Y then back-tracks to the 'corner' poles listed above.

positions as follows:

(a) Slite Beds at Dacker: 349°E, 19°S, based on 23 specimens;

(b) Slite Beds at Follingbo: 344°E, 21°S, six specimens; and

(c) Hemse Beds at Medbys: 351°E, 23°S, six specimens.

Localities reported by Claesson (1979) are indicated in Fig. 2.

Claesson (1979) provisionally concluded: (1) that the Mid–Late Silurian palaeopole lay in the vicinity of 350°E, 20°S; and (2) 'that any (future) detailed investigation would have to employ a more sensitive magnetometer'. In this context, the present work has been conducted using a two-axis CCL SQUID magnetometer. Also since 1979, it has become standard practice in palaeomagnetic studies to perform detailed stepwise-demagnetization experiments in preference to blanket treatments. Furthermore, sample data are now routinely analysed using least-squares techniques. We therefore aimed to determine whether the initial results reported by Claesson (1979) were sustainable using a more sensitive magnetometer, contemporary laboratory methods, and a more sophisticated data analysis.

PALAEOMAGNETIC SAMPLING

13 paleomagnetic sites were studied with a minimum of eight cores taken at each sampling site.

Seven sites (7–13) were located in the Upper Visby and Högklint Beds near to the base of the Gotland succession with a further six sites (1–6) positioned in the Burgsvik and Hamra Beds near the top of the stratigraphy (Fig. 2). Stratigraphic nomenclature is after Martinsson (1967). The age correlation depicted in Fig. 2 is taken from Jeppsson (1983). Alternative correlations, which differ only slightly, can be found in Bassett & Cocks (1974) and in Laufeld & Jeppsson (1976). Absolute ages are from Harland *et al.* (1989).

The sub-horizontal attitude of the limestones, which dip on average <1° to the SE, precludes a palaeomagnetic fold

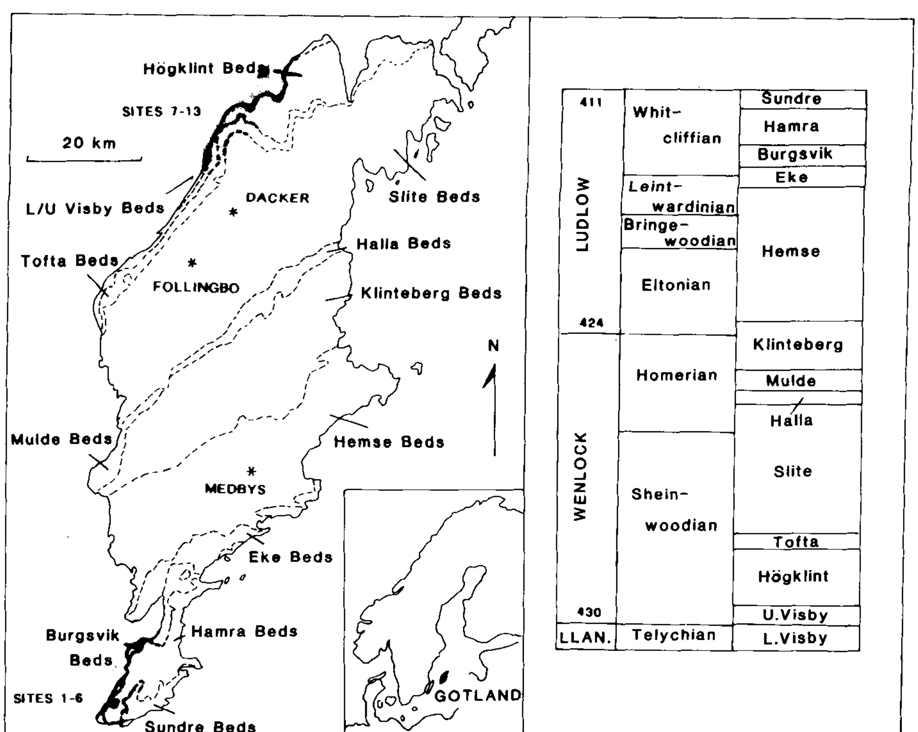

Figure 2. Geological sketch map of Gotland depicting stratigraphic subdivisions and palaeomagnetic sampling localities referred to in the text. Stratigraphic correlation of units (Jeppsson 1983) and absolute age constraints (Harland *et al.* 1989) are also shown.

test. A conglomerate test, however, was attempted within a reef-talus facies of the Hamra Beds, but no stable remanence was recovered (Site 6).

