PALAEOMAGNETIC STUDIES IN THE SCOTTISH PARATECTONIC CALEDONIDES.

BY

ALLAN TRENCH.

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To

BILL & RHIAN

for everything.

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Allan Trench,

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SYNOPSIS.

Presented in this thesis are three studies which document the palaeomagnetic record of rocks forming constituents of the Scottish paratectonic Caledonides.

The early Arenig Slockenray Formation within the Ballantrae Ophiolite, southwest Scotland, displays a multivectorial natural remanent magnetisation. Two components (S and M) are identified delineated by differing blocking temperature/coercivity spectra. Component (S) is removed following treatment to 200C/10mT and is regarded as of recent viscous origin. Component (M) forms the characteristic formation magnetisation and resides in both magnetite and hematite. Extensive sampling of all exposed lithologies reveals an (in situ) non-Fisherian distribution of the characteristic magnetisation defining an envelope from SE moderate positive to SW shallow negative directions. A negative intra-formation conglomerate test identifies this component as a pervasive overprint.

A second conglomerate test performed on the Benan Conglomerate of Llandeilo age, reveals dispersely directed magnetisations over a stability range equivalent to that of component M. This field test therefore defines a maximum remagnetisation window of 30 million years for the characteristic remanence.

Structurally-corrected site mean results from the Slockenray Formation are also non-Fisherian forming a small circle partial arc centred on a vertical axis (NW moderate positive to SW moderate positive diections). A combined palaeomagnetic fold and fault test suggests that acquisition of component M pre-dates both folding and faulting.

The resulting palaeolatitude of remanence acquisition (28.8°S) implies a tectonic position close to the southern Laurentian margin for the Ballantrae ophiolite in Arenig times.

A palaeomagnetic study of the late Silurian - early Devonian St. Abbs Head outlier, SE Scotland, reveals a multicomponent magnetic remanence structure. Three components of magnetisation are recognised termed (L), (I) & (H) pertaining to 'Low', 'Intermediate' and 'High' unblocking treatments respectively, (L:< 250°C/15mT., I:200-600°C/15-100mT., H:> 600°C/>>100mT).

Component (L) varies with the attitude of sample coring and is considered to represent a Drilling Induced Remanence (DIR). Component (I) fails both palaeomagnetic fold and conglomerate tests and is identified as a late Palaeozoic - early Mesozoic secondary magnetisation (pole position; 317.0°E, 50.9°S, dP=2.2°, dM=3.7°). Component (H) is in agreement with British Siluro-Devonian data <u>after</u> structural correction and is regarded as an original remanence (316.0°E, 29.0°N, dP=16.5°, dM=19.9°). Contrasting tectonic corrections applied to component (H) aid the location of the palaeohorizontal within the volcaniclastic succession.

Demagnetisation studies of the late Silurian 'Lintrathen Porphyry' both at Glenbervie (south of the Highland Boundary Fault, HBF) and at Loch Lintrathen (north of the HBF) reveal a complex component structure. Three components are recognised at Glenbervie termed (R, S & P) unblocking through treatments of <200°C, 200°-450°C and 450°-650°C respectively. Alternating field demagnetisation failed to yield an adequate separation of the magnetisations. Four components are determined at Loch Lintrathen referred to as (R, S, P & D); the first three of which are considered correlative with those revealed at Glenbervie. Component (D), uncovered at only a single site, unblocks at temperatures in excess of 640°C, resides exclusively in hematite, and represents a late Devonian - early Carboniferous overprint.

Component (R) is directed along a present field axis and is considered to be of viscous origin. Component (S) fails a fold test (Acadian deformation) and represents a late Palaeozoic - early Mesozoic overprint (357.9°E, 47.9°S, dP=3.0, dM=5.4). Component (P) passes the fold test and is regarded as a primary magnetisation. Consistent palaeolatitudes (component P) determined from either side of the HBF allow constraint to be placed upon any subsequent movement between the Midland Valley and Grampian Highlands (latitudes, Glenbervie 22.9°S +/- 1.8°., Loch Lintrathen 27.0°S +/- 3.5°).

Comparable demagnetisation structure (excluding component D) and equivalent acquisition of Gyroremanent Magnetisation (GRM) during alternating field treatment favours correlation of the Loch Lintrathen and Glenbervie porphyries.

A compilation of data presented in this thesis with published work allows construction of apparent polar wander paths for the Grampian Highlands, Midland Valley and Southern Uplands tectonostratigraphic terranes. These suggest that geological and geophysical incompatability between blocks results from predominantly palaeolongitudinal movements prior to late Silurian time. Additionally, a common late Silurian - early Devonian 'corner' in each path suggests the terranes to have docked (to within the errors of the determinations) by this time.

THESIS STRUCTURE.

In **Chapter 1**, the reader is guided in the basic principles of palaeomagnetism together with the methodology used in the completion of this research work. **Chapter 2** then serves as an introduction to the concept of terrane geology and its recent application within the British sector of the Caledonian Belt.

A thorough review of available British Ordovician data is made in **Chapter** 3 as a precursor to description of palaeomagnetic studies within the Ballantrae Ophiolite, southwest Scotland (**Chapter 4**). Similarly, Silurian and Devonian results are critically appraised in **Chapter 5** and subsequently followed by studies of the Old Red Sandstone St. Abbs Head outlier, southeast Scotland (**Chapter 6**) and from the 'Lintrathen Porphyry' near the Highland Border (**Chapter 7**).

A compilation of thesis results with previously published data allows the construction of Apparent Polar Wander Paths (APWP's) for the Grampian Highlands, Midland Valley and Southern Uplands tectonostratigraphic terranes (**Chapter** 8); the tectonic implications of these are then described.

CHAPTER 1: PALAEOMAGNETIC PRINCIPLES & METHODS.

1.1 THE ATOMIC BASIS OF MAGNETISM.

Electron spin about its own axis and in orbiting an atomic nucleus leads to the generation of a magnetic field. Where electrons are paired and have opposing spin directions within atomic orbitals, their resulting magnetic dipoles will cancel. For substances containing 'free' or unpaired electrons however, all the orbital magnetic fields are not self cancelling.

The introduction of an external magnetic field will cause interaction with the 'atomic scale' field. In a substance containing no free electrons, the orbitals realign creating a magnetic moment in opposition to the applied field which is then lost with external field removal. Behaviour of this type is termed diamagnetic. For a substance containing free electrons however, their spins become rotated so as to produce a moment parallel in direction to an applied field. This behaviour is referred to as paramagnetic. Diamagnetic and paramagnetic effects are generally weak and as they do not result in a permanent magnetisation, are geologically unimportant.

A few materials contain electrons which can be coupled either directly or via interstitial anions between atoms. If the potential energy for coupling is minimised with dipole moments in both parallel and additive alignment, then a strong spontaneous magnetisation results. This is termed ferromagnetic behaviour with the resulting magnetisation being retained even following removal of an applied field.

It is the retention of 'ancient' external fields by ferromagnetic materials that forms one of the cornerstones of palaeomagnetic study. In geological materials, dipoles may align either parallel, anti-parallel or oblique to an external field. Variations in the ferromagnetic behaviour can therefore result termed ferromagnetic (*sensu strictu*), ferrimagnetic, antiferromagnetic and canted antiferromagnetic (see Piper, 1987, p.10-11 for explanations).

1.2 THE DOMAIN THEORY OF MAGNETISATION.

The directional alignment of magnetic dipoles within a ferromagnetic substance is controlled by several factors. For a given structure there will be certain 'easy' magnetisation directions within the crystalline solid along which the dipoles will tend to align. Alignment along these directions reduces the magnetocrystalline energy of the substance. Taking the simplest case of a singular dipole orientation, this results in separate north and south poles occurring at the opposite extremeties of the crystal. A situation of this type is opposed by the magnetostatic attraction of the opposite poles however.

In resolving these opposing energies, magnetic domains are formed in the magnetic material within which dipoles are uniformly directed but between which magnetisation directions differ. The interfaces between domains are known as Bloch or domain walls and consist of gradually canted over atomic dipoles. (Magnetite domain walls are approximately 10 - 100nm in thickness). Magnetic grains which contain several domains are termed multidomain (MD). Grains that are too small to form several domains are single domain particles (SD). In grains containing only a few domains, domain wall movement may be restricted by either impurities, dislocations or the size and shape of the host grain. These particles are termed pseudo-single domain (PSD).

In a null field situation, the magnetic domains tend to form closure patterns (adjacent north and south poles) so minimising the magnetostatic energy. With the application of an external field, magnetic domains favourably oriented to this field will grow at the expense of others not so oriented by the unrolling of domain walls. For low fields these effects are reversable but with higher fields energy barriers are such as to prevent a complete return to the initial domain state on removal of the field. An isothermal remanence (IRM) has then been imparted to the material.

When all magnetic domains have unrolled and single domain dipoles rotated into alignment with the increasing applied external field, the ferromagnetic material reaches its saturation magnetisation. On removal of the saturation field a maximum isothermal remanence remains. The magnitude of an opposing field required to reduce this IRM to zero is the maximum coercivity of the material. These concepts are illustrated on a hysteresis loop (acquired magnetisation versus applied field) in Figure 1.1 (after Collinson, 1983).

1.3 MAGNETISATION ACQUISITION.

Increasing temperature relates to an increase in the thermal agitation of constituent atoms and an expansion of the crystalline lattice. Both these effects oppose the ferromagnetic coupling of atoms such that for a critical temperature, electron coupling and therefore ferromagnetism can no longer occur. The spontaneous magnetisation of the material then reduces to zero at what is known as the Curie point or temperature.

For a given temperature below the Curie point, the atomic thermal vibration will allow the magnetisation of certain highly agitated grains to move through the unrolling of domain walls. These will then align along low energy 'easy' magnetisation directions which, in the presence of an external field, will lead to the slow acquisition of an isothermal or viscous remanence (VRM). In the absence of an external field, domains will form closure patterns leading to a reduction in intensity of any existing remanence.

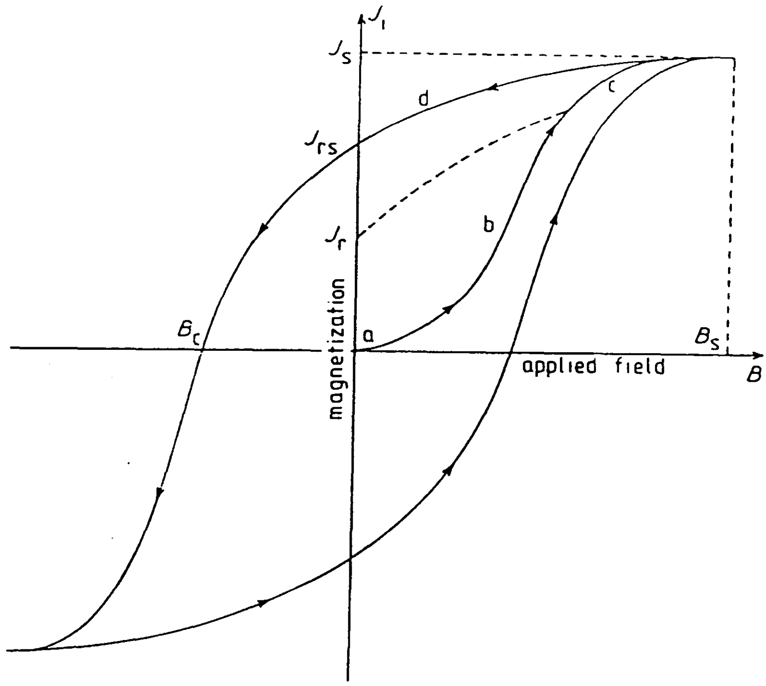


FIGURE 1.1: Acquired magnetisation (Ji) versus applied field (B)hysteresis loop.

With initial application and increase of an external field, the induced magnetisation increases linearly caused by reversible domain wall movement (curve segment a). Irreversible wall movement then takes place with domains aligned close to B growing preferentially (curve segment b). Finally, domain rotation (c) occurs and a saturation magnetisation (Js) at a saturating field (Bs) is reached. On reduction of B the curve follows path (d) to ultimately leave a saturation IRM (Jrs) or lower IRM (Jr) if saturation was not reached. With reversal of the applied field (-B), the IRM is reduced to zero at a value of B known as the coercive force (Bc).

For a single particle, the time for its magnetisation to relax to its thermal equilibrium value is termed the relaxation time (τ). In the absence of external forces this is given by :

(from Tarling, 1983).

$$\frac{1}{\tau} = 2f \ \exp(- \ VMsHc \ / \ 2kT)$$

where **f** is a frequency factor, **Ms** is the spontaneous magnetisation(Js)
Hc is the field required to reverse the direction of magnetisation along the 'easy' direction at absolute zero (coercivity term).
V is the volume, **k** is the Boltzmann constant, **T** is absolute temperature.

Accepting that for a given material, f, Ms, and Hc are approximately constant, this importantly implies the relaxation time to strongly depend on both grain volume and temperature (relaxation time being proportional to the log V/T). As a result, very small particles have extremely short relaxation times and effectively behave in a paramagnetic fashion but with ferromagnetic magnetisation intensities. This behaviour is termed superparamagnetic there being a critical volume above which the grain becomes single domain (SD) and the remanence effectively 'blocked'.

The concept of critical volume is important in palaeomagnetic work as chemical growth exceeding the superparamagnetic to SD volume will impart a stable remanence (e.g. the *in situ* post depositional growth of hematite in red beds). A magnetisation acquired in this manner is referred to as a chemical remanent manetisation (CRM).

Similarly for a given grain, there is a critical temperature or blocking temperature below which thermal agitation is insufficient to maintain superparamagnetic behaviour and ferromagnetic behaviour ensues. Further cooling below the blocking temperature is accompanied by increasing relaxation time to geological time spans. A 'cooling' remanence acquired in this manner is called a thermo-remanent magnetisation (TRM).

1.3.1 DEPOSITIONAL REMANENT MAGNETISATION.

The erosion and deposition of rock particles initially carrying a TRM or CRM may give rise to a further remanence type. During the settling of such magnetised particles within the earth's field, they are able to rotate their remanence into alignment with the external field. With subsequent preservation to form sedimentary rocks, the retention of this depositional remanence (DRM) may occur. As might be expected, complications to this apparent simplistic mechanism abound. King (1955), using experimental analogues, found that a systematic shallowing of a magnetite held remanence from the applied field or inclination error occurred. This he explained by the preferential alignment of discoid shaped particles parallel to the bedding orientation. Tauxe & Kent (1984) observe similar inclination errors using hematite redeposition.

Specific studies of red bed palaeomagnetism show that remanence acquisition can vary in these rocks from DRM (Elston & Purucker, 1979) through post-depositional DRM (PDDRM, Irving & Major, 1964) to CRM (Walker *et al.* 1981). For palaeotectonic purposes, preservation of a DRM may complicate interpretation given the possibility that inclination or bedding errors may occur.

1.4 DEMAGNETISATION METHODS.

1.4.1 THERMAL TREATMENT.

The progressive stepwise thermal demagnetisation technique applied in the laboratory 'cleaning' of palaeomagnetic samples effectively reverses the mechanism of TRM acquisition. Due to the varying magnetic grain sizes present in a given rock sample, a spectrum of blocking temperatures exists imparted during the natural cooling of an igneous rock. The complete TRM of the sample then represents the sum of remanences acquired over a range of blocking temperatures. For this reason, rocks are prone to partial thermal remagnetisation (PTRM) if they subsequently become heated to values within the blocking temperature spectrum but below the Curie point.

We have noted (1.3) that the relaxation time for a given magnetic grain is strongly temperature dependent. Therefore, the heating of a variable grain assemblage will reduce the relaxation time of some grains from geological time spans to around a few minutes. In the absence of an ambient field, these grains unblock and are prevented from acquiring a new PTRM. By stepwise increase of temperature and subsequent measurement therefore, geologically imparted PTRM and original TRM components of magnetisation might be separated for example.

The application of stepwise thermal demagnetisation in the studies recounted in this thesis proved very successful. The method was used extensively due to the obvious occurrence of hematite (unsuitable for alternating field treatment) notably in the Old Red Sandstones and volcanics at St. Abbs Head (Chapter 6).

1.4.2 ALTERNATING FIELD TREATMENT.

The variable grain size and shape distribution of magnetic minerals in naturally occurring samples gives rise to a similarly variable distribution or spectrum of coercive forces. This fact is utilised in the stepwise alternating field (AF) demagnetisation of samples which cycles the sample through hysteresis loops of gradually decreasing amplitude from an initial field setting, (Bi). In the stepwise technique the value of (Bi) is increased from one treatment to the next thus affecting (randomising) particles of sequentially higher coercive force.

The behaviour of SD and MD particles during AF demagnetisation is somewhat different. SD grains with a coercive force less than (Bi) will 'follow' the alternating field direction until the external field drops below the coercive force leaving the SD moments randomised in the sample. MD grains on the other hand will demagnetise to form 'closed' domain patterns which, in the absence of an external field, have no magnetic moment. Imperfect MD and PSD grains may retain a residual moment which, like the SD grains is random throughout the sample.

In practice, AF demagnetisation is usually predominantly used in the treatment of samples containing magnetite and titanomagnetite remanences. The strong crystalline anisotropy of hematite produces a coercivity well in excess of presently attainable 'clean' peak fields. Within the present work, AF demagnetisation has been performed on samples from each study area with varying success. For rocks of the Ballantrae Ophiolite (Chapter 4), it proved useful both in distinguishing magnetisation components and allowing comparisons to be made with previous studies. In the palaeomagnetic study of St. Abbs Head (Chapter 6), the technique proved of limited use due to the prevalence of hematite as a remanence carrier even within the volcanics.

The problems of the AF method centre on the acquisition of spurious magnetisations particularly with treatment to higher fields (>40 mT). The presence of minor even harmonics within the sinusoidal waveform may expose the sample to a residual direct field (Collinson, 1983, p.312) and subsequently lead to the acquisition of an anhysteretic remanence (ARM). A similar problem will result from the ineffective magnetic shielding of the sample.

A further disturbing remanence may have its origins in the magnetic anisotropy of the sample grain assemblage. This is known as gyroremanent magnetisation (GRM) which is directed perpendicular to both the easy magnetisation axis of the sample and the AF demagnetisation axis (Stephenson, 1981., Roperch & Taylor, 1986). The effects of this latter 'spurious' magnetisation can be removed using a multiple demagnetisation procedure (Dankers & Zijderveld, 1981). Their procedure is also capable of removing ARM effects if repeated with the sample axes reversed and subsequently averaged (7.6).

1.5 ASSUMPTIONS OF THE PALAEOMAGNETIC METHOD.

An important assumption in palaeomagnetic studies is that sampled lithologies accurately retain a record of a past orientation of the earth's magnetic field (1.1). This is due to the inclusion in the rock of a mineral fraction exhibiting a form of ferromagnetic behaviour.

For palaeomagnetic studies to be of use for palaeotectonic purposes however, the orientation of the field itself must be shown to vary in a systematic fashion with respect to the geographic poles both presently and for previous periods of geological time.

At present, approximately 90% of the earth's field can be modelled as that resulting from a geocentric magnetic dipole inclined at some 11.5° to the axis of rotation. This is termed the dipole field with the 'non-dipole' field accounting the remaining 10%. Both historic and archaeomagnetic records indicate changes in the orientation of the magnetic field over periods of hundreds to thousands of years. These changes are referred to as secular variations and are thought to follow an approximately cyclic pattern; (as such they will average out given a sufficient time sampling of the field).

When combined with palaeomagnetic observations made on rocks of the last few million years (e.g. Opdyke and Henry, 1969), the collective data conform to a model in which the time averaged palaeo-field approximates that of an axial geocentric dipole. An influence of long term non-dipole effects has been recognised however (e.g. Coupland & Van der Voo, 1980., Livermore *et al.* 1983) which may result in errors of a few degrees in estimating a pole.

In the geocentric axial dipole model, the field at the geographic poles is directed vertically downward (upward) for north (south) poles respectively. Similarly, the field at the geographic equator is directed horizontally. It is important in palaeomagnetic work to demonstrate that a sufficient time averaging of palaeosecular variation has occurred. In practise, the observation of polarity reversals within a given stratigraphic record satisfies this requirement. The axial geocentric dipole assumption allows the relation of field inclination to latitudinal position through the following relationship:

$$\tan I = 2 \tan \lambda$$

where I is the field inclination

& λ is the site latitude.

1.6 INSTRUMENTATION & LABORATORY PROCEDURE.

In accordance with presently accepted standards concerning laboratory cleaning, all samples of the reported studies have undergone stepwise demagnetisation by either thermal, stationary AF or combination (thermal & AF) demagnetisation. In several cases, due to observed complexities in component structure, this led to more than twenty demagnetisations being performed on particular samples.

1.6.1 SPINNER MAGNETOMETER.

A complete results fluxgate magnetometer (Molyneux, 1971) was used for measurement of both NRM and ensuing demagnetisation steps. The magnetometer at Glasgow is interfaced with a BBC microcomputer from which data files can subsequently be transferred to a VAX minicomputer for data processing purposes. Generally the 'short-spin' (6 second) facility was used in the measurement of samples unless the total moment dropped below approximately 1mA/m when the 'long-spin' (24 second) mode was employed. Better precision was sometimes observed using the latter spin mode for low intensites. The earth's field is attenuated at the 'mouth' of the spinner using a Helmholtz coil arrangement (diameter 65 cms). This precludes VRM acquisition by the sample upon reorientation during the 6-spin measurement procedure

Following each demagnetisation step, a computer drawn orthogonal projection allowed the choice of an appropriate further treatment.

1.6.2 'SINGLE THERMOCOUPLE' THERMAL DEMAGNETISER. (Glasgow University built, 1985-6).

The 'single thermocouple' (ST) thermal demagnetiser is capable of holding a maximum of eight core samples during one heating/cooling cycle. The demagnetiser is algorithm controlled by a BBC microcomputer receiving input from a chromal-constantan thermocouple initially situated at the centre of the sample array. With experience, the samples were arranged in a 5-thermocouple-3 formation to minimise the thermal gradient effects within the oven (more heat being lost from the 'open' end of the heating tube). No actual measurement of the gradient was attempted but it is approximated at 20-30°C from comparison of sample data from within a single site along the array. The oven of the ST demagnetiser is housed within four Mu-Metal shields for earth field attenuation. Residual fields are less than 4 nT.

1.6.3 'TRIPLE THERMOCOUPLE' THERMAL DEMAGNETISER.
(Glasgow University built, 1986).

The 'triple thermocouple' (TT) demagnetiser holds a maximum of ten core samples during a single treatment cycle. The demagnetiser is again interfaced with a BBC microcomputer operating a control algorithm receiving output from three thermocouples. These are positioned at both the ends and at the centre of the core sample array. The algorithm compensates observed thermal gradients within the oven during the heating cycle by varying the time over which three independent heating elements are powered.

For elevated temperatures (approx.>400°C), consistency to one or two degrees celcius is maintained over the sample array. This allows the accurate determination of unblocking temperatures particularly for thermally discrete samples. At lower temperatures, any residual thermal gradient is interpolated so that sample temperatures will again be correct to +/- 1 or 2°C. A similar four Mu-metal shield set up as for the ST demagnetiser attenuates the earth's field. Residual fields are again estimated at less than 4nT.

1.6.4 ALTERNATING FIELD DEMAGNETISER.
(Glasgow University built, 1986).

The AF demagnetiser operates using a stationary three axis demagnetising procedure. The sole noid is housed within two Mu-metal shields for ambient field attenuation to less than 15nT. The demagnetiser is interfaced with a BBC microcomputer which provides a digitally generated ramp multiplied by a pure 186Hz sine wave. The signal is then sent through an 8 pole Chebychev filter to attenuate harmonics. Peak demagnetising fields are predetermined to 0.1mT with ramp times to and from this peak setting being adjustable.

CHAPTER 1 : REFERENCES.

Collinson, D.W. 1983. *Methods in Palaeomagnetism and Rock Magnetism.* Chapman & Hall, London, 503pp.

Coupland, D.H. and Van der Voo, R. 1980. Long-term nondipole components in the geomagnetic field during the last 130 M.Y. *Journal of Geophysical Research,* 85, 3529-3548.

Dankers, P.H.M. and Zijderveld, J.D.A. 1981. Alternating field demagnetisation of rocks, and the problem of gyromagnetic remanence. *Earth & Planetary Science Letters,* 53, 89-92.

Elston, D.P. and Purucker, M.E. 1979. Detrital magnetization in red beds of the Moenkopi Formation (Triassic), Gray Mountain, Arizona. *Journal of Geophysical Research,* 84, 1653-1665.

Irving, E. and Major, A. 1964. Post-depositional DRM in a synthetic sediment. *Sedimentology,* 3, 135-143.

King, R.F. 1955. The remanent magnetism of artificially deposited sediments. *Mon. Not. Royal Astronomical Society., Geophysical Supplement,* 7, 115-134.

Livermore, R.A., Vine, F.J. and Smith, A.G. 1983. Plate motions and the geomagnetic field - 1. Quaternary and late Tertiary. *Geophysical Journal of the Royal Astronomical Society,* 73, 153-171.

Molyneux, L. 1971. A complete results magnetometer for measuring the remanent magnetisation of rocks. *Geophysical Journal of the Royal Astronomical Society ,* 24, 429-434.

Opdyke, N.D. and Henry, K.W. 1969. A test of the dipole hypothesis. *Earth & Planetary Science Letters,* 6, 139-161.

Piper, J.D.A. 1987. *Palaeomagnetism and the Continental Crust.* Open University Press, Milton Keynes. 434pp.

Roperch, P. and Taylor, G.K. 1986. The importance of gyromagnetic remanence in alternating field demagnetization. Some new data and experiments on G.R.M. and R.R.M. *Geophysical Journal of the Royal Astronomical Society,* 87, 949-965.

Stephenson, A. 1981. Gyroremanent magnetization in in a weakly anisotropy rock sample. *Physics of the Earth & Planetary Interiors,* 25, 163-166.

Tarling, D.H. 1983. *Palaeomagnetism, Principles and Applications in Geology, Geophysics and Archaeology,* Chapman & Hall, London, 379pp.

Tauxe, L. and Kent, D.V. 1984. Properties of a detrital remanence carried by haematite from study of modern river deposits and laboratory redeposition experiments. *Geophysical Journal of the Royal Astronomical Society,* 77, 543-561.

Walker, T.R., Larson, E.E. and Hoblitt, R.P. 1981. The nature and origin of hematite in the Moenkopi Formation (Triassic), Colorado Plateau: a contribution to the origin of magnetism in red beds. *Journal of Geophysical Research,* 86, 317-333.

CHAPTER 2 : THE TERRANE CONCEPT AS APPLIED TO THE BRITISH CALEDONIDES.

2.1 INTRODUCTION.

Tectonostratigraphic terranes are defined as fault bounded geological entities of regional extent, each having a distinct geological history from neighbouring terranes (Howell *et al.* 1985). The emergence of the terrane concept represents one of the major advances in the earth sciences since the advent of the plate tectonic paradigm in the late 1960's.

Terrane theory took shape during the 1970's following detailed work by the United States Geological Survey aimed at tracing the geological history of Alaska. Their detailed structural, sedimentological and metamorphic records for given areas were found to have much attenuated regional application and hence tectonostratigraphic zones or terranes each characterised by a unique history were recognised.

Since this early work, a traceable evolution of the growth of Western North America has been documented integrating the geological disciplines of palaeomagnetism, sedimentary provenence and faunal provinciality. Current understanding as to the evolution of the region has been summarised by Debiche et al. (1987).

The application of terrane theory to ancient orogenic systems has since taken place and found considerable support. The recognition of terranes within the British sector of the Caledonian - Appalachian belt has gained momentum throughout the eighties following an initial synthesis by Dewey (1982). Present research efforts are being directed at elucidation of the identity, origins and amalgamation history of constituent terranes within Palaeozoic Britain.

2.2 BRITISH PALAEOZOIC TERRANES.

Before outlining the present consensus relating to the identification of British Palaeozoic terranes, it is useful to document the history of research which led to the recognition of the former (Iapetus) ocean which lay between northern and southern Britain.

The initial suggestion was put forward by Wilson (1966) who advanced the 'Wilson Cycle' concept in which an ocean basin first opens and then subsequently closes. Dewey (1969) then invoked a model of ocean floor spreading with the formation of ocean-continent subduction zones to explain the observed pattern of Caledonian volcanism, sedimentation and plutonism. This proved to be the forerunner to several plate tectonic schemes for the British Caledonides (Figure 2.1., Anderton *et al.* 1979). A common feature of these is both their representation in terms of schematic 'across strike' sections and the ubiquitous preservation of all their constituent palaeo-tectonic elements.

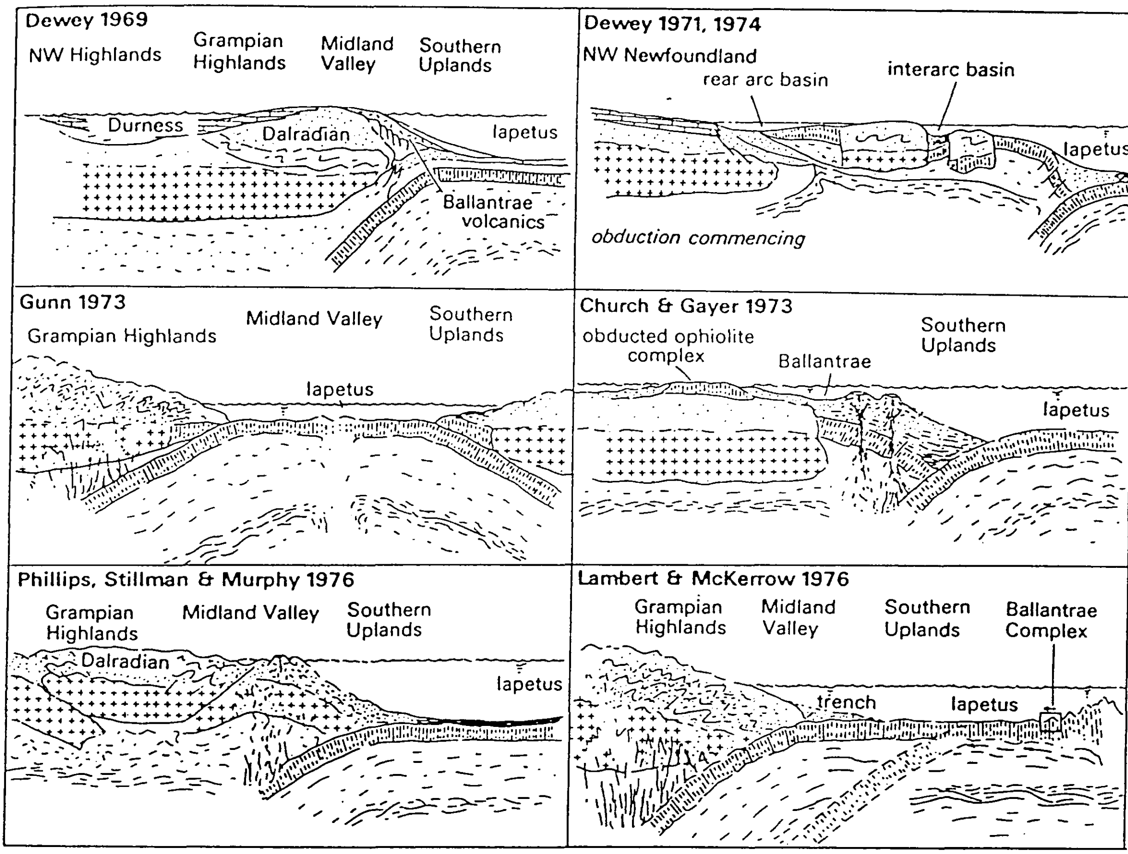


FIGURE 2.1: Early hypotheses relating to the evolution of the Southern Laurentian margin in Ordovician times (after Anderton *et al.* 1979).

Evidence on which these interpretations were based came from three main sources listed by Anderton *et al.* (1979) as follows:-

i) the presence of ophiolites as remnants of consumed ocean floor. (e.g Ballantrae Complex, see Chapter 4).
ii) the presence of features related to subduction zones. e.g. trench sediments, volcanic arcs.
iii) evidence of the former separation of continental plates. i.e. palaeomagnetism, faunal provinces. (Palaeomagnetic reviews form Chapters 3 & 5).

The accumulation of this evidence subsequently led to the widespread acceptance of the physical reality of Iapetus in some shape or form. The ancient suture marking the closure of the ocean basin is believed to lie along the Solway Line (Moseley, 1977) between the English Lake District and Southern Uplands of Scotland.

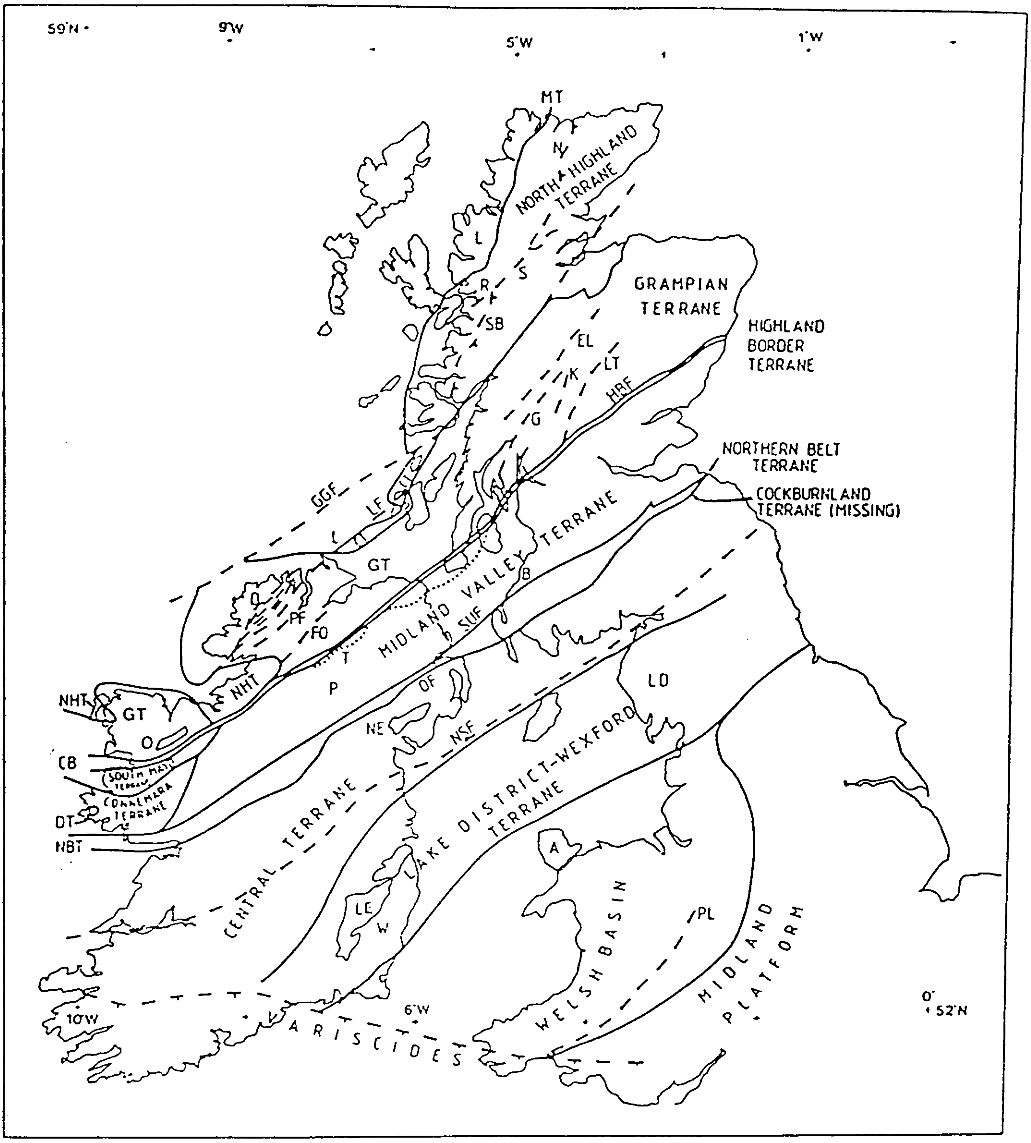
Recognition of diverse terrane assemblages within the British sector of the Caledonides led to the replacement of 'across strike' tectonic models based on orthogonal convergence (e.g. Dewey, 1969., Figure 2.1) with more mobilistic models incorporating the probability of strike slip movements parallel to the palaeo-continental margin (e.g. Bluck, 1984, 1985, Hutton, 1987). The realisation that major along-strike movements may have occurred during the assembly of the terrane collage adds considerable severity to the problem of establishing former relationships between presently juxtaposed blocks.

A Caledonian terrane map of the British Isles (Figure 2.2., Hutton, 1987) summarises presently recognised tectonostratigraphic divisions. A detailed interpretation of the Scottish sector is illustrated both in terrane map (a) and flow diagram (b) form in Figure 2.3. (courtesy., B.J.Bluck).

During the closure of an ocean basin such as Iapetus, it would be expected that some component of oblique slip movement be present. This will necessarily result from any converging plate configuration in which the opposing slip vectors depart from pure anti-parallelism. Debate therefore surrounds the problem of imaging this 'strike parallel' movement and estimating its relative importance.

The first suggestion of relative oblique movement during the closure of Iapetus was made by Phillips, Stillman & Murphy (1976). These authors envisaged about 1270 kms of late Ordovician to Devonian dextral displacement along the Iapetus suture generating 570 kms of foreland convergence in the East Greenland - Scandinavian Caledonides. Evidence supporting this model hinged on the diachronous ending of subduction related volcanism and plutonism observed across the orogen.

In subsequent studies, abundant evidence has emerged which supports sinistral



Caledonian terrane Map for the British Isles. Heavy lines = terrane boundaries. Dashed lines = other Caledonian faults cited in text. Dotted lines along Highland Boundary Fault = extension of Grampian Terrane south of end-Silurian/early Devonian HBF. Boundaries in the North Channel are based on Evans *et al.* (1980) and Institute of Geological Sciences (1983). Terrane abbreviations: CT = Colonsay Terrane; DT = Delaney Terrane; GT = Grampian Terrane; NBT = Northern Belt Terrane; NHT = North Highlands Terrane. Fault abbreviations: D = Donegal Shear Zone; EL = Ericht-Laidon Fault; FO = Foyle Fault; G = Garabal Fault; GGF = Great Glen Fault; HBF = Highland Boundary Fault; K = Killin Fault; LF = Leannan Fault; LT = Loch Tay Fault; MT = Moine Thrust; N = Naver Slide; NSF = Navan-Silvermines Fault; OF = Orlock Bridge Fault; PF = Pettigo Fault; PL = Pontesford Lineament; S = Strathconnan Fault; SB = Sgurr Beag Slide; SUF = Southern Uplands Fault. Geographical and other abbreviations: A = Anglesey; B = Ballantrae; CB = Clew Bay; L = Lewisian; LD = Lake District; LE = Leinster granite; NE = Newry granite; O = Ox Mountains; P = Pomeroy; R = Ratagain Granite; T = Tyrone inlier; W = Wexford.

FIGURE 2.2: Tectonostratigraphic divisions of Caledonian Britain (after Hutton, 1987).

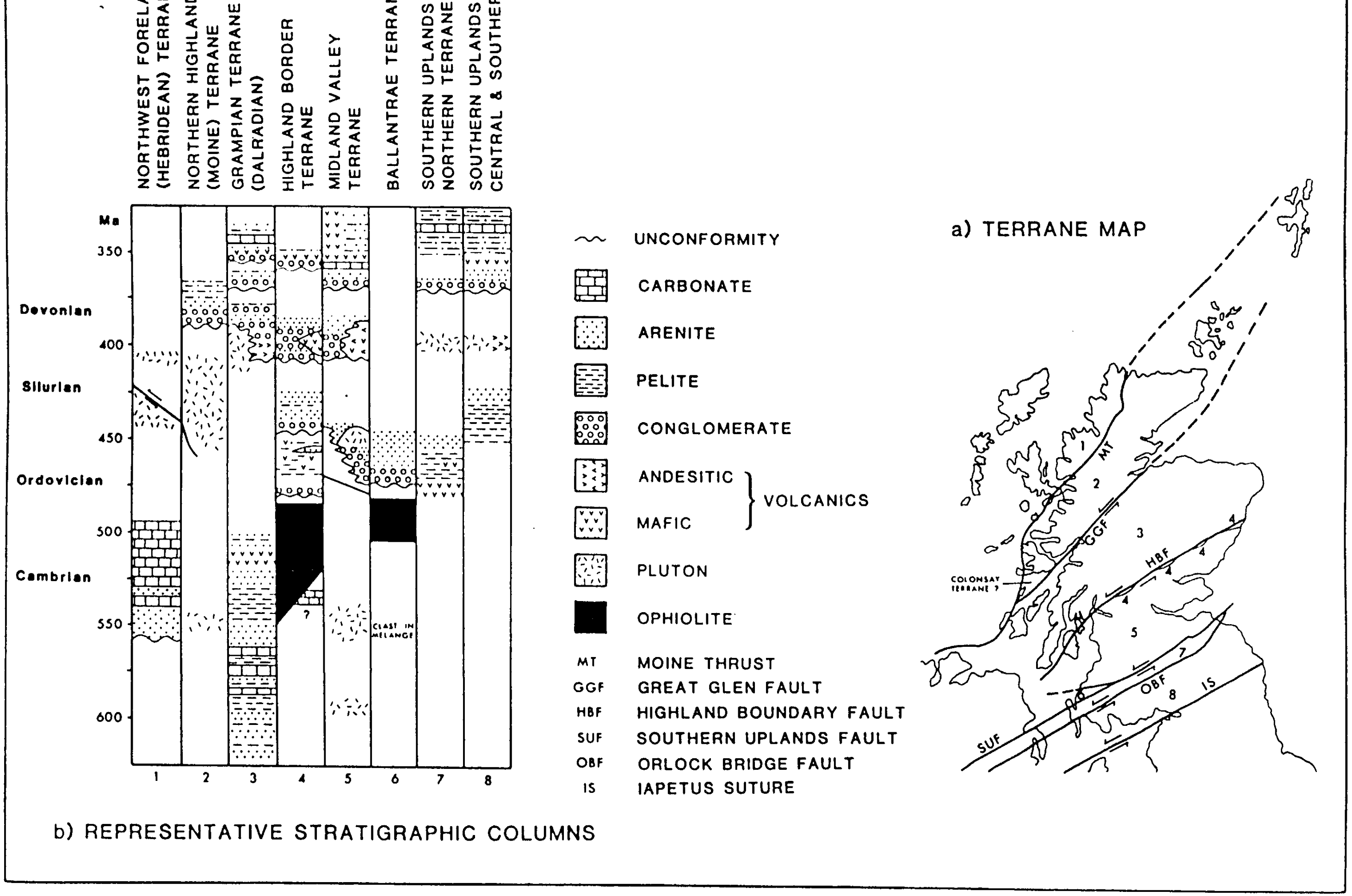


Fig. 2.3
TECTONOSTRATIGRAPHIC TERRANES OF THE SCOTTISH CALEDONIDES

rather than dextral transpression across the paratectonic Caledonides (e.g. Anderson and Oliver, 1986., Soper et al. 1987). The relative timing of this movement (or movements) differs between studies and may potentially reflect a long history of sinistral convergence at the southern Laurentian margin. Caution should be attached to such an inference however as few of the methods used in the identification of movement sense are quantitative. Indeed, several 'indicators' of displacement sense (e.g. microstructural fabric) may result from only small scale rather than 'terrane scale' displacement.

An exception to this qualitative approach is the sedimentological study of Elders (1987) which claims to link conglomeratic units of the Southern Uplands with a source area in Newfoundland. This would require a continuum of sinistral displacement from late Ordovician to Early Devonian times with a cumulative offset of some 1500 kilometres. Other studies involving provenence work (e.g. Bluck *et al.* 1984., Haughton, 1988), whilst able to demonstrate geological incompatability between adjacent terranes, cannot easily constrain either the sense or magnitude of the displacement which has resulted in their present juxtaposition. In some cases, (e.g. Robertson, 1987., Bluck, unpubl. data), the geometry of sedimentary sequences or their soft sediment deformation may provide evidence of lateral movement sense.

The faunal assemblages of McKerrow & Cocks (1976) and Cocks & Fortey (1982) have been used as evidence for the former separation of northern and southern Britain during the Cambro - Ordovician. The latter authors' palaeogeographic reconstruction for Arenig times incorporating both sedimentary facies and shelf/pelagic faunal evidence is illustrated in Figure 2.4. Cocks & Fortey add a cautionary note to their model to the effect that "no fix on longitude" is made and hence "no measure of transcurrent movement within the same latitudinal belt is possible". In context therefore, although faunal provinciality aptly demonstrates the existence of Iapetus, it is unable to image the suspected strike-slip dismemberment of terranes produced in response to oblique subduction.

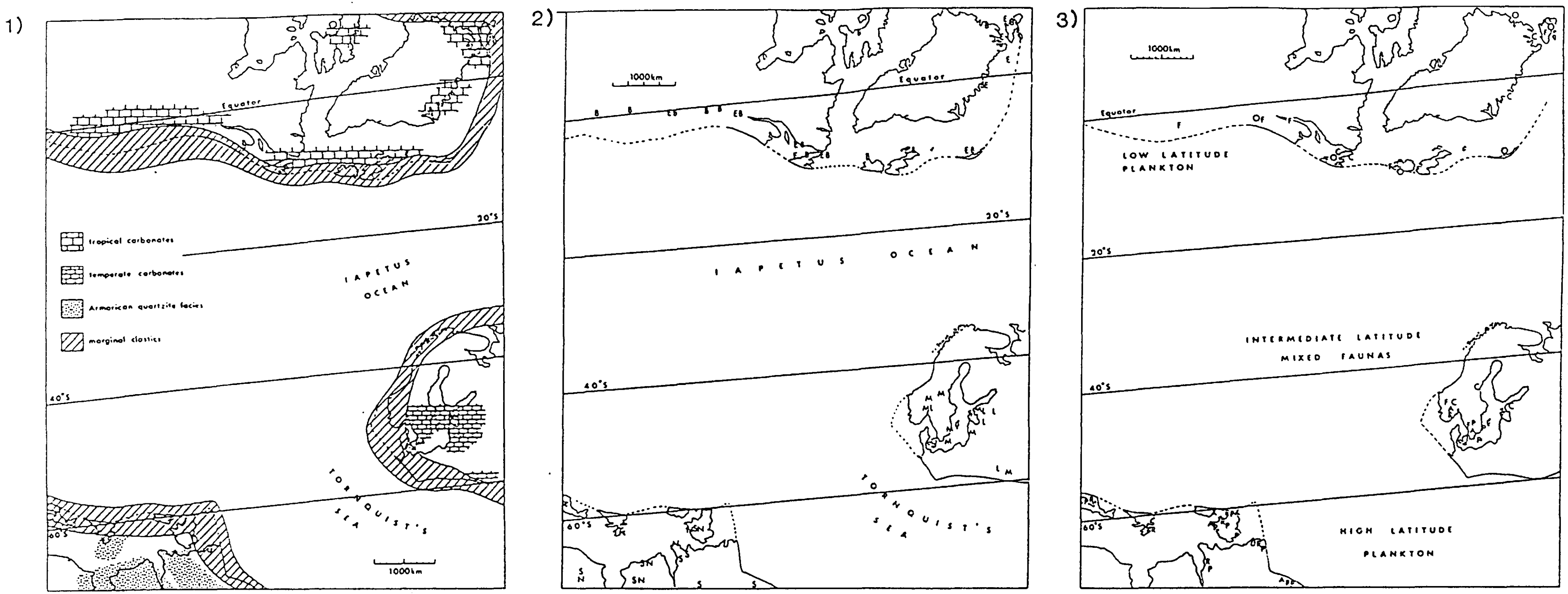
The palaeomagnetic method suffers a similar problem in longitudinal constraint to that described for faunal studies. As such, palaeomagnetic work within the Caledonides must relate either to the latitudinal positioning of terranes with respect to the ocean bordering continents (e.g. Ballantrae Complex, Chapter 4), or to the detection/constraint of strike-slip movements when the palaeoazimuth becomes favourably oriented for so doing (e.g. St. Abbs Head, Loch Lintrathen/Glenbervie, Chapters 6 & 7 respectively).

The input of the various methods of terrane analysis to our present understanding of paratectonic Caledonide evolution is briefly summarised as follows:-

(2.2.1) Structural evidence.

(2.2.2) Sedimentological evidence.

(2.2.3) Faunal/Palaeomagnetic evidence.



1) The chief sedimentary facies of the area surrounding Britain in Arenig times. Positions of the continents shown are consistent with a separation or closing rate of 2cm/year.

2) The distribution of selected shelf faunas in Arenig times; B, bathyurid trilobites; E, the mollusc *Euchasma*; M, megistaspid trilobites (*Megistaspis Lannacus*, and related genera); L, the brachiopods *Lycophoria, Clitambonites, Antigonambonites*; N, the trilobite *Neseuretus*; S, the trilobite *Selenopeltis.*

3) The distribution of selected graptolites and pelagic trilobites in Arenig times; O, *Oncograptus* and *Cardiogratus*; F, *Tetragraptus fructicosus*; C, the pelagic trilobite *Carolinites*; A, *Azygograptus*; R, *Corymbograptus*; P, cyclopygid trilobites.

FIGURE 2.4: A palaeogeographic reconstruction of the Iapetus bordering continents for Arenig times (after Cocks & Fortey, 1982).

(2.2.4) Palaeotectonic environment.

(2.2.5) General.

2.2.1 STRUCTURAL EVIDENCE.

The relative contribution of structural geology to the elucidated terrane history of the Caledonian orogeny far outweighs that for the Western Cordilleran belt in which terrane theory was founded. The reason for this stems from the equivocal sense of Caledonian terrane movement, (which has prompted much research effort), contrasted with the ongoing dextral movement of Cordilleran terranes with respect to cratonic North America.

Structural evidence of displacement sense in the paratectonic Caledonides has been recovered on widely differing scales and from both temporally and spatially separated strata. Hutton & Dewey (1986) recognise sinistral S-C fabrics, rotated porphyroblasts and extensional crenulation cleavages relating to D3 deformation of the Ox Mountains inlier, Western Ireland. This deformation is interpreted as synchronous-post intrusion of the Ox Mountains granodiorite (478 +/-12Ma., Pankhurst *et al.* 1976).

A further sinistral transpressive event is envisaged by Hutton & Dewey (once again imaged through structural fabric), considered approximately synchronous with intrusion of the Corvock granite (387 +/-12 Ma Rb/Sr., O'Connor *et al.* 1983). Interpretation of this second deformation as responsible for terrane scale displacement may be erroneous however particularly given the stratigraphical linkage of the Dalradian and Midland Valley evidenced through correlation of the Lintrathen/Glenbervie Porphyry (415 +/-6 Ma., Thirlwall, 1988., 7.7). Sinistral emplacement deformations have elsewhere been reported as operative during Siluro-Devonian times controlling the intrusion of the Newer Granite suite (Hutton,1982., Smith & Watson, 1983., Watson, 1984).

On a larger scale, Soper *et al.* (1987) interpret the cleavage/fold axis transection geometry of the English Lake District as representative of a late stage sinistral transpression. They refer to this transpression as the Acadian event interpreted on stratigraphic grounds as climaxing during Emsian times (394-387Ma, Harland *et al.* 1982) and recording the northward impingement of the Anglo-Welsh terrane onto the Laurentian margin. Woodcock *et al.* (1988) note similar sinistral convergence (although not as profound) for the Acadian orogeny in Wales.

Anderson & Oliver (1986) report structural and stratigraphic evidence in support of major (> 400kms) sinistral translation along the Orlock Bridge fault; the bounding fault of the Southern Uplands/Longford Down northern and central belts. Floyd *et al.* (1987) dispute this interpretation however claiming it to hinge on a 'misinterpretation of the available stratigraphic dating.'

2.2.2 SEDIMENTOLOGICAL EVIDENCE.

Studies of the sedimentary provenance in coeval terrane successions may be able to provide an important record of former tectonic relationships between presently juxtaposed blocks. Their potential importance has been outlined by Haughton (1988) as follows:-

- To constrain the timing and scale of relative displacements between terranes.
- To constrain the timing and type of eventual terrane amalgamation.
- To image the former presence of terranes not obviously preserved in the final crustal mosaic.

Jones *et al.* (1983) further illustrate the relative importance of this work in that provenence linkage forms one of their three 'main criteria' in establishing terrane accretion/amalgamation (Figure 2.5).

In the British sector of the Caledonides, the recognition of proven sediment sources as feeding particular basins has provoked much controversy (c.f. Simon & Bluck, 1982., with Allen & Crowley, 1983, for the ORS). Even accepting evidence for a particular source as unequivocal; arguments surrounding the resultant tectonic implications may still remain. An example of this type relates to the Ordovician versus Silurian collision/closure of the Iapetus basin (c.f. Murphy & Hutton, 1986., Hutton & Murphy, 1987. with Soper & Hutton, 1984., Soper *et al.*, 1987). In the Murphy/Hutton models, a distinctive siliceous microconglomerate facies of Wenlock age is recognised as deposited across the trace of the Iapetus suture in Ireland. The unit was interpreted as representative of an overstep sequence between terranes (see Figure 2.5 a) and hence thought to reflect a final stage in terrane amalgamation. Soper *et al.* (1987) suggest that one of the first signs of impending collision may be the appearence on one terrane of sediment sourced on the other. In this instance therefore, they interprete the presence of the microconglomerate as reflecting merely a precursor to terrane amalgamation.

Other evidence which has been used in documenting Caledonian terrane history is the present occurrence of what appear incompatable source-sediment dispersal relationships in the exposed column. Several examples are neatly illustrated within the Midland Valley as follows:-

i) The diverse lithological assemblages of the Highland Border Complex (Tremadoc-Ashgill; Whelan, 1988) contain no apparent sedimentary record of the now adjacent Dalradian block despite its contemporaneous uplift and deformation (Dempster, 1985). Such a lack of association therefore requires substantial subsequent relative movement to have occurred (Bluck, 1985., Bluck & Leake, 1986).

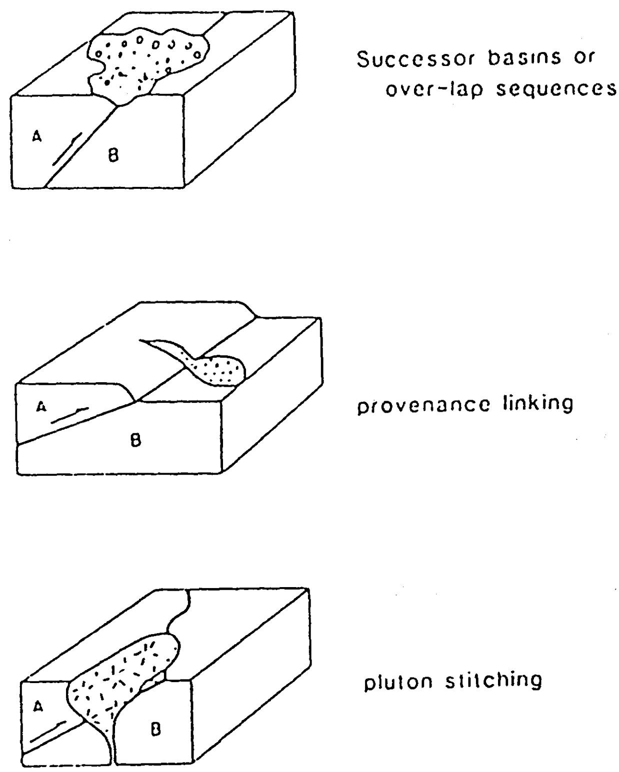


FIGURE 2.5: Geological criteria used in the establishment of terrane amalgamation and accretion (after Jones *et al.* 1983).

ii) Conglomerates of the Kincardineshire Old Red Sandstone contain palaeocurrent indicators which suggest both northerly and southerly source derivation. Those of southerly provenance record the unroofing of a heterogenous lithological sequence not presently preserved at outcrop. Subsequent burial of this source below an Upper Palaeozoic cover succession and/or its removal by strike slip migration is therefore implied (Haughton, 1988).

iii) Exposed within the Silurian inliers of the southern Midland Valley is the 'Igneous Conglomerate' interpreted as of southeasterly derivation (McGiven,1967). Such a source provenence is contrary to the present disposition of the Southern Uplands greywacke pile presently exposed to the south of the inliers and requires overthrusting or strike slip shuffling of terranes subsequent to conglomerate deposition (Bluck, 1983).

