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Notes

On the origin and stability of remanence and the magnetic fabric of the Torridonian Red Beds, NW Scotland

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Synopsis

Primary (compactional) magnetic fabrics and multicomponent remanences are recognized in the Stoer and Torridon Groups. Low temperature (LT) blocking remanences are randomized around 400–600°C and relate to a post-Torridonian magnetic overprint, possibly of early Mesozoic age. In the Stoer Group (and some Stoer boulders in the basal Torridon Group) LT remanences are partly or fully carried by magnetite (titanomagnetite). High temperature (HT) remanences are characterized by discrete unblocking above 600°C, having a specular haematite remanence carrier. Results of a conglomerate test of some Stoer boulders provides a positive stability test for HT remanences in the Torridon Group, and a convergence of evidence suggests that remanence acquisition of both the Stoer and Torridon Groups was facilitated by both detrital and early diagenetic processes. A fold test of the Stoer boulders (inclination data) indicates that the boulders have preserved a primary HT remanence. Secondary fabric is readily observed in the boulders, hence, HT remanences most likely reside in different grain- or mineral fractions than the bulk susceptibility.

The overall palaeomagnetic data (HT remanences), indicates that the angular unconformity, separating the Stoer and Torridon Groups, represents a considerable period of time. Palaeomagnetic results from the underlying Lewisian basement have traditionally been interpreted in terms of post-orogenic uplift associated with the Laxfordian event (*c.* 1800–1400 Ma). Due to an apparent polar fit between Lewisian and Stoer Group data, we address the question as to the significance of post-Laxfordian magnetic overprinting in the Lewisian Complex.

Introduction

The early Proterozoic Lewisian Complex, NW Scotland (Caledonian Foreland), has been affected by a series of metamorphic events including the Scourian (*c.* 2600 Ma) and Laxfordian (1800–1400 Ma), and locally by post-Laxfordian (*c.* 1100–1000 Ma) cataclasis and reheating (Watson 1975; Moorbath *et al.* 1967; Moorbath and Park 1972).

The Lewisian basement is unconformably covered by almost undeformed red-beds, collectively known as the Torridonian Supergroup. An angular unconformity, believed to represent a considerable time-span, divides this sequence into the Stoer and Torridonian Groups (Stewart 1966, 1969; Moorbath *et al.* 1967;

Scott. J. Geol. **23,** (1), 23–38, 1987

Moorbath 1969; Irving and Runcorn 1957; Stewart and Irving 1974; Smith *et al.* 1983). Radiometric ages (Rb/Sr, whole rock) of 968 and 777 Ma from the Stoer (siltstone) and Torridon (siltstone–shale) Group respectively, are thought to reflect the timing of diagenesis (isotopic homogenization of Sr). Prior to deposition of Cambro–Ordovician marine deposits, the two groups were weakly folded, uplifted and eroded.

This account deals with palaeomagnetic properties of the Torridonian sediments with particular emphasis on the origin and stability of remanence, and of the magnetic fabric. The Stoer Group, which comprises some 2 km of clastic sediments, was sampled from 15 sites covering the Stoer and Achiltibuie regions (Fig. 1). Palaeocurrent reversals in lake deposits suggest a rift controlled origin with active marginal faults (Stewart 1983). A similar origin has also been suggested for the younger Torridon Group, which embraces *c.* 7 km of essentially continental clastics divided into four formations (the Diabaig, Applecross, Aultbea and Cailleach Formations). The angular unconformity separating the Stoer and Torridon Groups is well exposed at Achiltibuie (Fig. 1), where three sites in the basal Diabaig Formation and 4 large boulders derived from the Stoer Group were sampled. The rocks of the Diabaig Formation have a mean dip of *c.* 15°S, while the Stoer Group dips *c.* 20°W. The bedding in the Stoer boulders is well preserved

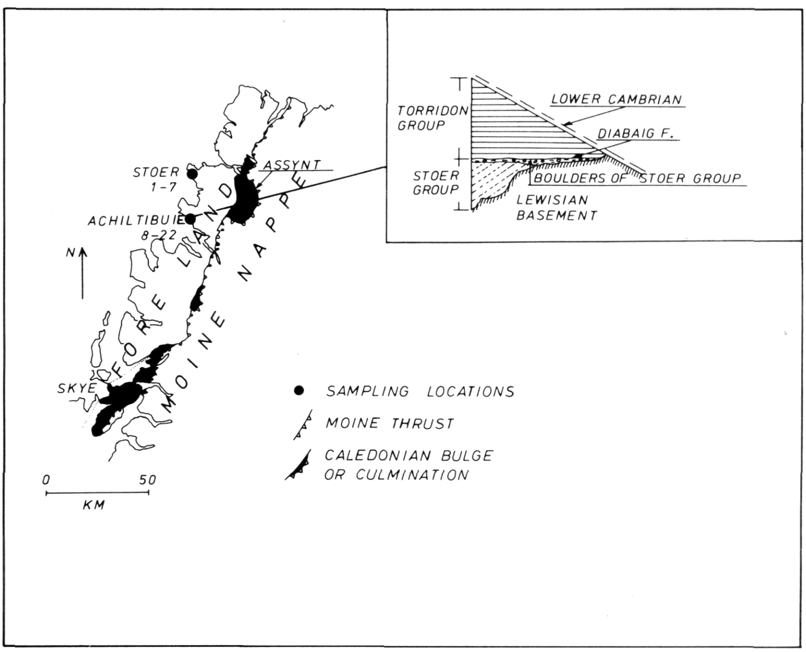

FIG. 1. Sketch map of NW Scotland, Caledonian Foreland (simplified from Johnson 1983). Sampling locations are denoted by solid circles. Inset map: schematic vertical profile redrawn from Stewart and Irving (1974).

and unambigious way-up could be established from sedimentary structures. Hence, the palaeomagnetic stability of both the Torridon and the Stoer Groups was tested by a combination of conglomerate and fold tests.