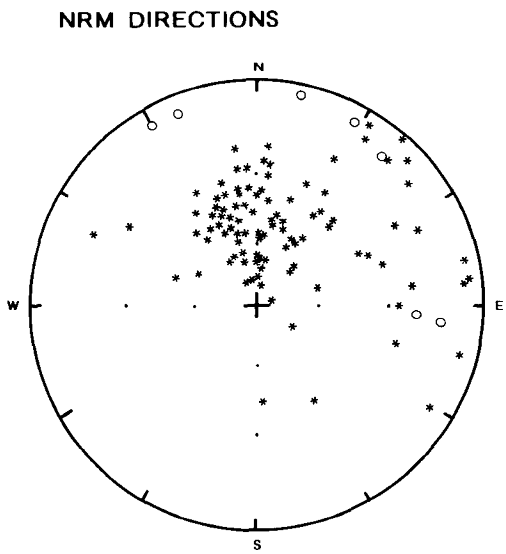

Figure 3. Distribution of NRM directions from the Silurian limestones (all samples). Equal angle projection. Stars (open circles) indicate projections on the lower (upper) hemisphere.

PALAEOMAGNETIC RESULTS

The NRM directions are scattered, but they are mostly characterized by northerly declinations and intermediate to steeply downward-dipping inclinations (Fig. 3). NRM intensities were uniformly weak and varied between 0.02 and 0.23 mA m^{-1}.

Both stepwise alternating field (AF) and thermal demagnetization experiments were attempted on the sample collection. AF treatment generally provided cleaner results when systematic demagnetization behaviour was observed. The majority of samples were therefore treated using this method. Unfortunately, only five of the 13 sites yielded stable magnetization directions. All of these sites (7, 8, 10, 11, 12) are from the base of the stratigraphy and are of Lower Wenlock age (Jeppsson 1983, Fig. 2). Remaining sites either demagnetized to the working noise level of the magnetometer (~0.005 mA m^{-1}) at low demagnetization treatments (100 °C, 5 mT), or were characterized by unstable viscous moments.

When stable to demagnetization, the NRM is characterized by two distinct magnetization components (Figs 4–7, in order of decreasing quality). The removal of a steeply downward-dipping component (L) below 10 mT/200 °C, is followed by the identification of a higher unblocking temperature/coercivity component (H) with NNE declinations and negative inclinations. The quality of demagnetiza-