The largest uncertainty inherent in provenence studies involving palaeocurrent indicators is the assumption of no subsequent block rotation. Such an assumption may be ill-founded when applied to regions believed to have undergone substantial strike-slip deformation, block rotation having been unequivocally demonstrated over a range of scales in such areas (e.g. Beck, 1976., 1980., Ron *et al.* 1984., Ron, 1987). The close integration of palaeomagnetic with sedimentological studies therefore remains a potentially advantageous area of research in the Caledonides.

2.2.3 FURTHER EVIDENCE FOR THE FORMER SEPARATION OF TERRANES.

i) Faunal Evidence.

The uses of palaeontology in studying terrane history and evolution can be subdivided into two categories. These are its use as an indicator of palaeo-faunal provinciality and its traditional use in the age dating of given lithological successions.

In the former case, the usefulness of faunal provinces in imaging the former existence of Iapetus has already been recounted (Figure 2.4). For the latter, the palaeontological dating of successions is inherent in all studies of terrane evolution not least within the British Caledonides where it has proved invaluable in the recognition of individual terranes (e.g. Highland Border terrane; Curry *et al.* 1984).

ii) Palaeomagnetic Studies.

The input of palaeomagnetic studies to Caledonian terrane evolution has been reviewed for the Ordovician - Devonian periods in Chapters 3 & 5. It is hoped that the work presented in this thesis both from the Arenig Ballantrae Ophiolite (Chapter 4), the Siluro-Devonian sediments and volcanics of St. Abbs Head (Chapter 6) and the Loch

Lintrathen & Glenbervie porphyries (Chapter 7) contribute substantially to this.

2.2.4 CONSIDERATION OF PALAEOTECTONIC ENVIRONMENT.

The assignment of a palaeo-tectonic origin to particular Caledonian terranes has proved the subject of much debate and diversity of opinion (see 'the Southern Uplands Controversy' Journal of the Geological Society, London, 144, part 5, 1987). Nevertheless, the allocation of a tectonic setting to a given terrane may have implications for its evolution with respect to neighbouring terranes.

A case illustrating this point can be described for the Girvan (Ordovician) terrane (Bluck, 1985) with respect to the neighbouring Southern Uplands terrane(s). The Girvan succession comprises a variety of conglomerates, sandstone turbidites and shallow water limestones ranging in age from Llanvirn to Ashgill (Ingham, 1978). It has been suggested to represent a remnant proximal fore-arc environment (Bluck, 1983). The sequence is presently preserved in fault contact with the coeval Coulter-Noblehouse succession of the Southern Uplands' northern belt which has been equated both in lithology and structure to that expected to occur within an accretionary prism (McKerrow *et al.* 1977). Their present juxtaposition therefore requires the removal (either through strike-slip shuffling or overthrusting) of a missing fore-arc succession (Bluck, 1983) implying a minimum of 45kms shortening to have occurred (see Dickinson, 1973).

2.2.5 GENERAL.

The assessment of the relative contributions of differing geological methods to our present understanding of the tectonic evolution of the Caledonides is necessarily somewhat artificial.

In reality, the successful elucidation of even a single terrane history will draw on evidence from a broad cross-section of techniques. Hence, considering the Ballantrae Complex for example, significant contributions pertaining to its traceable history include studies of palaeontology (Rushton *et al.* 1986), geochemistry (Thirlwall & Bluck, 1984), radiometric dating (Hamilton *et al.* 1984), sedimentology (Bluck, 1982), igneous petrology (Bloxam, 1968) and palaeomagnetism (Chapter 4).

CHAPTER 2 : REFERENCES.

Allen, J.R.L. and Crowley, S.F. 1983. Lower Old Red Sandstone fluvial dispersal systems in the British Isles. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 74, 61-68.

Anderson, T.B. and Oliver, G.J.H. 1986. The Orlock Bridge Fault: A major Late Caledonian sinistral fault in the Southern Uplands Terrane, British Isles. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 77, 203-222.

Anderton, R., Bridges, P.H., Leeder, M.R. and Sellwood, B.W. 1979. *A Dynamic Stratigraphy of the British Isles.* Allen and Unwin, London, 301pp.

Beck, M.E., Jr., 1976. Discordant paleomagnetic pole positions as evidence of regional shear in the western Cordillera of North America. *American Journal of Science,* 276, 694-712.

Beck, M.E., Jr., 1980. Paleomagnetic record of plate-margin tectonic processes along the western edge of North America. *Journal of Geophysical Research,* 85, 7115-7131.

Bloxham, T.W. 1968. The petrology of Byne Hill, Ayrshire. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 68, 105-123.

Bluck, B.J. 1982. Hyalotuff deltaic deposits in the Ballantrae ophiolite of SW Scotland: evidence for the crustal position of the lava sequence. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 72, 217-228.

Bluck, B.J. 1983. Role of the Midland Valley of Scotland in the Caledonian Orogeny. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 74, 119-136.

Bluck, B.J. 1984. Pre-Carboniferous history of the Midland Valley of Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 75, 275-295.

Bluck, B.J. 1985. The Scottish paratectonic Caledonides. *Scottish Journal of Geology,* 21, 437-464.

Bluck, B.J. and Leake, B.E. 1986. Late Ordovcian to Early Silurian amalgamation of the Dalradian and adjacent Ordovician rocks in the British Isles. *Geology,* 14, 917-919.

Bluck, B.J., Ingham, J.K., Curry, G.B. and Williams, A. 1984. Stratigraphy and tectonic setting of the Highland Border Complex. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 75, 124-133.

Cocks, L.R.M. and Fortey, R.A. 1982. Faunal evidence for oceanic separations in the Palaeozoic of Britain. *Journal of the Geological Society, London,* 139, 467-480.

Curry, G.B., Bluck, B.J., Burton, C.J., Ingham, J.K., Siveter, D.J. and Williams, A. 1984. Age, evolution and tectonic history of the Highland Border Complex, Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 75, 113-123.

Debiche, M.G., Cox, A. and Engebretson, D. 1987. The motion of allochthonous terranes. *Geological Society of America, Special Paper* no. 207, 49pp.

Dempster, T.J. 1985. Uplift patterns and orogenic evolution in the Scottish Dalradian. *Journal of the Geological Society, London,* 142, 111-128.

Dewey, J.F. 1969. Evolution of the Appalachian-Caledonian orogen. *Nature,* 222, 124-128.

Dewey, J.F.1982. Plate tectonics and the evolution of the British Isles. *Journal of the Geological Society, London,* 139, 371-412.

Dickinson, W.R. 1973. Width of modern arc-trench gaps proportional to past duration of igneous activity in associated magmatic arcs. *Journal of Geophysical Research,* 78, 3376-3389.

Elders, C.F. 1987. The provenance of granite boulders in conglomerates of the Northern and Central Belts of the Southern Uplands of Scotland. *Journal of the Geological Society, London,* 144, 853-863.

Floyd, J.D., Stone, P., Barnes, R.P. and Lintern, B.C. 1987. Constraints on the significance of the Orlock Bridge Fault within the Scottish Southern Uplands. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 78, 219-223.

Hamilton, P.J., Bluck. B.J. and Halliday, A.N. 1984. Sm-Nd ages from the Ballantrae Complex, SW Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 75, 183-187.

Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G. and Walters, R. 1982. *A geological time scale.* Cambridge University Press, Cambridge, 131pp.

Haughton, P.D.W. 1988. A cryptic Caledonian flysch terrane in Scotland. *Journal of the Geological Society, London,* 145, 685-703.

Howell, D.G., Jones, D.L. and Schermer, E.R. 1985. Tectonostratigraphic terranes of the circum-Pacific region. In : *Howell, D.G. (ed.); Tectonostratigraphic terranes of the circum-Pacific region :* Earth Science Series, 1, Houston, Circum-Pacific Council for Energy and Mineral Resources, 3-30.

Hutton, D.H.W. 1982. A tectonic model for the emplacement of the Main Donegal Granite, NW Ireland. *Journal of the Geological Society, London,* 139, 615-631.

Hutton, D.H.W. 1987. Strike-slip terranes and a model for the evolution of the British and Irish Caledonides. *Geological Magazine,* 124, 405-425.

Hutton, D.H.W. and Dewey, J.F. 1986. Palaeozoic terrane accretion in the Western Irish Caledonides. *Tectonics,* 5, 1115-124.

Hutton, D.H.W. and Murphy, F.C. 1987. The Silurian rocks of teh Southern Uplands and Ireland as a successor basin to the end Ordovician closure of lapetus. *Journal of the Geological Society, London,* 144, 765-772.

Ingham, J.K. 1978. Geology of a continental margin 2: Middle and Late Ordovician transgression, Girvan. In: *Bowes, D.R. and Leake, B.E. (eds) Crustal evolution in northwest Britain and adjacent regions.* Geological Society Special Publication, 10, 163-176.

Jones, D.L., Howell, D.G., Coney, P.J. and Monger, J.W.H. 1983. Recognition, character and analysis of tectonostratigraphic terranes in western North America. In: *Hashimoto, M. and Uyeda, S. (eds), Accretion tectonics in the circum-Pacific regions:* Boston, D. Reidel Publishing Co., p. 21-35.

McGiven, A. 1967. *Sedimentation and provenance of post-Valentian conglomerates up to and including the basal conglomerate of the Lower Old Red Sandstone in the southern part of the Midland Valley.* Ph.D. thesis, University of Glasgow (unpubl.).

McKerrow, W.S. and Cocks, L.R.M. 1976. Progressive faunal migration across the Iapetus Ocean. *Nature,* 263, 304-306.

McKerrow, W.S., Leggett, J.K. and Eales, M.H. 1977. Imbricate thrust model of the Southern Uplands of Scotland. *Nature,* 267, 237-239.

Moseley, F. 1977. Caledonian plate tectonics and the place of the English Lake District. *Geological Society of America Bulletin,* 88, 764-768.

Murphy, F.C. and Hutton, D.H.W. 1987. Is the Southern Uplands of Scotland really an accretionary prism? *Geology,* 14, 354-357.

Pankhurst, R.J., Andrews, J.R., Phillips, W.E.A. and Sanders, I.S. 1976. Age and structural setting of the Slieve Gamph igneous complex, Co. Mayo, Eire. *Journal of the Geological Society, London,* 132, 327-336.

Phillips, W.E.A., Stillman, C.J. and Murphy, T. 1976. A Caledonian plate and tectonic model. *Journal of the Geological Society, London*, 132, 579-609.

O'Connor, P.J., Long, C.B. and Hennessy, J. 1983. Radioelement geochemistry of Irish Newer Caledonian Granites. *Geological Survey of Ireland Bulletin,* 3, 125-140.

Robertson, S. 1987. Early sinistral transpression in the Lower Old Red Sandstone of Kincardineshire, Scotland. *Scottish Journal of Geology,* 23, 261-268.

Ron, H. 1987. Deformation along the Yammuneh, the restraining bend of the dead sea transform: Paleomagnetic data and kinematic implications. *Tectonics, 6,* 653-666.

Ron, H., Freund, R. Garfunkel, Z. and Nur, A. 1984. Block rotation by strike-slip faulting: structural and palaeomagnetic evidence. *Journal of Geophysical Research,* 89, 6256-6270.

Rushton, A.W.A., Stone, P., Smellie, J.L. and Tunnicliff, S.P. 1986. An early Arenig age for the Pinbain sequence of the Ballantrae Complex. *Scottish Journal of Geology,* 22, 41-54.

Simon, J.B. and Bluck, B.J. 1982. Palaeodrainage of the southern margin of the Caledonian mountain chain in the northern British Isles. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 73, 11-15.

Smith, D.I and Watson, J.V. 1983. Scale and timing of movements on the Great Glen Fault, Scotland. *Geology,* 11, 523-526.

Soper, N.J. and Hutton, D.H.W. 1984. Late Caledonian sinistral displacements in Britain : implications for a three-plate collision model. *Tectonics,* 3, 781-794.

Soper, N.J., Webb, B.C. and Woodcock, N.H. 1987. Late Caledonian (Acadian) transpression in north-west England: timing, geometry and geotectonic significance. *Proceedings of the Yorkshire Geological Society,* 46, 175-192.

Thirlwall, M.F. 1988. Geochronology of Old Red Sandstone magmatism in Northern Britain. *Journal of the Geological Society, London.* in press.

Thirlwall, M.F. and Bluck, B.J. 1983. Sr-Nd isotope and chemical evidence that the Ballantrae 'ophiolite', SW Scotland is polygenetic. In : *Gass, I.G., Lippard, S.J. and Shelton, A.W. (eds), Ophiolites and Oceanic Lithosphere,* Blackwell, Oxford, 215-230.

Watson, J.V. 1984. The ending of the Caledonian Orogeny in Scotland. *Journal of the Geological Society, London,* 141, 193-214.

Whelan, G.M. 1988. The palynology of the Highland Border Complex. *in prep.*

Wilson, J.T. 1966.'Did the Atlantic close and then reopen?' *Nature,* 211, 676-679.

Woodcock, N.H., Awan, M.A., Johnson, T.E., Mackie, A.H. and Smith, R.D.A. 1988. Acadian tectonics of Wales during Avalonia/Laurentia convergence. Tectonics, 7, 483-497.

CHAPTER 3 : BRITISH ORDOVICIAN PALAEOMAGNETISM.

3.1 INTRODUCTION

Ordovician rocks occur as scattered outcrops ranging throughout the British Isles. Consideration of their palaeo-tectonic environments supports the existence of the Iapetus Ocean during this period (Wilson 1966, 2.1-2.2). The study of palaeomagnetism provides the only quantitative method through which to assess the width of Iapetus at this time together with its variation thereafter.

To this end, considerable palaeomagnetic work has been performed on Ordovician rocks in Britain over the past thirty years. The majority of data come from volcanic successions. These are augmented by results from their plutonic equivalents and to a lesser extent from contemporaneous sediments. Due to the long history of palaeomagnetic research involving Ordovician rocks, they provide an ideal opportunity to reflect upon changes in laboratory methods and techniques through time. The effect of these changes on the quality of the derived palaeomagnetic record can then be perceived.

Two study areas are considered which have been subjected to several independent investigations and which subsequently chronicle developments in applied research methods. These areas are as follows:-

(3.1.1) Newer or Younger Gabbros of Aberdeenshire, Scotland.

(3.1.2) Builth Volcanic Series, Wales.

3.1.1 NEWER GABBROS, ABERDEENSHIRE.

The first palaeomagnetic investigation of the Newer Gabbros was that of Blundell & Read (1958). They measured the NRM of samples covering all the major masses in an attempt to determine whether the gabbros had been subjected to large scale Caledonian folding (F3). No laboratory demagnetisation was performed but samples were subject to storage tests. On the basis of broadly consistent *in situ* results between masses, they concluded that intrusion must post-date F3. Stewart & Johnson (1960) challenged this interpretation believing the internal variation in NRM data to result from structural deformation. Further to this, they suggested that deformation may have occurred at temperatures exceeding the blocking temperatures of the constituent magnetic minerals.

Sallomy & Piper (1973) undertook a second study of the gabbros aimed at resolving this problem. This formed one of a series of six thematic papers entitled 'Palaeomagnetic studies in the British Caledonides'. Both alternating field and thermal cleaning techniques were employed although to a somewhat restricted extent. One specimen from each site was subjected to progressive AF (Alternating Field) demagnetisation. On the basis of this, an optimum cleaning field was calculated (Briden, 1972) at which remaining samples were treated. Final sample directions for statistical analysis therefore generally relate to a single demagnetisation treatment. In addition, one or two samples from each site were thermally demagnetised in steps up to 685°C.

A fold test relative to igneous layering was found to be negative and the measured magnetisation therefore considered to post-date the major F3 folding. The Insch mass proved anomalous however having an *in situ* site mean direction somewhat removed from those of the other masses. In addition, correction for the igneous layering appeared to reduce this discrepancy. A purely tectonic origin was considered untenable however as the Insch mass forms an extension of the Boganclough mass which yielded concordant results. Following consideration therefore, a combined magnetic pole was calculated using the *in situ* directions of magnetisation.

The calculated pole of Blundell & Read (1958) differs from that obtained by Sallomy & Piper (1973) by sixteen degrees. The latter must be considered a better estimate however following the removal of low blocking temperature/coercivity contaminating effects. An overall shallowing of the resulting combined magnetisation direction with cleaning is consistent with removal of soft recent field effects from the NRM.

Carmichael & Storetvedt (1981) report a third examination of the magnetic properties of the gabbros. Initial study was aimed at palaeointensity determination of the Ordovician field. However, this proving unsuccessful, attention was diverted to thorough demagnetisation analyses. Specimens were cut from twelve oriented block samples and subjected to either stepwise thermal demagnetisation, progressive AF demagnetisation, or a combination of the two methods. Reported results differ markedly from those already described.

In addition to directions consistent with the results of previous studies, Carmichael & Storetvedt report two other axes of magnetisation. These they refer to as axes A and B, of flat lying SSE and flat lying SSW directions respectively. Magnetisations of both polarites are recorded for each axis. The stability ranges of the axes do not appear to be systematic however and components of dissimilar stability are grouped within supposed single axis populations.

The authors use an arbitrary vector subtraction method for selection of their data points. End point directions were calculated as the mean of at least three closely grouped points over a repeatable range of demagnetisation treatment. The results of previous investigations were regarded as not completely resolving axes A or B due to insufficient laboratory cleaning. Carmichael & Storetvedt took their A and B axes to define a segment of apparent polar wander for the Ordovician period. Non-agreement with reported results elsewhere in Britain (e.g. Briden & Morris, 1973., Morris *et al.* 1973) was seen as grounds for the re-examination of these earlier studies. Further to this, they note the wide scatter in Ordovician field determinations and suggest that up to this time (1981), there exists no satisfactory explanation of this. They suggest a failure of the dipole approximation as a possibility, citing evidence for a weak field intensity in the Palaeozoic era (Carmichael, 1967).

Watts & Briden (1984) replotted the data of Sallomy & Piper (1973) on a map of K-Ar biotite chrontours. They found a variation in magnetic direction with younging chrontour age which was paralleled by a shift in the correct sense along the published British Apparent Polar Wander Path (APWP) of Briden & Duff (1981). More extensive sampling was employed to further explore this relationship.

Both stepwise thermal and AF cleaning techniques were carried out. Emphasis was placed on the former to complement the AF analyses of Sallomy & Piper (1973). Orthogonal projections (Zijderveld, 1967) were used for standard demagnetisation analysis in contrast to the stereographic projections of the previous studies. The weighted principal component analysis algorithm (LINEFIND) of Kent *et al.* (1983) was also used in assignment of significance to demagnetisation trajectories.

The demagnetisation results of Watts & Briden (1984) establish the relationship between the APWP and the K-Ar chrontours. This conclusion was obviously at variance with that of Carmichael & Storetvedt (1981) and a re-examination of results from the earlier study was made. Watts & Briden (1984) convincingly demonstrate inaccuracies in the interpretation of Carmichael & Storetvedt (1981) whilst portraying the advantageous use of orthogonal projections over their stereographic equivalents (Figure 3.1).

Two problems are outstanding with respect to the magnetic signature of the gabbros. These are the assignment of an absolute age to the measured magnetisation/apparent polar wander and an explanation for its completely reversed polarity. Radiometric determinations are able to place constraints on the first of these problems.

The K-Ar biotite chrontours of Dewey & Pankhurst (1970) record the differential cooling of the terrain through approximately 300°C. The Rb-Sr whole rock age of 489 +/- 17 Ma (Pankhurst, 1970) can be interpreted as a crystallisation age at least for the Insch and Haddo House masses (Carmichael & Storetvedt, 1981).

If the magnetic signature dates from a period bounded by these limits, this would place the age of magnetisation between late Tremadocian and late Caradocian times of the Ordovician (from Harland *et al.* 1982). To further constrain this age range, a better estimate of the temperature at which the magnetisation was acquired is needed. Given a purely TRM origin this may be possible using laboratory unblocking temperatures and the

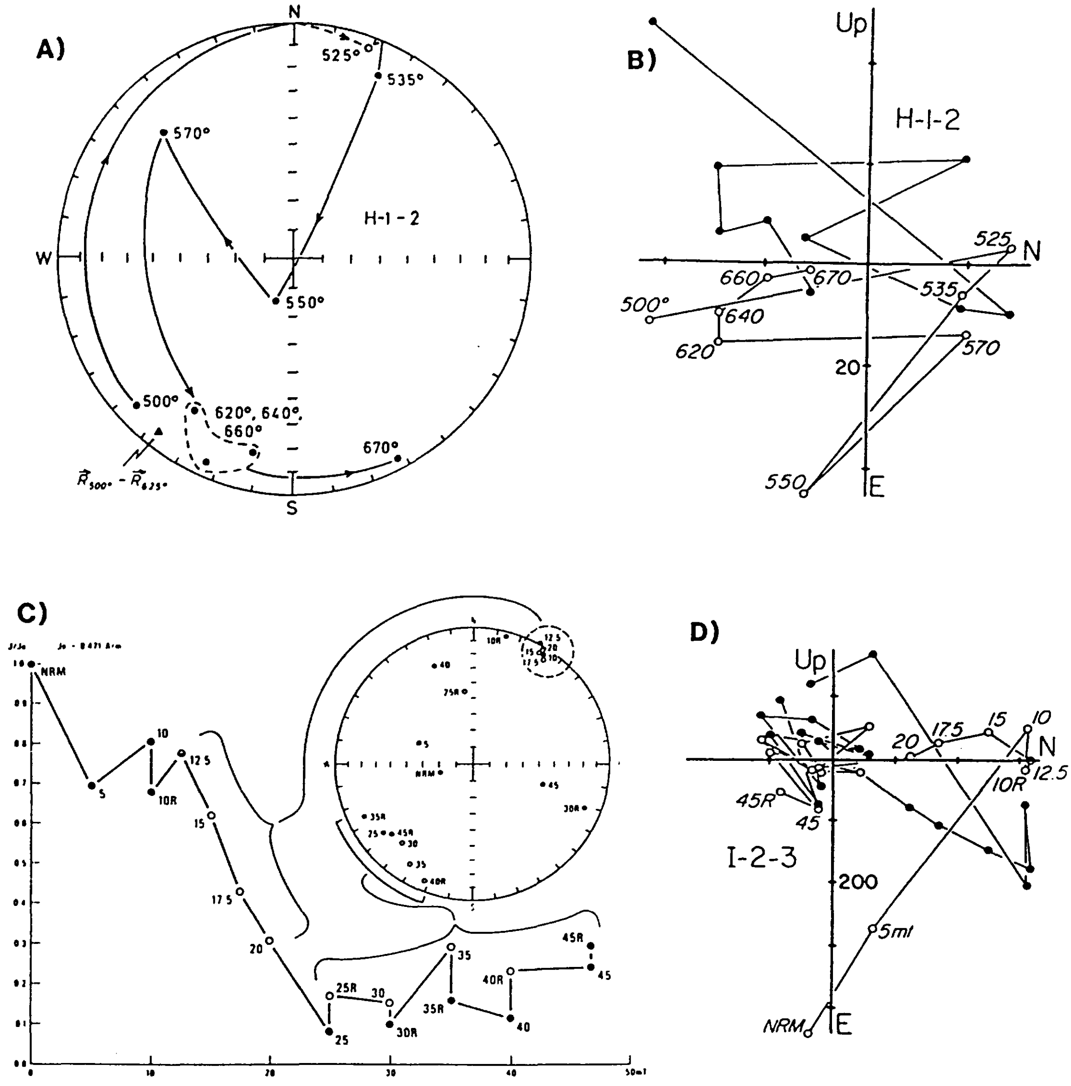


FIGURE 3.1: COMPARISON OF DATA PRESENTATION & INTERPRETATION: ABERDEENSHIRE GABBROS;
(A,C) Carmichael & Storetvedt (1981)., (B,D) Redrawn by Watts & Briden (1984).

SPECIMEN H-1-2., (A,B).
(A) Carmichael & Storetvedt report the existence of interacting N & R components. Thermal demagnetisation data are displayed in stereographic projection.
(B) Watts & Briden display the redrawn data in orthogonal projection. They draw attention to the erratic demagnetisation trajectory thought to be indicative of laboratory noise influence.

SPECIMEN I-2-3., (C,D).
(C) Carmichael & Storetvedt contend the existence of magnetisations of opposing polarities revealed upon A.F. demagnetisation. Data are presented using J/J and stereographic plots.
(D) Watts & Briden show the high treatment 'component' to result from non-repeatable demagnetisation steps close to the origin.

reference curves of Pullaiah *et al.* (1975). Briden *et al.* (1986) favour a CRM origin for the remanence however, the thermodynamic constraints on which are still poorly understood. A close agreement exists between the inferred youngest of the gabbro directions and stratigraphically constrained Silurian/Devonian results. This favours a low temperature origin for the observed swathe of results (Torsvik, 1985).

Watts & Briden (1984) note the inferred prolonged period (c.40Ma) required to magnetise the terrain and propose that the field almost certainly changed polarity over this duration. This proposal is consistent with the preliminary polarity time scale for the Palaeozoic era (Piper, 1987. p.337., largely from Khramov & Rodinov, 1980). Both this time scale and a numerical assessment of published results (by Watts & Briden) indicate a bias toward reverse polarity over this interval. The almost complete reverse polarisation of the gabbros is therefore explicable if the time for site magnetisation is long compared to the duration of the polarity chrons (Watts & Briden, 1984., see also Morgan, 1976).

3.1.2 BUILTH VOLCANIC SERIES, WALES.

A preliminary palaeomagnetic investigation of the Builth Wells-Llandrindod inlier was carried out by Nesbitt (1967) as part of a wider study aimed at deriving an Ordovician geomagnetic pole. The inlier comprises a predominance of volcanic rocktypes which are relatively undeformed and of low metamorphic grade. The volcanics are dated from the graptolite fauna of intercalated shale horizons as of Upper Llanvirn age (Jones & Pugh, 1949).

Twelve hand specimens were collected by Nesbitt (1967) in the initial study of which three were subsequently rejected. This was presumably due to either directionally anomalous or unstable results. Details of laboratory treatment are absent but the use of both thermal and AF methods is mentioned. Comparison with other reported results in the paper would suggest alternating fields of up to 85 Oersteds to have been used. The nine samples from which results are reported yield a north pole at 162°E 15°N.

Piper & Briden (1973) report results from fifteen sites in the Builth Volcanic Series together with twelve sites from intruding Ashgillian dolerites. The study forms a part of the same thematic series as that of Sallomy & Piper (1973, Aberdeenshire Gabbros) and laboratory methods are consequently comparable.

One or two specimens from each site were subjected to progressive AF demagnetisation up to a maximum field of 100 milliTesla. One specimen from each site was also cleaned using partial thermal demagnetisation. Optimum AF treatment was calculated using the Briden Stability Index (1972). Consequently, reported magnetisation directions are generally the result of a single treatment at fields of 30 mT or less. At higher fields several specimens acquired new magnetisations attributable to the limitations of the demagnetisation apparatus/technique (McElhinny, 1966).

Piper & Briden (1973) considered the sites from the Builth Volcanic Series to show a simple systematic variation with AF cleaning. A gradual approximately exponential decrease in magnetic moment was accompanied by only slight changes in the direction of NRM. Results of thermal demagnetisation at treatments of 200, 320 and 450°C were found to be "in general accord" with those of the AF method. Laboratory cleaning of the Ashgillian dolerites produced less systematic behaviour than the volcanics. As these intrusives have not been resampled however, they will not be further considered here. On the basis of the AF cleaning of samples from 15 sites (68 specimens) in the volcanics, Piper & Briden (1973) report a south pole at 359°E 16°S.

The considerable scatter in Ordovician palaeomagnetic directions has been used as evidence to support contrasting apparent polar wander paths for this period (3.2). A generally accepted discordance in the database exists across the Iapetus suture (Solway Line) however. This has been interpreted as representing a measurable width of the Iapetus Ocean (Deutsch 1980, 1981. Briden *et al.* 1984). The palaeomagnetic pole from the Builth Volcanic Series conflicted with this generality however and precluded confident estimation of the former width of the ocean.

Briden & Mullan (1984) reinvestigated the Builth pole to determine whether insufficient laboratory demagnetisation might explain this apparent conflict of results. Eleven stratigraphic horizons (49 specimens) were collected over the same 400 metre section to that sampled by Piper & Briden (1973). Detailed thermal demagnetisation was performed on the larger part of this collection together with AF treatment of a single specimen from each site for comparitive purposes. Demagnetisation data were displayed in both orthogonal and stereographic projection and processed using the principal component analysis routine of Kent *et al.* (1983).

A far more complex build up of NRM than previously reported was uncovered. Detailed thermal demagnetisation reveals three distinct components of NRM (termed P, S & R) between which there was very little blocking temperature or directional overlap (Figure 3.2 b-d). Comparative AF demagnetisation failed to completely resolve all three components of magnetisation except in the case of a single specimen. The overlapping coercivity spectra of components led to magnetisation directions intermediate between those resolved by thermal treatment.

As with the previous studies, the lack of a suitable geological structure prevented the performance of a statistically significant fold test. To overcome this, Briden & Mullan (1984) sampled an agglomerate horizon to enable provision of a conglomerate test. On the

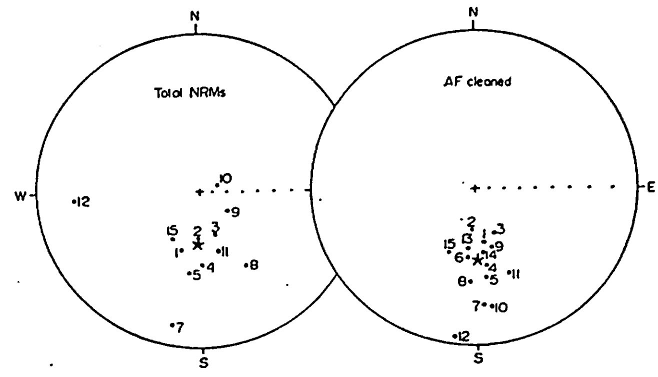


FIGURE 3.2 a: NRM and A.F. cleaned (15-30 mT) site mean data following dip correction: Piper & Briden, (1973).

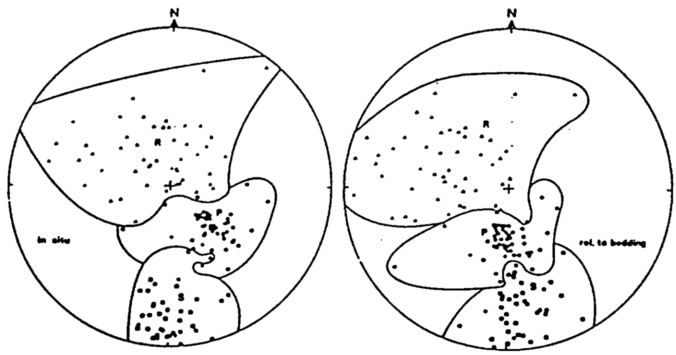


FIGURE 3.2 b: In situ and dip corrected component directions determined from stepwise thermal and A.F. demagnetisation: Briden & Mullan, (1984).

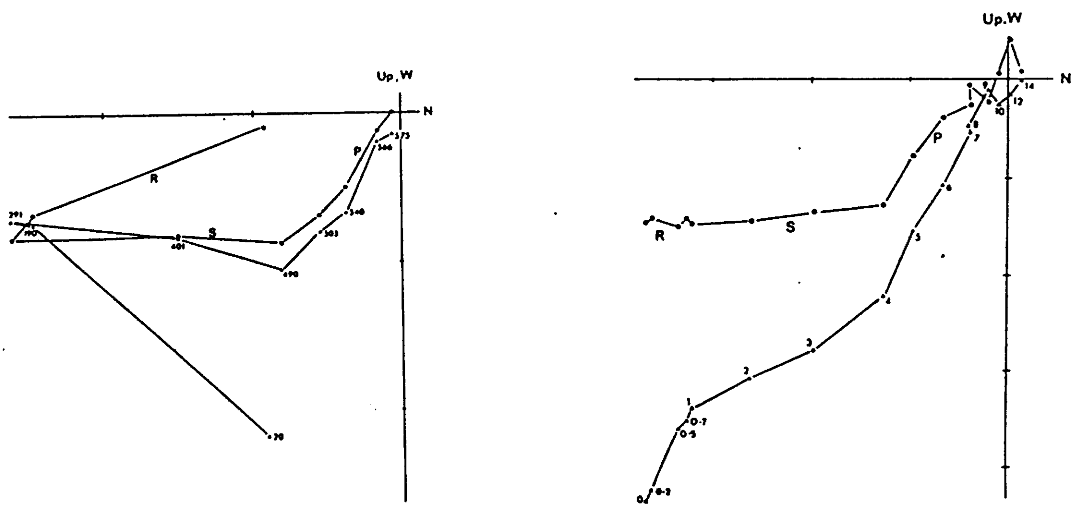


FIGURE 3.2 c, d: Thermal (c) and A.F. (d) orthogonal demagnetisation projections from Briden & Mullan (1984).
P- 'primary' (Ordovician)., S-'secondary' (Permo-Carboniferous)., R- 'recent' field components are indicated.

basis of this test and by reference to the known APWP for Southern Britain; magnetic ages were then attributed to each component.

A comparison of the demagnetisation data of Piper & Briden (1973) and Briden & Mullan (1984) is made in Figure 3.2. An explanation for the differences in the derived palaeomagnetic poles of the two studies then becomes apparent. Briden & Mullan report the presence of three components P, S and R to which they assign Ordovician, Permo-Carboniferous and Recent field origins respectively (Figure 3.2, b-d). Piper & Briden (1973) assign an Ordovician age to the resultant magnetic vector following AF cleaning to fields between 15 and 30 milliTesla (3.2 a). Figure 3.2 d shows the multicomponent build up of NRM when subjected to progressive AF cleaning (Briden & Mullan, 1984.) It is seen that the 'primary' Ordovician component (P) is removed at fields greater than 40 mT. Correspondingly, the 'secondary' Permo-Carboniferous direction (S) is removed over treatments between 10 and 40 mT.

It is evident therefore that the resultant magnetic vector measured by Piper & Briden (1973) contained subtantial contamination from a Permo-Carboniferous magnetisation. As this secondary magnetisation is entirely of reverse polarity (southerly sub-horizontal attitude), its presence led to an overall shallowing of the reported magnetisation direction. This in turn would lead to an apparent 'closing' of Iapetus with Builth having an artificially low palaeolatitude. The revised Ordovician pole calculated by Briden & Mullan (1984) is located at 2.8°S 355.2°E which is in better agreement with comporaneous results to the south of the Solway Line.

3.1.3 CHANGES IN LABORATORY/PROCESSING METHODS.

The two case studies which have been recounted neatly outline how changes in both laboratory and data processing techniques have greatly affected the quality and interpretation of palaeomagnetic results. Several key points become apparent which are summarised as follows:-

i) The introduction of orthogonal projections (Zijderveld, 1967) into standard demagnetisation analysis has had the advantage of incorporating both directional and intensity data in a single plot. Unfortunately, the use of orthogonal projections did not become commonplace amongst all workers until the mid 1970's - early 1980's. The merits of their use are well displayed in Figure 3.1. Stereographic projections still have important applications however notably for the display of data collections and for the uncovering of 'hidden' magnetisation components using either remagnetisation circle (Halls, 1976) or difference vector circle methods (Hoffman & Day, 1978).

ii) In both case studies, an earlier investigation using 'pilot' specimen techniques was superseded by later work involving full scale demagnetisation of all specimens. This progression has been helped by recent technological advances which have greatly reduced the laboratory time and effort required for such an undertaking. The general inadequacy of the pilot specimen technique becomes apparent in Figure 3.2 where the 'optimum' treatment of Piper & Briden (1973) lies within the stability field of a secondary magnetisation component (Briden & Mullan, 1984). An analogous situation is evident in early palaeomagnetic studies of the Old Red Sandstone (5.2.3) where blanket thermal treatments at 300°C (Turner & Archer, 1975. Tarling, 1976) appear insufficient to fully describe the complex magnetic signature of the sediments.

iii) More detailed cleaning of all specimens has the consequence of greatly increasing the volume of acquired demagnetisation data. In this respect, care must be taken in using only the statistically significant part of the overall dataset. Recent applications of statistical techniques to demagnetisation data have been aimed at the attachment of significance and error to determined magnetisation directions (Kirschvink, 1980., Kent *et al.* 1983). Use of one or other of these statistical treatments should negate the possibility of attaching significance to what may indeed be experimental artifacts within the data.

McFadden & Schmidt (1986) point out that whilst the estimated errors of particular directions are fundamental to the computer–based statistical methods, they have yet to be utilised in the overall mean analysis of data. They propose a weighted statistical analysis accounting the individual precision of each component direction. The application of this modified analysis changes the computed means of their examples by a few degrees. It is expected that their statistical treatment will find widespread usage amongst workers in the near future although it has not been applied in this thesis.

iv) Despite the advances with respect to both laboratory and computing facilities, some of the most fundamental problems relating to palaeomagnetic analyses still remain. These notably include the provision of sufficiently stringent age and structural controls to the measured remanences.

Once again the reported case studies provide a good basis on which to discuss these problems. For the Aberdeenshire Gabbros, the problem lies in correctly assigning a magnetisation age to the inferred apparent polar wander (APW) for the Grampian block. This is particularly problematical given the probable CRM or TCRM nature of the remanence. Differences in age interpretation allow the rival polar wander hypotheses of

Briden *et al.* (1984) and Piper (1987), (3.2).

In the case of the Builth Volcanic Series, the age of the demonstrated primary magnetisation is afforded through palaeontological evidence. Structural constraints are less stringent however. In particular, Piper & Briden (1973) note the succession to have been affected by dextral tear faulting prior to deposition of the earliest Silurian rocks in Late Llandovery times. Consideration of the possible rotation of both faults and fault blocks is therefore necessitated. Indeed, sizable rotations have been demonstrated within analogous areas of strike slip faulting (e.g. Ron *et al.* 1984). Where possible therefore, palaeomagnetic studies are extended over the maximum area of outcrop so as to image any local structural rotation.

3.2 APPARENT POLAR WANDER MODELS.

The scatter in determined Ordovician poles has led to the development of differing versions of the British Apparent Polar Wander Path (APWP) for the Lower Palaeozoic. Three published paths are outlined and the evidence on which each is based is then assessed. The published models are as follows:

3.2.1) Briden, Turnell & Watts, (1984).

3.2.2) Storetvedt & Deutsch, (1986).

3.2.3) Piper, (1987).

3.2.1 BRIDEN, TURNELL & WATTS. (1984).

Briden *et al.* (1984) attempt to construct Ordovician - Devonian APWP's for three major tectonic blocks within the British Isles. These are :-

a) North of the Great Glen Fault.

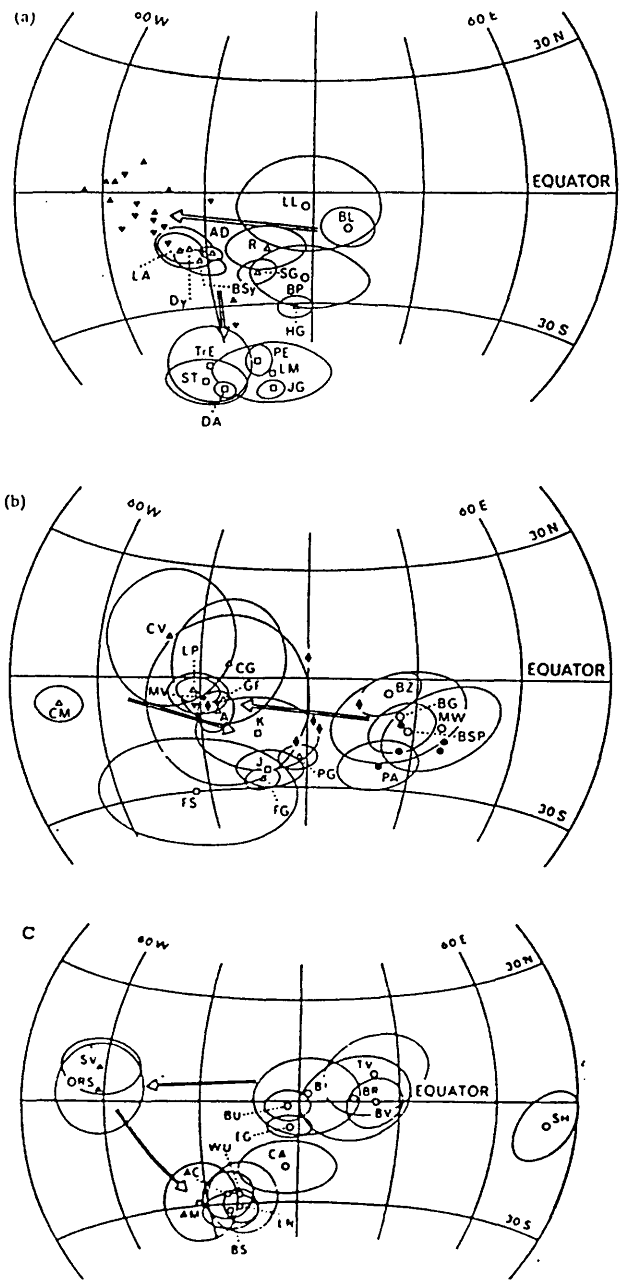
b) South of the Great Glen Fault and North of the Iapetus Suture.

c) South of the Iapetus Suture.

The determined paths from each of these form Figure 3.3 a, b & c respectively.

Differences in the respective APWP's may reflect palaeo-translations along the discontinuities separating the blocks. In this light, conclusions were drawn with respect to the former width of Iapetus and potential large offset along the Great Glen Fault (GGF).

Ordovician poles from north and south of the Iapetus Suture appear systematically offset by approximately 10° of latitude. On the basis of this, Briden *et al.* contend a minimum former width for the Iapetus ocean of 1000 kilometres. Unlike estimations based on consideration of singular poles (e.g. Deutsch, 1980), no formal error can be computed with respect to this figure. The comparison of segments of polar wander between continental blocks affords a more comprehensive approach to the problem however and incorporates a



Abbreviations are explained below but original references are only given for data not included by Briden *et al.* (1984). (a) Data from north of the Great Glen. In the Borrolan Complex BL = Ledmorite, BP = Pseudoleucite and BSy = syenite. LL = Loch Loyal, LA = Lock Ailsh, Dy = Assynt dykes, AD = Achmelvich dyke. Newer Granites: R = Ratagan (Turnell 1985), HG = Helmsdale (Torsvik *et al.* 1983), SG = Strontian (Torsvik 1984). Solid triangles = site mean poles from Moine metasediments; inverted triangles = high blocking temperature components and upright triangles = intermediate blocking temperature components. Orcadian Old Red Sandstone poles are John O'Groats Sandstone (JG) and Lower and Middle Old Red Sandstone (LM). Poles from Stornoway Beds (ST) and Duncansby Volcanic Neck (DA) are also shown although these magnetizations are likely to be Permian or younger (cf. Permian (PE) and Triassic (TrE) poles for Europe). (b) Data from south of the Great Glen. BG and BSP = gabbro and serpentinite of Ballantrae complex; MW = Mweelrea ignimbrites; BZ = Dalradian Barrovian Metamorphics (Watts 1985); PA = Port Askaig tillite (Stupavsky *et al.* 1982) Newer Granites: FG = Foyers (Torsvik 1984), PG = Peterhead (Trosvik 1985), CM = Comrie (Turnell 1985), A = Arrochar and GF = Garabal Hill-Glen Fyne, CG = Cheviot; MV and LP = 'Old Red Sandstone' lavas of Midland Valley and Lorne Plateau; CV = Cheviot Volcanics. Site means from Aberdeenshire Newer Gabbros are denoted by solid circle, diamond and inverted triangle according to whether the localities have inferred K-Ar cooling ages of >463, 463–443 or <443 Myr respectively. Middle and Upper Old Red Sandstone at Foyers (FS) and Jedburgh (J) are also plotted, and the Carboniferous Kinghorn Lavas (K) (Everitt & Belshé 1960).

FIGURE 3.3 ORDOVICIAN TO DEVONIAN PALAEOMAGNETIC POLE POSITIONS FROM THE BRITISH ISLES; Briden, Turnell & Watts. (1984,1986).

a) NORTH OF THE GREAT GLEN FAULT.
b) SOUTH OF THE GREAT GLEN FAULT & NORTH OF THE IAPETUS SUTURE.
c) SOUTH OF THE IAPETUS SUTURE.

much wider dataset. As such, determined estimates of former separation can be treated with greater confidence.

The palaeomagnetic result from the Carrock Fell Complex (Briden & Morris, 1973) contradicts the established relationship. This may be explicable either in terms of unresolved structure (suggested by Briden & Morris) or result from insufficient laboratory demagnetisation (analogous to the revision of the Builth Volcanic Series data, 3.1.2). Recently, Harris & Dagger (1987) suggest a structural reinterpretation which removes the discrepancy in pole position.

The APWP from north of the GGF shows a striking similarity to those of the other tectonic units. This is based largely on results from the Borollan Complex (Turnell & Briden, 1983) and on overprint magnetisations from the Moine metasediments (Watts, 1982). The similarity constitutes strong contradictory evidence to the model of Van der Voo & Scotese (1981) which invokes 2000 kilometres sinistral displacement along the GGF in Carboniferous times (5.3).

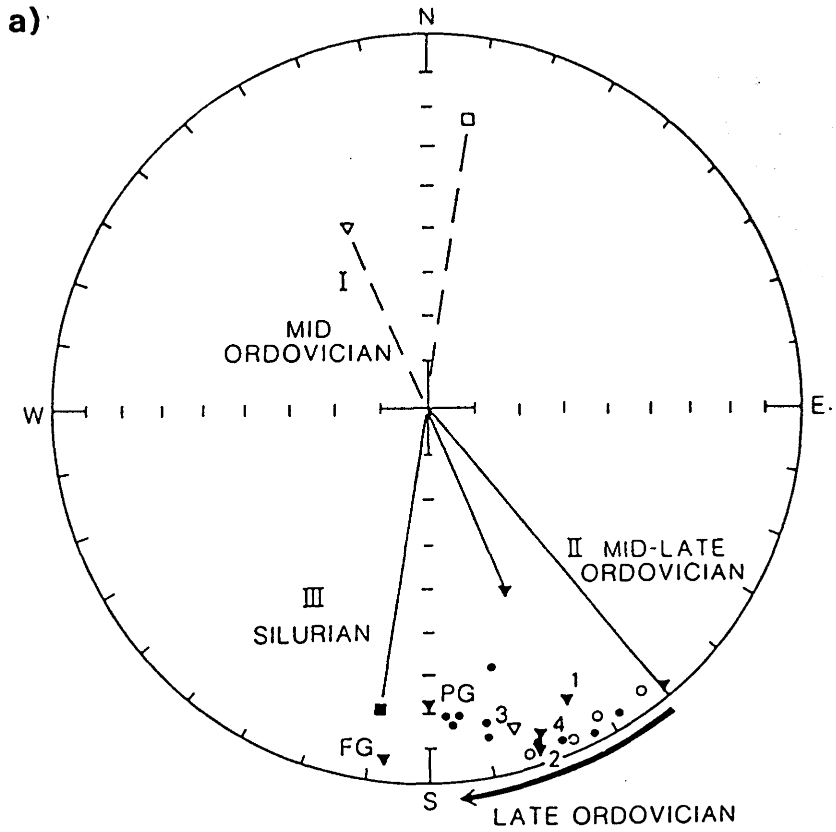
The APWP (Figure 3.3 c) constructed by Briden *et al.* does not include several steep inclination results (e.g Thomas & Briden,1976., Piper *et al.* 1978) reported from the southern margin of Iapetus. This is consistent with the interpretation of Thomas & Briden (1976) that their data reflect an anomalous geomagnetic period of approximately 10 million years. Piper (1979), accounting available radiometric and stratigraphic constraints, suggests this anomalous period to date from Caradocian times. Furthermore he points out that the occurrence of both polarities within the dataset might favour more than one such event.

3.2.2. STORETVEDT & DEUTSCH, (1986).

Storetvedt & Deutsch (1986) select data from the published studies of Turnell & Briden (1983), Stupavsky *et al.* (1982) and Torsvik (1984,1985b) which are then formulated into a proposed Ordovician - Silurian APWP for Scotland. Their revised polar wander path consists of three distinct magnetisation axes (I, II & III) dated as of Mid-Ordovician, Mid-Late Ordovician and Silurian ages respectively (Figure 3.4).

The contention of Watts & Briden (1984) and Briden *et al.* (1984) that the Aberdeenshire Gabbros record a segment of polar wander is rejected by Storetvedt & Deutsch. They argue that the observed directional swathe reflects the mixing of two separate magnetisation axes of equivalent stability. One axis is derived from that reported by Stupavsky *et al.* (1982) in the Upper Pre-Cambrian Port Askaig Tillite. The second axis is the well established Late Silurian - Early Devonian direction recorded in ORS volcanics and intrusives (e.g. Thorning, 1974., Briden, 1970., Torsvik, 1985a).

a)



b) Summary of Ordovician–Silurian palaeomagnetic data from Scotland discussed in the present paper.

Formation	$\bar{N}$	$\bar{D}$	$\bar{I}$	α_{95}	Axis (Fig. 8)	Pole	dp	dm	Reference
Ben Loyal (N & R) +	17	343.6,	-44	11.7	I	190E, 5N	8.6	13.8	Recalculated from Turnell & Briden 1983
Borrolan, inner phase (R)									
Ordovician overprint of									
Eocambrian tillites:									
I) high temp. magnetizn.	3-6	138.7,	-0.9	11.8	II	221E, 25N	5.9	11.8	From Stupavsky et al. 1982
II) clast remanences		155,	14	12	II-III				Stupavsky et al. 1982
III) tillite matrix		162,	4	9	II-III				"
IV) interbedded siltstones		166,	-12	6	II-III				Tarling 1974
Insch/Boganclogh mass	14	162.6,	7.6	7.5	II-III				Carmichael & Storevedt 1981
Borrolan, inner phase (N)	37	012.0[a],	-13.7	6.3	III	162E, 24N	3.3	6.4	Recalc. from Turnell & Briden 1983
Loch Ailsh	28	013.1[a],	-21.6	7.6	III	161E, 20N	4.3	8.1	"
'Assynt' dykes combined	25	007.2[a],	-24.0	5.2	III	167E, 19N	3.0	5.6	"
Peterhead granite		181,	22	5.2	III	178E, 21N	2.9	5.5	Torsvik 1985a
Foyers granite	41	188,	9.2	5.7	III	167E, 27N	2.9	5.8	Torsvik 1984

N is the number of specimen results used in calculation of overall directions. Exceptions are (b) where N is number of sites, and (c) where each of the three unit vectors represents the mean of independent data sets, including up to 44 specimens (clast remanence data). Mean palaeomagnetic declinations, D_m, from NW Scotland, suffixed a, have been corrected for a 20° net clockwise rotation of Northern Highlands (Storetvedt 1986). Other symbols are: I_m mean declination; α_{95} half-angle of the cone of 95 per cent confidence about the mean (in degrees); dp, dm, the semi-axies of the oval of 95 per cent confidence about the mean pole.

FIGURE 3.4 : MID-ORDOVICIAN TO SILURIAN FIELD PATTERN RELATIVE TO SCOTLAND; Storetvedt & Deutsch (1986).

a) Stereographic Projection.
b) Summary of Incorporated Data.

In reply, Briden *et al.* (1986) criticise this model emphasizing there to be no evidence for two overlapping components in their data. This is despite considerable ranges in petrology, intensity and blocking temperature observed over their 500 square kilometre sampling area. Furthermore they restate that the observed variation in K-Ar biotite ages (Dewey & Pankhurst, 1970) relates to waning of orogeny and not to later magmatic events as suggested by Storetvedt & Deutsch.

Magnetisation Axis (I).

Storetvedt & Deutsch define their axis (I) as of mid-Ordovician age derived from a recalculation of selected results from Turnell & Briden (1983).

Unfortunately age constraints relating to the intrusion of the NW Scotland syenites are poor. U-Pb zircon analyses resulted in a spread of results from Lower Silurian - Lower Devonian with a suggested intrusion age of 430 Myrs (van Breeman, Aftalion & Johnson. 1979). Turnell & Briden (1983) concluded their magnetic ages to range from late Ordovician to late Silurian times. Storetvedt & Deutsch (1986) prefer a mid-Ordovician origin for the earliest recorded magnetisations. All in all, the only warranted conclusion appears to be that both magmatic and magnetic ages remain particularly ill-constrained.

Storetvedt & Deutsch reject some of the data of Turnell & Briden as of composite origin drawing attention to smearing of component directions (their Figure 2c, p.1196). They then combine the results of two intrusions to give a best estimate of the mid-Ordovician field axis (I). Briden *et al.* (1986) contest this statistical combination (which enhances the apparent precision of the resulting pole) claiming the two results to be unrelated.

Finally, Storetvedt & Deutsch rotate their combined result through 20° about a local Euler pole. They suggest this to account the net relative rotation of NW Scotland produced by successive translations along the Great Glen Fault (Storetvedt,1987., 5.3).

Magnetisation Axis (II).

Storetvedt & Deutsch quote a revised magnetic overprint direction from the Port Askaig Tillite (Stupavsky *et al.* 1982) as their mid - late Ordovician axis (II). They suggest the smeared component distribution from the Borrolan Outer Phase (Turnell & Briden, 1983., Figure 2c of Storetvedt & Deutsch, 1986) to result from the incomplete resolution of this axis.

Once again the attachment of age and structural constraints to the considered magnetisation (in this case of the tillite) is difficult. Consideration of both the analysis of Storetvedt & Deutsch (1986) and Stupavsky *et al.* (1982) gives rise to several points.

These are discussed as follows:-

1) Storetvedt and Deutsch choose a SE (southeast) horizontal component as representative of the mid-late Ordovician field. Briden *et al.* (1986) note this to be both shallower and more easterly than that originally regarded as the best estimate. This difference arises partly from the laboratory methods employed by Stupavsky *et al.* Pilot specimen cleaning was carried out followed by demagnetisation of all remaining specimens at 20 mT, 550°, 650° and 670°C. Individual poles were calculated for both clasts and matrix of the tillite following each treatment. Best precision was obtained at 550°C and subsequently taken to be a best estimate. At higher treatments, the precision of the determined poles decreases substantially (Stupavsky *et al.*, Table 4 p. 65). This latter point may be attributed either to the influence of randomly orientated laboratory noise or to an invalid assumption that all specimens demagnetise in a similar fashion; the basis of the pilot specimen approximation. In either case, the attachment of special significance to the poorly determined high treatment directions (as adopted by Storetvedt and Deutsch) should be treated with extreme caution.

2), Stupavsky *et al.* show the characteristic magnetisation of the tillite to be a remanence overprint on the basis of a conglomerate test. They regard the overprint to be of pre-folding origin and infer a Lower Ordovician magnetisation age. Storetvedt and Deutsch revise the inferred magnetisation age to mid-late Ordovician but do not cite any new evidence to support this revision. This interpretation seems surprising considering that maximum deformation and metamorphism are thought to have occurred between 510 and 490 Ma (quoted by Stupavsky *et al.* 1982, Dewey and Pankhurst 1970). A minimum age for any pre-deformational overprint must therefore be early Ordovician time.