Magnetomineralogy

Stoer Group specimens, from the Stoer area, are dominated by specular haematite (<40 mu), though small amounts of secondary (?) goethite may be present. Achiltibuie specimens are more coarse-grained, and specular haematite (30–150 mu), martite textures (lamallae 10–15 mu), goethite, magnetite and detrital titanomagnetite showing both low (granulation) and high temperature oxidation features (TM oxidation class II–III; Ade-Hall *et al.* 1971) are recognized. Torridon Group specimens are characterized by specular haematite of slightly

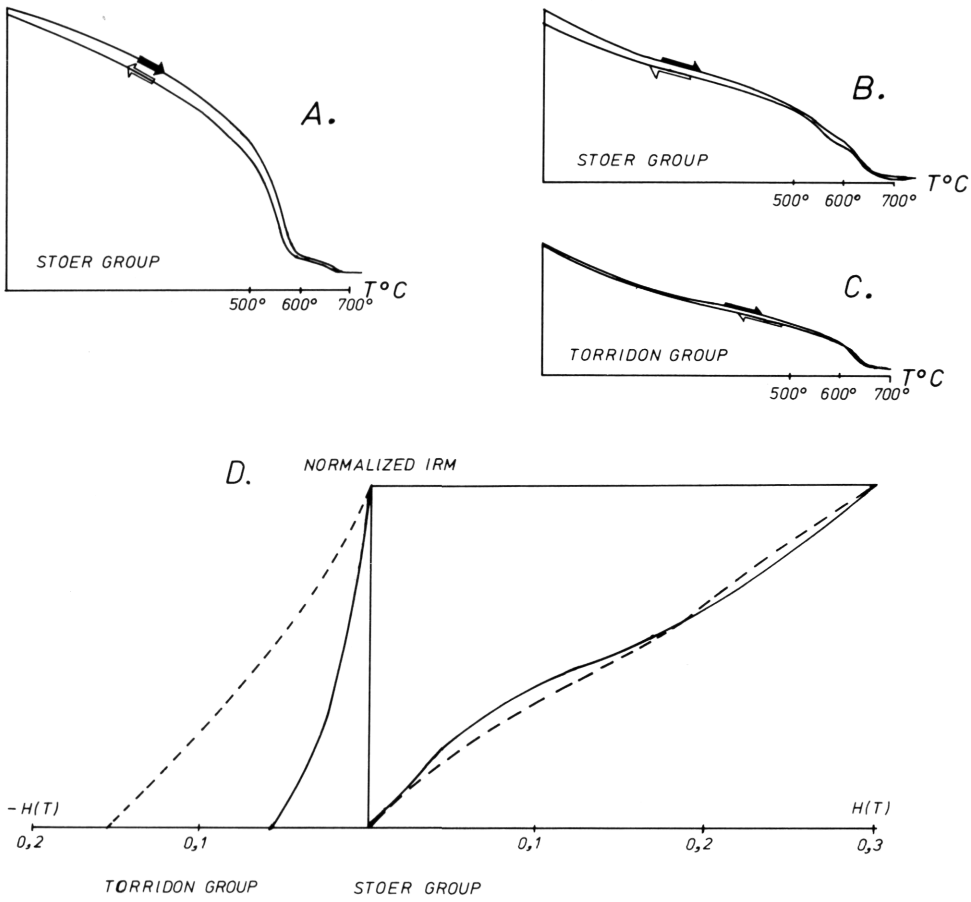

FIG. 2. Thermomagnetic (a, b, c) and IRM acquisition curves (d) for the Stoer and Torridon Groups.

smaller grain size (*c*. 30–80 mu) than the Stoer Group specimens (Achiltibuie). Additionally, both the Stoer and Torridon Group specimens are characterized by haematite staining of specularite grains and non-opaques as well as by interstitial cementing material (pigment).

Thermomagnetic analysis from the Stoer Group sediments (Fig. 2a,b) demonstrates a dominance by haematite, but variable proportions of magnetite (titanium poor titanomagnetite) may be present (Curie temperatures of 680°C and 580°C respectively). A minor reduction in saturation magnetization (and bulk susceptibility) after heating to 700°C is attributed to oxidation of magnetite. On the other hand, specimens from the Torridon Group show reversible heating and cooling curves, having single Curie temperatures of *c*. 680°C, i.e. haematite (Fig. 2c).

Isothermal remanent magnetization (IRM) versus increasing magnetization field (H) also define differences between the two groups; Torridon Group specimens are dominated by high coercivity phases ($H_{max} = 0{\cdot}3$ T), whilst Stoer Group specimens, additionally, show low coercivity peaks below 0·1 T (Fig. 2d) and reduced remanence coercive forces, typically around 500 mT.

THE MAGNETIC FABRIC

Anisotropy of magnetic susceptibility (AMS) was determined on a low-field susceptibility bridge (KLY-1) for a total of 11 sites. The magnetic susceptibility is a symmetric, second order tensor expressed as a triaxial ellipsoid. The orientation of the susceptibility ellipsoid is described by K_{max}, K_{int} and K_{min}, which are the principal axes of susceptibility. The axial ratios P1 (Lineation: K_{max}/K_{int}), P2 (Anisotropy: K_{max}/K_{min}), P3 (Foliation: K_{int}/K_{min}) and E (Eccentricity: P1/P2) are used to describe the shape of the magnetic ellipsoids. The magnetic fabric in undeformed sediments may comprise two elements: 1) a magnetic foliation essentially in the bedding plane due to gravitational forces (and post-depositional compaction), and 2) lineation or preferred grain orientation (either shape or magnetocrystalline origin) depending on the hydrodynamic environment or the influence of the external field (Rees and Woodall 1975).