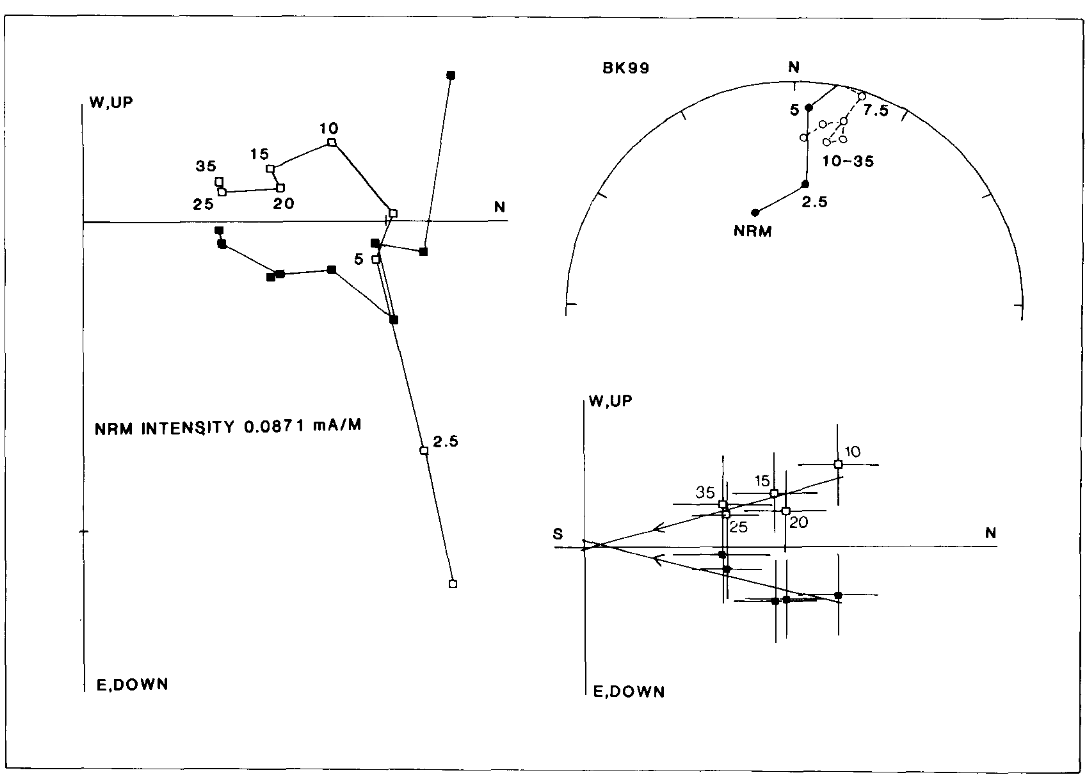

Figure 4. Note: in Figs 4–7, the conventions are as follows: (A) Orthogonal vector projection. Closed (open) symbols refer to the horizontal (vertical) projection plane. Numbers refer to maximum demagnetizing field/temperature. (B) Equal-angle projection of step-wise demagnetization. Open (closed) symbols represent projections in the upper (lower) hemisphere. (C) Expanded orthogonal projection in the vicinity of the origin. Individual confidence-limits (a_{95}, Briden & Arthur 1981) on each demagnetization step are indicated. In this example, component L is removed at treatments up to 10 mT. Component H is then identified above 10 mT, and appears to decay towards the origin of the diagram over the 10–35 mT range. Above 35 mT, viscous behaviour ensued.