3), The contention of both Stupavsky *et al.* (1982) and Tarling (1974) that the tillite magnetisation is pre-deformational appears open to question. Neither study is able to statistically demonstrate this point as the tillite is sampled over an area of uniform dip. Arguments therefore relate to the approximation of magnetisation directions to the British Phanerozoic APWP. Tarling (1974) reports two distinct magnetisation axes from the tillite; one is the aforementioned SE and approximately horizontal component (dip corrected); the second has a northeasterly (NE) declination and moderate-steep negative inclination when corrected. Stupavsky *et al.* (1982) interpret this latter direction to represent the widely reported late Silurian-early Devonian axis (e.g. Briden 1970, Latham and Briden 1975), suggesting a pre-deformational origin. A similar pre-deformational age was then inferred for the SE component due to its greater stability during demagnetisation. Despite this representing a plausible palaeomagnetic solution to the respective component ages, it fails to account for the geological controls however, since the Grampian deformation(s) are responsible for the present orientation of the tillite. (The logical implication that the Grampian Orogeny continued into Silurian-Devonian times is at variance with established geological constraints.) Also, their failure to reproduce the NE component on resampling further invalidates its use in constraining the age to deformation relationship of the SE component.

Stupavsky *et al.* contend that the resulting demagnetisation path of the tillite clasts lies within the Palaeozoic APWP when corrected, but outwith the path when uncorrected. Their uncorrected poles move successively away from a present day field direction at the sampling site however and are considered (here) to represent the removal of a recent viscous magnetisation (VRM). (In situ and corrected demagnetisation paths followed by tillite clasts are illustrated in Figure 3.5.) As such, the polar path followed during demagnetisation does not provide useful evidence with respect to the age of the SE directed remanence.

Finally, Stupavsky *et al.* point out that their best estimate results agree better with other Ordovician age data after tectonic correction. This is indeed the case given the then available Ordovician database (Stupavsky *et al.* Figure 6 p. 64). The subsequent revision of particular results, (e.g. the Aberdeenshire gabbros) and addition of new data (e.g. Watts 1985) yields an APWP which better approximates the uncorrected tillite data, however.

Both corrected and uncorrected results are plotted on the APWP of Torsvik (1985) on Figure 3.6. The better approximation is still not significant at the 95% confidence level however (as both corrected and uncorrected poles overlap with the Ordovician cluster) but the weight of evidence now favours a post- rather than pre-deformational magnetisation age. The remagnetisation of the Port Askaig tillite may well be analogous to that observed upon waning of orogeny both for the Aberdeenshire Gabbros (Watts & Briden,1984) and Barrovian zones (Watts,1985).

Given these facts, evidence supporting the proposed Scottish APWP of Storetvedt & Deutsch (1986), which relies heavily on the corrected tillite result, is considerably weakened.

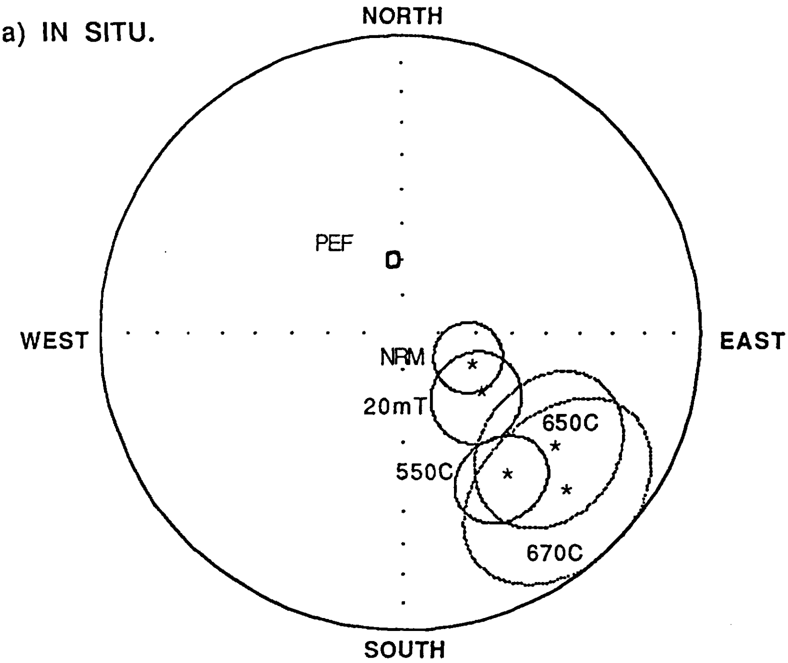
Magnetisation Axis (III)

Storetvedt & Deutsch again select data from Turnell & Briden (1983) together

PORT ASKAIG TILLITE (CLASTS):
MEAN DIRECTIONS DURING DEMAGNETISATION.

(Calculated from Stupavsky et al. 1982)

a) IN SITU.



b) STRUCTURALLY CORRECTED.

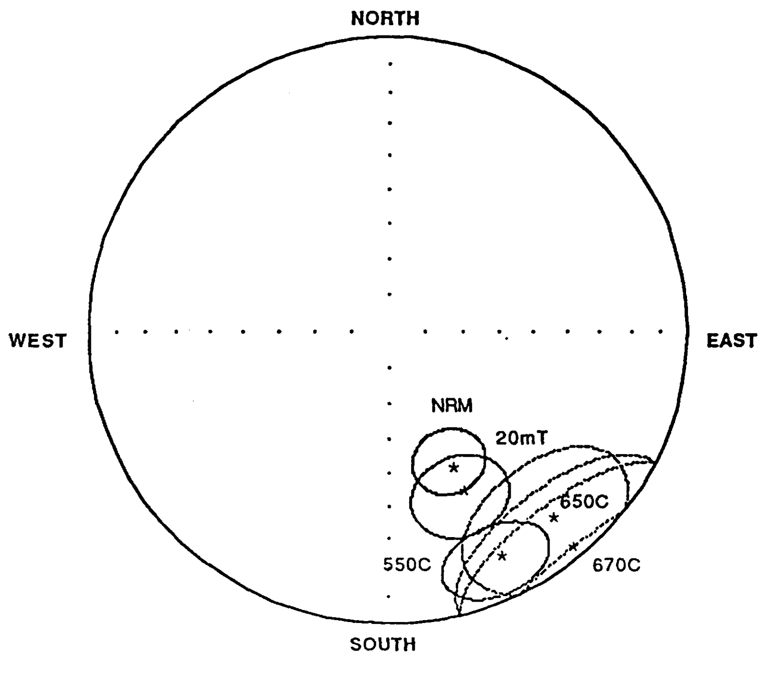


FIGURE 3.5 : IN SITU (a) & CORRECTED (b) DEMAGNETISATION MEAN DIRECTIONS OF PORT ASKAIG TILLITE CLASTS. (calculated from Stupavsky *et al.* 1982).

Note that upon progressive demagnetisation, the *in situ* directions (a) move successively away from a present field direction (PEF) at the site. This indicates removal of a VRM (viscous) component of recent origin.

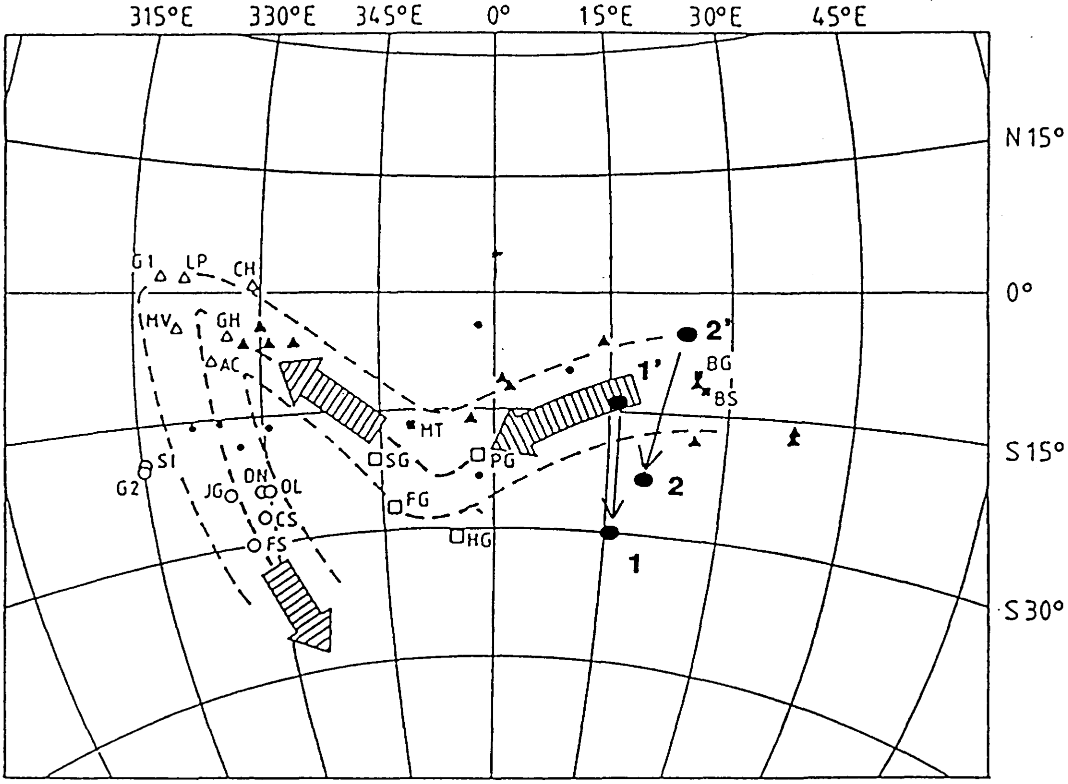


FIGURE 3.6 : UNCORRECTED & TILT CORRECTED POLE POSITIONS FROM THE PORT ASKAIG TILLITE; Stupavsky et al.(1982).

(RESULTS ARE PLOTTED ON THE APWP OF TORSVIK, 1985.)

KEY:
1 Corrected Matrix Pole (550'C).
1' Uncorrected Matrix Pole.
2 Corrected Clast Pole (550'C)
2' Uncorrected Clast Pole.

Note that the uncorrected pole positions better approximate the updated Ordovician data. Abbreviations as Torsvik (1985) & Figure 5.1.

with Newer Granite data (Torsvik 1984, 1985) for their third magnetisation axis (Figure 3.4). They infer any intermediate directed results to reflect incomplete resolution of either axes (II) & (III) e.g. Tarling, 1974., SSE component of Carmichael & Storetvedt, 1981.

Torsvik (1984, 1985) interpretes his Foyers and Peterhead granite poles to represent an earlier part of the APWP than poles derived from other Newer Granites (e.g. Briden 1970., see Figure 5.1). Storetvedt & Deutsch agree with this interpretation taking the granite results to adequately define their axis (III). Palaeomagnetic poles from Newer Granites both north and south of the Great Glen Fault are in general agreement (Torsvik,1985).

Briden *et al.* (1986) point out that the 20° rotation of the NW Highlands required by Storetvedt (1987) leads to internal inconsistency in the Newer Granite data. This point is not discussed in the model of Storetvedt & Deutsch; the Strontian and Helmsdale granite data not having been included in any of their datasets. This observation becomes relevant to the validity of axis (III) as it suggests the correction applied to the Loch Ailsch data (Figure 3.4) to be invalid.

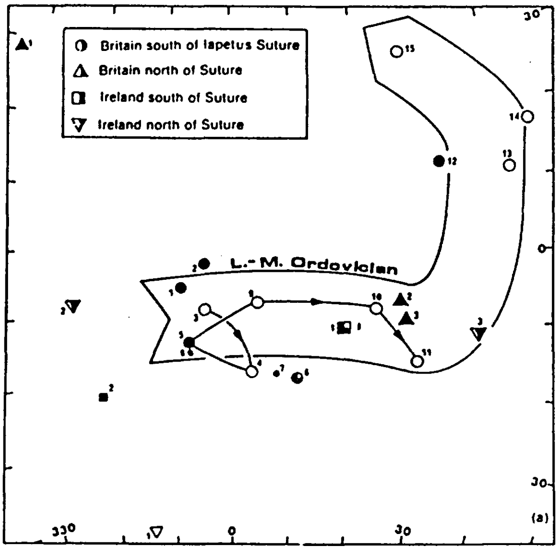
3.2.3 PIPER. (1987).

Piper (1987) suggests an APWP for Britain and Ireland which incorporates the 'steep inclination' data previously regarded as indicative of anomalous Ordovician field behaviour (Thomas & Briden, 1976., 3.2.1). His revised APWP is sub-divided by inferred magnetisation age into units of Lower-Middle Ordovician, Caradoc-Ashgill and Lower Silurian-Permian. These polar wander segments are illustrated in Figures 3.7, 3.8 & 3.9 respectively.

Piper suggests that the Lower-Middle Ordovician records a West to East polar wander for all the major tectonic units of the British Isles (Figure 3.7). This can be accounted by clockwise rotation about a local Euler pole within Britain. A rapid translation of Britain into high latitudes is then required by the Caradoc-Ashgill dataset. This would explain the steep inclination of remanences observed in the North Wales Igneous Province (Thomas & Briden, 1976) and in the Northern Lake District (Piper *et al.* 1979).

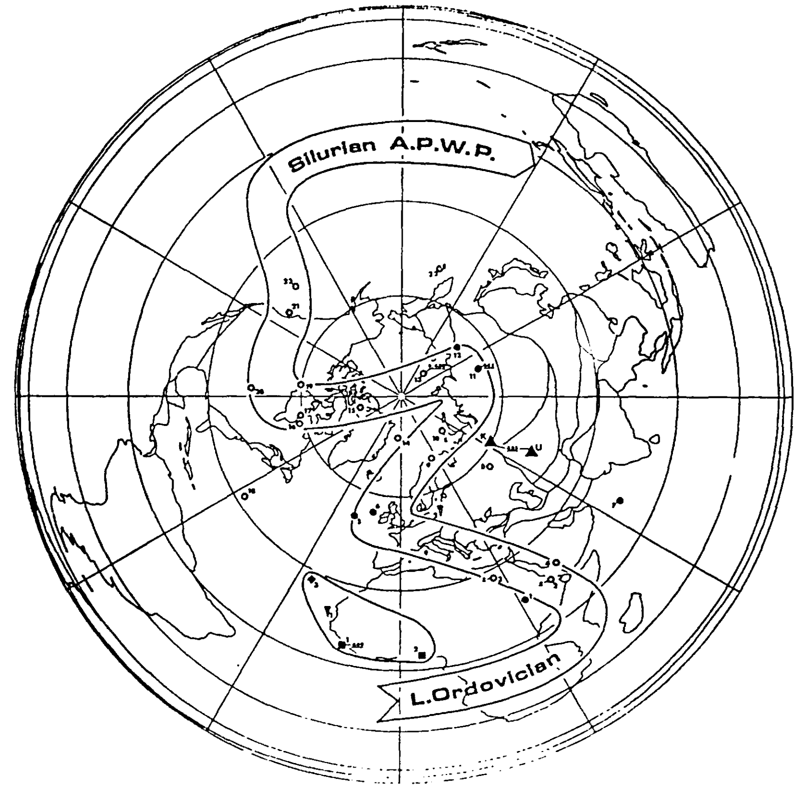
Such a model appears plausible for the southern margin of Iapetus given the considerable number of palaeomagnetic results available. The application of the determined polar wander path to the other tectonic units appears questionable however.

'Anomalous' or steep remanences are reported from a number of intrusives and volcanics from the southern margin of Iapetus but are absent from the northern margin (Figure 3.8). The only possible exception appears to be an overprint direction reported by Taylor (1988) from the Unst ophiolite of Shetland.



(a) Palaeomagnetic results from Britain *and* Ireland *assigned to* Lower and Middle Ordovician *times. The data are separated according to the following tectonic sub-divisions: BRITAIN SOUTH OF THE IAPETUS SUTURE (CIRCLES):* 1, *Trefgarn Andesitic Series (Ol, Arenig);* 2, *Builth Volcanic Series (Ol, Llanvirn);* 3, *Eycott Group (Ol, early Llanvirn);* 4, *Carrock Fell Complex (Ol);* 5, *Round Knott dolerite (Ol-m, <4);* 6, *Stapely Hill Volcanic Series (Ol, Llanvirn);* 7, *Caerfai Series (Cl, O diagenetic remanence);* 8, *Caerbwdy Sandstone (Cl, O magnetisation as for 7?);* 9, *Lowerr Borrowdale Volcanic Series (O, Llandeilo-Lower Caradoc);* 10, *Upper Borrowdale Volcanic Series (O, Llandeilo-Lower Caradoc);* 11, *Upper Borrowdale Volcanic Series, highest levels at Kentmere;* 12, *Haweswater dolerite (O, Upper Llanvirn-early Caradoc);* 13, *Dolerite intrusions, Shelve Inlier, tilt corrected (O, Caradocian);* 14, *E-W dolerite dyke swarm, Welsh Borderland (O, as for 13);* 15, *Moel-y-Golfa andesite (O, Caradoc);* 16, *E-W Kersantite dyke swarm, Northern England (Ou?);* 17, *Breidden Hill dolerite (Ou, Caradoc-mid Ashgill). BRITAIN NORTH OF THE IAPETUS SUTURE (upright triangles):* 1, *Canisp Porphyry (Ol, probably Arenig);* 2, *Ballantrae serpentinites;* 3, *Byne Hill gabbro (Ol-m, 475 KA). IRELAND SOUTH OF THE IAPETUS SUTURE (squares):* 1, *Tramore Volcanics (O, Llanvirn-early Caradoc);* 2, *Grangegeeth Volcanic Series (O, Llanvirn). IRELAND NORTH OF IAPETUS SUTURE (inverted triangles):* 1, *Loch Nafooey Spilites (O, Arenig);* 2, *Glensaul Felsite (O, Arenig);* 3, *Mweelrae ignimbrites (O, mid-Llanvirn).*

FIGURE 3.7 : LOWER - MIDDLE ORDOVICIAN APPARENT POLAR WANDER SEGMENT; Piper (1987).



The "anomalous" Upper Ordovician palaeomagnetic poles from Britain, Ireland and Armorica which define a rapid APW movement during Caradocian and Ashgill times. The preceding and succeeding APWPs are illustrated in Figures 10.2(a) and 10.2(b) respectively. The poles are numbered: BRITAN SOUTH OF THE IAPETUS SUTURE (circles): 1, Haweswater dolerite (Om-u); 2, Dolerite intrusions, Shelve Inlier (O, Caradocian); 3, Moel-y-Golfa andesite (O, Caradoc); 4, E-W dolerite dyke swarm, Welsh Borderlands; 5, Breidden Hill dolerite (Ou, Caradoc-mid Ashgill); 6, E-W kersantite dyke swarm, N. England (Ou); 7, Corndon Hill phacolith (Ou, Caradoc); 8, Gurndu granodiorite; 9, Foel Fras granodiorite; 10, Cader Idris basalts (Ou, Caradoc); 11, Threlkeld-St. John's microgranodiorite (445 RS); 12, WNW dyke swarm, N. England; 13, Stockdale rhyolite (Ou, mid-Ashgill, 430 RS); 14, Lower Borrowdale volcanics, overprint (post-Llandeilo); 15, Penmaenmawr granodiorite; 16, Carreg-y-Llan granodiorite; 17, Penmaenbach rhyolite; 18, Yr Eifl microgranite; 19, Garnfor granodiorite; 20, Bodeilias granodiorite; 21, Myndd Nefn granodiorite; 22, Cautley Fell rhyolite (Ou, Ashgill). IRELAND SOUTH OF IAPETUS SUTURE (diamond): 1, Lambey Island andesite (O). ARMORICAN MASSIF (squares): 1, Thouars massif rocks (Ou, 444 RS); 2, Moulin de Chateaupanne Formation (Ol, Ou diagenetic remanence?). IBERIAN PENINSULA (inverted triangle): limestone (Ol, Arenig-Llanvirn). Pole marked U is the Shetland (Unst) ophiolite A component (435–425 AA). This unit is emplaced onto Dalradian rocks at the northern margin of the Iapetus suture and may define the first closure of the ocean here; its tectonic relationship to the tectonic block south of the suture at this time is, however, unclear. Pole K is a pole from the Karmoy ophiolite of SW Norway with the magnetisation dated ca. 445 Ma. This unit is of similar age and tectonic setting to the Shetland ophiolite but is emplaced onto the opposite foreland of the Caledonian orogen.

FIGURE 3.8 : UPPER ORDOVICIAN (CARADOC-ASHGILL) RAPID APPARENT POLAR WANDER; Piper (1987).

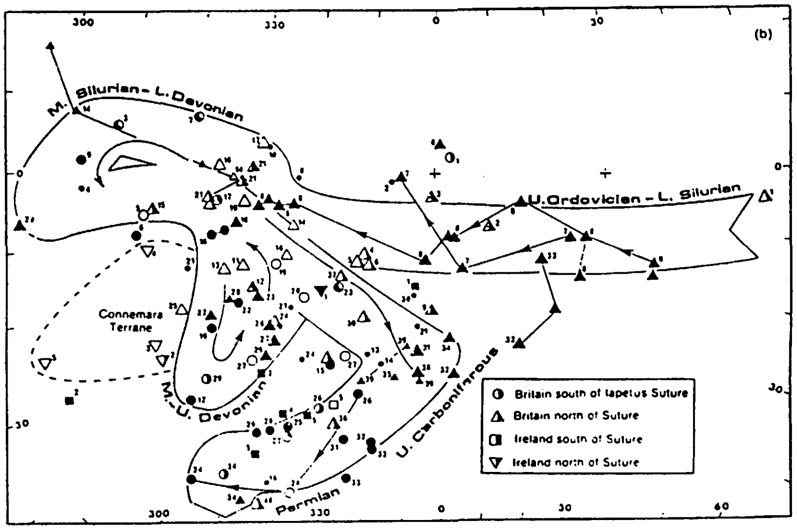


FIGURE 3.9 : SILURIAN - UPPER PERMIAN APPARENT POLAR WANDER SEGMENT; Piper (1987).

(b) Palaeomagnetic results from Britain *and* Ireland *assigned to the interval from* Lower Silurian *to* Upper Permian *times. The data are separated according to the following tectonic sub-divisions: BRITAIN NORTH OF IAPETUS SUTURE (upright triangles):* 1, *WNW-ESE components, micro-diorite – dolerite suite (450–420 KA, RS);* 2, *Borrolan Ledimorite;* 3, *Ben Loyal Complex;* 4, *Dolerite suite, main group (450–420 KA,RS);* 5, *Microdiorite suite (450–420 KA, RS);* 6, *Ratagan complex (415 RS);* 7, *Aberdeenshire gabbros, post-folding uplift remanence, chrontour zone means based mainly on a.f. demagnetised results for >468, 468–443, <443 K-Ar mica ages;* 8, *Aberdeenshire gabbros, uplift remanence, site means based on thermal demagnetisation;* 9, *Borrolan pseudoleucite (430 UP);* 10, *Achmelvich dyke;* 11, *Alkaline dykes, NW Scotland;* 12, *Borrolan syenite;* 13, *Loch Ailsh complex;* 14, *Ratagan and Dalradian metasediments, five poles;* 15, *Morar Division metasediments (480–410 KA);* 16, *Arrochar complex (Su, 418 KA);* 17, *Glencoe complex lavas (Lower ORS, Dl?);* 18, *Lorne Plateau lavas (Su-Dl, 409 KA, 401 RS);* 19, *Garabal Hill-Glen Fyne complex (412 KA, Su-Dl);* 20, *Comrie diorite (408 RS);* 21, *Lower Old Red Sandstone lavas and sediments, Strathmore region (Su-Dl);* 22, *John O'Groats Sandstone (Dm-u);* 23, *Orcadian Basin, Lower to Middle Old Red Sandstone (Dl-Dm);* 24, *Orkney lavas (Dm, 370 AA);* 25, *Esha Ness ignimbrite (Dm);* 26, *Duncansby volcanic neck, B component (258–239 KA, Du remanence?);* 27, *Caithness Sandstone (Dm);* 28, *Unst ophiolite, B component;* 29, *Foyers Old Red Sandstone sediments (Dm);* 30, *Foyers complex (400 KA);* 31, *Helmsdale granite, A group (420 UP, 400 KAB);* 32, *Mainland dykes, Shetland (370 AA);* 33, *Port Askaig tillite, Caledonian overprint, three poles;* 34, *Gamrie outlier red sediments, two poles (Dl-m?);* 35, *Unst ophiolite C component (Dm-u uplift remanence?);* 36, *Northern Highlands lamprophyre dykes (Dm-u);* 37, *Kinghorn lavas (Carbl);* 38, *E-W dolerite dyke swarm, NW Highlands (320 KA);* 39, *Mauchline lavas, sediments and intrusions (P);* 40, *Stornoway Formation, Isle of Lewis (P-T age inferred from remanence direction). BRITAIN SOUTH OF THE IAPETUS SUTURE (circles):* 1, *Dolerite intrusions, Builth Inlier (latest O-early S);* 2, *Diorite dyke, Stile End (Ou-Sl);* 3, *Somerset and Gloucestershire lavas (Sl-m, late Llandovery-early Wenlock);* 4, *Fishguard Volcanic Group (S-D remagnetisation);* 5, *NW-SE dykes, Anglesey (Ou-Du);* 6, *Cautley Fell dolerite (>Carbl);* 7, *Cheviot Volcanic Series (394–374 KA);* 8, *Cheviot granite (383–372 KA);* 9, *Anglo-Welsh Cuvette, Old Red Sandstones (Su-Dl);* 10, *Lizard Complex, tilt corrected (Dl?) remanence;* 11, *NE-SW Minnette dyke swarm, Northern England (Dm-u);* 12, *Shap granite (Su-Dl, 394 RS, 399–394 KA);* 13, *Hendre dolerite (D);* 14, *Blodwell keratophyre (D);* 15, *Upper Old Red Sandstone, Bristol District (Du-Cl);* 16, *Ashprington Volcanic Series (Dm-u, P-Carb remagnetisation?);* 17, *Derbyshire (Miller's Dale) lavas (Carbl);* 18, *Derbyshire lavas (Carbl);* 19, *Cumbrian hematite ore (Carbl?);* 20, *Cockermouth lavas (Carbl);* 21, *Clee Hill sills and contacts, three poles (Carb);* 22, *Draughton Limestone (Carbl, Visean);* 23, *Coal Measures sills and lavas;* 24, *Skomer-Volcanic Group (Sl, Carbu remagnetisation?);* 25, *Carboniferous limestones, Craven Basin (Carbl);* 26, *Carboniferous Limestones, Craven Basin, six poles in stratigraphic order (Carbl, Tournasian-Visean);* 27, *Carboniferous Limestones, Askrigg Block (Carbl, Upper Tournasian-Visean);* 28, *Pendleside Limestone (Carbl, Visean);* 29, *Shatterford intrusion (Carbu);* 30, *Wakerfield dyke (303 KA);* 31, *Whin Sill (295, 281 KA);* 32, *Devonshire sediments (Pl);* 33, *Exeter lavas (Pl, 280 KA);* 34, *St. Bees Sandstone (Pu-T)*. *IRELAND NORTH OF THE IAPETUS SUTURE (inverted triangles):* 1, *Derry Bay Felsite (<S, U. Llandovery);* 2, *Basal Keratophyre, Lough Nafooey (S, U. Llandovery);* 3, *Salrock Group (Sm, Wenlock);* 4, *Knocknaveen Group (S, Wenlock);* 5, *Microgranodiorite intrusion (<Sm, post-Wenlock). IRELAND SOUTH OF IAPETUS SUTURE (squares):* 1, *Chair of Kildare Volcanics (O-S, late Ashgill-early Llandovery)* 2, *Balbriggan-Sherrick's Island volcanics (O, Hercynian remagnetisation?);* 3, *Portrane andesite (O, Hercynian remagnetisation?);* 4, *Limestones, Limerick-Tipperary (Carbl);* 5, *Carboniferous Limestones, five poles (Carbl).*

Piper also suggests the steep magnetisations to be recorded in Baltica citing an occurrence in the Lower-Middle Ordovician limestones of the Baltic foreland in Sweden (Claessen, 1978). The limestones range in age from Arenig to Llanvirn and would therefore require a remagnetisation event to have impressed the observed 'steep' inclinations. In fact, Claessen (1978) reports the limestone remanence to be of 'polyphase' nature and not 'single component' as cited by Piper. Detailed stepwise demagnetisations carried out by Claessen to clarify the polyphase component spectra are shown in Figure 3.10. It is clear that the resultant magnetisations become progressively shallower with increasing thermal treatment and that no stable end point is reached. This evidence strongly suggests the magnetic signature to contain at least two components as put forward by Claessen. There is no evidence therefore to support Piper's contention that the remanence most likely has "a diagenetic origin in Upper Ordovician times".

Previous discussions of the steep inclination results from the southern Iapetus margin had discounted an explanation in terms of apparent polar wander (Thomas & Briden, 1976., Piper, 1979). This was due to the excessive rates of plate motion required by the inferred changes in palaeolatitude. Thomas & Briden (1976) calculate a minimum translation rate of 50 cm/year to be required to explain the 'anomalous' data.

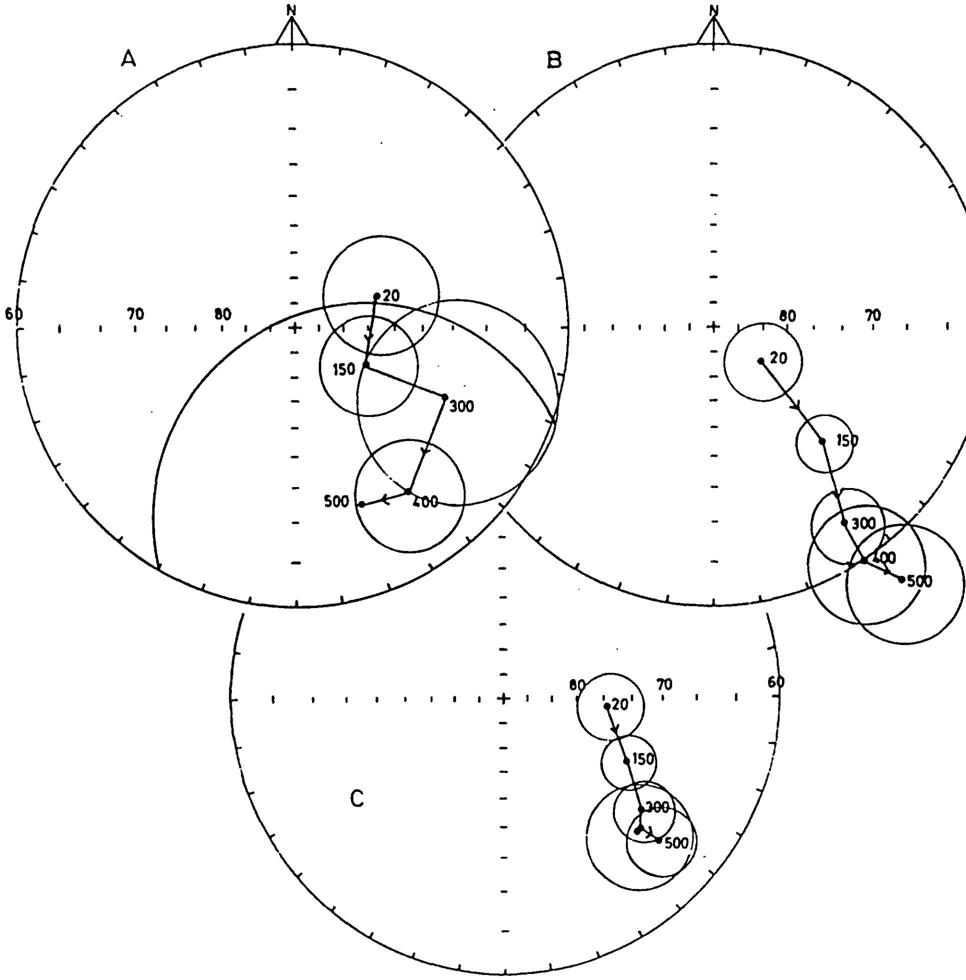
Piper notes that a period of thus far unrecognised rapid polar wander is required to reconcile the continued polarities of the Laurasian and Gondwanan APWP's. McElhinny, Giddings & Embleton (1974) identified this problem proposing a rapid shift in the Early Cambrian Laurentian path. Piper presents an alternative solution with rapid APW applying to both the 'British sub-plate' and one of the other major continents (probably Gondwana) in the mid-late Ordovician. This interpretation implies the APWP of Figure 3.7 to be of *northerly* polarity whilst that of Figure 3.9 becomes of *southerly* polarity.

The results from the Aberdeenshire Gabbros (Watts & Briden, 1984) are attributed a Silurian age (Figure 3.9). Remaining segments of Piper's APWP are equivalent to those of Briden *et al.* with the addition of the Carboniferous and Permian data.

3.3 COMMENTS ON POLAR WANDER MODELS.

The basis of three contrasting polar wander models relating to Ordovician times have been recounted. No single polar wander scheme is able to adequately explain the entire British Ordovician dataset without using either non-dipolar, rapid APW or composite magnetisation origins for some results.

Particular arguments of the model of Storetvedt & Deutsch (1986) have been shown to be ill founded (3.2.2). Also, the application of the rapid APW model of Piper (1987) to the northern margin of Iapetus and to Baltica is as yet inconclusive.



Mean directions of all pilot specimens for each province at different demagnetization levels. All inclinations are positive (down). The circles denote the values of α_{95}. Note the change of scale.
A. Närke, nine specimens. The large value of α_{95} is due to the specimens moving apart in a NE–SW system.
B. Östergötland, eleven specimens.
C. Öland, 30 specimens.

FIGURE 3.10 DIRECTIONAL CHANGES WITH PROGRESSIVE THERMAL DEMAGNETISATION; Claessen (1978).

Note the lack of a stable end point direction following treatment to 500'C.

The Briden *et al.* (1984,1986) model is favoured but relies on non-dipole behaviour to explain certain steep inclination data to the south of the Iapetus suture. Further detailed demagnetisation studies may be required to qualify the true extent of this 'anomalous' dataset (c.f. Claessen, 1978, for Baltica).

CHAPTER 3 : REFERENCES.

Blundell, D.J. and Read, H.H. 1958. Palaeomagnetism of the younger gabbros of Aberdeenshire and its bearing on their formation. *Proceedings of the Geological Association,* 69, 191-204.

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, 457-470.

Briden, J.C. 1972. A stability index of remanent magnetism. *Journal of Geophysical Research,* 77, 1401-1405.

Briden, J.C. and Duff, B.A. 1981. Pre-Carboniferous palaeomagnetism of Europe north of the Alpine orogenic belt. In *Palaeoconstruction of the Continents,* p. 137-149, McElhinny, M.W. and Valencio, D. A. (eds). American Geophysical Union, Washington, D.C.

Briden, J.C. and Morris, W.A. 1973. Palaeomagnetic studies in the Caledonides - III. Igneous rocks of the Northern Lake District, England. *Geophysical Journal of the Royal Astronomical Society,* 34, 27-46.

Briden, J.C. and Mullan, A.J. 1984. Superimposed Recent, Permo-Carboniferous and Ordovician palaeomagnetic remanence in the Builth Volcanic Series. *Earth & Planetary Science Letters,* 69, 413-421.

Briden, J.C., Turnell, H. and Watts, D.R. 1984. British palaeomagnetism, Iapetus Ocean, and the Great Glen Fault. *Geology,* 12, 428-431.

Briden, J.C., Turnell, H. and Watts, D.R. 1986. Reappraisal of Scottish Ordovician palaeomagnetism: Reply to Storetvedt and Deutsch. *Geophysical Journal of the Royal Astronomical Society,* 87, 1207-1213.

Carmichael, C.M. 1967. An outline of the intensity of the palaeomagnetic field of the Earth. *Earth & Planetary Science Letters,* 3, 351-354.

Carmichael, C.M. and Storetvedt, K.M. 1981. Multicomponent magnetization of Ordovician age in the younger gabbros, Aberdeenshire, Scotland. *Geophysical Journal of the Royal Astronomical Society,* 67, 199-215.

Claesson, C. 1978. Swedish Ordovician limestones: problems in clarifying their directions of magnetisation. *Physics of the Earth & Planetary Interiors,* 16, 65-72.

Deutsch, E.R. 1980. Magnetism of the Mid-Ordovician Tramore Volcanics, SE Ireland, and the question of a wide Proto-Atlantic Ocean. *Journal of Geomagnetism & Geoelectricity,* 32, Suppl. III, 77-98.

Dewey, J.F. and Pankhurst, R.J. 1970. The evolution of the Scottish Caledonides in relation to their isotopic age pattern. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 68, 351-389.

Everitt, C.W.F. and Belshé, J.C. 1960. Palaeomagnetism of British Carboniferous system. *Philosophical Magazine,* 5, 675-685.

Halls, H.C. 1976. A least squares method to find a remanence direction from converging remagnetisation circles. *Geophysical Journal of the Royal Astronomical Society,* 45, 297-304.

Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G. and Walters, R. 1982. *A geological time scale.* Cambridge University Press, Cambridge, 131pp.

Harris, P. & Dagger, G.W. 1987. The intrusion of the Carrock Fell Gabbro Series (Cumbria) as a sub-horizontal tabular body. *Proceedings of the Yorkshire Geological Society,* 46, 371-380.

Hoffman, K. A. and Day, R. 1978. Separation of multi-component NRM: a general method. *Earth & Planetary Science Letters,* 40, 433-438.

Jones, O.T. and Pugh, W.J. 1949. An early Ordovician shore-line in Radnorshire, near Builth Wells. *Quarterly Journal of the Geological Society, London,* 105, 65-99.

Kent, J.T., Briden, J.C. and Mardia, K.V. 1983. Linear and planar structure in ordered multivariate data as applied to progressive demagnetization of palaeomagnetic remanence. *Geophysical Journal of the Royal Astronomical Society,* 75, 593-621.

Khramov, A.N. and Rodionov, V.P. 1980. The geomagnetic field during Palaeozoic times. in: *Advances in Earth and Planetary Sciences,* 10, McElhinny, M.W., Khramov, A.N., Ozima, M. and Valencio, D.A. (eds). Academic publications, Tokyo, Japan, 99-116.

Kirschvink, J.L. 1980. The least-squares line and plane and the analysis of palaeomagnetic data. *Geophysical Journal of the Royal Astronomical Society,* 62, 699-718.

McElhinny, M.W. 1966. An improved method of demagnetising rocks in alternating fields. *Geophysical Journal of the Royal Astronomical Society,* 10, 369-374.

McElhinny, M.W., Giddings, J.W. and Embleton, B.J.J. 1974. Palaeomagnetic results and late Precambrian glaciations. *Nature,* 252, 557-561.

McFadden, P.L., and Schmidt, P.W. 1986. The accumulation of palaeomagnetic results from multicomponent analyses. *Geophysical Journal of the Royal Astronomical Society,* 86, 965-981.

Morgan, G.E. 1976. Palaeomagnetism of a slowly-cooled plutonic terrain in western Greenland. *Nature,* 259, 383-385.

Morris, W.A., Briden, J.C., Piper, J.D.A. and Sallomy, J.T. 1973. Palaeomagnetic studies in the British Caledonides - V. Miscellaneous new data. *Geophysical Journal of the Royal Astronomical Society,* 34, 69-105.

Nesbitt, J.D. 1967. Palaeomagnetic evidence for the Ordovician geomagnetic pole position, *Nature,* 216, 49-50.

Pankhurst, R.J. 1970. The geochronology of the basic igneous complexes. *Scottish Journal of Geology,* 6, 83-107.

Piper, J.D.A. 1979. Aspects of Caledonian palaeomagnetism and their tectonic implications. *Earth & Planetary Science Letters,* 46, 443-461.

Piper, J. D. A. 1987. *Palaeomagnetism and the continental crust.* Open University Press, Milton Keynes. pp.434.

Piper, J.D.A. and Briden, J.C. 1973. Palaeomagnetic studies in the British Caledonides - I. Igneous rocks of the Builth Wells-Llandrindod Wells Ordovician Inlier, Radnorshire, Wales. *Geophysical Journal of the Royal Astronomical Society,* 34, 1-12.

Piper, J.D.A., McCook, A.S., Watkins, K.P., Brown, G.C. and Morris, W.A. 1978. Palaeomagnetism and chronology of Caledonian igneous episodes in the Cross Fell Inlier and Northern Lake District. *Geological Journal,* 13, 73-92.

Pullaiah, G., Irving, E., Buchan, K.L. and Dunlop, D.J. 1975. Magnetisation changes caused by burial and uplift. *Earth & Planetary Science Letters,* 28, 133-143.

Ron, H., Freund, R. Garfunkel, Z. and Nur, A. 1984. Block rotation by strike-slip faulting: structural and palaeomagnetic evidence. *Journal of Geophysical Research,* 89, 6256-6270.

Sallomy, J.T. and Piper, J.D.A. 1973. Palaeomagnetic studies of the British Caledonides - II. The Younger Gabbros of Aberdeenshire, Scotland. *Geophysical Journal of the Royal Astronomical Society,* 34, 13-26.

Stewart, H.H. and Johnson, M.R.W. 1960. The structural problem of the Younger Gabbros of northeast Scotland. *Transactions of the Edinburgh Geological Society,* 18, 104-112.

Storetvedt, K.M. 1986. Major late Caledonian and Hercynian shear movements on the Great Glen Fault. *Terra Cognita,* 6, 341.

Storetvedt, K.M. 1987. Major late Caledonian and Hercynian shear movements on the Great Glen Fault. *Tectonophysics,* 142, 253-267.

Storetvedt, K.M. and Deutsch, E.R. 1986. Reappraisal of Scottish Ordovician palaeomagnetism. *Geophysical Journal of the Royal Astronomical Society,* 87, 1193-1206.

Stupavsky, M., Symons, D.T.A. and Gravenor, C.P. 1982. Evidence for metamorphic remagnetisation of Upper Precambrian tillite in the Dalradian Supergroup of Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 73, 59-65.

Tarling, D.H. 1974. A palaeomagnetic study of Eocambrian tillites in Scotland. *Journal of the Geological Society, London,* 130, 163-177.

Tarling, D.H., Donovan, R.N., Abou-Deeb, J.M. and El-Batrouk, S.I. 1976. Palaeomagnetic dating of haemetite genesis in Orcadian Basin sediments. *Scottish Journal of Geology,* 12, 125-134.

Thomas, C. and Briden, J.C. 1976. Anomalous geomagnetic field during the late Ordovician. *Nature,* 259, 380-382.

Thorning, L. 1974. Palaeomagnetic results from the Lower Devonian rocks of the Cheviot Hills. Northern England. *Geophysical Journal of the Royal Astronomical Society,* 487-496.

Torsvik, T.H. 1984. Palaeomagnetism of the Foyers and Strontian granites, Scotland. *Physics of the Earth & Planetary Interiors,* 36, 163-177.

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

Torsvik, T.H. 1985b. Palaeomagnetic results from the Peterhead granite, Scotland; implication for regional late Caledonian magnetic overprinting. *Physics of the Earth & Planetary Interiors,* 39, 108-117.

Torsvik, T.H., Lovlie, R. and Storetvedt, K.M. 1983. Multicomponent magnatization in the Helmsdale Granite, North Scotland: geotectonic implications. *Tectonophysics,* 98, 111-129.

Turner, P. and Archer, R. 1975. Magnetisation history of the Lower Old Red Sandstone from the Gamrie Outlier, Scotland. *Earth & Planetary Science Letters,* 27, 240-250.

Turnell, H.B. 1985. Palaeomagnetism and Rb-Sr ages of the Ratagan and Comrie intrusions. *Geophysical Journal of the Royal Astronomical Society,* 83, 363-378.

Turnell. H.B. and Briden, J.C. 1983. Palaeomagnetism of NW Scotland syenites in relation to local and regional tectonics. *Geophysical Journal of the Royal Astronomical Society,* 68, 279-291.

Van Breeman, O., Aftalion, M. and Johnson, M.R. 1979. Age of the Loch Borrolan Complex, Assynt, and late movements along the Moine Thrust Zone. *Journal of the Geological Society, London,* 136, 489-495.

Van der Voo, R. and Scotese, C. 1981. Palaeomagnetic evidence for a large (2000km) sinistral offset along the Great Glen Fault during Carboniferous time. *Geology,* 9, 583-589.

Watts, D.R. 1982. A multicomponent dual polarity palaeomagnetic regional overprint from the Moine of Northwest Scotland. *Earth & Planetary Science Letters,* 61, 190-198.

Watts, D.R. 1985. Palaeomagnetic resetting in the Barrovian zones of Scotland and its relationship to the late structural history. *Earth & Planetary Science Letters,* 75, 258-264.

Watts, D.R. and Briden, J.C. 1984. Palaeomagnetic signature of slow post-orogenic cooling of the north-east Highlands of Scotland recorded in the Newer Gabbros of Aberdeenshire. *Geophysical Journal of the Royal Astronomical Society,* 77, 775-788.

Wilson, J.T. 1966.'Did the Atlantic close and then reopen?' *Nature,* 211, 676-679.

Zijderveld, J.D.A. 1967. AC demagnetization of rocks; analysis of results. in: *Methods in Palaeomagnetism,* 254-286, Collinson, D.W., Creer, K.M. and Runcorn, S.K. (eds). Elsevier, New York.

CHAPTER 4: PALAEOMAGNETIC STUDY OF THE SLOCKENRAY FORMATION WITHIN THE BALLANTRAE OPHIOLITE: MAGNETOTECTONIC & REGIONAL TECTONIC IMPLICATIONS.

4.1 INTRODUCTION & GEOLOGICAL BACKGROUND.

The Early Ordovician Ballantrae Ophiolite is exposed over an area of approximately eighty square kilometres on the Ayrshire coast of SW Scotland. The ophiolite comprises a heterogeneous assemblage of oceanic and mantle derived lithologies which have become structurally juxtaposed during obduction (Thirlwall & Bluck, 1984). The outcrop area is dominated by two SW-NE trending tracts of ultramafic rocks and spilites referred to as the southern and northern belts of the ophiolite (Figure 4.1). The ophiolitic character of the complex was first recognised by Church & Gayer (1973) and Dewey (1974). Subsequently, the ophiolite has played an important role in the moulding of tectonic models for Caledonian Britain. The original tectonic setting is controversial however and various authors invoke ocean island, marginal basin and oceanic ridge settings for ocean crust generation (cf. Barrett *et al.* 1982., Bluck, 1982., Lambert & McKerrow, 1976).

The present palaeomagnetic study focuses on the Slockenray Formation of the northern belt. This unit is comprised of a sequence of spilitic lavas together with a variety of intercalated sediments. The present investigation considers samples from all the exposed lithologies of the Slockenray Formation including an intra-formational conglomeratic facies. The sampled area is bounded on the south side by a major fracture and to the north by an unconformable younger sedimentary sequence (Figure 4.1). Large scale outcrop maps (Bluck, 1982) were used to constrain stratigraphic, structural and geographic control for the palaeomagnetic sampling sites.

An additional palaeomagnetic conglomerate test was performed in the Benan Conglomerate of mixed source provenance containing volcanic clasts likely derived from the Ballantrae Ophiolite. This conglomerate forms part of a proximal fore-arc assemblage founded on the obducted ophiolite complex (Longman *et al.* 1979). Figure 4.1 shows the geographic and stratigraphic positions of the Slockenray Formation and Benan Conglomerate.

The Slockenray Formation is Arenig in age (Rushton *et al.* 1986., Stone, 1984) which accords well with radiometric determinations elsewhere in the ophiolite summarised by Hamilton *et al.* (1984). Macrofossil evidence from a lateral equivalent of the overlying Benan Conglomerate dates the unit as of Llandeilo age (Ingham, 1978., Ince, 1984).

Previous palaeomagnetic results from the ophiolite, i.e. Nesbitt (1967) and Piper (1978) have been incorporated with other British Ordovician data in apparent polar wander schemes (e.g. Briden *et al.* 1973., 1984). This carries the assumption of a

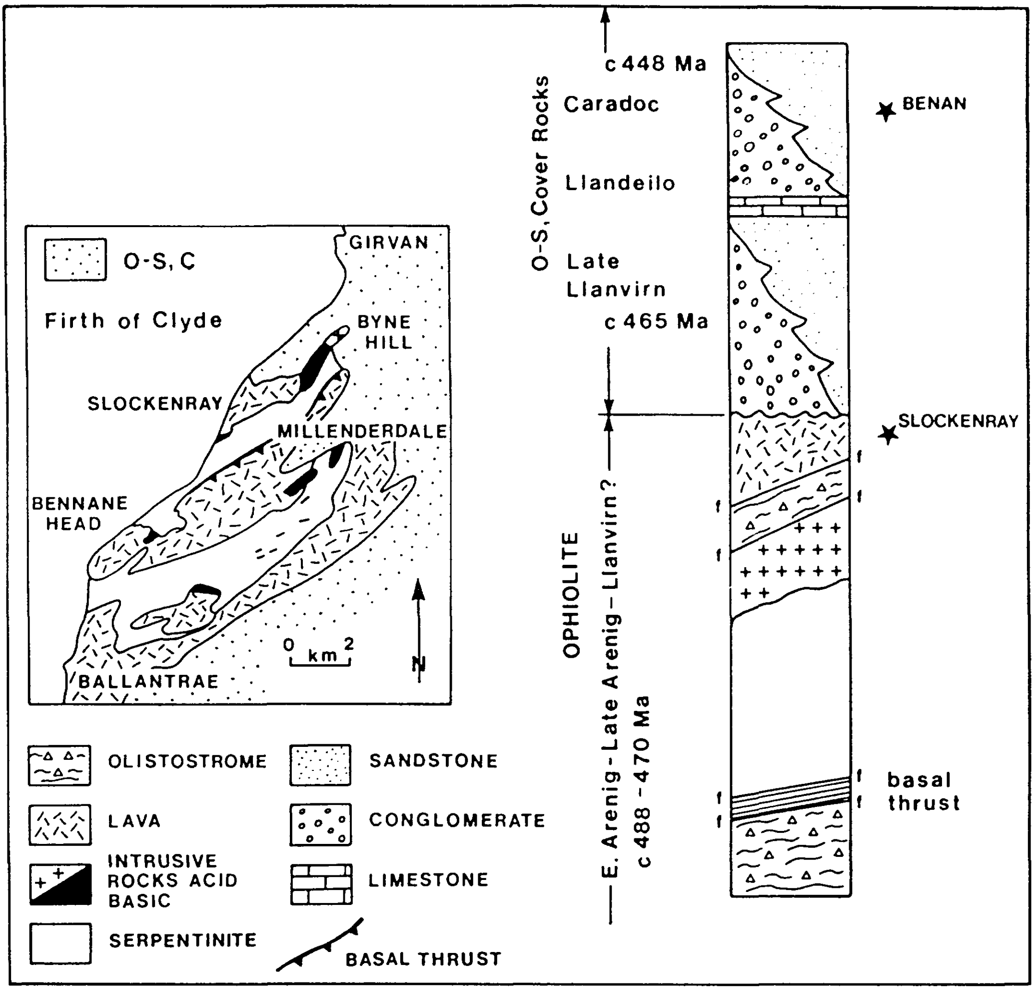


Figure 4.1 : Geological sketch map and stratigraphic vertical section of the Ballantrae area. Sampled Conglomerates are starred., f ; faulted contact., O-S; Ordovician/Silurian Cover rocks.

post-obduction origin for the recovered magnetisations as no accretion-related deformation was accounted for.

The present study was therefore aimed at the uncovering of 'primary' or pre-obduction magnetisations using more detailed demagnetisation analyses compared with these earlier studies. Also the availability of a detailed map of this part of the complex affords the opportunity to deal with structural complexity using the palaeomagnetic data interactively. It was hoped that constraints might then be placed with respect to the tectonic evolution of the ophiolite in the context of the British Caledonides.

4.2 SAMPLING & METHODS.

Palaeomagnetic sampling sites were chosen to incorporate all the exposed lithologies of the Slockenray Formation. These included sheet lavas, pillow lavas, shale, chert, lithic arenites and lithic tuffs (15 sites, 97 samples; Table 4.1). Both intra-and extra-formational conglomerates were sampled to test the stability of identified magnetisation components (Slockenray Conglomerate, 19 clasts; Benan Conglomerate, 21 clasts).

A portable petrol driven drill was used to collect 2.5 cm diameter samples oriented using both magnetic and solar compass wherever possible. All sites were located on the large scale outcrop maps (Bluck, 1982. & Figure 4.2) and comprised at least five independently oriented samples. Samples were later trimmed to 2.3 cms. in height in the laboratory.

Remanent magnetisation measurements were made using a complete result fluxgate magnetometer (Molyneux, 1971). Thermal and AF cleaning techniques were performed on samples in the approximate ratio 2:1. Thermal demagnetisation was carried out using two (mu-Metal shielded) ovens capable of holding a combined total of 18 samples. A.F. demagnetisation proceeded using a micro computer controlled static three-axis system working at 186 Hertz.

Demagnetisation results were plotted on Zijderveld (1967) diagrams/orthogonal projections and interpreted interactively utilising the LINEFIND statistical analysis algorithm (Kent *et al.* 1983).

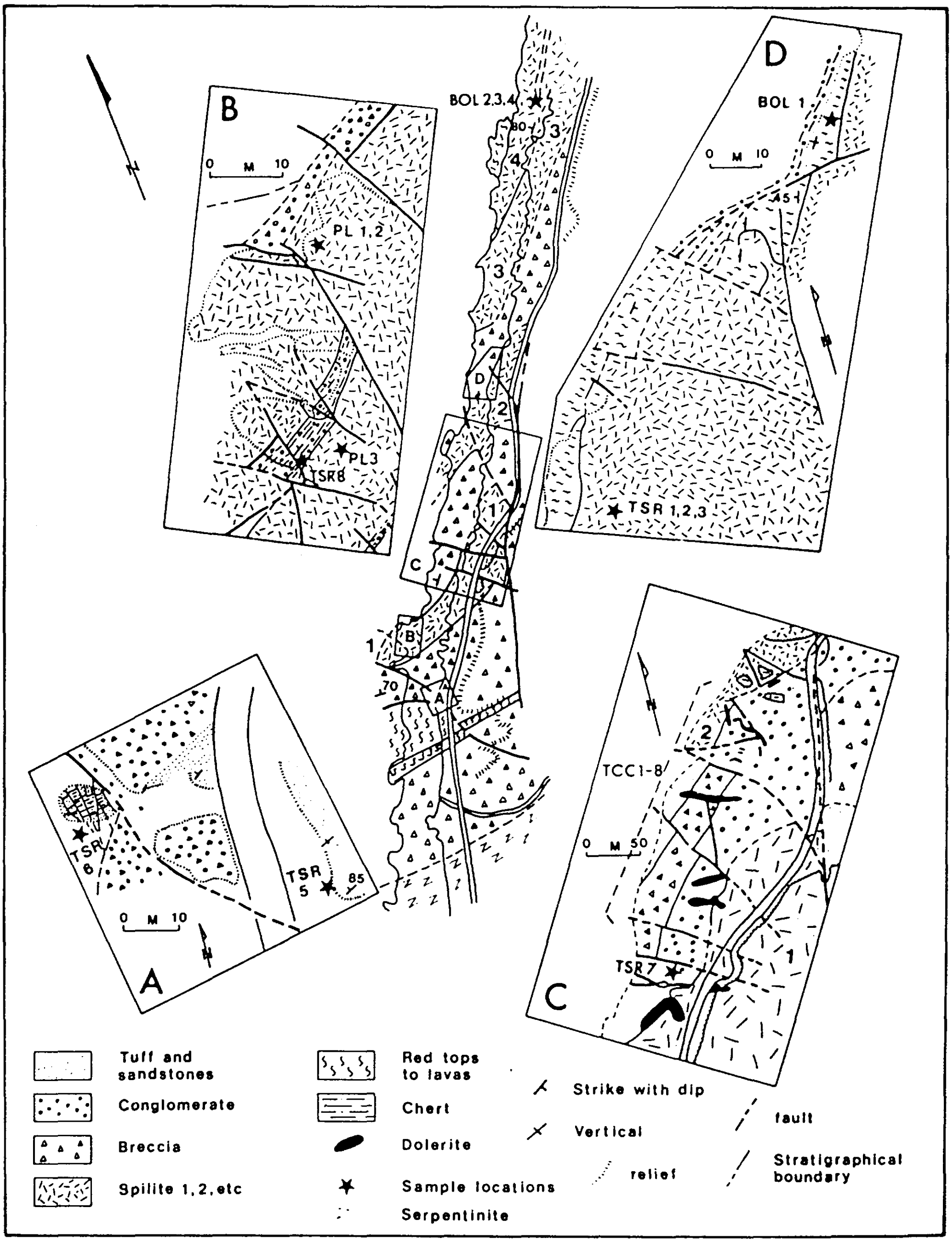


Figure 4.2 : Simplified large scale outcrop maps of the Slockenray section show the distribution of palaeomagnetic sampling sites. Spilite numbers are those of Bluck (1982).

