Geol. Mag. **125** (*1*), *1988, pp. 63–82. Printed in Great Britain*

Multiphase magnetic overprints in the Moine Thrust Zone

T. H. TORSVIK* & B. A. STURT†

* Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, U.K.
† Geological Survey of Norway, Leif Eirikssons vei 39, P.O. Box 3006, N-7001 Trondheim, Norway

(*Received* 23 February 1987; *accepted* 15 June 1987)

Abstract – Palaeomagnetic studies from the southern part of the Moine Thrust Zone (MTZ) indicate a complex pattern of four major secondary remanence components (A–D). Their relative ages appear to vary from mid-Ordovician to Recent/Tertiary. The oldest remanence (A) is tentatively interpreted as associated with the formation of the Lochalsh Syncline (D1) and/or D2. However, the consistency between component A and the regional southeast-plunging lineation, makes it uncertain to what extent component A reflects the structural grain rather than a true palaeofield record. Component B appears to be associated with early Devonian uplift along the MTZ relating to localized shearing/high level brittle thrusting, and is almost synchronous with the emplacement of lamprophyre and felsic dykes.

In the inverted limb of the Lochalsh Syncline, and beneath the Balmacara Thrust, possible Permian (component C) and Recent/Tertiary magnetic overprints are recognized. Component C is partly of high magnetic stability and may indicate localized shears in the inverted limb, usually considered as Caledonian shearing. It is uncertain to what extent the youngest component (D), essentially recorded in rocks close to the Balmacara Thrust in mylonites and fault breccias, reflects important tectonic reactivation and magnetic resetting. This component is governed by low stability magnetic phases with blocking temperatures below 200 °C.

1. Introduction

During the final stages of the Caledonian Orogeny, metasedimentary rocks of the Moine Nappe were thrust over a Foreland of Proterozoic (Lewisian, Torridonian) and Cambro-Ordovician rocks, to form a zone of thrust duplexes, the Moine Thrust Zone (Watson, 1975; McClay & Coward, 1981).

The early Proterozoic Lewisian Complex and the unconformably overlying Stoer (*c.* 1000 Ma) and Torridon groups (*c.* 800 Ma) in the Caledonian Foreland are remarkably unaffected by Caledonian deformation and thermochemical magnetic overprints (Stewart & Irving, 1974; Smith, Steam & Piper, 1983; Torsvik & Sturt, 1987). Torsvik & Sturt (1987), however, pointed to how the Stoer and Torridon groups are contaminated by magnetic overprinting of possible early Mesozoic age. Within the MTZ, however, the rocks have been involved in variable degrees of folding, thrusting and metamorphic reworking. The present account is addressed to the changes in remanence properties of the Torridonian sediments which have undergone tectonic deformation. For this purpose, the Kishorn Nappe, which represents the lowest tectonostratigraphic unit in the southern part of the Moine Thrust Zone, was selected as the prime target area with an extension into the Moine Nappe. Particular attention is given to remanence component analysis and the magnetic fabrics. Some of the interpretations are regarded as preliminary and in part speculative owing to the complexity of remanence in the studied rock assemblage, and certain aspects of the magnetomineralogy will be detailed elsewhere.

2. Geology and sampling details

The Kishorn Nappe (Fig. 1) is structurally overlain by the Balmacara and Moine nappes (Peach *et al.* 1907; Bailey, 1955; Barber, 1965; Johnson, 1960; Coward & Whalley, 1979), and embraces two formations of essentially grey-green arkosic sandstones, shales and grits of the Torridon Group, namely the basal Diabaig (referred to as Sleat Group by some authors) and the Applecross formations.

The structural development in the Kishorn Nappe has most recently been described by Coward & Whalley (1979). They argued for four major deformation phases, and indicated that the Torridonian sediments were affected at an early stage by low grade metamorphism and folded into a large recumbent syncline (D1), the *Lochalsh Syncline*. The axial trace trends NNW–SSE, and the western part of the Lochalsh peninsula embraces the gently northwest-dipping normal limb of the structure. The inverted limb which dips towards the southeast becomes gradually shallower towards Balmacara, where the beds are overthrust by deformed Lewisian gneisses (Balmacara Nappe).

Cleavage development, in the western part of the Kishorn Nappe (normal limb), is recognized in steeply dipping zones of pressure solution cleavage. In the inverted limb this cleavage (D2), which apparently postdates folding and inversion, becomes penetrative and is considered to be the result of differential movements set up in the Kishorn Nappe (Coward & Kim, 1981). A late bedding-parallel tectonic fabric (D3) is developed in the eastern part of the Kishorn Nappe, and finally the Balmacara Thrust cuts both

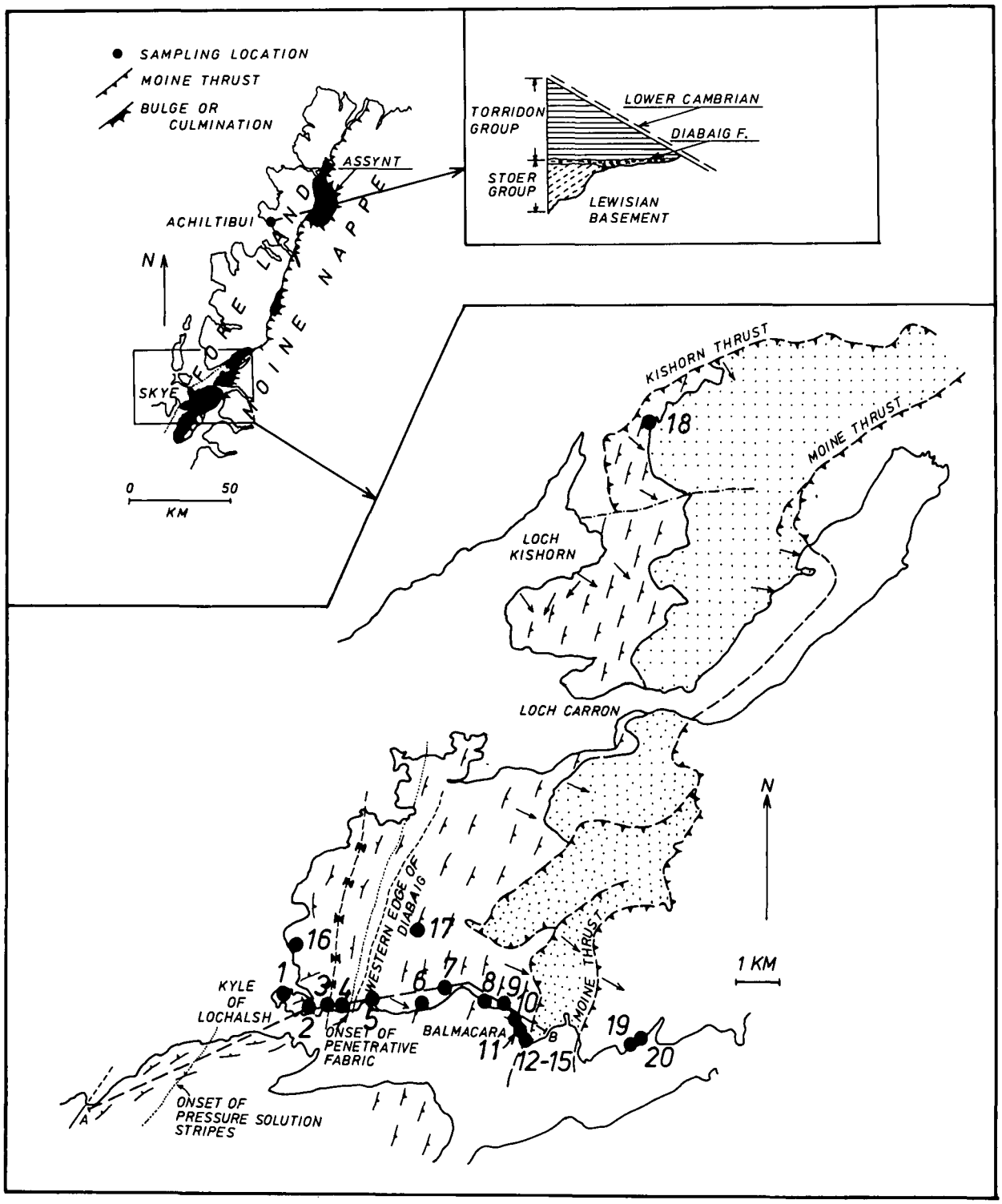

Figure 1. Map of the Kishorn–Lochalsh area (redrawn from Coward & Whalley, 1979). Orientation of bedding in the Torridonian, mineral lineations (arrows) and the sampling profile A–B in Coward & Whalley are shown along with present sampling areas (closed circles). Inset maps: Geographical position of the Kishorn-Lochalsh area showing bulge or culmination of Caledonian deformation (filled areas) and schematic vertical section through the Torridonian in the Foreland Zone (redrawn and simplified from Johnson, 1983 and Stewart & Irving, 1974).

the Lochalsh Syncline and the cleavage. Hence, the structure of D4 includes the final stage of deformation of the Kishorn Nappe.

Samples from 20 sites (Fig. 1) were examined for palaeomagnetic purposes. Sites 1–11, 16 and 17 correspond to section A–B in Coward & Whalley (1979), and there is an increasing rate of recovery (annealing, recrystallization) from west to east. Sites 1, 2 and 16 (Applecross Formation) were sampled in the normal limb of the Lochalsh Syncline, whereas sites 3–4 (Applecross Formation) and 5–11 and 17 (Diabaig Formation) were sampled close to the axial

trace and in the inverted limb. Near Balmacara, the Torridonian sediments are affected by local-scale asymmetrical folds, with N–S fold axes (e.g. site 11). Structurally they pass upwards into Torridonian mylonites (site 12) with a foliation dipping *c.* 15° E, which are succeeded by a *c.* 3–5 m zone of fault breccia (Balmacara Thrust, sites 13–15). The Lewisian rocks in the overlying Balmacara Nappe were not sampled owing to their strongly fractured nature.

In the Balmacara region two sites were also sampled from the Moine Nappe (Glenelg Inlier). Site 20 is from retrograded amphibolites whose foliation dips at a low angle to the east. Site 19 was sampled from a *c.* 2 m thick and reddish-coloured subvertical lamprophyre dyke trending 110°. This dyke forms part of the Northern Highland suite of minette lamprophyres and felsites (Smith, 1979), of probable Lower Devonian age, and is considered to postdate major movements in the MTZ.

An additional site (site 18) was sampled in the northern part of the Kishorn Nappe. In this part of the nappe, inverted Torridonian sediments are intensely foliated and structurally overlain by Lewisian rocks (deformed primary unconformity).

3. Palaeomagnetic experiments

The natural remanent magnetization (NRM) was measured on Digico and Molspin spinner magnetometers, and NRM stability for 190 specimens was tested by means of stepwise thermal demagnetization. However, certain specimens were not subjected to stability testing due to NRM intensities below 0.2–0.5 mA/m (including all specimens from sites 5 and 7).

Characteristic remanence components (ChRc) were obtained by least-square line fitting in orthogonal vector projections, and a compilation of ChRc for *all* tested rocks/sites (*in situ* co-ordinates) is given in Figure 2a. The directional spread is considerable and somewhat complex, but from inspection of remanence data at site level (Table 1, Fig. 3) it has been possible to explain this directional complexity by identifying at least *four* different magnetization components (Table 2, Fig. 2b). All of these apparently postdate the formation of the Lochalsh Syncline (D1). In order to justify this subdivision of remanence components, i.e. components, A to D (*in situ* group division; Fig. 2b), and to evaluate their characteristics, the different parts of the study area are described separately.

3.a. The normal limb (sites 1–2, 16)

In the normal limb two major remanence components can be identified (A and B). Component A has southeastward declinations mostly with downward pointing (positive) inclinations (sites 1–2, 16), whereas component B is characterized by southwestward declinations and downward dipping inclinations (site 1). All tested specimens from the normal limb show blocking temperatures (T_b) below 580 °C with Curie temperatures around 570–580 °C. Thus, magnetite is considered as the principal remanence carrier (Fig. 4). Isothermal remanent magnetization (IRM) curves, however, indicate the presence of an accessory high-

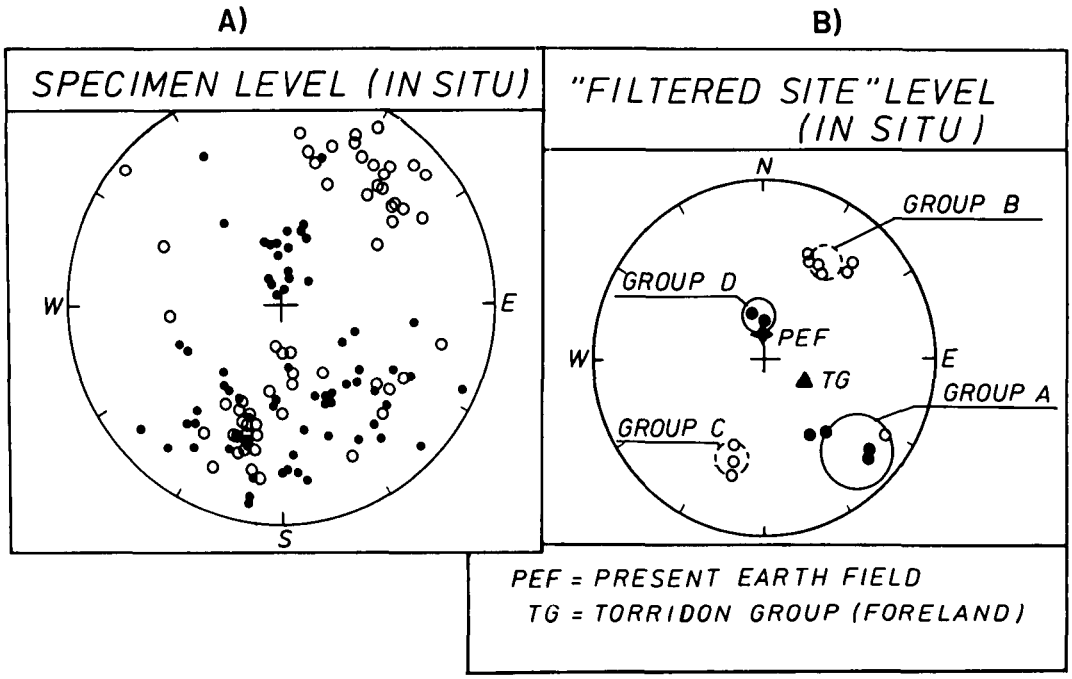

Figure 2. Characteristic remanence components obtained from all the investigated rocks (including dyke and amphibolites in the Moine Nappe), and (b) a stereoplot showing the relationship between the four remanence components (A–D) as advocated in the text ('site' mean values, cf. Tables 1, 2). Open (closed) symbols represent upward (downward) pointing remanences. Mean Torridon Group direction (Foreland) calculated from data cited in Torsvik & Sturt, 1987.

