Tectonophysics, 98 (1983) 111–129
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

MULTICOMPONENT MAGNETIZATION IN THE HELMSDALE GRANITE, NORTH SCOTLAND; GEOTECTONIC IMPLICATION

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(Received March 25, 1983)

ABSTRACT

Torsvik, T.H., Løvlie, R. and Storetvedt, K.M., 1983. Multicomponent magnetization in the Helmsdale granite, north Scotland; geotectonic implication. In: E. McClelland Brown and J. VandenBerg (Editors), Palaeomagnetism of Orogenic Belts. *Tectonophysics*, 98: 111–129.

A palaeomagnetic study of the Helmsdale granite (U/Pb-420 m.y., K/Ar-400 m.y.), northeast Scotland, has revealed a multicomponent remanence dominated by two characteristic axes of magnetization. The suggested oldest of these magnetizations, the direction of which is nearly horizontal and directed N–S, is thought to have been acquired in Upper Silurian–Lower Devonian times. The existence of this shallow direction of magnetization discounts a recent hypothesis of a ca. 2000 km sinistral offset along the Great Glen Fault. The second component of magnetization appears to be partly carried by haematite that apparently formed through disintegration of biotite and/or plagioclase. This secondary magnetization has a direction that can be associated with a Permian–early Mesozoic age. Similar overprinted magnetizations are characteristic features also in the Devonian sedimentary sequences north of Helmsdale.

INTRODUCTION

The most important structural event in the northern part of the British Isles is the Caledonian orogeny. Associated with the evolution of this zone of crustal deformation are intrusions of calc-alkaline granites. The youngest series of these rocks are termed "newer granites", and they are post-tectonic with respect to the main Caledonian orogeny in Middle Ordovician (Anderson and Owen, 1980). Radiometric dating suggests that they were intruded in the period 420–390 m.y. (Pidgeon and Aftalion, 1978; Harmon and Halliday, 1980).

Since Kennedy (1946) proposed a 100 km sinistral shift along the Great Glen Fault (GGF), based on petrological similarities between the younger granitic complexes of Foyers and Strontian, several authors have carried out investigations in the Northern and Grampian Highlands with this tectonic problem in mind (for example Dearnley, 1962; Holgate, 1969; Flinn, 1979; Garson and Plant, 1972; Winchester, 1973; Storetvedt, 1974), but this important question is still far from settled.

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Palaeomagnetism of formations adjacent to the GGF may provide an important bearing on the displacement problem. The present paper reports on the magnetic properties of the Helmsdale granite (Fig. 1) and discusses tectonic implications.

The Helmsdale granite was emplaced into metasedimentary rocks of the Moine series. To the northeast and southwest Devonian sandstone overlies the granite, and along the coast it is bounded by the Helmsdale fault. The rock is a pink adamellite with approximately equal proportions of quarts, K-feldspar and plagioclase. Biotite, zircon, apatite, magnetite and altered sphene are common accessories (Tweedie, 1979). The granite can be divided into an outer porphytic, and an inner fine-grained

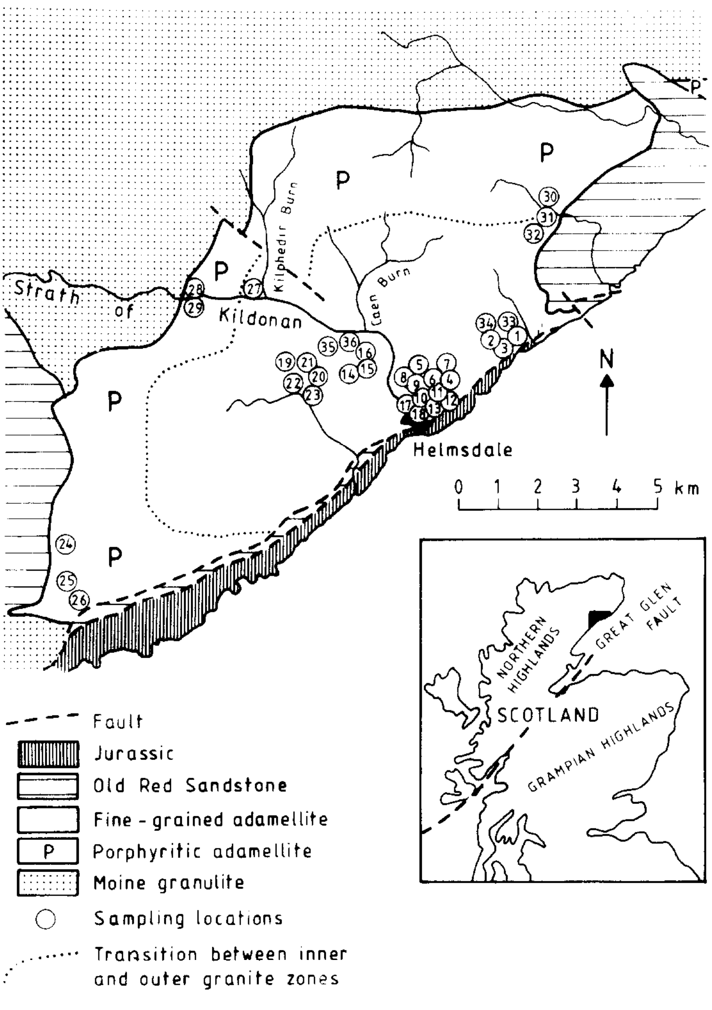

Fig. 1. Sketch map of the Helmsdale granite (simplified after Tweedie, 1979). Numbers refer to palaeomagnetic sampling locations.

adamellite. Intensive potassic alteration zones occur mainly within the fine-grained inner granite.

Radiometric ages obtained by U/Pb and K/Ar (biotite) yielded ages of 420 m.y. and 400 ± 15 m.y. respectively (Pidgeon and Aftalion, 1978). These ages are typical of Caledonian "newer granites", and suggest, along with the structural relationship, that the Helmsdale granite post-dates the main Caledonian regional folding and metamorphism. The granite is relatively unaffected by tectonic events since its emplacement in Upper Silurian–Lower Devonian time.