The Stoer Group sediments and the Stoer boulders are characterized essentially by oblate magnetic ellipsoids (apart from one site in the Stoer area) associated with 4 to 9 percent degree of anisotropy. The Torridon Group yields a lower degree of anisotropy (around 3 percent) and bulk susceptibility, weakly developed ellipticity, giving both prolate and oblate magnetic ellipsoids. Magnetic foliation planes (K_{max}–K_{int}) of the Stoer Group sediments strike almost N–S, dipping *c*. 20°W in agreement with observed bedding planes (Fig. 3a and b). Well-defined lineations due N–S (Stoer area) and W–E/SW–NE (Achilitibuie area) are observed. Bedding orientated magnetic foliations are also a characteristic feature of the Torridon Group (Fig. 3d). On the other hand, the magnetic foliation planes of the Stoer boulders are not parallel to the bedding preserved in the boulders, but are in closer

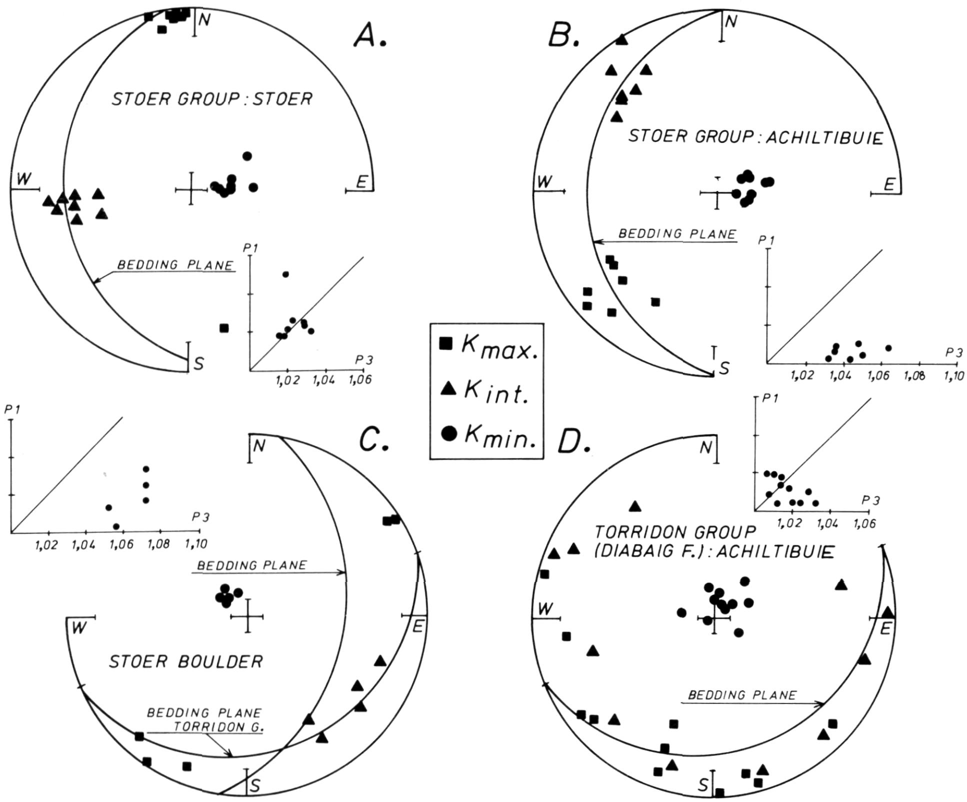

FIG. 3. Measurement of anisotropy of magnetic susceptibility (from individual sites) for the Stoer group (a, b), Stoer Boulder within the Diabaig Fm. (c) and the Torridon Group (d).

agreement with the regional bedding of the Torridon Group (Fig. 3c). This is illustrated in Figure 4(a,b), where the poles to magnetic foliation (K_{min}) are compared with poles to bedding. Notice the close fit within the Stoer and Torridon Group, whilst K_{min} from the Stoer boulders fits the Torridon Group bedding poles better than the original bedding poles in the boulders.

Palaeomagnetic experiments

The directions of natural remanent magnetization (NRM) from the Stoer Group are fairly well grouped in a NW direction and dipping 20–50 degrees below the horizontal plane. NRM intensities are typically in the 10–50 mA/m range. Thermal decay curves (Achiltibuie) are square-shaped, but show systematic intensity reduction (10–30%) in the early stages of demagnetization, followed by major discrete unblocking of remanence at temperatures above 630–650°C (Fig. 5). NRM is composite, and generally associated with removal of NE-northerly