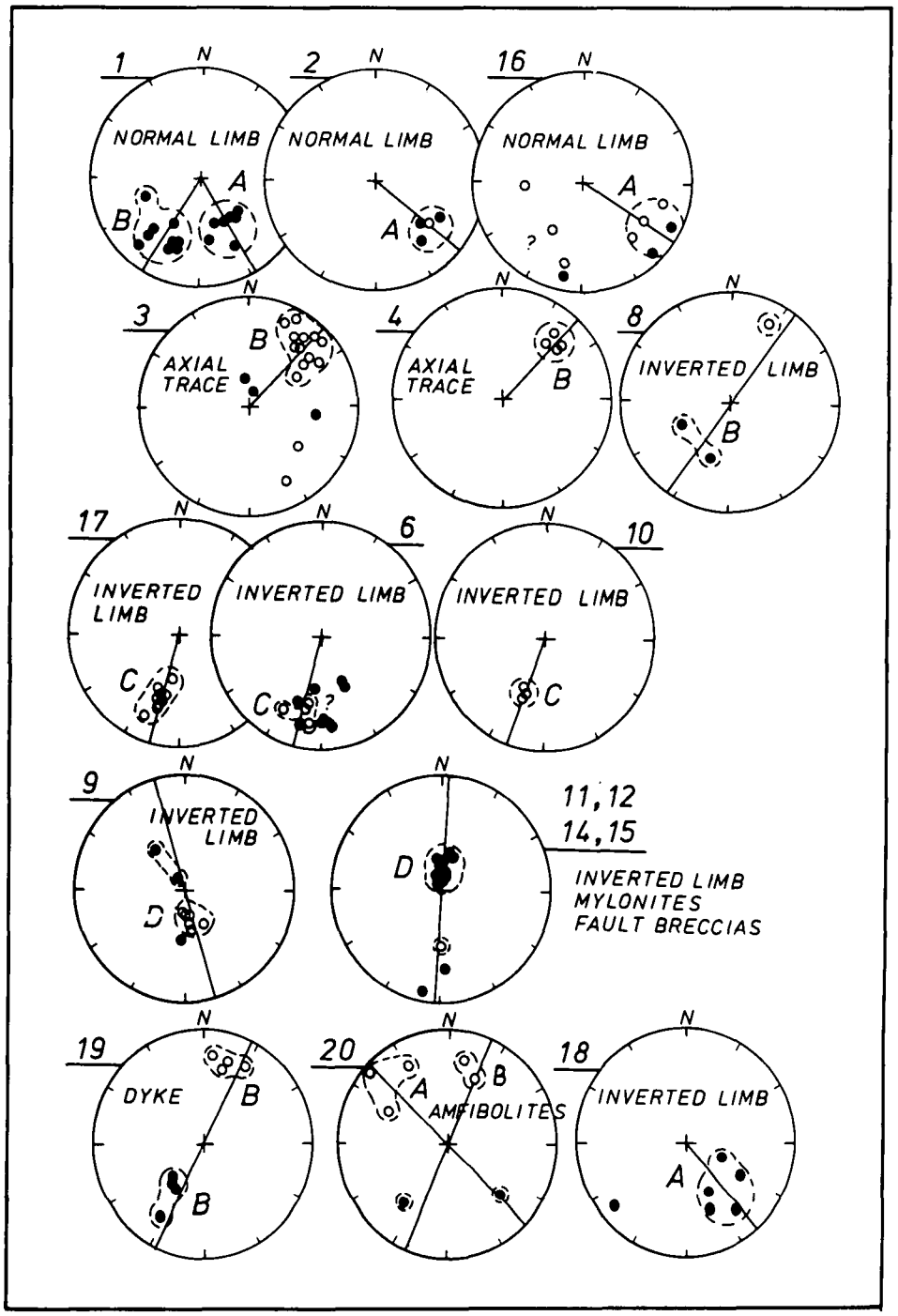

Figure 3. Characteristic remanence components from individual sites (apart from sites 11, 12, 14, 15 which are combined). These form the basis for construction of the component A–D in Figure 2b; sites with three or more relatively consistent remanences are averaged and cited in Table 1 and Figure 2b.

coercivity mineral phase (probably haematite) which is not saturated in the maximum available field of 0.9 T.

Surprisingly, the two remanence components exhibit the same T_b range (< 580 °C), though there is a notable difference in the shape of the decay curves: component B (seen at site 1) shows exclusively distributed unblocking (Fig. 4a), whereas component A specimens (sites 1, 2, and 16) have a more distinct discrete type of unblocking spectrum (Fig. 4c). The two components can rarely be separated at specimen level. A possible interplay between the two components is shown in Figure 4b, but normally the early stages of thermal demagnetization of, for example, component A specimens may show a certain complexity (Fig. 4c).

Sampling from site 1 (where the two components are both present) was confined to two beds with a vertical separation of *c.* 1 m and assumed to ensure a reasonable sampling homogeneity. The A component is, however, predominant in specimens from one of the beds, and B in specimens from the other bed.

Table 1. Overall palaeomagnetic data from the Kishorn and Moine Nappes

Site	Group	D	I	α_{95}	k	N
1	A	148	+36	9.1	33.5	7
	B	211	+26	10.3	20.5	9
2	A	130	+12	22.3	9.8	4
3	B	044	−16	6.9	34.2	12
4	B	045	−21	5.7	153.3	4
5	(NRM below instrumental noise level)					
6	(A or B)	177	+24	10.1	21.3	9
	C	196	−21	10.3	46	4
7	(NRM below instrumental noise level)					
8	B	215	+29	25.4	10.1	3
9	D	165	−60	8.8	31.3	8
10	C	200	−35	4.7	297.6	3
11–15	D	004	+66	8	27.7	11
16	A	122	−10	14.7	18	5
17	C	197	−27	4.9	72.8	11
18	A	139	+32	17	13.6	5
19	B	206	+27	10.5	22.4	8
20	A	313	−10	20.5	11.6	4
	B	023	−24	13.1	38.1	3

D = mean declination in degrees; I = mean inclination in degrees; α_{95} = 95% confidence circle; k = precision parameter (Fisher, 1953); N = number of specimen directions.

Table 2. Mean statistics for components A–D

Remanence Group	D	I	α_{95}	n	VGP LAT.	VGP LONG	VGP d_p/d_m
GROUP A (1, 2, 16, 18, 20)	134	+16	15.9	5	S14.5	E41.7	8/16
GROUP B (1, 3, 4, 8, 19, 20)	034	−24	6.8	6	S14.7	E320	4/7
GROUP C (6, 10, 17)	198	−28	7.2	3	S45.4	E329.1	4/8
GROUP D (9, 11–15)	354	+63	9	2	N76.5	E193	11/14

Mean Geographic Sampling Location: N57.4, W5.7. See Table 1 for conventions; n = number of sites apart from group D, which is a combined result of site 9 and sites 11–15 (n = 2). Numbers in parentheses refer to the sites involved. d_p, d_m = semi-axis of the oval of 95% confidence about the mean pole; VGP = virtual geomagnetic pole.

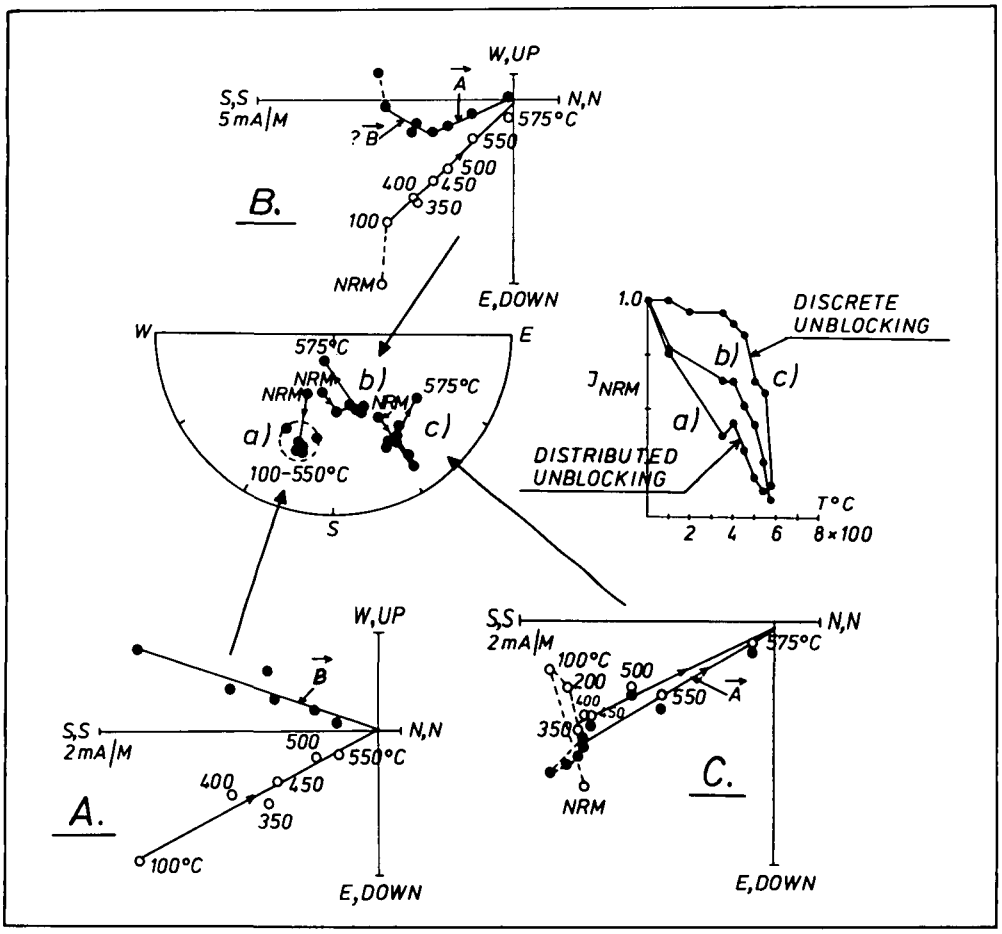

Figure 4. Examples of thermal demagnetization from site 1 specimens. (a) shows the B component, (b) a possible interplay of components B and A, whereas (c) indicates component A isolated above 350–400 °C. Note the difference in the thermal blocking spectra between (a) and (c), i.e. components B and A respectively. In the orthogonal vector diagrams open (closed) symbols represent points in the vertical (horizontal) plane. In some of the figures, the vector diagrams are optimally projected and α_{95} confidence circles during individual measurements are included in some of the stereoplots. The latter are essentially constructed on the basis of Briden & Arthur (1981). In the stereoplot and decay curve graph (a), (b), (c) correspond to the orthogonal vector diagrams.

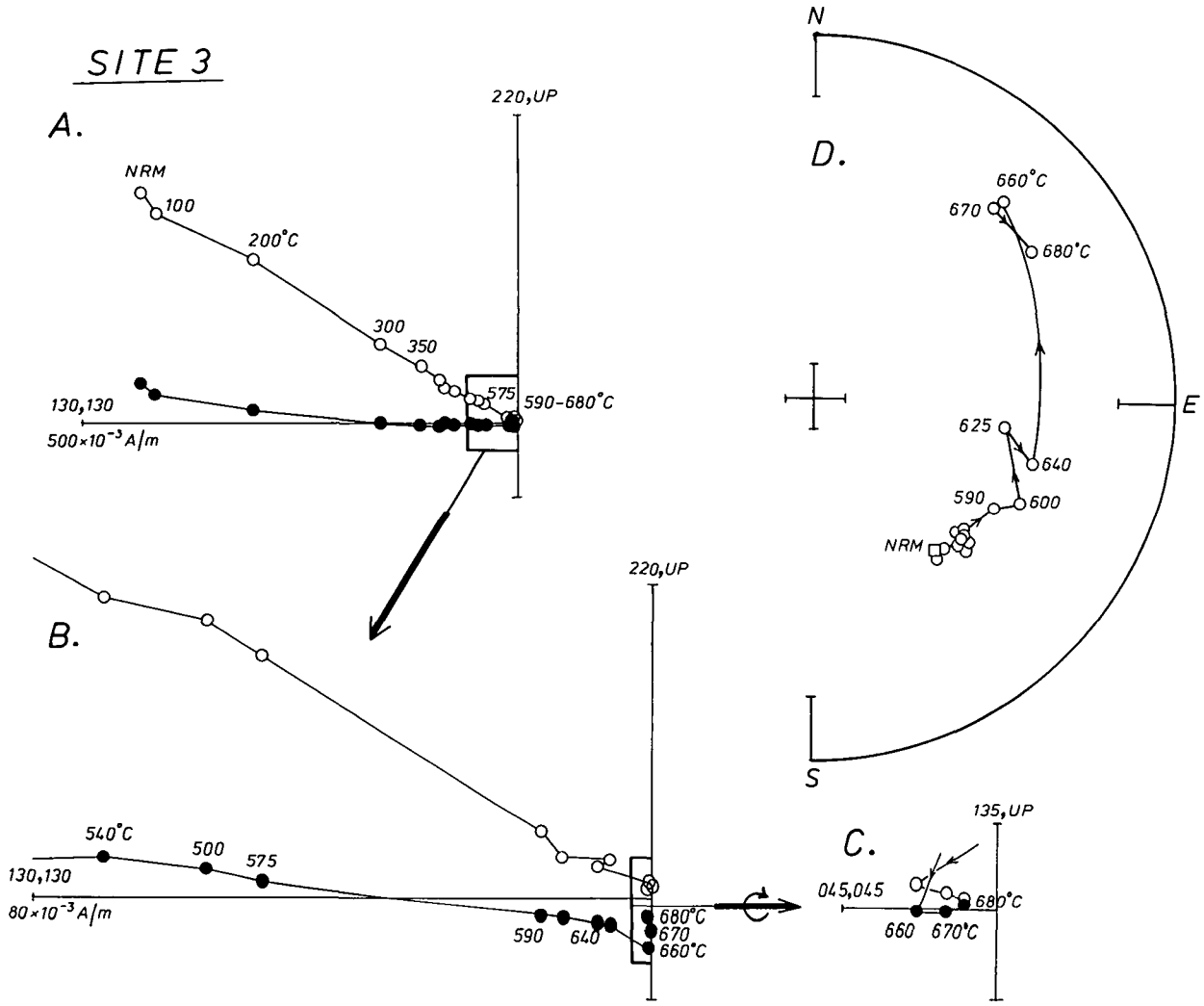

Figure 5(a)–(c). Thermal demagnetization of a site 3 sample (a)–(c). (b) shows expanded central region of (a), while (c) is an optimal projection of the extremely high temperature component (Component B, normal polarity). (d) corresponding stereoplot.