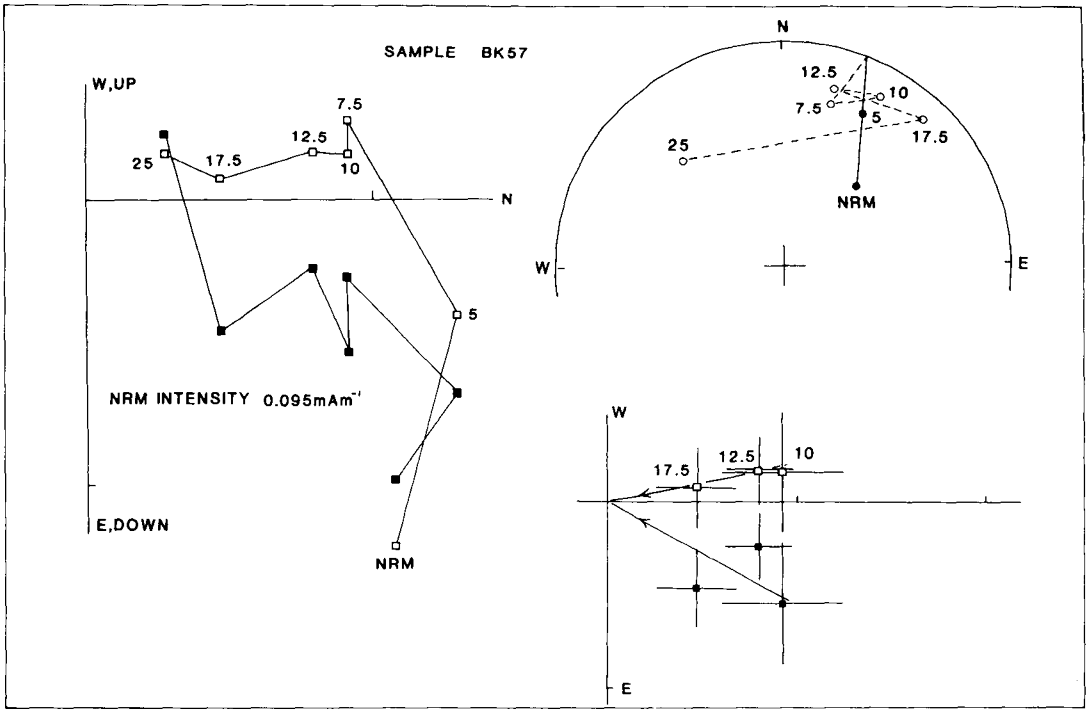

Figure 5. Component L is not sufficiently resolved to calculate a direction in this case. Component H is origin-anchored, incorporating treatments at 10, 12.5 and 17.5 mT. The final step (25 mT) is ignored in the analysis.

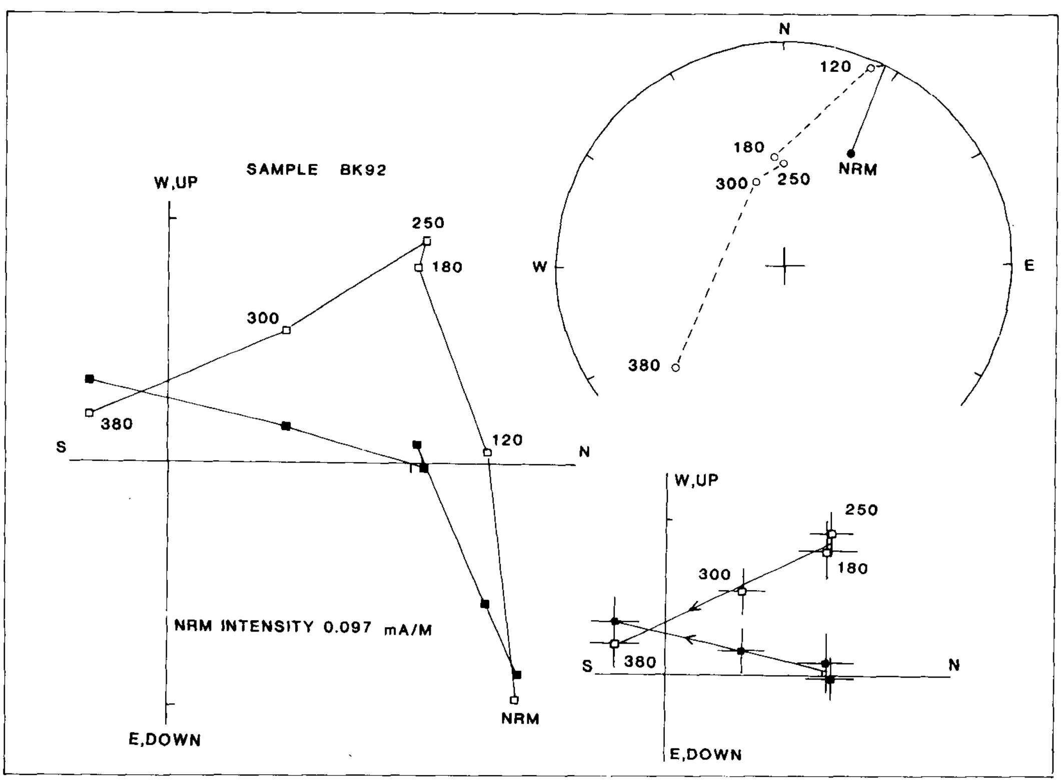

Figure 6. In this example, component L is removed below 250 °C. Component H, comparable with those observed upon AF demagnetization, is identified between 250° and 380 °C. Viscous behaviour ensued at higher treatments.

