*Physics of the Earth and Planetary Interiors*, 65 (1991) 283–291
Elsevier Science Publishers B.V., Amsterdam



# The Lower–Middle Ordovician palaeofield of Scandinavia: southern Sweden 'revisited'

Trond H. Torsvik and Allan Trench

*Department of Earth Sciences, University of Oxford, Oxford OX1 3PR (U.K.)*

(Received June 21, 1990; revision accepted July 1, 1990)

ABSTRACT

Torsvik, T.H. and Trench, A., 1991. The Lower–Middle Ordovician palaeofield of Scandinavia: southern Sweden 'revisited'. Phys. Earth Planet. Inter., 65: 283–291.

We present a palaeomagnetic pole for the Arenig–Llanvirn Swedish Orthoceras Limestones based on a new analysis of some earlier reported palaeomagnetic data. This new pole, 18° N and 046° E, differs from the original estimate of 30° N and 46° E. The revised pole probably represents the most reliable Ordovician pole from Baltica, although some uncertainties remain concerning the relative importance of diagenetic/depositional controls on remanence acquisition.

Based on the new pole from the Swedish Orthoceras Limestone and recent palaeomagnetic results from the northern Scandinavian Caledonides, it is now evident that Baltica lay within southerly latitudes of between 30 and 60° S in Cambro-Ordovician times. Subsequent anticlockwise rotation relative to eastern Avalonia (southern Britain) may indicate dextral shear across the Tornquist suture prior to Mid–Late Ordovician amalgamation of eastern Avalonia and Baltica.

## 1. Introduction

In 1978, Claesson reported a palaeomagnetic pole of 30° N and 46° E ($D = 132°$, $I = +70°$, $\alpha_{95} = 2.2$, $N = 73$ sites) from the Arenig–Llanvirn Swedish Orthoceras Limestones (SOL) from the Närke, Östergötland and Öland districts (Fig. 1). This pole was based on detailed thermal and alternating field (AF) demagnetization studies supplemented with blanket cleaning at temperatures of 150–300° C or AF fields of 15mT. The SOL pole, however, has traditionally been regarded as 'anomalous' in the literature, most importantly because Claesson (1978) questioned the reliability of her own results, and considered them to be unrepresentative of the Ordovician palaeofield.

In a recent paper, Torsvik et al. (1990b) reported Lower Ordovician (~ 490 Ma) and Silurian (Scandian) poles from northern Norway, and postulated new apparent polar wander (APW) paths for Baltica. In their APW analysis, they pointed out that the SOL pole could indeed be of Ordovician origin, and it was assigned as a key pole and given an Arenig–Llanvirn age. In this account we explore Claesson's (1978) reasons for questioning the SOL pole, and present a revised analysis of the original data (Claesson, 1977).

## 2. Geological background

In Sweden (Fig. 1), a relatively complete succession of autochthonous or parautochthonous Ordovician limestones outcrop in the districts of Öland, Närke, Östergötland, Dalarna (Siljan), Västergötland, Skåne and along the Caledonian