Haematite is the dominant oxide mineral, being present in association with plagioclase, biotite and chlorite, often occurring along micro-cracs. Plagioclase is characterized by anhedral to subhedral grains, and is generally intensely altered, especially in the inner anorthite-rich areas of the crystals. The most common alteration products are fine-grained mica, aggregates of iron-hydroxides, haematite and chlorite. Alteration of the plagioclase might be related to the formation of iron-oxides (hydroxides) along structural imperfections within the crystals during a metasomatic-hydrothermal event (Tweedie, 1979). Less common is very fine-grained magnetite, with no obvious association with other minerals. Also present is a very fine-grained, opaque mineral, which is embedded in almost unaltered plagioclase grains. Although it is likely to be magnetite, direct identification has not been successful due to the fine particle size.

During field trips in 1976 and 1980 a total of 250 hand samples (He 1–140) and drill cores (H 1–110) from 36 different locations were collected (cf. Fig. 1). The deviation between magnetic and sun compass orientations was found to be -10 ± 2, i.e. in agreement with the present local declination.

LABORATORY EXPERIMENTS

The direction and intensity of the natural remanent magnetization (NRM) was measured both on an astatic magnetometer and on a Digico spinner magnetometer. Stability of NRM was investigated by progressive alternating field (AF) demagnetization. In addition, stepwise thermal demagnetization experiments were performed using two different furnaces, one situated within three layers of μ-metal tube (2 m in length) and the other in the center of a self-compensating Helmholtz coil system (coil diameter ca. 2 m). Ambient fields during thermal demagnetization were below 15γ.

The magnetization in the Helmsdale granite is rather complex; progressive demagnetization (thermal and AF) was performed on 262 specimens of which more than 70% revealed irregular directional behaviour, as illustrated by the two examples in Fig. 2.

NRM intensities are in the range $5–20 \cdot 10^{-6}$ emu/cm^3, and the associated directions of magnetization are distributed around the present geomagnetic field direction suggesting the contribution of a significant viscous magnetization (VRM)

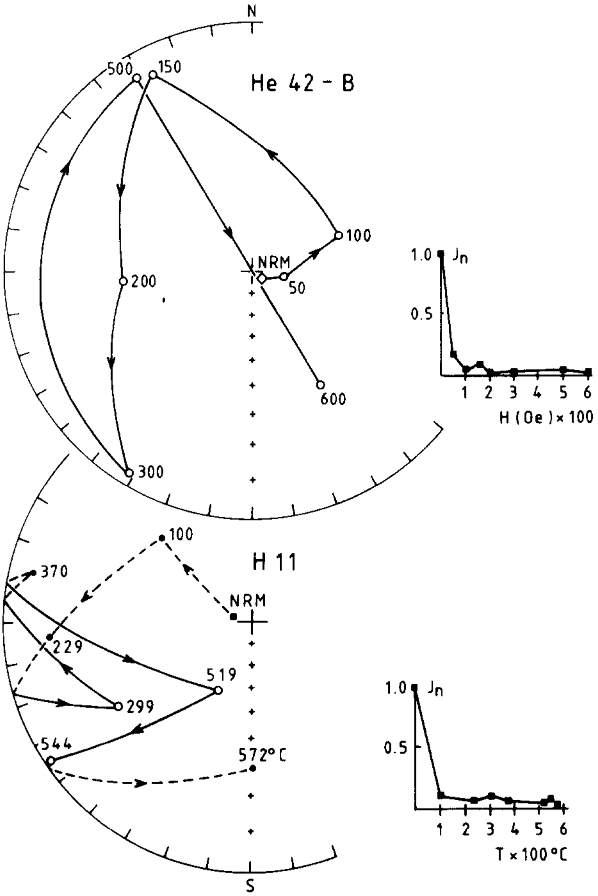

Fig. 2. Stereoplots showing examples of irregular directional behaviour upon AF and thermal demagnetization. Open symbols are upward pointing directions and closed symbols downward pointing directions. The unstable character of the remanence directions is supported by the very rapid intensity decay on demagnetization.

component. AF-demagnetization reveals a low stability remanence showing a typical intensity reduction of some 80% upon demagnetization to 100 Oe. Also, thermal demagnetization reveals a dominant low-temperature blocking component giving a similar rapid fall in intensity upon demagnetization to 100°C.

Thermal demagnetization discloses two characteristic axes of magnetization. Axis *B* is almost horizontal and directed N–S (both polarities). Axis *A* is directed south and characterized by intermediately steep, negative (up) inclinations (Fig. 3, Table I). Examples of thermal demagnetization are shown by Figs. 4–8. Directional stability is reached at $T > 100°C$, but due to the low intensity ($< 0.5 \cdot 10^{-6}$ emu/cm^3) at higher temperatures, directional reliability often ceases above ca. 500°C. This increased scatter is attributed to instrumental noise.

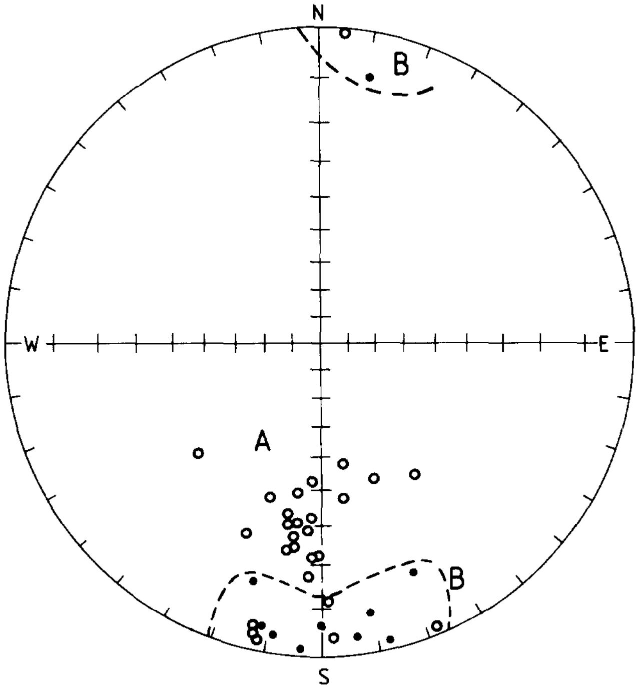

Fig. 3. Stereographic projection of directional distributions for palaeomagnetically stable specimen obtained by thermal demagnetization (cf. Table I).