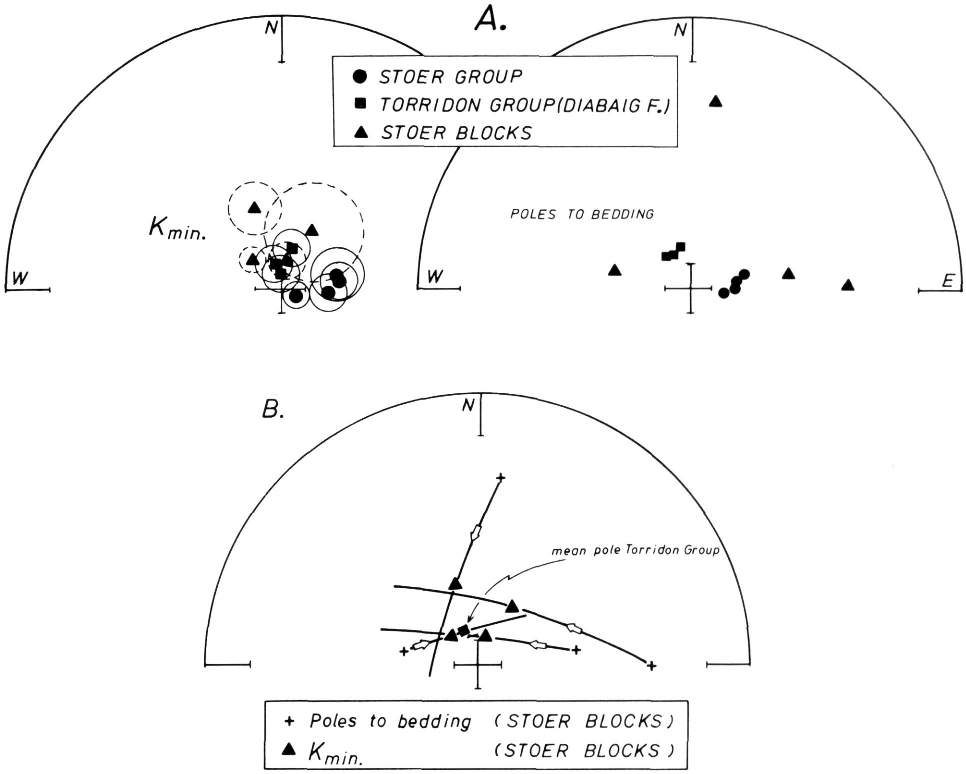

FIG. 4. Comparison of K_{min} and poles to bedding (a, b).

downward pointing magnetizations in the early stages of demagnetization (<600°C) which is superimposed on shallower N-westerly components.

Thermal properties of tested samples from the Stoer area differ from those at Achiltibuie in that the former reveal distributed unblocking (Fig. 5), which may relate to the finer grained texture. Thermal cleaning above 600–630°C was frequently not successfull due to viscous and irregular directional behaviour. A major part of the remanence was still left at these temperatures, but linear segments towards the origin of vector-diagrams do not suggest that other components are present (Fig. 5).

High temperature (HT) components obtained from the Stoer Group form a well-defined directional group of N-westerly and downward dipping magnetizations (Fig. 6). Bedding correction causes shallower inclinations, but the statistical precision parameters (Table 1) are not significantly affected (due to minor differences in bedding between individual sites). Compared with some earlier studies of the Stoer Group (Fig. 6), the present data reveal somewhat shallower inclinations. The investigated sediments, particularly from the Achiltibuie area, reveal composite magnetizations, and blanket cleaning temperatures of 500°C