0031-9201/91/$03.50 

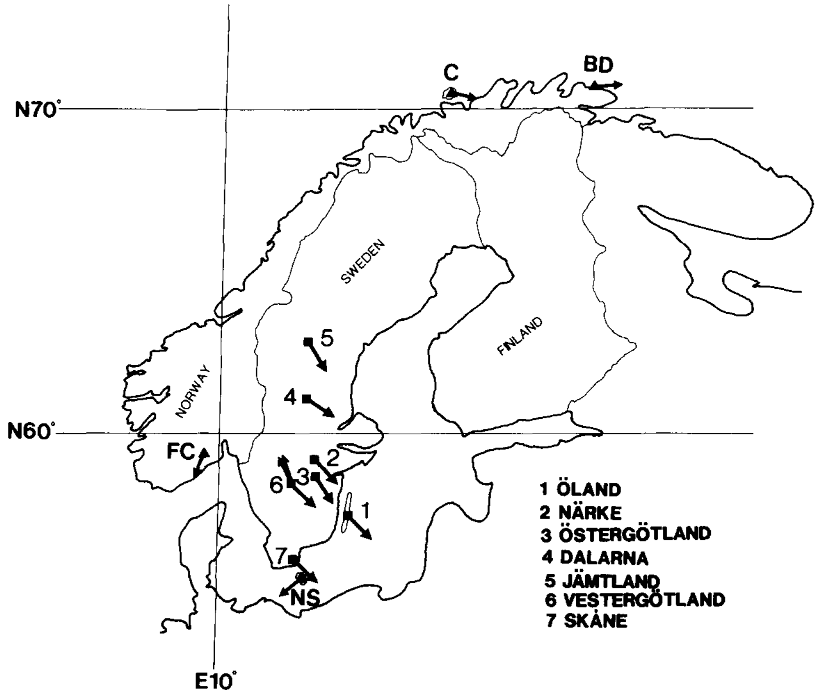


Fig. 1. Ordovician sampling areas (numbered 1 to 7) in southern Sweden (Claesson, 1977) together with the geographic locations of some selected palaeomagnetic results portrayed in Fig. 4. Arrows represent local declination values. For the Swedish areas, declinations represent bedding-corrected component I directions. Symbols are as follows: C = Seiland Igneous Province (component C, ~490 Ma; Torsvik et al., 1990b); BD = Båtsfjord Dykes (Kjøde et al., 1978—Late Precambrian, 640 Ma, or possible Late Cambrian–Early Ordovician overprint); FC = Fen Complex (Poorter, 1972—565–603 Ma); NS = Nexø Sandstone (Prasad and Sharma, 1978—Lower Cambrian).

front in Jämtland (Thorslund and Jaanusson, 1960; Thorslund, 1962; Lindström, 1971; Bruton et al., 1985). The limestones are of only moderate thickness (< 150 m) and deposition rates average to 2–3 mm 1000 year$^{-1}$ (Jaanusson, 1976). Apart from local post-Silurian fault movements (Bölau, 1972), the region is remarkably unaffected by Phanerozoic deformation, and most of the Ordovician succession is almost flat-lying.

## 3. Original interpretation of the Swedish Orthoceras Limestones

Claesson (1978) characterized the typical demagnetization behaviour of the SOL on the basis of visual inspection of stereoplots and through calculation of the most stable temperature and field ranges. Optimal temperatures and fields were then used for blanket cleaning of remaining samples. Claesson (1978) questioned her overall results, however, owing to their "smeared distribution and the movement of the provincial mean directions" during successive treatments. The mean magnetization direction was therefore interpreted as a 'multi-component' caused by: (1) unresolved normal and reverse sub-components with almost identical unblocking and coercivity spectra, or (2) a predominant steeply downward dipping and southeast-directed component together with a subordinate multi-component system as in (1).

## 4. Revised analysis

Two hundred and one pilot specimens, either stepwise thermal or AF demagnetized, were originally studied by Claesson (1978). These palaeomagnetic data cover seven different areas in southern Sweden (Fig. 1), of which the results of three areas (Närke, Öland and Östergötland) were published (Claesson, 1978). We have re-examined these raw data (Claesson, 1977), examined the demagnetization behaviour in orthogonal vector projections, and calculated remanence components by least square analysis. We did not consider samples which were subjected to blanket cleaning.

Figure 2A shows an example of thermal demagnetization presented by Claesson (fig. 2A in Claesson, 1978), and originally interpreted to portray 'continuous' directional movement during demag-