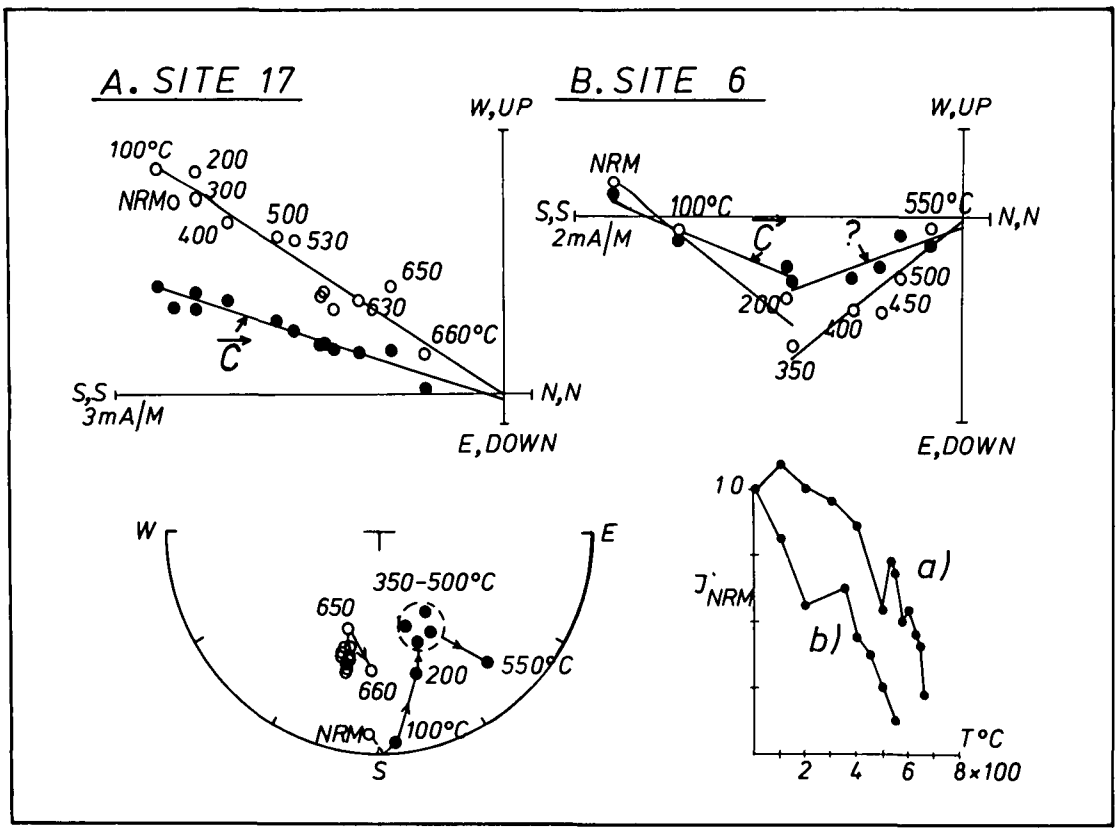

Figure 6. Further examples of thermal demagnetization. (a) High stability C component recorded from site 17; (b) isolation of component C in a specimen from site 6 below < 350 °C.

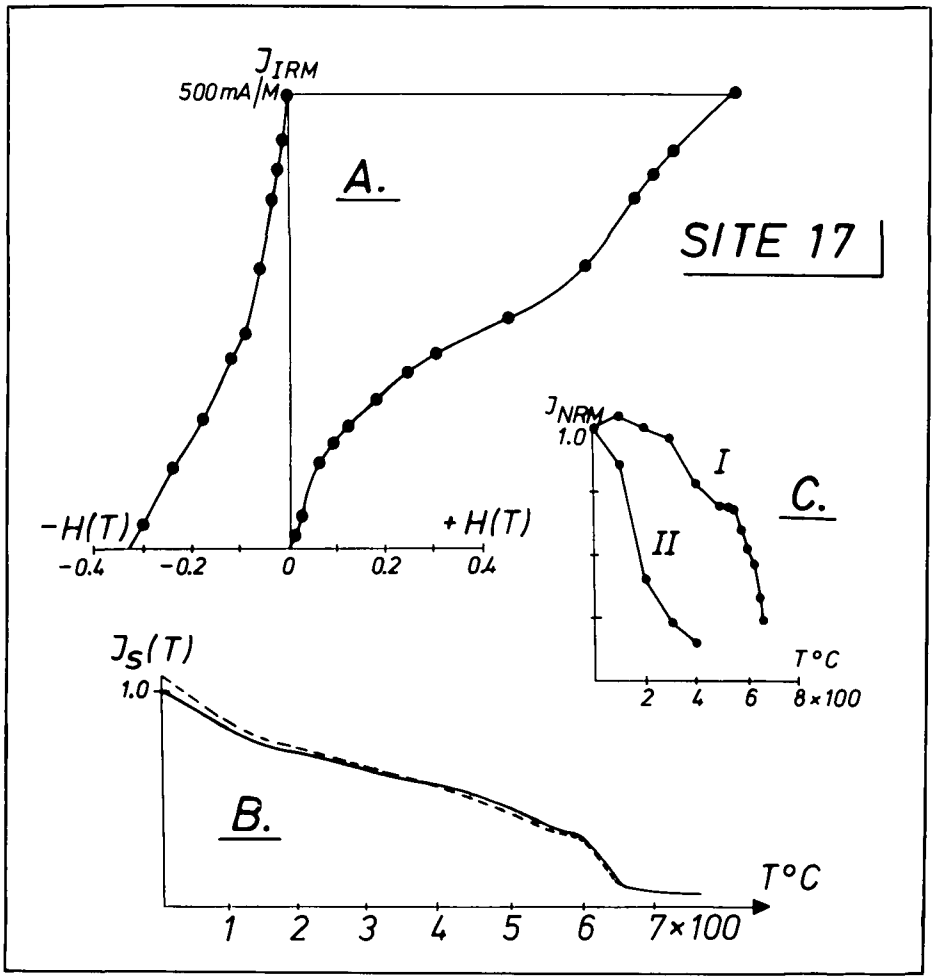

Figure 7. Typical IRM acquisition (a) and thermomagnetic curve (b) from site 17 samples (c) The two different blocking spectra, as observed from site 17, are shown: (I) unblocking up to 670–680 °C, and (II) distributed unblocking below 400 °C.

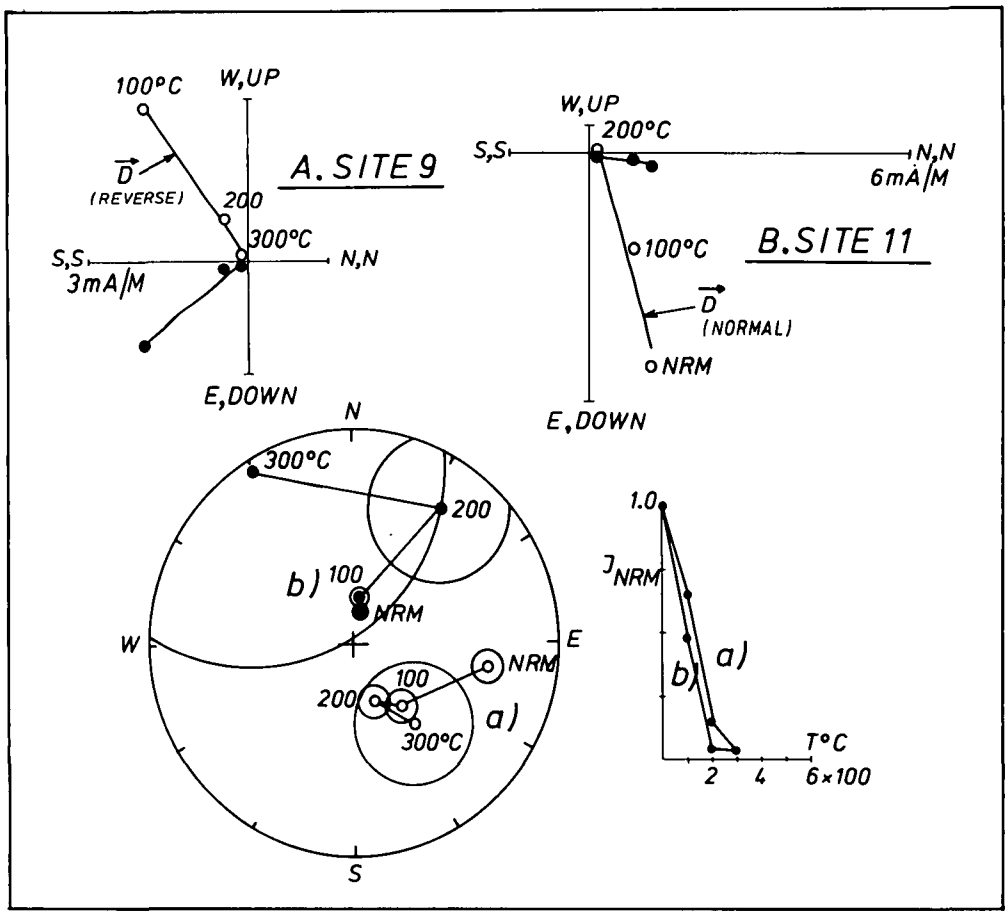

Figure 8. Examples of low-stability remanences (component D) as observed from sites 9 and 11. Note that total unblocking takes place below 200–230 °C, attended by large measurement uncertainties (cf. α_{95} in stereoplots).

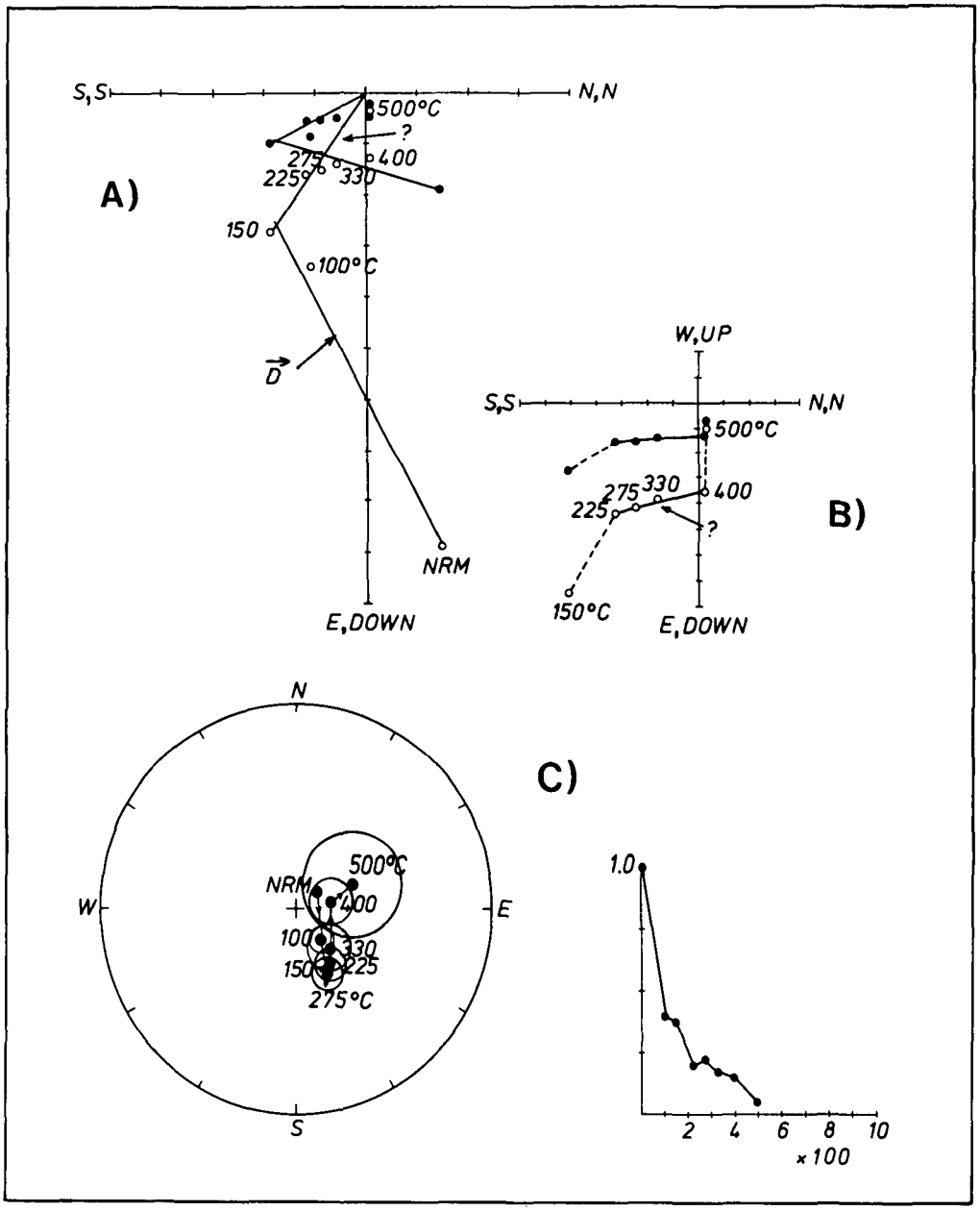

Figure 9. Thermal demagnetization of a fault breccia specimen (site 15; see text).