4.3 RESULTS OF PALAEOMAGNETIC ANALYSIS.

4.3.1 GENERAL.

NRM intensities vary considerably between sample sites expectantly reflecting the variation in sampled lithology. In general, the volcanic samples have greater magnetic moments than the intervening sediments although sites of particularly weak intensity (< 5 mA/m) for both lithological realms were discovered. Ranges of NRM intensity determined at each site are illustrated in Figure 4.3. Laboratory cleaning techniques produced good results independent of initial NRM intensity throughout the study.

NRM directions are reasonably well grouped with southerly declinations and moderate positive inclinations. Generally, on cleaning, resultant directions tended towards shallower inclinations reflecting the removal of a present day field direction (cf. Figure 4.4 a & b).

Both thermal and A.F. cleaning methods were both found to successfully resolve magnetisation components for the majority of site lithologies. Usually two components of magnetisation are resolved within the samples of the study. A 'soft' component (S) generally removed below 200°C/10mT evolves gradually to a more stable component (M) which decays linearly to the origin by approximately 560°C/60-100mT. Typical examples of characteristic demagnetisation behaviour are illustrated in Figure 4.5 for both thermal (a) and AF (b) treatment.

The soft component (S) aligns close to a present day field in situ and is undoubtedly of VRM (viscous) origin. The more stable component (M) varies in attitude in situ and forms a swathe of directions of SE-SW declination and moderate positive to shallow negative inclinations, (Figure 4.4 b, Table 4.1). Component (M) forms the characteristic magnetisation of the formation and occurs in all samples; Component (S) is sometimes absent or only expressed as a minor kink in the demagnetisation projection following the first demagnetisation step.

Exceptions to this typical demagnetisation behaviour are three-fold:

a) Sites BOL1-BOL3.

These sites comprise a reddened lava top (BOL1) and reddened lithic tuff units (BOL2-3) within the Formation. Although true boles (palaeosoils) are not developed, Smellie (1984) suggests subaerial weathering as a possible explanation for the reddening. Thermal and AF demagnetisation of these sites is dual component as for previous sites but the stability spectrum of component (M) is extended. Thermal demagnetisation produces two discrete unblocking temperatures of remanence in the 500-560°C and >600°C thermal

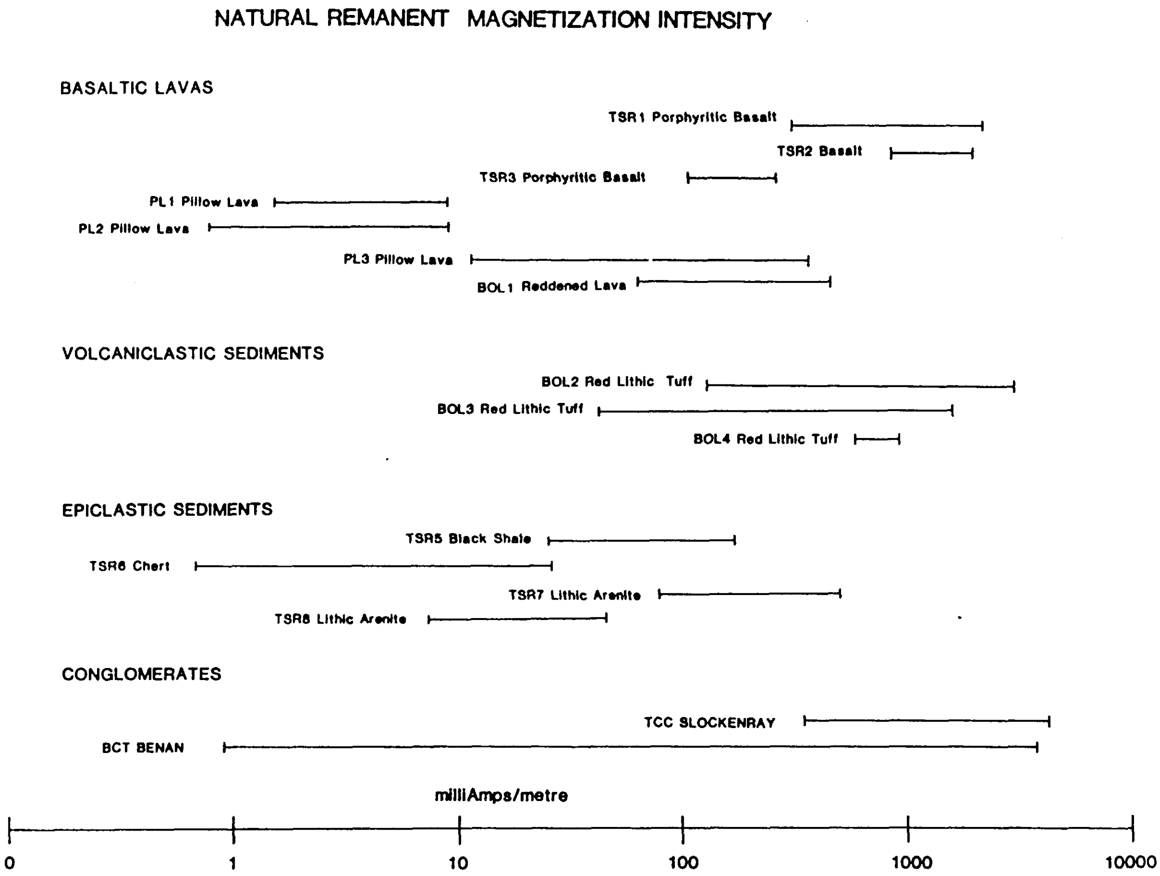
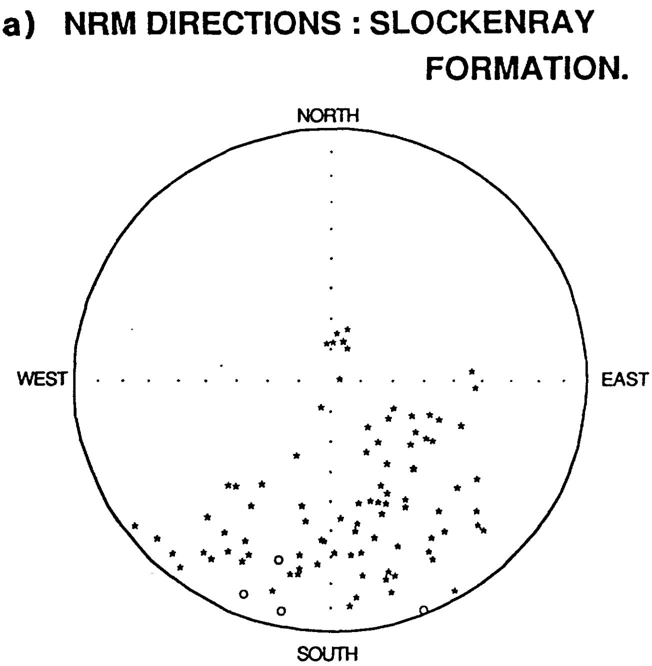


Figure 4.3 : Ranges of Natural Remanent Magnetisation (NRM) intensity determined for different sampling sites. Values are plotted against a logarithmic scale.



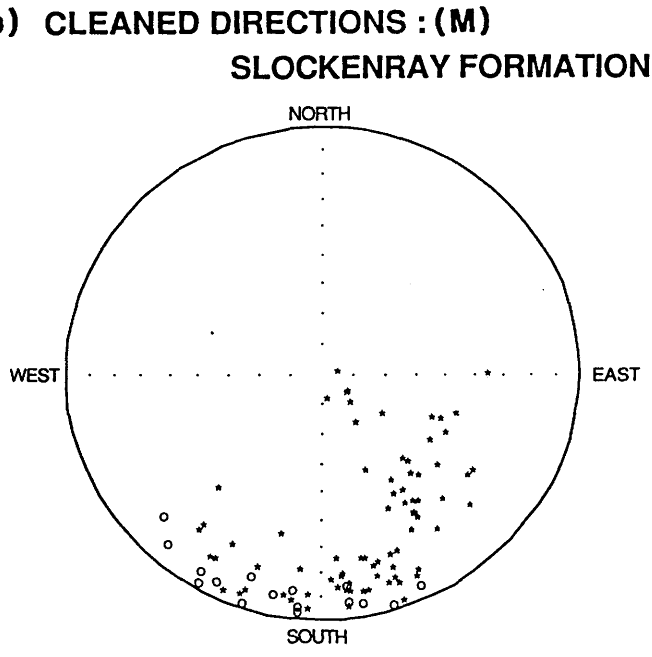


Figure 4.4 : Directional distribution of NRM (a) and component (M), (b), from the Slockenray Formation. Starred symbols denote downward pointing magnetisations; open circles upward pointing magnetisations.

SITE LITHOLOGIES & SITE MEAN FISHER STATISTICS. (COMPONENT M)

LITHOLOGY	SITE	N	α 95	K	(In Situ) D°	(In Situ) I°	(Strike Corrected) D°	(Strike Corrected) I°	(Plunge Fold Corrected) D°	(Plunge Fold Corrected) I°
PORPHYRITIC BASALT	TSR1	5	9.7	62.8	150.1	43.6	301.5	48.6	278	48.6
BASALT	TSR2	6	9.7	49.0	155.7	26.9	279.8	60.7	258	60.7
PORPHYRITIC BASALT	TSR3	6	7.1	91.1	144.5	40.2	306.3	53.1	285	53.1
BLACK SHALE	TSR5	5	14.6	28.3	204.1	1.5	249.6	51.6	202	51.6
CHERT	TSR6	6	19.9	12.3	210.1	11.4	276.3	49.3	222	49.3
LITHIC ARENITE	TSR7	6	8.9	57.0	164.9	15.4	212.1	44.6	207	44.6
LITHIC ARENITE	TSR8	6	11.8	33.1	176.3	-2.3	203.2	36.0	198	36.0
PILLOW LAVA	PL1	11	6.9	44.2	167.2	10.2	209.3	56.1	207	56.1
PILLOW LAVA	PL2	8	6.4	77.0	174.5	11.1	215.0	49.8	211	49.8
PILLOW LAVA	PL3	7	12.0	26.4	188.2	4.5	213.8	29.4	202	29.4
REDDENED LAVA	BOL1	6	12.7	28.6	206.6	9.6	222.7	9.3	216	9.3
RED LITHIC TUFF	BOL2	7	18.4	11.7	128.4	27.8	265.9	53.4	258	53.4
RED LITHIC TUFF	BOL3	7	13.4	21.3	126.7	51.6	279.2	39.8	278	39.8
RED LITHIC TUFF	BOL4	5	4.9	241.5	150.3	76.8	283.0	15.2	282	15.2
SLOCKENRAY CONGLOMERATE	TCC1-8	30*	9.0	9.5	171.0	21.3				
		19#	10.3	11.5	167.9	21.4				
BENAN CONGLOMERATE	BCT1-24	37*	22.4	2.1	351.5	56.7				
		21#	29.2	2.2	354.9	61.9				

TABLE 4.1 : Site Lithologies and Site Mean Fisher Statistics for the Slockenray Formation (Component M) and Benan Conglomerate.

Statistics are outlined both by Clast (#) and by Sample (*) for the Conglomerate analyses. Notation is as follows;

N:- Number of samples., K:- Fisher Precision Parameter., D°:- Palaeomagnetic declination.,

I°:- Palaeomagnetic Inclination., α95:- cone of 95% confidence.

note: Component M was not recovered from ten samples of clast TCC1 (Slockenray Conglomerate) or from two samples of site BOL4 (AF demagnetisation).

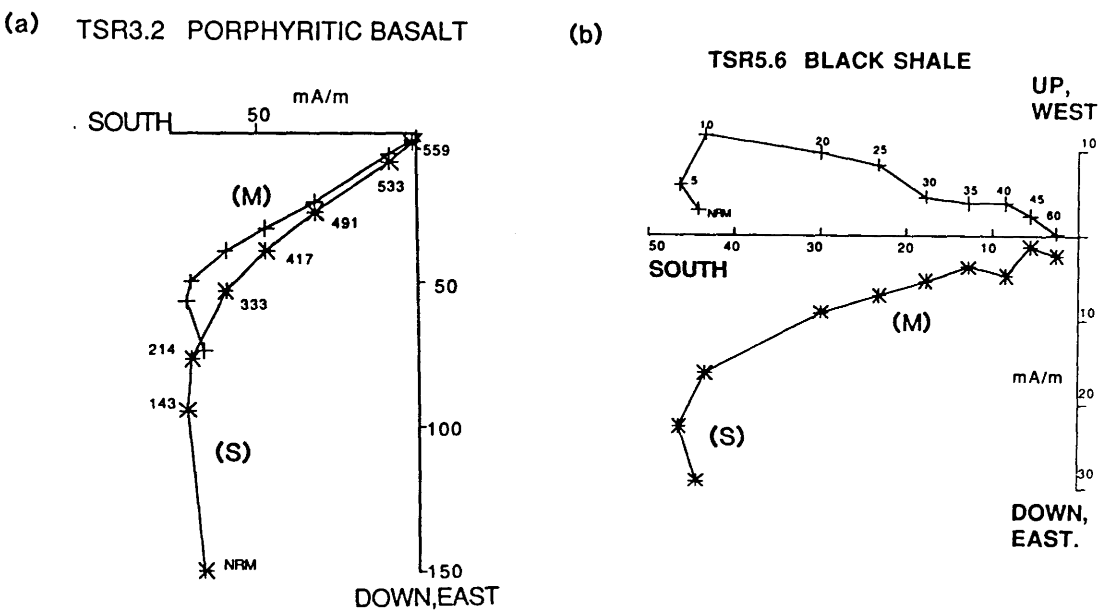


Figure 4.5 : Examples of orthogonal projections showing components (S) and (M) defined by both thermal (a) and AF (b) cleaning methods for the Slockenray Formation. Throughout this paper crossed symbols in the orthogonal vector diagram refer to points in the horizontal plane and starred symbols to points in the vertical plane. Thermal (AF) treatments are always given in degrees Celsius (milliTesla).

windows. Figures 4.6 a-c illustrate this behaviour for sample BOL1.3. LINEFIND analysis confirms the decay of the magnetic vector to be univectorial spanning both unblocking spectra. A.F. demagnetisation of samples is incomplete at 100mT indicating the presence of a high coercivity remanence phase (Figure 4.6 d).

b) Site BOL4.

This site was also sampled in a reddened lithic tuff unit. Demagnetisation using both cleaning methods again reveals the presence of two components of magnetisation. The stability properties of components (S) and (M) are markedly different from those previously described however. Component (S) is found to predominate over component (M) in relative intensity at this site. Thermal demagnetisation removes only component (S) until temperatures exceeding 250°C and curvature of orthogonal projections indicates considerable overlap of component stability to temperatures approaching 600°C (Figure 4.7 a-b). AF demagnetisation is incomplete after treatment at 100mT and reveals only component (S). The existence of component (M) is demonstrated as the demagnetisation does not proceed to the origin however (Figure 4.7 c-d).

c) Site TSR6.

For several samples of the study, the LINEFIND statistical algorithm is unable to successfully include the origin within the stable magnetisation decay defined by component (M). This effect is particularly evident for the cherts sampled (TSR6) for which component (M) visibly decays past the origin (Figure 4.8).

Possible explanations for this behaviour are discussed by Klootwich (1980) and are as follows:-

-Inhomogenous magnetisation (Collinson, 1977) which becomes more prominent as demagnetisation continues.

-Presence of an unidentified additional magnetic component. Noise levels preclude the identification of such a component for this site.

-VRM acquisition due to a residual field within the magnetic shield of the thermal demagnetiser.

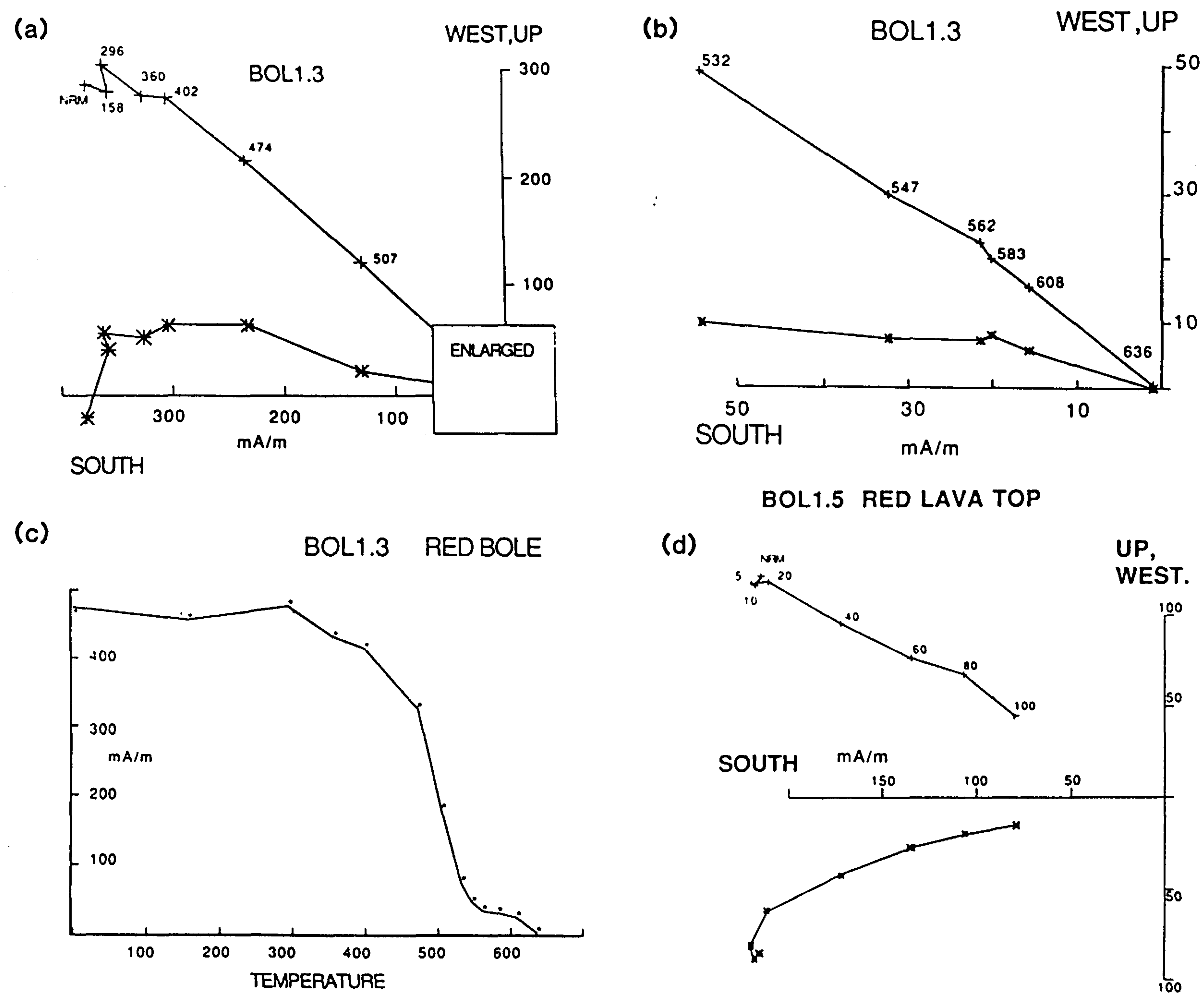


Figure 4.6 : Orthogonal projections (a,b,d) and Intensity/Temperature distribution (c) record the response of site BOL1 to thermal (a,b,c) and A.F. (d) cleaning. The high treatment results of sample BOL1.3 (a) have been enlarged (b) to illustrate their linear demagnetisation close to the origin.

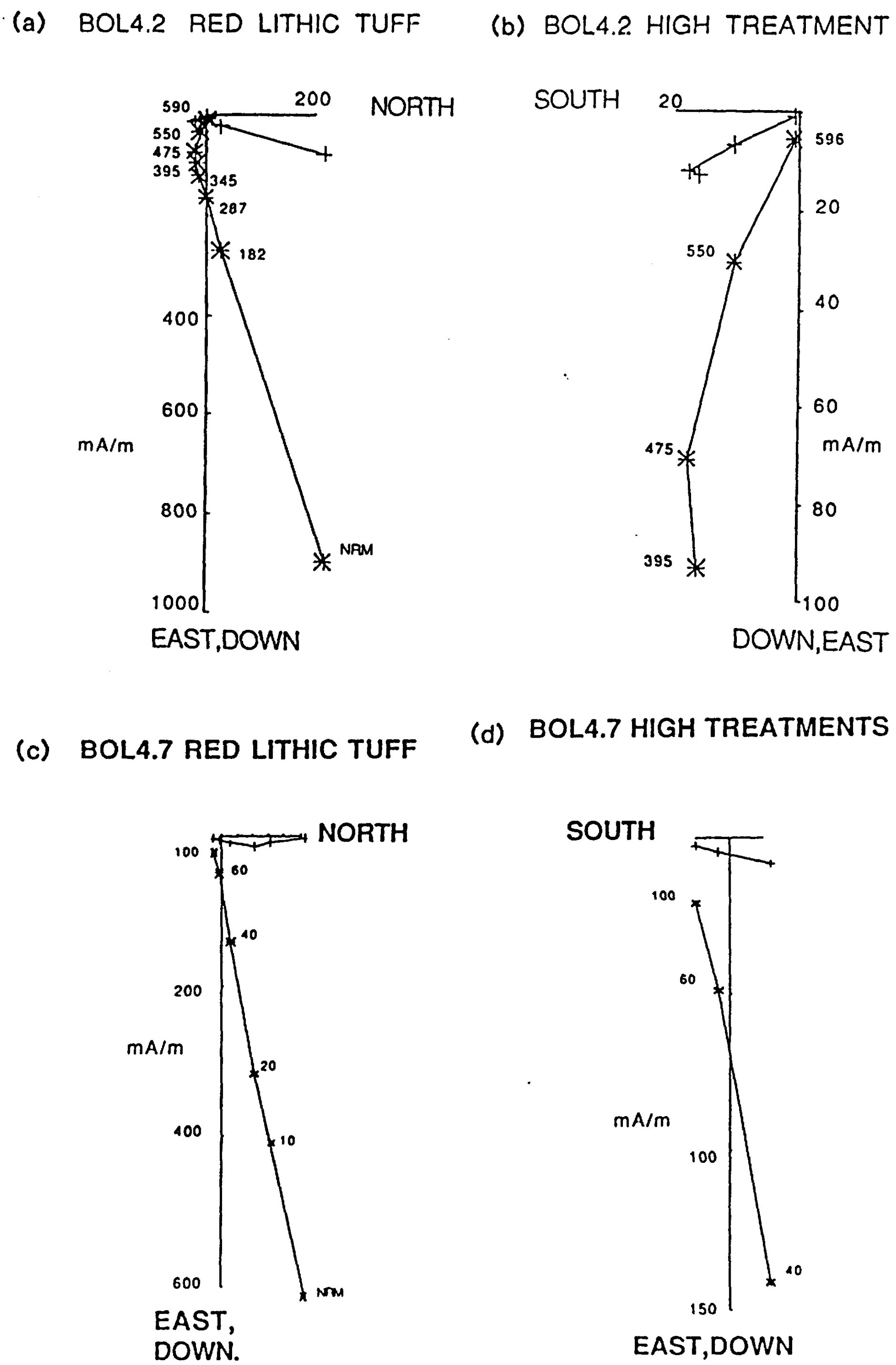


Figure 4.7 : Orthogonal projections record the demagnetisation behaviour of site BOL4 to thermal (a,b) and AF (c,d) cleaning. Enlarged projections (b,d) are included to show the dual component nature of remanence revealed close to the origin.

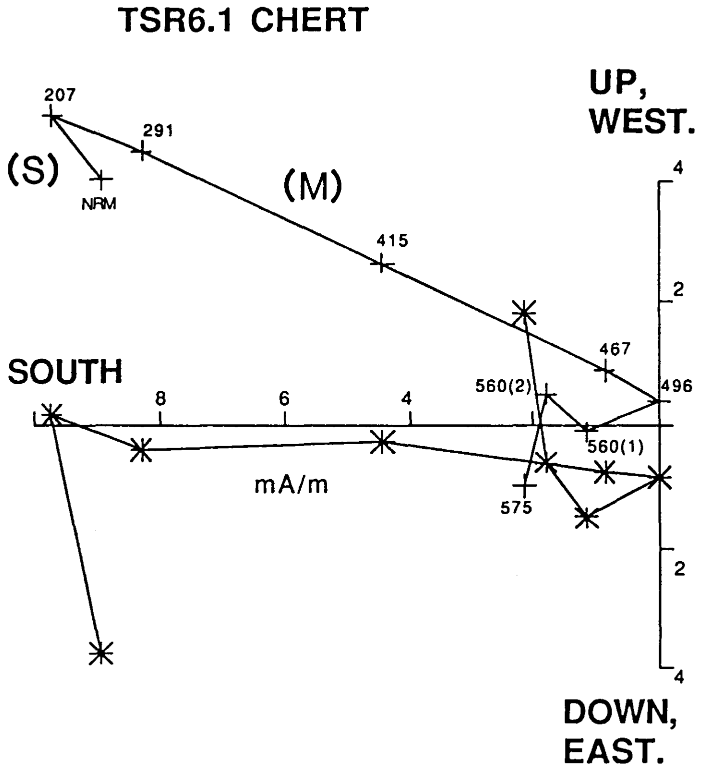


Figure 4.8 : An orthogonal projection shows typical demagnetisation behaviour for site TSR6 with component (M) not proceeding to the origin. Treatment at 560°C was repeated to show the magnitude of laboratory noise at elevated temperatures.

4.3.2 CONGLOMERATE TESTS.

Two conglomerate tests were performed within the course of the study as follows:

i) Slockenray Formation intra-formational conglomerate facies.

The conglomeratic unit of the Slockenray Formation forms the proximal facies of a hyalotuff delta sourced from the Slockenray basalts themselves (Bluck, 1982). A total of forty samples were collected from nineteen clasts for laboratory analysis. NRM directions agree closely with those obtained from the parent flows (southerly declination, moderate positive inclination). Intensities of magnetisation from the conglomerate clasts are slightly higher than those observed in the parent flows but are of the same order (Figure 4.3).

A two-component magnetisation signature characterises clasts and is analogous to that observed for the rest of the Slockenray Formation. A 'soft' component (S) of steep inclination and generally northward declination is removed by 250°C/10mT. This leaves a more stable component (M) of southerly declination and moderate positive inclination which decays linearly to the origin following treatment to 560°C/100mT. In situ stereographic projection of component (M) and representative orthogonal projections for the Slockenray Conglomerate form Figure 4.9. Statistical analysis of component (M) from the conglomerate is included in Table 4.1.

Atypical behaviour to that described above occurred in only one sampled clast (TCC1). Eleven samples were cored from this clast of which only one showed the characteristic demagnetisation behaviour. The remainder of the samples appeared to contain only component (S) which was of unusually high stability decaying linearly to the origin by 550°C/65mT. Representative demagnetisation analyses for samples of site TCC1 are illustrated in Figure 4.10.

ii) Benan Conglomerate.

The Benan conglomerate has a dual provenance comprising lithologies of the underlying ophiolite and those of an eroded arc terrane (Longman *et al.* 1979). Thirty-seven samples were collected from twenty one clasts of the conglomerate exposed directly above the ophiolite at Byne Hill (Figure 4.1). NRM directions showed a widely dispersed distribution but with some clustering close to the present field orientation at the site. NRM intensities covered a range similar to those determined within the ophiolite; (Figure 4.3). Many clasts were found to display a 'soft' magnetic component (S) again aligned, in situ, close to a present day field orientation. Magnetisation components of similar stability properties to component (M) do not display a singular orienation however. In situ stereographic projection of these 'high treatment' components and typical orthogonal projections for basalt clasts from the Benan Conglomerate form Figure 4.11.

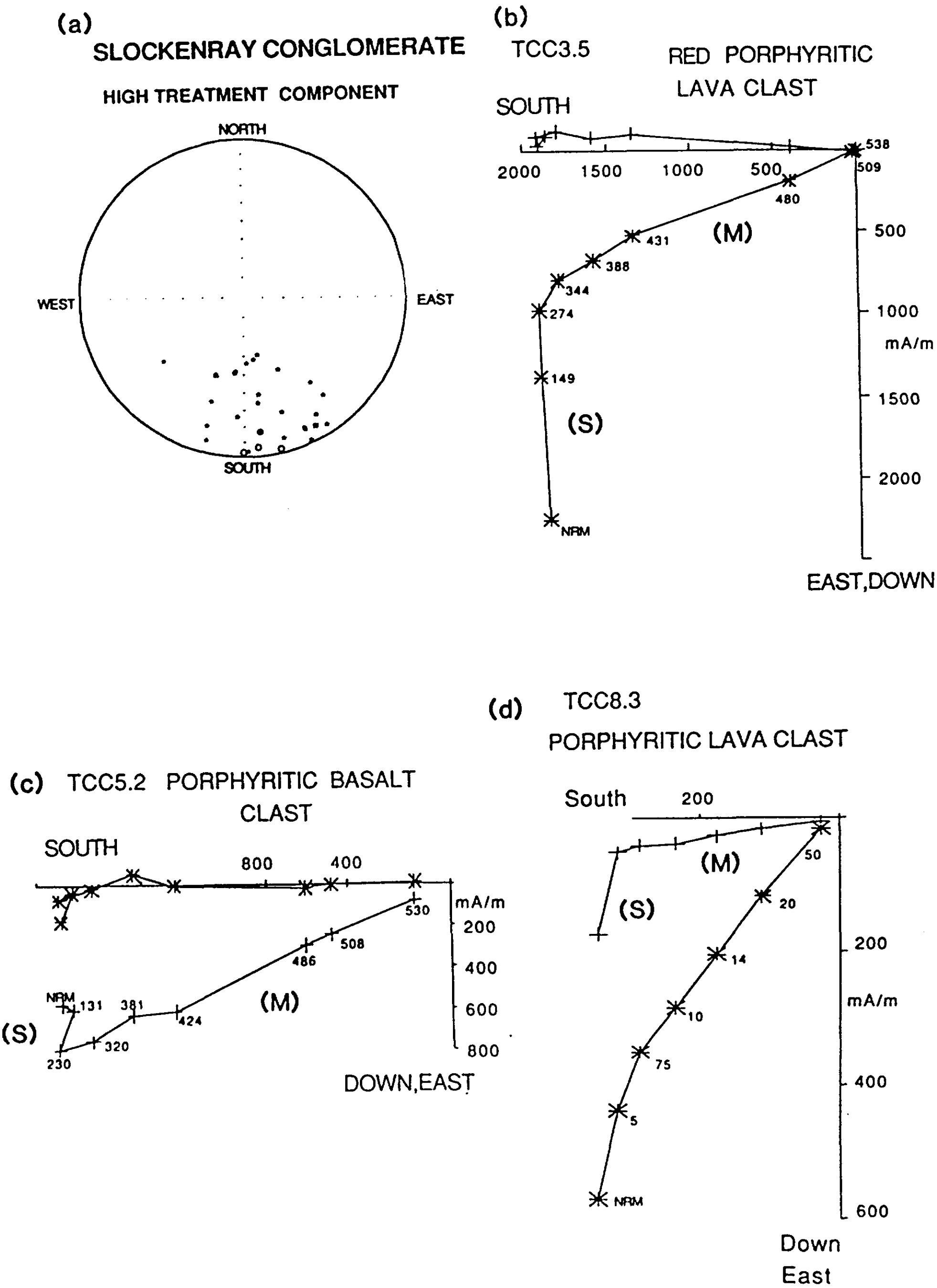
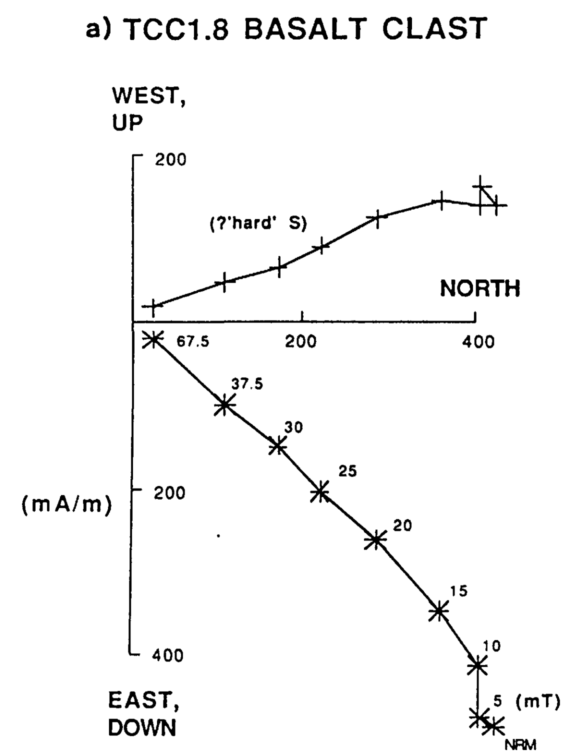


Figure 4.9 : (a) Directional distribution of Component (M) magnetisations for the intra-formational Slockenray Conglomerate. Starred symbols refer to projections on the lower hemisphere; open circles to projections on the upper hemisphere. (A similar convention is adopted for Figures 4.11, 4.13 & 4.14). Thermal (b,c) and AF (d) orthogonal projections show typical demagnetisation trajectories.



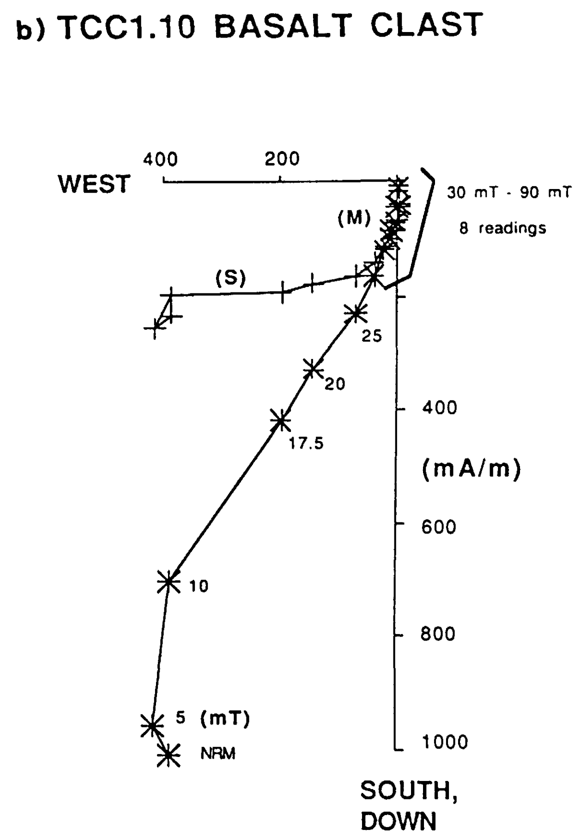


Figure 4.10 : Examples of AF demagnetisation behaviour of the atypical clast (TCC1) from the Slockenray Conglomerate facies.

(a) 'Hard' component (S) is the only magnetisation present decaying to the origin at treatments of approximately 65mT. (10 samples from TCC1).

(b) The characteristic 'two-component' component structure typifying the Slockenray Conglomerate. (1 sample from TCC1).

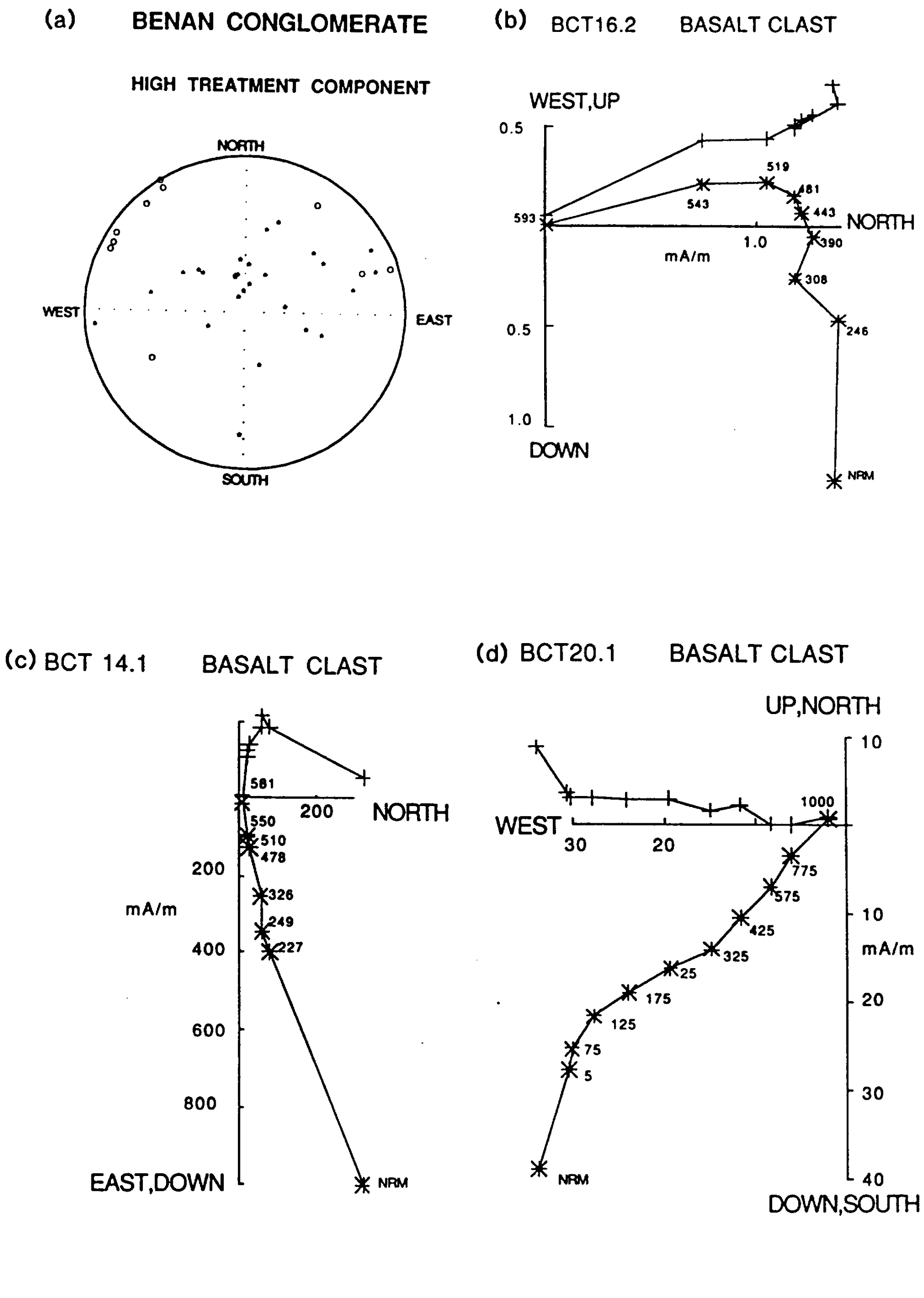


Figure 4.11 : (a) Directional distribution of cleaned magnetisation components from the Benan Conglomerate. Typical thermal (b,c) and AF (d) orthogonal projections show the directionally dispersed nature of the high treatment component magnetisations.

4.3.3 PALAEOMAGNETIC FOLD & FAULT TESTS.

The Slockenray Formation has a general NE-SW strike younging, (where determinable), toward the northwest. The observed dips vary from steep to subvertical (Figure 4.2).

Both original depositional and tectonic components of bedding are identified (Bluck, 1982) consistent with the interpretation that the unit formed at a palaeo-shoreline. Large scale foresets, identified at sites TCC 1-8 (Slockenray Conglomerate), have not been structurally corrected. Elsewhere, observed bedding and/or lava tops have been taken as representative of the palaeo-horizontal. Despite the broad similarity in bedding attitude throughout the sequence, a comparison of pre and post structural correction site mean distributions has been made in an effort to relate magnetisation age to deformation. Furthermore, comparison of magnetisation directions between small scale fault blocks (identified from outcrop maps; Figure 4.2) has been performed. This allows the relation of magnetisation age to fault deformation.

i) <u>Fold test.</u>

Poles to bedding at each sampling locality form a partial great circle distribution (Figure 4.12). The pole to this plane has declination 290°, inclination 80° and represents the axis of a plunging fold structure affecting the Slockenray Formation. The structural correction of the palaeomagnetic data may therefore be problematical. Two differing tectonic corrections have therefore been applied to the in situ distribution of the characteristic magnetisation component (M).

Firstly, tilt can be assumed to have taken place about a horizontal strike axis at each site and restored using the conventional tilt correction. Secondly, sequential unplunging and unfolding of the determined fold axis can be performed. The effects of these two contrasting tectonic corrections applied to the Slockenray data are illustrated in Figure 4.13.

The in-situ site means form a circular swathe which varies in both declination and inclination (Figure 4.13 a). By contrast, the structurally corrected site mean distributions show considerably less variation in inclination than declination (Figure 4.13 b-c). Exceptions to this relationship are the mean results from sites BOL1 and BOL4 which appear markedly shallow in inclination.

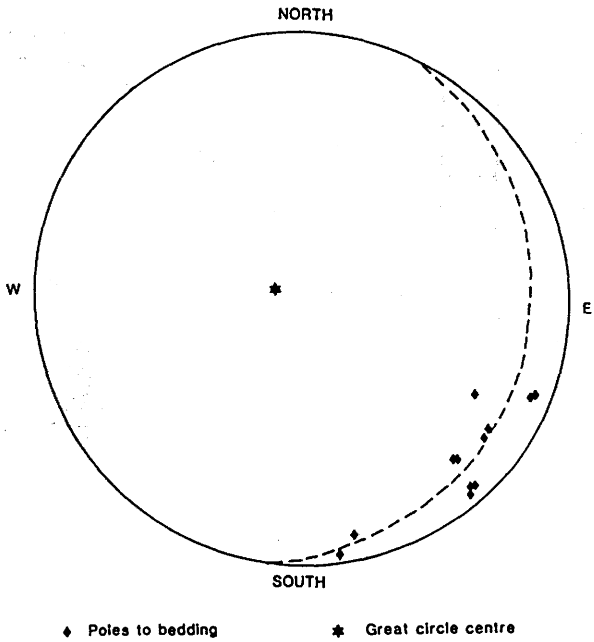


Figure 4.12 : Equal angle stereographic projection shows the partial great circle distribution of poles to bedding for palaeomagnetic sampling sites.

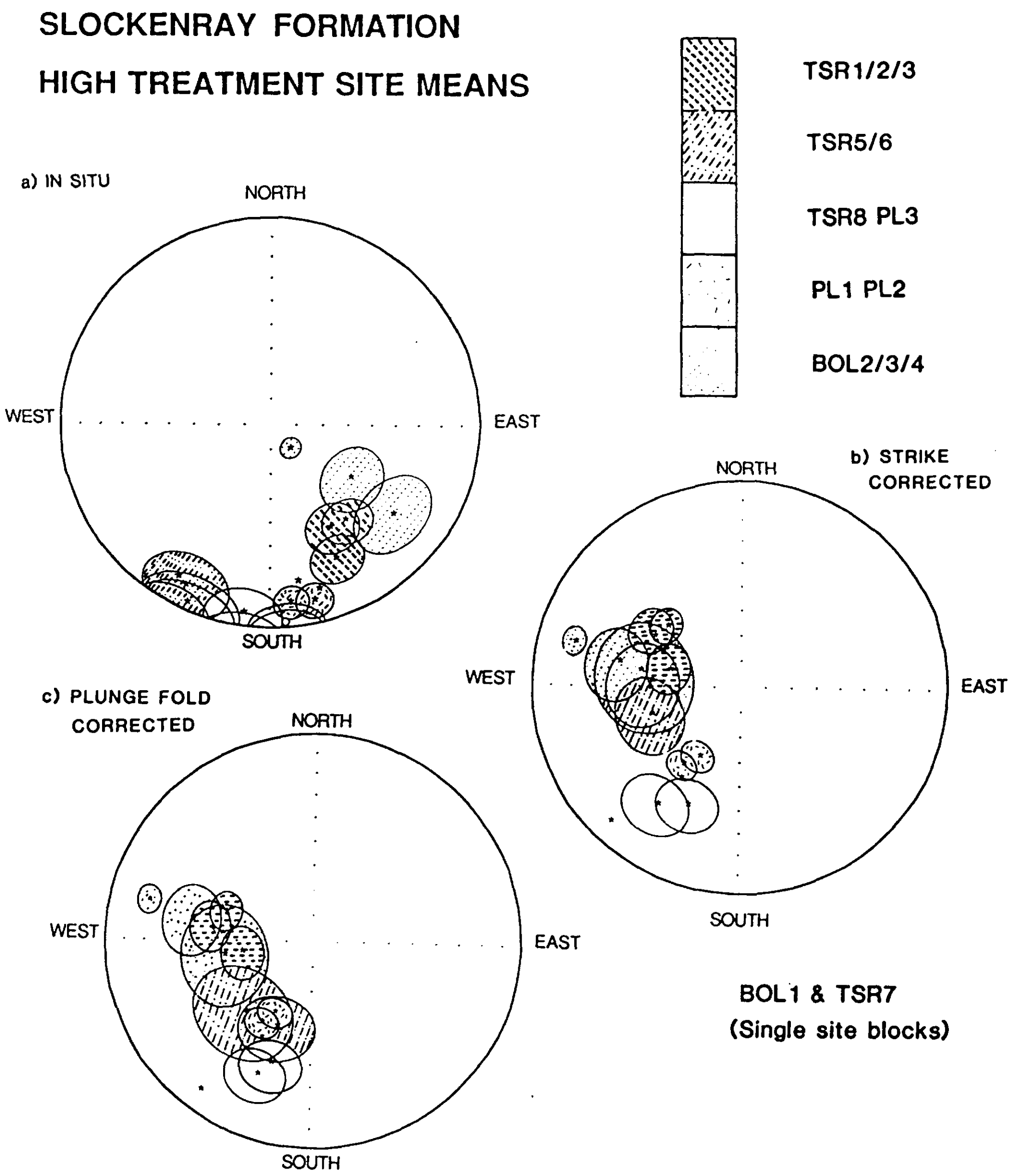


Figure 4.13 : In Situ (a), strike corrected (b) and plunging fold corrected (c) site mean distributions (component M) for the Slockenray Formation plotted in equal area stereographic projection. Ovals depict cones of 95% confidence for each site mean. Intra-fault block sites are denoted by consistent ornamentation. Confidence cones for single site blocks have been omitted.

ii) <u>Fault test.</u>

Numerous small scale faults transect the study area as becomes evident in Figure 4.2. A comparison of magnetisation directions both within and between fault blocks has been carried out and is illustrated in Figure 4.13 (Consistent ornament denotes sampling sites from within individual blocks). Fault blocks themselves were defined as bound by discontinuities of sizable or unknown displacement. Within-site minor offsets of decimetre to metre scale were therefore ignored.

Component (M) site means are found to overlap at the 95% confidence level within blocks but significant departures are apparent when results are compared between fault blocks. This relationship appears to be valid both for in situ and corrected site mean distributions. Once again site BOL4 is an exception proving statistically different from other intra block sites (BOL2,3) at 95% confidence.

4.4 INTERPRETATION OF PALAEOMAGNETIC RESULTS.

4.4.1 IDENTIFICATION OF REMANENCE PHASES.

Laboratory unblocking temperatures approaching 560°C for the characteristic magnetisation component (M) at most sites is consistent with a magnetite - low Ti titanomagnetite-held remanence. Persistence to temperatures in excess of 600°C for the reddened lava top (BOL1) and reddened lithic tuffs (BOL2-4) indicates hematite to be an important remanence carrier at these sites however. Incomplete demagnetisation following cleaning to 100mT confirms the presence of high coercivity hematite. Both results are in accordance with reddening resulting from sub aerial exposure of the lava/tuff sequence at or soon after extrusion/deposition (Smellie, 1984). The affirmed uni-vectorial nature of both magnetite and hematite demagnetisation (Figure 4.6) suggests their remanence to have been acquired synchronously.

4.4.2 CONGLOMERATE TESTS & REMAGNETISATION AGE CONSTRAINT.

Magnetisation components of comparable stability spectra have been identified in both the Slockenray Conglomerate facies and the overlying Benan Conglomerate. In the former case, this characteristic component (M) is of similar attitude to that found in the remainder of the Formation (Table1). This forms a negative palaeomagnetic conglomerate test with respect to component (M) and identifies it as a pervasive remanence overprint.

The 'soft' magnetisation component (S) aligns along a present day field direction for both conglomerates consistent with its interpretation as of recent VRM origin.

For the Benan Conglomerate, a magnetisation component of similar stability criterion to component (M) displays no evidence of pervasive overprinting compatible with that for the Slockenray Formation (Figure 4.11). This constitutes a positive conglomerate test and therefore defines a remagnetisation age window for the underlying Slockenray Formation. Maximum width of this window is approximately 30Ma when assigned ages of the conglomerates are considered (base Arenig - top Llandeilo, 488-458Ma, Harland *et al.* 1982).

Directions from the Benan Conglomerate are not completely random in orientation however owing to the presence of 'hard' VRM in some of the clasts. This phenomenon would also account the demagnetisation behaviour of clast TCC1 of the Slockenray Conglomerate (Figure 4.10., 4.3.2) and explain the change in stability spectra of components (S) and (M) for site BOL4 (Figure 4.7., 4.3.1).

Hard viscous remanence has been noted in ophiolitic rocks previously (Beske-Diehl & Banerjee, 1979), where it occurs in intimate association with rocks containing VRM of 'normal' stability. The 'hard' viscous magnetisation reported here appears resistant to both thermal and A.F. cleaning methods (Figure 4.7).

The overprinted magnetisation component (M) ubiquitously resides in magnetite for clasts of the Slockenray Conglomerate. Attempts to follow demagnetisation to hematite unblocking temperatures proved unsuccessful despite the sampling of reddened basalt clasts (see Figure 4.9b). The problem of whether both magnetic phases are overprinted therefore remains. Figure 4.6 clearly shows both magnetite and hematite remanences to be univectorial and implies synchronous magnetisation (4.4.1). Metamorphism of the lava pile is to low grade (zeolite to prehnite-pumpellyite facies; Oliver *et al.* 1984) and may reflect operation of a submarine hydrothermal system (Lewis, 1975). Maximum temperatures are therefore insufficient to effect thermal remagnetisation using the unblocking criterion of Pullaiah *et al.* (1975) but may result in at least resetting of magnetite applying the alternative theory of Walton (1980). Magnetite remagnetisation by hydrothermal circulation sufficiently apace after lava formation as to preserve directional consistency between magnetic phases is therefore suggested. Such an interpretation is consistent with the differential application of unblocking theories proposed by Kent & Miller (1987). They invoke the Walton theory to be applicable to multidomain magnetite but the Pullaiah theory to apply in the case of single domain hematite.

4.4.3 RELATIONSHIP OF COMPONENT (M) TO BEDDING ATTITUDE & SMALL SCALE FAULTING.

We have ascertained (4.4.2) that the characteristic magnetisation component (M) identified for the Slockenray Formation forms a remanence overprint; i.e. it post-dates the deposition of the intra-formational Slockenray Conglomerate. There remains the problem of deducing the temporal relationship of this magnetisation to the observed fold and small-scale fault deformations however. The ages of these deformations are poorly constrained and may relate to either ophiolite obduction, main phase Caledonian compression, or in the case of the faulting, even to opening of the present Atlantic.

The polyphase structural history described by Williams (1959) for the Ballantrae cover sequence is not readily recognisable within the rocks of the ophiolite basement. Furthermore, Piper (1978) argues that Caledonian movements did not effect major refolding in the ophiolite based on the directional consistency of remanence data from the northern serpentinite belt. The weight of evidence therefore suggests the bulk of folding to relate to obduction (Stone, 1984) with the age of small-scale faulting remaining uncertain.

Neither the 'in situ' nor the 'corrected' site mean distributions from Slockenray are Fisherian (Figure 4.13) and therefore a meaningful application of the classical fold test (Graham, 1949., McElhinny, 1964) is not possible. An inspection of Figure 4.13 reveals that whilst 'in situ' results vary both in declination and inclination; 'corrected' results vary predominantly in declination only. This behaviour can result from the incorrect assumption that folding of the magnetisation took place about the local strike direction (MacDonald, 1980) producing the effect of apparent tectonic rotation about local vertical axes. A corrected pre-folding magnetisation will then form a small circle partial arc centred on a vertical axis (cf. Figure 4.13 b & c).

In the present case, localised fault blocks between which true tectonic rotation may have taken place have been identified during plane table mapping. Statistically significant directional differences become apparent between blocks both before and after tectonic correction backed up by internal consistency of directions within individual blocks. It is not therefore possible to fully evaluate the relative contributions of true and apparent tectonic rotation to the remaining small circle partial arc distribution following tectonic correction. The existence of this vertically centred small circle does strongly suggest component (M) to be of pre-folding origin however. Similarly the existence of statistically significant directional differences between blocks would favour a pre-faulting age for the component.

Two site mean results (BOL1, BOL4) appear to disobey the described relationship in that neither lies on the small-circle partial arc described by the remainder of the sampling site means following tectonic correction. In addition, site BOL4 remains statistically different from its corresponding intra-block sites (BOL2, BOL3).

The explanation of this latter disparity becomes evident when the previously described stability properties of components (S) and (M) at site BOL4 are considered (Figure 4.7). Note also that in Figure 4.13 a, the BOL4 site mean lies close to a remagnetisation circle between a present Earth's field direction (PEF) and the in situ palaeo-field direction determined from the other sites of the particular block. Therefore, although the LINEFIND algorithm detects linearity in the region 550°C - Origin, this is in fact the result of blocking temperature overlap between components (S) and (M). The true orientation of component (M) for site BOL4 is therefore never attained but is expected to be close to those of sites BOL2 & 3.

For site BOL1, there are unfortunately no intra fault block sites with which to draw direct comparison. The demagnetisation characteristics for the site reveal the presence of both magnetite and hematite remanence phases (Figure 4.6) and do not appear in any way 'anomalous' other than in direction following tectonic correction. This suggests that the applied stuctural correction for the site may be in error and implies that the measured lava top may not accurately record the palaeo-horizontal. Such problems may well have been predicted given the prevalence of syn-depositional dip components in the hyalotuff delta environment (Bluck, 1982). For these reasons, both sites BOL1 and 4 have been omitted from overall statistical analyses.