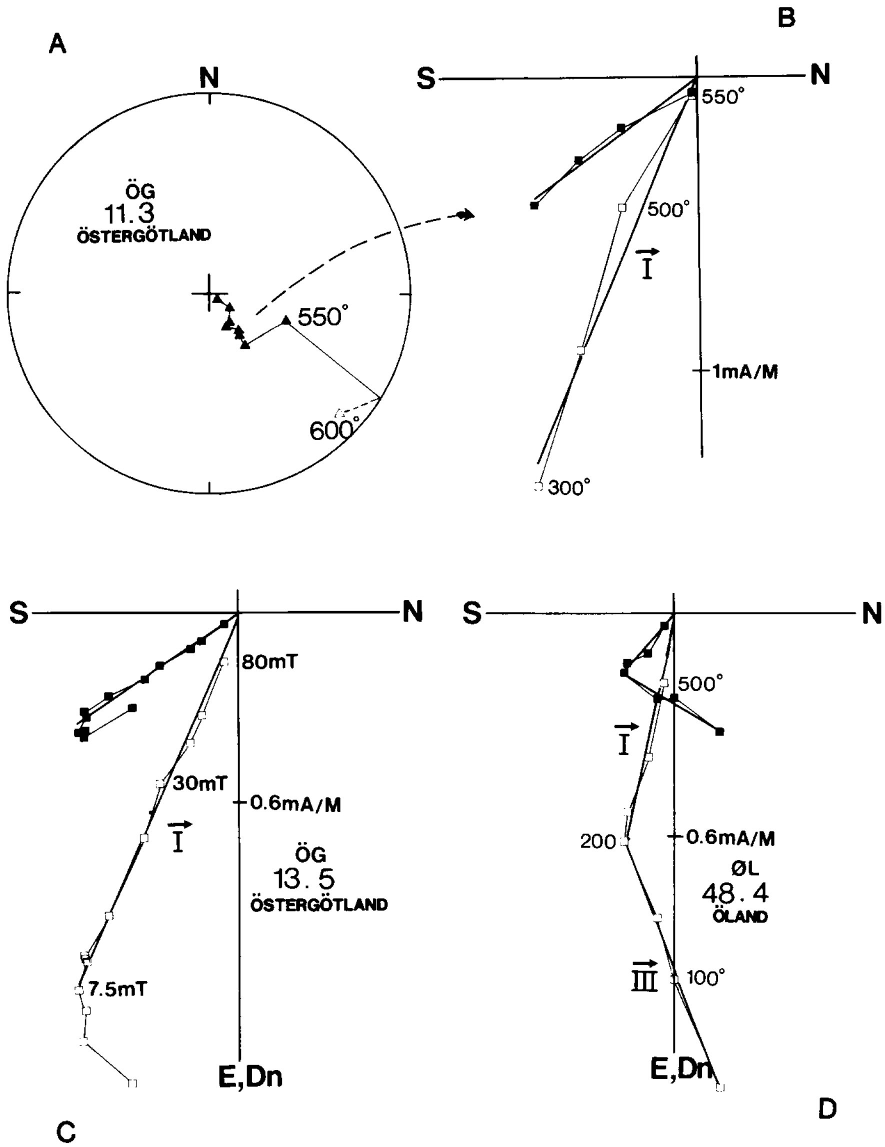


Fig. 2. Examples of thermal and AF demagnetization behaviour of samples from Östergötland (A–C) and Öland (D). In stereoplots, open (closed) symbols represent negative (positive) inclinations. In orthogonal vector projections, open (closed) symbols represent points in the vertical (horizontal) plane. Note that in (B) only points in the vertical and horizontal plane are plotted from 300 °C to 550 °C.

netization. When the same data are examined in an orthogonal vector projection, however (Fig. 2B), a steep downward-dipping component with southeast declination is reasonably defined above 300 °C. The intensity at 550 °C is 0.09 mA $m^{-1}$, which approaches the sensitivity of the spinner magnetometer (Digico) used in the original study. We note that the demagnetization trajectory in the 300–500 °C range, however, does not point towards the origin of the diagram. Measurements of the same rocks conducted on a squid magnetometer show that this phenomenon can be attributed to the acquisition of an induced component ($+X$, $-Y$ specimen coordinates) during measurement (Jackson, personal communication, 1990). Hence, the 'continuous' demagnetization behaviour described by Claesson is in part the result of an instrumental artefact (K.C. Jackson, personal communication, 1990).

Figure 2A,B is a relatively poor example of demagnetization, and in Fig. 2C,D we present more typical examples of AF and thermal behaviour. Generally, the directional movements during demagnetization are confined to low fields (temperatures), leaving a well-defined, high-unblocking component above 7.5 mT 200 °$C^{-1}$ (Figs. 2C, D). All palaeomagnetic results from Arenig–Llanvirn sediments, covering the areas of Öland,