Local tectonics (folding) can be ruled out, and an explanation in terms of localized grain-size contrasts is perhaps more plausible. Judged by the thermal blocking spectra the B component seems to be carried by the most fine-grained magnetite phases (distributed unblocking). The significance of this observation is discussed in a later section.

3.b The axial trace (sites 3, 4)

Along the axial trace of the Lochalsh Syncline component A apparently disappears, and B remanences (normal polarity and fairly anti-parallel to those of site 1) dominate the total NRM (Fig. 3). From sites 3 and 4 almost univectorial and high-stability B components with T_b below 500–550 °C are observed, but site 3 shows an unusual pattern. NRM intensities vary between 3–500 mA/m within a few centimetres, indicating a high degree of magnetic inhomogeneity. Specimens with high NRM intensity are characterized by multicomponent magnetizations, some of Recent/Tertiary origin (steeply downward pointing directions of Fig. 3; see below), but often also by SE(E) magnetizations which partly overlap component B of normal polarity (Fig. 5a, b). In such instances, the normal polarity B components are associated with discrete unblocking above 650 °C, i.e. having a haematite remanence carrier. The SE(E) components which are randomized in the early to middle T_b spectra could correspond to component A from the normal limb, but there are generally severe problems in isolating this component due to partly

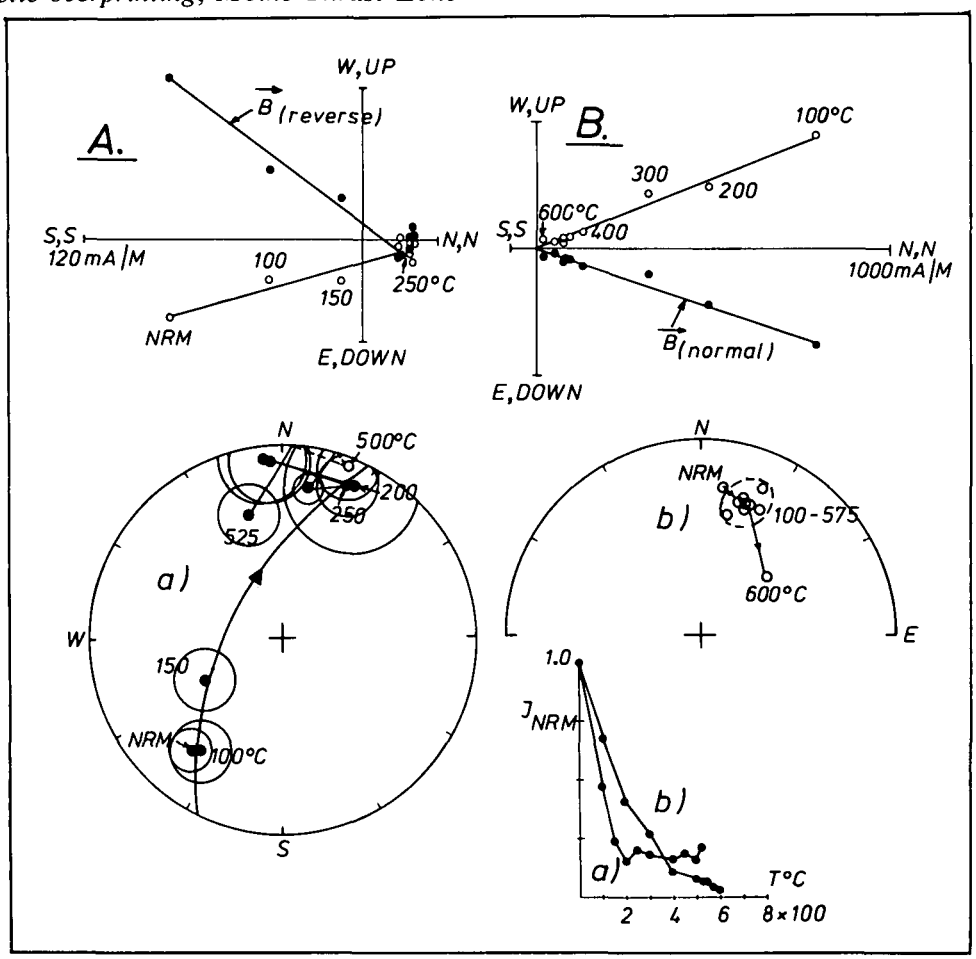

Figure 10. Two types of behaviour during thermal demagnetization as observed in a lamprophyre dyke in the Moine Nappe. (a) Single component magnetization of normal polarity (component B). (b) Removal of a low-blocking B component of reverse polarity; the directional movement is indicated with the best-fitted great circle, though the high-temperature component was not identified.

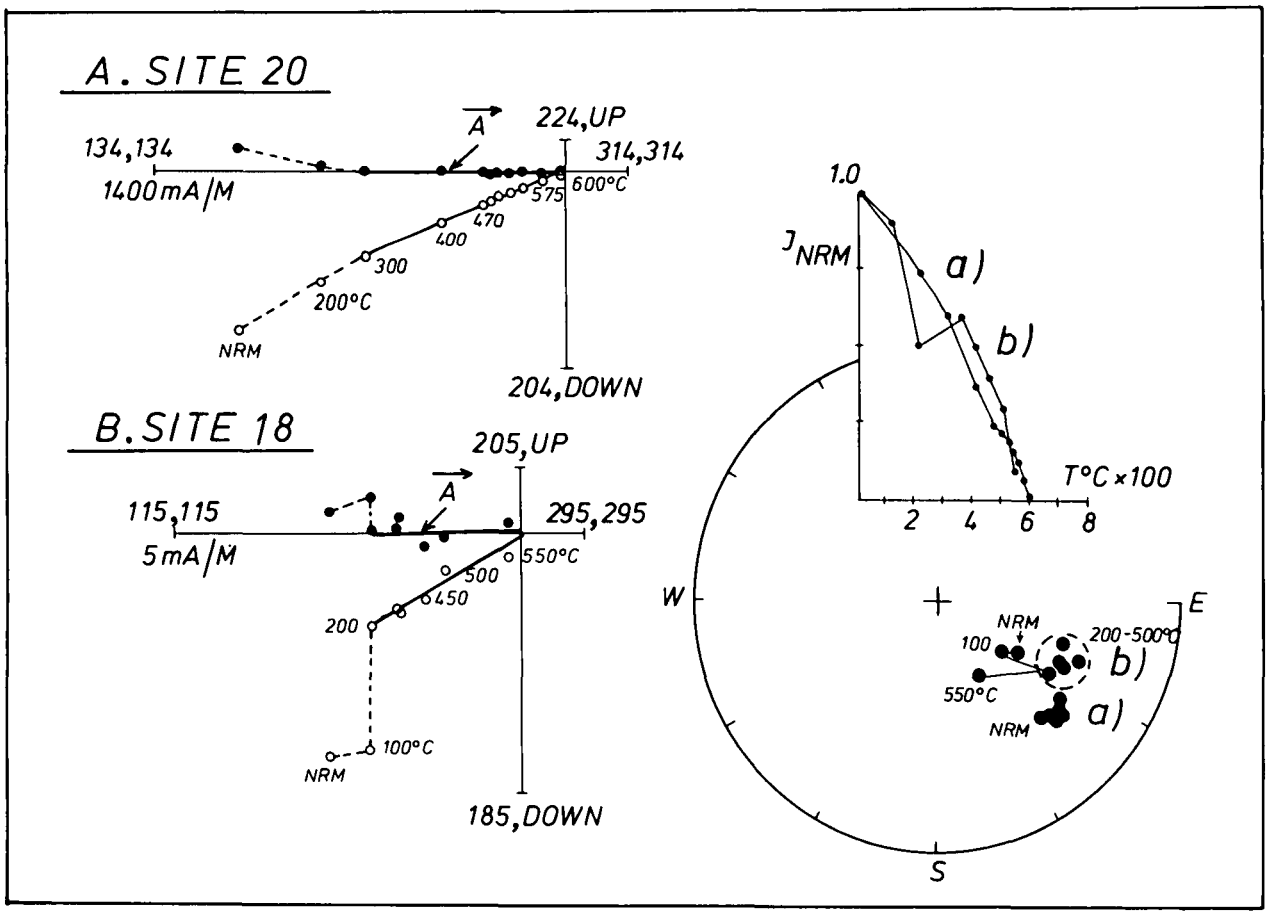

Figure 11. Comparison of a thermally demagnetized sample from amphibolites in the Moine Nappe (a), and a Torridonian sample from the Northern part of the Kishorn Nappe (b).

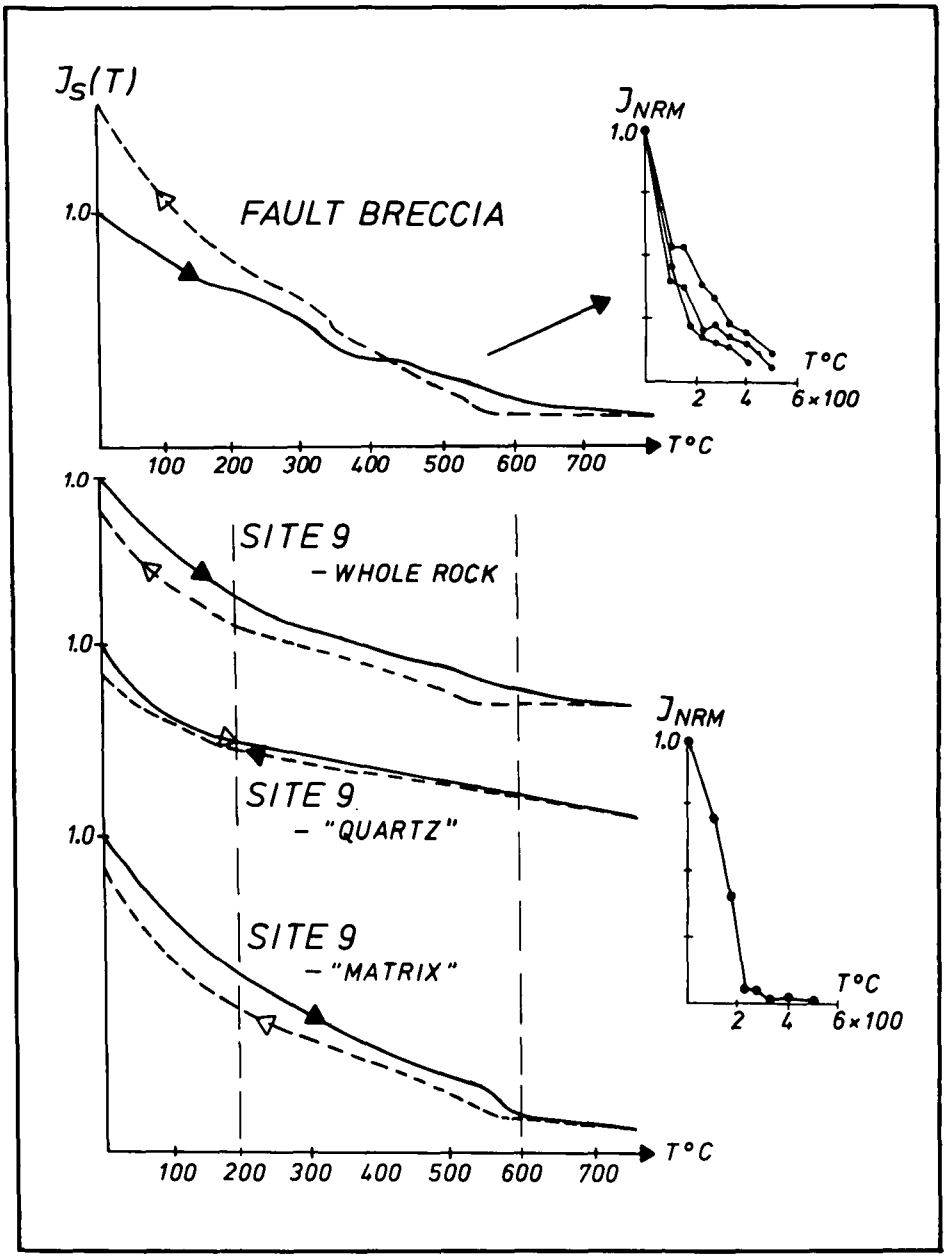

Figure 12. Thermomagnetic curves and blocking spectra from a fault breccia specimen and a site 9 specimen (see text).

overlapping spectra with the B component (curved segments when viewed in orthogonal vector projections).

