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On the palaeogeography of Baltica during the Palaeozoic: new palaeomagnetic data from the Scandinavian Caledonides

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SUMMARY

Based on new palaeomagnetic results from the North Norwegian Caledonides, we propose new apparent polar wander paths for Baltica during the Early–Mid Palaeozoic and discuss their palaeogeographic implications.

In Cambrian and Early Ordovician times, Baltica occupied southerly latitudes of the order of 30° to 50°, but was 'inverted' with respect to its present orientation. Consequently, the Russian Platform faced Avalonia and Gondwana, the latter continent occupying high southerly latitudes. Closure of the Tornquist Sea was then accompanied by continental scale, anticlockwise rotation of Baltica relative to Avalonia. This rotation probably occurred during mid-Ordovician times, although as yet, the timing of final suturing is poorly constrained by available palaeomagnetic data. At this time Laurentia occupied an equatorial position.

Baltica then moved northwards in Late Ordovician and Silurian times, and subsequently collided obliquely with Laurentia to produce the Mid-Silurian to Early Devonian Scandian Orogeny. Oblique convergence set up sinistral orogen-parallel shear zones, on which major movements ceased by Late Silurian times. After amalgamation, Baltica and Laurentia occupied equatorial to tropical southerly latitudes.

Reconstructions for the Siluro-Devonian boundary are now relatively straightforward. Euramerica was assembled by that time, and occupied equatorial (N. Baltica) to high (*c.* 60°) southerly latitudes (S. Laurentia) prior to northerly movement and the final assembly of Pangea.

Key words: Baltica, Iapetus Ocean, palaeomagnetism, Palaeozoic reconstructions, Tornquist Sea.

INTRODUCTION

Palaeozoic reconstructions for the circum-Atlantic region recount the former movements of the bordering continents and the opening and closing of the intervening oceans. Faunal distributions, petrotectonic assemblages, sedimentary facies and palaeomagnetic data concur in suggesting the existence of the Iapetus Ocean (Harland & Gayer 1972; Roberts & Gale 1978), separating Laurentia* from Baltica and Avalonia† during Ordovician times. Data discrepancies exist, however, and have resulted in a number of contrasting palaeogeographic models (Cocks & Fortey 1982; Perroud, Van der Voo & Bonhommet 1984; McKerrow 1988; Miller & Kent 1988; Van der Voo 1988; Torsvik *et al.* 1990; Scotese & McKerrow 1990).

The position of Laurentia is now reasonably well constrained by palaeomagnetic data. However, a sparsity of reliable Early Palaeozoic results from Baltica makes its Ordovician–Silurian position uncertain (Torsvik *et al.* 1990). Similarly, the movement history of Eastern Avalonia based on palaeomagnetic data is contentious (Briden & Mullan 1984; McCabe & Channell 1990; Torsvik *et al.* 1990), and thus the significance of the intervening Tornquist Sea (Cocks & Fortey 1982) is unclear. In an attempt to address these problems, we have initiated palaeomagnetic studies of Palaeozoic rocks from N. Norway, S. Sweden and S. Britain (Wales). This account concerns the palaeomagnetic signature of intrusive rocks from N. Norway.

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* N. America, Greenland, W. Newfoundland and N. Britain.
† S. Britain, E. Newfoundland and E. Maritime Provinces.

REGIONAL GEOLOGY AND SAMPLING

Two major orogenic events have been postulated for the development of the northern Scandinavian Caledonides, i.e. a Late-Cambrian–Early-Ordovician event, known as the 'Finnmarkian' and a Silurian to Early Devonian, 'Scandian' event (Sturt, Miller & Fitch 1967; Pringle & Sturt 1969; Sturt, Pringle & Ramsay 1978; Ramsay *et al.* 1985; Roberts 1988a).

Western Finnmark (Fig. 1) is characterized by a series of nappes and thrust sheets. The uppermost Magerøy Nappe was emplaced by Scandian thrusting, with the syn-orogenic but pre-thrusting Finnvik granite on Magerøy dated at 411 ± 7 Ma (Rb/Sr whole rock; Andersen *et al.* 1982). The underlying Kalak Nappe Complex (KNC; Fig. 1) comprises a variety of rock units of different ages. A psammitic sequence (Klubben Group) predominates, passing up into pelites, limestones and finally turbidites (see reviews in Ramsay *et al.* 1985; Gayer *et al.* 1987). A Late Proterozoic to Cambrian age has been assumed for this succession, but some parts may be older than *c.* 800 Ma (Aitcheson, Daly & Cliff 1989). The rocks of the KNC have undergone polyphasal deformation and amphibolite–facies metamorphism. Garnet–biotite geothermometry indicates post-metamorphic peak temperatures in the range of 551 ± 78° to 649 ± 57 °C (Gayer *et al.* 1987). Both Finnmarkian and Scandian tectonothermal events have been recorded (Dallmeyer 1988). The KNC is intruded by a complex series of assumed syn-tectonic intrusions, the Seiland Igneous Province (SIP), which have yielded Rb–Sr isotopic age-dates in the range of 540–490 Ma (Sturt *et al.* 1967, 1978; Ramsay *et al.* 1985). More recent U–Pb zircon dating has placed a younger age limit of 523 ± 2 Ma on the SIP magmatism (Pedersen, Dunning & Robins 1989).

A total of 27 sites (310 drill-cores) from three major areas, Sørøy, Øksnes and Altenes-Alta, were investigated (Figs 1–3 and Table 1; site numbers are not sequentially listed). A separate study of gabbros from Magerøy [area IV in Fig. 1(a)] will be reported elsewhere (Torsvik *et al.*, in preparation).

From Sørøy, the Breivikbotn Gabbro and mafic dykes (Sites 20, 21, 22a, 22b, 24–25) were sampled in addition to the Hasvik Gabbro and cross-cutting dykes (sites 10a, b and 26). The Klubben Group psammites and cross-cutting mafic dykes were studied at sites 11, 12, 15 and 23 (Fig. 2). Folding and regional foliation development on Sørøy is essentially related to two principal deformation periods, D_1 and D_2 of Sturt & Ramsay (1965). These authors suggested that the Breivikbotn gabbro was emplaced during a late stage of D_1. Aplitic granodiorite veins yield ages from 533 ± 17 (Rb/Sr whole rock isochron) to 420–390 Ma (K/Ar biotite; Sturt *et al.* 1978). An attempt to date a nepheline syenite cutting the Breivikbotn gabbro by means of Ar^{39}/Ar^{40} (nepheline) was undertaken by Dallmeyer (1988). Although a plateau age was not obtained, a total gas age of 425 ± 8.4 Ma was reported.

The Breivikbotn Gabbro is cut by a younger alkaline complex from which Sturt *et al.* (1967) report a Rb/Sr whole-rock age of 483 ± 27 Ma, considered to represent an emplacement age.

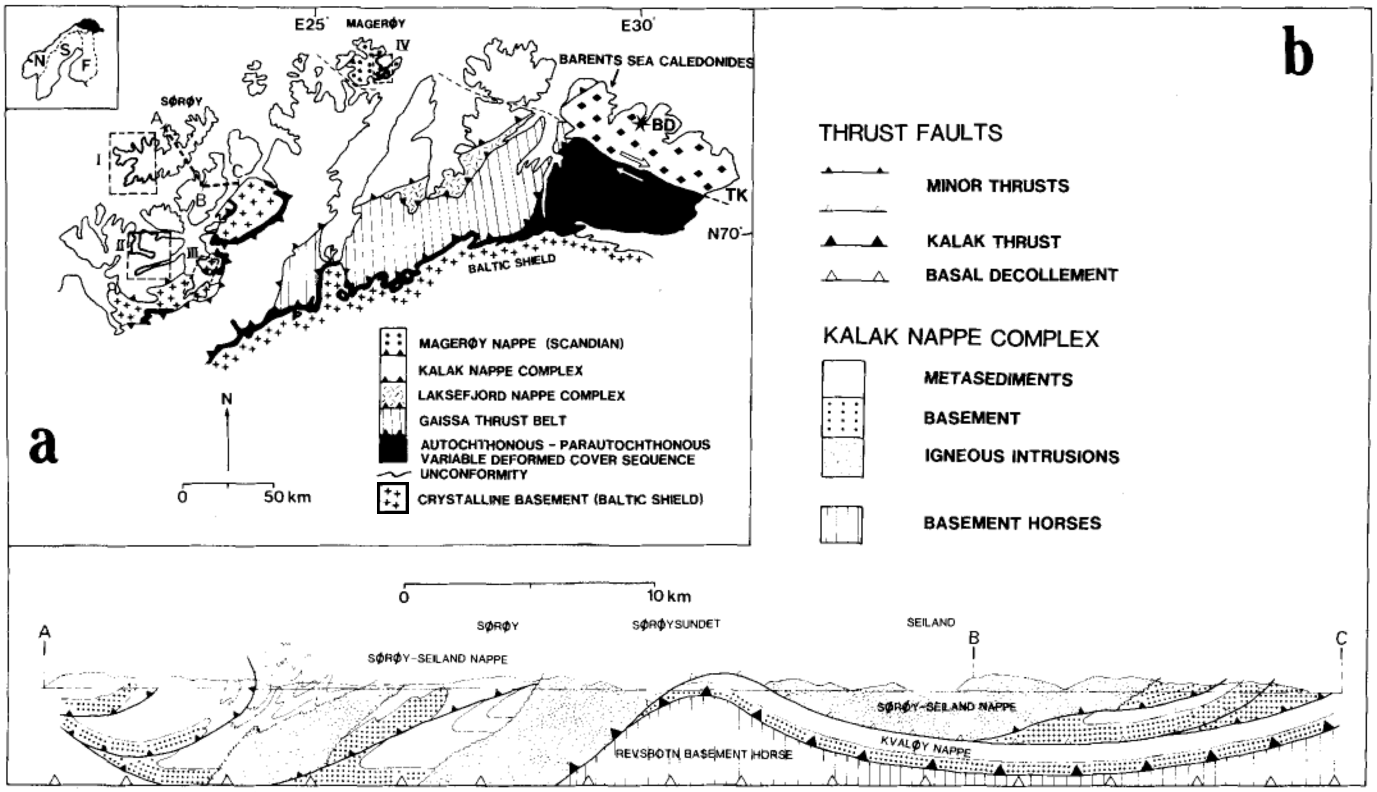


Figure 1. (a) Geological sketch map (simplified from Gayer *et al.* 1985) of the northern Norwegian Caledonides. This account reports on study area I–III (shaded). Sampling area IV is detailed in Torsvik *et al.* (in preparation). BD = Båtsfjord Dykes, TK = Trollfjord–Komagelv Fault. Inset: N = Norway; S = Sweden; F = Finland. (b) Interpreted cross-section from Sørøy to Vargsund (from Gayer *et al.* 1987). Cross-section is shown in (a) as a stippled line.

Table 1. Sampling details.

Site	Code	Description
Sørøy:		
10A	(D)	Dyke intruding Hasvik Gabbro
	(G)	Hasvik Gabbro
10B	(D)	Dyke intruding Hasvik Gabbro
	(G)	Hasvik Gabbro
11	(P)	Klubben Group Psammites
	(D1$_1$)	Dyke intruding Klubben Group Psammites
	(D1$_2$)	Dyke intruding Klubben Group Psammites
	(D2)	Dyke intruding Klubben Group Psammites & cutting D1$_1$/D1$_2$
12	(P)	Klubben Group Psammites
	(D)	Dyke intruding Klubben Group Psammites
15	(D)	Dyke intruding Klubben Group Psammites
	(P)	Klubben Group Psammites
20	(G)	Breivikbotn Gabbro
21	(G)	Breivikbotn Gabbro
	(D)	Dyke intruding Breivikbotn Gabbro
22A	(G)	Breivikbotn Gabbro
	(D1)	Dyke intruding Breivikbotn Gabbro
	(D2)	Dyke intruding Breivikbotn Gabbro & cutting D1
22B	(G)	Breivikbotn Gabbro
23	(D)	Dyke intruding Klubben Group Psammites
24	(D)	Dyke intruding Breivikbotn Gabbro
25	(G)	Breivikbotn Gabbro
	(D)	Dyke intruding Breivikbotn Gabbro
26	(G)	Hasvik Gabbro
Øksnes:		
40	(G)	Layered Syenogabbro
41	(G)	Layered Syenogabbro
42	(G)	Layered Syenogabbro
43	(G)	Layered gabbro
44	(G)	Layered gabbro
45	(Pe)	Peridotite
46	(G)	Layered gabbro
Altenes-Alta:		
70	(MB)	Metabasalt (Kværvik)
71	(MB)	Metagabbro (Kåfjorden)
72	(MB)	Metabasalt (Tverrelvdalen)
73	(MG)	Metagabbro (Kviby)
74	(MG)	Metagabbro (Kviby)
75	(MG)	Metagabbro (Kåfjorden)
76	(MG)	Metagabbro (Kværvik)

The Hasvik Gabbro was considered to have intruded during the peak of Finnmarkian metamorphism (Sturt & Ramsay 1965), and was thus considered of *critical* importance for dating the Finnmarkian metamorphism. Sturt *et al.* (1978) reported a Rb/Sr age of 521 ± 27 Ma from an anatectic dyke from the Hasvik Gabbro. New Sm–Nd mineral isochron ages for the Hasvik Gabbro, however, suggest a pre-700 Ma emplacement age (Aitcheson *et al.* 1989; see later discussion).