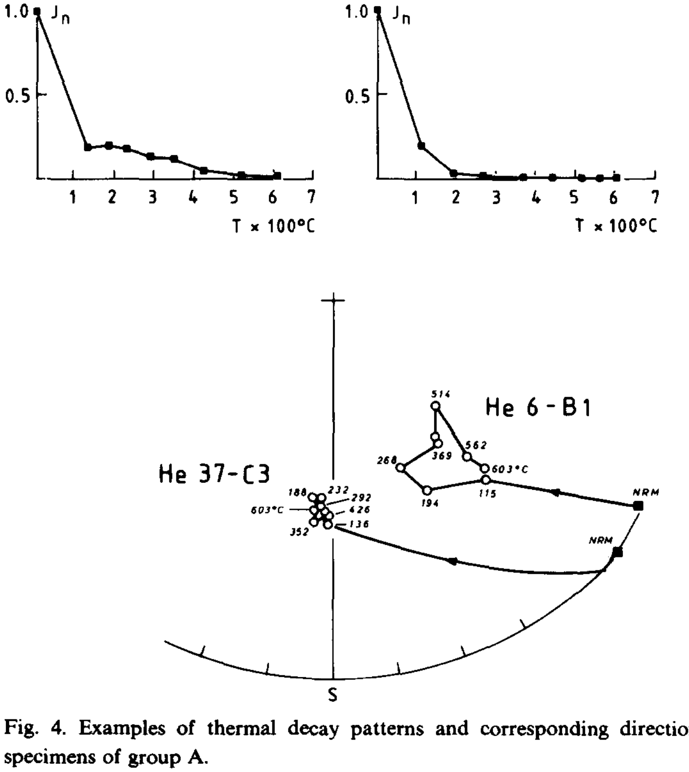

Fig. 4. Examples of thermal decay patterns and corresponding directions of magnetization for two specimens of group A.

TABLE I

Thermal demagnetization results from the Helmsdale granite with characteristic directions (*D* and *I*) for individual specimens

Site	Specimen	*D* (°)	*I* (°)	Group	Range (°C)
1	He 6bl	145	−36	A	115–605
3	He 12a4	184	2	B	100–400
3	He 14a1	188	−30	A	115–440
3	He 14a2	191	−32	A	130–400
3	He 14a3	188	−26	A	130–400
4	He 17b	196	16	B	115–400
4	He 20a3	192	5	B	115–400
5	He 23a1	173	4	B	130–400
6	He 26a1	179	−12	B	115–450
7	He 30a1	218	−36	A	NRM–605
7	He 30a2	193	−3	B	130–515
8	He 31b	156	−26	A	100–590
8	He 35a3	170	8	B	115–400
9	He 37c3	183	−32	A	135–605
9	He 39a2	158	−2	B	135–400
10	He 50b2	192	−24	A	250–620
11	He 50b3	190	4	B	NRM–400
12	He 52b2	193	−2	B	100–530
12	He 55b	183	−21	A	100–605
13	He 57b2	167	2	B	400–570
13	He 59a1	159	−40	A	115–440
21	He100a2	193	−4	B	400–560
22	He105a1	184	−17	A	130–400
22	He105a3	178	−5	B	110–450
27	H 7b	005	−1	B	400–550
29	H 38	185	−28	A	185–535
29	H 39	172	−37	A	110–400
29	H 40	185	−42	A	185–400
29	H 41	170	−47	A	110–510
31	H 45	158	14	B	400–580
33	H 66	188	−24	A	500–580
33	H 70	011	10	B	360–580
33	H 71	189	−38	A	200–500
33	H 73	190	−29	A	200–510
33	H 74	198	−35	A	185–450
33	H 75	183	−21	A	100–400
36	H 88	189	−23	A	500–615
36	H 91a	180	6	B	200–400

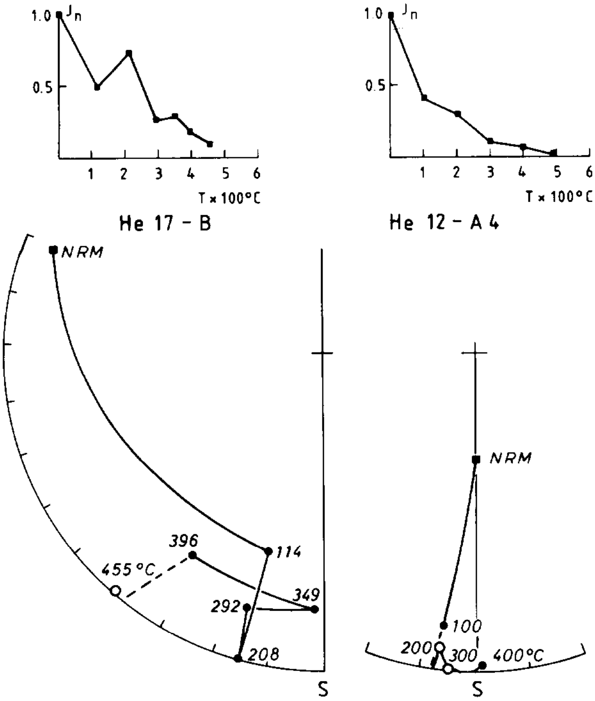

Fig. 5. Examples of thermal decay pattern and corresponding directional behaviour for two specimens of group B.