TABLE 1

Areal and overall statistics

| Area (°N, °E) | Rock age | Component | In situ | | | | | Corrected $S_0$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $N$ | $D$ | $I$ | $\alpha_{95}$ | $k$ | $D$ | $I$ | $\alpha_{95}$ | $k$ |
| 1 Öland | Arenig– | I | 38(7) | 136 | +68 | 1.8 | 164 | 136 | +68 | | |
| (57.2, 16.9) | Llanvirn | III | 9(6) | 025 | +71 | 6.4 | 66 | 025 | +71 | | |
| 2 Närke | Arenig | I | 8(3) | 138 | +64 | 9.4 | 36 | 138 | +64 | | |
| (59.1, 15.1) | | III | 5(3) | 048 | +61 | 9.7 | 63 | 048 | +61 | | |
| 3 Öster- | Arenig– | I | 19(3) | 135 | +64 | 7.1 | 24 | 148 | +62 | 2.8 | 143 |
| Götland | Llanvirn | III | 6(3) | 008 | +56 | 11.3 | 36 | 340 | +73 | 43.2 | 3 |
| (58.5, 15.2) | | | | | | | | | | | |
| 4 Dalarna | Arenig– | I | 3(2) | 130 | +61 | 18.7 | 45 | 126 | +59 | 21.7 | 33 |
| (61.1, 14.7) | Llanvirn | III | 2(2) | 026 | +57 | 24.7 | 105 | 031 | +53 | 21.0 | 143 |
| 5 Jämtland | Arenig– | I | 7(3) | 132 | +69 | 17.4 | 13 | 148 | +60 | 9.6 | 40 |
| (62.9, 14.8) | Llanvirn | III | 9(3) | 021 | +61 | 10.0 | 27 | 030 | +69 | 8.8 | 36 |
| 6 Väster- | Arenig– | I | 16(1) | 135 | +53 | 8.2 | 21 | 135 | +53 | | |
| Götland | Llanvirn | II | 55(7) | 197 | −8 | 3.9 | 25 | 197 | −8 | | |
| (58.3, 13.9) | (*Late Llanvirn and Mid Llandeilo | I | 4(1) | 340 | −52 | 16.2 | 33 | 340 | −52 | | |
| | (*Early Caradoc | I | 2(1) | 330 | −52 | 26.0 | 94 | 330 | −52 | 7 | |
| 7 Skåne | Arenig | I | 2(2) | 135 | +53 | 89.7 | 10 | 135 | +61 | 113.0 | |
| (55.7, 14) | | II | 5(4) | 205 | −7 | 12.6 | 38 | 206 | −4 | 17.5 | 2 |
| | | III | 10(7) | 012 | +56 | 10.8 | 21 | 013 | +58 | 10.9 | 2 |
| *Final statistics* | | | | | | | | | | | |
| Component I (R) [2] | | | 6 [1] | 134 | +63 | 5.1 | 173 | 138 | +62 | 5.1 | 176 |
| | | | Pole: N18, E46 $dp/dm = 6/8$ (Corrected $S_0$) | | | | | | | | |
| Component II (N) [3] | | | 2 [1] | 335 | −52 | 13.4 | 206 | 335 | −52 | | |
| | | | Pole: N3, E35 $dp/dm = 13/18$ (Corrected $S_0$) | | | | | | | | |
| Component II [2] | | | 2 [1] | 202 | −12 | 18.5 | 184 | 202 | −10 | 19.0 | 174 |
| | | | Pole: S34, E348 $dp/dm = 10/19$ (In situ) | | | | | | | | |
| Component III [2] | | | 6 [1] | 023 | +61 | 7.6 | 78 | 024 | +65 | 10.0 | 46 |
| | | | Pole: S68. E325 $dp/dm = 9/12$ (In situ) | | | | | | | | |

$D$ = mean declination; $I$ = mean inclination; $\alpha_{95}$ = 95 percent confidence circle; $k$ = precision parameter; $S_0$ = bedding; $N$ = specimen (included sites) of areas [1].

[2] Mean values calculated after converting each area $D$ and $I$ to a common geographic latitude (59 °N) and longitude (15 °E).

[3] Sampling locality = 58.3° N and 13.7° E; * Moderate data quality.

Note that the component I(R) result from Skåne has been excluded in the final statistics owing to unacceptable high $\alpha_{95}$.

Närke, Östergötland, Dalarna and Jämtland (areas 1–5 in Fig. 1), show the low- and high-unblocking temperature interplay depicted in Fig. 2. These magnetizations are subsequently referred to as components III (low stability) and I (high stability) respectively. Component I compares fairly well with the original mean direction reported by Claesson (1978). In Östergötland, component I passes a fold-test at the 99% confidence level (Table 1), whereas component III fails a fold-test at the same confidence level. For Jämtland, component I also passes a fold-test (95% confidence level), but component III is insignificantly statistically altered. From Dalarna, none of the components provided statistically significant fold-tests.

The palaeomagnetic results from Västergötland and Skåne differ from the remaining areas, most notably owing to strong palaeomagnetic overprinting by southerly and mostly upward pointing remanence components. These overprints relate to the extensive Permo-Carboniferous intrusive activity. An example is shown in Fig. 3A, in which