4.5 COMPARISON OF RESULTS TO PREVIOUS PALAEOMAGNETIC WORK.

4.5.1 SLOCKENRAY LAVAS

Two previous palaeomagnetic investigations have been performed which include data from the Slockenray lavas; those of Nesbitt (1967) and Piper (1978). The present work improves on both previous studies on a number of counts as follows:

- the use of large scale plane table outcrop maps (Bluck,1982) enabling the relation of remanence to small scale fault blocks; a form of palaeomagnetic 'fault' test.
- the undertaking of two conglomerate tests.
- the sampling of the interbedded sediments in addition to the lavas.
- the use of detailed thermal demagnetisation in conjunction with the previously used AF method.

Nesbitt (1967) reports results from twelve hand samples collected from four sites in the Slockenray lava sequence. Following AF cleaning at 8.5mT, a better clustering of sample vectors prior to tilt correction was described. This was interpreted as possibly reflecting an Ordovician overprint direction at declination 189° and inclination +40° for the formation. In the light of the present evidence, this explanation becomes suspect given the apparent effects of later faulting and the arguments for a pre-deformational magnetisation. It may also be debatable whether cleaning at fields of 8.5mT will be sufficient to completely remove presumed 'soft' magnetisation components in some cases (cf. Figure 4.7).

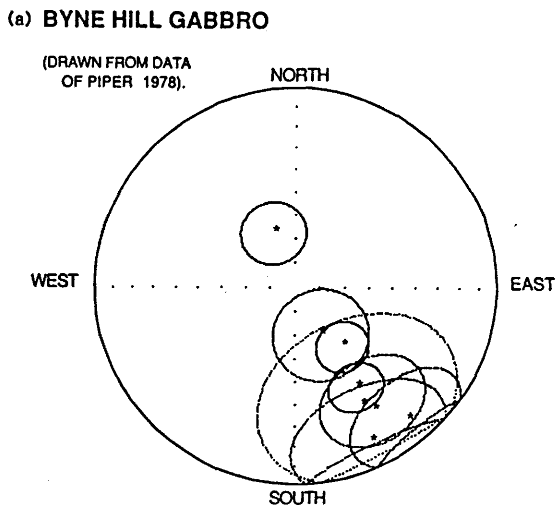
Piper (1978) states that the Slockenray pillow lavas "did not yield an overall significant direction" and attributes this to "variable amounts of remagnetisation during folding and metamorphism". In contrast, the current study presents evidence for a pervasive remagnetisation (at least of the magnetite held remanence) as evidenced from the negative Slockenray conglomerate test (Figure 4.9). The problems in determining "an overall significant direction" therefore result from the dispersion caused by both fold and fault deformations.

4.5.2 BYNE HILL GABBRO & NORTHERN BELT SERPENTINITE (Piper, 1978).

Piper (1978) reports palaeomagnetic data from eight sites (41 specimens) in the Byne Hill Gabbro and nine sites (57 specimens) from serpentinites in the northern belt. Directions result largely from AF demagnetisation complimented by those from a limited number of thermally demagnetised pilot specimens.

Site mean results of this study are plotted in stereographic projection on Figure 4.14. The resultant distribution from the Byne Hill Gabbro is found to be clearly non-Fisherian smearing along a NW-SE oriented great circle. This effect results from either incomplete resolution of magnetisation components (compare sites BOL4 vs. BOL2/3, Figure 4.13a) or less likely, may reflect unresolved structure affecting the gabbro. In either eventuality, the calculation of a Fisher mean and its interpretation as representative of a single Ordovician palaeofield becomes suspect. The northern belt serpentinite data form a better approximation to the Fisherian distribution and yield a mean direction of declination 147.7°, inclination +32.4°. This magnetisation was similarly attributed an Ordovician age and probably relates to magnetite generation during serpentinisation. Serpentinsation itself took place during late syn- to post obduction of the ophiolite as evidenced through its geochemical influence on Arenig dyke suites cross-cutting the metamorphic sole (Holub *et al.* 1984).

The questioning of the Byne Hill Gabbro result as indicative of an Ordovician field removes one of the 'large error' determinations currently problematical for the statistically significant resolution of Iapetus during the Ordovician period. This problem arises due to the partial overlap of polar confidence circles determined in studies of



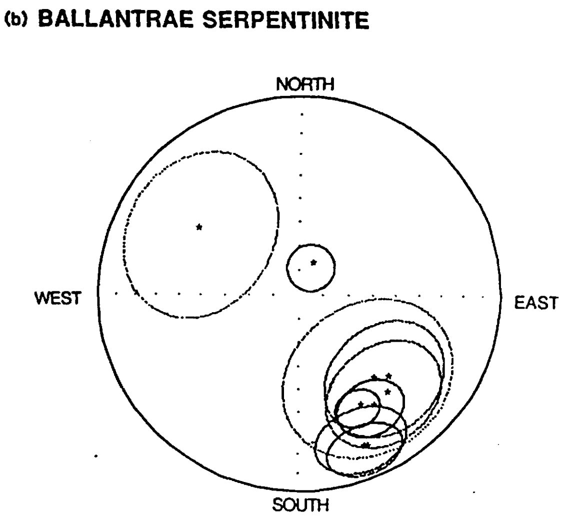


Figure 4.14: Equal area projections show the site mean distributions of Piper (1978) for the Byne Hill Gabbro (a) and Ballantrae northern belt Serpentinite (b).

Ordovician rocks either side of the Solway Line (see Figure 1 of Briden *et al.* 1986).

4.6 DISCUSSION & TECTONIC IMPLICATIONS.

The realisation that the characteristic magnetisation component (M) predates obduction related folding allows the calculation of a palaeolatitude. Furthermore, if remanence dates from the circulation of an early hydrothermal system, then the resulting latitude will approximate that of ophiolite formation.

Certain difficulties remain, however, in the statistical derivation of the latitude. Inappropriate calculation of a Fisher mean from a small circle partial arc centred on a vertical axis will result in a mean inclination that is artificially steep and consequently in a latitude that is incorrectly high (Macdonald, 1980). This relationship is apparent in Table 4.2 where calculated Fisher means of strike and plunging–fold–corrected arcuate distributions yield palaeolatitudes of 34.5°S and 32.8°S respectively. A more reliable estimate is given through one dimensional analysis of inclination data only which yields a mean palaeolatitude of 28.8°S.

If the declination scatter following structural correction is attributed solely to a combination of true and apparent tectonic rotation about vertical axes, then the site mean results can be artificially constrained in declination (cf. Achache *et. al.* 1984). An example of this is given in Table 4.2 producing a palaeolatitude confidence of +/- 4.1°. This result should be treated with caution however as the analysed distribution is necessarily non-Fisherian.

Unfortunately the absence of a well preserved sheeted dyke complex within the ophiolite precludes calculation of a palaeospreading orientation (cf. Pozzi *et al.* 1984). Nevertheless, the calculated palaeolatitude warrants comparison with existing Ordovician data from the Iapetus margins. A good agreement.is evident when the result is compared to recently published palaeomagnetic data bordering the southern Laurentian margin (Vick *et al.*, 1987. Noel *et al.*, 1987., both 22°S). Conversely, results agree poorly with time equivalents from the Armorican massif (i.e. Hercynian Europe excluding southern Britain, cf. Perroud *et al.* 1984) and Gondwana which are both estimated to lie in high southerly latitudes during Ordovician times (Perroud *et al.* 1984).

With reference to the British database, the Ballantrae palaeolatitude lies within 'Iapetus' as imaged by the 10° polar discordance in results to the north and south of the Solway Line (Briden *et al.*, 1984, 1986). Any resultant pole will not lie on the Ordovician segment of the British APWP however due to the sizable tectonic rotation (approximately 80° clockwise when referred to contemporaneous British poles). This rotation may have been acquired either at the time of generation of the sequence, during ocean crust migration

FORMATION / CORRECTION.	N	D,deg.	dD.	I,deg.	$\alpha 95$	P(°S)	dP.	K
SLOCKENRAY., (ABOUT STRIKE)	12	248.3	24.9	53.9	14.7	34.5	14.4	9.7
SLOCKENRAY., (FOR PLUNGING STRUCTURE, DEC. 290'., INC. 80')	12	231.2	22.0	52.2	13.5	32.8	12.7	11.3
SLOCKENRAY., (CONSTRAINED DECLINATION)	12	248.3	(7.1)	47.7	4.8	28.8	4.1	83.6
SLOCKENRAY., (INCLINATION ONLY.,SITE)	12	---	---	47.7	---	28.8	(σ =8.9)	---
SLOCKENRAY., (INCLINATION ONLY.,SAMPLE)	80	---	---	47.5	---	28.6	(σ =11.5)	---

TABLE 4.2 : <u>Summary of Corrected Magnetic Directions and Statistical Analyses for the Slockenray Formation.</u>

N:- Number of Sample Sites., D,I:- Declination & Inclination of site mean remanence vector., dD:- Uncertainty on the declination., P:- Palaeolatitude., dP:- Uncertainty on the palaeolatitude., K:- Fisher Precision Parameter., ∂:- Standard Deviation for one dimensional analysis.

on to the Laurentian margin, or by subsequent rotation after terrane amalgamation.

The results from the northern belt serpentinites (Piper, 1978) appear concordant in declination with other British data and yield a palaeolatitude of 17.5°. If this magnetisation relates to post obduction serpentinisation then both a cessation of tectonic rotation and a palaeomagnetic record of northward obduction are implied.

Formation of the Ballantrae Ophiolite at a spreading axis close to the Laurentian margin is required by the palaeolatitudinal data. The nature of such an axis has been the cause of differing opinion (cf. Barrett *et al.* 1982, Bluck, 1982., Lambert & McKerrow, 1976) and cannot be addressed by the present data. The latitudinal similarity between southern Laurentia and Ballantrae is consistent with the short lived pre-obduction history of the ophiolite suggested by both radiometric and stratigraphic constraints however (Hamilton *et al.* 1984., Bluck, 1985).

Finally, consideration of palaeolatitudinal data both north/south of the Solway Line and from Armorica suggests measurable separation between each block at least for a part of Ordovician times. The Southern British terrane ('Eastern Avalonia', Soper *et al.* 1987) is separated from Laurentia by the Iapetus Ocean to the north and from Armorica by the Rheic Ocean to the south. The possibility that southern Britain represents a far travelled micro continental fragment which may have undergone rapid drift therefore becomes apparent. A fuller understanding of its role will await the reconciling of disparities between published apparent polar wander schemes for the period however (cf. Briden *et al.* 1984, 1986. Storetvedt & Deutsch, 1986., Piper, 1987). This uncertainty in the former position of southern Britain is reflected in the palaeo-reconstruction shown in Figure 4.15.

4.7 SUMMARY & CONCLUSIONS.

The magnetic signature of both sediments and volcanics of the Slockenray Formation is multivectorial. Two components (S and M) are identified on orthogonal projection differentiated on the basis of differing stability criteria. The less stable component (S) aligns (in situ) close to a present day field direction and is of recent viscous origin. Component (S) occasionally displays higher stability both to thermal and A.F. cleaning attributed to the presence of 'hard' viscous remanence.

Component (M) forms the characteristic magnetisation of the formation residing in both magnetite and hematite remanence phases. This component fails a conglomerate test on an intra-formational lava conglomerate and is identified as a remanence overprint. Remagnetisation may have taken place during circulation of an early hydrothermal system which effected magnetite resetting.

A magnetisation component of similar stability criterion to component (M) is

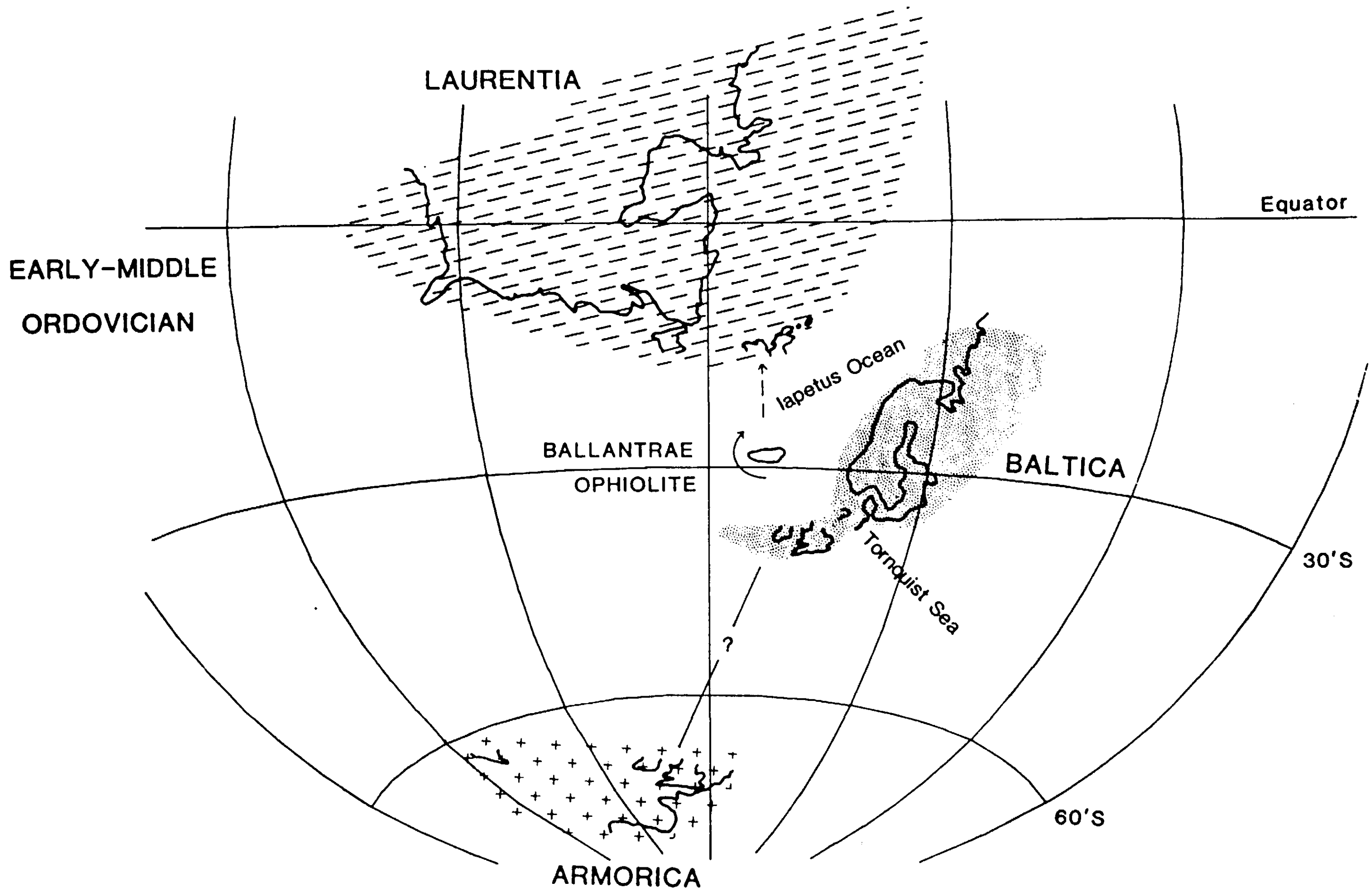


Figure 4.15 : An Early-Middle Ordovician palaeo-reconstruction for the Ballantrae Ophiolite and Iapetus bordering continents.

Ophiolite rotation may take place either outboard, during migration or subsequent to terrane docking. The former positions of Laurentia, Baltica and Armorica are based on data from Briden *et al.* (1984, 1986) and Perroud *et al.* (1984). (Outlines of Iapetus bordering continents are based on a reconstruction provided courtesy of T.H.Torsvik).

found to display a near random distribution in the Benan Conglomerate of mixed provenance stratigraphically overlying the Slockenray Formation. This forms a positive conglomerate test and constrains a remagnetisation window for the characteristic magnetisation to a maximum of 30Ma from Arenig to Llandeilo times.

The relation of component (M) to both folding and fault deformations suggests it to be pre-obduction in age. This allows the calculation of a palaeolatitude (28.8°S) for the complex during the Arenig which is consistent with a tectonic position close to the southern Laurentian margin at the time of ocean crust generation.

CHAPTER 4 : REFERENCES.

Achache, J., Courtillot, V., & Xiu, Z.Y. 1984. Paleogeographic and tectonic evolution of Southern Tibet since Middle Cretaceous time: New paleomagnetic data and synthesis. *Journal of Geophysical Research,* 89, 10311-10340.

Barrett, T.J., Jenkyns, H.C., Leggett, J.K., & Robertson, A.H.F. 1982. Comment and reply on 'Age and origin of the Ballantrae ophiolite and its significance to the Caledonian orogeny and the Ordovician time scale'. *Geology,* 10, 331-333.

Beske-Diehl, S., & Banerjee, S.K. 1979. An example of magnetic properties as indicators of alteration in ancient oceanic lithosphere: The Othris Ophiolite. *Earth & Planetary Science Letters,* 44, 451-462.

Bluck, B.J. 1982. Hyalotuff deltaic deposits in the Ballantrae ophiolite of SW Scotland: evidence for crustal position of the lava sequence. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 72, 217-228.

Bluck, B.J. 1985. The Scottish paratectonic Caledonides. *Scottish Journal of Geology,* 21, 437-464.

Briden, J.C., Morris, W.A. & Piper, J.D.A. 1973. Palaeomagnetic studies in the British Caledonides, VI. Regional and global implications. *Geophysical Journal of the Royal Astronomical Society,* 34, 107-134.

Briden, J.C., Turnell, H.B. & Watts, D.R. 1984. British palaeomagnetism, Iapetus Ocean and the Great Glen fault. *Geology,* 12, 428-431.

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, 1207-1213.

Church, W.R., & Gayer, R.A. 1973. The Ballantrae Ophiolite. *Geological Magazine,* 110, 497-510.

Collinson, D.W. 1977. Experiments relating to the measurement of inhomogenous remanent magnetism in rock samples. *Geophysical Journal of the Royal Astronomical Society,* 48, 271-278.

Dewey, J.F. 1974. Continental margins and ophiolite obduction: Appalachian Caledonian system. in *Geology of Continental Margins,* K. A. Burke and C. L. Drake, eds., New York, Springer, 933-950.

Graham, J.W. 1949. The stability and significance of magnetism in sedimentary rocks. *Journal of Geophysical Research,* 54, 131-167.

Hamilton, P.J., Bluck, B.J., & Halliday, A.N. 1984. Sm-Nd ages from the Ballantrae Complex, SW Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 75, 183-187.

Harland, W.B.A., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G. & Walters, R. 1982. *A Geological Time Scale.* Cambridge University Press, pp.131.

Holub, F.V., Klapova, H., Bluck, B.J. & Bowes, D.R. 1984. Petrology and geochemistry of post-obduction dykes of the Ballantrae Complex, SW Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 75, 211-223.

Ince, D. 1984. Sedimentation and tectonism in the Middle Ordovician of the Girvan district, SW Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 75, 225-237.

Ingham, J.K. 1978. Geology of a continental margin: Middle and late Ordovician transgression, Girvan. in *Crustal Evolution in Northwestern Britain and Adjacent Areas*, D. R. Bowes and B. E. Leake, eds., Special Publication of the Geological Society, London. 10,163-176.

Kent, D.V. & Miller, J.D. 1987. Redbeds and thermoviscous magnetization theory. *Geophysical Research Letters,* 14, 327-330.

Kent, J.T., Briden, J.C. & Mardia, K.V. 1983 Linear and planar structure in ordered multivariate data as applied to progressive demagnetization of palaeomagnetic remanence. *Geophysical Journal of the Royal Astronomical Society,* 75, 593-621.

Klootwijk, C.T. 1980. Early Palaeozoic Palaeomagnetism in Australia. *Tectonophysics,* 64, 249-332.

Lambert, R.St.J. & McKerrow, W.S. 1976. The Grampian Orogeny. *Scottish Journal of Geology,* 12, 271-292.

Lewis, A.D. 1975. *The geochemistry and geology of the Girvan-Ballantrae ophiolite and related Ordovician volcanics in the Southern Uplands of Scotland.* Ph.D. Thesis, University of Wales,(unpublished).

Longman, C.D., Bluck, B.J. & van Breeman, O. 1979. Ordovician conglomerates and the evolution of the Midland Valley. *Nature,* 280, 578-581.

MacDonald, W.D. 1980. Net tectonic rotation, apparent tectonic rotation and the structural tilt correction in palaeomagnetic studies. *Journal of Geophysical Research,* 85, 3659-3669.

McElhinny, M.W. 1964. Statistical significance of the fold test in palaeomagnetism. *Geophysical Journal of the Royal Astronomical Society,* 8, 338-340.

Molyneux, L. 1971. A complete results magnetometer for measuring the remanent magnetization of rocks. *Geophysical Journal of the Royal Astronomical Society,* 24, 429-434.

Nesbitt, J.D. 1967. Palaeomagnetic evidence for the Ordovician geomagnetic pole position. *Nature,* 216, 49-50.

Noel, J.R., Spariosu, D.J. & Dallmeyer, R.D. 1988. Paleomagnetism and 40Ar/39Ar ages from the Carolina Slate Belt, Albemarle, N. C.: Implications for terrane history. *Geology ,* (in press).

Oliver, G.J.H., Smellie, J.L., Thomas, L.J., Casey, D.M., Kemp, A.E.S., Evans, L.J., Baldwin, J.R. & Hepworth, B.C. 1984. Early Palaeozoic metamorphic history of the Midland Valley, Southern Uplands-Longford Down massif and the Lake District, British Isles. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 75, 245-258.

Perroud, H., Van der Voo, R. & Bonhommet, N. 1984. Palaeozoic evolution of the Armorican plate on the basis of palaeomagnetic data. *Geology,* 12, 579-582.

Piper, J.D.A. 1978. Palaeomagnetism and palaeogeography of the Southern Uplands block in Ordovician times. *Scottish Journal of Geology,* 14, 93-107.

Piper, J.D.A. 1987. *Palaeomagnetism and the Continental Crust.* Open University Press, Milton Keynes. pp.434.

Pozzi, J.P., Westphal, M., Girardeau, J., Besse, J., Zhou, X.Y., Chen, X.Y. & Xing, L.S. 1984. Paleomagnetism of the Xigase ophiolite abd flysch (Yarlung Zangbo suture zone, southern Tibet): latitude and direction of spreading. *Earth & Planetary Science Letters,* 70, 383-394.

Pullaiah, G., Irving, E., Buchan, K.L. & Dunlop, D.J. 1975. Magnetization changes caused by burial and uplift. *Earth & Planetary Science Letters,* 28, 133-143.

Rushton, A.W.A., Stone, P., Smellie, J.L., & Tunnicliff, S.P. 1986. An Early Arenig age for the Pinbain sequence of the Ballantrae Complex. *Scottish Journal of Geology,* 22, 41-54.

Smellie, J.L. 1984. Accretionary lapilli and highly vesiculated pumice in the Ballantrae Ophiolite Complex: Ash-fall products of subaerial eruptions. *Reports of the British Geological Survey,* 84, 36-40.

Soper, N.J., Webb, B.C. & Woodcock, N.H. 1987. Late Caledonian (Acadian) transpression in north-west England: Timing, geometry and geotectonic significance. *Proceedings of the Yorkshire Geological Society,* 46, 175-192.

Stone, P. 1984. Constraints on genetic models for the Ballantrae Complex, SW Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 75, 189-191.

Storetvedt, K.M. & Deutsch, E.R. 1986. Reappraisal of Scottish Ordovician palaeomagnetism. *Geophysical Journal of the Royal Astronomical Society,* 87, 1193-1206.

Thirlwall, M.F. & Bluck, B.J. 1984. Sr-Nd isotope and geochemical evidence that the Ballantrae "ophiolite", SW Scotland, is polygenetic. In I.G. Gass, S. J. Lippard and A. W. Shelton (eds). *Ophiolites and Oceanic lithosphere,* Special Publication of the Geological Society, London, 13, 215-230.

Vick, H.K., Channell, J.E.T. & Opdyke, N.D. 1987. Ordovician docking of the Carolina Slate Belt: paleomagnetic data. *Tectonics,* 6, 573-583.

Walton, D. 1982. Time dependent relations in the magnetization of assemblies of single domain grains. *Nature,* 286, 245-247.

Williams, A. 1959. A structural history of the Girvan district, SW Ayrshire. *Transactions of the Royal Society of Edinburgh,* 63, 629-667.

Zijderveld, J.D.A. 1967. AC demagnetization of rocks: Analysis of results, In *Methods in Palaeomagnetism,* D. W. Collinson, K. M. Creer and S. K. Runcorn, eds., Elsevier, Amsterdam, 254-286.

CHAPTER 5 : BRITISH SILURIAN-DEVONIAN PALAEOMAGNETISM.

5.1 GENERAL

Late Silurian and Devonian times in Britain were characterised by deposition of a series of continental red beds. These are referred to collectively as the 'Old Red Sandstone' (ORS; Conybeare & Phillips, 1822). The obvious presence of hematite in the sediments and the occurrence of relatively untectonised interbedded volcanics has consequently led to an extensive history of palaeomagnetic research .

The earliest NRM results from ORS sediments were reported by Creer (1957) which were apparently confirmed by similar data recorded in Russian Devonian sediments. Controversy arose however, when results from Scottish Midland Valley volcanics (Stubbs, 1958) were found to differ significantly. Thermal demagnetisation studies (Chamalaun & Creer, 1964) resolved the apparent discrepancy yielding a two component NRM. The component of higher blocking temperature (>600°C) was found to broadly coincide with Stubbs' (1958) pole which was later substantiated by the results of Creer & Embleton (1967), McMurry (1968, 1970) and Embleton (1968, 1970). The component of lower blocking temperature was interpreted as of Permo-Carboniferous age and thought to have originated during tropical weathering (Creer, 1968).

Storetvedt (1970) disputed the validity of the Scottish lava data claiming them to have been remagnetised during low temperature oxidation processes. He believed that the lavas did not accurately record the Devonian field and used this to explain differences with respect to coeval Norwegian sediments (Storetvedt & Gjellestad, 1966., Storetvedt *et al.* 1968).

Subsequent work on the Midland Valley lavas (Sallomy & Piper, 1973., Torsvik, 1985a) and Lorne Plateau lavas (Latham & Briden, 1975) essentially confirm the initial results of Stubbs (1958) and must be considered overwhelming evidence for the validity of the resulting pole position. They also refute the critcism of the lavas as not being reliable rocks for palaeomagnetic study (see Storetvedt, 1971).

More recent ORS work (Torsvik *et al.* 1983. Torsvik 1984, 1985b) has centred on the plutonic equivalents of the volcanics; namely the Newer Granite suite. These intrusions yield north pole positions at approximately 25°N 170°E which differ significantly from the Midland Valley lava results and from those of other near contemporaneous intrusives (Briden, 1970). They were interpreted (Torsvik, 1985a) as representing an older part of the Apparent Polar Wander Path (APWP) as defined North of the Iapetus suture (Figure 5.1).

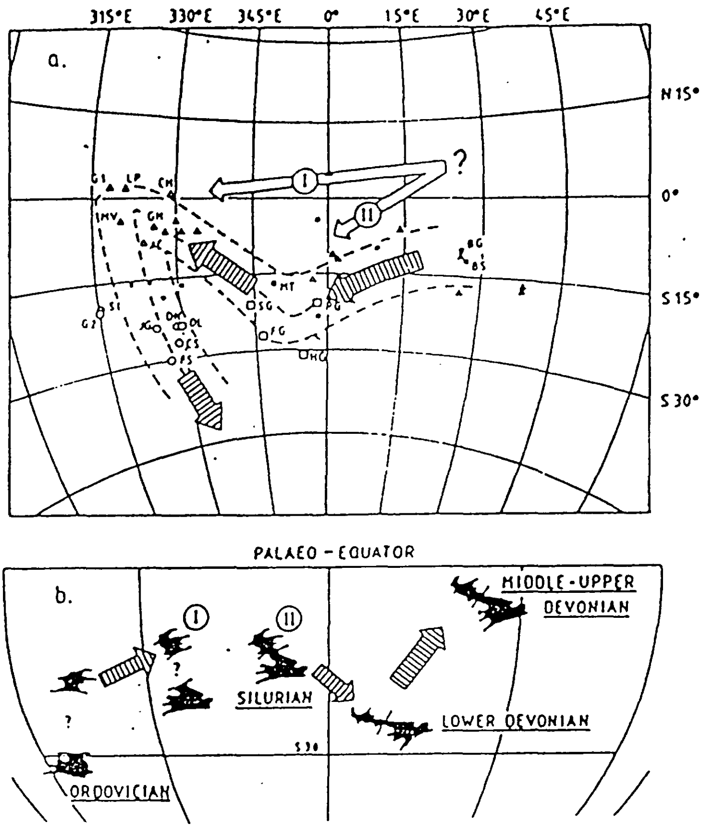


FIGURE 5.1a: ORDOVICIAN TO MIDDLE-UPPER DEVONIAN POLAR WANDER PATH NORTH OF THE IAPETUS SUTURE. (from Torsvik,1985a).

KEY:
SOLID TRIANGLES - WATTS & BRIDEN (1984). Aberdeenshire Gabbros.
SOLID CIRCLES - TURNELL & BRIDEN (1983). Northern Syenites.

<u>ORDOVICIAN</u>
BG BS - PIPER (1978). Ballantrae Complex.
<u>NEWER GRANITES</u>
HG - TORSVIK et al. (1983). Helmsdale.
FG SG - TORSVIK (1984). Foyers , Strontian.
PG - TORSVIK (1985b). Peterhead.
<u>LOWER DEVONIAN</u>
GH AC - BRIDEN (1970) Garabal Hill,Arrochar
CH - THORNING (1974) Cheviot.
LP - LATHAM & BRIDEN (1975) Lorne Plateau
MV - SALLOMY & PIPER (1973) Midland Valley lavas.
G1 - TORSVIK (1985a) Midland Valley lavas.
<u>MIDDLE-UPPER DEVONIAN</u>
OL - STORETVEDT & PETERSEN (1972) Orkney Lavas.
DN - STORETVEDT et al. (1978) Duncansby Neck.
JG - STORETVEDT & CARMICHAEL (1979) John O'Groats Sst.
CS - STORETVEDT & TORSVIK (1983) Caithness Sst.
FS - recalc. from KNEEN(1973) Foyers Sst.
SI - STORETVEDT & TORSVIK (1985) Shetland Ignimbrites
G2 - TORSVIK (1985a) Midland Valley overprint

FIGURE 5.1b: PALAEOLATITUDINAL RECONSTRUCTION OF THE BRITISH ISLES FROM ORDOVICIAN TO DEVONIAN.

5.2 ORCADIAN BASIN.

The Orcadian Basin ORS has been subjected to a most intensive history of palaeomagnetic study. Despite, or perhaps resulting from this, the magnetisation history of the basin is highly controversial. In a review of published work, Tarling (1985) outlines two main remanence groupings identified upon previous work. These are referred to as groups (A) and (B) having approximate southerly declination, moderate negative inclination and southerly declination, horizontal inclination respectively. Controversy concerns the inferred ages of these groups and in the case of (B), its physical reality.

5.2.1 GROUP (A) REMANENCES.

Group (A) remanences occur in nine independent studies of the Orcadian ORS and contemporaneous intrusives (Tarling 1985) and have subsequently once again been identified (Robinson, 1985). Individual studies have attributed remagnetisation ages ranging from Devonian to Tertiary to this component dependent on its proximity to the APWP for northwest Europe (e.g. McElhinny, 1973., Tarling, 1983). Assuming identification of the group as a single remagnetisation to be correct, a contrasting approach is to pool the results of all studies. Pole determinations from both individual and combined studies are outlined in Table 5.1 (after Tarling, 1985).

The Group (A) pole positions fall on the Triassic section of the European path although there is considerable scatter between studies (Figure 5.2). This may be due both to differing levels in laboratory cleaning and potentially to unresolved local tectonic effects. Tarling argues for a Permian remagnetisation effected in the Kiaman reverse polarity interval. This would explain the single polarity of the results and correlate with Potassium-Argon determinations from the Duncansby necks (Storetvedt et al.1978).

(Suggested ages and potential origins for Group (A) magnetisations are summarised in Table 6.5).

5.2.2 GROUP(B) REMANENCES.

Tarling cites six studies performed by Storetvedt and co-workers which he interprets to be Group (B) remanences. Subsequently, a further occurrence has been reported by Storetvedt & Torsvik (1985) from the Middle-Upper Devonian Esha Ness ignimbrite of West Shetland.

Group (B) components are resolved at higher blocking temperatures than Group (A) largely when only a small percentage of the initial NRM remains. This led Van der Voo & Scotese (1981) to question their physical reality (see Figure 5.3). Furthermore, Xu (1984) has convincingly shown that viscous or magnetometer components can occur at high laboratory treatments which could potentially be taken for geologically significant

Name	Sites	Spec.	Pol.	Tmt.	Group	Dec	Inc	A_{95}	Pole N	Pole E	Ref
(a) *Sediments*											
Orcadian Ssts	3	7	M	20°C	O	175	43	—	7	179	(1)
John O'Groats	9	60	R	300°C	A	192	−37	8	51	158	(2)
Caithness Sst		5	M	600°C	B	211	14	16	20	144	(5)
Gamrie grp 'a'		?	M	300°C	O	184	42	20	8	174	(6)
grp 'b'		7	R	300°C	A	214	−40	17	47	128	(6)
Pilot grp 1		7	R	300°C	O	176	79	41	36	179	(6)
Pilot grp 2		6	R	300°C	O	177	6	14	29	181	(6)
Pilot grp 3		7	R	300°C	A	212	−37	14	46	132	(6)
Orcadian ORS	10	85	R	300°C	A	190	−39	15	50	165	(7)
Achanarras Lmst		110	R	250°C	A	170	−50	—	61	195	(8)
John O'Groats	10	43	M	300°C	A	188	−41	4	54	164	(9)
John O'Groats		12	R	500°C	B	209	6	10	24	146	(9)
Basal Caithness		27	M	500°C	B	205	3	6	27	149	(11)
(b) *Igneous*											
Orkney		7	M	550°C	B	205	8	9	24	150	(3)
Orkney/Shetland	7	36	R	400°C	O	216	46	14	−2	147	(4)
Duncansby Neck		26	R	10mT	A	208	−55	2	60	127	(10)
Duncansby Neck		20	R	500°C	B	205	8	6	24	149	(10)
Helmsdale A		21	R	500°C	A	183	−32	6	49	171	(12)
Helmsdale B		17	M	500°C	B	181	2	6	31	175	(12)
Duncansby Necks		18	R	300°C	A	209	−49	2	55	130	(13)
(c) *Combined Means*											
	A (9 studies)					196	−43	9	55	149	
	B (6 studies)					203	7	10	26	150	

The treatment (Tmt) is only an indication of the level at which component was defined—in some cases, combined treatments have been involved (see text). The classification into groups, A, B and O are based on their mutual similarities (Figure 1). The reference is to numbered comments in the text where the publication references are given. Spec.-number of specimens used; Pol-polarity (N, R, M); Tmt.-demagnetisation treatment.

REFS:

(1) Stubbs (1958)
(2) El Batrouk (1971)
(3) Storetvedt & Petersen (1972)
(4) Morris et al. (1973)
(5) Waage & Storetvedt (1973)
(6) Turner & Archer (1975)
(7) Tarling et al. (1976)
(8) Turner (1977)
(9) Storetvedt & Carmichael (1979)
(10) Storetvedt et al. (1978)
(11) Storetvedt & Torsvik (1983)
(12) Torsvik et al.(1983)
(13) Xu (1984)

TABLE 5.1 : FISHER STATISTICS & POLE POSITIONS FOR PALAEOMAGNETIC STUDIES IN THE ORCADIAN BASIN. (TARLING 1985).

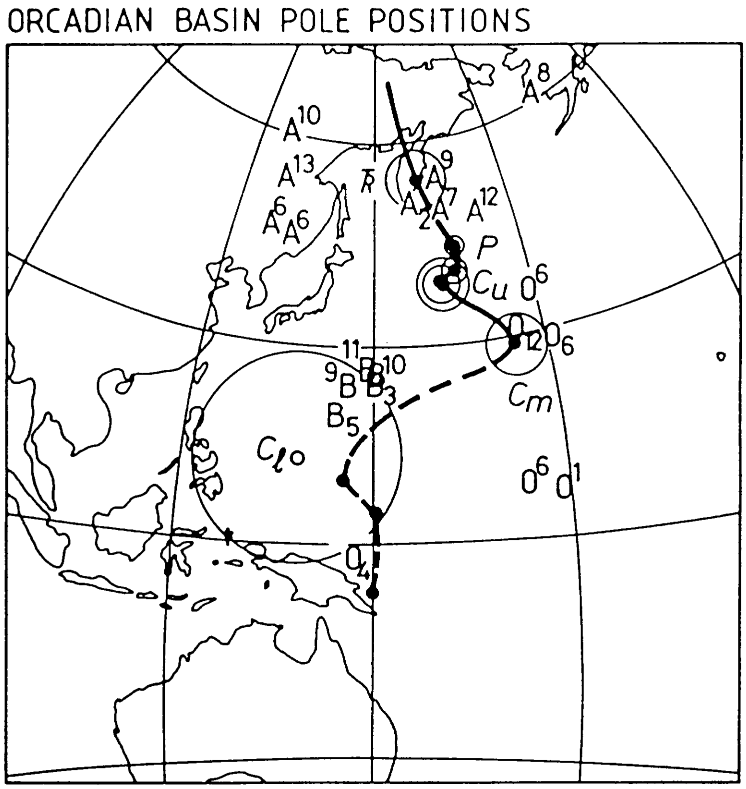


FIGURE 5.2 : GROUP (A) & GROUP (B) ORCADIAN BASIN POLE POSITIONS (after Tarling, 1985) PLOTTED ON THE EUROPEAN APWP (Tarling, 1983).

KEY
Tr - Triassic
P - Permian
C - Carboniferous

Circles are 95% confidence limits, References are as given in TABLE 5.1.

A - Group (A)
B - Group (B)
O - Miscellaneous Other results.

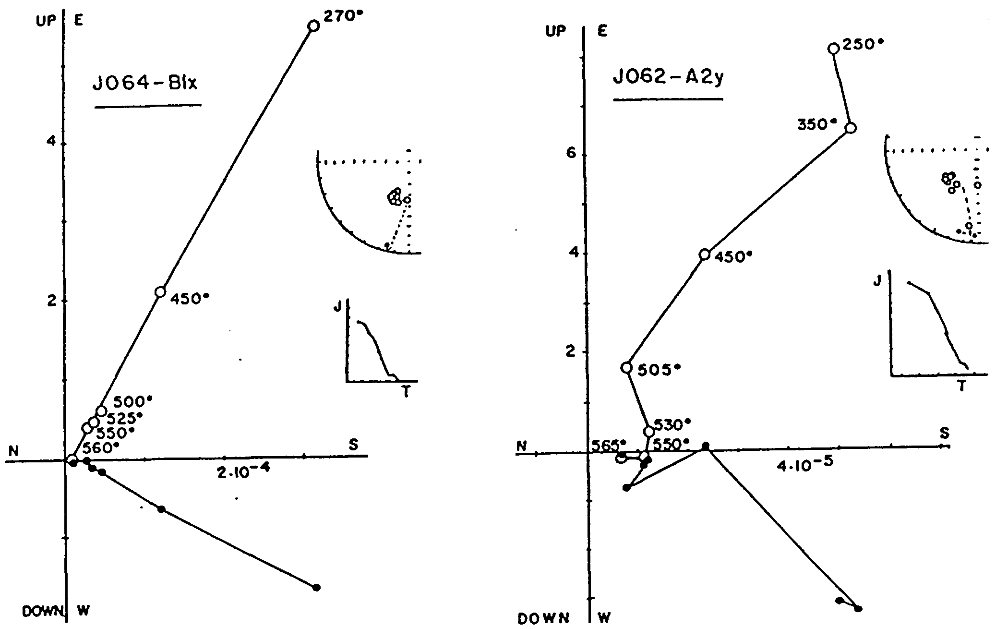


FIGURE 5.3: TYPICAL DEMAGNETISATION DIAGRAMS CONSTRUCTED BY VAN DER VOO & SCOTESE (1981) FROM DATA OF STORETVEDT & CARMICHAEL (1979).

Storevedt & Carmichael favour the existence of a high treatment component demagnetised at temperatures greater than 550°C. Van Der Voo & Scotese argue that the magnetisation has no physical basis and cannot be distinguised above laboratory noise.

magnetisations.

Storetvedt & Torsvik (1983) stress the need for detailed examination of the final stages in demagnetisation of individual samples and call for the common use of expanded orthogonal projections. This method can be particularly useful but due to its very nature is hazardous because interpretation may hinge on only a very few data points close to the origin. It is essential therefore that it be used in conjunction with a sophisticated line fitting technique (e.g LINEFIND, Kent *et al.* 1983) which is able to account the errors of the individual measurements. Failure to do so may lead to the attachment of geological significance to laboratory-induced remanences.

The results obtained from the Esha Ness Ignimbrite (Storetvedt & Torsvik, 1985) are of superior quality to previously reported (B) remanences. The component is thermally discrete (unblocking through temperatures of 620°-670°C) and lacks contamination by stable secondary magnetisations (Figure 5.4).

The authors report the remanence to predate possible Devonian folding although this relies on a single site and tectonic correction only changes the mean result by less than one degree. Precision actually decreases with strike correction but a marginal improvement is observed when magnetic fabric data is used. As the fold test is not statistically significant, any inference regarding remanence age must remain inconclusive.

Both normal and reverse polarities are reported from what is presumed a single ignimbrite sheet. This, it is argued, suggests secular variation to have been averaged out in the final mean. The implied duration of remanence acquisition would seem at variance with the intuitive cooling period of an ignimbrite sheet although no comment is made with respect to this. (The geographical restriction of differing polarity to opposing fold limbs also requires explanation or further investigation). Despite these reservations, the Esha Ness result is seen as strong evidence for the physical reality of Group (B).

The question of the inferred remanence age is outstanding and will remain so until a statistically significant fold or conglomerate test is applied within the Orcadian Basin. Tarling (1985) suggests a Permo-Carboniferous age based on proximity to the European APWP (Figure 5.2).

Torsvik (1984,1985a) implies Group (B) remanences (as listed by Tarling; Table 5.1) to represent two discrete ages of magnetisation acquisition. The Newer Granite results are interpreted as of late Silurian age whereas red bed results are seen as of Middle-Upper Devonian age. This interpretation discrepancy clearly requires the performance of a contact test on one or all of the granites. Such a test was carried out by Kneen (1973) for the Foyers Complex but data are regarded as insufficient by Tarling (1985) although accepted by Van der Voo & Scotese (1981). Briden (1970) reports a positive contact test for the Garabal Hill Complex although this pole compares with other

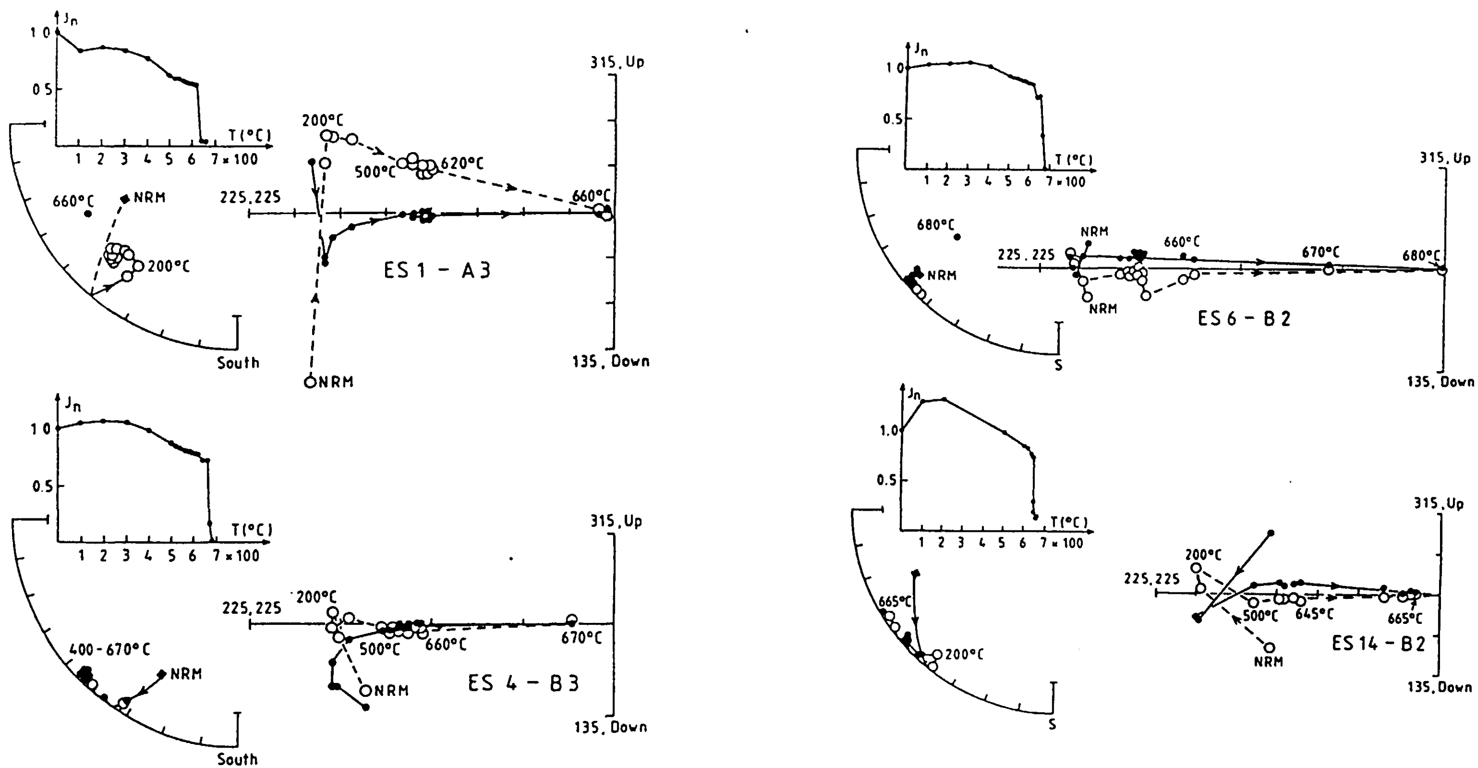


FIGURE 5.4 : REPRESENTATIVE VECTOR PROJECTIONS FROM THE MIDDLE-UPPER DEVONIAN ESHA NESS IGNIMBRITE (Storetvedt & Torsvik,1985).

Jn/T graphs illustrate the thermally discrete nature of the remanence in contrast to other Group(B) components (e.g. Storetvedt & Carmichael,1979. FIGURE 5.3).

Lower Devonian data (e.g Latham & Briden, 1975) and not Torsvik's granite results and as such cannot resolve the problem.

5.2.3 COMMENTS ON ORCADIAN BASIN PALAEOMAGNETIC WORK.

The controversy in interpretation of data from the Orcadian Basin in many ways reflects the changes in accepted standards of laboratory treatment with time. It may have been expected that studies which favour bulk demagnetisation at 300°C (e.g Tarling *et al.*, 1976. Turner & Archer, 1975) would not reveal remanence directions which unblock at temperatures above 500°C (Torsvik,1984) and sometimes in excess of 600°C (Storetvedt & Torsvik,1983).

The use of pilot specimens in earlier studies has also perhaps led to an oversimplification of reported magnetic signatures and the loss of vital information. The discrepancies in age interpretation of Orcadian Basin magnetisations may well be resolved if sufficient field tests with respect to each component can be effected. For example, although Storetvedt & Torsvik (1985) report the presence of agglomerates in the Esha Ness succession, no conglomerate test is attempted. It would also be interesting to study the demagnetisation behaviour of ORS sediments from the northern Midland Valley where at least the contemporaneous interbedded lavas have a widely accepted magnetic age. Important lessons may then be learnt with respect to equivalent and younger sediments of the Orcadian Basin.

5.3 TECTONIC CONSTRAINTS AND PROPOSED FAULT DISPLACEMENTS.

Various interpretations of the Siluro-Devonian palaeomagnetic data have been quoted as evidence for large scale translations within the Caledonides (e.g. Storetvedt, 1974, 1975., Van der Voo & Scotese, 1981). By çontrast, certain equivalence of results transecting major dislocations have been used to constrain potential movements (Harte *et al.* 1984 ., Briden *et al.* 1984).

Storetvedt (1974) explains differences existing in Group (B) determinations from north of the Great Glen Fault (GGF) and Norway by invoking 200-300 kilometres of sinistral strike slip movement. This was initially opposed on geological grounds by Mykura (1975) who argued that this would lead to stratigraphical incompatibility. In reply, Storetvedt (1975) states this to be a minimum estimate and lengthens inferred movement to of the order of 500 kilometres. Donovan *et al.* (1976) similarly oppose large displacement on stratigraphic grounds outlining that ORS sediments on both sides of the fault have similar development histories unique in the British Isles.

Differences in Devonian palaeomagnetic data between Britain and Norway were earlier noted by Briden (1970) who outlined potential causes of the disparity. One possibility essentially forms the basis of Storetvedt's argument in that "Britain and Norway belonged to different crustal plates between which large relative movements have since occurred." Briden notes that failure of the geomagnetic dipole approximation or differing ages of remanence could also explain the results.

Storetvedt (1987) has maintained the need for sinistral displacement (now 600 kms) evidenced in Group (B) directions despite criticism on palaeomagnetic grounds (Briden *et al.* 1984., see also 6.6, 7.4.2, 7.5.1, Figure 7.10). He further suggests a compensating dextral movement (300 kms) in 'Hercynian time' based on apparent contrasts in Group (A) results across the GGF.

Briden *et al.* (1984) point out that the Norwegian data differ significantly from British results south of the GGF and hence require an alternative explanation. Newer Granite results (i.e. Torsvik et al. 1983, Torsvik, 1984, 1985) do not indicate sizable transcurrent motion. These are explained by Storetvedt as being "not sufficiently well defined to enable reasonable assessment of the model involving a few hundred kilometres translation."

Storetvedt & Deutsch (1986) use the hypothesis of sinistral then dextral transcurrent motion to correct data from northwest Scotland syenites (Turnell & Briden, 1983) by twenty degrees in declination and subsequently construct a new Lower Palaeozoic APWP for Scotland (3.2.2).

Van der Voo & Scotese (1981) presented palaeomagnetic evidence for c.2000 kilometres sinistral displacement on the Great Glen Fault during Carboniferous times. Their proposal was based on selected British data and proved comparable in scale with similar mega shear postulated for the Appalachian Belt (see Kent & Opdyke, 1978, 1979). Displacement would resolve palaeomagnetic latitudinal differences between Europe and North America on the Bullard et al. (1965) reconstruction. Geological evidence quoted in support of the hypothesis is the great similarity reported between the Pre-Cambrian of Greenland and that of the Lewisian of Scotland (Tarney et al.1972). Palaeomagnetic results West of the Great Glen were re-examined in the light of the proposed offset. Group (A) remanences originally regarded as secondary (e.g. Tarling *et al.* 1976) were reinterpreted as of primary origin and thought to reflect a discordancy across the fault zone (e.g. with respect to Kneen, 1973). The reported group (B) results (e.g. Storetvedt & Carmichael, 1979) were considered to have no physical basis (Figure 5.3).

This model has subsequently been opposed both on geological (e.g. Smith & Watson, 1983) and palaeomagnetic grounds (Briden *et al.* 1984, Torsvik, 1984, Torsvik *et al.* 1986). Briden *et al.* point out that displacement of this magnitude is not compatible with a single Eulerian rotation for the exposed length of the fault. Further they provide evidence (largely from Turnell & Briden, 1983) that the APWP North of the GGF is of "British" rather than "American" affinity. Turner & Archer (1975) recognised a group (A) remanence of identical direction and unblocking properties south of the GGF in the Gamrie outlier not considered by Van der Voo & Scotese. Similarly, the (I) component of the St.Abbs outlier (6.6) is demonstrably a secondary magnetisation and in this context would also argue against a model for 2000 kilometres displacement (6.7).

Palaeomagnetic data within the paratectonic Caledonides can also provide constraints on the timing and magnitude of potential displacements between tectonostratigraphic blocks. Bluck & Leake (1986) have summarised the geological evidence for disparate positioning of the Grampian and Midland Valley blocks during Ordovician times. Watts, (in Harte et al.1984), notes the identity of Lower ORS poles from either side of the Highland Boundary Fault (HBF) and infers constraint on late-stage (post ORS) displacement to "less than the errors of location of the palaeomagnetic poles". The lack of detectable motions between the blocks following extrusion of the Old Red lavas is consistent with correlation of the 'Lintrathen Porphyry' across the HBF for late Silurian time (Paterson & Harris, 1969., 7.7).

Briden *et al.* (1984) note there to be no discrepancy in Silurian-Devonian data across the Solway Line (Iapetus Suture). They suggest that, if this represents closure of Iapetus, then a minimum rate of ~2cm per year is implied. Piper (1979) suggests that a certain longitudinal difference in poles from north and south of the suture is consistent with, but does not establish, the 1000 kilometres of dextral shear postulated by Phillips et al. (1976). The poles used in this analysis are poorly constrained however (e.g. Cautley Dolerite., Piper,1979. Cheviot., Thorning, 1974) and of uncertain age (Fishguard Volcanic Group, secondary magnetisation). A sinistral shear sense is now thought to have predominated during Lower ORS times by most workers (e.g. Hutton,1987., see 2.2) but may not have effected major translation (7.7).

The motion of the British Isles as derived from palaeomagnetic data can be considered in two phases during Ordovician-Devonian times (see Figure 5.1a). Firstly, an east-west polar wander can be explained by an *in situ* anticlockwise rotation with respect to the present pole. This rotation occurred through Ordovician to Late Silurian time.

Palaeolatitudinal translation is then required between early and late Devonian time (or mid-Devonian to early Carboniferous time; see Torsvik *et al.* 1988) producing a north-south spread of poles. A moderate southerly latitude hence becomes a more equatorial latitude by late Devonian (early Carboniferous) time. Torsvik (1985a) suggests a 'kink' in the polar wander path to accommodate his Newer Granite data. This produces the north-south-north palaeolatitude movement indicated in Figure 5.1b.

CHAPTER 5 : REFERENCES.

Bluck, B.J. and Leake, B.E. 1986. Late Ordovician to Early Silurian amalgamation of the Dalradian and adjacent Ordovician rocks in the British Isles. *Geology,* 14, 917-919.

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, 457-470.

Briden, J.C., Turnell, H. and Watts, D.R. 1984. British palaeomagnetism, Iapetus Ocean, and the Great Glen Fault. *Geology,* 12, 428-431.

Bullard, E.C., Everitt, J.E. and Smith, A.G. 1965. The fit of the continents around the Atlantic. *Philosophical Transactions of the Royal Society of London, Series A,* 258, 41-51.

Chamalaun, F.H. and Creer, K.M. 1964. Thermal demagnetization studies of the Old Red Sandstones of the Anglo-Welsh Cuvette. *Geophysical Journal of the Royal Astronomical Society,* 69, 1607-1616.

Conybeare, W.D. and Phillips, W. 1822. *Outlines of the Geology of England and Wales.* Crown. London. 471pp.

Creer, K.M. 1957. Palaeomagnetic investigations in Great Britain IV. The natural remanent magnetization of certain stable rocks from Great Britain. *Philosophical Transactions of the Royal Society of London, Series A,* 250, 114-129.

Creer, K.M. 1968. Palaeozoic Palaeomagnetism. *Nature,* 219, 246-250.

Creer, K.M. and Embleton, B.J.J. 1967. Devonian palaeomagnetic pole for Europe and N. America. *Nature,* 214, 42-43.

Donovan, R.N., Archer, R., Turner, P. and Tarling, D.H. 1976. Devonian palaeogeography of the Orcadian Basin and the Great Glen Fault. *Nature,* 259, 550-551.