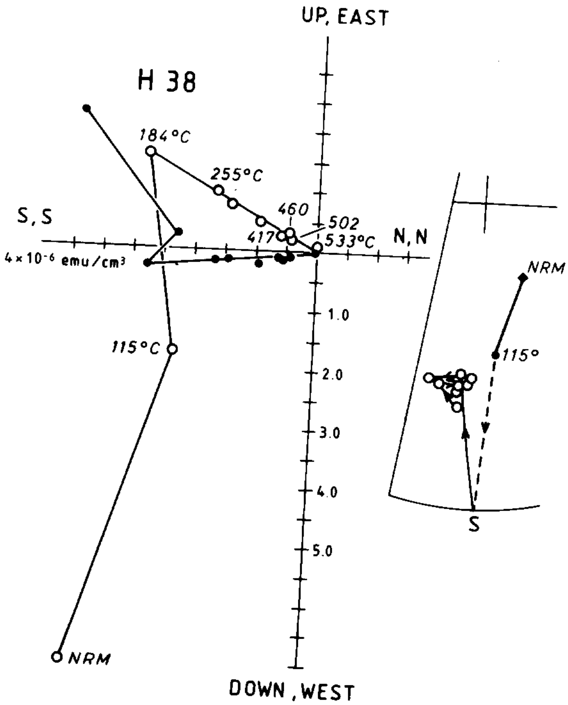

Fig. 6. Stereoplot and orthogonal vector projection of a specimen of palaeomagnetic group A. In the orthogonal vector projection open symbols represent points in the vertical plane and solid symbols are points in the horizontal plane. Stereoplot conventions as for Fig. 2.

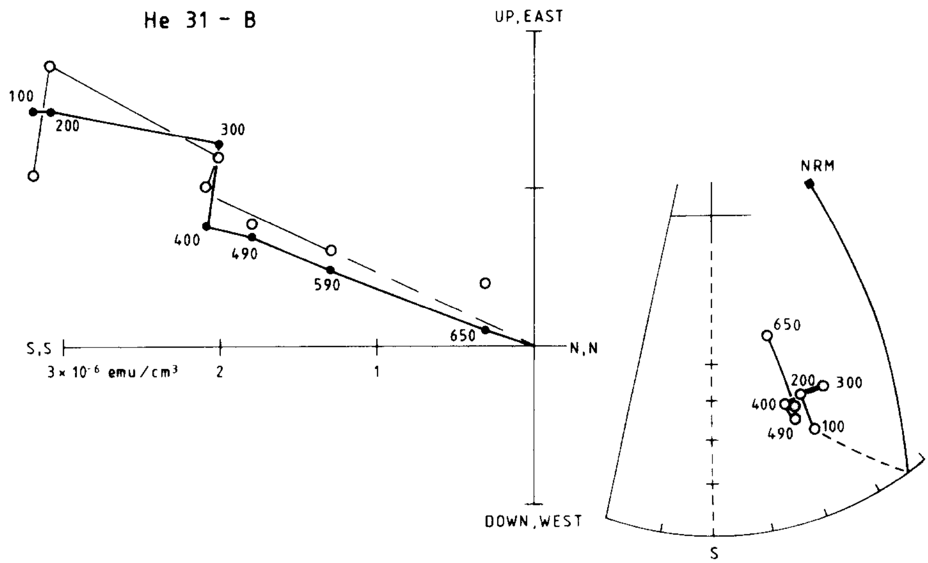

Fig. 7. Stereoplot and orthogonal vector projection of a specimen of group A. Diagram explanation as for Fig. 6.

Figures 6 and 7 show typical vector diagrams (Zijderveld, 1967) and stereographic representations of the directional movement upon thermal demagnetization. Above ca. 200°C (400°C in Fig. 7) the vector end-points follow an almost straight line

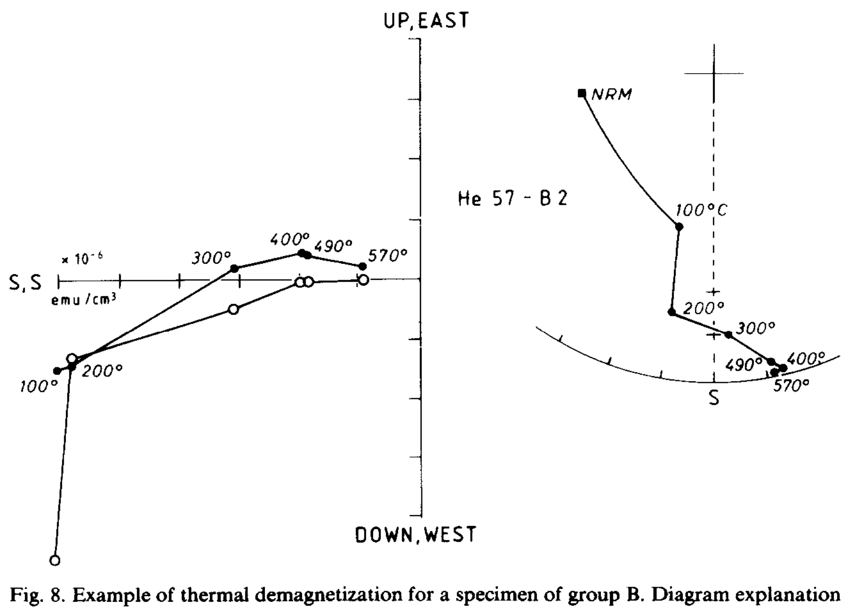

Fig. 8. Example of thermal demagnetization for a specimen of group B. Diagram explanation as for Fig. 6.

towards the center of the vector diagram, indicative of a single-component remanence. As evidenced from Fig. 7, the stability range for specimen He 31-b is between 100° and 590°C, as stated in Table I. The deviating direction (in inclination) obtained after demagnetization to 650°C is probably due to superimposed instrumental noise ($J_{650} < 0.4 \cdot 10^{-6}$ emu/cm^3). Hence, 590°C is unlikely to represent the upper blocking-temperature of the high temperature component.