3.c. The inverted limb

Apart from one single example (Fig. 3), measurements from the northern part of the Kishorn Nappe (site 18) define a magnetization axis near to southwest, i.e. component A, with T_b in the 200–580 °C range (Fig. 11). In the Lochalsh region it is noted that the B component predominates along the axial trace, but in the inverted limb some important changes occur on approaching the Balmacara and Moine thrusts accompanied by a transition to two new remanence components.

Apart from site 8 (and site 6), where only three successfully tested specimens define a NE–SW magnetization axis (component B), components A and B are almost obliterated in the inverted limb when approaching the Balmacara Thrust. Intermediate to steeply inclined magnetizations near SSW–NNE and S–N respectively (components C and D) predominate. Component C is observed from sites 6, 10 and 17 and is usually associated with T_b up to 350–500 °C. From site 17, however, some unusually high stability C components with T_b well above 600 °C (haematite) are observed (Fig. 6a), whereas other specimens show maximum T_b around 400 °C (see decay curves of Fig. 7c). The directional distribution of the low blocking phases tends to be smeared towards the somewhat steeper D component. T_b spectra, thermomagnetic

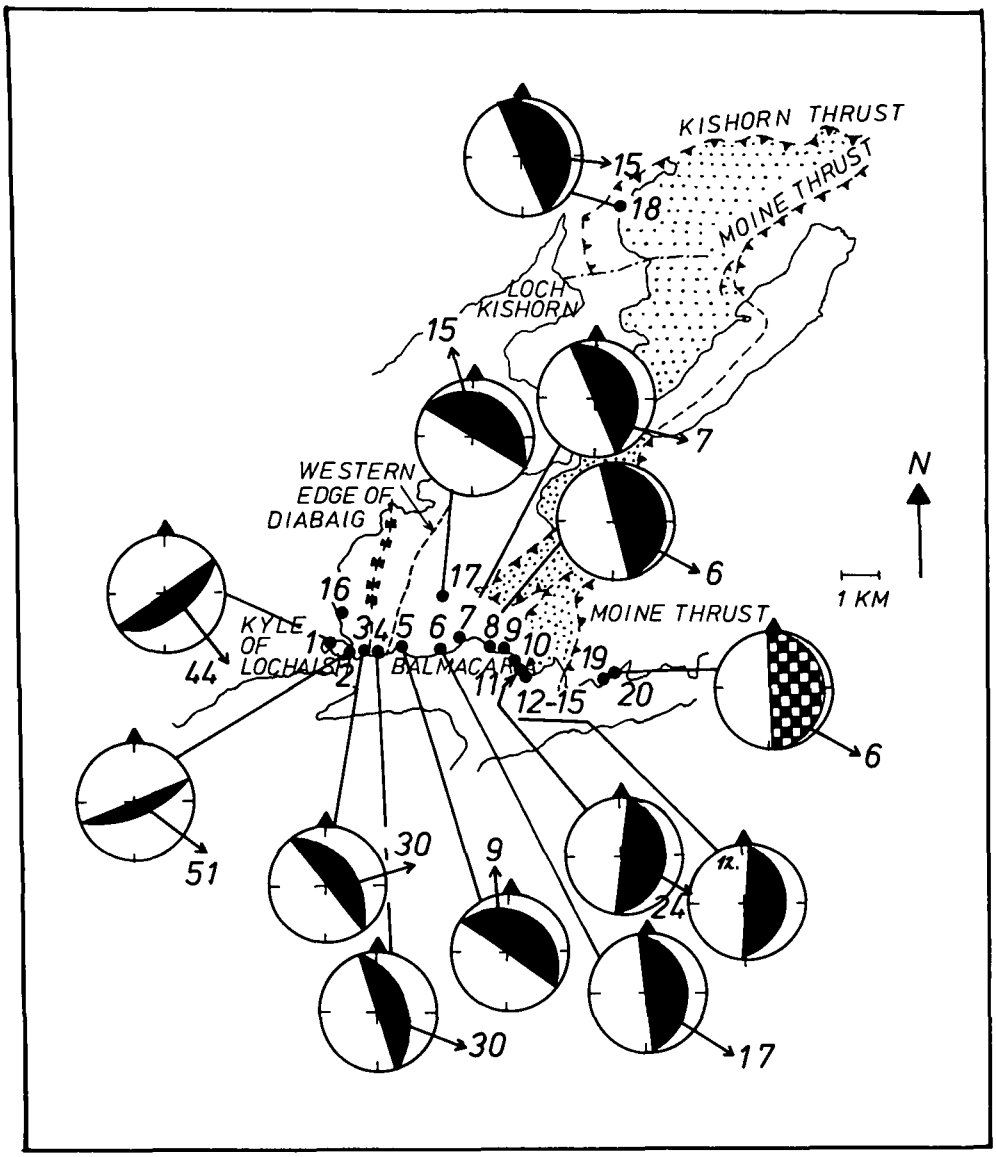

Figure 13. Regional magnetic fabric data from the Kishorn and Moine nappes. Orientation and downward dip of the magnetic foliation planes are shown in stereoplots. The site mean lineation is shown as arrows with indicated downward plunge.

and IRM curves clearly show that both magnetite and haematite contribute to the bulk magnetic properties (see Fig. 7).

From site 6 the C component occupies the lower T_b range (< 350–450 °C Fig. 6b): tested specimens show distinct multicomponent features, in which the C component was isolated at an early to intermediate stage. The directional distribution of high-T_b components (T_b < 580 °C) intermingles with both components A and B and was thus not classified in our general remanence component subdivision.

Site 17 directions (Fig. 3) show a slight directional smearing towards the D component. Apart from directional differences, however, there are strong blocking temperature contrasts between these two components. Close to the Balmacara and Moine thrusts there is a dramatic change in the remanence stability. *All* specimens (apart from those from site 10 which conform to component C) are characterized by a low total NRM intensity with an 80–90 % intensity reduction at temperatures around 200 °C (viscous at higher temperatures – NRM intensity dropping below the instrumental noise level) associated with steeply inclined remanences of both polarities near N–S (Figs. 3 and 8). Component D totally dominates in specimens from sites 9 and 11, i.e. Torridonian mylonites (site 12) and the overlying fault breccia (sites 13–15), and is considered to represent Recent/Tertiary magnetizations. Though the presence of pyrrhotite was frequently indicated, thermomagnetic analysis (whole-rock; see Fig. 12) of deformed Torridonian sediments/mylonites in this area suggests the domi-

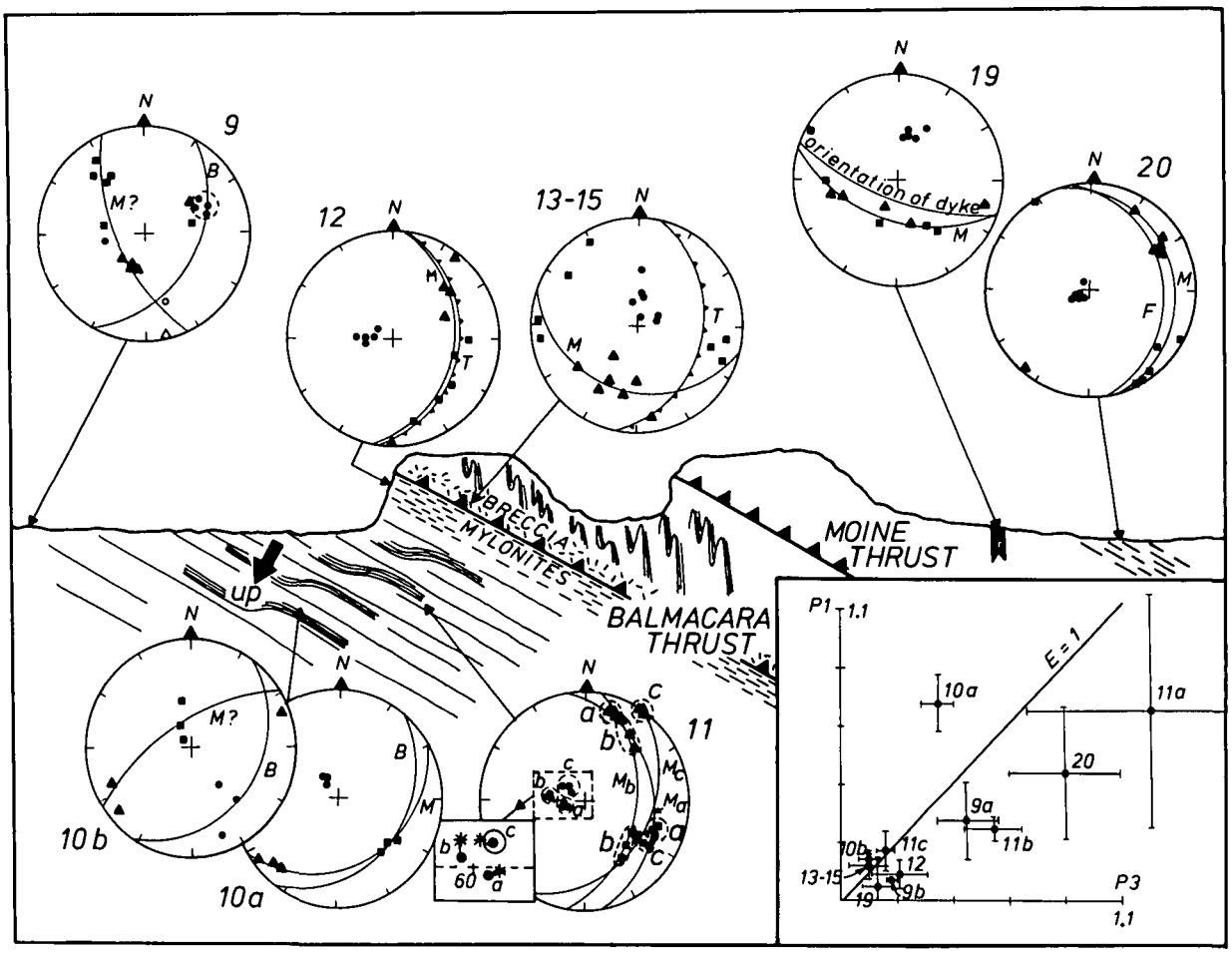

Figure 14. Details in the magnetic fabrics close to the Balmacara and Moine thrusts and a Flinn diagram. In the stereograms, downward-dipping planes denoted M, B, T, F, denote magnetic foliation, bedding, thrust-plane/mylonitic foliation and foliation respectively. K_{max}, K_{int} and K_{min} are shown as squares, triangles and circles, respectively. In the Flinn plot (inset), site 11 has been divided into 11 a, b, c, signifying the different sampling positions in an asymmetrical fold structure. Note that the magnetic foliation is folded.

nance of a phase with low Curie temperature around 200 °C in addition to some magnetite and possible paramagnetic phases. Torridonian rocks close to the Balmacara Thrust show clear signs of silica mobilization with quartz segregation bands almost parallel to the bedding. Separation of quartz and matrix show that the low-Curie-temperature phase tends to be primarily related to this secondary quartz (plus a paramagnetic constituent), whereas the matrix is dominated by magnetite/paramagnetic phases.

Specimens from the fault breccia (sites 13–15) indicate that the low-T_b magnetic phases relate to the pyrrhotite which partly inverts to magnetite at temperatures above 350 °C. In the fault breccias the D component (somewhat higher thermal stability than the other D sites; cf. decay curves in Fig. 12) is clearly superimposed on an underlying component. However, this latter has proved difficult to identify as illustrated in Figure 9. A poorly defined, but dominating, D component is randomized in the NRM–150 °C range associated with a southerly directional trend. Some viscous behaviour, as observed at high temperatures (cf. α_{95} in stereoplot; Fig. 9c), can be attributed to partial inversion of pyrrhotite to magnetite, and in this particular case it remains uncertain if (i) a southwest component is established above 150–225 °C (plus noise; Fig. 9a), or (ii) there are in fact two components left at these temperatures, i.e. an intermediate with shallow inclination and southerly declination (Fig. 9b) and the high-temperature component not identified.

3.d. Moine Nappe (sites 19, 20)

The lamprophyre dyke (site 19) and the retrograded amphibolites (site 20) in the Moine Nappe (Glenelg Inlier) shed light on the relative age relationships of components A and B identified in the Kishorn Nappe. Dyke specimens show reasonable dual-polarity magnetizations near NE–SW (Fig. 3), which are compatible with *component B* observed in parts of the Kishorn Nappe. Almost single component magnetizations of normal polarity components can be

recognized (Fig. 10b) with $T_b < 580$ °C, but the more frequently identified low-T_b components of reverse polarity ($T_b < 300$ °C) carry more than 80% of the total NRM. In the latter case (Fig. 10a), the high-T_b normal polarity directions (clearly present) were often impossible to estimate owing to the rapid intensity loss attendant on substantial viscous behaviour.

The amphibolite specimens (site 20) define two principal magnetization groups: (i) a poorly defined low-T_b remanence trending NE–SW, i.e. similar to the principal dyke magnetization (component B), and (ii) a better defined magnetization trending NW–SE. This latter (Fig. 11a) may correspond to component A identified in the Kishorn Nappe (cf. site 18 and 20 specimens in Fig. 11 and Fig. 3), but differs in that it represent a dual-polarity structure. The B component contamination in the amphibolites cannot relate to baking effects (sampled 100 m from the nearest observed dyke) and hence reflect a regional or localized thermal disturbance. The dual-polarity structure in the dyke (and the narrow dyke width) may suggest dyke intrusion at a considerable depth. The dyke, however, clearly postdates the main metamorphic peak during which the foliation of the amphibolites was produced (see section 4). It is evident that the component relationship observed between the dyke and amphibolites indicates that the B component is younger than the A component.

4. The magnetic fabric

The anisotropy of magnetic susceptibility (AMS) in rocks from the Kishorn Nappe has previously been described by Coward & Whalley (1979). In order to unravel any systematic relationship between remanence and the structural fabrics and to ensure a one-to-one comparison with our sampling sites, the magnetic fabrics are re-examined in this account. The AMS was studied using a low-field (0.1 mT) induction bridge.