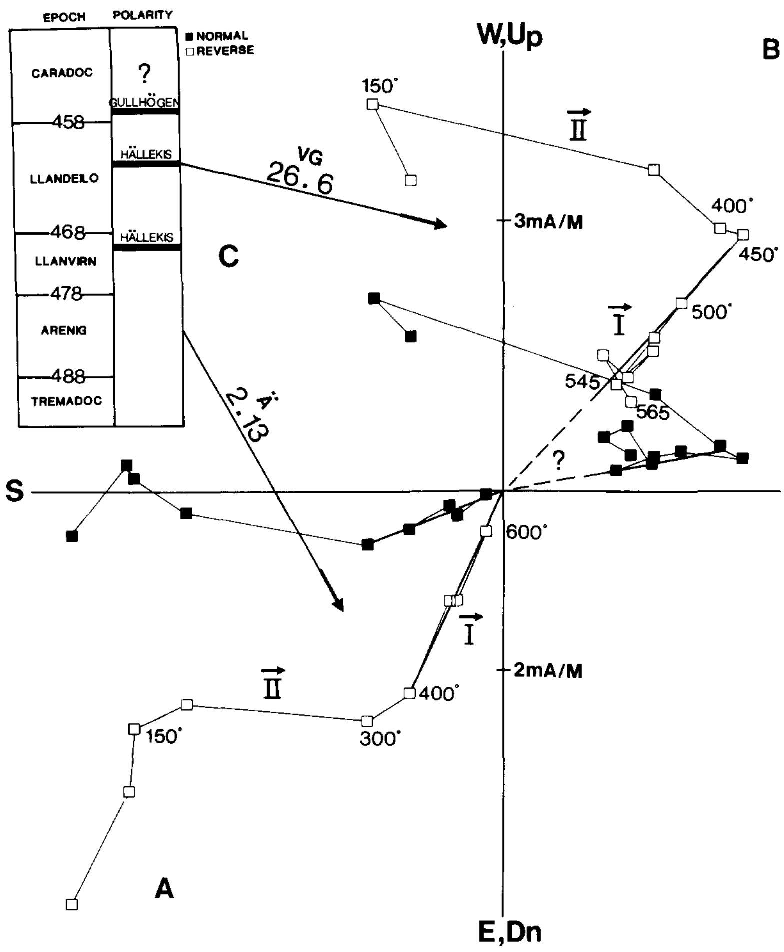


Fig. 3. Examples of thermal demagnetization of samples from Västergötland (A, B, locality Hällekis), together with a tentative magnetic stratigraphy for the Ordovician rocks of southern Sweden. The Arenig–Llanvirn is characterized by reverse polarity (A), a polarity conforming to Early Ordovician (Tremadoc) results from northern Norway (pole C in Fig. 4), but three stratigraphic positions, onwards from the Late Llanvirn, suggest the presence of normal polarity data (B). The normal polarity data are found at the Hällekis and Gullhögen localities.

both the overprint (150–300 °C—not clearly defined in this example), denoted component II and the characteristic I component (400–600 °C) are evident. Additionally, a low-unblocking temperature component (< 150 °C) is often observed. From Skåne, the low-blocking component proved similar to component III identified in the other areas (Table 1). Overprinting by component II is extensive and in many cases it completely overprints component I.

Claesson's (1977) sampling from Skåne and Västergötland also included Cambrian and Silurian sediments. Data quality is poor for these lithologies, however, and the tested specimens are dominated by components II and III. Fold-tests proved inconclusive from Skåne.

All I components identified in the abovementioned Arenig and Llanvirn limestones were of positively inclined, reverse polarity. Two sites from Västergötland, Hällekis and Gullhögen, suggest the presence of a normal polarity counterpart to component I (Fig. 3C). Six specimens with normal polarity are stratigraphically constrained to the Late Llanvirn, Mid-Llandeilo and Early Caradoc. The data quality is only moderate in these cases however (Fig. 3B). Once again, overprinting by component II is evident (150-400 °C, cf. Figs. 3A,B). Detailed sampling is required to confirm the existence of these normal polarity zones.

## 5. Discussion

The original palaeomagnetic data reported from the Ordovician rocks of Sweden (Claesson, 1977) are generally of high quality, and the comprehensive documentation of laboratory results (Claesson, 1977) has allowed the reappraisal of these data. Three remanence components are isolated, named I, II and III (Table 1 and Fig. 4A). Areas 1–5 reveal a simple two-component in structure in which the Ordovician (see later) component I is partially overprinted by component III, of Mesozoic, possibly Mid-Jurassic, or younger age. In Skåne and Västergötland (areas 6 and 7 in Fig. 1), the remanence is multi-component and is strongly contaminated by Permo-Carboniferous overprinting (II). The component II pole position compares with Upper Carboniferous (~ 300 Ma) palaeomagnetic results from Sweden (Pesonen et al., 1989). Components II and III most likely post-date folding.