Layered gabbros (sites 40–44 and 46) and peridotites (site 45; Fig. 3) were sampled from Øksnes. Brueckner (1973) has reported a Rb–Sr whole-rock isochron of 612 ± 17 Ma from the layered syeno-gabbros (near site 40). On the other hand, Dallmeyer (1988) reported an Ar^{39}/Ar^{40} (hornblende) plateau age of 486 ± 4.4 Ma for the basement gneisses immediately SW of site 42 (Fig. 3). This age probably dates post-metamorphic cooling through temperatures required for retention of argon in hornblende, i.e. *c.* 500 °C (Dallmeyer 1988).

Preliminary sampling was also undertaken from the Altenes (sites 73, 74) and Alta–Kvæenangen tectonic windows sites 70–72, 75–76; Fig. 1(a), area III; Table 1, and included Precambrian (Karelian) metabasalts (sites 70, 72) and metagabbros (sites 71, 73–76.)

THE MAGNETIC FABRICS—CONTACT RELATIONSHIPS ON SØRØY

The anisotropy of magnetic susceptibility (AMS) was measured on a low-field induction bridge (KLY-2). AMS and anisotropy of remanence data are described in a separate paper (Torsvik & Walderhaug, in preparation), and only some pertinent general observations from Sørøy are outlined here.

The magnetic foliations ($K_{max} - K_{int}$) from the Klubben Group psammites are closely parallel to the observed megascopic foliation (S_1). On Sørøy, D_1 and D_2 fold-axes are almost coaxial, and low-angle magnetic lineations (K_{max}), N–S or NE–SW, are fold-axis parallel to both (Figs 2 and 4a–c). Sites 11–12, 15 and 23 also include sheared and partly amphibolitized dykes which intrude the Klubben Group psammites. The dyke margins from sites 12 and 15 parallel the psammitic foliation (Fig. 4a–c). Both dyke and psammite samples from site 12 show well-defined oblate ellipsoids (Fig. 4d), display a similar degree of anisotropy, and have comparable K_{min} directions and NE-directed lineations (Figs 2 and 4b). The dyke of site 15 is amphibolitized and boudinaged. Both dyke and psammite samples show high anisotropies, 30–50 per cent of strongly developed prolate ellipsoids and a southerly directed K_{max} (Fig. 4c and d). Sites 12 and 15 provide clear evidence for the dykes having a pre- or possible syntectonic origin.

Site 11 embraces two generations of basic dykes which cut obliquely across foliated and partly migmatized Klubben Group sediments (see Figs 2 and 4a). Psammites are characterized by a steeply dipping magnetic foliation which coincides with the megascopic foliation, and lineations plunge due south. A steeply inclined foliation is also recorded in the oldest dykes (denoted D1 in Figs 2 and 4a), but with a different orientation, and no lineation is

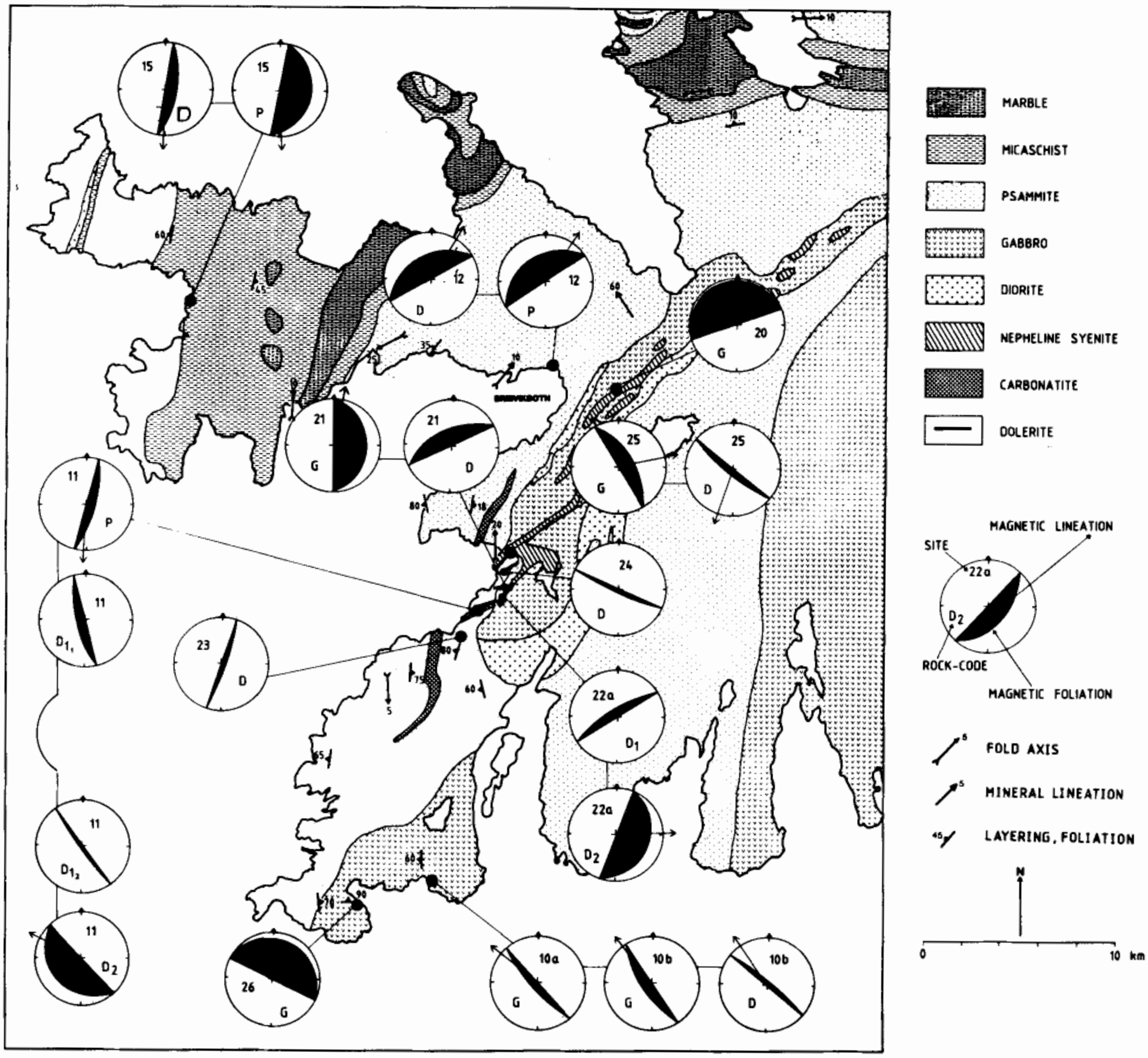


Figure 2. Geological sketch map of Sørøy, including sampling sites and magnetic fabric data. In stereoplots, magnetic foliation planes ($K_{\max} - K_{\text{int}}$) are shown as downward dipping planes. Magnetic lineations ($K_{\max}$) are indicated as arrows. Rock codes in stereoplots are as follows: P = Psammite; G = Gabbro; D = Dyke (D_1, D_2 etc. denote dyke age relationship, D_1 being the oldest dykes based on cross-cutting relationship).

developed. Conversely, the magnetic fabrics obtained from the D2 dyke, cutting and offsetting D1 dykes, show no correspondence with Klubben Group foliations or D1 dyke foliations. In addition, the D2 dykes show a low degree of anisotropy (<5 per cent), whereas D1 dykes show a wider range which converges toward psammite values of around 10 per cent of anisotropy (Fig. 4d). Krill & Zwaan (1987) have suggested that *all* dykes on Sørøy are pre-fold and hence pre-tectonic. Although magnetic competence contrasts might explain the 'strain' variations as exemplified from site 11, both field evidence and magnetic fabric data clearly indicate that some of the mafic dykes on Sørøy post-date the regional foliation. These relationships have recently been highlighted by Sturt & Ramsay (1988) and Roberts (1988b).

The magnetic fabric relationship between dykes intruding the Breivikbotn and Hasvik gabbros is less definitive. Some sites are also directionally isotropic (sites 10a—dyke; 22a—gabbro, 22b—gabbro), i.e. individual samples show a 'random' directional pattern, thus complicating direct comparisons. Most commonly, however, dykes appearing

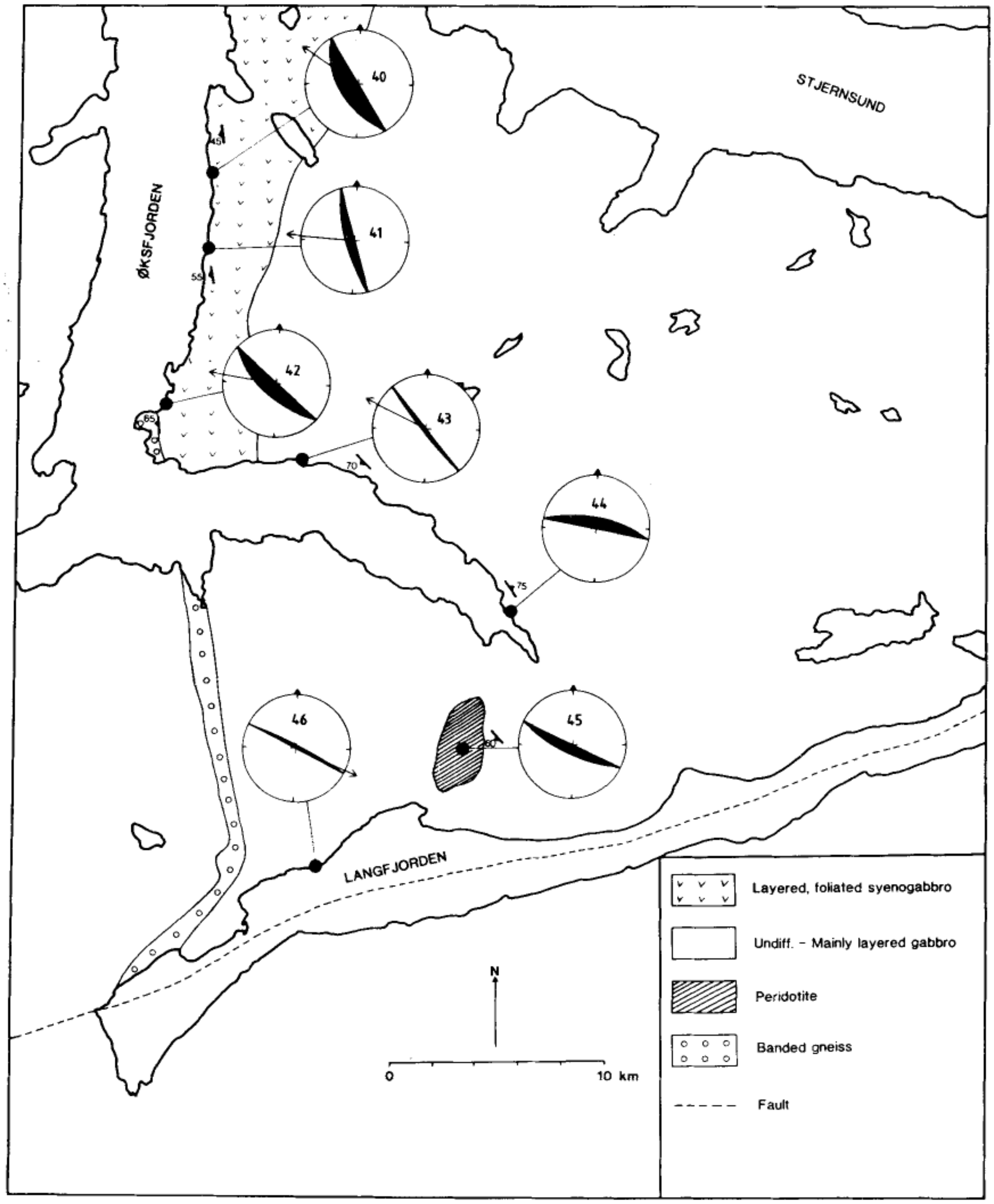


Figure 3. Geological sketch map of Øksnes, sampling sites, and magnetic fabric data. Conventions as Fig. 2.

fresh in hand-specimen show little if any microfabric relationship to the host gabbros (compare e.g. sites 21, 22a and 25; Fig. 2). Site-mean degree of anisotropy in gabbroic samples varied from 6 to 25 per cent, commonly an order of magnitude higher than in dyke specimens (Fig. 5). Only sites 10a (gabbro) and 10b (gabbro & dyke) provided clear evidence for compatible magnetic fabrics (Fig. 2).