Sites 1 and 2 (normal limb) of the Lochalsh Syncline

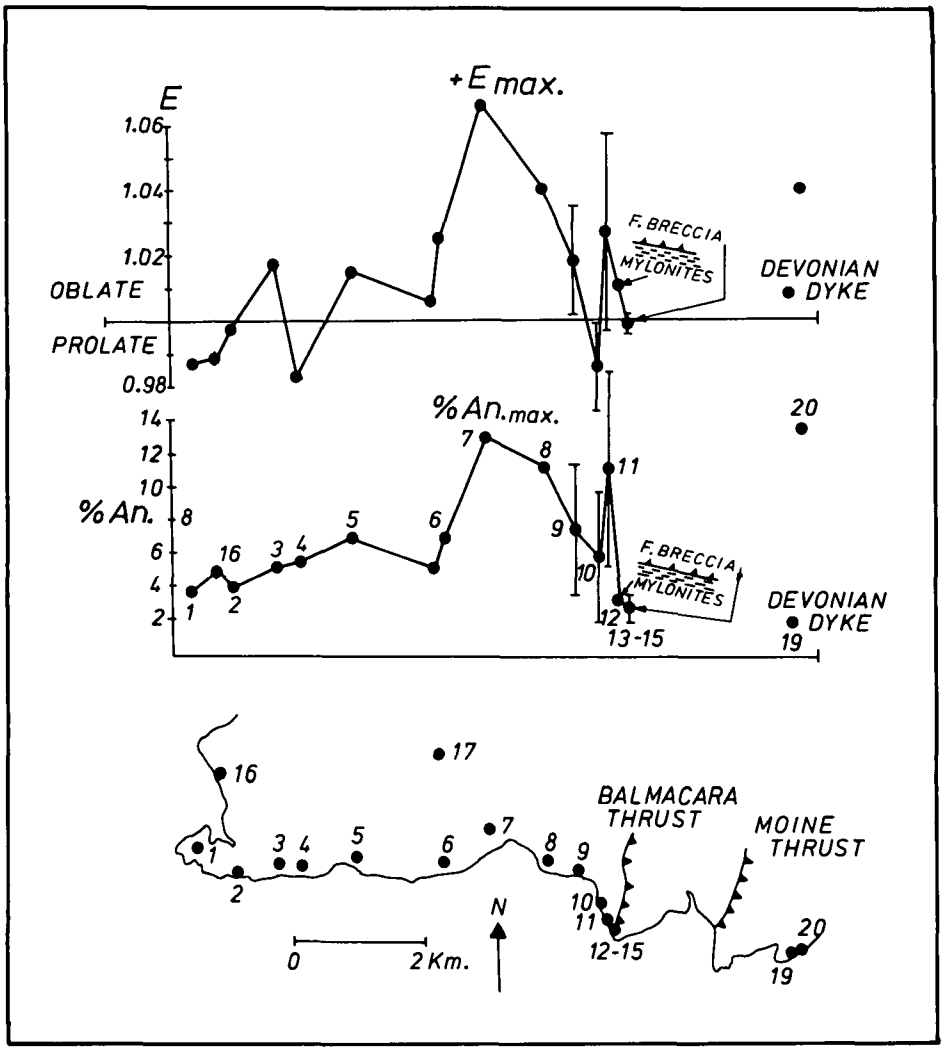

Figure 15. Variation of apparent shape of the magnetic ellipsoids (E) and degree of anisotropy (%An) for the investigated sites. Error bars are included for sites which show a high degree of inhomogeneity often associated with magnetic intereference patterns.

show steeply dipping magnetic foliation planes (K_{max}/K_{int}) trending northeast, with well-defined lineations (K_{max}) plunging to the southeast (Fig. 13). At site 16, however, the Torridonian rocks are strongly fractured and no distinct magnetic fabric pattern could be established. The orientation of the magnetic foliations in the normal limb are oblique to the axial trace of the syncline, and both along the axial trace and in the inverted limb the strike of this foliation changes to a north-northwest trend (sites 3–5, 17). K_{max} plunges towards the southeast, though the orientation is somewhat irregular in the area of the fold hinge.

In the inverted limb, towards the Balmacara and Moine thrusts and in the northern part of the Kishorn Nappe (site 18), the magnetic foliation trends near N–S with southwestward plunging lineations. The magnetic foliation planes have shallower dips and become substantially bedding-parallel (cf. Coward & Whalley, 1979). The magnetic fabric in the Torridonian mylonites is controlled by the foliation, whereas that of the overlying fault breccia is nearly isotropic (Fig. 14), though a weakly developed magnetic foliation can be detected. The late asymmetrical folding affects the magnetic fabrics, as can be observed at site 11. In Figure 13 a site mean result is given but, as indicated by Figure 14, both the foliation and lineation show minor refolding. Some of the sites (notably sites 9 and 10) in the Balmacara area give complex magnetic fabric patterns (Fig. 14), which we attribute to magnetic interference patterns. From site 10, some individual samples tend to define the gently dipping foliation in the area, (Fig. 14: stereoplot 10a), whereas others (Fig. 14: stereopolot 10b), indicate a steeply dipping inclined northeast foliation (probably axial planar to smaller scale folds). Also, the magnetic fabric from site 9 is unclear, with a preferential development of a steeply inclined, N–S trending foliation.

In the Moine Nappe (site 20), the structural fabrics correspond closely to those observed from parts of the inverted limb of the Lochalsh Syncline (Figs. 13, 14), i.e. shallow easterly dipping magnetic foliations with southeast plunging lineations. This latter is the principal lineation feature in all the thrust sequences within the MTZ. In contrast, the magnetic fabrics in the lamprophyre dyke (Fig. 14) do not conform to the regional structural fabrics. The dyke clearly postdates the main Caledonian deformation, and the observed magnetic foliation is essentially subparallel to the dyke margins, and most likely represents an original intrusive fabric.

The shape and degree of anisotropy (% An) varies

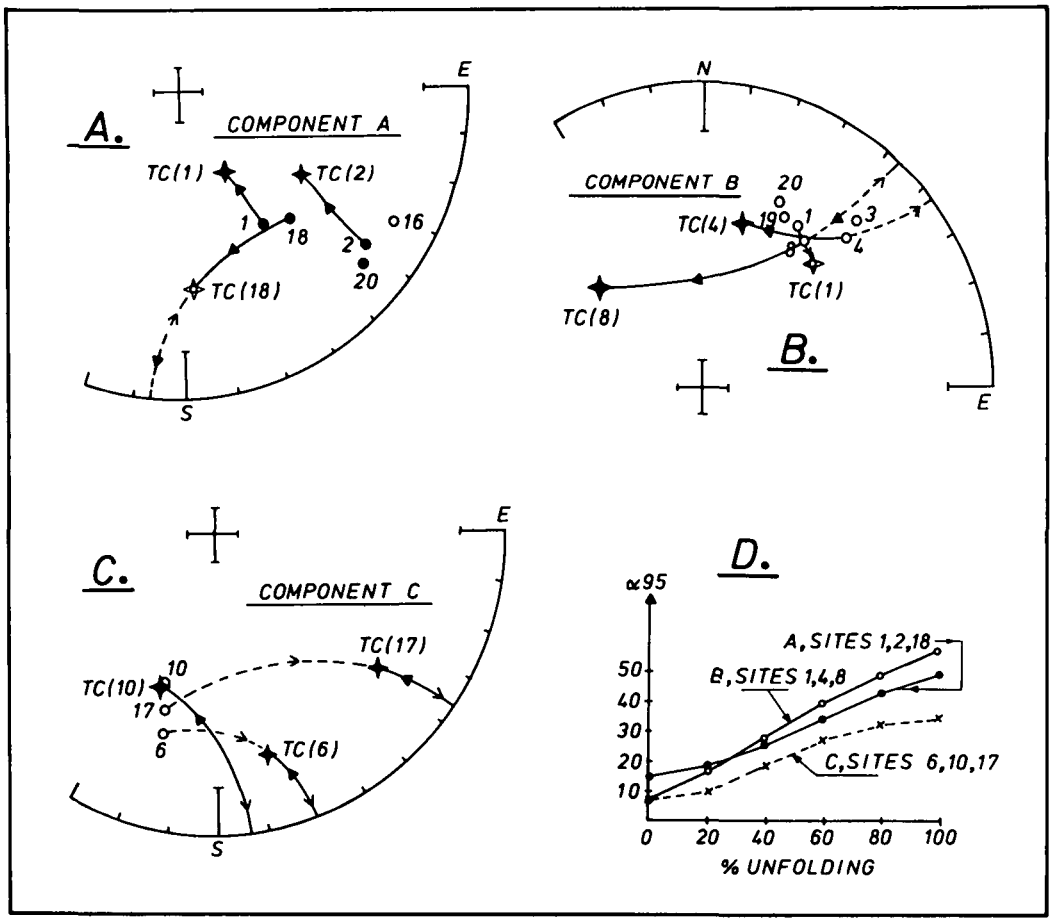

Figure 16. Fold test for the Torridonian rocks (component A–C) where the bedding is unambiguously distinguishable from the cleavage. As indicated in (d), all components show an increasing α_{95} during progressive unfolding, indicating a post-D1 origin.

through the Kishorn Nappe (Fig. 15). In the normal limb (sites 1, 2) the degree of anisotropy is around 4% and the magnetic ellipsoids lie just within the apparent prolate field. Along the axial trace and in the inverted limb, the magnetic ellipsoids tend to be oblate and associated with an increase in % An. In the inverted limb (site 7), % An and degree of apparent flattening 'strain' reach a maximum. The consistency of the magnetic fabric data are generally good, but to the east of site 8 large within-site differences (inhomogenities) occur (Fig. 15). There is, however, a general decreasing trend in the fabric parameters approaching the thrust, and rocks which show the strongest degree of recovery have the lowest magnetic anisotropies. The degree of anisotropy in the amphibolites (Moine Nappe) show values around the maximum recorded within the Kishorn Nappe (18%).

Undeformed Torridonian sediments (Diabaig Formation) in the Caledonian Foreland typically exhibit primary/compactional magnetic fabrics (Torsvik & Sturt, 1987). Coward & Whalley (1979) indicated how the regional, though non-penetrative, cleavage (D2) in the western part of the Kishorn Nappe is superimposed upon the sedimentary fabric. This could be expected to have produced an interference pattern in the normal limb with intersection lineations compatible with mineral lineations in the more deformed rocks in the eastern part of the Kishorn and the Moine Nappes. Oblate bedding-orientated tectonic fabrics (D3) are developed in the inverted limb with anisotropies up to 10–15%, and document an increase in late Caledonian strains towards the Balmacara and Moine thrusts. This late tectonic flattening strain is compatible both in magnitude and orientation with the structural fabrics in the Moine Nappe. Coward & Whalley (1979) report on prolate ellipsoids beneath the Balmacara Nappe, suggesting a change in the deformation pattern associated with shear close to the Balmacara Thrust. It is likely that the apparent maximum degree of magnetic flattening strain in the inverted limb coincides with changes in the magnetic properties due to a substantial increase in the rate of

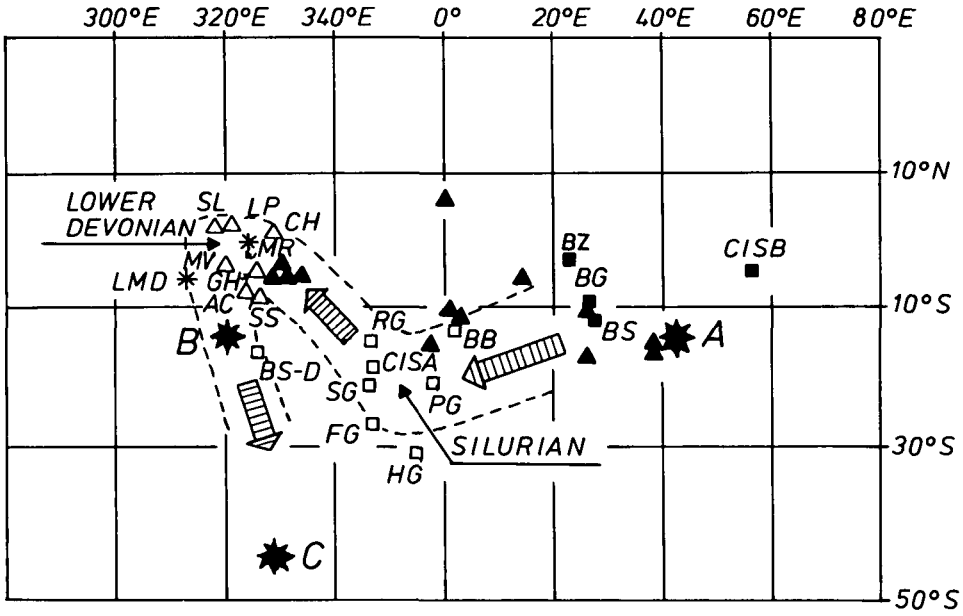

Figure 17. Apparent Polar Wander path from the British Isles (northern sector of the Iapetus system) in the Ordovician–Lower Devonian range (modified and updated from Torsvik, 1985*a*, *b*). Closed squares: BG, BS = Ordovician Ballantrae Gabbros and Ballantrae Serpentinites respectively (Piper, 1978); BZ = Barrow Zone Schist (Watts, 1985); CISB = northwest magnetizations reported from the Moine Nappe (Esang & Piper, 1984). Undenoted solid triangles: site means from the Ordovician Aberdeenshire Gabbros (Watts & Briden, 1984), though to reflect a segment of the APW path, probably in the Ordovician–Lower Devonian range. The 'Newer Granites', northwestern Scotland syenites and Caledonian intrusives are shown by opens squares as follows: HG = Helmsdale Granite (Torsvik, Løvlie & Storetvedt, 1983); FG = Foyers Granite (Torsvik, 1984); SG = Strontian Granite (Torsvik, 1984); PG = Peterhead Granite (Torsvik, 1985*b*); RG = Ratagen Granite (Turnell, 1985); CISA = Caledonian Intrusive Suites (Esang & Piper, 1984); BB = mean pole for the Borrolan Ledmorite, Loch Loyal and the Ben Loyal Complex (calc. from Turnell & Briden, 1983); BS-D = mean pole for the Borrolan Syenite and lamprophyre dykes to the west of the Borrolan Complex–note that this latter pole differs substantially from the BB pole (?L. Devonian). The Lower Devonian poles are denoted by open triangles and are as follows: GH = Garabal Hill (Briden, 1970); AC = Arrochar Complex (Briden, 1970); CH = Cheviot Hills (lavas, granites and metasediments; Thorning, 1974); LP = Lorne Plateau Lavas (Latham & Briden, 1975); MV = Midland Valley Lavas (Sallomy & Piper, 1973); SL = Strathmore Lavas (Torsvik, 1985*a*). Additionally, palaeomagnetic poles from Moinian rocks west of Ratagen (MR: Turnell, 1985) and the Lower Morar Division (LMD: Watts, 1982) are included (probably of Lower Devonian age). The latter pole is a mean value of high and intermediate blocking components (excluding site 10; see table 1 in Watts, 1982). Poles (A–C) from the present study are shown as large stars. Note that some of the poles referenced above may represent combined poles for *reasons of diagram simplicity* (e.g. northwestern Scotland syenites and Lower Morar Division).

recrystallization/annealing compared with the rate of dynamic strain. Local D3 'retrogression' related to late asymmetrical folds is probably also significant.