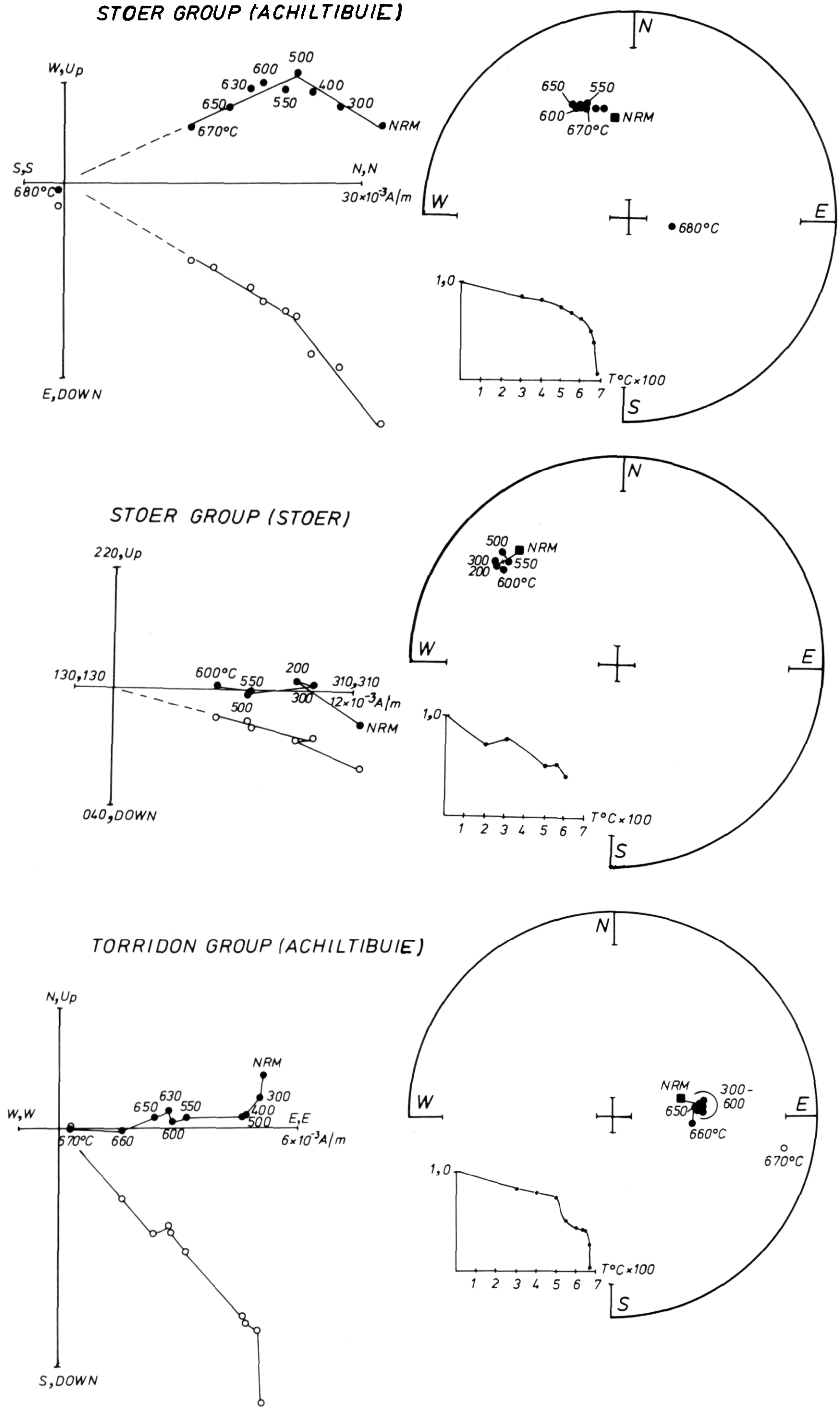

FIG. 5. Examples of thermal demagnetization from the Stoer Group (Achiltibuie), Stoer Group (Stoer) and Torridon Group. In stereoplots open (closed) symbols are upward (downward) pointing magnetizations. In orthogonal vector-diagrams open (closed) symbols represent points in the vertical (horizontal) plane. Note that the Stoer Group (Stoer) specimen example is optimal vector—projected (310, 310).

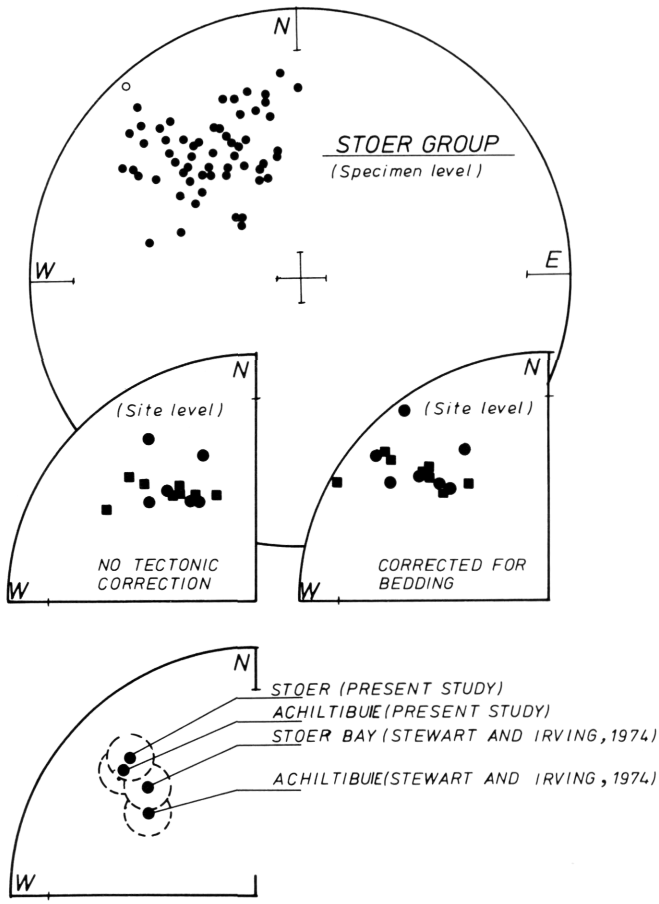

FIG. 6. Distribution of characteristic remanence directions from the Stoer Group at specimen level (no tectonic correction), site level (no tectonic correction & bedding corrected: circles and squares denote Stoer and Achiltibuie region respectively) and comparison of mean palaeomagnetic data from the present study and previous results from the Stoer and Achiltibuie region.

(Stewart and Irving 1974) may not have been sufficient in some instances to isolate the characteristic HT components. This is demonstrated in Figs. 5 and 7a, which show that in the early stages of demagnetization the remanence vectors show systematic movements (10–15 degrees of arc), finally isolating the top-component above 600°C.

Studies of the Torridon Group (Diabaig Fm.) were restricted to 3 sites from Achiltibuie. NRM directions are clearly unlike the Stoer Group, as well as having significantly lower NRM intensity, normally below 10 mA/m. Characteristic HT components differ only slightly from the NRM (Fig. 5), through removal of NE-northerly and steeply or less steeply downward pointing magnetizations. LT

TABLE 1

Overall palaeomagnetic data from the Stoer and Torridon Groups.

Rockgroup, area	D(°)	I(°)	N	k	α_{95}	VGP N	VGP E	dp/dm
Stoer Group:								
Stoer area	uc: 325	+28	7	40·2	8·3	39·5	220·6	5/9
	c: 318	+16	7	42·4	8·1	30·5	225·0	4/8
Achiltibuie	uc: 322	+30	8	30·0	7·9	39·5	224·8	5/8
	c: 315	+17	8	40·4	7·8	29·9	228·4	4/8
Torridon Group:								
Achiltibuie	uc: 090	+69	3	64·4	10·1	42·3	50·1	15/17
(Diabaig Fm.)	c: 118	+59	3	69·4	9·7	20·6	41·2	11/14
LT Components ($T <$ 500–600°C) (Stoer, Torridon Group & Boulders):								
	uc: 030	+52	33⋆	21·1	6·1	57·5	123·0	6/8

D(°) = mean declination; I(°) = mean inclination; N = number of sites (⋆ samples); k = precision parameter (Fisher 1953); α_{95} = 95 percent confidence circle.

(uc and c denotes uncorrected and corrected for bedding respectively).

components are compatible with those from the Stoer Group, and have been randomized at temperatures around 400–500°C. The investigated specimens provide directional results (HT components) in agreement with previous studies (Table 1). As for the Stoer Group, a conventional fold test cannot distinguish between a pre- or post(syn)-folding origin of magnetization.