PALAEOMAGNETIC RESULTS

The natural remanent magnetization (NRM) was measured on a two-axis SQUID magnetometer and a Molspin magnetometer. The stability of NRM was tested by thermal demagnetization and to a lesser extent alternating field (AF) demagnetization. Characteristic remanence components were calculated by least-squares analysis.

Øksnes

All sites from Øksnes are dominated by magnetite, but minor amounts of accessory pyrrhotite (rare) were observed from thermomagnetic analysis. Sites 40–46 yield susceptibilities in the range 0.01–0.1 SI, and natural remanent magnetization (NRM) intensities varied from 0.3 to 1.4 A m^{-1}.

Characteristic remanence components from Øksnes show

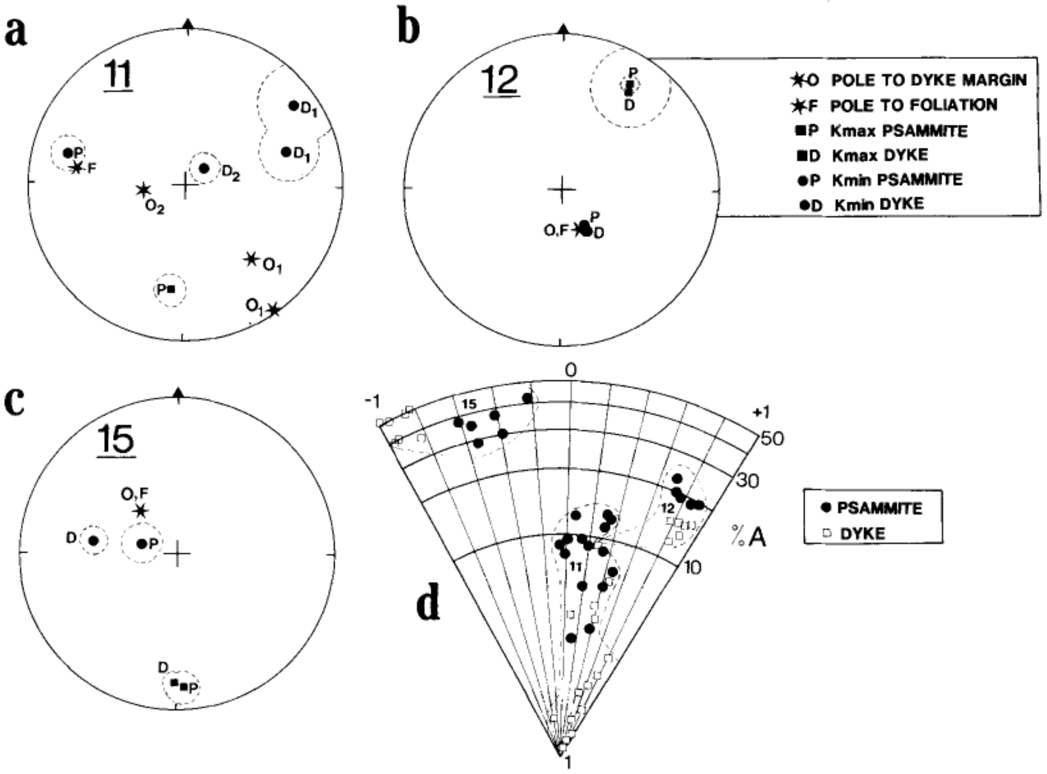


Figure 4. Magnetic fabrics from sites 11–12 and 15, Sørøy. Site mean values of $K_{\min}$, $K_{\max}$ and their associated 95 per cent confidence circles (stippled) are shown together with poles to dyke margin/observed foliation (a–c). All data are plotted as downward-dipping points. D_1, D_2 in (a) denote two sets of dykes (D_2 youngest). In (d) the shape of the susceptibility ellipsoid for individual samples is portrayed in a Hsu (1966) diagram utilizing the quantity $V = (2K_{\text{int}} - K_{\max} - K_{\min})/(K_{\max} - K_{\min})$ plotted around the circumference and percentage of anisotropy [percentage $A = (K_{\max} - K_{\min})/K_{\text{mean}}$] plotted logarithmically as the radius. $V = -1$ depict uniform extension, $V = 0$ plain strain, and $V = +1$ uniform shortening.

E–SE or S–SW declinations and steeply to intermediate downward-pointing inclinations. These directions are designated components C and B, respectively (Fig. 6b; Table 2). They commonly co-exist at sample level (sites 40, 42, 44 and 45) and a simple two-component structure is occasionally observed (Fig. 7a). C is usually identified as the low-coercivity component during AF demagnetization when co-existing with the B component, but unblocking temperature spectra analysis reveals a more complex pattern. At some sites (sites 42, 44 and 45), component C occupies the higher unblocking spectra (Fig. 7a), whereas the opposite relationship is observed from sites 40 and 41. A more complicated directional relationship was observed in a few samples from site 45. Thermal demagnetization identifies the C component in the NRM-510 °C range, then the B component is randomized between 510° and 545 °C, and finally the C component is once more identified above 545 °C (Fig. 7b). Thus, B appears to intervene between or split the C component blocking spectra. The intervening components varied in direction, probably all B in origin, but proved difficult to identify due to overlapping blocking spectra.

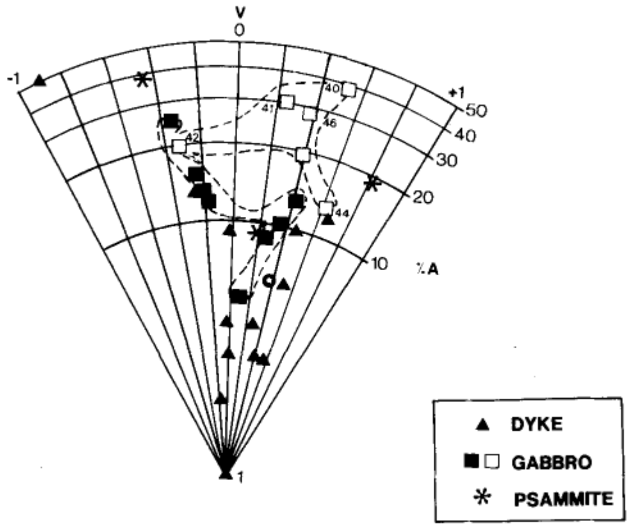


Figure 5. Hsu diagram showing site-mean magnetic fabric ellipsoids from Sørøy and Øksnes. Open squares (numbered) represent sites from Øksnes. Conventions as Fig. 4.

Site 46 gave normal-polarity magnetizations due NE and upward-dipping inclinations, a magnetization component commonly observed from Sørøy (Figs 6a and b; Table 2). This component is designated component A.

Sørøy

A large number of sites from Sørøy, including *all* psammites and sheared and partly amphibolitized dykes, i.e. pre- or syn-tectonic dykes in relation to F_2 folds, appeared viscous and directionally unstable to both thermal and AF demagnetization.

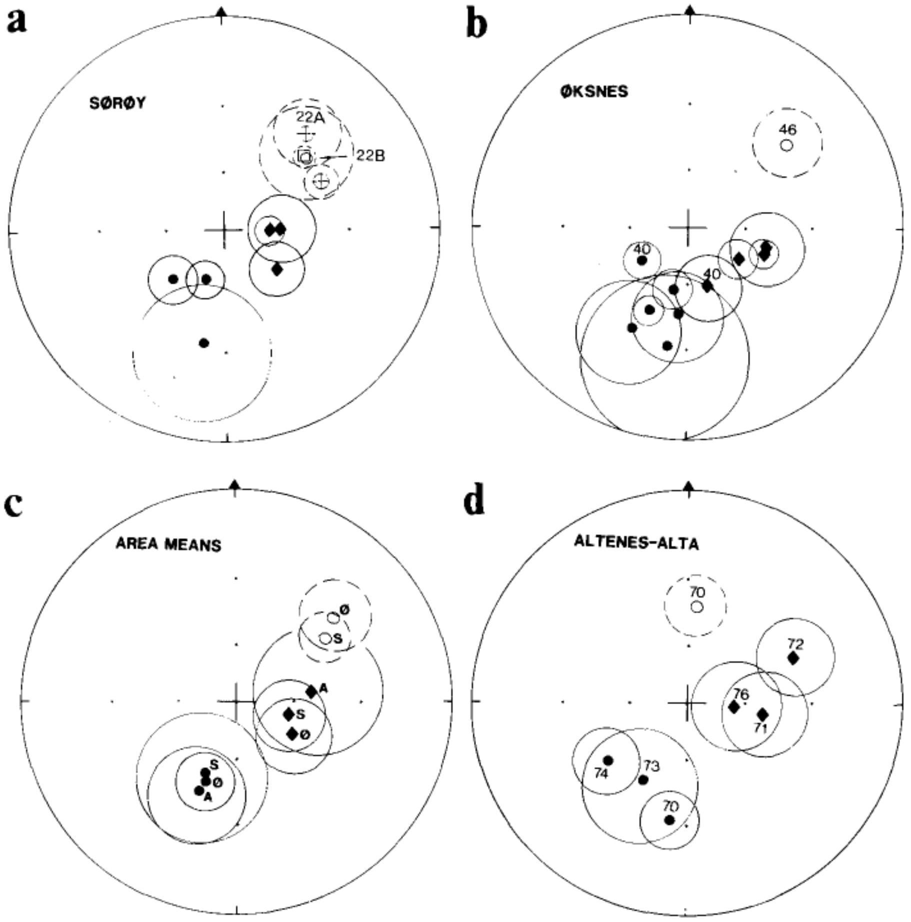


Figure 6. Site-mean remanence components from Sørøy (a), Øksnes (b), Altenes-Alta (d), in addition to area mean directions (c). In stereoplots open (closed) symbols represent upward (downward) pointing inclinations. Diamond symbols represent component C directions (see text). Small circles represent B directions. In (a), open squares denote a gabbroic site (22B), and open circles marked with a cross give dyke directions and contact gabbro. Symbols in (c) are as follows: S = Sørøy, Ø = Øksnes and A = Altenes-Alta. All directions in (a–d) are shown in '*in situ*' coordinates, and *not* adjusted for possible TRM deviation (see text).

Gabbroic samples characteristically gave susceptibilities in the order of 0.0001–0.025 (SI) and NRM intensities between 0.005 and 1.5 A m^{-1}. Dyke (psammite) sample values varied between 0.0001–0.037 (0.00003–0.002) SI and 0.01–9 (0.0006–0.2) A m^{-1}.

The Hasvik and Breivikbotn Gabbros are dominated by components C and B. When co-existing at sample-level, component C always displays a higher unblocking temperature spectra than B (site 26). Magnetically stable dyke samples, all appearing fresh in hand-specimen (hereafter referred to as fresh dykes), *always* reveal component A. From site 22a, samples from dykes intruding the Breivikbotn Gabbro gave almost single component A remanences with very discrete unblocking spectra above 540°–555 °C (Fig. 7c). Contact gabbro samples are also dominated by the A component, clearly identified above 20 mT (Fig. 7d). Unfortunately, non-baked gabbroic samples at site 22 proved viscous. Both gabbroic and dyke samples from site 22a are dominated by variable amounts of magnetite and pyrrhotite.