The A magnetization is often associated with temperatures above 600°C (Fig. 7), which indicates that haematite may carry at least part of this remanence.

AF-demagnetization was not successful in isolating the two directional groups (A and B) uncovered by thermal treatment. Figure 9 shows a stereonet of stable directions obtained by stepwise AF demagnetization (Table II). The elongated directional distribution suggests that even after demagnetization treatment some of the stable directions are still composed of more than one component. Hence, AF demagnetization was not successful in resolving the A and B directions as determined by the thermal treatment. In addition to A and B components, vector analysis suggests that these multicomponent directions in part also consist of a remanence vector aligned along the present geomagnetic field direction.

Isothermal remanent magnetization was obtained in a maximum field of 9 kG, and the remanence coercive force (RCF) was found by applying a magnetic field in

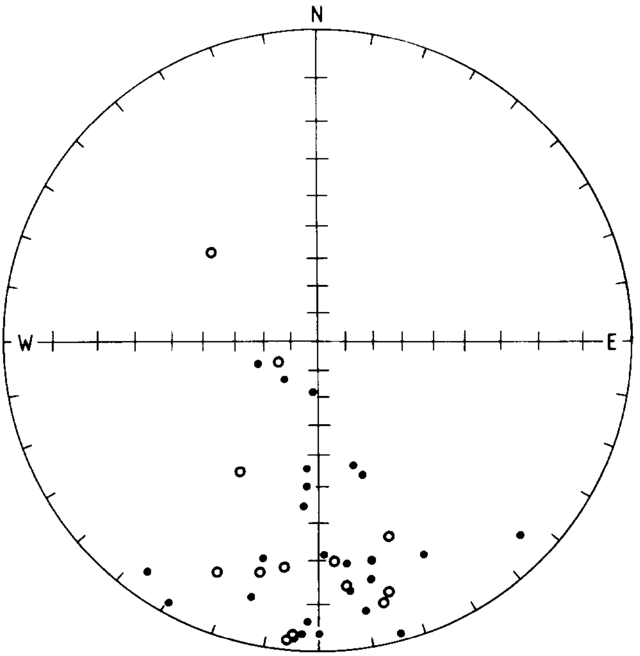

Fig. 9. Stereographic projection showing the directional distribution of palaeomagnetically stable specimens obtained by AF-demagnetization.

TABLE II

AF demagnetization results from the Helmsdale granite with characteristic directions (D and I) for individual specimens

Site	Specimen	D (°)	I (°)	Range (Oe)
1	He 3a2	170	8	100–700
1	He 3b	310	−42	150–550
1	He 6a2	185	35	150–400
2	He 8a2	211	−39	150–700
2	He 10b2	173	−14	40–700
2	He 10c	176	−20	50–300
3	He 12b3	210	3	150–700
4	He 18a3	204	−13	150–700
4	He 21a3	185	−4	150–400
4	He 21b	194	19	100–450
5	He 22b	165	45	100–450
5	He 23a2	162	42	100–400
5	He 23b2	168	15	200–400
5	He 24a2	194	−16	300–700
5	He 24b2	180	4	100–700
6	He 25a2	154	16	150–500
6	He 25b2	174	14	100–500
6	He 26a2	134	7	100–400
7	He 30a3	243	−75	200–700
8	He 35c	185	4	100–500
9	He 36a2	165	−11	100–700
9	He 36b1	166	−9	150–700
9	He 36b2	174	2	150–700
9	He 40a	189	−18	150–700
11	He 50a3	216	5	100–600
13	He 56b	250	67	50–600
13	He 58a3	167	19	100–600
13	He 58b	195	10	100–400
13	He 59a3	182	5	100–400
13	He 59b3	185	−4	100–400
14	He 65a3	185	4	150–400
15	He 69b	186	72	120–550
16	He 71b	179	22	100–400
16	He 71a3	184	40	100–400
16	He 72a3	173	19	100–400
20	He 95b2	222	82	100–400
22	He105a4	185	45	150–400
30	H 42a	160	−23	100–700

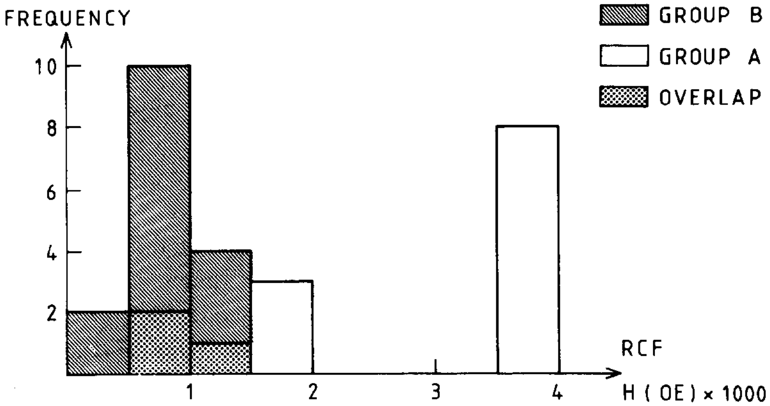

Fig. 10. Histogram showing the distribution of Remanence Coercive Force (RCF) for group A and group B specimens. Isothermal remanent magnetization was obtained in a maximum field of 9 kilogauss (kG).