5. Discussion of remanence data and geodynamic aspects

The palaeomagnetism of metamorphic rocks from polystructural terranes has inherent uncertainties regarding the origin of remanence. Hence the unravelling of a complete magnetic history which can be tied to specific structural events is complex. There are also problems in differentiating true palaeofield directions from remanences governed by structural grain, particularly from high strain sites.

Four different remanence components (A–D) have been isolated on directional criteria and partly from T_b contrasts; the D component exhibits the lowest T_b (youngest). Considering the structural history of the Kishorn Nappe, the reasonable fit between site grouping (*in situ*) of components A–C, and that components A and B can also be traced into the Moine Nappe, a post-(?syn)-tectonic origin with respect to the Lochalsh Syncline (D1) is indicated. No tectonic correction is applicable to the rocks in the Moine Nappe (sites 19, 20), but well-bedded sites within the Kishorn Nappe have been stepwise unfolded by means of a rigid body rotation (components A–C; Fig. 16). All components indicate a secondary origin due to the steadily increasing radius of confidence during unfolding (negative fold-test). Potts (1982), however, has pointed out that palaeomagnetic data from the Ord Syncline could be restored to their original Torridonian position after a rigid body rotation. It is evident that the A component from the

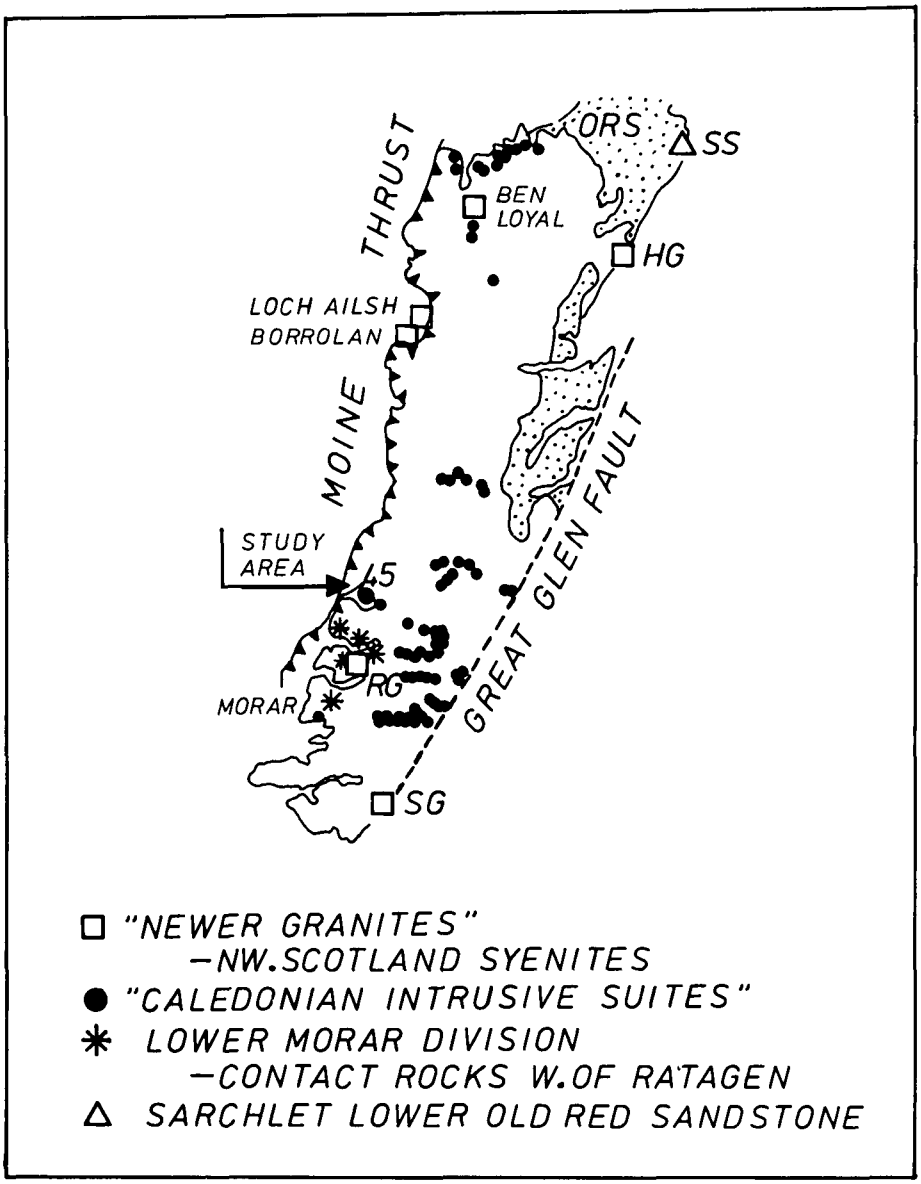

Figure 18. Location of some of the palaeomagnetic data from the Northern Highlands discussed in the text (and Fig. 17).

normal limb (Fig. 16a) can be reasonably restored back to a Torridonian palaeofield. However, tectonic corrections from the other sites (e.g. site 18 from the inverted limb) do not bring component A back to its primary direction.

The bulk remanence properties of the rocks in the Kishorn Nappe are considered to be secondary, mostly carried by magnetite, but an increasing importance of haematite is noticed along the axial trace and at some of the sites in the inverted limb. Reduction of haematite must have taken place during regional metamorphism of the Torridonian sediments, since the sediments in the Foreland are indeed red beds and the magnetomineralogy is dominated by specular haematite, as opposed to the grey-green magnetite-bearing sediments in the Kishorn Nappe. Magnetite, however, has been reported in undeformed Torridonian sediments (e.g. Smith, Stearn & Piper, 1983), and it may occur in heavy mineral banding. Reduction of haematite must have been of major importance in removing the characteristic red colour of the sediments, under lower greenschist facies metamorphism.

There is an increasing rate of recovery from west to east, and it is likely that magnetite (which later may have oxidized to haematite) formed during breakdown of iron-bearing silicates, micas and clay minerals. Samples close to the Balmacara Thrust are clearly dominated by an unidentified mineral phase with blocking temperatures around 200–230 °C. The latter is related to recrystallization and formation of new quartz.

The relative pole positions for components A–C (Fig. 17) are viewed in the frame of a suggested British APW path (modified from Torsvik, 1985*a* and in overall correspondence with that presented by Briden, Turnell & Watts, 1986), and the geographic location of some of the areas discussed in the text are shown in Figure 18. Only poles *proposed* to be of Lower Devonian or older age (north of the Iapetus Suture) are included in the diagram for reasons of simplicity. Pole A is considered as the oldest and analogous to, for example, the proposed oldest poles from the ordovician Aberdeenshire Gabbros (Watts & Briden, 1984) and some of the palaeomagnetic data (Esang & Piper, 1984) reported from the Moine Nappe. Pole A may be of mid-Ordovician or at least post-Lower Ordovician age and provides a *minimum* age for the formation of the Lochalsh Syncline (D1) and/or D2 in the Kishorn Nappe. The authors, however, are concerned about pole A: (i) a D1/D2 origin implies the possibility of post-acquisition block rotation/tilting; (ii) it is evident (Fig. 19) that there is a remarkable similarity between component A and the southeast-plunging lineation; and (iii) the observation from site 1 that component A may be carried in the coarsest grain fractions. Thus, component A could be biased by the structural grain, either by passive deflection of pre-tectonic remanences or syn-shear controlled remanences with no or modest amounts of stress relaxation.

Of the four obtained remanence components, the highest palaeomagnetic reliability is assigned to component B, which is observed in the normal limb,

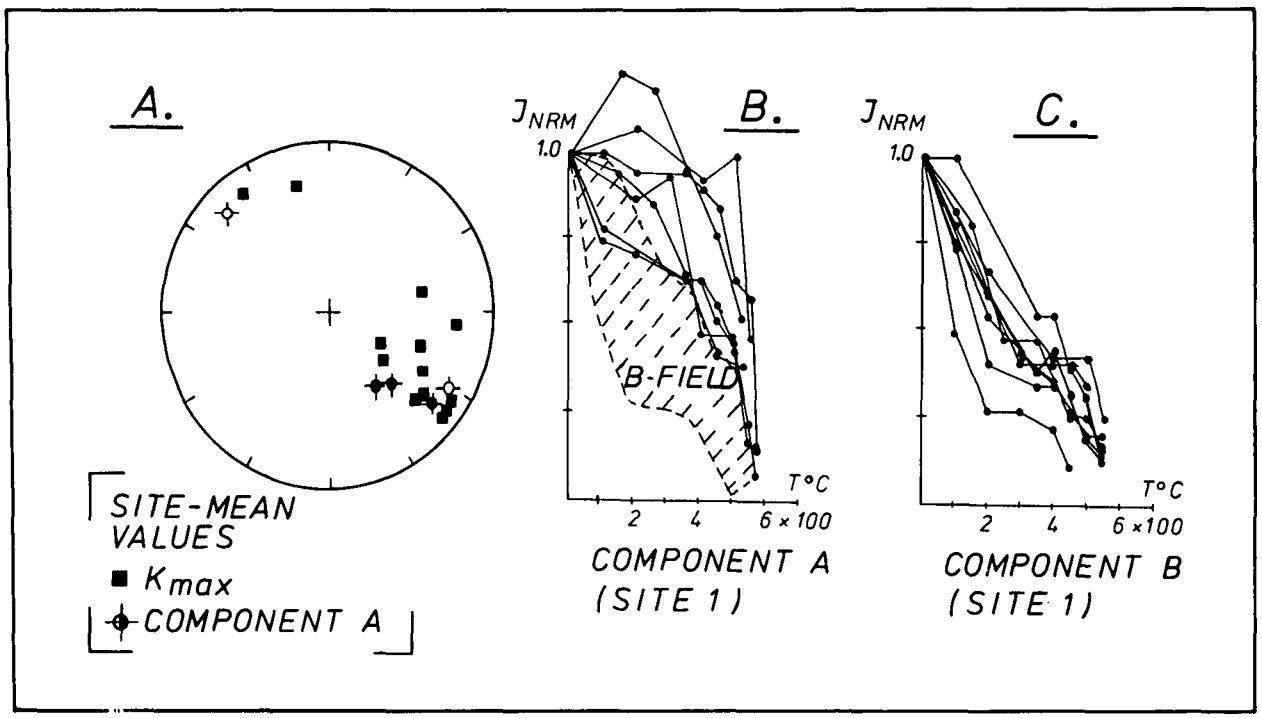

Figure 19. (a) Comparison of site mean values of component A and magnetic lineations. (c) Blocking spectra for site 1 specimens dominated by component B. (b) Part (c) is shown as inset, together with the blocking spectra for component A specimens.

the axial trace and partly in the inverted limb of the Lochalsh Syncline, independent of the structural fabrics. It is particularly well defined in the lamprophyre dyke as well as partly contaminating the retrograded amphibolites. In a study of Caledonian intrusives and Moinian rocks in the Northern Highlands (cf. sampling areas in Fig. 18), Esang & Piper (1984) subdivided the directional findings into two major remanence groups: one similar to the A component, whereas a younger one fits the 'Newer Granites' and parts of the Borrolan and Ben Loyal Complex (Turnell & Briden, 1983). Their table 1 shows that palaeomagnetic data from a dyke, closest to the present sampling area (site 45; Fig. 18), indicates a mean remanence direction (Dec = 214, Inc = 31) close to our B component. Similarly, Watts (1982) and Turnell (1985) report on remanence directions in the Lower Morar Division and Moinian rocks west of Ratagen Granite respectively (Figs. 17, 18), which correspond reasonably well with the B pole. Finally, lamprophyre dykes in the Foreland and the Borrolan *Syenite* and the Loch Ailsh Complex (Turnell & Briden, 1983) provide palaeomagnetic data in correspondence with the B pole. The Borrolan Complex is traditionally considered to syn-date late movements in the MTZ (430 Ma; Van Breemen, Aftalion & Johnson, 1979), but parts of the complex are affected by later thrust movements (Parsons, 1979). The identification of two major remanence components led Turnell & Briden (1983) to conclude that there are either significant intrusive age differences, or alternatively (but considered less likely) that the youngest (corresponding to lamprophyre dykes east and north of the Assynt District) was acquired by post/syn-thrust remagnetization. This latter corresponds to the B component, which thus seems to be well developed along the length of the MTZ. Compared with the pole position obtained from the Lower Old Red Sandstone (ORS) of Sarchlet (Storhaug & Storetvedt, 1986), the other Lower Devonian poles from the British Isles, the B pole is assigned to Lower Devonian time, or at least is assumed to predate the majority of *suggested* mid–late Devonian poles from the British Isles.