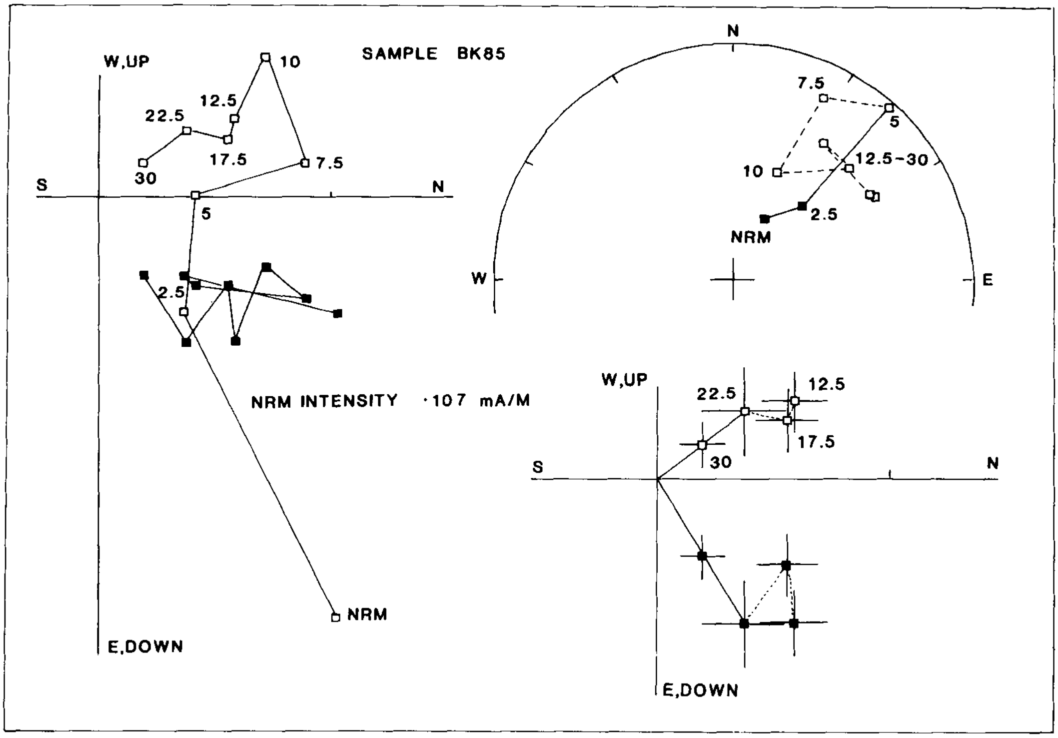

Figure 7. The interpretation of component H is equivocal in this example. We select a component including steps at 22.5, 30 mT and the origin. However, given the uncertainties at each demagnetization step, an origin-anchored line above 12.5 mT would be equally plausible.

tion data is poor/moderate however, due both to the low NRM intensities and the viscous behaviour of many samples. Remanence component analysis of both the low and high unblocking components therefore proved difficult.

We draw attention to the following remanence characteristics (Figs 4–7).

(1) Remanence stability commonly ceased in fields/temperatures of approximately 30 mT/350 °C. Distinct viscous behaviour was observed at higher treatments.

(2) At each demagnetization step, there is considerable directional uncertainty (a_{95} typically about 10°–20°; Briden & Arthur 1981).

(3) Although component analyses are not clear-cut, fitted lines were ensured to lie within the error of the individual measurement steps (see Figs 4–7).

(4) The maximum angular deviation (MAD, Kirschvink 1980) for fitted lines are quite high, typically in the order of 15°.

(5) The higher unblocking component (H) converges, although somewhat irregularly, toward the origin of the orthogonal projections before the onset of viscous behaviour.