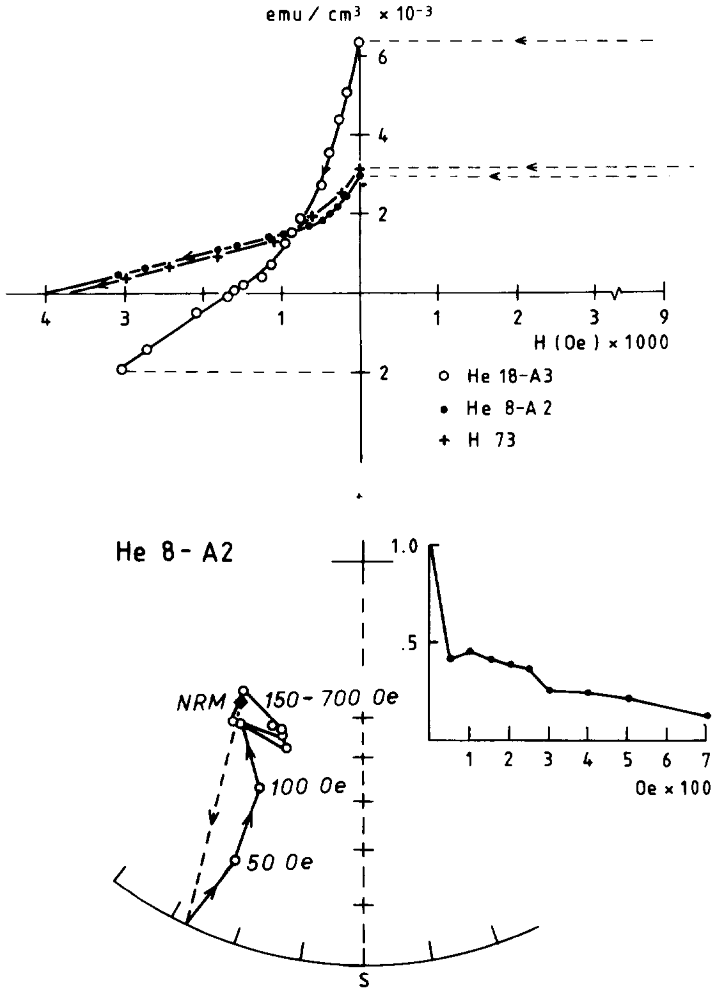

Fig. 11. Examples of Remanence Coercive Force measurements for group A specimens. For one of the specimens, He8-A2, the Af-demagnetization results are also included.

the opposite direction until the remanence was reduced to zero. For group A specimens it was not possible in some cases to obtain saturation, indicating that RCF's for group A have to be regarded as minimum values. The RCF values determined for 30 specimens, revealed fairly clear differences between groups A and B as shown in Fig. 10.

Group A specimens have typical RCF exceeding 1500 Oe (Fig. 11), indicative of a high coercivity mineral fraction. Only a few examples of RCF values down to 500 Oe have been encountered in specimens carrying the A magnetization. Group B specimens are characterized by lower RCF values, typically below 1200 Oe (Fig. 12). The RCF results suggest therefore that there is a distinct difference in the bulk magneto-mineralogical properties between A and B specimens.

The properties of the remanence carrying minerals were further investigated by measuring the NRM during cooling in field free space to liquid nitrogen boiling temperature (−196°C). All investigated samples showed a steady decay pattern with decreasing temperature, revealing a fairly well defined transitional "point" at around −160°C. Upon heating to room temperature the NRM intensity had dropped by around 70% (Fig. 13a). Such a behaviour is indicative of multi-domain magnetite as carrier of the remanence (Stacey and Banerjee, 1974). As shown by Fig. 13a, low-temperature measurement of a TRM, obtained by cooling (in air) in the Earth's magnetic field from 650°C, did not reveal any transitional temperature at all, the intensity remaining almost constant from room temperature to −196°C. This

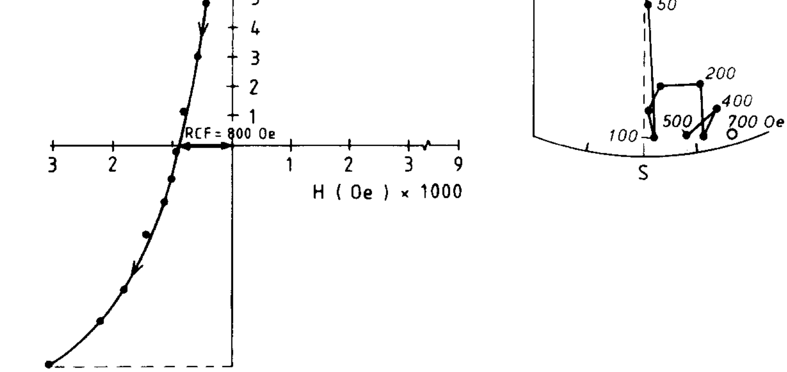

Fig. 12. The Remanence Coercive Force for a group B specimen along with the directional AF behaviour.

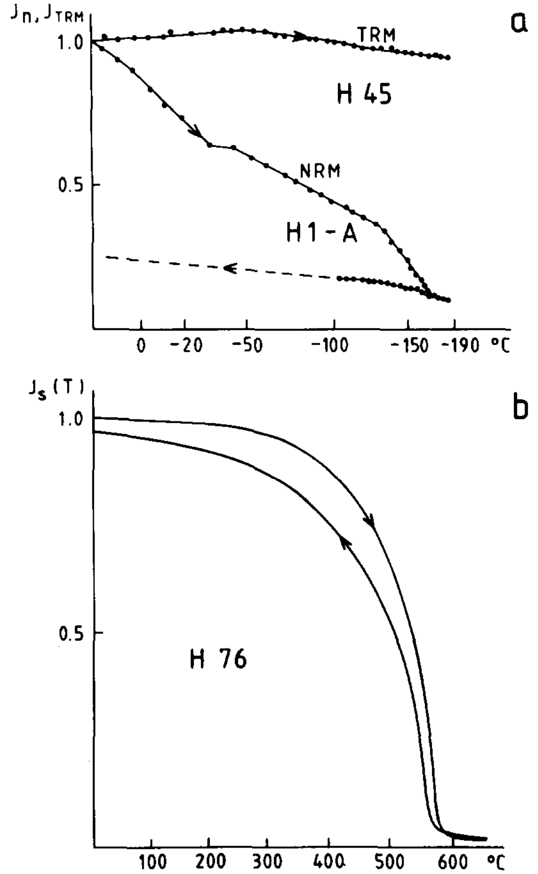

Fig. 13. Diagram a shows low temperature experiments, (1) on a TRM induced magnetization ($T = 650°C$), specimen H45, and (2) on an NRM, specimen H1-A. Diagram b demonstrates a typical example of saturation magnetization versus temperature.

suggests that heating of the specimens has introduced irreversible magneto-mineralogical changes that affect the remanence properties. The lack of magnetite transitional temperature after heating in air may indicate a nearly complete oxidation to haematite or, alternatively, a "magnetic" disintegration of the multidomain magnetite grains into grains in a different magnetic state (single/pseudo-single domain). The absence of a Morin transition may suggest that haematite does not contribute significantly to the TRM.