Stoer boulders: combined conglomerate and fold test

The magneto-mineralogy of some Stoer boulders, within the Diabaig Fm., is broadly similar to that encountered in the Stoer Group. The principal remanence carrier is haematite, which is linked to the discrete unblocking above 630–650°C. Most samples show a two-component structure, associated with removal of NE-northerly and downward dipping magnetizations below 400–500°C. From one boulder, a 3-component magnetization structure can be observed (Fig. 7b):

1) in the NRM-400°C range, a northerly and downward-dipping magnetization was randomized (compatible with LT component in the Stoer and Torridon Groups; cf. Fig. 5,

2) an easterly directed component (? Torridon Group magnetization) is demagnetized in the 400–625°C range, and finally,

3) a shallow, N-easterly magnetization was isolated above 625°C. Although the principal remanence resides in haematite (blocking temperatures above 600°C), it is evident from the thermal decay curves of the Stoer Group and the Stoer boulders, that magnetite (titanomagnetite) contributes to the remanence

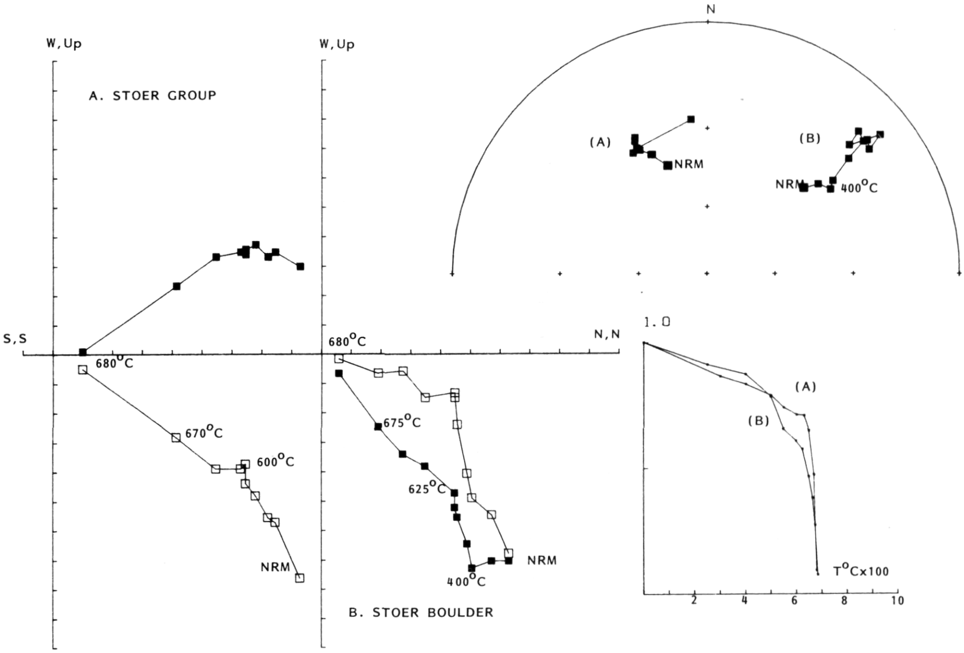

FIG. 7. Examples of thermal demagnetization of a Stoer Group (a) and a Stoer Boulder specimen (b). Conventions as for Figure 5.

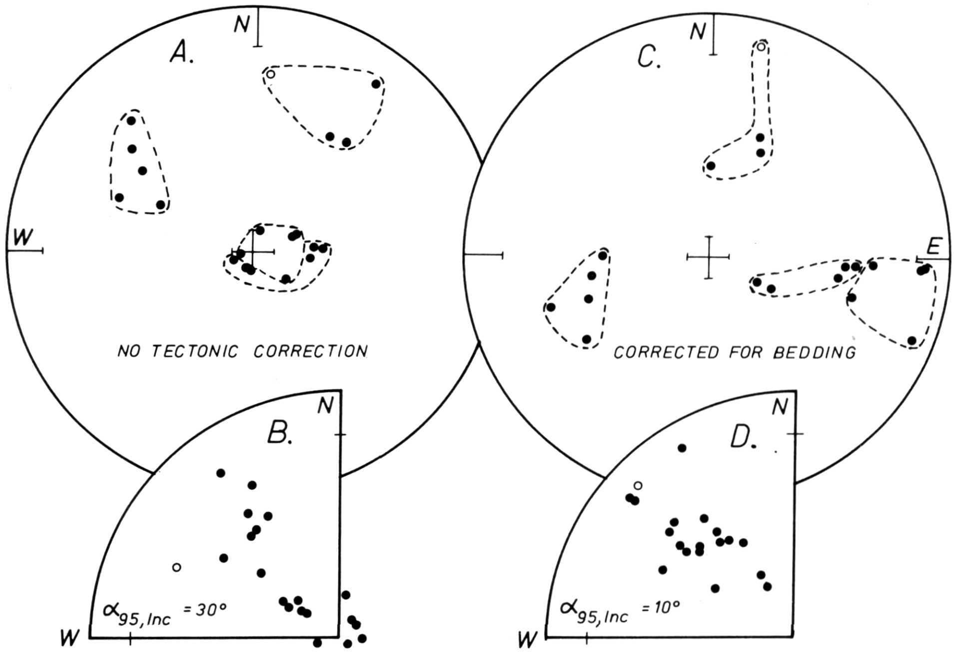

FIG. 8. Comparison of *in situ* and bedding-corrected remanence components from the Stoer Boulders (a, c). In (b, d) remanence components have been rotated into the mean Stoer Group magnetization axis (optional).

properties, and it may have particular significance regarding the LT components (note an intensity plateau on thermal decay curves between 500 and 600°C).

HT components from the Stoer boulders reveal internally consistent magnetizations (Fig. 8 a–d). Two boulders have fairly similar remanence directions, but also similar orientations of bedding. In Figure 7b HT magnetizations have been rotated *vis à vis* the mean Stoer magnetization (optional). Note that the spread in inclination, and Fisher statistics (Fisher 1953) on the inclination data (declination fixed) reveal an α_{95} of 30 degrees. In order to test whether the inclination data of the boulders are compatible with the Stoer Group, boulder-magnetizations have been rotated back to the horizontal plane (according to the bedding planes) succeeded by a rotation into the mean Stoer magnetization (Fig. 7d). A significant decrease in α_{95} from 30 to 10 degrees demonstrates a positive fold-test and the bedding corrected inclination data furthermore makes a reasonably good match with the Stoer Group inclinations (cf. Fig. 6).