Site 21 embraces a 20 cm wide dyke intruding the Breivikbotn Gabbro (Fig. 8). Thermal and AF demagnetization of dyke specimens show exemplary A magnetizations (Figs. 8a,b and d). Baked gabbro samples are also dominated by the A component. On the other hand, non-baked gabbroic samples are influenced by component C, usually identified above 350°–450 °C after randomizing a somewhat more NE-directed component (Fig. 8c and d). The NRM of dyke samples from site 21 is dominated by magnetite, whereas gabbroic samples show a mixture of pyrrhotite and magnetite. Gabbroic samples commonly showed a somewhat 'noisy' irregular directional pattern below 350 °C, attendant on 70–90 per cent intensity reduction. This we relate to the influence of pyrrhotite. The contrasting magnetic fabrics between the dyke and the host gabbro are also portrayed in Fig. 8(e) (see also Fig. 2). The host gabbro is dominated by a shallow eastward-dipping foliation with lineations plunging due north, whereas the dyke is dominated by a more steeply inclined foliation dipping toward the NNW and no lineations are developed. This observation is consistent with the remanence data, and signifies that the dyke has intruded *after* foliation of the gabbro.

Altenes-Alta

Characteristic remanence components from the Altenes-Alta area (Fig. 6c and Table 2) generally display

Table 2. Site-mean statistics.

Site	Code	Range	Dec	Inc	N	a95	C	TDec/TInc
Sørøy:								
20	(G)	LB^1	226	+53	4	11.4	B	221/+59
21	(G)	HB	091	+66	17	7.4	C	092/+64
	(**D**,CG)	HB,HC	064	−36	8	7.4	A	067/−38
22A	(**D**,CG)	HB,HC	041	−29	13	13.1	A	037/−26
22B	(G)	HB^2	049	−36	6	20.3	A	054/−32
	(G)	HB^2	201	+62	5	9.5	B	214/+61
24	(**D**)	HB	048	−36	6	5.2	A	051/−33
25	(G)	HB	128	+56	5	13.4	C	139/+57
26	(G)	HB	090	+61	8	16.3	C	091/+70
	(G)	LB	191	+33	3	27.1	B	184/+42
Øksnes:								
40	(G)	HB/HC	234	+61	9	9.3	B	217/+68
	(G)	LB	161	+58	4	16.3	C	138/+63
41	(G)	HB	204	+44	5	6.9	B	250/+25
42	(G)	HB/LC	121	+59	8	10.4	C	105/+59
	(G)	LB/HC	186	+46	6	19.8	B	176/+46
43	(G)	HB	193	+57	4	10.1	B	190/+50
44	(G)	HB/LC	104	+49	7	17.0	C	113/+51
	(G)	IB/HC	208	+34	4	21.5	B	203/+33
45	(Pe)	HB/LC	108	+49	21	7.5	C	107/+50
	(Pe)	LB/HC	189	+31	3	32.0	B	193/+23
46	(G)	HB	049	−28	7	14.0	A	043/−19
Altenes-Alta:								
70	(MB)	HB	005	−41	9	13.6	B(?)	
	(MB)	LB	188	+32	4	11.9	B	
71	(MB)	HB	098	+51	6	20.4	C	
72	(MB)	HB	066	+34	3	15.7	C	
73	(MG)	HC	209	+45	4	25.3	B	
74	(MG)	HB/HC	233	+41	10	14.4	B	
76	(MG)	HC	093	+65	3	22.6	C	

CG=Contact gabbro; see Table 1 for other rock codes.
Dec=mean declination; Inc=mean inclination; N=number of samples; a_{95}=95 percent confidence circle; C=Component; TDec/Tinc=mean declination /inclination accounting for possible TRM deviation (Sørøy & Øksnes).
LB=Low temperature unblocking;LC=Low coercivity unblocking;
HB=High temperature unblocking;HC=High coercivity unblocking;
[1] High blocking component unidentified;
[2] Components are identified at two separate outcrops within the site.

components B and C (Fig. 9a). The palaeomagnetic data from site 70, however, are ambiguous. Most samples from this site show an anti-parallel and dual-polarity interplay of a southerly, downward-dipping, low-blocking component and a northerly, upward-pointing, high-blocking component (Fig. 9b). Due to this dual-polarity at sample level, and the declination discordance with the NW-directed A component, we have designated the northerly component as the normal polarity counterpart of component B. The majority of tested samples are dominated by magnetite, but site 71 shows evidence of haematite with blocking temperatures and directional stability up to 675 °C.

REMANENCE AND TRM DEVIATION ANALYSIS

The comparison of area mean directions (Fig. 6d; Tables 2 and 3) suggests that remanence acquisition post-dates local folding and/or rotational thrusting, and components B and C most likely relate to post-metamorphic cooling/uplift or phases of thermal overprinting.

Thermo-remanent magnetization (TRM) acquisition in anisotropic rocks may involve considerable remanence deviation. Remanence deviation depends on grain-size, the degree of *remanence* anisotropy and more importantly on the angular relationship between the inducing ambient field and the pre-existing magnetic foliation. In order to explore the effect of TRM deviation, the anisotropy of remanence (AR) was tested from Sørøy and Øksnes (detailed in Torsvik & Walderhaug, in preparation) Anisotropy of low-field (4 mT) isothermal remanence (IRM) was examined since TRM and IRM anisotropy tensors are intrinsically identical (Stephenson, Sadikun & Potter 1986).

Following Stephenson *et al.* (1986) and Cogne (1988), the Cartesian coordinates J_i of TRM as a function of field H_j through the TRM anisotropy tensor $\boldsymbol{M}_{ij}$ can be denoted as $J_i = \boldsymbol{M}_{ij} H_j$ $(i, j = 1, 2, 3)$. A site-mean TRM tensor $\boldsymbol{M}_{ij}$ was determined from measurement of IRM induced in three orthogonal axes (x, y, z), typically based on 2–5 samples. The true TRM or ambient magnetic field direction from each site was subsequently calculated as $H_i = \boldsymbol{M}_{ij}^{-1} J_j$.

The eigenvectors of the AR ellipsoids proved similar to AMS eigenvectors, but the AR eigenvalues were an order of magnitude higher. Percentage anisotropy of remanence varied between 5 and 123 per cent (Fig. 10c). Site-mean angular deviation, however, is typically less than 10° (Fig. 10b), but values as high as 42° were predicted from site 41. The effect on the overall statistics, however, is not significant (Table 3). This relates to the variable orientation of the magnetic foliation planes (Figs 2 and 3). Thus, TRM deviation analysis is of considerably more importance in deformed regions with a 'simple' and consistent deformation pattern. In such cases, TRM deviation would produce systematic errors in the average field-direction. In the more

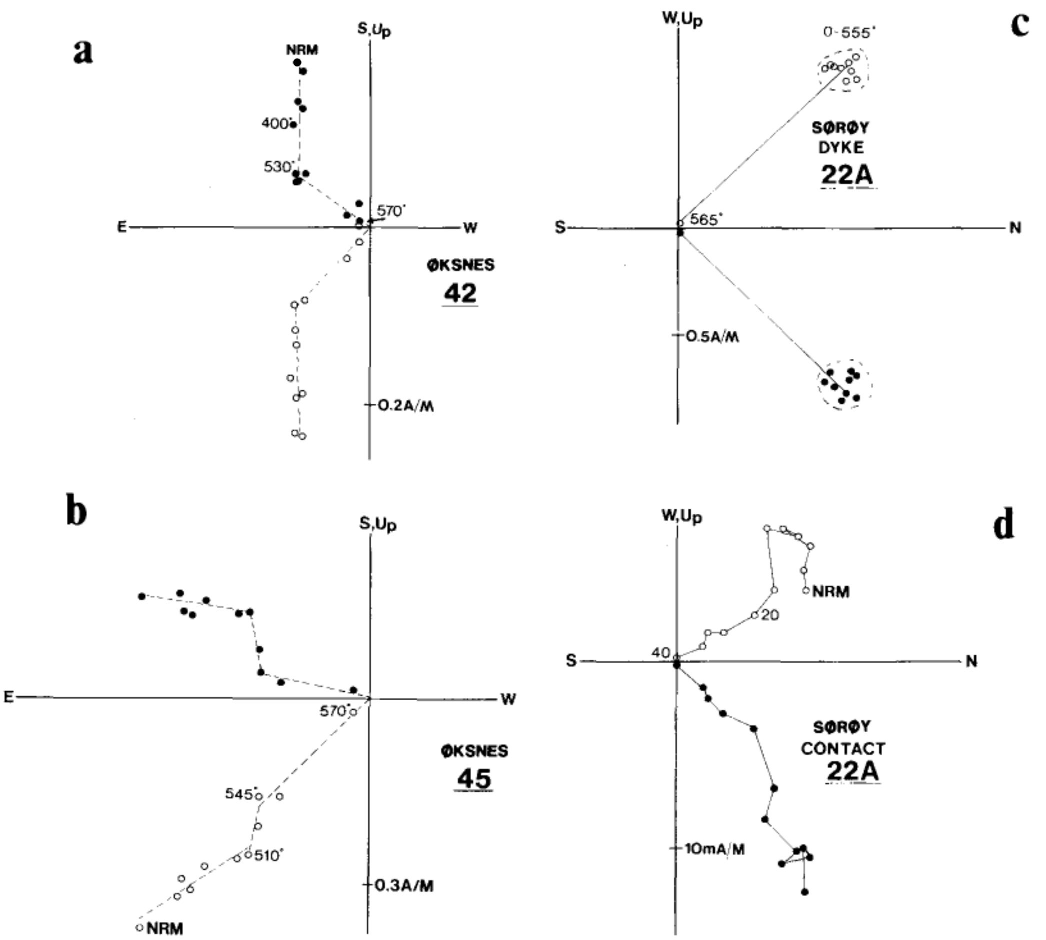


Figure 7. Examples of demagnetization for gabbroic samples from Øksnes (a and b), a dyke sample (c) and baked gabbro sample (d), Sørøy. In orthogonal vector projections open (closed) symbols represent point in the vertical (horizontal) plane. Site numbers are underlined.

complex case presented here, mean directions are fairly correct, but increased between-site scatter is to expected.

The highest degree of anisotropy of remanence (and anisotropy of susceptibility; Fig. 5) is recorded from the Øksnes gabbros, and it is evident that component B and C from Øksnes show a directional overlap caused by the SE position of the C component from site 40 (Fig. 6b). This site has a high degree of anisotropy of remanence (123 per cent). The '*in situ*' mean direction converges toward the other site-mean C components when accounting for TRM deviation, and the directional overlap with the mean B components is also reduced (*cf.* Figs 10a and 6b). Only component C displays a lower dispersion after correcting for TRM deviation (Table 3). Thus, in Fig. 10(a) component B is left '*in situ*', whereas the C components have been corrected for TRM deviation.

The technique outlined above only applies to the acquisition of a TRM, and in the case of chemical remanent magnetization (CRM) or TCRM the technique may have no relevance or would result in an overcorrection of the remanence data. As demonstrated earlier, a somewhat complex and intriguing thermal blocking-spectra relationship between components B and C (Øksnes gabbros) suggests that one of these components has a CRM or TCRM origin. We propose that component C has a TRM origin as indicated by the reduced scatter after TRM deviation analysis, and further corroborated by laboratory TRM experiments (Torsvik & Walderhaug, in preparation). Component B has a younger TCRM origin, possibly acquired by inversion of primary pyrrhotite to form magnetite, but also as a PTRM in magnetite. The former process would be expected to produce the somewhat complicated blocking-temperature spectra as were, for example, observed from the Øksnes gabbros.

Component A recovered from dykes was not notably changed after TRM deviation analysis. The percentage of remanence anisotropy is small, however (<5–8 per cent), and the predicted TRM deviations are consequently less than 3–4 degrees of arc. A primary TRM origin, however, is indicated by the positive contact test (Figs 7c,d and 8).

REMANENCE AGES AND ASPECTS OF APPARENT POLAR WANDER

The nature and timing of the Finnmarkian Orogenic event is a matter of some dispute (see Townsend & Gayer 1989). Krill, Rodgers & Sundvoll (1989) reject a *dichotomous* Finnmarkian–Scandian model, and suggest that these represent a single orogenic event, implying the stacking of the KNC to be entirely Scandian.