The youngest magnetization components (C and D) are seen in the inverted limb and towards the Balmacara and Moine thrusts, and components A and B are virtually absent. Component D has a Recent/Tertiary origin (see Fig. 2b) and is carried by mineral phases with extremely low blocking temperatures. This component could relate to recent reactivation, but due to its low magnetic stability is more likely to be connected with an increase in geothermal gradient relating to the Tertiary volcanic centre at Skye. It may, however, simply represent a present-day viscous remanent magnetization (VRM). The D magnetization resident in pyrrhotite in the fault breccia could be attributed to a late stage of fluid circulation in the fault zone. The observed low stability mineralogy in the rocks beneath the Balmacara Thrust, however, was most likely produced during the peak of Caledonian deformation and easily overprinted by later disturbances. The C component has a higher magnetic stability, and is in part carried by a high stability haematite phase, though the origin of this component is uncertain. The extent to which numerous shears, notably in the inverted limb, are uniquely of Caledonian age is questioned. Alternatively they may represent localized shearing during Permain times, which indeed is the suggested age from the relative pole position.

The status of the Great Glen Fault is a subject of considerable controversy, and explanations based on palaeomagnetism vary from elevating the structure to a major megashear (Van der Voo & Scotese, 1981; Storetvedt & Deutsch, 1986), which would be in disagreement with the polar comparison given above, to those compatible with geological models (Briden, Turnell & Watts, 1984; Torsvik, 1984; Briden, Turnell & Watts, 1986). Comparison of palaeomagnetic data across the fault shows a close correspondence between Silurian and Lower Devonian data, and thus favours a limited displacement model for the GGF, though even here there is the possibility of a certain degree of circular argument. The apparent continuity of the Orcadian ORS across the fault, scarcity of intense brittle/ductile deformation, and the deep crustal signature (Matthews & Cheadle, 1986), however, indicate that post-Devonian movments along the fault that could be detected palaeomagnetically are at best unlikely.

6. Conclusion

Recent regional geological studies indicate that the major folds such as the Lochalsh Syncline, considered to be time-equivalent with the formation of mylonites in the Moine Nappe, represent an early event in the deformation history and predate the superposition of the main regional cleavage (Coward & Whalley, 1979; McClay & Coward, 1981; Potts, 1982). These observations have been confirmed in the present study, where particular attention is drawn to the orientation of the magnetic foliations (Fig. 8).

The magnetic fabrics of this study are in general agreement with the data of Coward & Whalley (1979), and the dominating fabric postdates the formation of the Lochalsh Syncline (D1). Towards the Balmacara and Moine thrusts, steeply dipping magnetic foliations (oblique to bedding) gradually change to bedding-orientated foliations (D3) attended by maximum values of % An, and apparent flattening strains in the central part of the inverted limb are closely similar to the observed fabrics in the Moine Nappe. The preferred mineral lineations as recorded from quartz and muscovite (Coward & Whalley, 1979) are gener-

ally aligned southeast, i.e. in accord with the magnetic lineations.

No primary Torridonian magnetization is apparently preserved in the Kishorn Nappe and the observed remanence components (A–D) postdate the formation of the Lochalsh Syncline. In this respect, the oldest component (A) implies that the Lochalsh Syncline and its related folds are of mid–late Ordovician age. However, the correspondence between component A and the southeast-plunging lineations must be stressed, and thus this interpretation based on palaeomagnetism is speculative at best. It is of interest, however, that metamorphism of mid–late Ordovician age has been identified in the western part of the Moine (Powell & Phillips, 1985; A. L. Harris, pers. comm. 1984).

The magnetic fabric data from the Kishorn Nappe are consistent with increasing late Caledonian strains towards the Balmacara and Moine thrusts. The apparent lack of component A and also B in that direction, suggests successively younger magnetic overprints which culminate with a low stability component (D) of Recent/Tertiary origin.

Component B tends to be a dominant feature along the length of the MTZ, and it is reasonable to assume that major thermochemical events, local shearing and uplift in the MTZ continued into Devonian times. The relatively young magnetic ages observed partly in the inverted limb of the Lochalsh Syncline and close to the Balmacara Thrust indicate magnetic overprints during Mesozoic and Cenozoic times. Late normal fault movements on the sites of Caledonian thrusts have recently been given considerable prominence (Matthews & Cheadle, 1986), a feature which is compatible with our data.

Acknowledgements. T.H.T. acknowledges the Norwegian Research Council for the Humanities and Science (NAVF) for financial support. Considerable improvements to the manuscript by Dr A. McCaig, Professor D. M. Ramsay and an anonymous referee are gratefully acknowledged. Norwegian Lithosphere Contribution (21).

References

BAILEY, E. B. 1955. Moine tectonics and metamorphism in Skye. *Transactions of the Edinburgh Geological Society* **16**, 93–166.

BARBER, A. J. 1965. The history of the Moine Thrust Zone, Locharron and Lochalsh, Scotland. *Proceedings of the Geologists' Association* **76**, 215–42.

BRIDEN, J. C. 1970. Palaeomagnetic results from the Arrochar and Garabal Hill Glen Fyne igneous complexes, Scotland. *Geophysical Journal of the Royal Astronomical Society* **21**, 457–70.

BRIDEN, J. C. & ARTHUR, G. R. 1981. Precision of measurement of remanent magnetization. *Canadian Journal of Earth Sciences* **18**(3), 527–38.

BRIDEN, J. C., TURNELL, H. B. & WATTS, D. R. 1984. British palaeomagnetism, Iapetus Ocean, and the Great Glen Fault. *Geology* **12**, 428–31.

BRIDEN, J. C., TURNELL, H. B. & WATTS, D. R. 1986. Reappraisal of Scottish Ordovician palaeomagnetism: Reply to Storetvedt and Deutsch. *Geophysical Journal of the Royal Astronomical Society* **87**, 1207–13.

COWARD, M. P. & KIM, J. H. 1981. Strain within thrust sheets. In *Thrust and Nappe Tectonics* (ed. K. R. McClay and N. J. Price), pp. 275–92. Special publication of the Geological Society of London no. 9.

COWARD, M. P. & WHALLEY, 1979. Texture and fabric studies across the Kishorn Nappe, near Kyle of Lochalsh, Western Scotland. *Journal of Structural Geology* **1**, 259–73.

ESANG, C. B. & PIPER, J. D. A. 1984. Palaeomagnetism of Caledonian Intrusive Suites in the Northern Highlands of Scotland: Constraints to tectonic movements within the Caledonian orogenic belt. *Tectonophysics* **104**, 1–34.

FISHER, R. A. 1953. Dispersion on a sphere. *Proceedings of the royal Society of London* Series A, **217**, 295–305.

JOHNSON, M. R. W. 1960. The structural history of the Moine Thrust Zone at Loch Carron, Wester Ross. *Transactions of the Royal Society of Edinburgh* **64**, 139–68.

JOHNSON, M. R. W. 1983. Torridonian–Moine. In *Geology of Scotland* (ed. G. Y. Craig), pp. 49–75. Edinburgh: Scottish Academic Press.

LATHAM, A. G. & BRIDEN, J. C. 1975. Palaeomagnetic field directions in Siluro-Devonian lavas of the Lorne Plateau, Scotland, and their regional significance. *Geophysical Journal of the Royal Astronomical Society* **43**, 243–52.

MCCLAY, K. R. & COWARD, M. P. 1981. The Moine Thrust Zone: an overview. In *Thrust and Nappe Tectonics* (ed. K. R. McClay and N. J. Price), pp. 41–54. Special Publication of the Geological Society of London no. 9.

MATTHEWS, D. H. & CHEADLE, M. J. 1986. Deep reflections from the Caledonian and Variscian west of Britain and comparison with the Himalayas. In *Reflection Seismology: A Global Perspective* (ed. M. Barajangi and L. Brown), pp. 5–20. Geodynamic Series no. 13. Published by American Geophysical Union, Washington.

PARSONS, I. 1979. The Assynt alkaline suite. In *The Caledonides of the British Isles Reviewed* (ed. A. L. Harris, C. H. Holland, and B. E. Leake), pp. 677–681. Edinburgh: Scottish Academic Press. Special Publication of the Geological Society of London, no. 8.

PEACH, B. N., HORNE, J., GUNN, W., CLOUGH, C. T., HINXMAN, L. W. & TEALL, J. J. H. 1907. *The Geological Structure of the North West Highlands of Scotland.* Memoir, Geological Survey of the United Kingdom.

PIPER, J. D. A. 1978. Palaeomagnetism and palaeogeography of the southern Uplands in Ordovician times. *Scottish Journal of Geology* **14**, 93–107.

POTTS, G. J. 1982. Finite strains within recumbent folds of the Kishorn Nappe, Northwest Scotland. *Tectonophysics* **88**, 313–19.

POWELL, D. & PHILLIPS, W. E. A. 1985. Time of deformation in the Caledonide Orogen of Britain and Ireland. In *The Nature and Timing of Orogenic Activity in the Caledonian Rocks of the British Isles* (ed. A. L. Harris), pp. 17–40. Geological Society of London, Memoir no. 9.

SALLOMY, J. T. & PIPER, J. D. A. 1973. Palaeomagnetic studies in the British Caledonides. IV. Lower Devonian lavas of the Strathmore region, Scotland. *Geophysical Journal of the Royal Astronomical Society* **34**, 47–68.

SMITH, D. 1979. Caledonian minor intrusions in the N. Highlands of Scotland. In *The Caledonides of the British Isles – Reviewed* (ed. A. L. Harris, C. H. Holland and B. E. Leake), pp. 683–97. Geological Society of London Special Publication no. 8.

SMITH, R. L., STEARN, J. E. F. & PIPER, J. D. A. 1983. Palaeomagnetic studies of the Torridonian sediments, NW Scotland. *Scottish Journal of Geology* **19**, 29–45.

STEWART, A. D. & IRVING, E. 1974. Palaeomagnetism of Precambrian sedimentary rocks from NW Scotland and the apparent polar wandering path of Laurentia. *Geophysical Journal of the Royal Astronomical Society* **37**, 51–72.

STORETVEDT, K. M. & DEUTSCH, E. R. 1986. Reappraisal of Scottish Ordovician palaeomagnetism. *Geophysical Journal of the Royal Astronomical Society* **87**, 1193–1206.

STORHAUGH, K. & STORETVEDT, K. M. 1986. Palaeomagnetism of the Sarchlet Sandstone (Orcadian Basin): age perspectives. *Scottish Journal of Geology* **20** (3), 275–84.

THORNING, L. 1974. Palaeomagnetic results from Lower Devonian rocks of the Cheviot Hills, Northern England. *Geophysical Journal of the Royal Astronomical Society* **36**, 487–96.

TORSVIK, T. H. 1984. Palaeomagnetism of the Foyers and Strontian granites, Scotland. *Physics of the Earth and Planetary Interiors* **36**, 163–77.

TORSVIK, T. H. 1985*a*. Magnetic properties of the Lower Old Red Sandstone Lavas in the Midland Valley, Scotland; palaeomagnetic and tectonic considerations. *Physics of the Earth and Planetary Interiors* **39**, 194–207.

TORSVIK, T. H. 1985*b*. Palaeomagnetic results from the Peterhead Granite, Scotland; implications for regional late Caledonian magnetic overprinting. *Physics of the Earth and Planetary Interiors* **39**, 108–17.

TORSVIK, T. H., LØVLIE, R. & STORETVEDT, K. M. 1983. Multi-component magnetization in the Helmsdale Granite, North Scotland; geotectonic implication. *Tectonophysics* **98**, 111–29.

TORSVIK, T. H. & STURT, B. A. 1987. On the origin and stability of remanence and the magnetic fabric of the Torridonian Red Beds, NW Scotland. *Scottish Journal of Geology* **23**, 1–16.

TURNELL, H. B. 1985. Paleomagnetism and Rb-Sr ages of the Ratagen and Comrie intrusions. *Geophysical Journal of the Royal Astronomical Society* **83**, 363–78.

TURNELL, H. B. & BRIDEN, J. C. 1983. Palaeomagnetism of NW Scotland syenites in relation to local and regional tectonics. *Geophysical Journal of the Royal Astronomical Society* **75**, 217–34.

VAN BREEMAN, O., AGTALION, M. & JOHNSON, M. R. W. 1979. Age of the Loch Borrolan Complex, Assynt, and late movements along the Moine Thrust Zone. *Journal of the Geological Society of London* **136**, 489–95.

VAN DER VOO & SCOTESE, C. 1981. Palaeomagnetic evidence for a large (ca. 2000 km) sinistral offset along the Great Glen Fault during Carboniferous time, *Geology*, **9**, 583–589.

WATSON, J. V. 1975. The Lewisian Complex. In *A Correlation of the Precambrian Rocks in the British Isles* (ed. A. L. Harris), pp. 15–29. Special Report of the Geological Society of London no. 6.

WATTS, D. R. 1982. A multicomponent, dual-polarity palaeomagnetic regional overprint from the Moine of northwest Scotland. *Earth and Planetary Science Letters* **61**, 190–8.

WATTS, D. R. 1985. Palaeomagnetic resetting in the Barrovian Zones of Scotland and its relationship to the late structural history. *Earth and Planetary Science Letters*, **75**, 258–64.

WATTS, D. R. & BRIDEN, J. C. 1984. Palaeomagnetic signature of slow post-orogenic cooling of the northeast Highlands of Scotland recorded in the Newer Gabbros of Aberdeenshire. *Geophysical Journal of the Royal Astronomical Society* **77**, 775–88.