Positively inclined component I directions characterize the high-blocking magnetic signature of the Arenig–Llanvirn limestones. Since local folding/tilting is probably of post-Silurian origin, statistically significant positive fold-tests (at 95 and 99% confidence level) from Östergötland and Jämtland do not prove a Lower Ordovician remanence origin. The identification of a few normal polarity directions (Fig. 3B,C), although of only moderate data quality, stratigraphically constrained from Late Llanvirn to Early Caradoc sediments, suggests however, that the reverse polarity remanences may at least be of pre-Early-Llandeilo diagenetic origin (Mid-Ordovician).

In Fig. 4B, the component I pole positions are compared with two suggested APW paths for Baltica, the original SOL pole (Claesson, 1978), and selected Late Precambrian to Early Ordovician poles from Scandinavia (see Torsvik et al., 1990b for details). The new pole from the SOL (Arenig–Llanvirn—reverse polarity, $I_R$) differs from the old pole. We ascribe this to the unidentified multi-component magnetizations in the original data analysis. We report a higher $\alpha_{95}$ for the revised pole, but this relates to the statistical level, i.e. site-statistics (Claesson, 1977) vs. area-statistics (this study).

Since the APW paths of Torsvik et al. (1990b) were constrained by the old SOL pole, both paths (Fig. 4B) should be shifted somewhat southwards in order to accommodate the revised result from the SOL ($I_R$). The normal polarity pole ($I_N$ in Fig. 4B), which is based on only six Late Llanvirn–Early Caradoc specimens should not be considered reliable at this stage. Interestingly, however, it falls on the younger part of the suggested APW paths.

Based on the C pole of Fig. 4B (see geographic location in Fig. 1), and relating this pole to remanence acquisition during Finnmarkian uplift (~ 490 Ma), Torsvik et al. (1990b) argued for a southerly position of Baltica, spanning latitudes of 30 °S to 60 °S (Fig. 4C), during Early Ordovician and Cambrian times. This is consistent with Early