A considerable amount of isotopic age-data are available from igneous (SIP) and basement rocks within the KNC

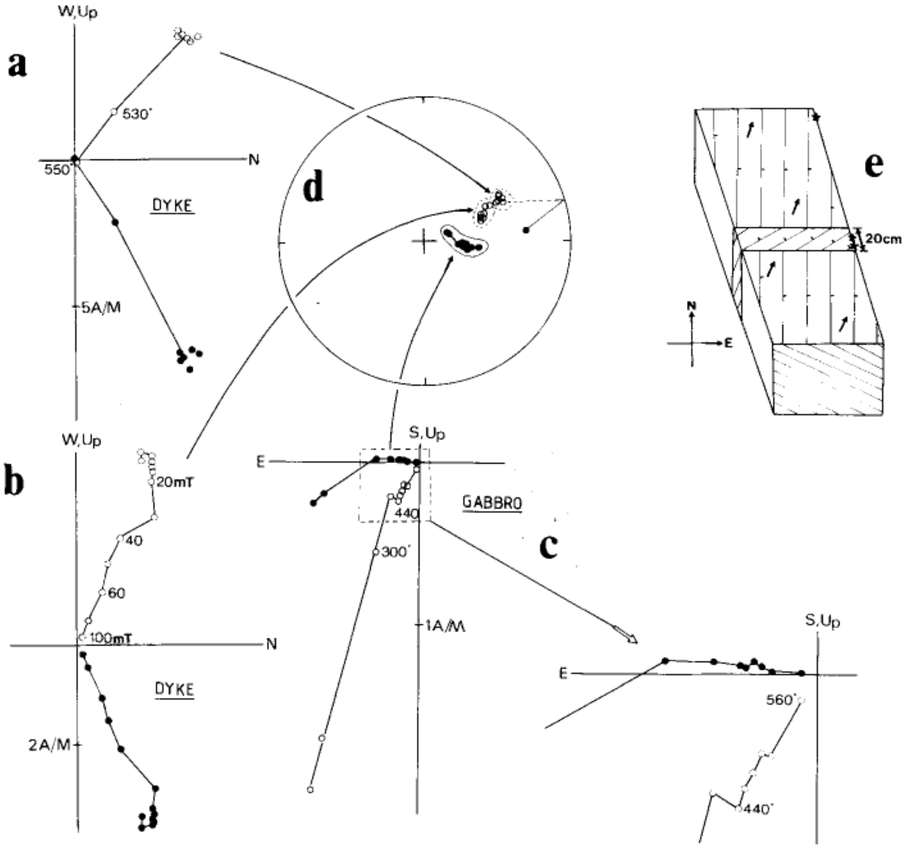


Figure 8. Examples of demagnetization of two dyke samples (a and b) from Sørøy and a non-baked gabbroic sample (c). Bottom right diagram in (c) is an expansion of the central area of the diagram. (d) shows a stereographic representation of the same samples. A block diagram of site 21 is shown in (e). Magnetic foliation planes (bedding symbol) and lineations (arrows) are indicated.

which have been compiled in Fig. 11 (updated from Pedersen *et al.* 1989). New Ar^{39}/Ar^{40} *plateau* ages (Dallmeyer 1988), Sm/Nd, U/Pb zircon and a few Rb/Sr whole-rock data (including the Breivikbotn and Hasvik Gabbros) yield ages of around 530 Ma. According to Pedersen *et al.* (1989) this age records the crystallization of late alkaline rocks emplaced at shallow crustal levels. Since these rocks cut deformed rocks of the SIP, 530 Ma must represent a younger age limit for early Caledonian metamorphism (Pedersen *et al.* 1989). As the alkaline rocks were subsequently deformed amd metamorphosed, there is evidence of both pre- and post-530 Ma tectonometamorphic events (see also Roberts 1988b). Based on a recent Sm–Nd mineral age of *c.* 700 Ma (not included in Fig. 11) from the Hasvik Gabbro, which cuts D_2 structures on Sørøy, Aitcheson *et al.* (1989) argue for an even older, Late

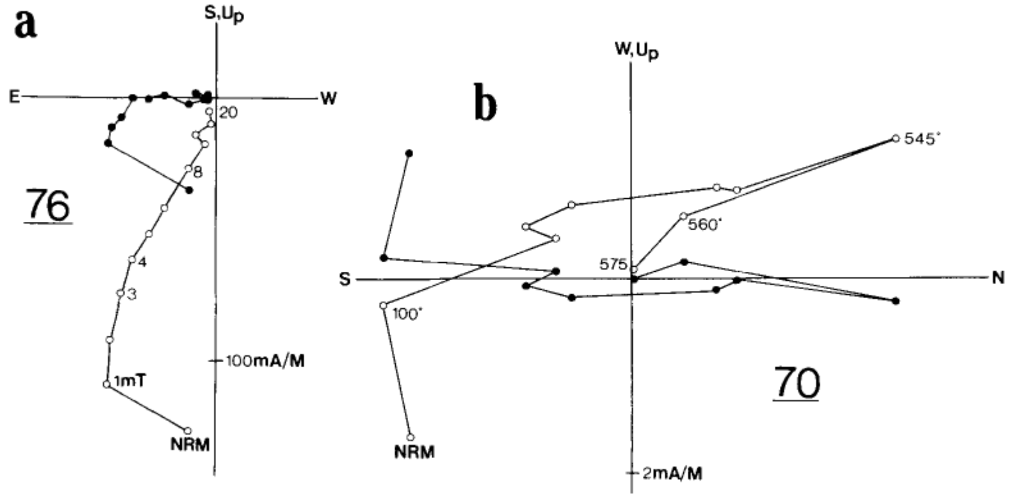


Figure 9. Examples of demagnetization of samples from the Alta area (site 76, a, and site 70, b). (a) Component C, (b) dual polarity component B.

Table 3. Final statistics.

	Dec	Inc	N	a95	k	Lat	Long	dp	dm
Sørøy:									
Component A	054	-36	3	11.1	125.3				
Component B	204	+52	3	29.7	18.3				
Component C	105	+62	3	18.1	47.2				
Øksnes:									
Component A	049	-28	7	14.0	19.6[1]				
Component B	201	+46	6	13.7	24.9				
Component C	121	+56	4	18.0	26.9				
Altenes-Alta:									
Component B	203	+41	4	20.6	20.9				
Component C	083	+51	3	30.3	17.6				
Sørøy & Øksnes combined:									
Component A	050	-33	5	7.7	99.7	N05	E335	5	9
A^t	050	-30		11.6	44.3				
Component B	202	+48	9	10.4	25.2	N10	E002	8	12
B^t	204	+48		15.1	12.5				
Component C	115	+59	7	10.7	32.9	N03	E076	12	16
C^t	113	+60		8.9	46.9				
All areas combined:									
Component A	050	-33	5	7.7	99.7	N05	E335	5	9
Component B	203	+46	13	8.4	25.1	N09	E002	7	11
Component C	104	+57	10	10.6	21.6	N31	E086	11	15

k=precision parameter (Fisher, 1953);Lat=pole latitude; Long=pole longitude; Dp,Dm=semi-axis of the oval of the 95 percent confidence about the mean pole;N=number of sites;
^{t}Mean directions corrected for possible TRM deviation (Note that uncorrected directions are used in all figures apart from **C** components in Fig. 10); Cf. Table 2 for further legend.

Proterozoic orogenic event overprinted by the younger Caledonian deformations.

Some Rb/Sr whole-rock ages and Ar^{39}/Ar^{40} hornblende mineral ages cluster around 490 Ma; these were ascribed by Dallmeyer (1988) to Early Ordovician post-metamorphic uplift. Preliminary Rb–Sr dating of ductile mylonites from the base of KNC in one area has yielded an isochron age of 479 ± 15 Ma (Roberts & Sundvoll 1989). Finally, Rb/Sr biotite, K/Ar biotite, Ar^{39}/Ar^{40} nepheline–hornblende and Ar^{39}/Ar^{40} muscovite ages cluster around 430–410 Ma. This youngest peak suggests that Scandian metamorphism in the Magerøy Nappe (411 ± 7 Ma) was broadly synchronous with an internal tectonothermal event within the KNC (Dallmeyer 1988), and that the final translation of the KNC was

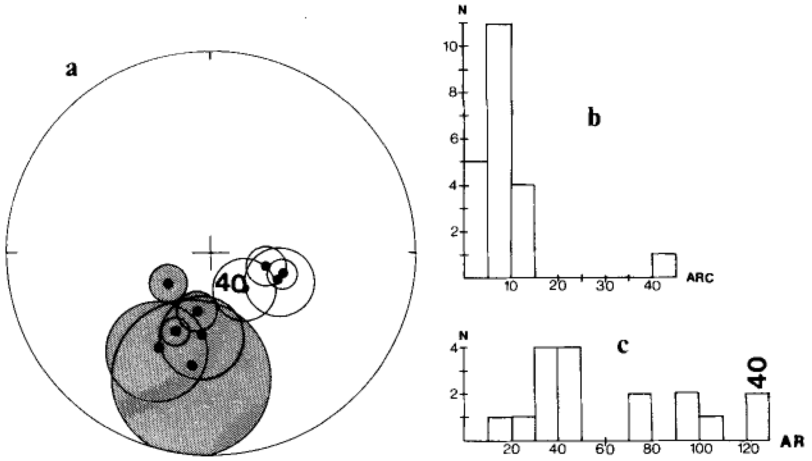


Figure 10. (a) Example of TRM deviation analysis on site-mean directions from Øksnes. Component B directions (shaded 95 per cent confidence circles) are plotted in '*in situ*' coordinates, whereas component C directions (confidence circles unshaded) are corrected for TRM deviation. (b) Histogram shows site-means of angular difference in degrees (arc) between '*in situ*' directions and directions corrected for possible TRM deviation. (c) Histogram shows percentage degree of anisotropy of remanence [$AR = 100(1 - k_1/k_3)$, where k_1, k_2 and k_3 represent eigenvalues]. In (b) and (c) the vertical axis represents number of sites.

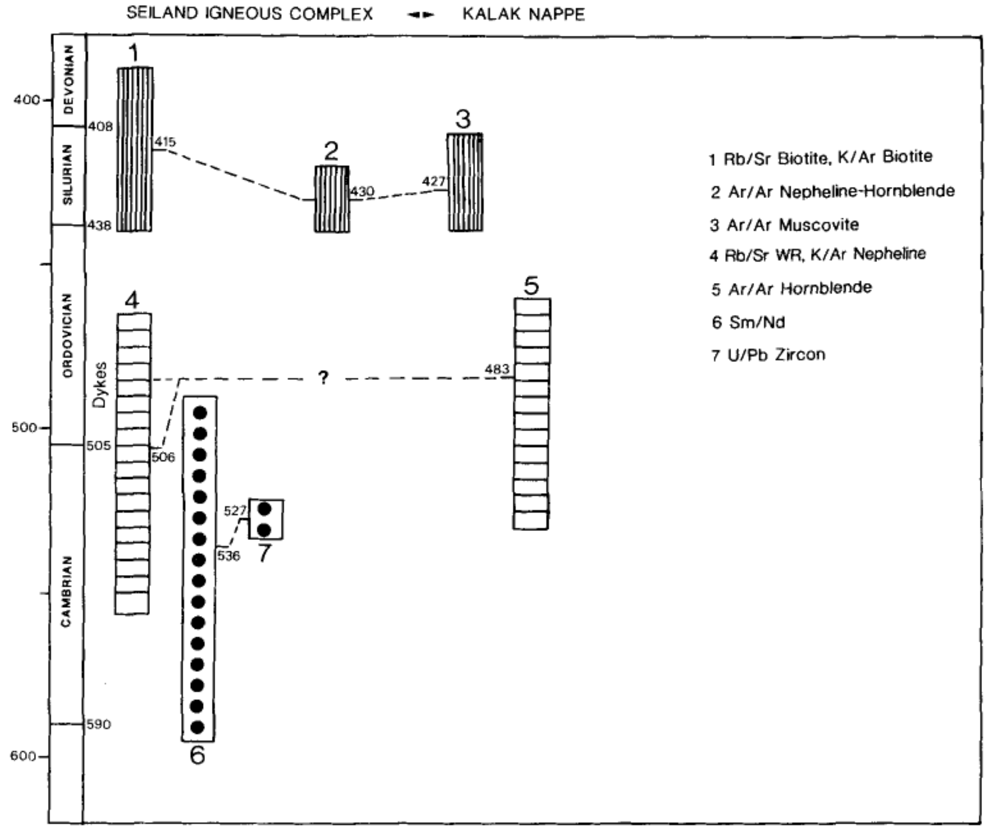


Figure 11. Compilation of isotopic age data from the Seiland Igneous Complex and the Kalak Nappe. Updated from Pedersen *et al.* (1989) with new Ar^{39}/Ar^{40} reported by Dallmeyer (1988). Ages (small numbers) represent mean-values for the various age groups. Note that the vertical length of each 'age' bar embraces the maximum error of confidence within each 'age' group. Large numbers displayed at the top of each 'age' bar refer to age method listed in the right part of the diagram. Note that 'age' bars 1 and 2 and 4–6 are from the Seiland Igneous Complex, whereas 3 and 5 are from basement rocks located to the Kalak Nappe.