El-Batrouk, S.I. 1971. *A palaeomagnetic study of the Caithness sandstone.* University of Newcastle upon Tyne, M.Sc. dissertation (unpubl.).

Embleton, B.J.J. 1968. Laboratory stability tests applied to Devonian rocks from Scotland. *Geophysical Journal of the Royal Astronomical Society,* 16, 239-251.

Embleton, B.J.J. 1970. Some recent palaeomagnetic data from Europe: A brief discussion. *In S.K. Runcorn (ed.), Palaeogeophysics.* Academic Press, London, 171-175.

Harte, B., Booth, J.E., Dempster, T.J., Fettes, D.J., Mendum, J.R. and Watts, D. 1984. Aspects of post-depositional evolution of Dalradian and Highland Border Complex rocks in the Southern Highlands of Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 75, 151-163.

Hutton, D.H.W. 1987. Strike-slip terranes and a model for the evolution of the British ans Irish Caledonides. *Geological Magazine,* 124, 405-425.

Kent, J.T. and Opdyke, N.D. 1978. Palaeomagnetism of the Devonian Catskill Red beds: evidence for the motion of the coastal New England-Canadian Maritime region relative to Cratonic North America. *Journal of Geophysical Research,* 83, 4441-4450.

Kent, J.T. and Opdyke, N.D. 1979. The early Carboniferous palaeomagnetic field of North America and its bearing on the tectonics of the northern Appalachians. *Earth & Planetary Science Letters,* 44, 365-372.

Kent, J.T., Briden, J.C. and Mardia, K.V. 1983. Linear and planar structure in ordered multivariate data as applied to progressive demagnetization of palaeomagnetic remanence. *Geophysical Journal of the Royal Astronomical Society,* 75, 593-621.

Kneen, S.J. 1973. The palaeomagnetism of the Foyers plutonic complex, Invernesshire. *Geophysical Journal of the Royal Astronomical Society,* 32, 53-64.

Latham, A.G. and Briden, J.C. 1975. Palaemagnetic field directions in the Siluro-Devonian lavas of the Lorne Plateau, Scotland and their regional significance. *Geophysical Journal of the Royal Astronomical Society,* 43, 243-252.

McElhinny, M.W. 1973. *Palaeomagnetism and Plate Tectonics.* Cambridge University Press, Cambridge, 358pp.

McMurry, E.W. 1968. *A palaeomagnetic study of Tertiary and Devonian igneous rocks from Britain.* University of London. Ph.D. thesis, (unpubl.).

McMurry, E.W. 1970. Palaeomagnetic results from Scottish Lower Devonian age rocks. *In S.K. Runcorn (ed.), Palaeogeophysics.* Academic Press, London, 253-262.

Morris, W.A., Briden, J.C., Piper, J.D.A. and Sallomy, J.T. 1973. Palaeomagnetic studies in the British Caledonides - V. Miscellaneous new data. *Geophysical Journal of the Royal Astronomical Society,* 34, 69-105.

Mykura, W. 1975. Comment on 'Possible large-scale sinistral displacement along the Great Glen Fault in Scotland'. *Geological Magazine,* 112, 91-2.

Paterson, I.B. and Harris, A.L. 1969. Lower Old Red Sandstone ignimbrites from Dunkeld, Perthshire. *Report of the Institute of Geological Sciences,* 69/7.

Piper, J.D.A. 1978. Palaeomagnetism and palaeogeography of the Southern Uplands block in Ordovician times. *Scottish Journal of Geology,* 14, 93-107.

Piper, J.D.A. 1979. Aspects of Caledonian palaeomagnetism and their tectonic implications: *Earth & Planetary Science Letters,* 44, 176-192.

Phillips, W.E.A., Stillman, C.J. and Murphy, T. 1976. A Caledonian plate and tectonic model. *Journal of the Geological Society, London,* 132, 579-609.

Robinson, M.A. 1985. Palaeomagnetism of volcanics and sediments of the Eday Group, Southern Orkney. *Scottish Journal of Geology,* 285-300.

Sallomy, J.T. and Piper, J.D.A. 1973. Palaeomagnetic studies in the British Caledonides - IV. Lower Devonian Lavas of the Strathmore region, Scotland. *Geophysical Journal ol the Royal Astronomical Society,* 34, 47-68.

Smith, A.C. and Watson, J.V. 1983. Scale and timing of movements along the Great Glen Fault, Scotland. *Geology,* 11, 523-526.

Storetvedt, K.M. 1970. On remagnetization problems in palaeomagnetism: further considerations. *Earth & Planetary Science Letters,* 3, 444-448.

Storetvedt, K.M. 1971. Some palaeomagnetic problems of strongly oxidised rocks. *Z. Geophysics,* 37, 487-492.

Storetvedt, K.M. 1974. A possible large-scale sinistral displacement along the Great Glen Fault in Scotland. *Geological Magazine,* 111, 23-30.

Storetvedt, K.M. 1975. Possible large-scale sinistral displacement along the Great Glen Fault in Scotland (reply). *Geological Magazine,* 112, 93-94.

Storetvedt, K.M. 1987. Major late Caledonian and Hercynian shear movements on the Great Glen Fault. *Tectonophysics,* 142, 253-267.

Storetvedt, K.M. and Gjellestad, G. 1966. Palaeomagnetic investigation of an Old Red Sandstone formation of Southern Norway. *Nature,* 212, 59-61.

Storetvedt, K.M., Halvorsen, E. and Gjellastad, G. 1968. Thermal analysis of the natural remanent magnetism of some Upper Silurian Red Sandstones in the Oslo region. *Tectonophysics,* 5, 413-426.

Storetvedt, K.M. and Peterson, N. 1972. Palaeomagnetic properties of the Middle-Upper Devonian volcanics of the Orkney Islands. *Earth & Planetary Science Letters,* 14, 269-278.

Storetvedt, K.M., Carmichael, C.M., Hayatsu, A. and Palmer, H.C. 1978. Palaeomagnetism and K/Ar results from the Duncansby Volcanic Neck, NE Scotland: superimposed magnetizations, age of igneous activity and tectonic implications. *Physics of the Earth & Planetary Interiors,* 16, 379-392.

Storetvedt, K.M. and Carmichael, C.M. 1979. Resolution of superimposed magnetization in the Devonian John'O Groats Sandstone, North Scotland. *Geophysical Journal of the Royal Astronomical Society,* 58, 769-784.

Storetvedt, K.M. and Torsvik, T.H. 1983. Palaeomagnetic re-examination of the basal Caithness Old Red Sandstone; aspects of local and regional tectonics. *Tectonophysics,* 98, 151-164.

Storetvedt, K.M. and Torsvik, T.H. 1985. Palaeomagnetic results from the Esha Ness Ignimbrites, Shetland. *Physics of the Earth & Planetary Interiors,* 31, 169-173.

Storetvedt, K.M. and Deutsch, E.R. 1986. Reappraisal of Scottish Ordovician palaeomagnetism. *Geophysical Journal of the Royal Astronomical Society,* 87, 1193-1206.

Stubbs, P.M. 1958. *Continental drift and polar wandering: A palaeomagnetic study of the British and European Trias, and of the British Old Red Sandstone.* University of London. Ph.D. thesis, (unpubl.).

Tarling, D.H. 1983. *Palaeomagnetism, Principles and Applications in Geology, Geophysics and Archaeology.* Chapman and Hall, London. 379pp.

Tarling, D.H. 1985. Palaeomagnetic studies of the Orcadian Basin. *Scottish Journal of Geology,* 21, 261-273.

Tarling, D.H., Donovan, R.N., Abou-Deeb, J.M. and El-Batrouk, S.I. 1976. Palaeomagnetic dating of haemetite genesis in Orcadian Basin sediments. *Scottish Journal of Geology,* 12, 125-134.

Tarney, J., Skinner, A.C. and Sheraton, J.W. 1972. A geochemical comparison of major Archean gneiss units from northwest Scotland and east Greenland: *International Geological Congress, 24th, Montreal, Proceedings,* 1, 162-174.

Thorning, L. 1974. Palaeomagnetic results from the Lower Devonian rocks of the Cheviot Hills. Northern England. *Geophysical Journal of the Royal Astronomical Society,* 487-496.

Torsvik, T.H. 1984. Palaeomagnetization of the Foyers and Strontian granites, Scotland. *Physics of the Earth & Planetary Interiors,* 36, 163-177.

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

Torsvik, T.H. 1985b. Palaeomagnetic results from the Peterhead granite, Scotland; implication for regional late Caledonian magnetic overprinting. *Physics of the Earth & Planetary Interiors,* 39, 108-117.

Torsvik, T.H., Lovlie, R. and Storetvedt, K.M. 1983. Multicomponent magnatization in the Helmsdale Granite, North Scotland: geotectonic implications. *Tectonophysics,* 98, 111-129.

Torsvik, T.H., Lovlie, R. and Sturt, B.A. 1985. Palaeomagnetic argument for a stationary Spitsbergen relative to the British Isles (Western Europe) since late Devonian and its bearing on North Atlantic reconstruction. *Earth & Planetary Science Letters,* 75, 278-288.

Torsvik, T.H., Lyse, O., Atteras, G., and Bluck, B.J. 1988. Palaeozoic palaeomagnetic results from Scotland and their bearing on the British apparent polar wander path. *Physics of the Earth & Planetary Interiors,* in press.

Turnell. H.B. and Briden, J.C. 1983. Palaeomagnetism of NW Scotland syenites in relation to local and regional tectonics. *Geophysical Journal of the Royal Astronomical Society,* 68, 279-291.

Turner, P. 1977. Remanent magnetism of Middle Old Red Sandstone lacustrine and fluviatile sediments from the Orcadian Basin, Scotland. *Journal of the Geological Society, London,* 133, 37-50.

Turner, P. and Archer, R. 1975. Magnetisation history of the Lower Old Red Sandstone from the Gamrie Outlier, Scotland. *Earth & Planetary Science Letters,* 27, 240-250.

Van der Voo, R. and Scotese, C. 1981. Palaeomagnetic evidence for a large (2000km) sinistral offset along the Great Glen Fault during Carboniferous time. *Geology,* 9, 583-589.

Waage, H.L. and Storetvedt, K.M. 1973. The Devonian geomagnetic axis relative to the Orcadian Basin, N. Scotland. *Z. Geophysics,* 39, 937-951.

Xu, T.C. 1984. *Palaeomagnetic studies of Upper Palaeozoic rocks in Scotland.* University of Newcastle upon Tyne Ph.D. thesis, (unpubl.).

CHAPTER 6: PALAEOMAGNETIC STUDY OF THE O.R.S. VOLCANICS AND SEDIMENTS OF ST.ABBS HEAD, BERWICKSHIRE, S.E.SCOTLAND.

6.1 INTRODUCTION.

The volcanics and sediments of St. Abbs Head represent an outlier of Lower Old Red Sandstone which unconformably overlies the Silurian greywackes of the Southern Uplands (A.Geikie, 1864). They form a minor southerly constituent of a voluminous volcanic suite ranging from the Cheviot Hills to the Grampian Highlands of Scotland (Figure 6.1., Thirlwall, 1981).

Current geological evidence suggests large scale transcurrent movements within the British paratectonic Caledonides persisting into early Devonian times (Hutton, 1987., Elders, 1987., Soper *et al.* 1987., Anderson & Oliver, 1986., see Chapter 2 for review). Recent palaeomagnetic studies from Norway (Douglass, 1988) show substantial separation between Britain and Norway to have persisted until at least middle - late Devonian times. There exists therefore, the possibility of revealing palaeomagnetic anomalies between individual terranes within the Caledonian mosaic through the study of the O.R.S.

A palaeomagnetic investigation was initiated at St. Abbs Head in an attempt to image the translations and/or rotations expected from the geological models. The coeval Siluro-Devonian pole derived from the northern Midland Valley volcanics (Sallomy & Piper, 1973., Torsvik, 1985) might then be used comparatively to resolve relative movements between the two areas subsequent to lava extrusion. Elsewhere, palaeomagnetic constraint is offered by a pole position from the Cheviot Volcanics (Thorning, 1974) which, although having a large error and being derived from a younger member of the volcanic suite, is in general agreement with the Midland Valley result.

Further to this, the O.R.S. outcrop at St. Abbs Head afforded the opportunity to investigate and compare the palaeomagnetic properties of both volcanics and sediments; previous work from the Orcadian Basin having revealed substantial complexities in their signatures (Tarling, 1985., 5.2).

6.2 GEOLOGICAL BACKGROUND.

The St. Abbs Head outlier comprises a sequence of reddened andesitic lavas interstratified with water lain bedded tuffaceous horizons of equivalent composition. The tuffaceous horizons range in bed thickness from centimetre to metre scale and in grainsize from ash to boulder grade. Clast composition is universally intra-formational (J. Geikie, 1887). The St. Abbs Head outcrop covers an approximate one and a half square kilometre

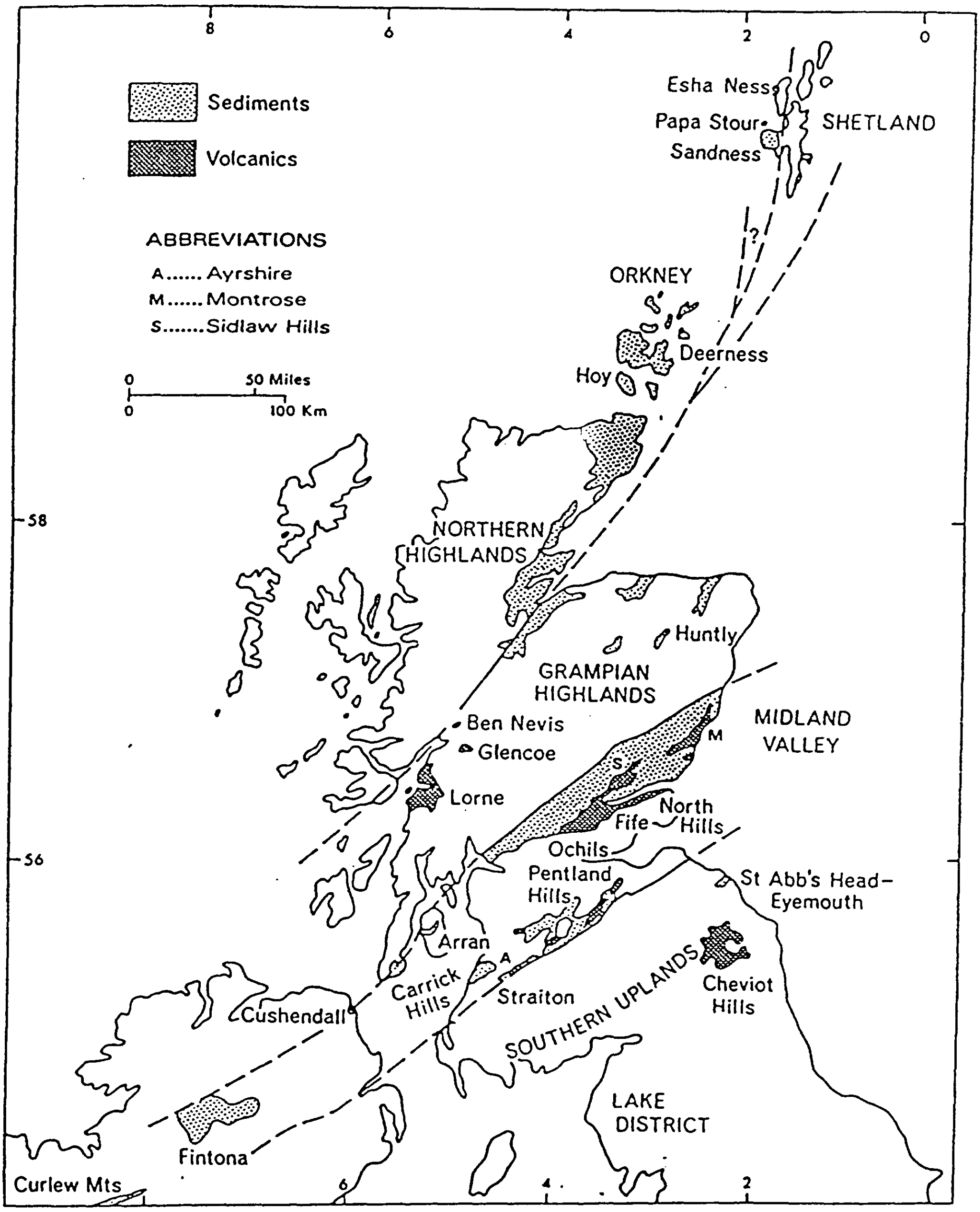


FIGURE 6.1: Distribution of Lower & Middle Old Red Sandstone sediments and volcanic rocks in northern Britain (from Thirlwall, 1981).

area bounded to the west by the St. Abbs Head fault and possibly to the south by the Halterem's Loup Fault (Figure 6.2). Further poorly exposed O.R.S. volcanics occur south of St. Abbs at Mordington, Eyemouth and in a SW-NE belt between Auchencrow and Coldingham.

The lava/tuff succession unconformably overlies Llandovery greywackes, siltstones and shales which form a component of the Southern uplands accretionary prism (McKerrow *et al.* 1977). An outlier of the Lower O.R.S. 'Great Conglomerate' which comprises clasts of these greywackes occurs in fault contact with the St. Abbs Head volcanics at Bell Hill (918680) and is inferred present at depth below the volcanics (J.Geikie, 1887., Rock & Rundle, 1986).

A minimum age for the lava succession is provided by an intruding biotite - lamprophyre dyke (400 +/- 9 Ma; K-Ar Biotite, Rock & Rundle, 1986) which forms one of a suite of such dykes concentrated in the southern half of the Central Belt and northern edge of the Southern Belt of the Southern Uplands (Rock *et al.* 1986).

The structure of the St. Abbs Head succession is equivocal due to the great difficulty in obtaining reliable dip indicators south of Burnmouth Harbour (Figure 6.2). To the north of this point, the strata generally dip to the southeast at values between 18° and 35°. Further south, the volcanics are thought to be upended against the Halterem's Loup fault to produce a complementary NW directed dip and hence may form a synclinal structure (see J.Geikie, 1887., map & Fig.2. p.181).

The trend of this structure is comparable to that of the Strathmore syncline - Sidlaw Anticline fold pair of the northern Midland Valley and hence may also date from the late Caledonian (Acadian) transpression. Stratigraphically, the deformation is regarded as having climaxed during Emsian times (Soper *et al.* 1987., 394-387 Ma; Harland *et al.* 1982).

There is no direct evidence which relates to the post-emplacement thermal history of the lava/tuff succession but indirect evidence can be gleaned from studies of the underlying greywackes. Oliver *et al.* (1984) report illite crystallinity and acritarch colouration data from the Coldingham and Linkim beds which suggest metamorphism transitional between zeolite and prehnite-pumpellyite facies (i.e. thermal conditions of 90° - 200°C). They infer heating to result from burial under "an unknown thickness of Upper Silurian and early Devonian sediments" hence providing an upper palaeo-temperature limit to the base of the O.R.S. cover sequence.

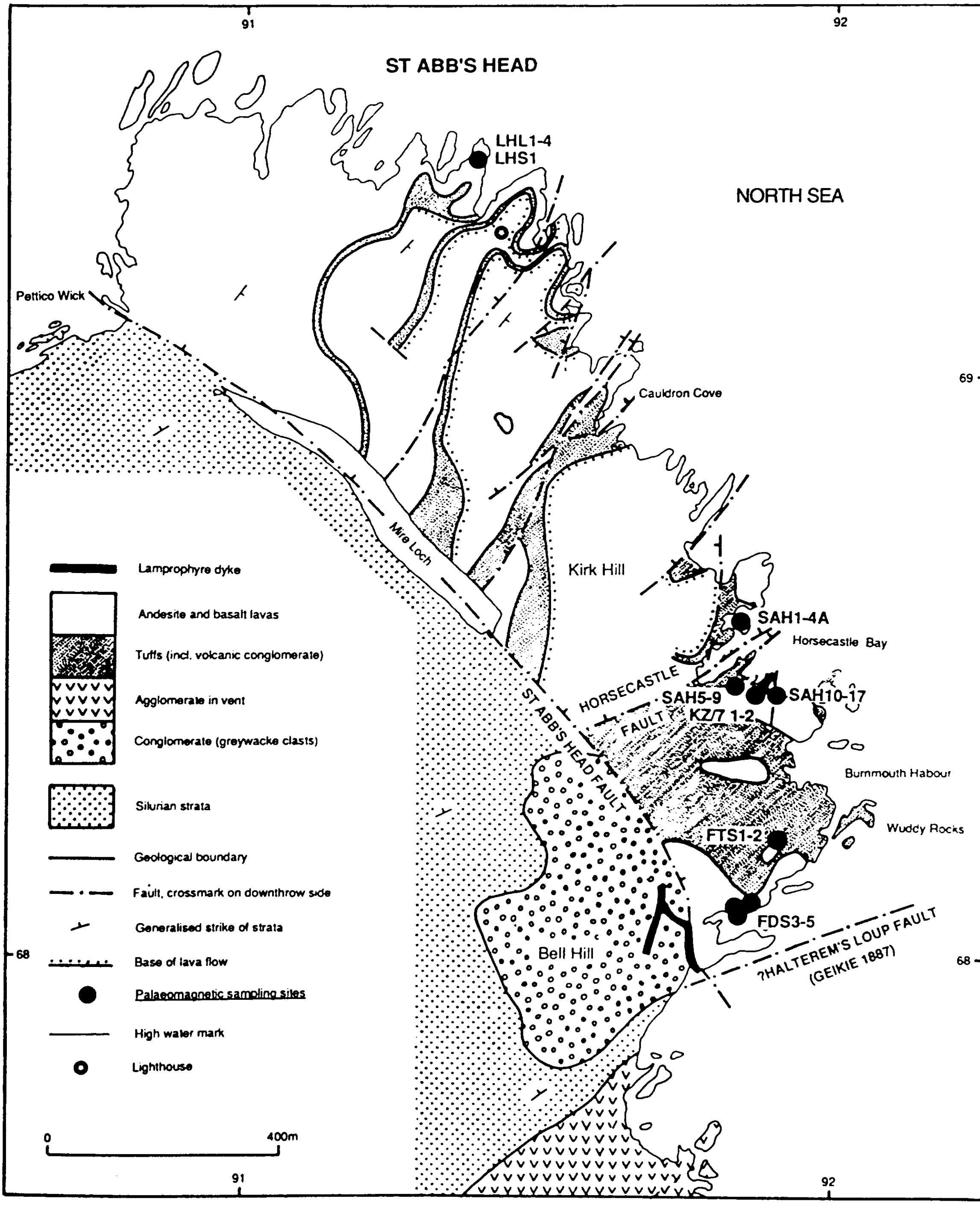


FIGURE 6.2: Geological Sketch Map of St. Abbs Head, Berwickshire, depicting palaeomagnetic sampling sites (largely after Greig, 1988., with additions).

6.3 SAMPLING & METHODS.

Palaeomagnetic sampling sites were chosen so as to potentially afford maximum relative age constraint to the recovered magnetisation components. Sites were geographically dispersed to include the proposed upended strata at the southern end of the promontary (fold test), a boulder grade facies of inter-stratified tuff (conglomerate test), and a traverse across the dated lamprophyre dyke (contact test).

In addition, it became evident at Horsecastle Bay (918685, SAH 1-4A), that both original aswell as tectonic components of dip were present. It was hoped therefore that palaeomagnetic studies would complement sedimentological work initiated at this locality aimed at determining the palaeo-horizontal. Table 6.1 outlines the sampled site lithologies and their use in the respective field tests for the St. Abbs Head section.

TABLE 6.1. ST. ABBS HEAD: SITES, SAMPLES, & FIELD TESTS.

LITHOLOGY	SITE(S)	SAMPLES N	(n)	FIELD TEST
ANDESITE	LHL1	6	(5)	(F)
a/a	LHL2	7	(6)	(F)
a/a	LHL3	7	(7)	(F)
a/a	LHL4	8	(8)	(F)
Fine Tuff	LHS1	6	(6)	(anomalous)
ANDESITE	FTS1	6	(5)	(F)
a/a	FTS2	6	(5)	(F)
LAPILLISTONE	FDS3	11	(11)	(F)
ANDESITE	FDS4	7	(7)	(F)
a/a	FDS5	6	(6)	(F)
LITHIC TUFF	SAH1-4A	26	(22)	(TS/FS)
DYKE & CONTACT	KZ/7 1-2	24	(21)	(TS/FS, CT)
LAVA CONGLOMERATE	SAH5-17	27	(27)	(CO = 13 CLASTS)

FIELD TESTS:
(F)= FOLD TEST
(TS/FS)= TOPSET/FORESET DIFFERENTIATION
(CO)= CONGLOMERATE TEST
(CT)= CONTACT TEST
N = Total samples collected.,
(n) = Samples used in calculation of statistical means.

For sites north of Horsecastle Bay and sites SAH 5-17 & KZ/7 1-2, tectonic control was obtained from inter-stratified tuffaceous horizons within the volcanic succession. For the remainder of sites however (FTS1-2, FDS3-5), although a general northward dip may be inferred from the orientation of columnar joints/cross joints within the volcanics, absolute measurement proved difficult and dips therefore represent best estimates only.

Samples were cored using a portable petrol driven drill (diameter, 2.5 cms) and later trimmed in the laboratory to heights between 1.8 and 2.3 centimeters dependent on the quality of recovered cores. Each sample was individually oriented in the field using both magnetic and sun compasses wherever possible.

Detailed demagnetisation experiments were undertaken using both stepwise thermal and static three-axis alternating field methods. Thermal demagnetisation data predominate as many samples were found to contain magnetisations which could not be removed by the AF method (i.e. coercivites greater than 100 milliTesla). Several samples were treated using combined demagnetisation firstly with alternating field then subsequently with thermal treatment. Remanent magnetisation measurements were made using a micro computer controlled complete result spinner magnetometer (Molyneux, 1971). Orthogonal projections were computer plotted after each demagnetisation step so as to allow optimum choice of ensuing treatments. Results were interpreted using the LINEFIND statistical algorithm of Kent *et al.* (1983); selected lines being checked by visual inspection of data.

6.4 PALAEOMAGNETIC RESULTS.

Variations in the NRM intensity and apparent susceptibility determined for the volcanics and tuffaceous sediments are illustrated in Figure 6.3.

Following detailed stepwise demagnetisation, a maximum of three remanence components were identified as present in any given sample. These were termed components (L), (I) & (H) pertaining to 'Low', 'Intermediate' and 'High' unblocking spectra respectively. A brief description of the properties of each magnetisation component now follows:-

(Examples of orthogonal projections revealing the characteristic components are illustrated in Figure 6.4 and further referred to in the following text. The distribution of magnetisation components between palaeomagnetic sampling sites is summarised in Table 6.2. Site mean and sample statistics for components (I) and (H) are given in Table 6.3).

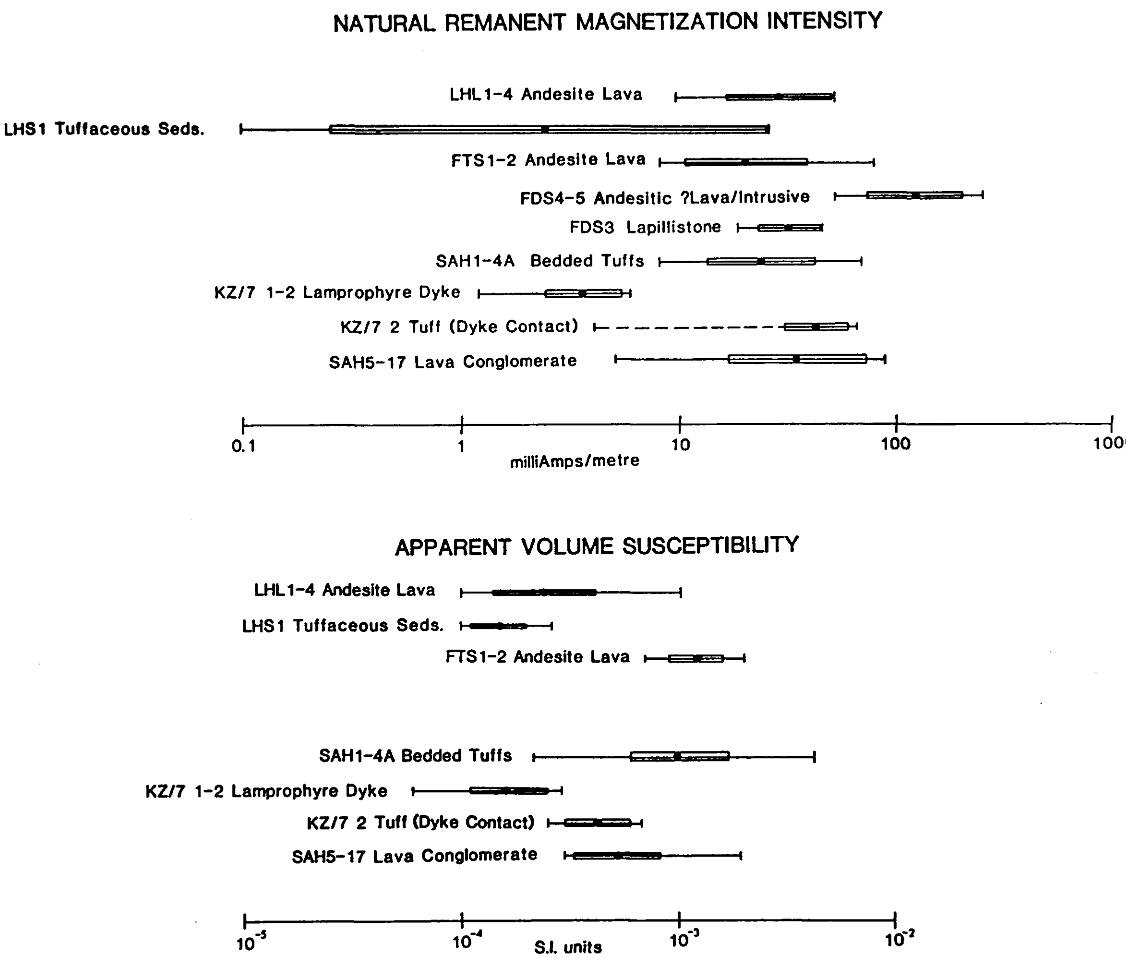


FIGURE 6.3: Observed variations in NRM Intensity and Apparent Volume Susceptibility for the differing palaeomagnetic sampling sites. Parameters are plotted on a logarithmic scale. Solid circles indicate distribution means. Triple bars delineate the extent of one standard deviation. Single bars mark the total observed range.

TABLE 6.2 : DISTRIBUTION OF COMPONENTS BETWEEN SAMPLING SITES.

SITE	COMPONENT (L)	COMPONENT (I)	COMPONENT (H)
LHL1-4	√	√	X
LHS1	√	?	?
FTS1-2	√	√	X
FDS3-5	√	√	X
SAH1-4a	√	√ *	√ *
SAH5-17	√	√	X
KZ/7 1-2	√	√	√

(* No statistical mean calculated as component distribution is non-Fisherian).

6.4.1 COMPONENT (L).

The relative magnitude of component (L) with respect to the other components varies considerably between sites and to a lesser extent between samples of a given site. It may be expressed merely as a minor 'kink' in the demagnetisation trajectory, (i.e. <5% total NRM), or form the predominant component present in a particular sample (c.f. Fig. 6.4., a & b, respectively). Component (L) is generally removed following treatment to approximately 250°C/15milliTesla upon demagnetisation. The component is poorly constrained in direction often being defined only by the difference vector of the NRM and ensuing first demagnetisation treatment (e.g. Fig.6.4 a-d).

A correlation was observed between the direction of component (L) and the orientation of field drilling. This is particularly evident at sites where the component forms a relatively high proportion of the NRM (i.e. sites SAH1-4A). Examples of this relationship are illustrated in Figure 6.5.

The correlation strongly suggests at least a proportion of component (L) to be imparted during sampling. As such, it can be of little or no geological significance. Recent field (viscous) effects may also contribute to the component.

Drilling Induced Remanence (DIR) has been previously reported by Burmester (1977) and Jackson & Van der Voo (1985). It is ascribed to the acquisition of a stress-aided viscous magnetisation by large surficial magnetite grains during sawing or drilling. Burmester (1977) suggests a method for its removal based upon etching of the sample surface with HCl. In the present study however, little or no spectra overlap was observed between component (L) and components of higher magnetic stability (e.g. Figures

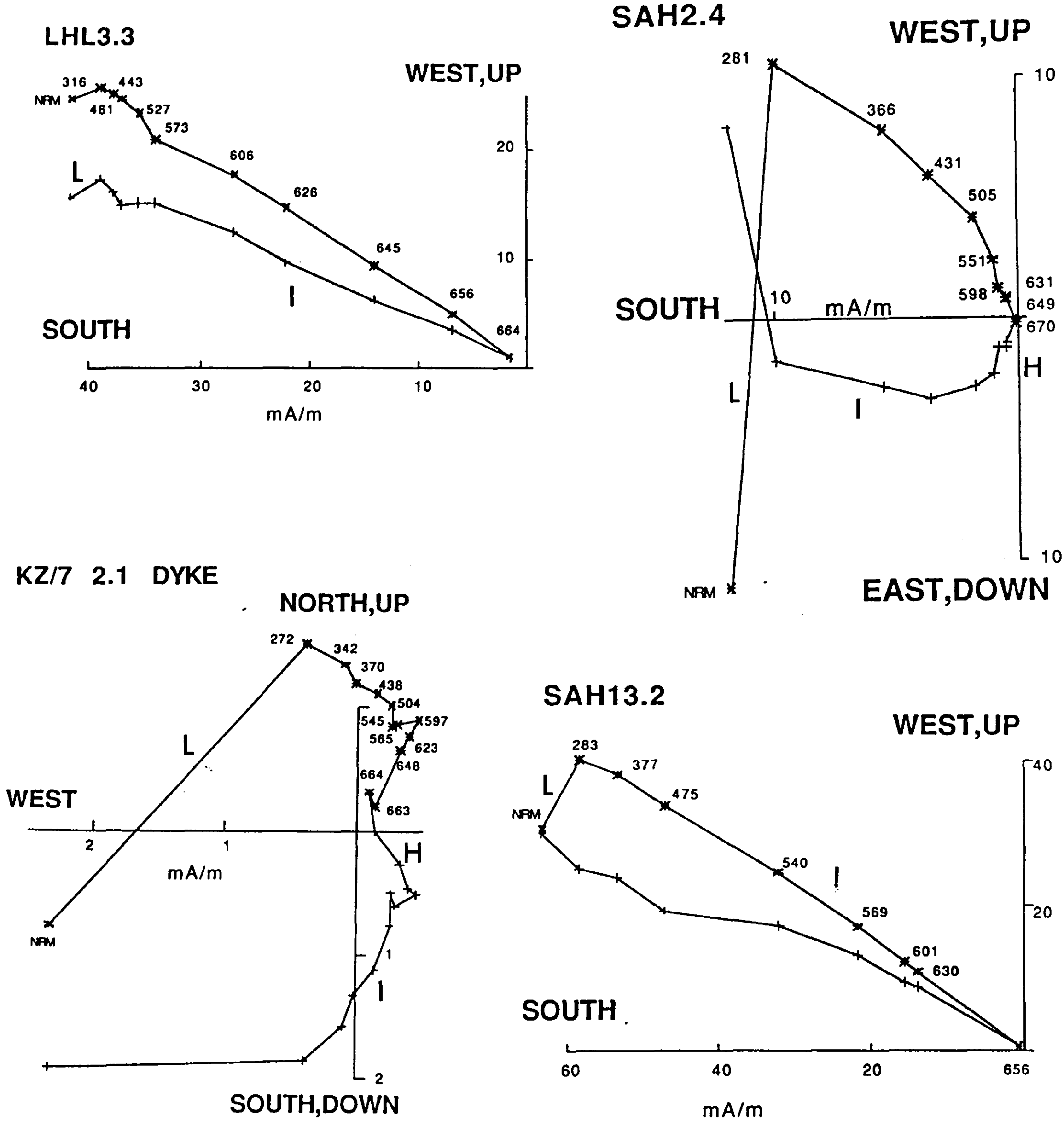


FIGURE 6.4: Examples of orthogonal projections showing combinations of components (L), (I) & (H) defined following thermal demagnetisation. In all examples, crosses (stars) refer to projection in the horizontal (vertical) plane. Treatments are denoted in degrees Celcius.

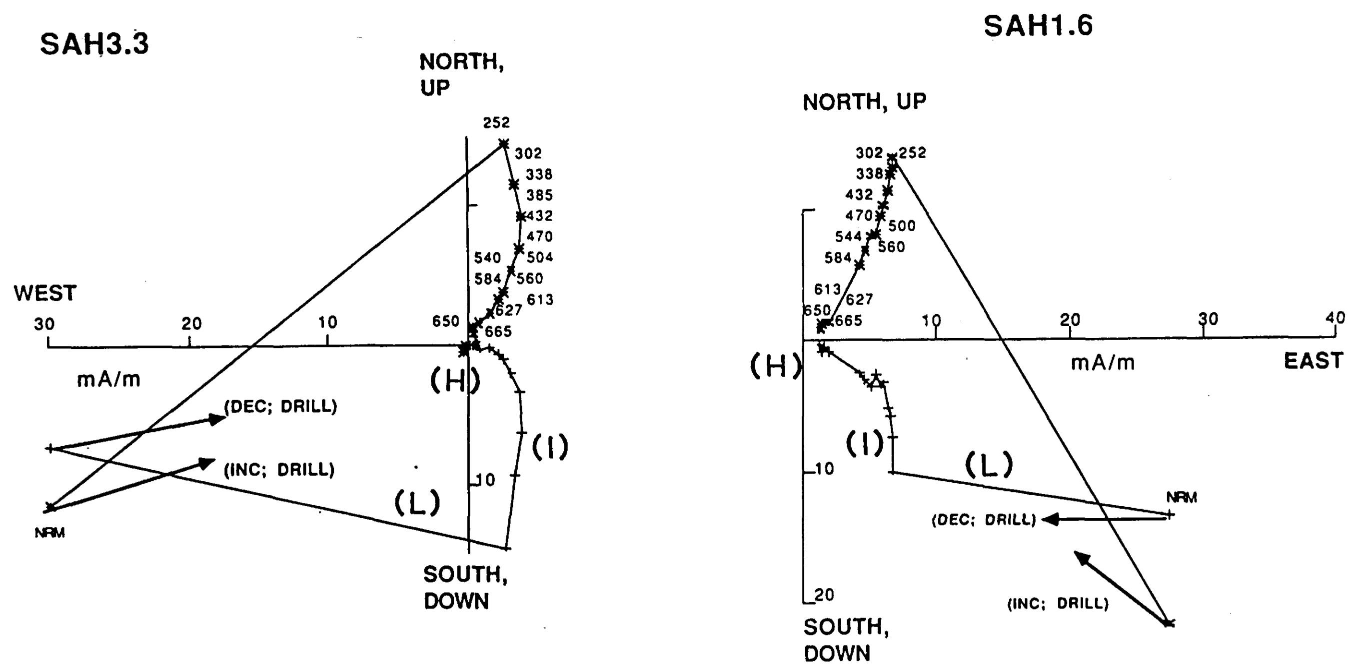


FIGURE 6.5: Example orthogonal projections show the directional correlation between component (L) and the orientation of sample drilling.

6.4 & 6.5). Traditional cleaning methods were therefore regarded as adequate for its removal.

It is notable that the DIR orientation survives the later disturbing effect of sample trimming in the laboratory. This process should act to degrade any correlation between component (L) and the sample drilling axis. In this respect, the reported DIR is akin to that described by Watts (1979, p.191) for the Upper Cambrian Eau Clair Formation and somewhat unlike those of Burmester (1977) and Jackson & Van der Voo (1985) both of which were reset to the direction of the ambient field during sample preparation.

6.4.2 COMPONENT (I).

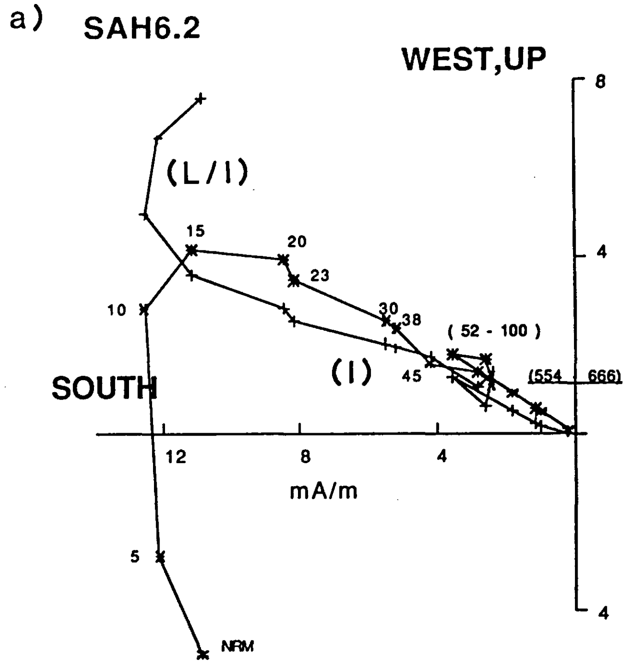
Component (I) occurs in all samples of the study with the exception of site LHS1 (Table 6.2). It generally unblocks between treatments of approximately 200-600°C/15 -100mT but stability may exceed the upper limit in the absence of component (H), (Figure 6.6a). This suggests both single/pseudo-single domain magnetite and hematite to carry proportions of the remanence.

In situ, the component is south - southwesterly directed and of moderate negative inclination. Thermal stability overlap is rare with respect to component (L) but common with component (H) indicated by substantial curvature of the demagnetisation trajectory (Figure 6.6b). Some overlap of coercivity spectra with component (L) is evident upon AF demagnetisation (Figure 6.6a).

6.4.3 COMPONENT (H).

This component is restricted in occurrence to the tuffaceous sediments of Horsecastle Bay (SAH 1-4A) and to the biotite lamprophyre dyke (KZ/7 1-2; Table 6.2). In situ, the magnetisation has east - southeasterly declinations and is of moderate - steep negative inclination. Unblocking occurs at temperatures in excess of 600°C during thermal demagnetisation and it is not removed upon AF treatment to maximum fields of 100mT. This indicates the remanence to reside exclusively in hematite.

When present, component (H) is usually uncovered within the final 10 - 15% of NRM remaining following successive demagnetisations (Figure 6.4 b & c). As such, it becomes particularly prone to the disturbing effects of laboratory induced noise, level of instrument resolution etc.



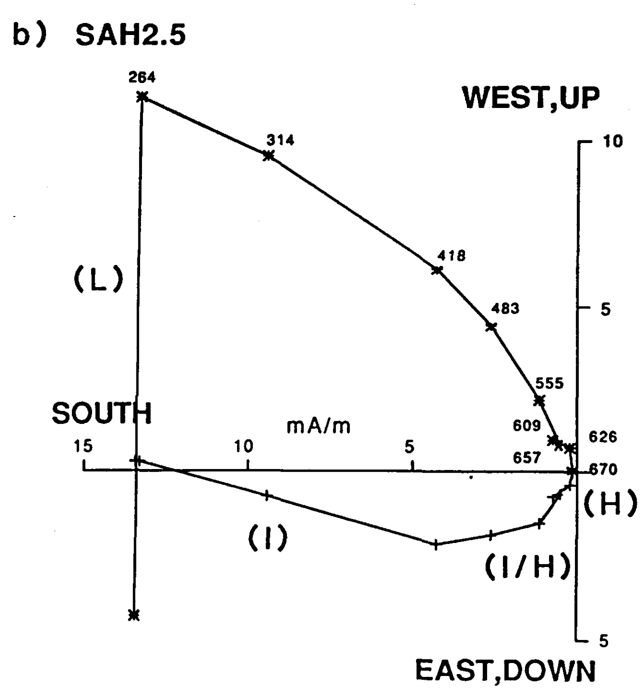


FIGURE 6.6: Orthogonal projections display a marked curvature indicating the overlap of component stability spectra.

a) SAH 6.2: Components (L) & (I) overlap in coercivity spectra. Treatments are given in milliTesla. 'Spiralling' of the orthogonal projection during demagnetisation at treatments of 52 to 100 mT indicates minor GRM acquisition. Demagnetisation was then continued using thermal treatment.

b) SAH 2.5: Components (I) & (H) overlap in unblocking temperature spectra. Little or no overlap occurs between components (L) and (I).

6.4.4 ANOMALOUS RESULTS FROM SITE LHS1.

Both NRM and demagnetisation studies of site LHS1 are atypical to the characteristic behaviour previously described. In situ, NRM directions are of southeasterly declination and moderate negative inclination becoming south-southeasterly directed and of steep negative inclination with tectonic correction (Table 6.3). NRM intensity and magnetic susceptibility values are low when referred to the observed range at St. Abbs Head (Figure 6.3). With cleaning, a minor low blocking temperature/coercivity component gives way to a stable magnetisation of similar direction to the total NRM. This unblocks at temperatures between 200° - 650°C and at coercivities of between 15 and 100mT. A small proportion of remanence remains after maximum AF treatment (100mT).

No satisfactory explanation becomes apparent for this 'anomalously directed' component although it has been omitted from statistical analyses. Constraints upon bedding are particularly good for the site such that an aberrent structural interpretation is precluded. An explanation in terms of the 'mixing' of magnetisation components (I) and (H) remains possible however (as the anomalous direction is intermediate between these components).

6.5 PALAEOMAGNETIC FIELD TESTS.

6.5.1 FOLD TEST.

The uneven distribution of both remanence components and palaeo-horizontal indicators between sampling sites greatly hinders the successful application of a fold test at St. Abbs Head.

As previously described, component (L) appears related to sample drilling axes and therefore any fold test would be inappropriate. The restriction of component (H) to Horsecastle Bay precludes its employment in a fold test; tectonic correction being additionally complicated by the presence of syn-depositional dip surfaces. For this reason, all sites within the bay were omitted from the fold test analyses.

A test was therefore only attempted for the component of intermediate unblocking (I). The results are outlined in Figure 6.7 showing site mean distributions of the component before/after tectonic correction (a,b) together with evolving Fisher statistical parameters upon incremental correction (c). Employing the criteria of McElhinny (1964), the intermediate component fails a fold test (i.e. is post deformational) at the 99% confidence level.

TABLE 6.3 : COMPONENT (I) and (H) STATISTICS & POLE DETERMINATIONS.

COMPONENT (I): IN SITU, (SITE MEANS)

SITE	N	DEC	INC	α95	k	R
LHL1	5	213.2	-27.0	3.5	482.1	4.99
LHL2	6	216.4	-30.1	9.2	53.8	5.91
LHL3	7	214.1	-28.7	4.4	188.9	6.97
LHL4	8	217.2	-36.7	2.6	454.3	7.98
FTS1	5	190.4	-43.3	6.1	157.0	4.97
FTS2	5	190.1	-36.1	8.4	84.1	4.95
FDS3	11	208.8	-47.7	4.7	94.4	10.89
FDS4	7	186.2	-48.2	6.3	92.5	6.94
FDS5	6	205.9	-38.9	4.9	191.9	5.97

LHS 1 (ANOMALOUS COMPONENT ; SITE MEAN).

LHS1 (IN SITU)	6	140.2	-42.4	9.7	48.4	5.90
LHS1 (CORRECTED)	6	163.2	-69.5	a/a	a/a	a/a

COMPONENT (I) POLE DETERMINATIONS.

SITE/LOCATION (N = No. Samples)	N	DEC	INC	α95	k	POLE POSN. LAT.	LONG.	dP	dM
NORTH LIMB (LHL1-4)	26	215.4	-31.2	2.6	116.9	308.9E	42.7S	1.6	2.9
SOUTH LIMB (FTS1-2, FDS3-5)	34	198.1	-44.3	3.4	52.6	326.6E	57.4S	2.7	4.2
BOTH LIMBS (above combined)	60	206.4	-38.9	3.1	36.3	317.0E	50.9S	2.2	3.7
CONGLOMERATE (SAH5-17)	26	203.4	-35.0	4.5	40.6	322.6E	49.5S	3.0	5.2
DYKE (KZ/7 1-2)	21	198.1	-38.3	5.3	37.5	329.0E	53.2S	3.7	6.3

COMPONENT (H) (STRUCTURALLY CORRECTED)

DYKE (SAMPLE)	11	65.1	-67.1	12.0	15.5	316.0E	29.0N	16.5	19.9

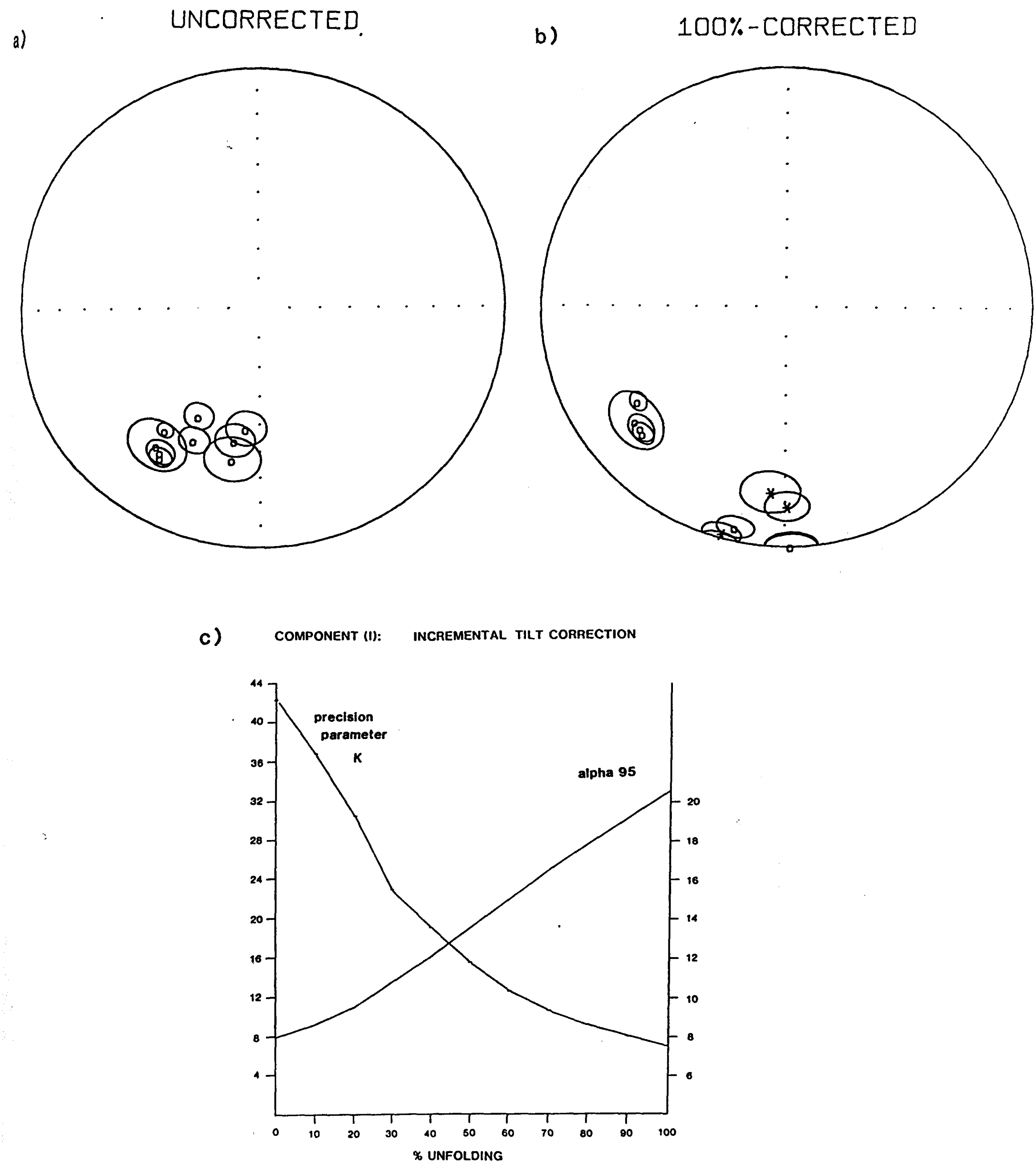


FIGURE 6.7: Site mean distributions plotted in equal area projection both prior to (a) and following (b) simple tilt correction. Circles (stars) refer to projections in the upper (lower) hemisphere. Evolving Fisher precision parameter and apical half angle of 95% confidence are also illustrated (c).

CONGLOMERATE CLASTS

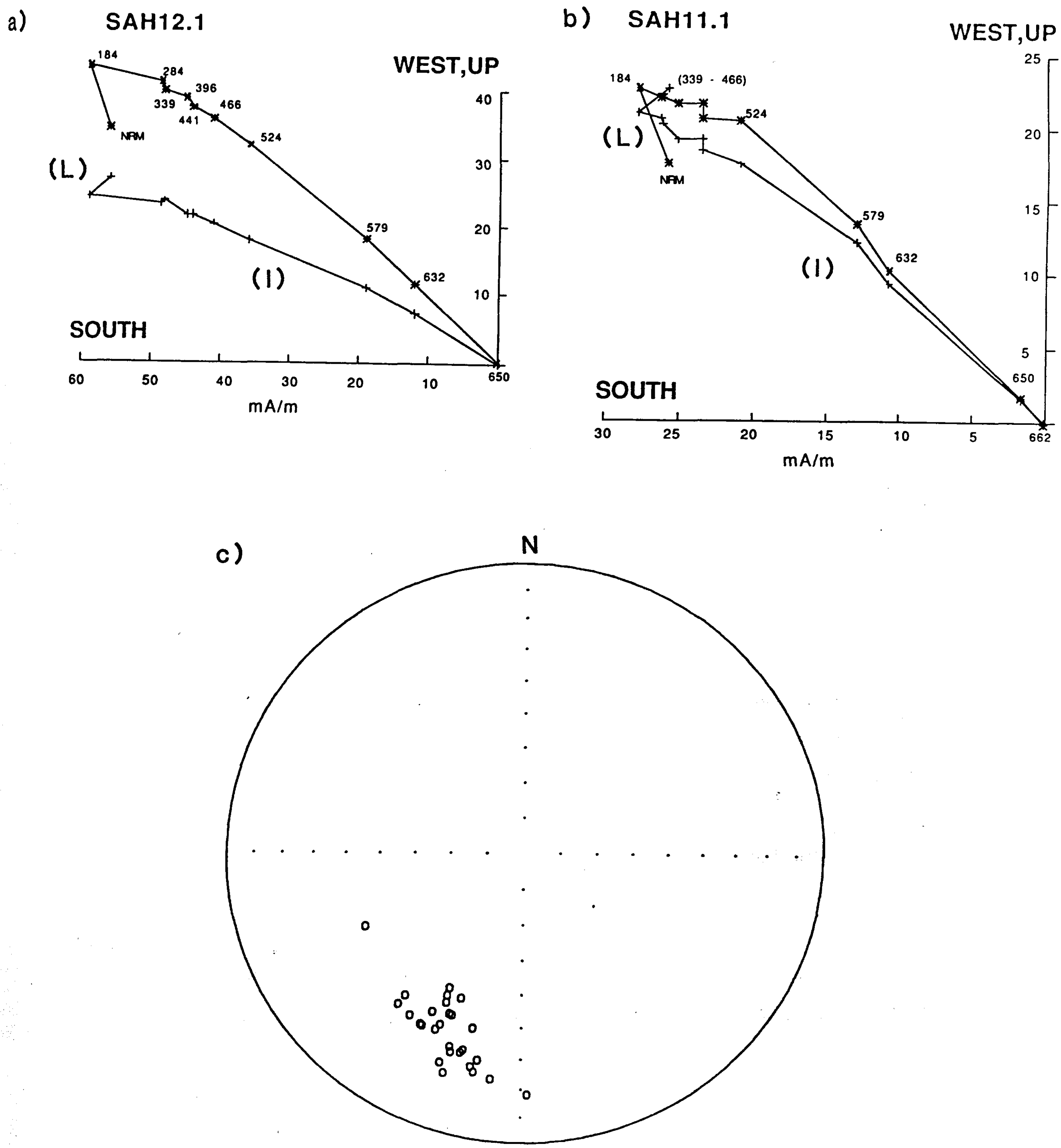


FIGURE 6.8: Orthogonal projections (a,b) show the presence of components (L) & (I) during conglomerate clast demagnetisation. An equal area plot of individual Component (I) directions is shown in (c).