Owing to the generally low saturation magnetization J_s–T curves could only be obtained for a small number of specimens. The curves define distinct Curie temperatures (T_c) and they all show the same curve pattern as in Fig. 13b. The almost square-shaped and reversible heating/cooling curves define T_c around 580°C, indicative of nearly pure magnetite. The fairly reversible pattern of J_s–T behaviour suggests that no significant bulk magneto-mineralogical changes have occurred during heat treatment. These results do not of course exclude the presence of haematite.

MAGNETIZATION HISTORY

The thermal demagnetization experiments define two significantly different directional distributions, groups A and B. Both specimen groups are characterized by large proportions of low coercivity/low blocking temperature magnetization. Storage test and directional analysis suggest that a VRM contributes significantly to the NRM. It is likely that the VRM is carried by multi-domain magnetite, which is identified by low temperature experiments.

The A magnetization is frequently associated with blocking temperatures exceeding 600°C, indicative of haematite as a remanence carrier. This suggestion is also supported by the high RCF values, ranging between 1500 and 4000 Oe. Haematite also dominates the opaque mineralogy as observed by reflection microscopy. Haematite may partly be of primary origin, but it is more likely that a substantial part of this mineral formed through disintegration of plagioclase and/or biotite. Thus the A component is most likely associated with magnetic minerals post-dating the granitic emplacement.

The B magnetization has blocking temperatures never exceeding 580°C, suggesting that magnetite is the principal remanence carrier. However, corresponding RCF values for the B component specimens, mainly between 500 and 1200 Oe, may also suggest the presence of haematite, but such relatively high RCF values can also be a feature of single-domain magnetite due to an extreme shape-effect (Stacey and Banerjee, 1974). Direct observations of such grains are not available, but the opaque grains imbedded in plagioclase may represent this mineral phase.

The unsuccessful resolution of the A and B directions by AF-demagnetization suggests that the presumed "primary" B magnetization, residing in high coercivity magnetite phases, has overlapping coercivity-spectra with the suggested "secondary" A magnetization partly carried by haematite.

TABLE III

Overall palaeomagnetic parameters for the two palaeomagnetic groups (A and B) obtained from thermal demagnetization

	N	R	k	α_{95}	D_m	I_m	Pole *
Group A	21	20.3	28.9	6°.0	183°.1	−31.5	48°.9N, 171°.8E $d_p = 3.8$, $d_m = 6.7$
Group B	17	16.5	32.2	6°.0	181°.2	1.5	31°.1N, 174°.9E $d_p = 3.0$, $d_m = 6.0$

* Sampling locality 58°.1N, 3°.7W.

The overall palaeomagnetic properties of the A and B magnetizations (thermal data) are listed in Table III. The palaeomagnetic build-up in the Helmsdale granite is closely similar to results obtained in the Devonian strata of Caithness (Storetvedt et al., 1978; Storetvedt and Carmichael, 1979; Storetvedt and Torsvik, 1983, this volume). When seen in conjunction with the relative polar wander path for Europe the Helmsdale poles support the inferences based on rock magnetism properties, i.e. (1) the B component is the oldest magnetization, most likely impressed at the time the granite cooled, and (2) the A magnetization is of secondary origin and probably related to hydrothermal alterations in Permian–Lower Mesozoic times.

GEOTECTONIC IMPLICATION AND POSSIBLE ASPECTS OF RELATIVE POLAR WANDER

Several hypotheses concerning the tectonic history of the Great Glen Fault differing in age, sense and magnitude of suggested lateral movements, have been proposed (Holgate, 1969; Dewey and Pankhurst, 1970; Garson and Plant, 1972; Brown and Hughes, 1973; Winchester, 1973; Storetvedt, 1974, 1975; Van der Voo and Scotese, 1981).

In a recent paper Van der Voo and Scotese propose a 2000 km sinistral shift along the Fault during the Carboniferous. This is based on a re-examination of Middle–Upper Devonian paleomagnetic data from the Northern Highlands (north of GGF), compared with data south of GGF, assuming a paleolatitude difference of more than 15° for ORS formation now being "juxtaposed". This proposal is based on the assumption that the shallow inclined magnetization that characterizes the Devonian of West Europe does not exist in the Devonian rocks from Northern Highlands. However, this flatlying magnetization is probably represented in the Helmsdale granite by group B. Thus, adopting the view of a negligible relative polar-wander between Upper Silurian–Lower Devonian and Middle Devonian times, the hypothesis of Van der Voo and Scotese must be rejected (c.f. also discussion below).

A shallow magnetization axis has previously been found in the Middle Devonian rocks north of Helmsdale (Storetvedt et al., 1978; Storetvedt and Carmichael, 1979), although with a slightly more westerly declination than the Helmsdale B direction. These results were rejected by Van der Voo and Scotese, but the interpretation of Storetvedt et al. gains support from the presented palaeomagnetic history of the Helmsdale granite as well from the results obtained for the lower Caithness Old Red Sandstone strata (Storetvedt and Torsvik, 1983, this volume).