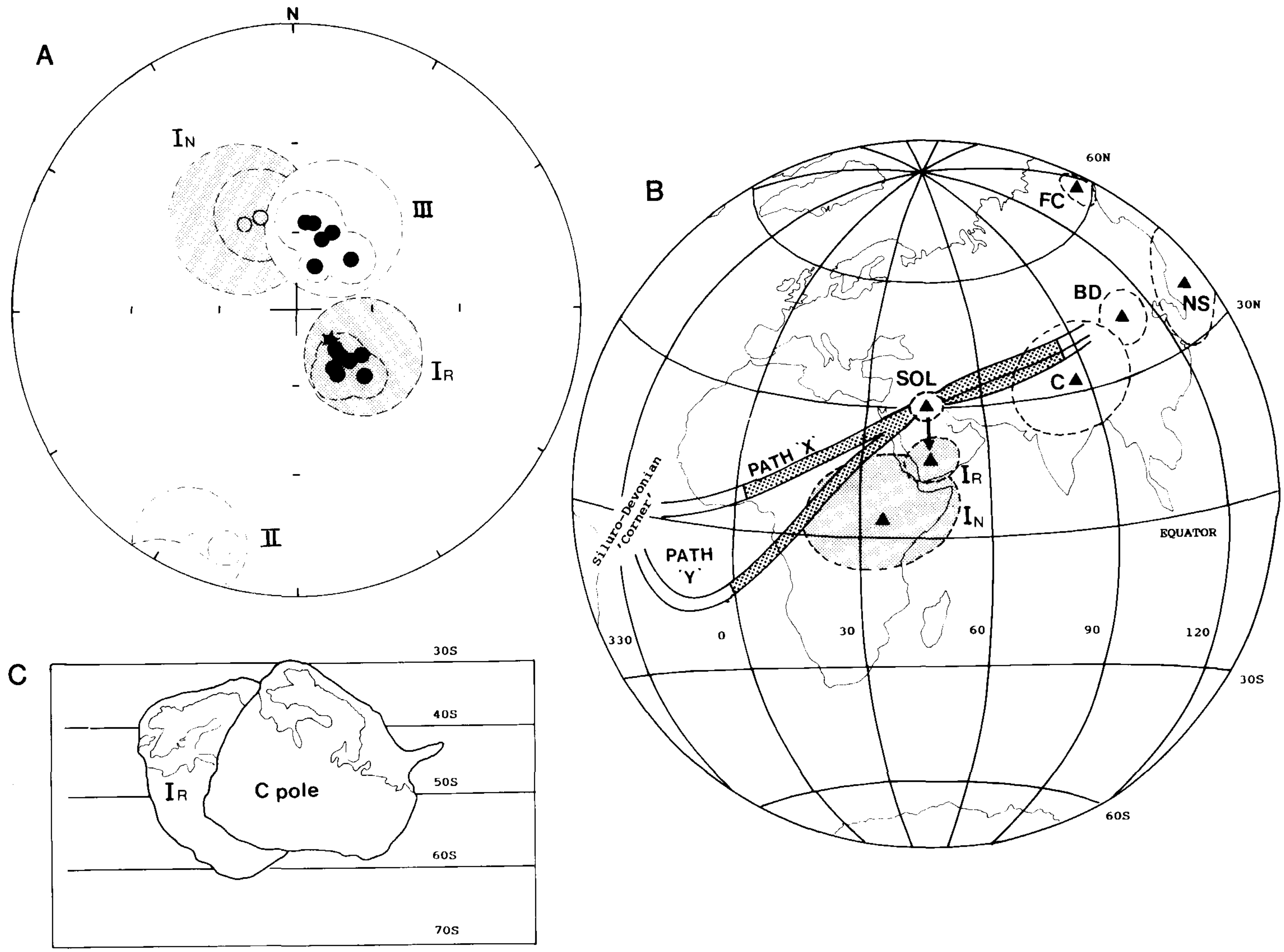


Fig. 4. (A) Compilation of components II ('in situ' coordinates), III ('in situ' coordinates) and $I_R$ and $I_N$ (bedding corrected coordinates). The earlier mean direction of Claesson (1978) is shown as a star. This result compares reasonably well with component $I_R$. Area mean directions (Table 1) are shown with $\alpha_{95}$ confidence circles, except component I from Skåne. (B) Comparison of component $I_R$ and $I_N$ with the previous result by Claesson (1978—pole SOL) and selected Late Precambrian to early Ordovician poles from Scandinavia (symbols as Fig. 1). Two suggested APW paths (X and Y) for Baltica are also included (Torsvik et al., 1990b). These paths may now require some modification given the new analysis of the SOL data. The Ordovician sections of the paths are shaded. (C) Palaeogeographical reconstruction of Baltica based on the C pole (B) and the new $I_R$ pole. The two reconstructions probably present Early Ordovician, Tremadoc (pole C), and pre-Llandeilo (pole $I_R$) tectonic scenarios.

and Mid-Ordovician carbonates from Baltica which do not indicate a warm climate until Late Ordovician times thus heralding Baltica's approach to equatorial latitudes (Jaanusson, 1973; Webby, 1980; Bruton et al., 1985; Scotese and McKerrow, 1990). Importantly, however, Baltica was 'inverted' with respect to its present day geography in Early Ordovician times (Fig. 4C, pole C), and therefore the closure of the Tornquist Sea, separating Baltica and eastern Avalonia (Cocks and Fortey, 1982) was accompanied by anticlockwise relative rotation and possible intervening dextral shear. The SOL pole is critical in constraining when the bulk of this relative rotation occurred, but is presently hampered by uncertainties in the timing of remanence acquisition. If the remanence is linked to depositional age, then a substantial part of the rotation must have taken place during the earliest Ordovician (compare reconstructions based on pole C and $I_R$ in Fig. 4C), i.e. coeval with the Finnmarkian Orogeny in northern Norway. If remanence originated during subsequent Ordovician diagenesis, however, then the rotation indicated in Fig. 4C may have taken place throughout Ordovician times. Detailed magnetostratigraphic studies are required to resolve this issue. Despite uncertainties concerning the remanence age of the SOL, the $I_R$ pole converges towards Middle Ordovician poles from eastern Avalonia (McCabe and Channell, 1990; Trench and Torsvik, 1990; Torsvik et al., 1990a). The discordance between the APW paths of Baltica and eastern Avalonia is, therefore, reduced by Mid(?)-Ordovician times, and essentially ceases by the Late Ordovician when the intervening Tornquist Sea closes.

## Acknowledgements

Norwegian Research Council for the Humanities and Science (NAVF), National Environmental Research Council (NERC) and Norwegion Geological Survey (NGU) are thanked for financial support. Logistic assistance from the staff of the Hollybush during the course of this study is acknowledged. We thank Warren Dransfield for his tireless enthusiasm. C. Jackson, H. Perroud and V. Bachtadse are thanked for constructive criticism of the original manuscript. Norwegian Lithosphere Contribution (113).