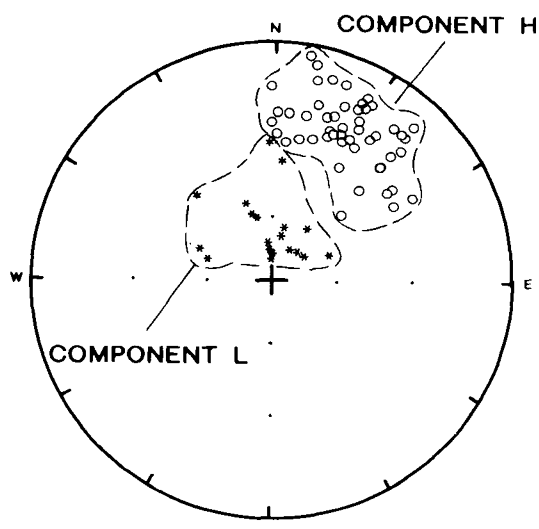

Figure 8. Characteristic remanence directions from the Silurian limestones of Gotland. Components are as follows: L—'low' coercivity/unblocking temperature component. H—'Higher' coercivity/unblocking temperature component. Stars (open circles) refer to the lower (upper) hemisphere. Equal angle projection.

SUMMARY OF PALAEOMAGNETIC RESULTS

Despite the poor/moderate data quality, the calculated remanence components L and H are reasonably grouped (Fig. 8, Table 1). Component L is distributed about the present-day field direction for Gotland and is therefore interpreted as a recent viscous magnetization. This interpretation is consistent with maximum unblocking temperatures in the order of 200 °C.

Component H directions have a N-NE declination and are negatively inclined (Fig. 8, Table 1). The mean direction (Dec. 0.25, Inc. −19) is similar to earlier results reported by Claesson (1979). This indicates that blanket demagnetiza-

Table 1. Statistical details of components L and H determined from the Gotland limestones. Notations are as follows. Numbers (7, 8, 10, 11, 12) refer to stable sites. L—'low' unblocking component L. H—'higher' unblocking component H. Dec.—declination, Inc.—inclination, N(N#)—number of samples (sites), $a95$—cone of 95 per cent confidence about the mean direction (Fisher 1953), k—Fisher precision parameter (Fisher 1953). VGP Lat, Long—latitude and longitude of virtual geomagnetic pole. dp/dm—apical half-angles of 95 per cent confidence about the calculated pole.

SITE		DEC	INC	N	a95	k	--- VGP --- LAT	LONG	dp/dm
7	L	357	+71	5	13.0	35.8			
	H	028	-20	11	11.1	18.0			
8	L	003	+58	4	21.4	19.3			
	H	026	-23	13	9.1	21.9			
10	H	028	-19	9	8.5	37.9			
11	L	040	+65	3	19.1	42.7			
	H	028	-20	8	13.5	17.7			
12	L	323	+64	6	18.5	14.0			
	H	017	-15	8	9.7	33.4			
SITE-MEAN									
	L	001	+67	4#	16.2	33.2	N82	E194	22/27
	H	025	-19	5#	5.1	227.1	S19	E352	3/5
SAMPLE-MEAN									
	L	356	+65	18	9.6	14.1	N79	E213	13/16
	H	026	-20	49	4.3	23.2	S19	E351	2/5

MEAN SAMPLING LOCALITY: 57.5° North, 18.5° East.

tion (Claesson 1979), successfully removed component L in most cases. However, inspection of Fig. 2 of Claesson (1979) indicates that a few sample directions were not resolved (i.e. they maintain steeply downward, northerly directions).

CONSIDERATION OF COMPONENT H MAGNETIZATION AGE

Although the attempted conglomerate test did not yield interpretable data, and component H always displays a normal polarity, several factors suggest a Silurian magnetization age as follows.

(i) Underlying Ordovician carbonates in SE Sweden have experienced only minor palaeomagnetic overprinting similar to component L of this study (see Torsvik & Trench 1990; Perroud *et al.* 1991).

(ii) Stable magnetizations within the SE Swedish Ordovician limestones are directionally distinct from component H and generally of opposite polarity. This is considered evidence for APW between Ordovician and Silurian times, and cannot result from pervasive later overprinting.

(iii) Palaeotemperature estimates determined by Conodont Alteration Index (CAI) are generally low in the Gotland area (1–1.5; R. J. Aldridge 1991, personal communication). These data indicate that the Gotland limestones have not attained temperatures in excess of approximately 90°C during their geological history. By contrast, Ordovician limestones in the Västergotland area of southern central Sweden have experienced higher palaeotemperatures linked to Permo-Carboniferous intrusive activity. However, even these elevated temperatures were insufficient to fully remagnetize the limestones which maintain a reversal stratigraphy (Torsvik & Trench 1991).