Figure 14 shows the Helmsdale poles in conjunction with relevant palaeomagnetic pole positions from western Europe. It is apparent that the Helmsdale B pole agrees fairly well with some other Paleozoic palaeomagnetic results from Europe. On the other hand, palaeomagnetic results from for example the Midland Valley volcanics and from the Arrochar and Garabal Hill–Glen Fyne igneous complex (Briden, 1970) suggest pole positions around 5°N, 145°E. One might argue that if these latter data

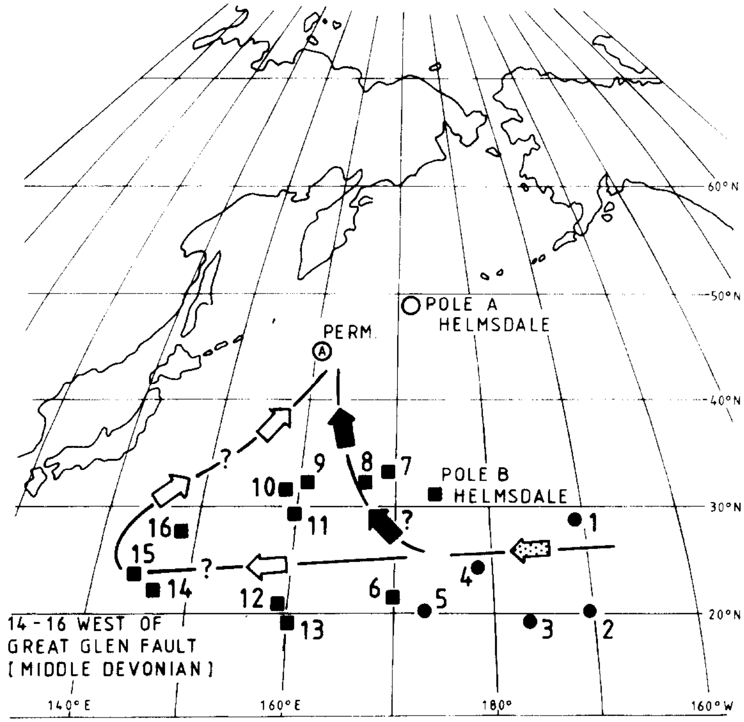

Fig. 14. The Helmsdale poles, *A* and *B*, seen in conjunction with other relevant European palaeomagnetic poles. Circular symbols denote Ordovician poles and square symbols are Upper Silurian–Devonian data. The Permian mean pole is taken from McElhinny (1973). The numbered poles are as follows: *1* = Carmichael and Storetvedt (1981); *2* = Piper (1979); *3* = Piper (1979); *4* = Piper (1978); *5* = Piper (1979); *6* = Lie et al. (1969); *7* = Piper (1978); *8* = Piper (1978); *9* = Van der Voo and Scotese (1981); *10* = Morris et al. (1973); *11* = Van der Voo and Scotese (1981); *12* = Storetvedt et al. (1968); *13* = Storetvedt and Gjellestad (1966); *14* = Storetvedt et al. (1978); *15* = Storetvedt and Carmichael (1979); *16* = Storetvedt and Torsvik (1983, this volume).

correspond to true palaeomagnetic directions from the time the rocks formed, and if the shallow inclination found in the Helmsdale granite represents a primary magnetization, a pronounced post-Upper Silurian relative movement along the GGF may be inferred. However, we question the reliability of these Upper Silurian–Lower Devonian results south of GGF, hence, they have not been included in Fig. 14. AF based data from the Arrochar and Garabal Hill–Glen Fyne igneous complex is unlikely to define single component directions owing to the pronounced elongated distribution of "cleaned" magnetic directions. For the same reason results from the Midland Valley have previously been questioned by Storetvedt (1970).

The presented pole B from the Helmsdale granite is in better agreement with Upper Silurian–Lower Devonian results from Norway as well as with Devonian results from Britain south of GGF. Re-examination of the Foyers granitic complex (a "newer" granite south of GGF; Rb/Sr 415 ± 15 m.y., Hamilton et al., 1980) also yields a pole position in close agreement with the Norwegian result and does not differ significantly from the Helmsdale B pole (Torsvik, in prep.).

Since our B pole represents a rock body situated to the north of the GGF, as opposed to the other results which are from south of the Fault (Fig. 14), it may be concluded that any movement along this fracture zone appears to be less than the resolution of the considered palaeomagnetic data. This conclusion is apparently opposed to the discordance in Devonian palaeomagnetic directions across the GGF which has been interpreted to reflect a few hundred kilometres sinistral movement along this major dislocation (Storetvedt, 1974, 1975). The apparent contradiction between these conclusions may be due to differences in magnetic ages between the Helmsdale B pole and the reference data from south of the GGF, but it may also arise from a certain error in declination of the Helmsdale B group as demonstrated by a certain smeared distribution in the horizontal plan (accomplished by superimposed normal and reverse *B*-axis components). Alternatively, the relative polar wander path for Europe may follow a more westerly trend in Middle–Upper Devonian times (i.e. along the track marked by open arrows in Fig. 14 and not along the path indicated by solid arrows). It must be stressed, however, that in order to apply palaeomagnetic data to the displacement problem of the Great Glen Fault, it is vital to make the comparisons with rocks that have coinciding magnetic ages (which is not necessarily the physical rock age). Further detailed palaeomagnetic studies are therefore necessary.

The A component has a pole position agreeing fairly well with a Permian–early Mesozoic palaeomagnetism for continental Europe. This age of magnetic overprinting is a characteristic feature of the remanent magnetization in the Devonian rocks north of Helmsdale. The A magnetization is probably related to hydrothermal alteration of the granitic body, associated with disintegration of biotite and/or plagioclase. This magnetization may be tied to the tectonic development (normal faulting) of the GGF, during which relative movement induced circulating meteoric water into the granite, causing the observed mineral disintegration and chemical precipitation (Tweedie, 1979).

ACKNOWLEDGEMENT

T.H.T. acknowledges the Norwegian Research Council for Science and the Humanities for financial support. We thank Mr. Ø. Nordgulen for carrying out the microscopic analysis.

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