Scandian rather than Finnmarkian. This appears to be confirmed by Rb–Sr dating work by Roberts & Sundvoll (1989), late phase shear-banded mylonites yielding a Devonian isochron age.

Given the ages outlined above, the maximum unblocking temperatures of magnetite ($T_{b,max} = 580\,°C$) and its time-dependence, remanence acquisitions should range from Late Cambrian to Late Silurian or even Early Devonian times, unless younger low-temperature chemical alterations occurred below the isotopic blocking-temperature of, for example biotite, *c.* 200 °C. Seen in conjunction with Ar^{39}/Ar^{40} mineral ages, remanence ages may straddle the 490–410 Ma range (Fig. 11).

In view of the clear deficiency of reliable pre-Devonian Palaeozoic palaeomagnetic data from Scandinavia (Pesonen *et al.* 1989; Torsvik *et al.* 1990) the reported palaeomagnetic data are compared with British Apparent Polar Wander Paths (APWP). All British APWPs show a marked counterclockwise loop during the Palaeozoic (Fig. 12), and they are characterized by a Siluro-Devonian (mid-Silurian to mid-Devonian) 'corner' where they converge to produce a common path. This 'corner' is also recognized from data from North America and Greenland when rotated into a Bullard, Everett & Smith (1965) reconstruction (Fig. 13c). Moreover, Smethurst & Khramov (in preparation) have reported that palaeomagnetic data from the Lower ORS facies sediments of the western Ukraine, Russian Platform, also plot in this 'corner'.

The relative south-poles for component A and B plot within the Ordovician–Silurian section of the APWP for Southern Britain (Fig. 12). This apparent temporal match, however, should be treated with caution since the APWP for S. Britain is poorly time-constrained. McCabe & Channell (1990) have also challenged the reliability of the Ordovician poles which were used to constrain the path of Fig. 12 (Torsvik *et al.* 1990).

Component A approaches the 'corner' in the British APWPs. Contact tests clearly favour A as the youngest recorded remanence, and viewed in relation to a range of isotopic age-data averaging around 415–430 (Fig. 11), a mid-Silurian age is most likely. Whilst pole A (and B) apparently compares with Ordovician–Silurian poles from Southern Britain, a comparison with the only 'reliable' Silurian palaeomagnetic pole from Norway, the Wenlock–Ludlow Ringerike Sandstone pole (Douglass 1988), appears enigmatic (Fig. 13). If the Ringerike pole is older than the A pole, this implies that the Baltic APWP joins the Laurentian APWP by mid-Silurian time (Fig. 13), followed by convergence toward the 'corner' through pole A (see discussion).

Component C is clearly pre-Silurian or pre-Scandian in age, unless subsequent large (>90°) tectonic rotations of

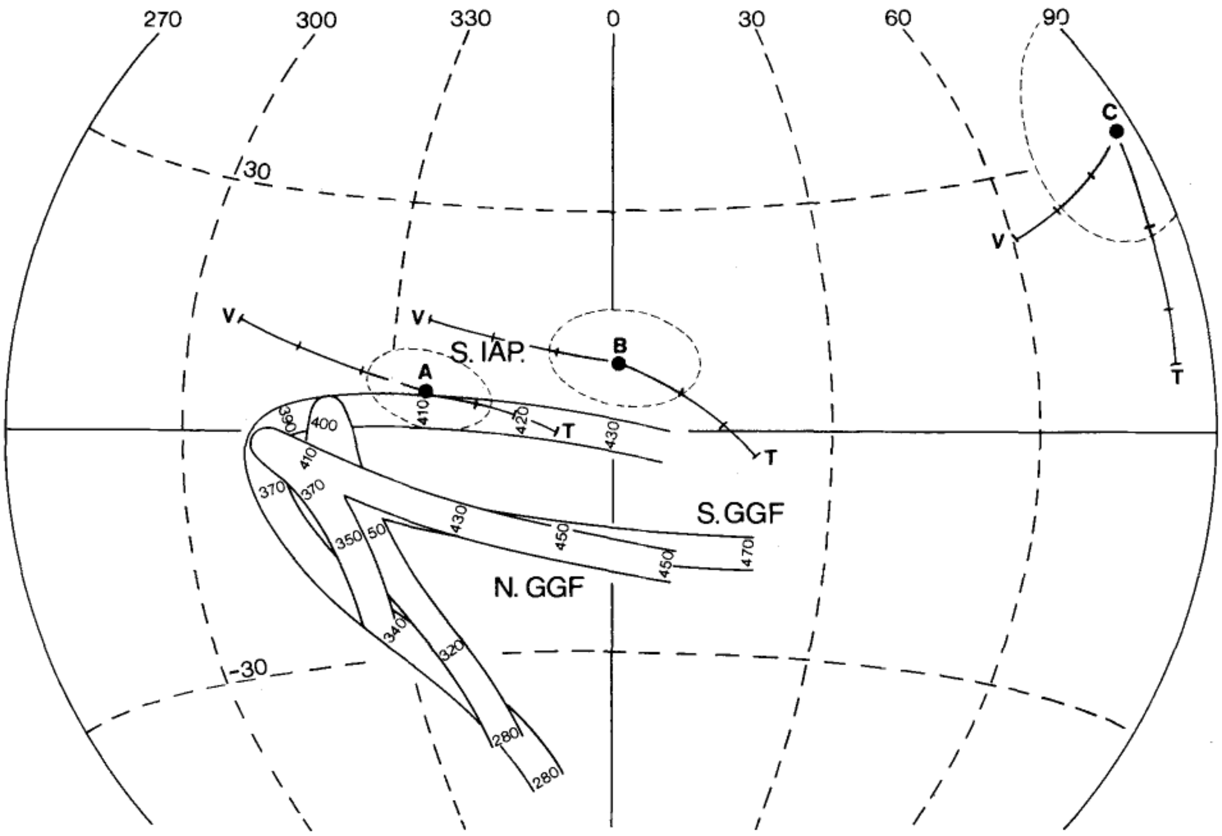


Figure 12. The relative pole position for components A, B and C viewed in relation to some suggested British APWPs (Torsvik *et al.* 1990). APWSs are as follows: S.IAP = South of the Iapetus Suture; S.GGF = North of the Iapetus Suture, South of the Great Glen Fault, Scotland, N.GGF = North of Great Glen Fault. Anticlockwise rotations on vertical axes (V) and continental scale tilting (T) on orogen parallel axes (045°) are portrayed in steps of 10° (up to 30°). Equal area projection.

the KNC have occurred (Fig. 12). In a recent summary of palaeomagnetic data from Fennoscandia, Pesonen *et al.* (1989) considered the Lower Cambrian Nexø Sandstone pole (Prasad & Sharma 1978), the 565–603 Ma (Rb/Sr biotite) Fen Complex pole (Poorter 1972) and the Båtsfjord dykes pole (Kjøde *et al.* 1978) dated to 640 Ma (K/Ar biotite) as the most reliable Late Precambrian to Cambrian poles. The component C pole plots close to these poles (Fig. 13a).

The Båtsfjord pole has previously been used to deduce large-scale Late Precambrian dextral movements (1000 km) along the Trollfjord–Komagelv Fault (Kjøde *et al.* 1978). Such movements along the Trollfjord Komagelv Fault (Fig. 1a) have been advocated on geological grounds (Siedlecka & Siedlecki 1967; Roberts 1972; Harland & Gayer 1972; Johnson, Levell & Siedlecka 1978; Rice *et al.* 1989), but the amount of dextral movement indicated by Kjøde *et al.* (1978) is questionable as the Båtsfjord pole was compared with Sveconorwegian and Torridonian (Scotland) poles, i.e. poles some 100–150 Ma older. A more realistic comparison (Pesonen *et al.* 1989) suggests more moderate differences, but detailed future work is required to test the postulates of movements on the Trollfjord Komagelv Fault. The C pole and the Båtsfjord dyke pole partly overlap (Fig. 13a), but we do not consider the C pole to be Late Precambrian (640 Ma) in age, given the isotopic constraints (Fig. 11). A Cambrian (*c.* 530 ma) age for pole C combined with insignificant APW during the Late Precambrian–Cambrian presents a plausible solution, but we may equally well dispute the *magnetic* and perhaps also the isotopic age (Rb/Sr biotite) for the Båtsfjord pole. The Båtsfjord dykes are situated immediately beneath the overthrusted KNC, and the dykes have a magnetic structure closely similar to e.g. the Øksnes gabbros. Indeed, fig. 5 of Kjøde (1980) shows a mixture of an easterly component (comparable with C) and a SW component (comparable with B). Thus, we would argue that the C component, and perhaps also the B component, is compatible with palaeomagnetic data from the Båtsfjord dykes.

DISCUSSION AND PALAEOGEOGRAPHIC CONSIDERATIONS

Palaeomagnetic studies of igneous rocks within the Kalak Nappe Complex and of metagabbros and basalts within the tectonic windows of Karelian rocks reveal three major remanence components (termed A, B and C). The consistency of these components over a wide geographic (*c.* 3500 km^2) and complex geological area (*cf.* the suggested cross-section in Fig. 1b) suggests that they all post-date folding and local rotational thrusting. Some of the tested rocks possess high anisotropies of remanence, but TRM deviation analysis predicts only minor modification of the overall mean directions. The magnetic fabrics from mafic