(iv) The Gotland palaeopole is in excellent agreement with data from the Wenlock Ringerike Sandstones of the Oslo area (Douglass 1988). The latter results are sustained by a positive fold test and the observation of stratigraphically linked magnetic reversals.

Given the above considerations, we interpret component H as of primary or early diagenetic origin, and attribute an approximate magnetic age of 428 Ma (Fig. 2).

DISCUSSION: IMPLICATIONS FOR THE BALTIC APPARENT POLAR WANDER PATH

Torsvik *et al.* (1990a) proposed two alternative Baltic APW paths for Lower Palaeozoic times termed X and Y (Fig. 1). The paths were similar for Cambrian–Ordovician times but diverged in the Silurian period. The Silurian segment of path X was interpolated between Cambro-Ordovician and Siluro-Devonian (Scandian) poles (Fig. 1). However, whereas path X did not include the Ringerike Sandstone pole (Douglass 1988), path Y was anchored to this pole at *c.* 425 Ma. The previous Gotland results, although similar to the Ringerike data, were not included in the APW analysis given their limited demagnetization.

The mid-Silurian palaeogeography based on path Y indicates oblique convergence between Baltica and Laurentia culminating in the Scandian Orogeny (Torsvik *et al.* 1990a). However, the reconstruction also implies that the Tornquist Sea remained open into Silurian times, contrary to palaeontological evidence for Ashgill closure (Cocks & Fortey 1982). Path X presented a solution to this discrepancy, requiring little or no continental separation between Baltica and Southern Britain after Ordovician times (see Trench, Torsvik & McKerrow 1991).

Our confirmation of the previous Gotland data using modern laboratory methods and data analysis suggests that these results should not be overlooked in the construction of a Baltic APWP. The data therefore lend support to an APWP closely similar to the previously defined path Y. This path also concurs with some new 'Silurian' data from the Norwegian Caledonides (Piper *et al.* 1990) although the latter results contain uncertainties in both remanence age and local tectonics.

The most reliable Ordovician and Silurian palaeomagnetic poles from Baltica are plotted in Fig. 9. The APWP implies a continued northward movement of Baltica reaching an equatorial position by Mid-Silurian times (Gotland approx. 10°S). The Baltic APWP connects with the Laurentian path by mid-Silurian times (Scandian Orogeny) but is still separated from that of Southern Britain at this time (Fig. 9). Present palaeomagnetic evidence thus suggests that the Tornquist Sea was not closed until late Silurian times. Reliable palaeomagnetic data are now urgently required from Southern Britain in order to determine the existence and/or extent of the implied 'Silurian' Tornquist Sea.

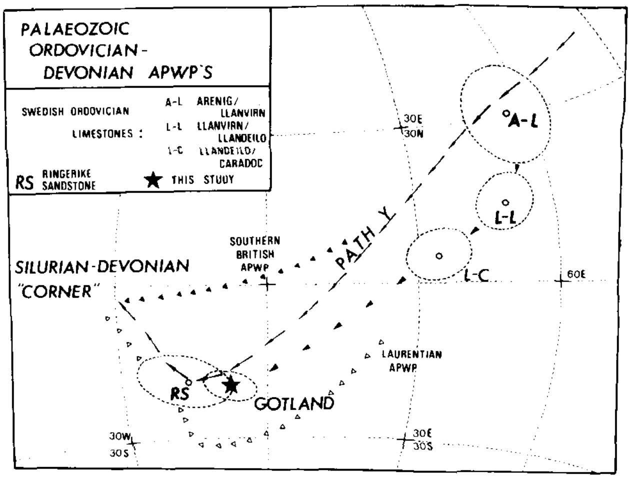

Figure 9. Reliable palaeomagnetic pole positions from Baltica compared to Southern British and Laurentian paths. 95 per cent confidence limits on Baltic poles are shaded. Poles from Baltica are as follows: A–L; Arenig–Llanvirn (Lower–Middle Ordovician) limestones (Perroud *et al.* 1991), L–L; Llanvirn–Llandeilo (Middle Ordovician) limestones (Torsvik & Trench 1991), L–C; Llandeilo–Caradoc limestones (Torsvik & Trench 1991), RS–Wenlock Ringerlike Sandstone (Douglass 1988). Laurentian path (excluding Scotland) is from Torsvik *et al.* (1990b). Southern British path is from Trench & Torsvik (1991). All paths converge on the Silurian–Devonian 'corner' position. Equal area projection.