6.5.2 CONGLOMERATE TEST.

An extensive bed of cobble-boulder grade tuff (volcanic conglomerate) was sampled for provision of a palaeomagnetic conglomerate test at Horsecastle Bay (Figure 6.2). The unit is matrix supported and comprises clasts of intra-formational andesitic lava. In total, thirteen clasts, (27 samples), were collected for palaeomagnetic analyses.

Following demagnetisation treatment, components (L) and (I) were obtained from all clasts but no evidence of component (H) was recovered. Examples of conglomerate demagnetisation trajectories are plotted in Figure 6.8 a,b. The distribution of component (I) within the conglomerate is shown in Figure 6.8 c.

The directional consistency of component vectors between clasts represents a negative palaeomagnetic conglomerate test; that is, component (I) forms a post depositional magnetisation.

6.5.3 DYKE STUDY & CONTACT TEST.

Twenty four oriented cores were sampled from the biotite lamprophyre dyke and contact zone intruding the lava/tuff succession on the south side of Horsecastle Bay. The dyke is thought an extension of that exposed within the Lower O.R.S. (Great) conglomerate at Bell Hill (Greig, 1975) dated at 400Ma +/-9., (Rock & Rundle, 1986).

A traverse through the country rock, contact zone (northern dyke margin) and dyke interior was sampled for comparison of both magnetic properties and magnetisation component structure. Variations in the NRM Intensity, volume susceptibility, Koenigsberger Ratio and component build-up are graphically illustrated in Figure 6.9.

Several points arise from inspection of this Figure as follows:-

<u>Figure 6.9 a : NRM Intensity.</u>

- A significant difference in NRM intensity between the lamprophyre dyke and surrounding tuffaceous sediments (country rock) is apparent, intensities being up to an order of magnitude greater in the country rock.
- Intensites of magnetisation in the country rock increase <u>away</u> from the (northern) dyke contact zone.

<u>Figure 6.9 b : Volume Susceptibility.</u>

- Susceptibility increases <u>away</u> from the (northern) dyke contact into the country rock; no systematic variation is observed within the dyke interior.

<u>Figure 6.9 c : Koenigsberger Ratio.</u>

- A local 'peak' in Koenigsberger ratio is apparent in the country rock close to the (northern) dyke margin.

Figure 6.9 d,e ; % Component Structure, I/H Component Ratio.

- Trends in the predominence of magnetisation components across the sampled profile were investigated in some detail but proved largely non-systematic with dyke geometry.
- Apparent systematic variations at the northern dyke margin (KZ/7 2.4 - 2.9) are generally in direct conflict with those observed for the southern dyke margin (KZ/7 1.11 - 1.12).
- The preservation of component (H) outwith the dyke margin is noted for samples KZ/7 1.11 & KZ/7 1.12. Component stability is atypical for these samples however; component (H) unblocking in the magnetite range.

Representative orthogonal projections from the sampled dyke traverse are illustrated in Figure 6.10.

Brunhes (1906) pointed out that if magnetisation directions from an igneous body and its contact aureole were similar, then they could be regarded as stable. Everitt and Clegg (1962) extended this stability test to include consideration of surrounding unbaked country rocks. Thus, if both intrusion and baked aureole were shown to be significantly different from unbaked rocks, the possibility of complete remagnetisation of all phases was removed. Subsequent investigations have proven the usefulness of contact studies in palaeomagnetic work (e.g. Wilson 1961, 1962. Buchan *et al.* 1980, McClelland-Brown, 1981).

The present investigation looks at a dyke and associated contact zone found to have undergone substantial remagnetisation (Component I) but which also retains evidence of a high temperature component possibly reflecting an original remanence (Component H).

Although remagnetisation now obscures much of the effects of intrusion, some changes in magnetic properties are still apparent close to the dyke margin (Figure 6.9a-c). Whether these presently observed trends in NRM intensity, susceptibility and Q ratio date entirely from the time of intrusion is uncertain however. They more likely represent a summed response of the magnetic mineralogy to i) changes induced upon heating in the dyke aureole, and ii) effects of differential later remagnetisation possibly controlled by porosity/permeability contrasts along the profile.

The present test is also complicated by the fact that dyke intrusion most probably took place soon after deposition of the surrounding tuffs. As such, both dyke and country rock may have had originally similar magnetisation directions. A criterion of the contact test requiring dissimilar orientations was therefore never met.

The problem of 'picking' component (H) directions above laboratory noise is

FIGURE 6.9 : Variations in the magnetic/demagnetisation properties across the lamprophyre dyke - country rock profile (Sites KZ/7 1-2).
Sample numbers are indicated along the horizontal axis for each parameter. Dyke width is approximately 1.5 metres; horizontal axis is not to scale.

a) NRM Intensity. (mA/m); closed (open) circles refer to the right (left) hand intensity scale.

b) Apparent Volume Susceptibility: Additional measurements were taken between cored samples for the dyke interior.

c) Konigsberger Ratio.(Q).

$$Q=\left(\frac{I}{\chi H}\right)$$

I = NRM Intensity.
χ = Susceptibility
H = Earth's Field at sampling site.

d) % Component build up of NRM. e.g. for Component (L) below:

$$\%\vec{L} = \frac{\vec{L}}{\vec{L}+\vec{I}+\vec{H}}$$

where component vectors are determined by vector subtraction.

e) I/H Component Ratio.
That is, the magnitude ratio of secondary magnetisation (I) to primary magnetisation (H) for each sample along the profile; magnitudes determined by vector subtraction.

(FIGURE 6.9 IS ILLUSTRATED OVER PAGE).

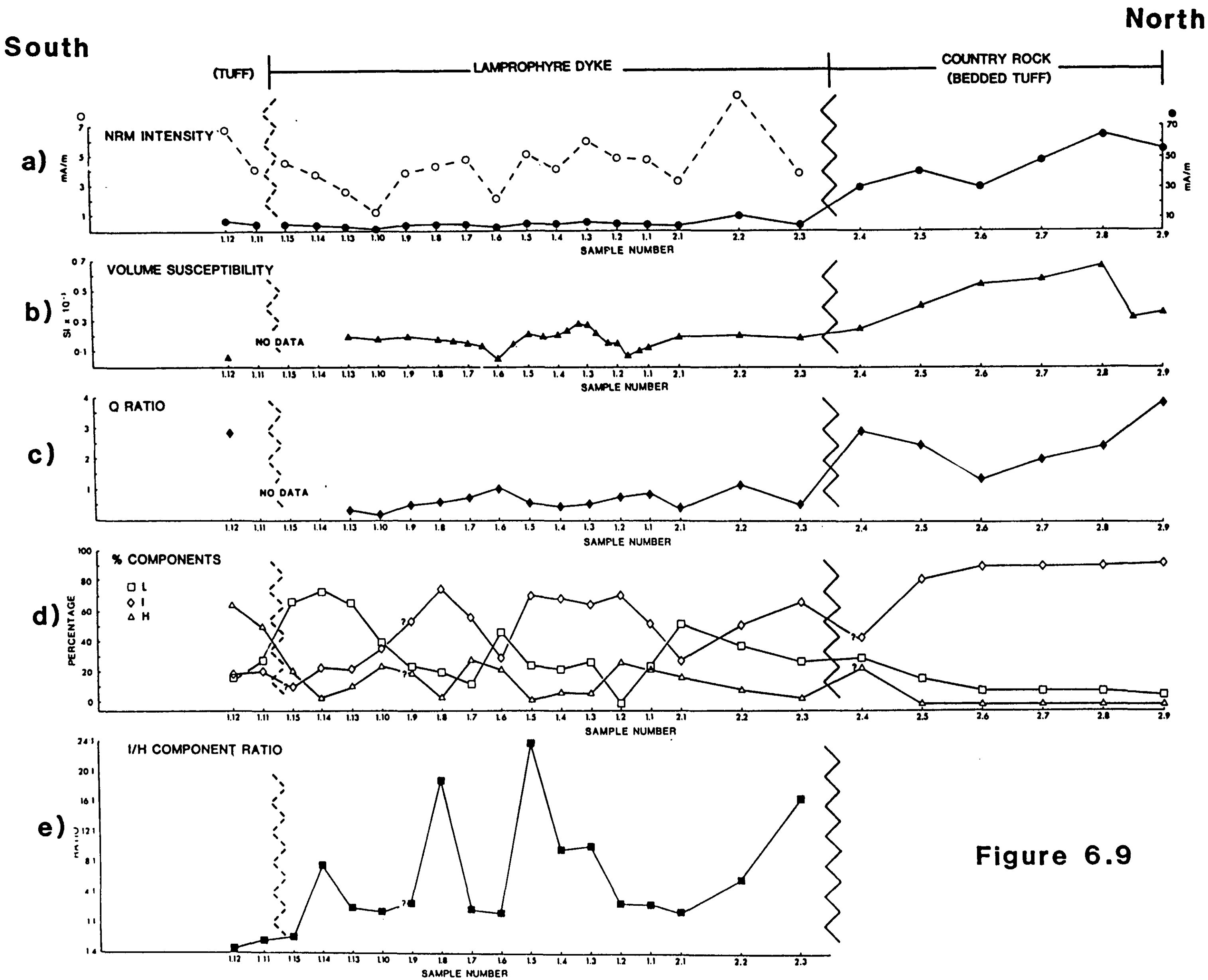

South
North
(TUFF)
LAMPROPHYRE DYKE
COUNTRY ROCK
(BEDDED TUFF)
a)
NRM INTENSITY
mA/m
SAMPLE NUMBER
b)
VOLUME SUSCEPTIBILITY
SI x 10⁻¹
NO DATA
SAMPLE NUMBER
c)
Q RATIO
NO DATA
SAMPLE NUMBER
d)
% COMPONENTS
L
I
H
PERCENTAGE
SAMPLE NUMBER
e)
I/H COMPONENT RATIO
RATIO
SAMPLE NUMBER

Figure 6.9

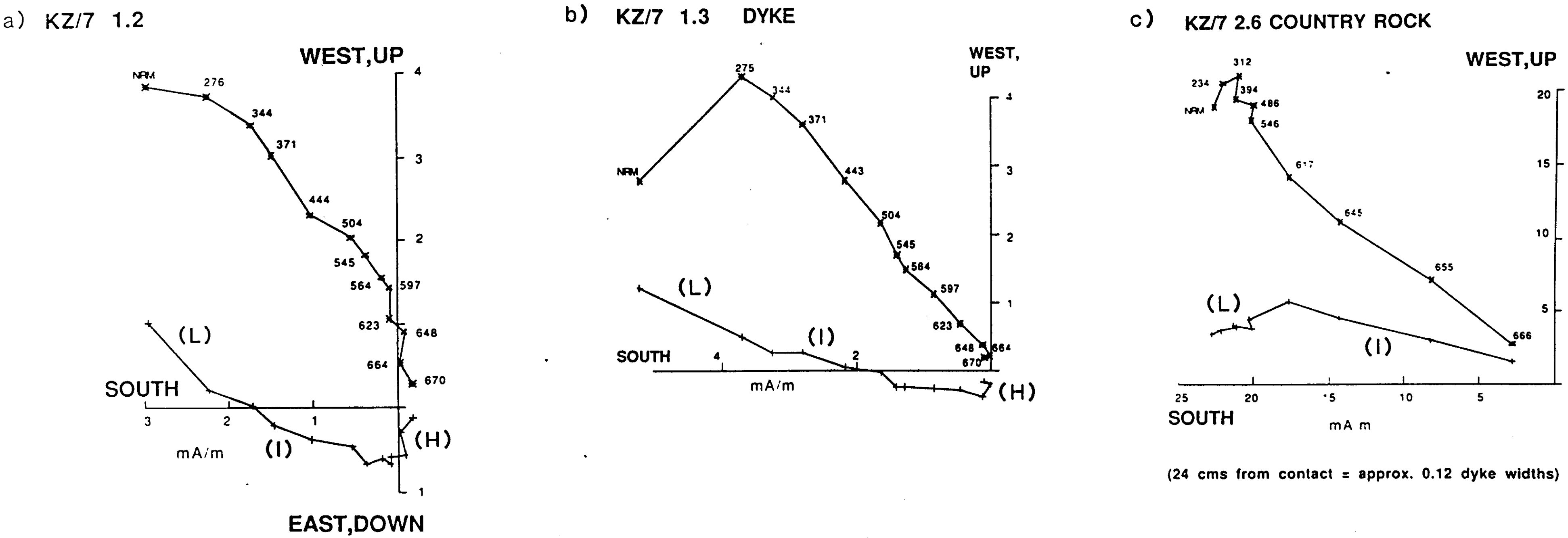


FIGURE 6.10: Representative orthogonal projections for the dyke interior (a,b) and surrounding country rock (c).

particularly acute given the low initial NRM intensity of the dyke samples. In some instances, although samples showed the presence of this component, no directional determination was considered reliable due to the large error encompassed in its computation.

Limits of line data quality were therefore set as follows using the LINEFIND algorithm: Acceptance criteria; error arc tolerence (RADTOL) <20° for excess standard deviation parameter (RHO) = minimum 0.8. (see Kent *et al.* for explanation of statistical parameters).

In situ distributions of components (I) and (H) recovered from samples of the traverse are shown in stereographic projection on Figure 6.11a. Tectonic correction was then performed about southerly dipping metre scale stratification observed in the surrounding tuffs. Mean corrected directions for both components and their associated cones of 95% confidence are shown in Figure 6.11b. Also denoted are the overall results from the northern Midland Valley volcanics (Torsvik, 1985), Cheviot volcanics (Thorning, 1974).

The restricted occurrence of component (H) precludes its inclusion in a palaeomagnetic fold test (6.5.1). Consideration of the respective ages of magnetisation and deformation therefore relies entirely on the proximity of the component to the British APWP both in situ and following structural correction.

The in situ orientation of component (H) in the dyke is unlike that of any recognisable Phanerozoic field for the British Isles. Following correction of dyke data for southerly dipping conglomeratic units however, the component is in close agreement with reported directions from other Siluro-Devonian rocks (Figure 6.11b). This strongly suggests component (H) to be pre-deformational. A significant 'steepness' of corrected dyke components (DHC., Figure 6.11b)) with respect to Midland Valley data may reflect either contamination by a corrected (I) component (DIC), relate to the insufficient averaging of palaeosecular variation or potentially have a palaeotectonic origin. Any palaeotectonic interpretation is considered premature however particularly given the small dataset and the likelihood that the other possibilities prevail.

These results prompt the following conclusions;

i) Dyke intrusion took place prior to deformation of the succession when the strata were still horizontal. This accords well with available radiometric and stratigraphic constraints; that is, a dyke emplacement age of 400Ma followed by Acadian transpression in Emsian times (394 -387Ma).

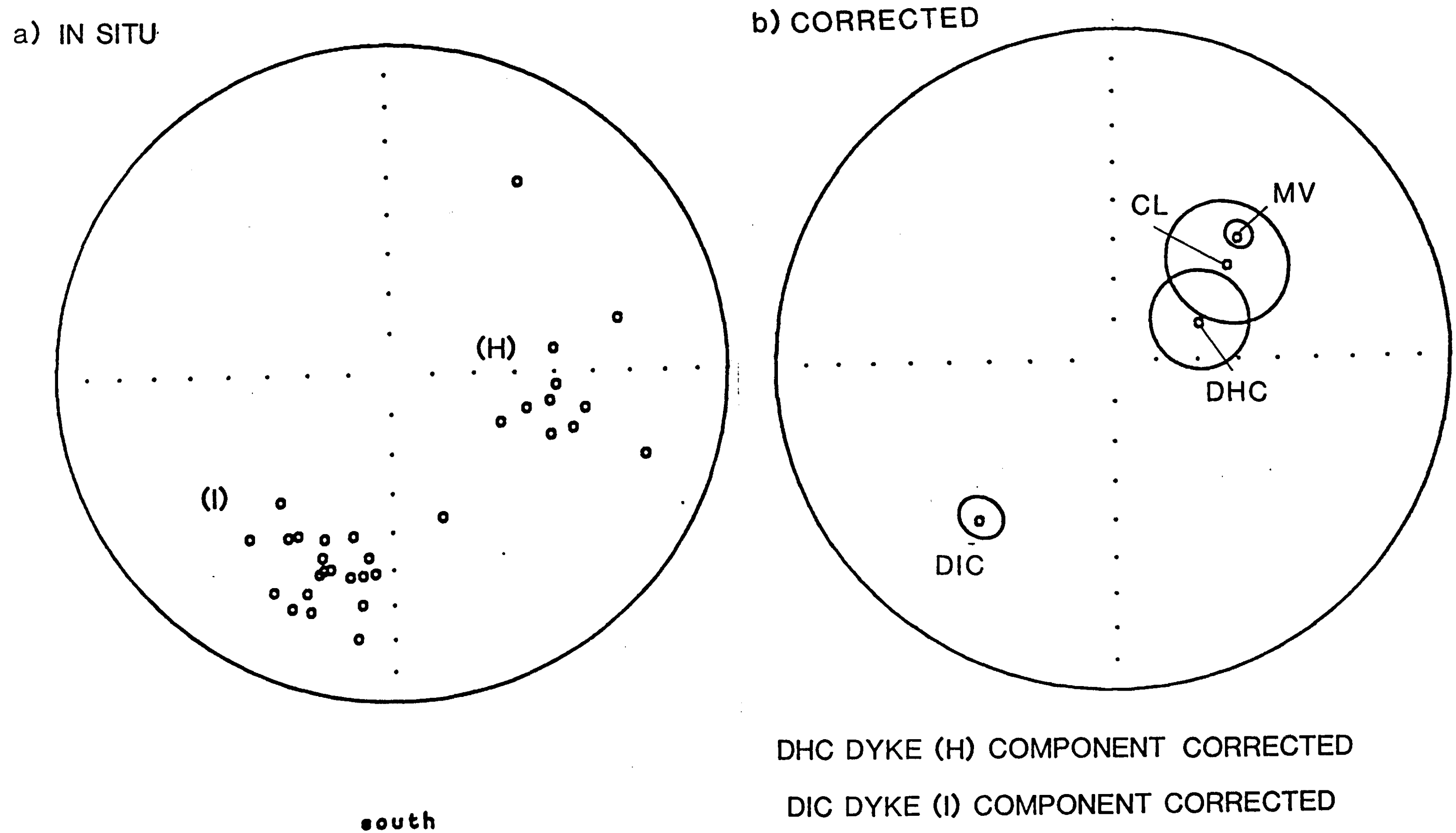


FIGURE 6.11: In situ (a) and tectonically corrected (b) equal area projections of dyke components (I) and (H). Individual sample directions (a) and Fisher mean / cone of 95% confidence (b) are shown. Mean directions from the Midland Valley volcanics (MV; Torsvik, 1985) and Cheviot Lavas (CL; Thorning, 1974) are included in (b) for comparison.

ii) Directional agreement of component (H) with coeval results following correction for southerly dip attests to its accurate recording of the palaeohorizontal and is consistent with field evidence for a topset-foreset relationship between the southerly/easterly dipping units respectively (Figure 6.12).

iii) The preservation of component (H) in tuffs immediately adjacent to the dyke margin (Figure 6.9d, samples KZ/7 1.11., 1.12) indicates a local baking of the country rocks. The dyke's greater resistance to complete remagnetisation may reflect a lower porosity/ permeability than the surrounding tuffs.

6.5.4 DIFFERENTIATION OF LARGE SCALE TOPSETS & FORESETS.

The orientation of bedding surfaces within Horsecastle Bay is such as to preclude their formation by tectonic means alone. Angular discordances between beds are interpreted as reflecting the presence of syn-depositional dip, i.e. large scale foreset bedding, within the succession.

South of the Horsecastle Fault, southerly dipping units appear to form topsets to easterly dipping foresets (Figure 6.12). North of the Horsecastle fault only easterly dipping sets are evident however. The problem arises therefore, as to how best to correct the palaeomagnetic data from the lithic tuff sites (SAH1-4a) to the palaeohorizontal.

Tectonic corrections for both easterly (?foresets) and projected southerly (?topsets) were therefore attempted for component (H). In situ and corrected component directions are shown in Figure 6.13. Examples of the three component demagnetisation structure ubiquitous for the lithic tuffs are shown in Figure 6.14.

The in situ distribution of components (I) & (H) forms a continuous directional swathe approximating that of a partial great circle arc (Figure 6.13a). Such a non-Fisherian distribution suggests neither component to have been completely isolated using the thermal demagnetisation technique. This situation results despite the employment of the LINEFIND algorithm accompanied by visual inspection of chosen line segments.

The probability that 'picked' component (H) directions for these sites actually reflect composite magnetisations resulting from blocking spectra overlap of two components becomes evident. The overlapping components may be the intermediate unblocking component (I) direction, (SSW declination, upward pointing) and a 'true' (H) component orientation positioned at or past the eastern limit of the partial great circle arc (Figure 6.13a). This inference is supported by a degree of curvature between components (I) and (H) in many tuff samples when viewed in orthogonal projection (notably Figs. 6.4b, 6.6b).

Correction for easterly dip (c), somewhat reduces the smearing of the component

(i)

(ii)

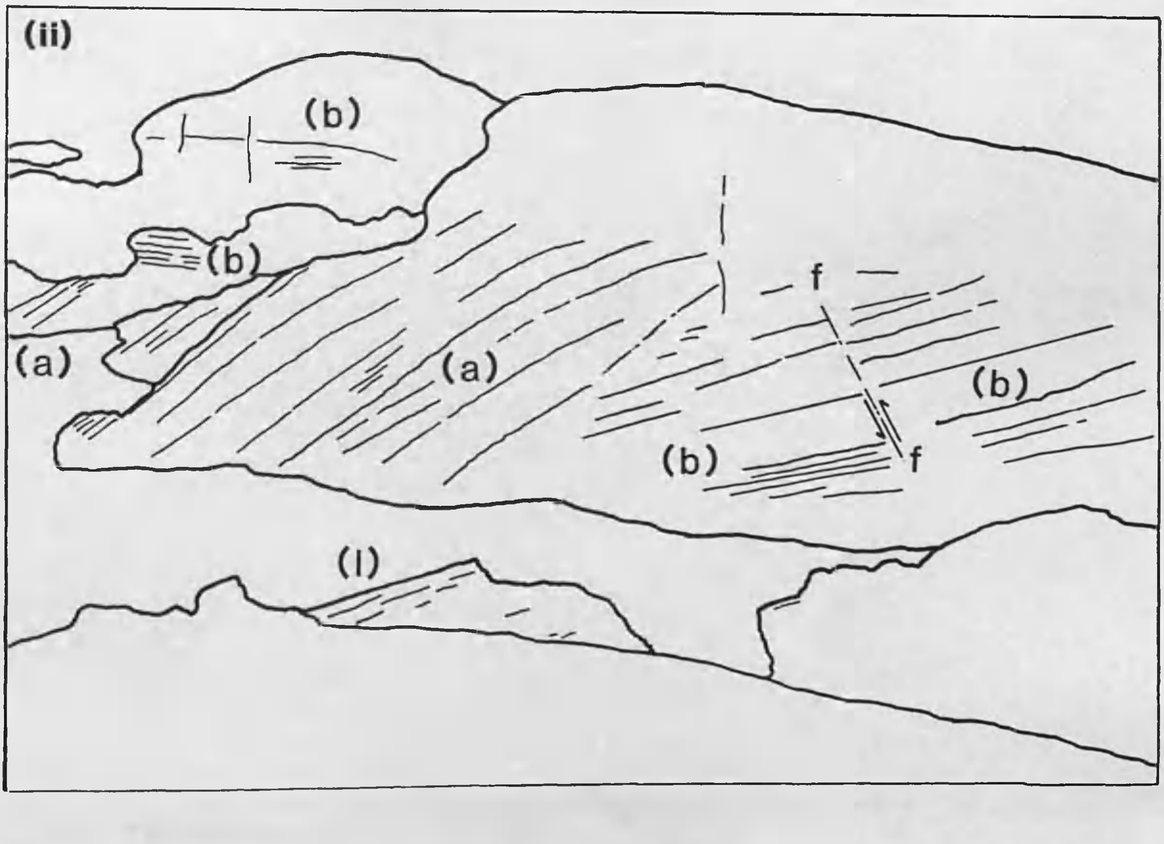


FIGURE 6.12: Photographic (i) and line drawing (ii) illustration of dipping sedimentary units at Horsecastle Bay. Annotations are as follows: (a) Easterly dipping units (?Foresets), (b) Southerly dipping units (?Topsets), (l) lava top, (f) fault.

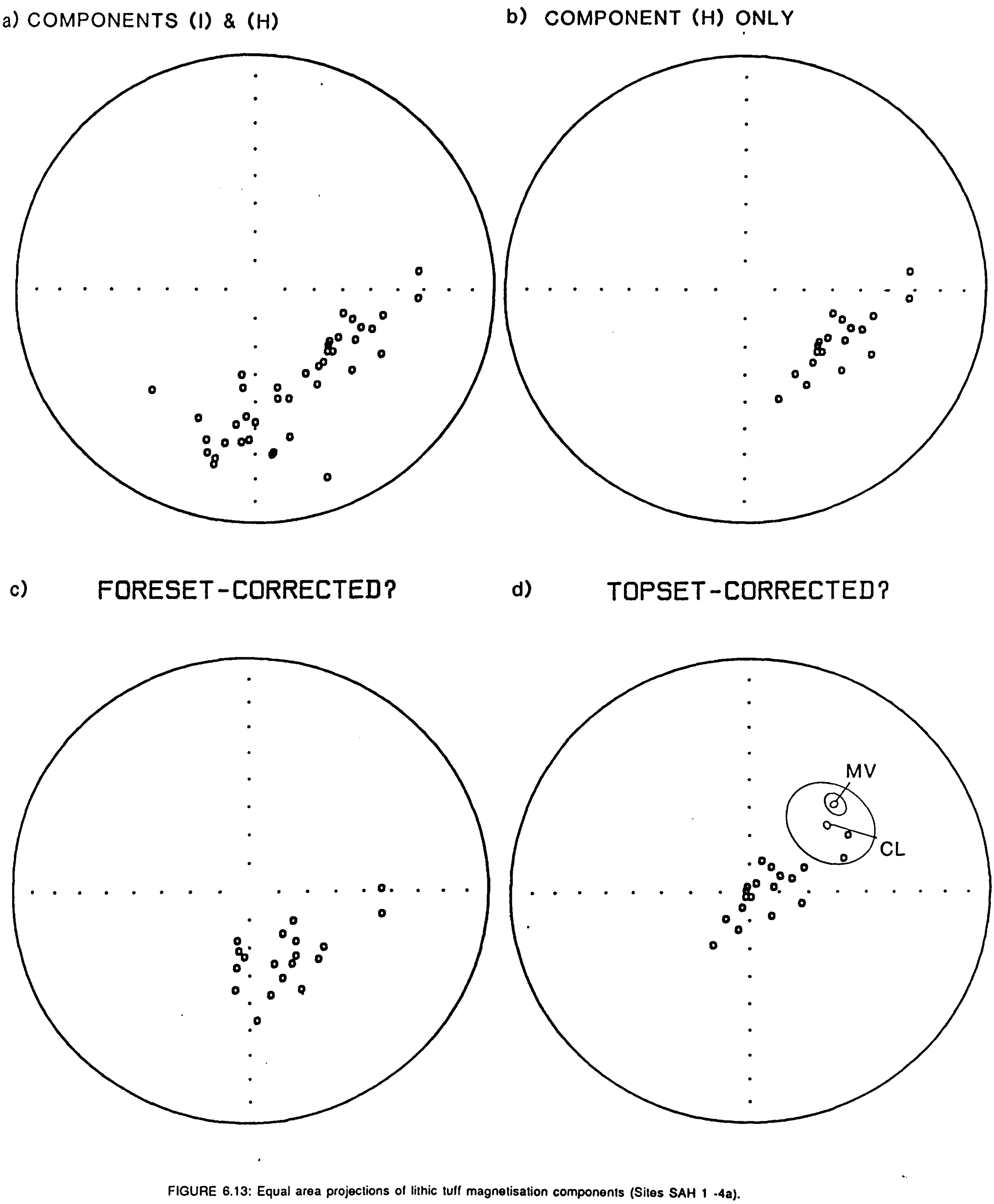


FIGURE 6.13: Equal area projections of lithic tuff magnetisation components (Sites SAH 1 -4a).

a) In situ projection of components (I) and (H).

Component (I) directions plot at the southwest end of the swathe.

b) Component (H) in situ only.

c) Component (H) directions tectonically corrected for easterly dipping strata.

d) Component (H) tectonically corrected for projected southerly dipping units.

Directions from contemporaneous rocks are again shown; see Figure 6.11.

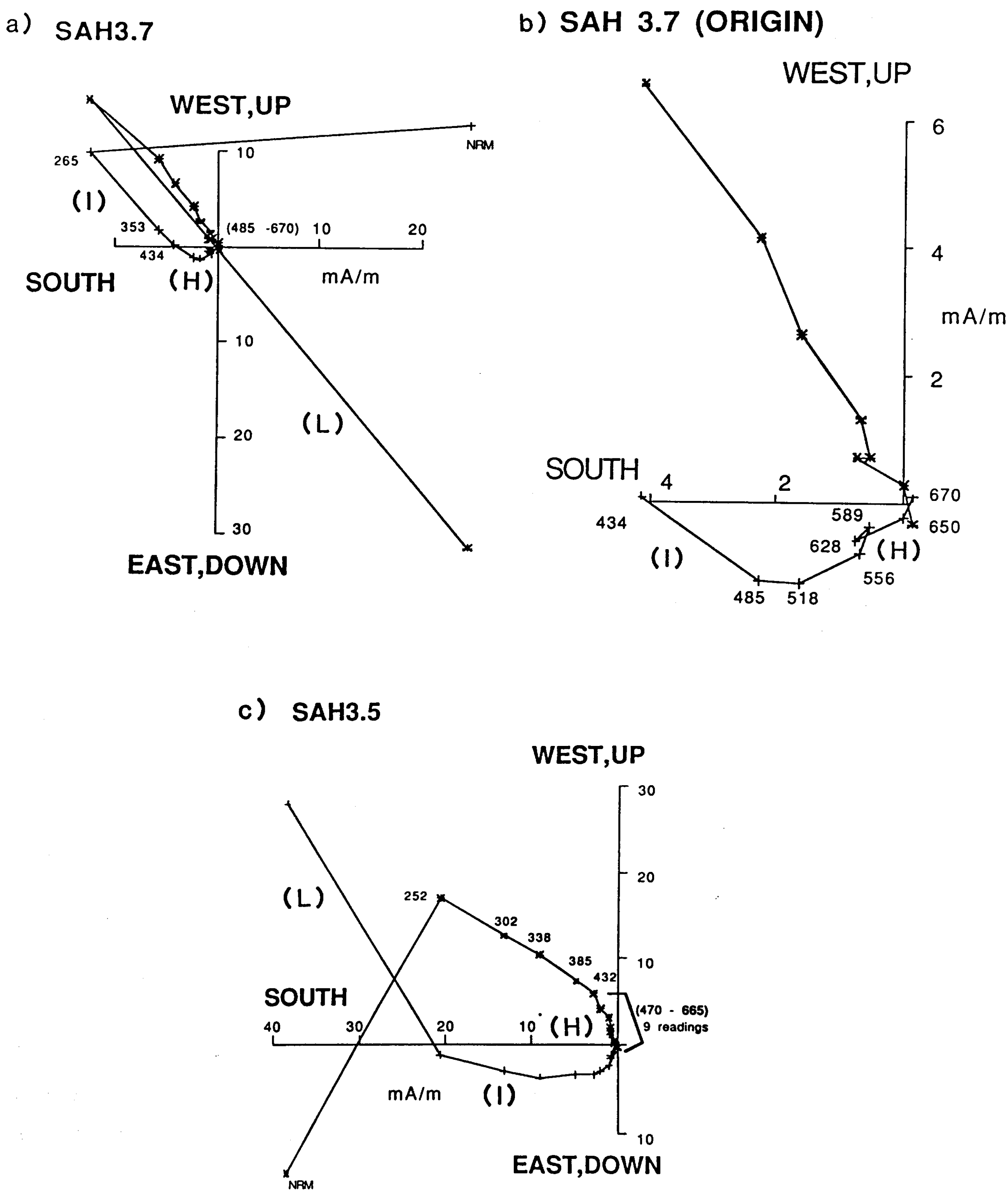


FIGURE 6.14: Orthogonal projections show the three component demagnetisation structure of the lithic tuffs.
Results from sample SAH3.7 (a) are expanded near the origin (b) to reveal the presence of the high treatment component (H).
c) The stability and reproducible nature of component (H) at low intensities is illustrated by SAH3.5.
(Further examples of lithic tuff demagnetisation are shown in Figures 6.4b & 6.6b).

distribution. As the smear is thought to be due to overlapping blocking temperatures, this change is not seen as significant. Further to this, the resulting direction is not in accord with that of any plausible magnetisation age for the tuffs.

Upon correction for the projected southerly dip (d), the distribution becomes reconcilable with a Siluro-Devonian axis of magnetisation. That is, results from the Midland Valley volcanics (Torsvik, 1985) and Cheviot volcanics (Thorning, 1974) plot at the eastern end of the swathe (see also Loch Lintrathen and Glenbervie porphyries, Figure 7.12b). As the component (H) distribution remains non-Fisherian, no statistical mean has been calculated.

Reconciliation with contemporaneous results is again taken as evidence both of an original Siluro-Devonian magnetisation age and that the projected southerly dip adequately records the palaeohorizontal. Palaeomagnetism therefore proves a useful tool in the differentiation of large scale sedimentary structures at this locality.

The elongate distribution (Figure 6.13d) is interpreted to reflect contamination by a now corrected component (I) direction although mixing of a dual polarity Siluro-Devonian axis cannot be precluded.

6.6 AGE & ORIGIN OF SECONDARY REMANENCE: COMPONENT (I).

Component (I) fails both fold (6.5) and conglomerate (6.6) tests performed in the present study. Such tests provide limited age constraint to the component requiring remagnetisation to take place in post Emsian times (see Soper *et al.* 1987).

Comparison of the component (I) pole positions (listed in Table 6.3) with the European reference path of Jowett *et al.* (1987) suggests a Triassic age for remagnetisation (approx. 220Ma when referred to 20 Ma interval path).

Magnetisations of similar stability criterion obtained from redbed studies in the Orcadian Basin also plot on the Triassic section of the European APWP (Tarling, 1985., Figure 5.2). Considerable debate currently exists concerning the age and origin of such 'Group A' magnetisations. A list of published rival hypotheses is summarised in Table 6.4.

The mechanism of secondary remanence acquisition is still far from fully understood. Probable factors thought to control sediment remagnetisation history are discussed at length by Turner (1977, 1980); (see also Tarling *et al.* 1976., Robinson, 1985). A much abbreviated synthesis is given below;

- The Depositional Environment controls the amount, grain size and composition of detrital magnetic grains incorporated into the host sediment. It will also influence the redox potential during diagenesis hence controlling whether Fe oxides are subject to oxidation.

TABLE 6.4 : ORCADIAN BASIN 'A' REMANENCES & PROPOSED ORIGIN.

AUTHORS/FORMATION	AGE	ORIGIN
Storetvedt & Carmichael, 1979. (John 'o Groats Sst.)	Mesozoic	Burial metamorphism, Hematite formation by oxidation & dehydration.
Turner & Archer, 1975. (Gamrie Outlier)	Permo-Carb.	In situ oxidation of magnetite.
Storetvedt et al. 1978. (Duncansby Neck)	Mid-Jurassic.	Burial-related, North Sea subsidence.
Storetvedt & Ottera. 1988. (Orkney Dykes)	Kiaman, Permo-Carb.	Thermo-chemical activity relating to the Great Glen Fault.
Robinson, 1985. (Eday Group Seds.)	Late Palaeozoic, Kiaman.	Continent wide overprinting through *in situ* oxidation beneath weathering surface.
Tarling, 1985. (Synthesis)	Kiaman.	Unrelated to burial. Possibly due to circulating fluids during the low water table conditions of the Permo - Triassic desert.
Cisowski, 1984. (Synthesis)	Tertiary.	Hydrothermal activity related to the British Tertiary Igneous Province.

- Diagenetic processes may involve the production of new Fe oxides resulting from the breakdown of detrital Fe-silicates.

- Effective Cementation may inhibit authigenic reactions. Likewise, cementing may 'seal' magnetic remanence carriers from subsequent alteration. Dolomitisation-dedolomitisation of Ferroan calcite cement may lead to the production of Ferric oxide capable of carrying a remanence.

For the St. Abbs Head succession, a burial-related remagnetisation is not thought tenable due to the low palaeo-temperatures recorded in the underlying Southern Uplands greywackes (Oliver *et al.* 1984). Similarly, Tertiary remagnetisation (c.f. Cisowski, 1984) is thought unlikely due both to the distant positioning of St.Abbs Head from the British Tertiary Igneous Province (BTIP) and to the 'shallowness' of the component (I) magnetisation.

A deep oxidative 'weathering' mechanism similar to that invoked by Robinson (1985) and Tarling (1985) is therefore tentatively favoured. Such an explanation was suggested as implausable for equivalent late Palaeozoic remagnetisations of the North American craton (Miller & Kent, 1986). These authors infer overprinting to be syn-tectonic (Alleghanian folding) employing the use of incremental fold tests. More recently, Van der Pluijm (1987) suggests caution should be adopted in the interpretation of syn-tectonic magnetisations. He demonstrates that grain scale deformation can equally well result in local maxima of Fisher precision parameter during percentage unfolding.

The inferred age of component (I)/group A magnetisations inspires a list of several possibilities as follows:

1. The component is Triassic in age as indicated through the comparison of its resultant pole with the Triassic sector of the APWP (see Figure 5.2).

Comment: This explanation fails to explain the characteristic reversed polarity of the component; the Triassic being a period of mixed polarity.

2. The magnetisation dates from the Permo-Carboniferous reversed superchron (Kiaman Interval) hence explaining its singular polarity. Departure from the Permo-Carboniferous APWP segment might then be explained either through insufficient laboratory cleaning (Tarling, 1985) or by later tectonism perhaps related to North Sea subsidence (c.f. Storetvedt *et al.* 1978).

Comment: Insufficient laboratory cleaning would now appear unlikely given the rigourous modern techniques employed in the present study. This explanation cannot be discounted completely however given that linear demagnetisation may result through synchronous unblocking of two components of equivalent stability (section 6.8). A post-overprint tectonic origin remains a possible explanation.

3. Group A magnetisations do not represent a single overprinting event but have discrete explanations in terms of local geology for each study area.

Comment: This interpretation has the highest degree of freedom and for example would allow Mesozoic overprinting of the Caithness succession (Storetvedt *et al.* 1978) contrasted with Permo-Carboniferous overprinting in the Midland Valley (Torsvik *et al.* 1988). A 'local geology' explanation would appear fortuitous in explaining the intra-continental occurrence of late Palaeozoic reversed polarity remagnetisations however.

Presently therefore, the age of the overprint is equivocal and cannot be constrained with any certainty beyond a late Palaeozoic - early Mesozoic estimate.

The distributions of component (I) to the north and south of Horsecastle Bay (i.e. on the north/south limbs of the synclinal structure) are found to differ significantly at the 95% confidence leval (Table 6.3). Both resulting poles suggest an approximate late Triassic magnetisation age however.

The disparity stems either from;

i) increasing blocking spectra overlap with component (H) at the southern end of the St. Abbs Head promontary hence producing a deflection of component (I) towards an in situ component (H) orientation (see Figure 6.13a, section 6.5.4).

Or, ii) result from previously unrecognised tectonic effects. Such tectonics are implied to have only local significance and do not require large scale structural models to be invoked c.f. Storetvedt (1987) for the Great Glen Fault System.

6.7 GEODYNAMIC IMPLICATIONS & CONCLUSIONS.

The recovery of both a primary magnetisation (component H) and a late Palaeozoic - early Mesozoic overprint (component I) from St. Abbs Head gives rise to a number of salient points.

The equivalence of component (I) to the Group 'A' magnetisations of the Orcadian Basin has earlier been noted (6.6). Van der Voo & Scotese (1981) argued this component to represent an original palaeofield for the Devonian redbeds. Through the absence of similar inclinations on the 'European' side of the Great Glen Fault (GGF), they subsequently inferred a total sinistral offset of some 2000 kilometres during Carboniferous times. The present recognition of an equivalent magnetisation at St. Abbs Head (southeast of the GGF), together with its demonstrably secondary nature (6.5.1,6.5.2), invalidates such a tectonic model (see also 5.3).

Component (I) is also relevent in considering the suggestions of Storetvedt (1987) relating to former movements along the GGF. Storetvedt uses a declination discrepancy in the Group 'A' magnetisations (attributed a Permo-Carboniferous age), to invoke 300 kilometres of dextral movement produced during 'Hercynian time'.

The SSW declinations of the St.Abbs Head component (I) results are consistent with the sense of this discrepancy. Several observations suggest caution in the application of the inferred tectonic model however. Firstly, a smearing of component (I) toward southeasterly declinations has been noted (Figure 6.13a) and attributed to blocking spectra overlap with component (H) (6.5.4). Similar smeared distibutions recorded in Orcadian basin sediments were suggested by Storetvedt to reflect continous deformation / magnetisation processes.

Also, a statistically significant directional discordance in component (I) is recognised within the St. Abbs Head succession.. This may have an explanation either in terms of local block rotation or once again may indicate insufficient separation of components. Notably such a discordance does not imply the existence of a major crustal linea ment transecting the promontary.

It is felt that the construction of tectonic models heavily dependent on the Group 'A'/component (I) results is at this stage premature. Such tectonic applications must await a consensus on several points:

i) an accepted origin for the overprint magnetisations.

i i) reconciliation of the differing proposed ages of remagnetisation.

iii) the distinction of 'local tectonic' effects from possible 'regional' variation.

iv) preclusion of the use of contaminated 'compound magnetisations' in tectonic applications. Given the difficulty of adequate cleaning in this study, the use of 'group A' results derived from previous less stringent work is not recommended.

The recovery of a primary magnetisation (component H) from St. Abbs Head allows its comparison with contemporaneous palaeomagnetic results from other Caledonian tectonic blocks (e.g. Figure 6.11b).

The (H) component direction is in broad agreement with data recovered from the Grampian Block (Lorne Plateau, Latham & Briden, 1975., Loch Lintrathen Porphyry, Chapter 7), the northern Midland Valley (Strathmore Lavas, Torsvik, 1985., Glenbervie Porphyry, Chapter 7), Iapetus Suture Zone (Cheviot Hills, Thorning, 1974) and south of the suture (Somerset Lavas, Piper, 1975). A comparison can also be drawn with secondary magnetisations to the north of the Great Glen (Watts, 1982).

These comparisons preclude the possibility of subsequent inter-block movement outwith the errors of the palaeomagnetic determinations. Unfortunately, both in the present case and in the study of the Cheviot Hills, the computed errors are comparatively large (this study $\alpha 95$ =12°). Relative translations of the order of 1000kms along the margins to the Southern Uplands cannot be addressed using presently available data therefore.

The consistency in declination between studies is noteworthy and allows further comment on the possibility of subsequent strike slip translations. Palaeomagnetically detectable strike slip movements are generally accompanied by sizable tectonic rotation of the transported terrane elements (e.g. Beck, 1980). Localised block rotation is also prevalent in areas of strike slip tectonics (e.g. Ron *et al.* 1984). Given the general lack of tectonic rotation between the aforementioned blocks, the inference follows that any major transcurrent movements had largely been completed by this time. This has important consequences in consideration of the Acadian transpression which postdates much of the Lower O.R.S. i.e. this deformation could not have been accompanied by mega-scale strike parallel displacements for this sector of the Caledonides. Such a generalisation is contradictory to recently published data from Baltica however (Douglass, 1988) in which declinations are concordant but inclinations discordant from British results. This requires substantial post Lower Devonian mega shear between Britain and at least a fragment of Baltica but precludes any related tectonic rotation taking place.

CHAPTER 6 : REFERENCES.

Anderson, T.B. and Oliver, G.J.H. 1986. The Orlock Bridge Fault: A major late Caledonian sinistral fault in the Southern Uplands Terrane, British Isles. *Transactions of the Royal Society Edinburgh, Earth Sciences,* 77, 203-222.

Beck, M.E. 1980. Palaeomagnetic record of plate-margin tectonic processes along the western edge of North America. *Journal of Geophysical Research,* 85, 7115-7131.

Brunhes, B. 1906. Recherches sur la direction d'aimantation des roches volcaniques. *Journal de Physique,* 5, 705-724.

Buchan, K.L., Schwarz, E.J., Simmons, D.T.A. and Stupavsky, M. 1980. Remanent magnetization in the contact zone between Columbia plateau flows and feeder dykes: evidence for ground water layer at time of intrusion. *Journal of Geophysical Research,* 85, 1888-1898.

Burmester, R.F. 1977. Origin and stability of drilling induced remanence. *Geophysical Journal of the Royal Astronomical Society,* 48, 1-14.

Cisowski, S.M. 1984. Evidence for the Tertiary remagnetisation of Devonian rocks from Orcadian Basin, northern Scotland, and associated transcurrent fault motion. *Geology,* 12, 369-372.

Douglass, D.N. 1988. Palaeomagnetics of Ringerike Old Red Sandstone and related rocks, southern Norway: implications for pre-Carboniferous separation of Baltica and British terranes. *Tectonophysics,* 148, 11-27.

Elders, C.F. 1987. The provenance of granite boulders in conglomerates of the Northern and Central Belts of the Southern Uplands of Scotland. *Journal of the Geological Society, London,* 144, 853-863.

Everitt, C.W.F. and Clegg, J.A. 1962. A field test of palaeomagnetic stability. *Geophysical Journal of the Royal Astronomical Society,* 6, 312-319.

Geikie, A. 1864. The geology of Eastern Berwickshire. *Memoirs of the Geological Survey, U.K.,* 22-32.

Geikie, J. 1887. Geology and petrology of St Abb's Head. *Proceedings of the Royal Society of Edinburgh,* 14, 177-193.

Greig, D.C. 1975. St. Abb's head. In : The geology of the Lothians and south east Scotland. *Edinburgh Geological Society Excursion Guide,* 118-130. Scottish Academic Press.

Greig, D.C. 1988. Geology of the Eyemouth District. *Memoir of the British Geological Survey.,* Sheet 34 (Scotland), 78pp.

Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G. and Walters, R. 1982. *A geological time scale.* Cambridge University Press, Cambridge, 131pp.

Hutton, D.H.W. 1987. Strike-slip terranes and a model for the evolution of the British and Irish Caledonides. *Geological Magazine,* 124, 405-425.

Jackson, M. and Van der Voo, R. 1985. Drilling-induced remanence in carbonate rocks: occurrence, stability and grain-size dependence. *Geophysical Journal of the Royal Astronomical Society,* 81, 75-87.

Jowett, E.C., Pearce, G.W. and Rydzewski, A. 1987. A mid-Triassic Paleomagnetic Age for the Kupfersciefer mineralization in Poland, based on a revised apparent polar wander path for Europe and Russia. *Journal of Geophysical Research,* 92, 581-598.

Kent, J.T., Briden, J.C. and Mardia, K.V. 1983. Linear and planar structure in ordered multivariate data as applied to progressive demagnetization of palaeomagnetic remanence. *Geophysical Journal of the Royal Astronomical Society,* 75, 593-621.

Latham, A.G. and Briden, J.C. 1975. Palaeomagnetic field direction in Siluro-Devonian lavas of the Lorne Plateau. *Geophysical Journal of the Royal Astronomical Society,* 43, 243-252.

McClelland-Brown, E. 1981. Palaeomagnetic estimates of temperatures reached in contact metamorphism. *Geology,* 9, 112-116.

McElhinny, M.W. 1964. Statistical significance of the fold test in palaeomagnetism. *Geophysical Journal of the Royal Astronomical Society,* 8, 338-374.

McKerrow, W.S., Leggett, J.K. and Eales, M.H. 1977. Imbricate thrust model of the Southern Uplands of Scotland. *Nature,* 267, 237-239.

Miller J.D. and Kent, D.V. 1986. Synfolding and pre-folding magnetizations in the Upper Devonian Catskill Formation of eastern Pennsylvania. *Journal of Geophysical Research,* 91, 12791-12803.

Molyneux, L. 1971. A complete results magnetometer for measuring the remanent magnetisation of rocks. *Geophysical Journal of the Royal Astronomical Society,* 24, 429-434.

Oliver, G.J.H., Smellie, J.L., Thomas, L.J., Casey, D.M., Kemp, A.E.S., Evans, L.J., Baldwin, J.R. and Hepworth, B.C. 1984. Early Palaeozoic metamorphic history of the Midland Valley, Southern Uplands-Longford Down massif and the Lake District, British Isles. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 75, 245-258.

Piper, J.D.A. 1975. Palaeomagnetism of Silurian lavas of Somerset and Gloucestershire, England. *Earth & Planetary Science Letters*, 28, 470-478.

Robinson, M.A. 1985. Palaeomagnetism of volcanics and sediments of the Eday Group, Southern Orkney. *Scottish Journal of Geology,* 285-300.

Rock, N.M.S. and Rundle, C.C. 1986. Lower Devonian age the 'Great (basal) Conglomerate', Scottish Borders. *Scottish Journal of Geology,* 22, 285-288.

Rock, N.M.S., Gaskarth, J.W. and Rundle, C.C. 1986.. Regional late Caledonian dyke-swarms of southern Scotland. *Journal of Geology,* 94, 505-523.

Ron, H., Freund, R. Garfunkel, Z. and Nur, A. 1984. Block rotation by strike-slip faulting: structural and palaeomagnetic evidence. *Journal of Geophysical Research,* 89, 6256-6270.

Sallomy, J.T. and 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.

Soper, N.J., Webb, B.C. and Woodcock, N.H. 1987. Late Caledonian (Acadian) transpression in north-west England: timing, geometry and geotectonic significance. *Proceedings of the Yorkshire Geological Society,* 46, 175-192.

Storetvedt, K.M. 1987. Major late Caledonian and Hercynian shear movements on the Great Glen Fault. *Tectonophysics,* 142, 253-267.

Storetvedt, K.M. and Carmichael, C.M. 1979. Resolution of superimposed magnetization in the Devonian John'O Groats Sandstone, North Scotland. *Geophysical Journal of the Royal Astronomical Society,* 58, 769-784.

Storetvedt, K.M. and Otterå, L.E. 1988. Palaeozoic reconfiguartions of N. Scotland based on palaeomagnetic results from Orkney dykes. *Physics of the Earth & Planetary Interiors,* in press.

Storetvedt, K.M., Carmichael, C.M., Hayatsu, A. and Palmer, H.C. 1978. Palaeomagnetism and K/Ar results from the Duncansby Volcanic Neck, NE Scotland: superimposed magnetizations, age of igneous activity and tectonic implications. *Physics of the Earth & Planetary Interiors,* 16, 379-392.

Tarling, D.H. 1985. Palaeomagnetic studies of the Orcadian Basin. *Scottish Journal of Geology,* 21, 261-273.

Tarling, D.H., Donovan, R.N., Abou-Deeb, J.M. and El-Batrouk, S.I. 1976. Palaeomagnetic dating of haemetite genesis in Orcadian Basin sediments. *Scottish Journal of Geology,* 12, 125-134.

Thirlwall, M.F. 1981. Implications for Caledonian plate tectonic models of chemical data from volcanic rocks of the British Old Red Sandstone. *Journal of the Geological Society, London,* 138, 123-138.

Thorning, L. 1974. Palaeomagnetic results from the Lower Devonian rocks of the Cheviot Hills. Northern England. *Geophysical Journal of the Royal Astronomical Society,* 487-496.

Torsvik, T.H. 1985. Magnetic properties of the Lower Old Red Sandstone lavas in the Midland Valley, Scotland; palaeomagnetic and tectonic considerations. *Physics of the Earth & Planetary Interiors,* 39, 194-207.

Turner, P. 1977. Remanent magnetism of Middle Old Red Sandstone lacustrine and fluviatile sediments from the Orcadian Basin, Scotland. *Journal of the Geological Society, London,* 133, 37-50.

Turner, P. 1980. *Continental Red Beds.* Developments in sedimentology No.29, Elsevier, Amsterdam, 562pp.

Turner, P. and Archer, R. 1975. Magnetisation history of the Lower Old Red Sandstone from the Gamrie Outlier, Scotland. *Earth & Planetary Science Letters,* 27, 240-250.

Van der Pluijm, B.A. 1987. Grain-scale deformation and the fold test ; evaluation of syn-folding remagnetization. *Geophysical Research Letters,* 14, 155-157.

Van der Voo, R. and Scotese, C. 1981. Palaeomagnetic evidence for a large (2000km) sinistral offset along the Great Glen Fault during Carboniferous time. *Geology,* 9, 583-589.

Wilson, R.L. 1961. Palaeomagnetism in Northern Ireland. Part II. On the reality of a reversal of the Earth's magnetic field. *Geophysical Journal of the Royal Astronomical Society,* 5, 59-69.

Wilson, R.L. 1962. The palaeomagnetic history of a doubly baked rock. *Geophysical Journal of the Royal Astronomical Society,* 6, 397-399.

Watts, D. R. 1979. *Upper Keweenawan and Lower Paleozoic paleomagnetism of the North American craton.* Ph. D. thesis, University of Michigan (unpubl.).

Watts, D.R. 1982. A multicomponent dual polarity palaeomagnetic regional overprint from the Moine of Northwest Scotland. *Earth & Planetary Science Letters,* 61, 190-198.

CHAPTER 7 : PALAEOMAGNETIC STUDY OF THE 'LINTRATHEN PORPHYRY', HIGHLAND BORDER REGION, CENTRAL SCOTLAND: TERRANE LINKAGE OF THE GRAMPIAN & MIDLAND VALLEY BLOCKS IN LATE SILURIAN TIME?

7.1 INTRODUCTION & RESEARCH BACKGROUND.

The displaced terrane hypothesis explains many aspects of the geology of the Caledonian - Appalachian system (2.1,2.2). Palaeomagnetic tests of this hypothesis can be divided into two categories; those concerning the former separation of continental blocks and those which relate to the timing of their subsequent amalgamation and suturing. The present study looks at this latter episode in the tectonic evolution of the Grampian and Midland Valley* terranes of Central Scotland presently juxtaposed across the Highland Boundary Fault (HBF).

The two terranes have demonstrably unrelated geological histories prior to late Ordovician time, becoming unambiguously linked in the late Devonian (Bluck, 1985., Figure 7.1). A proposed correlation of the Loch Lintrathen and Glenbervie porphyries across the HBF (Allan, 1928., Paterson & Harris, 1969) implies an earlier docking in late Silurian times however (Loch Lintrathen porphyry, 415 +/-6Ma, Thirlwall, 1988). The palaeomagnetic study of 'Lintrathen porphyry'*° samples recovered from either side of the Highland Boundary forms the subject of this investigation.

The limitations of the palaeomagnetic method generally result in a minimum resolution of some hundreds of kilometres relative movement between crustal units. In the present context however, this obstacle may be overcome if any peculiarities in the palaeomagnetic signature of the sampled units prove diagnostic allowing unambiguous correlation of porphyry flow units between terranes.