Discussion and conclusions

On the origin of remanence and fabric

The NRM of the Stoer and Torridon Group sediments (and boulders) can generally be accounted for in terms of a two component magnetization structure. LT components are typically randomized between 400 and 600°C, and HT components carry more than 70 percent of the total NRM. The pattern of discrete unblocking above 600°C indicates that specular haematite is the principal remanence carrier. HT components from the Stoer and Torridon Group are significantly different (in overall agreement with previous studies), and results from the conglomerate test imply that the principal magnetization of the Stoer Group pre-dates the Torridon Group magnetization. Furthermore, comparison of ***in situ*** and unfolded HT inclination data from the Stoer boulders indicates that the boulders are likely to have retained a "primary" magnetization, compatible with the Stoer Group magnetization.

Bedding orientated magnetic foliation planes and low anisotropy parameters observed from the Stoer and Torridon Group are "typical" of undeformed sediments. Secondary fabrics in the Stoer boulders are indicated by re-orientation of the initial magnetic foliation (bedding-orientated) which produces a compactional fabric inclined to the original bedding plane. Secondary magnetic fabrics and "primary" remanence components suggest that the dominating magnetic susceptibility is carried by a different grain-size or mineral fraction than the remanence. It is tentatively suggested that the secondary fabric resulted from passive grain rotation, which was more effective in the coarse grained fractions.

Acquisition of detrital remanent magnetization (DRM), depends on the alignment of magnetic grains with the external field during deposition, and a

DRM/early diagenetic origin has been claimed for parts of the Stoer Group, due to the observation that disrupted Stoer sediments (caused by disturbance of a volcanic mudflow—Stac Fada Member) show random magnetizations (Irving and Runcorn 1957; Stewart and Irving 1974). Similarly, random magnetizations in some sedimentary slumps in the Torridon Group favours a DRM origin, though other slumps are reported to have a uniform magnetization (Irving 1957) hence indicating a post-depositional DRM (pDRM) origin of remanence (early diagenic), presumably facilitated before final compaction and dewatering of the sediments. Systematic relationship between K_{max} and remanence, which may be taken as a feature of DRM in haematite (Løvlie and Torsvik 1984) has not yet been recognized in the Stoer Group (Torridon Group gave no lineations). On the other hand, the magnetic fabric and remanence may be carried by different grain-fractions; in this case the orientation of the coarse-grained fractions may have been imparted by hydrodynamic forces.

Chemical remanent magnetization (CRM) is generally considered to be of major importance in red beds and is acquired through pigmentation, *in situ* oxidation of detrital magnetite (specularite) and alteration of minerals such as iron bearing silicates and clays (Collinson 1974; Turner 1980; Larson and Walker 1975; Walker *et al.* 1981). Specularite, which may have a detrital and/or chemical origin is the main remanence carrier in the investigated sediments, and pigment (CRM) is probably of minor importance; this is supported by chemical leaching studies (Smith *et al.* 1983). Petrological studies show large variations of oxidation state within a single specimen. Magnetite/titanomagnetite are most likely of depositional origin, but do not contribute substantially to the principal HT remanences. HT components show very good grouping (in particular the Stoer Group), and a purely DRM in specularite tends to involve remanence scatter and directional complexities (hydrodynamic randomizing forces), due to the low magnetic torque acting on haematite grains (unless still-water). It is suggested, in general agreement with previous studies, that remanence acquisition, at least for the Stoer Group, was mainly facilitated by pDRM and CRM processes. CRM implies unknown time of remanence acquisition, but CRM in the Stoer Group must clearly pre-date deposition of the Torridon Group, and is most likely an early diagenetic feature.

LT components, identified in the Stoer and Torridon Group (and Stoer boulders) record a post-Torridonian magnetic overprint. Thermal demagnetization experiments from the Stoer Group indicate minor overlap between LT and HT components, suggesting that LT components were acquired by thermo-viscous processes (TVRM). LT components most likely reflect burial and uplift, and for the Stoer Group (and boulders), this component is partly or fully held by magnetite/titanomagnetite (originally of detrital origin). Demagnetization experiments from the Torridon Group may indicate substantial overlap of LT and HT remanences hence LT remanences may partly have originated by chemical (CRM) or thermo-chemical (TCRM) processes. In the context of British (European) palaeomagnetic data, the relative pole position (N57.5, E123) suggests an early Mesozoic age (?Triassic–Jurassic), but this age is arguable due to problems of differentiating between late Precambrian and Mesozoic pole-positions. Recent/Tertiary and Caledonian magnetic overprints were noticed by Smith *et al.* (1983), but not outlined in detail. A certain Recent/Tertiary overprint (notably the Torridon Group) is likely, but "typical" Caledonian magnetizations have not been identified in the present study.

Palaeomagnetic considerations

A general discussion of palaeomagnetic results from NW Scotland in the context of Proterozoic palaeomagnetism is beyond the scope of the present study, and is dealt with elsewhere (Stewart and Irving 1974; Smith *et al.* 1983; Smith and Piper 1984). Palaeomagnetic directions from the Torridonian rocks (corresponding to our HT components) have been considered to coincide with the Laurentian Apparent Polar Wander (APW) path on the Bullard *et al.* (1965) reconstruction of the North Atlantic continents. Inclination differences between the Stoer and Achiltibuie area and the basal Stoer sediments (main outcrop: Tournaig) have been attributed to depositional (or early diagenetic) age differences (Smith *et al.* 1983), explaining the observed polar migration of Figure 9. Tentatively, the palaeomagnetic data suggest that NW Scotland was confined to northerly palaeolatitudes of 10–20 degrees during deposition of the Stoer Group. During subsequent uplift and erosion, NW Scotland drifted southwards, and the Torridon group sediments were deposited at southerly palaeolatitudes of 30–40 degrees. Thus, the angular unconformity, separating the Stoer and Torridon Group sediments may represent a period equivalent to say some 40 degrees southerly drift of NW Scotland.