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REFERENCES

Bassett, M. G. & Cocks, L. R. M., 1974. A review of Silurian brachiopods from Gotland, *Fossils Strata*, **3**, 1–56.

Briden, J. C. & Arthur, G. R., 1981. Precision of measurement of remanent magnetization, *Can. J. Earth Sci.*, **18**, 527–538.

Claesson, C., 1979. Early Palaeozoic geomagnetism of Gotland, *Geologiska Föreningens i Stockholm Forhandlingar*, **101**, 149–155.

Cocks, L. R. M. & Fortey, R. A., 1982. Faunal evidence for oceanic separations in the Palaeozoic of Britain, *J. geol. Soc. Lond.*, **139**, 465–478.

Douglass, D. N., 1988. Palaeomagnetism of Ringerike Old Red Sandstone and related rocks, southern Norway: Implications for pre-Carboniferous separation of Baltica and British terranes, *Tectonophysics*, **148**, 11–27.

Fisher, R. A., 1953. Dispersion on a sphere, *Proc. R. Soc. Lond.*, A, **217**, 295–305.

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

Jeppsson, L., 1983. Silurian conodont faunas from Gotland, *Fossils Strata*, **15**, 121–144.

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

Laufeld, S. & Jeppsson, L., 1976. Silicification and bentonites in the Silurian of Gotland, *Geologiska Föreningens i Stockholm Forhandlingar*, **98**, 31–44.

Martinsson, A., 1967. The succession and correlation of ostracode faunas in the Silurian of Gotland, *Geologiska Föreningens i Stockholm Forhandlingar*, **89**, 350–386.

Perroud, H., Robardet, M. & Bruton, D. L., 1991. Palaeomagnetic constraints upon the palaeogeographic position of the Baltic shield in the Ordovician, *Tectonophysics*, in press.

Piper, J. D. A., Poppleton, T. J., Mason, R. & Griffiths, A. J., 1990. The uplift magnetisation record in the central Scandinavian Caledonides: results from basic igneous complexes, *Tectonophysics*, **184**, 137–156.

Torsvik, T. H. & Trench, A., 1990. The Lower-Middle Ordovician palaeofield of Scandinavia: Southern Sweden 'revisited', *Phys. Earth planet. Inter.*, **65**, 283–291.

Torsvik, T. H. & Trench, A., 1991. Ordovician magnetostratigraphy: Llanvirn-Caradoc limestones of the Baltic platform, *Geophys. J. Int.*, **107**, 171–184.

Torsvik, T. H., Olesen, O., Ryan, P. D. & Trench, A., 1990a. On the palaeogeography of Baltica during the Palaeozoic: new palaeomagnetic data from the Scandinavian Caledonides, *Geophys. J. Int.*, **103**, 261–279.

Torsvik, T. H., Smethurst, M. A., Briden, J. C. & Sturt, B. A., 1990b. A review of Palaeozoic palaeomagnetic data from Europe and their palaeogeographical implications, in *Palaeozoic Palaeogeography and Biogeography*, Geological Society Memoir no. 12, pp. 25–41, eds McKerrow, W. S. & Scotese, C. R., London.

Trench, A. & Torsvik, T. H., 1991. A revised Palaeozoic apparent polar wander path for Southern Britian (Eastern Avalonia), *Geophys. J. Int.*, **104**, 227–233.

Trench, A., Torsvik, T. H. & McKerrow, W. S., 1991. The palaeogeographic evolution of Southern Britain during Early Palaeozoic times: A reconciliation of palaeomagnetic and biogeographic data, *Tectonophysics*, in press.