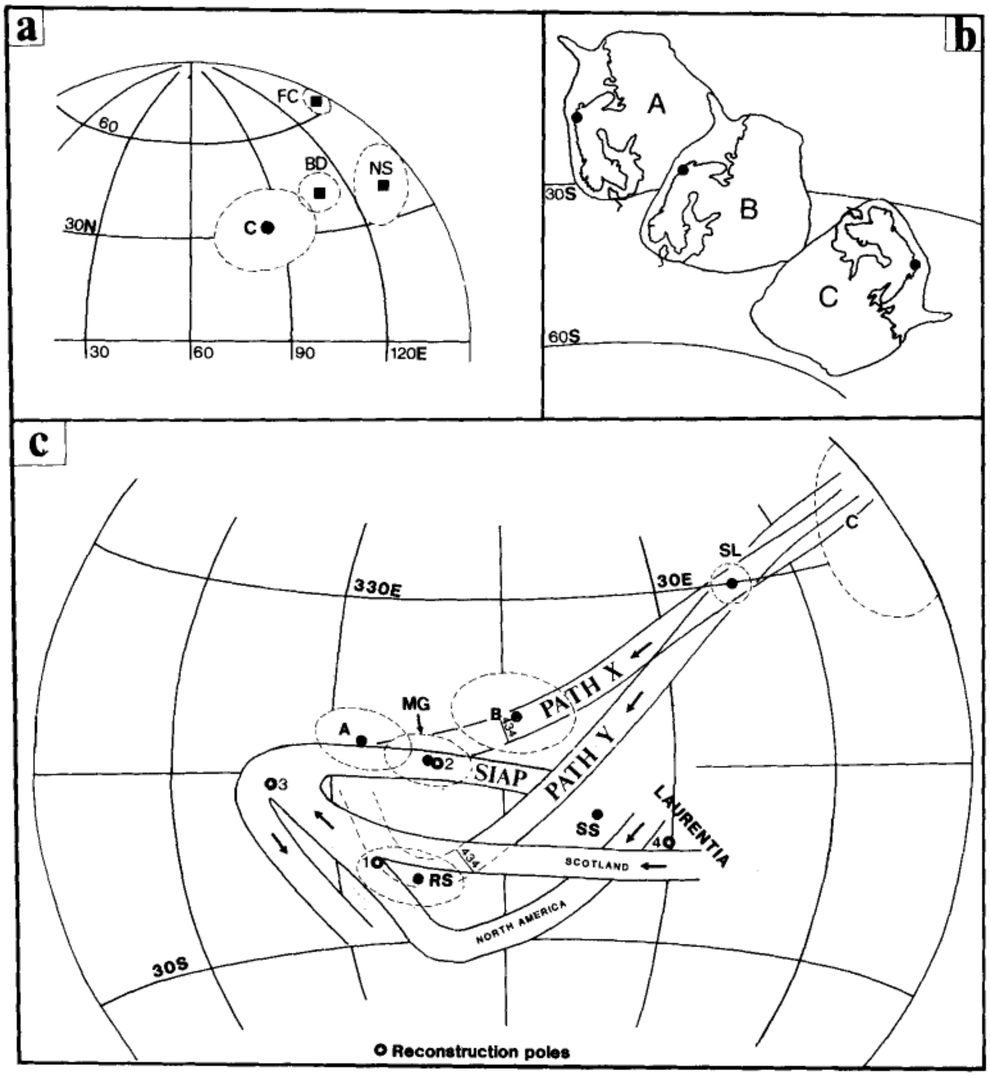


Figure 13. (a) Pole C compared with some Late Precambrian–Cambrian poles from Scandinavia, i.e. FC = Fen Complex, NS = Nexø Sandstone and BD = Båtsfjord Dyke (*cf.* geographic location of BD in Fig. 1a). (b) Palaeolatitudinal positions of Baltica based on poles A, B and C. (c) APWPs for Britain, South of the Iapetus Suture (SIAP), Laurentia (Scotland and North America) and Baltica. All paths are schematically joined by the Siluro-Devonian 'corner'. The path for North America (Table 4) is based on a smooth path fit (Jupp & Kent 1987; see also Torsvik *et al.* 1990) of poles listed in Kent & Van der Voo (1990) with the inclusion of a recently reported Middle-Ordovician pole for North America (Farr & Sprowl 1989). British Paths from Torsvik *et al.* (1990). The two Baltic paths (X and Y) are constructed by using all the poles shown in Fig. 13(a and c). Path X, however, ignores the Ringerike Sandstone pole (RS), whereas path Y is anchored by the RS pole (*cf.* text). Time-calibration of the two Baltic paths is approximate (Table 4), and we have only marked the Lower Silurian position in the paths (434 Ma). Lettering is as follows: RS = Ringerike Sandstone Pole; MG = Honningsvåg Gabbro pole; SS = Southern Scandinavia pole [no error estimates provided by Bøhm *et al.* (1989)]; SL = Swedish Limestone pole (Arenig–Llanvirn). Reconstruction poles are as follows: 1 = Laurentia/Baltica in Wenlock–Ludlow times; 2 = Avalonia in Wenlock–Ludlow times; 3 = Laurentia/Baltica/Avalonia Siluro-Devonian Boundary; 4 = Laurentia Cambro-Ordovician (Lower Ordovician). Note that Baltica is positioned according to pole C during Lower Ordovician times.

dykes from Sørøy provide evidence for pre-, syn- and post-tectonic origins. Only the post-tectonic dykes provided stable palaeomagnetic directions.

Component A is identified in fresh and undeformed dykes, and a positive contact test proves a primary TRM origin. Two gabbroic sites were also overprinted by this component. The normal polarity A component is the only magnetic signature as yet identified in the Honningsvåg Gabbro (Torsvik *et al.*, in preparation; pole MG in Fig. 13c), which is situated within the overlying Scandian Magerøy Nappe (Fig. 1a). The studied area is remarkably unaffected by Late Palaeozoic–Mesozoic magnetic overprinting, which presents a major problem in Southern and Central Norway (Torsvik *et al.* 1986, 1987, 1988, 1989).

According to Gayer *et al.* (1987), early Caledonian peak metamorphism within the KNC occurred prior to initial thrust stacking of the nappes. An early phase of SE-thrusting occurred under ductile conditions, whereas later thrust movements took place under brittle conditions (chlorite grade) accompanied by an anticlockwise change in transport direction toward the ESE (Townsend 1987). Component C may relate to uplift following the early ductile deformation, or may have been acquired as foreland-propagating thrust units ascended to shallower more brittle conditions. Any associated rotations, however, appear to pre-date acquisition of component C.

Aitcheson *et al.* (1989) have recently suggested that some of the SIP gabbros are older than 700 Ma, and that a Late Proterozoic orogenic event (> 800 Ma) is represented in parts of the KNC. These authors have suggested that Caledonian deformation of the KNC was restricted to movements along major nappe boundaries and internal shear zones after 520–530 Ma, but this is difficult to reconcile with Ar^{39}/Ar^{40} data. Seen in relation to Ar^{39}/Ar^{40} hornblende ages (Fig. 11), with blocking temperatures of about 500 °C, it is suggested that C was acquired during post-metamorphic cooling in Early Ordovician time, approximately 490 Ma, although a Cambrian age (*c.* 530 Ma) cannot be excluded. We propose that component C 'dates' the initial emplacement of the KNC onto the margin of continent Baltica.

A pole from the Swedish Orthoceras Limestones (Claesson 1978), previously described as 'anomalous' in the literature, may provide a lower age limit for the C pole. These Arenig to Llanvirn limestones record steep downward-dipping magnetizations due ESE. Although Claesson (1978) had some reservations concerning the reliability of her results, the site-mean directions form a very well-defined group (based on 73 sites), clearly removed from the present-day field (see also Piper 1987, p. 265), and the relative pole-position shows no similarity with poles from younger times (Fig. 13c). We have assigned a primary Arenig–Llanvirn age (> = 470 Ma) for this pole, although uncertainties remain concerning the relative importance of diagenetic/depositional controls on remanence aquisition. The relative pole position for component C, plotting between Late Precambrian–Cambrian poles and the Arenig–Llanvirn pole described above (Fig. 13a and c), and isotopic age data concur in suggesting an Late-Cambrian–Early-Ordovician (530–490 Ma) age for pole C.

Component B reflects a younger, possibly Late Ordovician or Silurian (?) thermo-chemical overprint, facilitated by inversion of primary pyrrhotite to form magnetite and as a PTRM in magnetite. As previously described, component A is related to a subordinate mafic dyke phase and localized thermal enhancement in the Silurian, probably in post-Wenlock times (see later). Whether this dyke activity relates to a phase of crustal extension following the Scandian collision and crustal thickening remains unclear. A regional gravity anomaly 30 km to the NW of Sørøy can be interpreted in terms of a thinned crust (Olesen *et al.* 1990). Superimposed on this positive regional gravity anomaly there is a high-frequency negative anomaly interpreted as a sedimentary basin of Late Palaeozoic age.

Any relative rotations between the tested areas is below the resolution of the present palaeomagnetic data. It is important, however, to consider large-scale rotations of the entire Caledonian nappe pile and/or continental scale tilting of the margin of Baltica. The former suggestion implies that the tectonic windows, including the Komagfjord Antiformal Stack of Gayer *et al.* (1987) are allocthonous. As an example, the effect of anticlockwise rotations on a vertical axis is portrayed in Fig. 12, a sense of rotation which corresponds to the observed change of thrust transport direction from SE (ductile) to ESE (brittle). Such a rotation would bring the C pole closer to the A and B poles, and remove it from its apparent match with Late Precambrian–Cambrian poles from Scandinavia. If C was 'Scandian' in origin, more than 90° of anticlockwise rotation would be required. Aeromagnetic and gravity data however, indicate that the Komagfjord Antiformal Stack becomes less allochthnous towards the southwest, eventually becoming 'autochthonous' near Kvænangen (Olesen *et al.* 1990). The matching of components B and C from the tectonic windows, the KNC and probably also the Båtsfjord area precludes significant relative rotations.

Poles A, B, and C predict palaeolatitudes of 18°, 27° and 38° respectively for northern Norway (Fig. 13b). While unaffected by rotations on a vertical axis, rotations on inclined or horizontal axes will influence these palaeolatitude estimates. In terms of rotations on a horizontal axis, we can consider the isostatic response to loading/unloading associated with thrusting (Gretener 1981), continental scale tilting caused by subduction (Mitrovicia, Beaumont & Jarvis 1989) or post-Caledonian erosion and differential uplift. The envelope of the Kalak Thrust front strikes NE–SW, orthogonal to the early SE directed thrusting phase (Gayer *et al.* 1987), and the rocks of the SIP define a gently NW-dipping disc-shaped body in the central part of the KNC (Olesen *et al.* 1990). Using an orogen-parallel axis (045°) as the rotation axis we can tentatively model the affect of tilting. Since the declinations for components A and B are close to this tilt-axis, tilting would most seriously effect the C component (Fig. 12). Indeed, moderate SE tilts of the order of 15–20° (assuming initially steeper NW dips) can bring the C pole in correspondence with palaeolatitude estimates based on the B or A component.

Given the tectonic uncertainties outlined above, the *precise* pole positions of B and C should be treated with some caution. The youngest pole, however, pole A, shows a clear convergence toward the Siluro-Devonian 'corner' seen in all the British APWP's, and we assign the highest reliability to this pole. The convergence of pole C toward Late Precambrian–Cambrian poles from Scandinavia is also noteworthy.

The APWPs for Laurentia, based on data from Scotland and North America/Greenland (Table 4) viewed in a Bullard *et al.* (1965) fit, and S. Britain (Avalonia) show convergence in Silurian–Early Devonian time. There is still, however, a minor discordance in the Ordovician–Silurian section of the Scottish and North American paths (Fig. 13c).

Table 4. Approximate apparent polar wander paths, Upper Cambrian to Lower Devonian for North America (European coordinates) and Baltica in 10 Ma intervals.

	N. America		Baltica **X**		Baltica **Y**	
Age	lat	long	lat	long	lat	long
400	−6	323				
410	−8	328	+2	341	−7	336
420	−15	335	+4	350	−15	340
430	−23	341	+5	355	−18	348
440	−29	343	+9	005	−11	001
450	−32	346	+12	013	−3	011
460	−31	355	+18	023	+9	022
470	−28	004	+24	034	+21	034
480	−20	014	+30	046	+30	046
490	−11	022	+33	058	+35	058
500			+35	069	+38	070
510			+36	076	+39	078
520			+38	087	+40	089

If correct, Scotland (based on data from the Northern and Grampian Highlands and the Midland Valley) was positioned to the south or possibly to the SW of the North American craton. The latter position requires considerable sinistral strike-slip faulting during Ordovician times, most of which must have taken place offshore Northern Scotland. To a first approximation, however, North American and Scottish data now form a reasonably consistent path, and in the reconstructions given below we have positioned North America and Scotland as a coherent unit in a Bullard *et al.* (1965) fit.

Cambro-Ordovician reconstruction

A reconstruction of Early Ordovician or possibly Late Cambrian times (490–530 Ma), depending on the age calibration of the C pole, is shown in Fig. 14. During Early Ordovician times Gondwana occupied high southerly latitudes with Avalonia probably plotting close to NW Africa (Van der Voo 1988). In contrast, Laurentia occupied equatorial latitudes with Scotland confined to latitudes around 15°–20° S (Fig. 14).

Pole C implies that Baltica was 'inverted' with respect to its present orientation in pre-Scandian times. This is also indicated by Late Precambrian–Cambrian palaeomagnetic poles from Scandinavia (Fig. 13a). Recently, Pesonen *et al.* (1989) presented the alternative view, i.e. Baltica in its present orientation at 30° N during the Late Precambrian–Cambrian. We now prefer Baltica 'inverted' in southerly latitudes during Late Precambrian–Cambrian to possibly Early Ordovician times. This configuration has important implications for Early Palaeozoic reconstructions and implies that the Russian Platform was facing Avalonia/Gondwana during Cambrian and possibly Early Ordovician times. Avalonia has been placed marginal to Gondwana on faunal grounds (Cocks & Fortey 1982) given a lack of reliable *Lower* Ordovician palaeomagnetic data from Southern Britain. With Baltica 'inverted', the Lower Ordovician limestones in Southern Scandinavia would have faced the equator (Fig. 14) rather than the South Pole as portrayed in traditional reconstructions (e.g. Scotese & McKerrow 1990). This scenario implies that the closure of the Tornquist Sea (Cocks & Fortey 1982) was accompanied by continental scale anticlockwise rotation of Baltica. The anticlockwise rotation relative to Avalonia was reduced by Arenig–Llanvirn times (*cf.* pole SL in Fig. 13c), and probably ceased by Late Ordovician times. It is possible that component B correlates with the amalgamation of Baltica and Avalonia (?). A southerly latitude for Baltica during Cambrian and Early Ordovician times resembles the palaeogeographic scenario of Scotese & McKerrow (1990), but with Baltica now 'inverted'. A northern hemisphere position during Cambrian times (Pesonen *et al.* 1989) requires 50°–60° southerly latitudinal drift during Ordovician times.