Smith *et al.* (1983) argued for a delay of isotopic homogenization compared with remanence ages, but to a first approximation it is reasonable to assume that HT remanences from the Stoer and Torridon Group probably relate to ages around 1000 Ma and 800 Ma, respectively. In the opinion of the present authors, the palaeomagnetic reliability of the underlying Lewisian Complex is less certain, and a review of all available data from the Lewisian Complex has recently been published by Smith and Piper (1982). The data are complicated, and relative pole-positions have been divided into 6 different mean poles (Fig. 9). Smith and Piper argued for a general palaeomagnetic shift from Stoer and southwards towards the Torridon region (poles A2–A5), interpreted in terms of diachronous uplift between 1800 and 1400 Ma (Laxfordian time), in correspondence with the general view of Morgan (1976) and Piper (1979). Comparison of Lewisian (A2–A5) and Stoer Group poles (Fig. 9), show a remarkable polar fit as well as having similar palaeo-field polarity. The correspondance of pole A1 (?B), with the Torridon Group poles is probably a coincidence, since random magnetizations in a

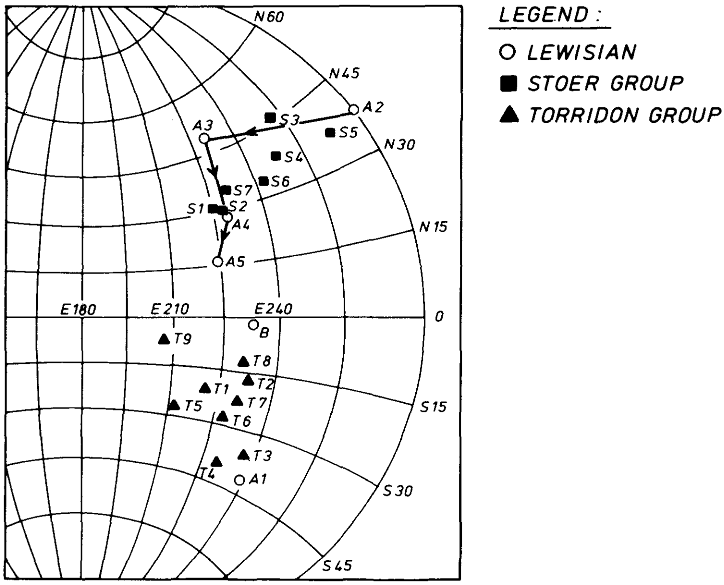

FIG. 9. Virtual geomagnetic poles of the Stoer and Torridon Group along with poles from the Lewisian Complex. Stoer Group poles are denoted S1–S7 and are as follows: S1 = Stoer (present study); S2 = Achiltibuie (present study); S3 = Main Outcrop (Smith *et al.* 1983); S4 = Rubha Reidh (Stewart and Irving 1974); S5 = Enard Bay (combined pole calculated from Smith *et al.* 1983 and Stewart and Irving 1974); S6 = Achiltibuie (Stewart and Irving 1974); S7 = Stoer Bay (Stewart and Irving 1974). The Torridon Group poles are as follows: T1 = Achiltibuie (present study); T2 = Diabaig (Smith *et al.* 1983); T3 = Cape Wrath (Smith *et al.* 1983); T4 = Applecross Fm. (Smith *et al.* 1983); T5 = Coigach area (Smith *et al.* 1983); T6 = Basal Applecross Fm. (Stewart and Irving 1974); T7 = Applecross Fm. (Smith *et al.* 1983); T8 = Aultbea (Smith *et al.* 1983). Lewisian poles: A2 & B = Central Zone (Piper 1979); A1, A2–A5 = Southern Zone (Smith and Piper 1982).

basal Torridon Group conglomerate (Lewisian boulders) show that Lewisian poles predate deposition of the Torridon Group. The Lewisian rocks, however, provide no strong evidence for pre-Stoer Group magnetization ages. A Laxfordian aged origin of remanence also implies that Lewisian poles must be tectonically adjusted for the post-Laxfordian structural history of NW Scotland, which includes three major unconformities, before detailed comparisons with similar aged poles. Furthermore, LT remanences observed in the Stoer and Torridon Group, most likely are present in the Lewisian rocks, unless there are very strong contrasts in the magnetic stability.

Local reheating of post-Laxfordian origin (?Grenville) is indicated by isotopic ages in the southern areas (*c.* 1000–1100), prior to Stoer Group sedimentation (Moorbath *et al.* 1967). On the other hand, if the Lewisian Complex has suffered burial effects and uplift associated with Stoer Group sedimentation, the sedimentary thickness must have been considerably greater than the minimum thickness observed today (*c.* 2 km). Furthermore, uplift and blocking of remanence should coincide or be younger than the youngest Stoer poles (if APW). This is not readily observed from Figure 9, but poles A4 and A5 could very well be a late post-Stoer Group magnetization.

Although the above considerations do not neccessarily invalidate previous models regarding the magnetic signature of the Lewisian Complex, they show clear evidence for a remarkable polar fit of the Lewisian and Stoer Group poles. Hence, we must address the question for future studies as to whether the Lewisian Complex, partly or completely reflects magnetic ages which are significantly younger than the Laxfordian event.

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