## References

Bölau, E., 1972. Genese und Alter der Horste Schonens. Geol. Føren. Förhandl., 94: 411–422.

Bruton, D.L., Lindström, M. and Owen, A.W., 1985. The Ordovician of Scandinavia. In: D.G. Gee and B.A. Sturt (Editors), The Caledonide Orogen-Scandinavia and Related Areas. Wiley, Chichester, pp. 273–282.

Claesson, K.C., 1977. Palaeomagnetic studies of Swedish Lower Palaeozoic rocks. Ph.D. Thesis, University of Newcastle, 349 pp.

Claesson, K.C., 1978. Swedish Ordovician limestones: Problems in clarifying their directions of magnetizations. Phys. Earth Planet. Inter., 16: 65–72.

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

Jaanusson, V., 1973. Aspects of carbonate sedimentation in the Ordovician of Baltoscandia. Lethaia, 6: 11–34.

Jaanusson, V., 1976. Faunal dynamics in the Middle Ordovician (Viruan) of Baltoscandia. In: M.G. Basset (Editor), The Ordovician System: proceedings of a Palaeontological Association symposium, Birmingham, 1974, University of Wales Press and National Museum of Wales, Cardiff, pp. 301–326.

Kjøde, J.K., Storetvedt, K.M., Roberts, D. and Gidskehaug, A., 1978. Palaeomagnetic evidence for large-scale dextral movements along the Trollfjord–Komagelv fault, Finnmark, north Norway, Phys. Earth Planet. Inter., 16: 132–144.

Lindström, M., 1971. Von Anfang, Hochstand und Ende eines Epikontinentalmeeres, Geol. Rundschau., 60, 419–438.

McCabe, C.R. and Channell, J.E.T., 1990. Palaeomagnetic 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.

Pesonen, L.J., Torsvik, T.H., Bylund, G. and Elming, S-A., 1989. Crustal evolution of Fennoscandia: Palaeomagnetic constraints. In: R. Freeman, M. von Knorring, H. Korhonen, C. Lund and St. Mueller (Editors), The European Geotraverse, Part 5: The polar profile. Tectonophysics, 162: 27–49.

Poorter, R.P.E., 1972. Preliminary palaeomagnetic results from the Fen carbonatite complex, S. Norway. Earth Planet. Sci. Lett., 17: 194–198.

Prasad, S.N. and Sharma, P.V., 1978. Palaeomagnetism of the Nexø sandstone from Bornholm Island, Denmark. Geophys. J.R. Astron. Soc., 54: 669–680.

Scotese, C.R. and McKerrow, W.S., 1990. Revised World maps and introduction. In: W.S. McKerrow and C.R. Scotese (Editors), Palaeogeography and Biogeography, Mem. Geol. Soc. Lond. 12; 1–21.

Thorslund, P., 1962. Kambro–Siluravlagringar utanför Fjällkedjan, In: N.H. Magnusson, P. Thorslund, F. Brotzen, B. Asklund and O. Kulling (Editors), Beskrivning till karta över Sveriges berggrund. Sver. Geol. Unders., Serie B, 16: 113–153.

Thorslund, O. and Jaanusson, V., 1960. The Cambrian, Ordovician, and Silurian in Västergötland, Närke, Dalarna, and Jämtland, Central Sweden. Guide to excursions No. A23 and C18. Intern. Geol. Congress XXI Session Norden, Stockholm, 51pp.

Torsvik, T.H., Smethurst, M.A., Briden, J.C. and Sturt, B.A., 1990a. A review of Palaeozoic palaeomagnetic data from Europe and their palaeogeographic implications. In: W.S. McKerrow and C.R. Scotese (Editors), Palaeogeography and Biogeography, Mem. Geol. Soc. Lond., 12: 25–41.

Torsvik, T.H., Olesen, O., Ryan, P.D. and Trench, A., 1990b. On the palaeogeography of Baltica during the Palaeozoic: New palaeomagnetic data from the Scandinavian Caledonides, Geophys. J. Inter., in press.

Trench, A. and Torsvik, T.H., 1990. Discussion of Palaeomagnetic results from the rocks of the Shelve Inlier, Wales: evidence for a wide Late Ordovician Iapetus Ocean in Britain, by Chad McCabe and James E.T. Channell. Earth Planet. Sci. Lett., in press.

Webby, B.D., 1980. Biogeography of Ordovician stromatoporoids. Palaeogeogr., Palaeoclimatol., Palaeoecol., 32: 1–19.