Wenlock–Ludlow reconstruction

Using our A and B poles, a Late Ordovician pole recently reported by Bøhm *et al.* (1989), and a preliminary pole from

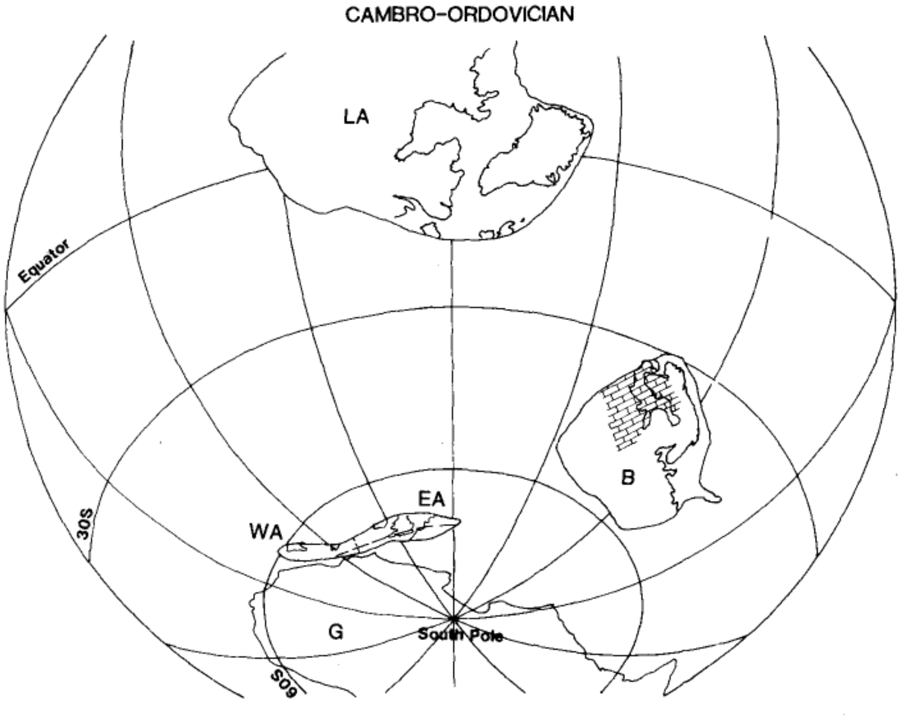


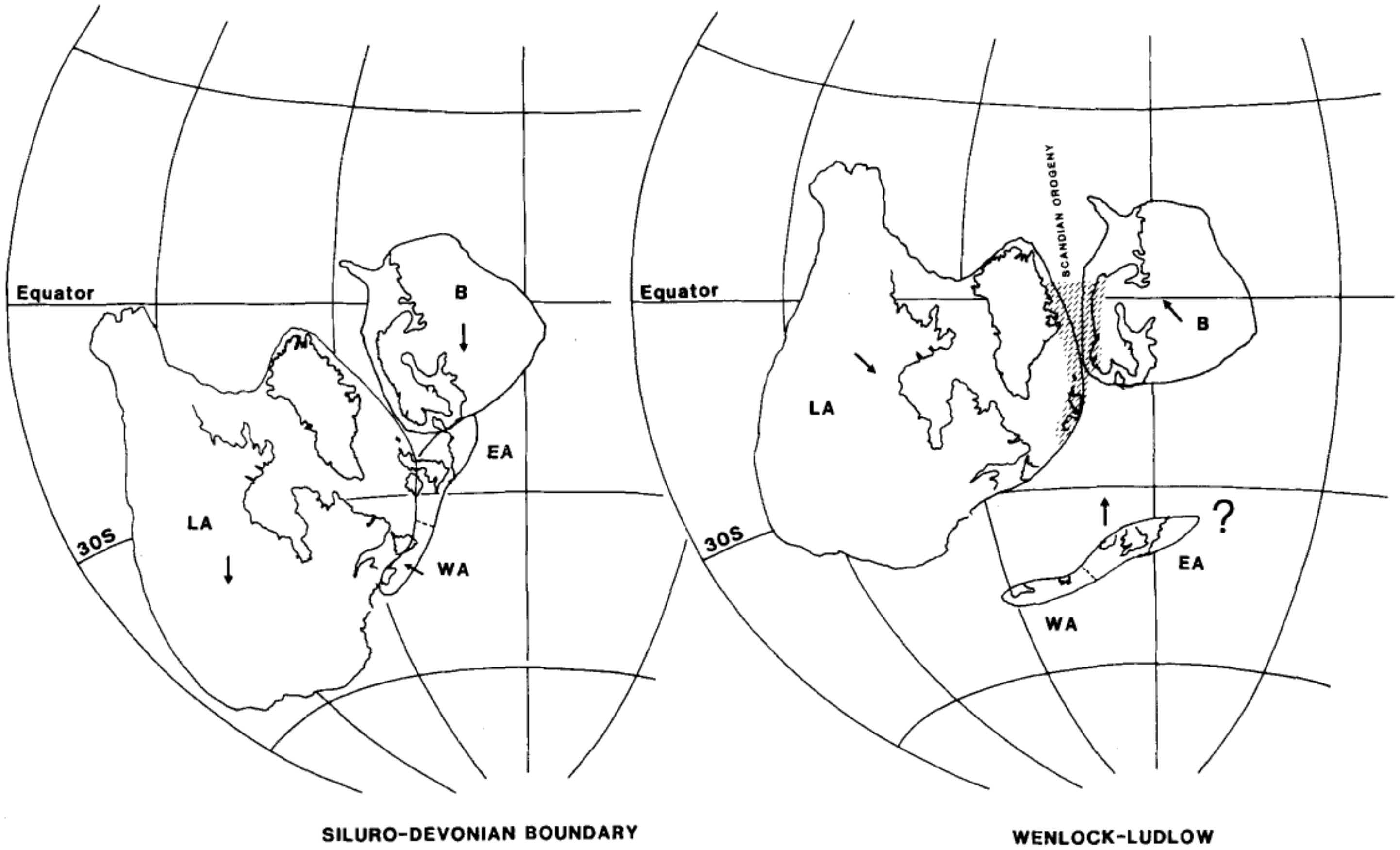
Figure 14. A Cambro-Ordovician to Lower Ordovician palaeoreconstruction showing Baltica in an 'inverted' position at intermediate southerly latitudes. Baltica is positioned according to pole C. Note that the distribution of Lower Ordovician limestones, brick ornament, faces the equator in this reconstruction rather than the South Pole. Laurentia is positioned according to a pole of 13°S and 29°E [European coordinates; Bullard *et al.* (1965) fit], representing an average of data from North America and Scotland (see Fig. 13). Gondwana is positioned using a Lower Ordovician pole of 28°N and 1°E (African coordinates) reported by Bachtadse, Van der Voo & Haelbich (1987). For simplicity, Avalonia is shown as an integral part of Gondwana and positioned NW of Africa (see Van der Voo 1988). Symbols are as follows: LA = Laurentia, B = Baltica, G = Gondwana, WA = Western Avalonia and EA = Eastern Avalonia.

the Honnigsvåg Gabbro (Torsvik *et al.*, in preparation) it is feasible to connect the paths for Avalonia and Baltica (Path X in Fig. 13c; Table 4) by Late Ordovician time. This would imply effective closure of the Tornquist Sea by that time and a termination of the relative rotation between Baltica and Avalonia. Furthermore, given that some British 'corner' poles are as old as mid-Silurian (e.g. the mid-Silurian Salrock Formation pole of Smethurst & Briden 1988), one might argue that this 'corner' represents the continental docking of Laurentia and Baltica.

Path X, however, ignores the Ringerike Sandstone pole of Douglass (1988), a pole which is constrained by fold-tests and a stratigraphically related magnetic polarity pattern. If one considers the Ringerike Sandstone pole to be reliable, the Baltic path (Path Y in Fig. 13c; Table 4) joins the Laurentian path by Mid–Late Silurian times. Alternatively, this convergence may mark the Scandian collision of Laurentia and Baltica, either as a collision of Scandinavia–Greenland or Scandinavia–Scotland (McKerrow 1988). Path Y for Baltica (Fig. 14) assigns the highest reliability to the Ringerike Sandstone pole, and the older section of the path is tentatively drawn between the B pole and the Late Ordovician pole reported by Bøhm *et al.* (1989), followed by convergence toward the C pole. Path Y takes pole A to be younger than the Ringerike Sandstone pole.

A Mid-Silurian scenario (*c.* 425 Ma) marking the convergence of Laurentia and Baltica is portrayed in Fig. 15. We use a common palaeomagnetic pole of 16°S, 337°E (European coordinates) for Baltica (Path Y) and Laurentia. Avalonia is latitudinally constrained using a pole of 2°N and 348°E [420 Ma pole for S. Britain listed in table 7 of Torsvik *et al.* (1990)]. Baltica progressed in a NW direction relative to Laurentia during the Silurian, and during the collision stage Baltica/Laurentia occupied equatorial to tropical southerly latitudes (Fig. 15). The oblique convergence of Baltica and Laurentia led to sinistral orogen-parallel shear-zones, on which major movements took place prior to Late Silurian times. The consistency of Late Silurian–Devonian poles from the various Scottish terranes precludes any subsequent large-scale movement between them (Trench *et al.* 1989; Torsvik *et al.* 1990; Trench & Haughton 1990).

The position of Avalonia with respect to Baltica (using Path Y) and Laurentia during the Silurian is enigmatic. Following Cocks & Fortey (1982), the similarity of Baltic and S. Britain fauna suggests effective closure of the intervening Tornquist Sea by Late Ordovician times. In marked contrast, the reconstruction of Fig. 15 suggests a wide Tornquist Sea between Avalonia and Baltica in Silurian times (*c.* 2500 km). Given the geological constraints we find this palaeogeography somewhat unreasonable. Path X for Baltica (Fig. 13c), however, ignoring the Ringerike Pole, presents a solution to this problem (*cf.* earlier discussion). If so, the Wenlock–Ludlow reconstruction (Fig. 15) is identical to the Silurian–Lower Devonian boundary reconstruction given below.



SILURO-DEVONIAN BOUNDARY

WENLOCK-LUDLOW

Figure 15. Wenlock–Ludlow (Baltica; Path Y) and Siluro-Devonian boundary reconstructions (see text). Arrows indicate relative movement directions *prior* to the shown reconstructions. Symbols as Fig. 14.

Silurian–Devonian boundary reconstruction

Whereas the Mid-Silurian scenario is enigmatic with respect to Avalonia and the Tornquist Sea, the palaeogeographic setting for the Siluro–Devonian boundary is now relatively straightforward. The APWPs for Laurentia, Baltica and Avalonia all converge during Late-Silurian–Early-Devonian time (Fig. 13c), and Euramerica retains its most southerly position prior to northward drift and the final assembly of Pangea. The Baltic resemblance with the other paths is justified in view of the A pole reported here and new data from the Russian Platform (Smethurst & Khramov, in preparation). The Siluro-Devonian reconstruction (Fig. 15) is based on a common palaeomagnetic pole of 2°S and 319°E (European coordinates). Considering the resolution power in palaeomagnetic studies, a small remnant of the Iapetus Ocean can be left open between North America and Western Avalonia in order to allow for the younger Acadian Orogeny (see e.g. Scotese & McKerrow 1990). The Siluro-Devonian palaeoreconstruction is closely similar to that presented by Kent & Van der Voo (1990), but we position Laurentia and Baltica in slightly higher southerly latitudes.

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