Such a correlation would have important consequences for the stratigraphic and structural evolution of the Highland Boundary and need be accounted in any proposed Caledonian terrane models.

The Lower Old Red Sandstone (L.O.R.S.) of the northern Midland Valley and southern Grampian Highlands comprises a heterogenous assemblage of conglomerates, sandstones and lavas which reach an estimated total thickness of some 9000 metres and cover an area of approximately 4000 square kilometres (Armstong & Paterson, 1970). The succession is divided into six lithostratigraphic groups outlined in Table 7.1.

Dacitic volcanic rocks at several localities north of the HBF (first termed the 'Lintrathen Porphyry' by Teall, 1888) were originally regarded as intrusive into the

* this in fact refers to a composite terrane comprising the Highland Border Complex (HBC) and Midland Valley blocks.

*° 'Lintrathen Porphyry' is used collectively to refer to both Loch Lintrathen & Glenbervie

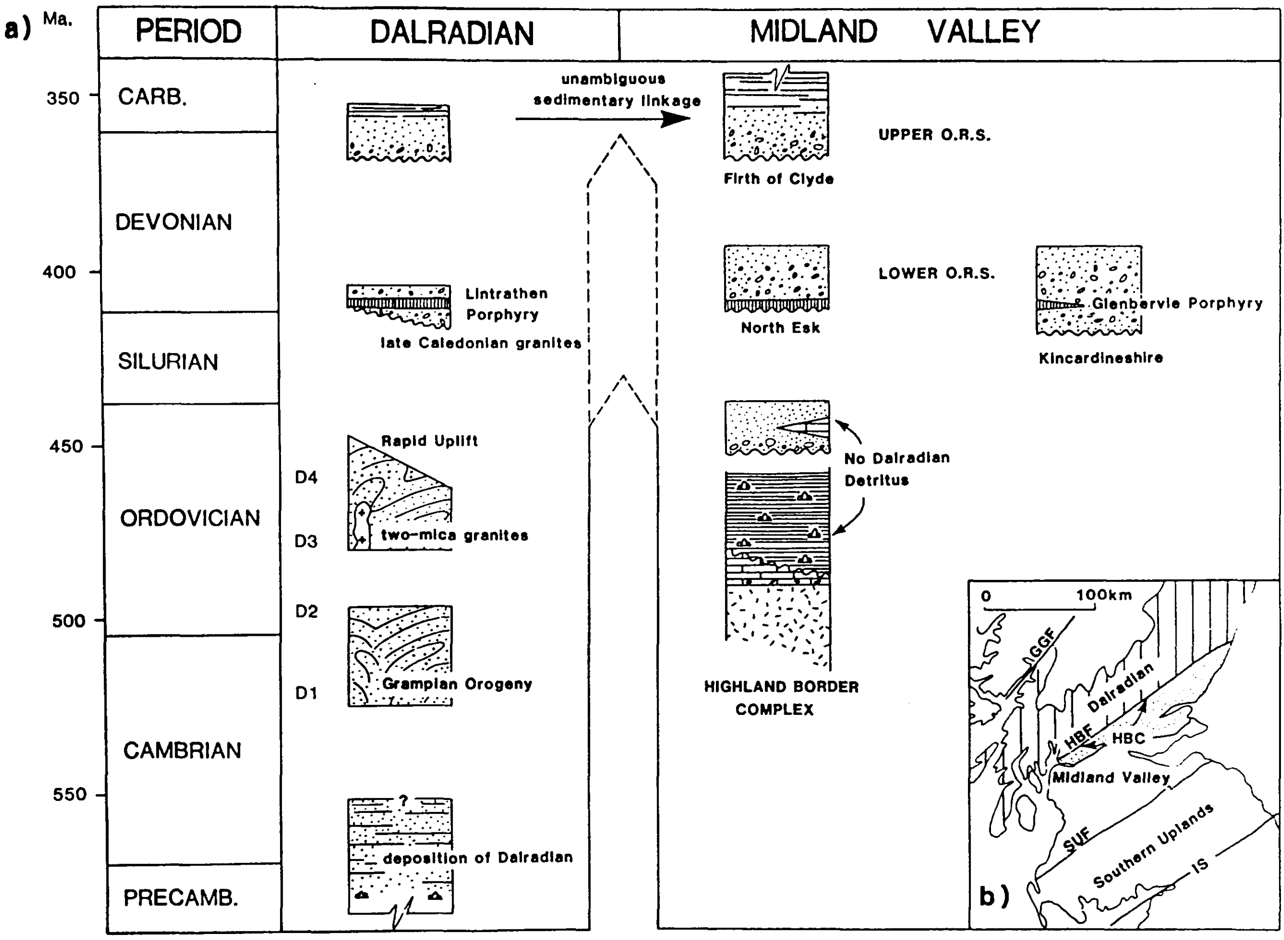


FIGURE 7.1: a) Schematic stratigraphic columns depict the geological evolution of the Grampian Highlands (Dalradian) & Midland Valley terranes.

The lack of Dalradian detritus within the now juxtaposed Highland Border Complex requires the two terranes to be separated in Ordovician times. Unambiguous linkage is recorded by the preservation of unequivocal Dalradian clasts within Upper O.R.S. conglomerates (Bluck, 1985).

b) Inset geological sketch map of Scotland with major tectonic elements.

surrounding sediments (Teall, *ibid.*, Geikie, 1897). The dacites are characterised by distinctive quartz, feldspar and biotite phenocrysts set in a cryptocrystalline matrix.

TABLE 7.1

Major Divisions	Thickness
STRATHMORE GROUP	2000m
GARVOCK GROUP	1525m
ARBUTHNOTT GROUP	2100m
CRAWTON GROUP	2200m
DUNNOTTAR GROUP	1660m
STONEHAVEN GROUP	1550m

Campbell (1913) recognised rocks of similar appearence to the south of the HBF at Glenbervie which he considered to be extrusive. Allan (1928), in a re-examination of the Loch Lintrathen porphyry, concluded it to be extrusive citing the occurrence of a porphyry boulder within the overlying conglomerates and the lack of any apparent contact metamorphism. He subsequently proposed the correlation of the Glenbervie and Loch Lintrathen porphyries.

This description was further amended by Paterson & Harris (1969) who suggested that the dacites represent ignimbrite sheets; the geologically preserved products of nueé ardentes. The proposed correlation was formalised by Armstrong & Paterson (1970) who assigned the porphyry horizon to the top of the Crawton group.

The geographic distribution of the porphyries along the Highland Border is indicated in Figure 7.2. Lower O.R.S deposition appears to overstep westward (Armstrong & Paterson, *ibid.*) such that 'Lintrathen porphyry' lies with basal unconformity on the Dalradian (West Cult., Paterson & Harris, 1969) and Highland Border Complex (North Esk) but occurs some 4kms from the base of the succession at Glenbervie.

South of the HBF, the Lower O.R.S. is exposed in the asymmetrical Strathmore syncline (Figure 7.2), the Glenbervie porphyry outcropping on its northern limb and dipping steeply to the south. North of the HBF however, the Loch Lintrathen porphyry dips gently to the north conveniently allowing a fold test to be undertaken between localities.

Formation of the Strathmore syncline and complimentary Sidlaw anticline is stratigraphically constrained to occur during Emsian times (Soper *et al.* 1987). Subsequent to deposition, the succession has undergone only burial associated metamorphism with temperatures not exceeding 120°-150°C (vitrinite reflectence; Strathmore & Arbuthnott Groups; D. A. Kennedy, personal communication, 1988). Estimates from the Stonehaven Group indicate similarly low maximum palaeo-temperatures (J. Marshall, work in

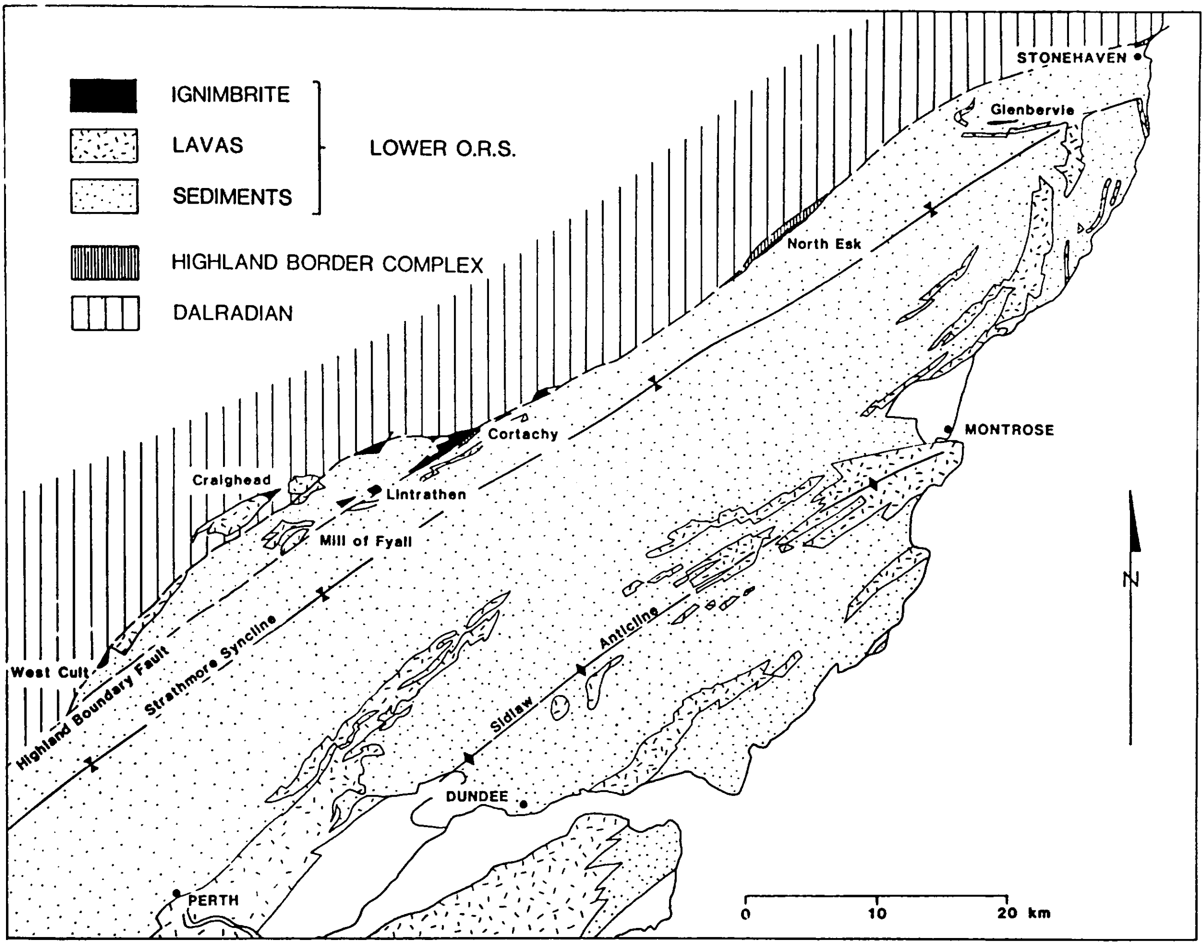


FIGURE 7.2: The geographical distribution of the 'Lintrathen Porphyry' (ignimbrites) along the Highland Border. Sampling localities at Loch Lintrathen and Glenbervie are indicated to the north and south of the Highland Boundary Fault respectively. The northeasterly trending Strathmore syncline - Sidlaw anticline fold pair are labelled.

progress).

A brief history of palaeomagnetic research concerning the Scottish 'Devonian' lavas has been outlined in Section 5.1. In the present context, the studies of interest are those of Sallomy & Piper (1973) and Torsvik (1985). The former study is important in that seven sites (46 samples) were taken from porphyry outcrops at three localities namely West Cult (3 sites, N of HBF), Loch Lintrathen (3 sites, N of HBF) and Glenbervie (1 site, S of HBF). No multicomponent behaviour was recognised during pilot specimen demagnetisation, and optimum AF treatments were calculated using the Briden Stability Index (1972). Following treatment between 30 and 80 mT, three sites were found to be 'normally' magnetised and a fourth site attributed to an intermediary 'group A' direction. The remaining sites were 'unclassified' with two being statistically significant in grouping but directionally anomalous. The results of Sallomy & Piper (1973) are summarised in Table 7.2 below.

TABLE 7.2.
'LINTRATHEN PORPHYRY'; SALLOMY & PIPER (1973).
(after AF cleaning & tectonic correction).

Site	Location	N/S of HBF	N	R	k	$\alpha95$	Dec°	Inc°	Polarity
176	West Cult	N	5	4.59	9.7	25.8	93	+48	A
177	West Cult	N	4	3.71	10.5	29.8	332	+14	U
105	West Cult	N	5	4.88	32.2	13.7	263	-53	U
174	Loch Lintrathen	N	5	4.70	13.2	21.8	45	-28	N
107	Loch Lintrathen	N	9	8.83	47.6	7.5	31	-45	N
173	Loch Lintrathen	N	4	----	----	----	----	----	U
133	Glenbervie	S	8	7.93	94.9	5.7	38	-48	N

(Polarities as assigned by Sallomy & Piper; i.e. N - normal, U - unclassified, A - 'group A' intermediate direction.)

Torsvik's (1985) study is of significance in that presently accepted levels of laboratory treatment were applied to the Midland Valley lavas (although no 'Lintrathen Porphyry' was sampled). Direct comparison of component structure between the 'Lintrathen Porphyry' and surrounding lavas of the Crawton and Arbuthnott groups therefore becomes possible.

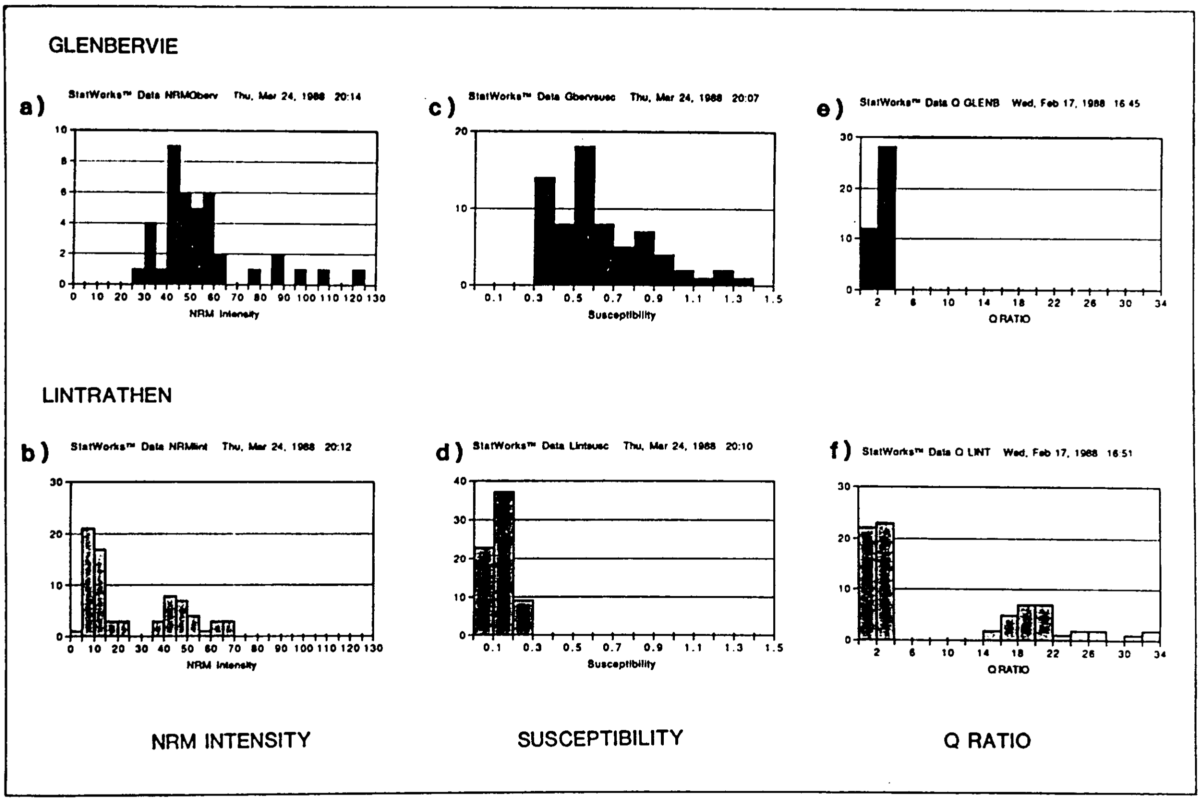


FIGURE 7.3: Histograms of determined magnetic properties for the Glenbervie & Loch Lintrathen porphyries.
(a,b) NRM Intensity : milliAmps/metre.
(c,d) Apparent Volume Susceptibilty : S.I. Units x 10-3.
(e,f) Koenigsberger Ratio (Q) : no units.
Parameters are all plotted on a linear scale.

7.2 SAMPLING & METHODS.

Samples were cored using portable drilling apparatus and subsequently oriented using both magnetic and sun compasses wherever possible. A foliation within the porphyry enabled a local estimate of the palaeo-horizontal to be made at each site. The contrasting attitude of this foliation between sampling localities allowed the performance of a palaeomagnetic fold test.

Magnetic moments of trimmed core samples were measured using a spinner magnetometer (Molyneux, 1971). Magnetic susceptibilities were measured using a Micro-kappa Kappameter Model KT-5 portable susceptibility meter. Measurements were made wherever possible on flat and unweathered surfaces close to or at the position of sample drilling. This minimised the negative effects of surface roughness. Stepwise thermal demagnetisation was predominantly employed during the laboratory cleaning of samples due to;

i) the presence of high coercivity hematite remanence in many samples, and,
ii) the introduction of 'spurious' magnetisations during high field static AF cleaning observed as a 'spiralling' of the orthogonal projection towards the origin with successive treatments.

The field identification or separation of individual flow units was not possible at either locality. Following laboratory treatment of the initial sample collection, sites 12 & 15 (both at Loch Lintrathen), were further sampled. This was undertaken due to their possessing particular demagnetisation complexity and an anomalous direction respectively (7.4).

7.3 MAGNETIC PROPERTIES;
(NRM INTENSITY, SUSCEPTIBILITY, & KOENIGSBERGER RATIO).

Magnetic property data from both the Loch Lintrathen and Glenbervie porphyries are illustrated graphically in Figure 7.3. Koenigsberger ratios were calculated by combining the laboratory sample NRM intensity with the appropriate field measured susceptibility value. Histograms have been plotted using a linear scale from which the log-normal distribution of parameters becomes apparent (Irving *et al.* 1966., Tarling, 1966., notably Figures 7.3 a, b & c).

Significant contrasts in the NRM Intensity, susceptibility and Koenigsberger ratio are observed between the two localities. The cause of these contrasts is presently equivocal. This is particularly the case given the lack of comparable studies in the literature; reported work generally concerning the reliability of palaeomagnetic directions from particular ignimbrites, e.g. Reynolds, 1977 .

Any of the following explanations must therefore be considered plausible:

i) the two porphyries are derived from compositionally different volcanic sources.

ii) the contrasts reflect the sampling of proximal/distal elements derived from a single volcanic source.

iii) observed contrasts reflect a vertical stratification of magnetic properties within an ignimbrite column; differing levels having been preserved on either side of the HBF.

7.4 PROGRESSIVE DEMAGNETISATION.

7.4.1 GLENBERVIE PORPHYRY.

NRM directions from the Glenbervie Porphyry reside in the southeasterly quadrant and possess moderate negative inclinations (in situ). Directional behaviour upon progressive thermal demagnetisation proved complex and led to the recognition of three contrasting remanence components. These were termed (R), (S) & (P) being delineated by their respective directions and unblocking criteria as follows:-

(Orthogonal projections displaying these three components for the Glenbervie Porphyry are illustrated in Figure 7.4).

i) <u>Component (R).</u>

Component (R) is readily removed during laboratory cleaning usually unblocking at temperatures below 200°C and at coercivities less than 10mT. Occasional overlap of blocking spectra with component (S) is noted indicated by curvature in orthogonal projection. This extends the stability range of the component to a maximum of 250-300°C.

In situ, (R) has steep positive inclination and generally northward declination (Figure 7.5 a). This accords with its interpretation as a recent viscous remanent magnetisation (VRM). A degree of north - south polarisation of directions to form a non-Fisherian 'swathe' reflects the overlap with component (S). Some of the observed scatter also results from poor laboratory definition; the component often determined as the vector subtraction of NRM and ensuing first demagnetisation step only.

ii) <u>Component (S).</u>

Component (S) generally unblocks at temperatures of between 200°C and 450°C. In situ, it has a southerly declination and moderate negative inclination. Occasional overlapping stability with the recent viscous remanence (R) has been noted above. Similarly, stability overlap with component (P) is considerable in some samples whilst negligible in others (c.f. Figure 7.4 c & a respectively). Although the presence of the component is deduceable in most thermally demagnetised samples, its direction has not

GLENBERVIE PORPHYRY.

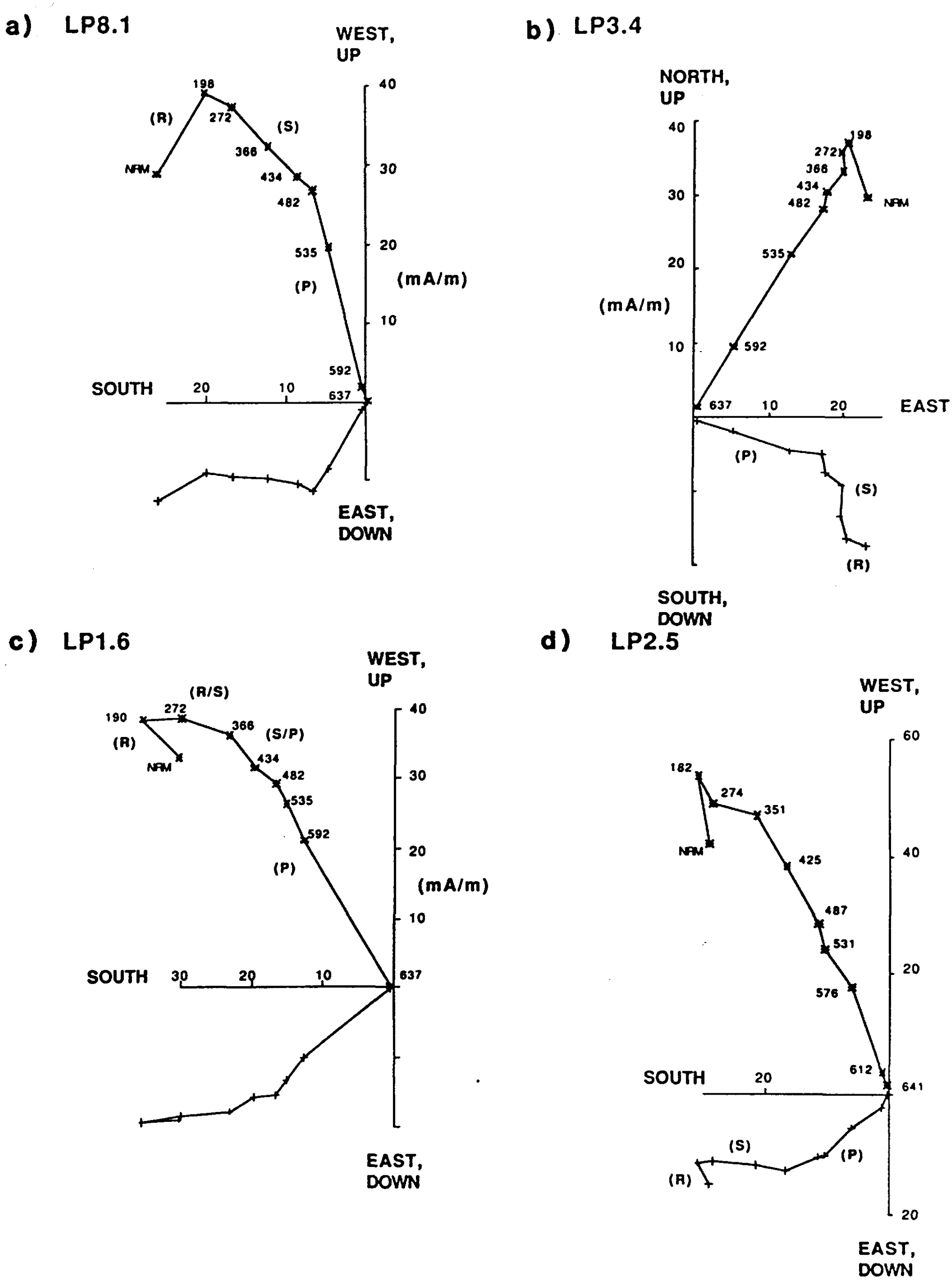


FIGURE 7.4: Representative orthogonal projections show characteristic demagnetisation behaviour of the Glenbervie Porphyry. Components of NRM are labelled.

(a, b, d) : Three component structure (R, S & P) with little overlap of blocking spectra.

(c) : The presence of three components is determinable but considerable overlap of unblocking spectra is evident.

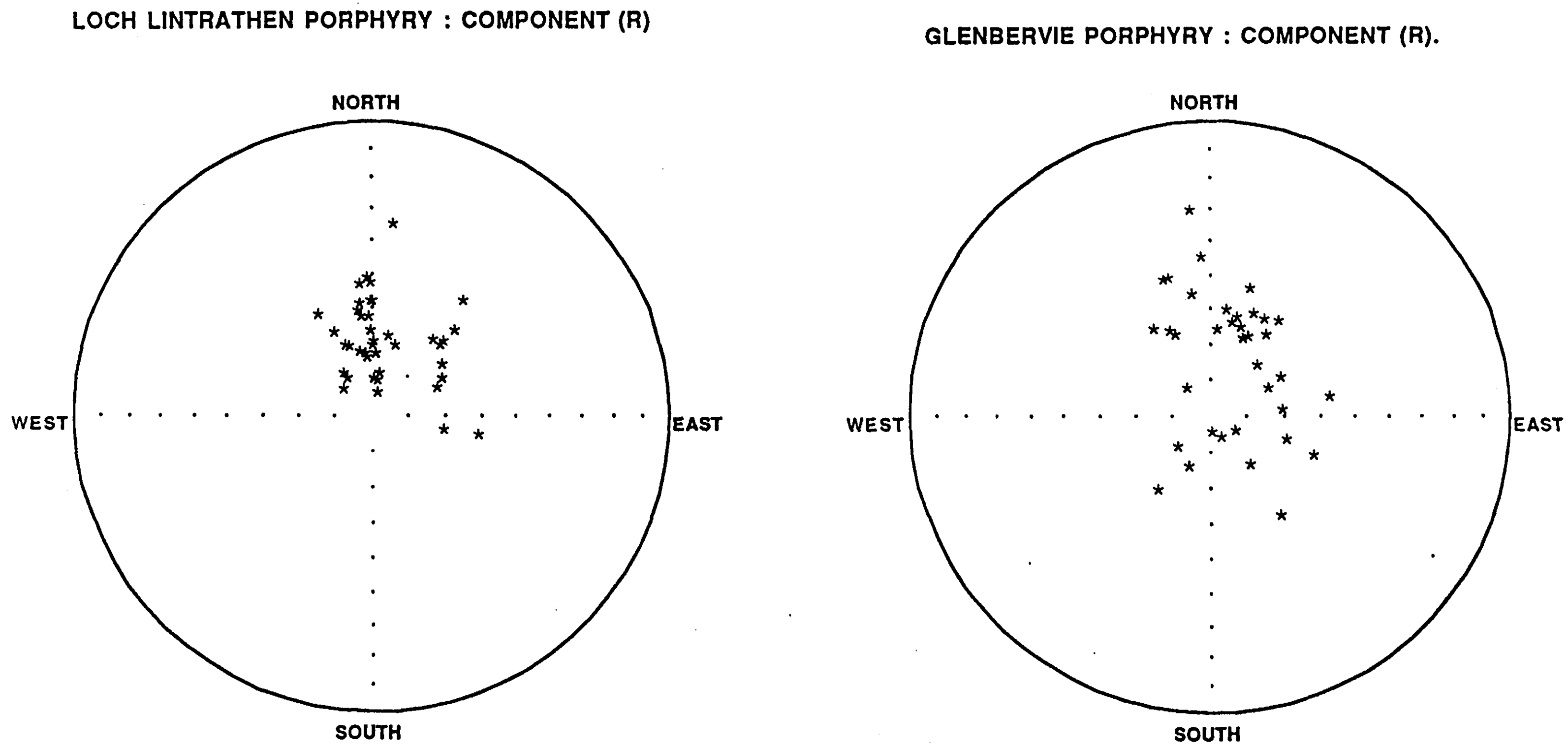


FIGURE 7.5: In situ stereographic projection of Component (R) from the Glenbervie (a) and Loch Lintrathen (b) porphyries.

always been determined given this spectra overlap and ensuing 'curved' demagnetisation trajectories.

Component resolution upon AF demagnetisation of samples from sites known to possess a three component behaviour proved poor. Removal of a low coercivity component at treatments approaching 10mT was followed by broadly linear decay towards the origin to 40mT. Subsequent 'spiralling' of demagnetisation results following treatment at higher fields has been attributed to the acquisition of a GRM (Gyroremanent magnetisation,7.6). Linear trajectories for the interval 10-40mT are interpreted to represent 'pseudo-components' resulting from the incomplete separation of (S) and (P) and have accordingly been omitted from statistical analyses (cf. chemical demagnetisation of the Catskill redbeds, Miller & Kent, 1986).

iii) Component (P).

Component (P) unblocks between 450°C and 650°C decaying directly to the origin (Figure 7.4). In situ, it has southeasterly declination and moderate - steep negative inclination. It is present in all samples (excepting those which were AF cleaned) usually forming the predominent magnetisation component.

7.4.2 LOCH LINTRATHEN PORPHYRY.

In situ NRM directions from the Loch Lintrathen Porphyry have northeasterly declinations and shallow positive - negative inclinations. Demagnetisation response to thermal treatment is again complex revealing the presence of three major components. The presence of a fourth component was suspected at Site 12 which, upon resampling and subsequent demagnetisation (Site 12A), indeed proved to be the case. The similarity of demagnetisation structure with the Glenbervie Porphyry was felt sufficient for an identical component nomenclature to be adopted, i.e. components R, S & P. The additional component identified at site 12/12A was termed component D. An increased diversity in the presence/absence and relative magnitudes of the constituent components is observed for the Loch Lintrathen porphyry however.

(Examples of the various components revealed during demagnetisation are shown in Figure 7.6 and further referred to in the following text. Demagnetisation results from site 12A showing all four components are illustrated in Figure 7.7 with expanded projections near the origin being shown in Figure 7.8).

i) Component (R).

Removal of component (R) during thermal demagnetisation was generally achieved at temperatures below 200°C. In situ, the component is northerly directed with steep

LOCH LINTRATHEN PORPHYRY.

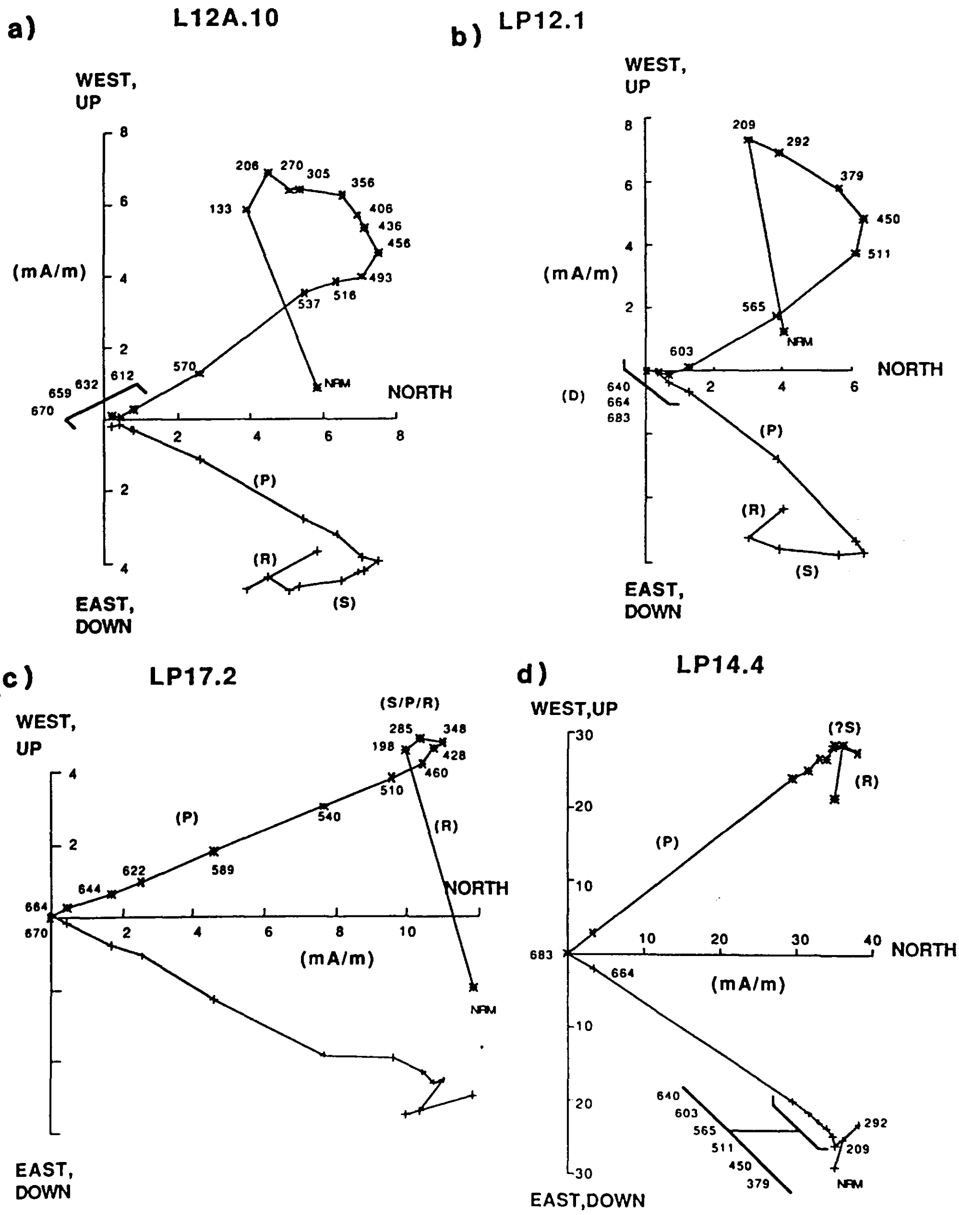


FIGURE 7.6: Representative orthogonal projections show characteristic demagnetisation behaviour of the Loch Lintrathen Porphyry. Interpreted components of NRM have been labelled.
(a,b) : Four component demagnetisation (R,S,P,D) over recounted unblocking temperatures.
(c) : Predominant component (P) at site 17. Presence of a vestigal component (S) is indicated by a 'looping' of the orthogonal projection in the range 200°-400+°C.
(d) : A thermally discrete component (P) dominates the NRM at Site 14.

SITE 12A : LOCH LINTRATHEN PORPHYRY.

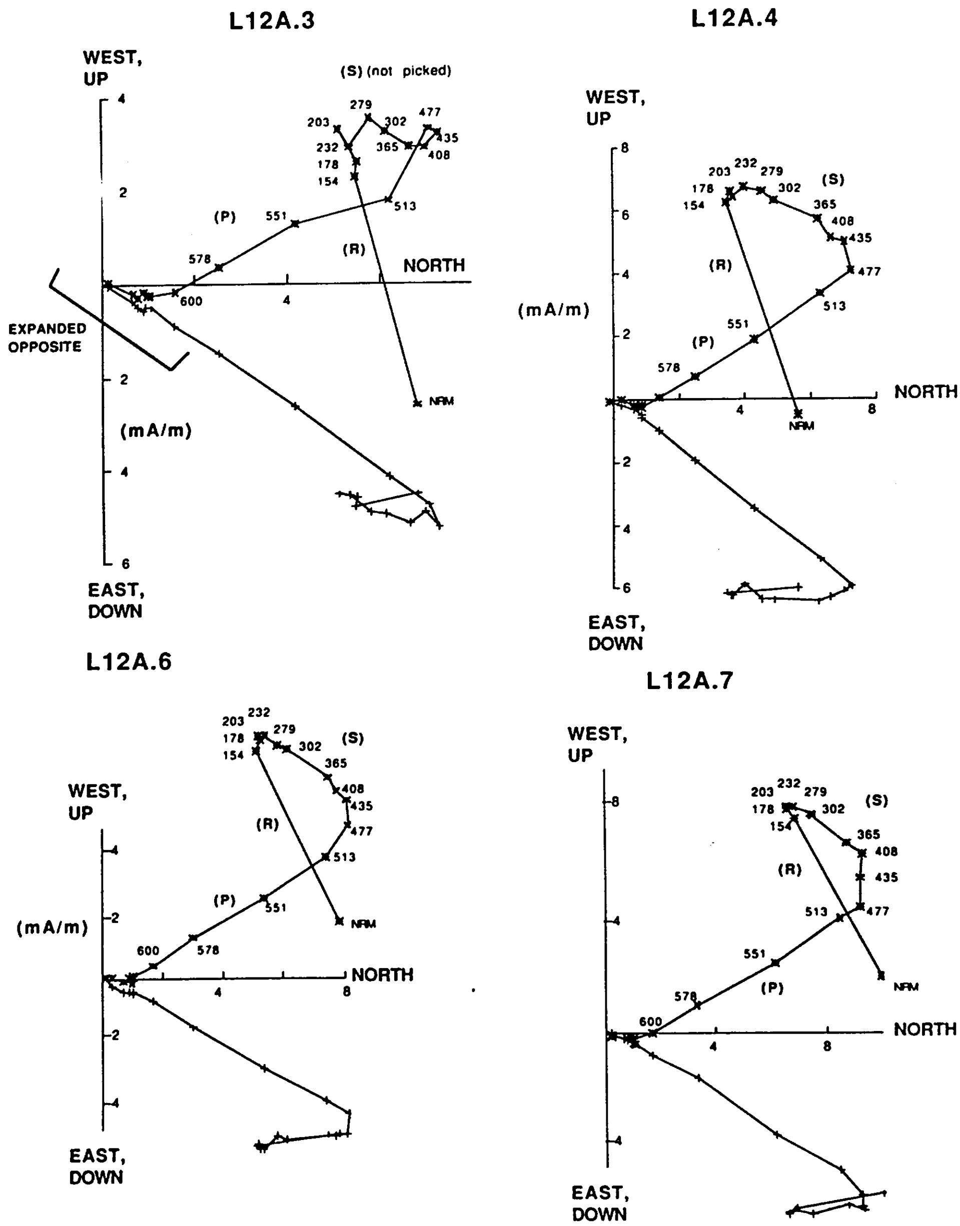


FIGURE 7.7: Orthogonal projections from Site 12A show a four component demagnetisation. Magnetisation components are labelled.

SITE 12A : LOCH LINTRATHEN PORPHYRY. (ORIGIN).

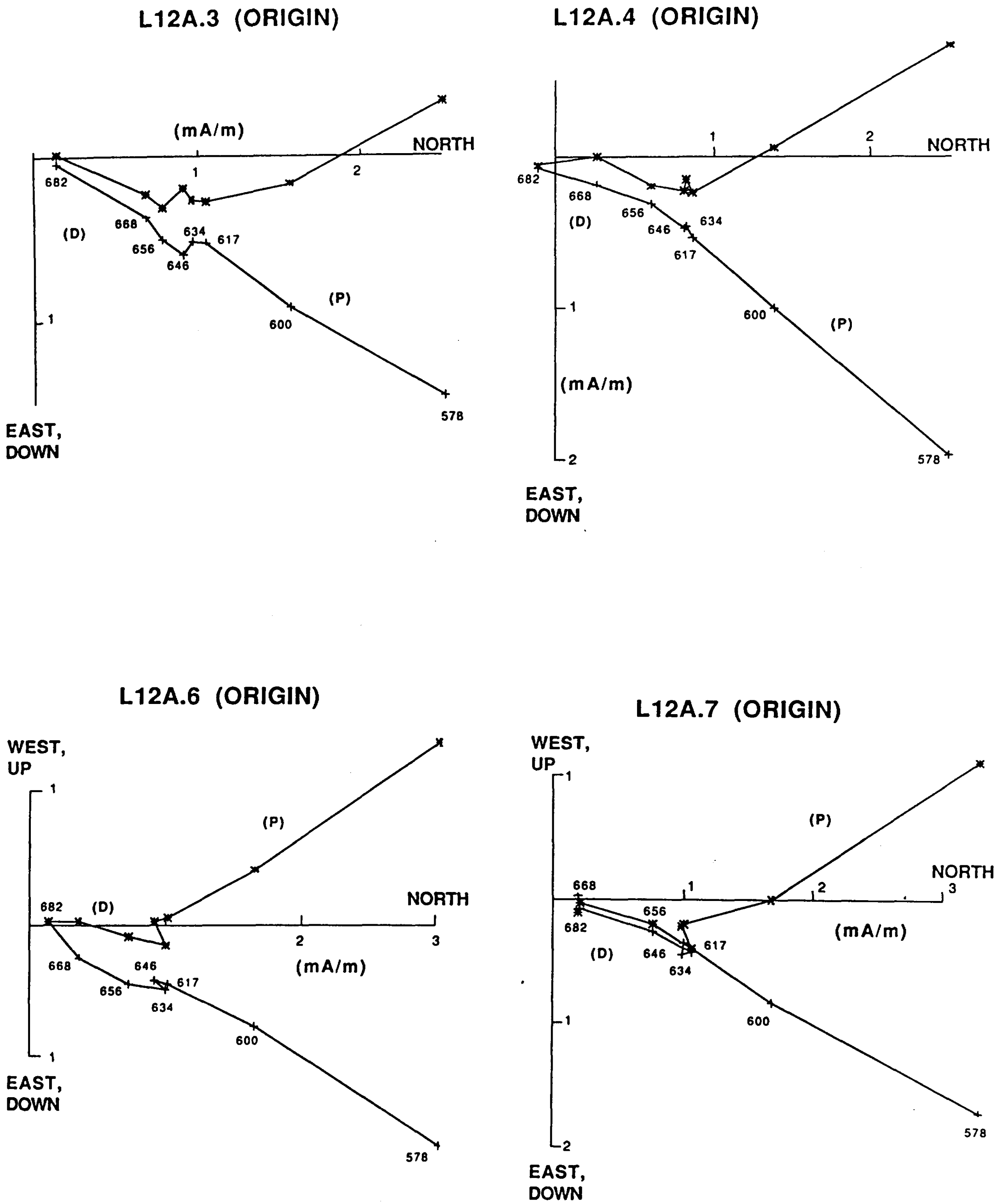


FIGURE 7.8: Expanded projections (near the origin) from Site 12A illustrate the presence of component (D) and the restricted blocking temperature range of component (P).

positive inclinations (Figure 7.5 b). It is regarded (analogous to the Glenbervie porphyry) to represent a recent field viscous overprint (VRM). Occasional stability overlap with component (S) (when present) is revealed during demagnetisation; once again this extends the unblocking range of the component to temperatures of approximately 250°-300°C.

ii) Component (S).

Component (S) was revealed as a linear segment only at sites 12/12A and in two samples from site 17. When observed, the component unblocks at temperatures between 200° - 450°C and is southerly directed (in situ) with moderate negative inclinations. Its presence within other samples could be deduced from a 'looping' of the orthogonal projection over the appropriate blocking temperature range (Figure 7.6 c). No accurate determination of the component orientation proved possible in these circumstances however.

iii) Component (P).

This component unblocks at temperatures in excess of 450°C during thermal demagnetisation. In the majority of samples, it decays directly to the origin approaching temperatures of 670°C (Figure 7.6 c, d). For sites 12/12A however, the component has a restricted unblocking temperature range between 450° and 630°C (Figure 7.6 a, b & Figure 7.7) and does not decay to the origin (Figure 7.8). In situ, component (P) is of northeasterly declination and has shallow - moderate negative inclination.

AF demagnetisation of samples from sites 10 & 14 produced a comparable component structure, i.e. presence of components (R) & (P), to that revealed upon thermal treatment for these sites. Component (P) determinations (three results) were therefore included in the statistical treatment. An AF demagnetisation from site 17 revealing (R) & (P) was omitted however as linear component (S) segments were revealed on thermal treatment of two samples from the site. AF cleaned samples showed a 'spiralling' of the demagnetisation trajectory at treatments greater than 40 mT however comparable to that observed for the Glenbervie porphyry (7.4.1).

iv) Component (D).

Component (D) has been recorded only at sites 12 and 12A (although it may be present in a sample from site 10). It unblocks exclusively in the 640°-670°C hematite temperature range forming only a small percentage of the total NRM. Detailed demagnetisation analyses of samples from site 12A prove it to be reproduceable (Figures 7.7 & 7.8). In situ, the component has a NE-NNE declination and shallow positive inclination (Figure 7.9 a) and is of normal polarity. When corrected for a shallow northerly dip, it assumes shallow negative inclination (Figure 7.9 b., Table 7.3). The lack

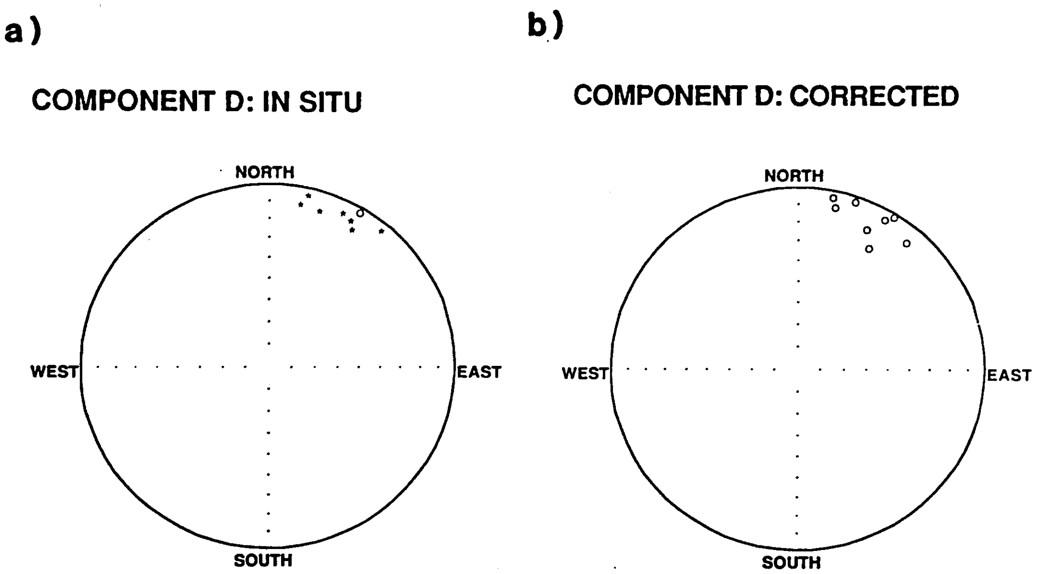
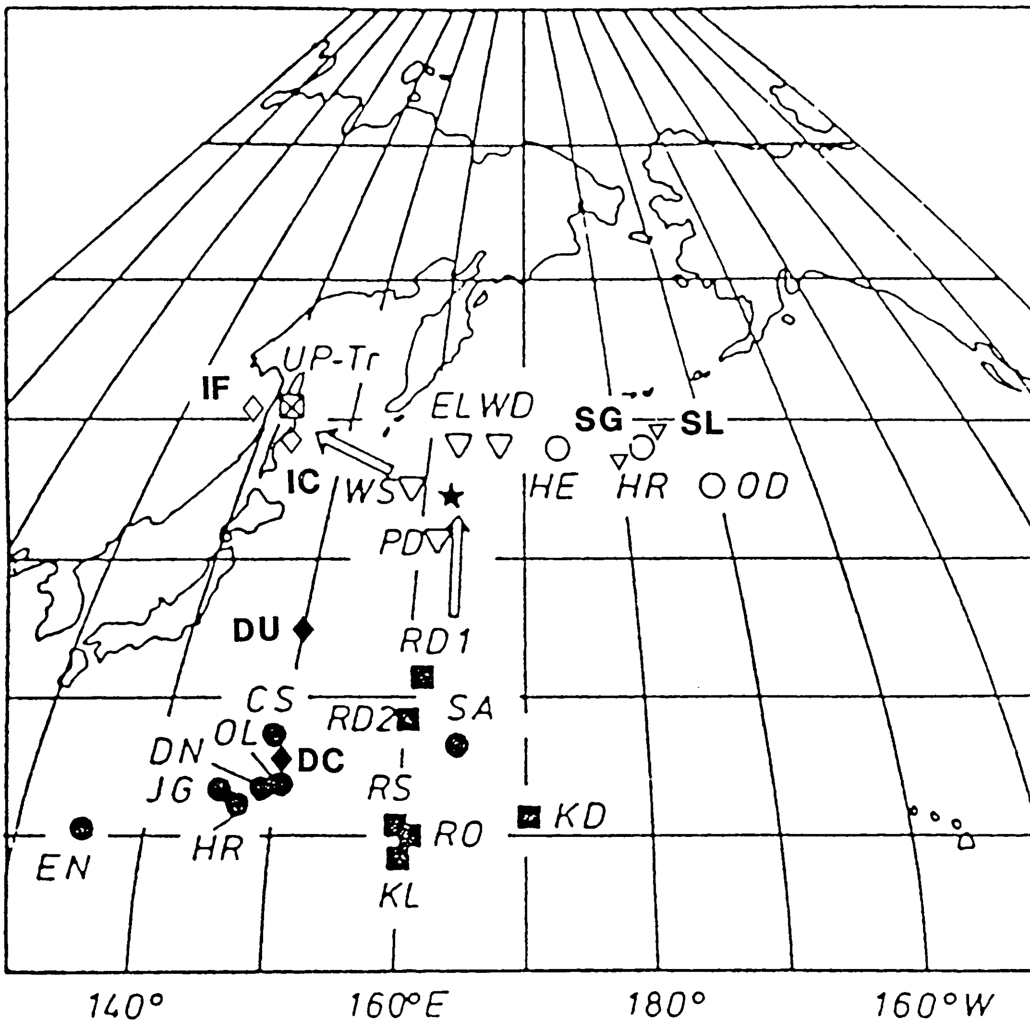


FIGURE 7.9: In situ (a) and structurally corrected (b) component (D) distributions for the Loch Lintrathen porphyry.



'ORS - LOWER CARB.' POLES WEST OF THE GGF. (SOLID CIRCLES) (GROUP'B')
EN - ESHA NESS (STORETVEDT & TORSVIK, 1985)
HR - HOY ROCKS (STORETVEDT & MELAND, 1985)
OL - ORKNEY LAVAS (STORETVEDT & PETERSEN, 1972)
JG - JOHN O'GROATS SST (STORETVEDT & CARMICHAEL, 1979)
DN - DUNCANSBY NECK (STORETVEDT et al. 1978)
CS - CAITHNESS SEDIMENTS (STORETVEDT & TORSVIK, 1983)
SA - SARCLET SST (STORHAUG & STORETVEDT, 1985)
'ORS - LOWER CARB' POLES EAST OF THE GGF. (SOLID SQUARES) (GROUP'B')
KL - KINGHORN LAVAS (WILSON & EVERITT, 1963)
RO - RORAGEN SEDS (STORETVEDT & GJELLESTAD, 1966)
RS - RINGERIKE SEDS (STORETVEDT et al. 1968)
KD - KVAMSHESTEN SEDS (LIE et al. 1969)
RD1 - ORS LENINGRAD (VAN DER VOO & SCOTESE, 1981)
RD2 - ORS WESTERN URALS (VAN DER VOO & SCOTESE, 1981)
LATE PALAEOZOIC OVERPRINT POLES WEST OF THE GGF. (OPEN CIRCLES) (GROUP'A')
HE - HELMSDALE GRANITE (TORSVIK et al. 1983)
HR - HOY ROCKS (STORETVEDT & MELAND, 1985)
OD - ORKNEY DYKES (STORETVEDT & OTTERA, 1988)
LATE PALAEOZOIC OVERPRINT POLES EAST OF THE GGF. (INVERTED TRIANGLES) (GROUP'A')
PD - PETERHEAD DYKE (TORSVIK, 1985)
WS - WHIN SILL (STORETVEDT & GIDSKEHAUG, 1969)
EL - EXETER LAVAS (CORNWELL, 1967)
WD - WACKERFIELD DYKE (TARLING et al. 1973)
(SOLID STAR IS MEAN PERMO-CARBONIFEROUS POLE FOR EUROPE; McELHINNY, 1973).

THIS STUDY.
OVERPRINT MAGNETISATION EAST OF THE GGF. (INVERTED TRIANGLES) (GROUP'A')
SG - COMPONENT (S): GLENBERVIE PORPHYRY.
SL - COMPONENT (S): LOCH LINTRATHEN PORPHYRY.
OPEN DIAMONDS (GROUP'A')
IF - COMPONENT (I) : ST. ABBS HEAD; FOLD LIMBS.
IC - COMPONENT (I) : ST. ABBS HEAD; CONGLOMERATE.
'ORS - LOWER CARB' POLES EAST OF THE GGF. (SOLID DIAMONDS) (GROUP'B')
DU - COMPONENT (D): LOCH LINTRATHEN PORPHYRY, IN SITU.
DC - COMPONENT (D): LOCH LINTRATHEN PORPHYRY, CORRECTED.

(FOR ALL REFERENCES, SEE STORETVEDT, 1987).

FIGURE 7.10: Component (S) and (D) poles from this study compared to the proposed discordance of Group 'A' and Group 'B' magnetisations across the Great Glen Fault (Storetvedt, 1987). Determined poles have been plotted directly on the original APWP (Figure 4 of Storetvedt, 1987).

of a comparable remanence component for the Glenbervie porphyry precludes the inclusion of component (D) in a fold test (7.5).

The similarity in pole position of component (D) with results reported from Middle - Upper Devonian rocks is noted (e.g. Storetvedt & Torsvik, 1983, 1985., Group B remanences; 5.2.2). Agreement between poles is better following tectonic correction but, due to the size of the overall cluster, no firm conclusion is possible as regards the magnetisation/deformation age relationship.

The magnetic age of these directions has been equivocal in the absence of statistically significant field tests (5.2.2., 5.2.3). Recently however, Torsvik *et al.* (1988) suggest an early Carboniferous age based upon negative fold and conglomerate tests recorded in ORS rocks from the western Midland Valley. They consider overprinting to be 'thermo-chemical' relating to a high geothermal gradient during extrusion of the Lower Carboniferous lavas.

It is notable that the Component (D) orientation at Loch Lintrathen is in direct contradiction to that expected through application of Storetvedt's (1987) model to account movements along the Great Glen (i.e. the Loch Lintrathen data coincides with poles obtained west of the GGF; see Figure 7.10). This supports the notion that such models are presently premature (cf. 6.7 & 7.5.1 for the Group A remanences).

TABLE 7.3.
COMPONENT D: IN SITU & STRUCTURALLY CORRECTED.

LOCATION	N	DEC	INC	k	α95	POLE		dP	dM
(IN-SITU)	(Samples)					(Long)	(Lat)		
LINTRATHEN	8	24.1	9.8	45.2	8.3	327.0E	35.0S	4.2	8.4
(CORRECTED)									
LINTRATHEN	8	24.0	-10.9	45.2	8.3	330.2E	24.9S	4.3	8.4

v) Anomalous directions from Site 15.

NRM and demagnetisation results from site 15 do not conform with the component structure outlined above (i-iv). A minor (steep inclination) component removed at low treatments (<200°C) gives way to a predominent component of southeasterly declination and moderate negative inclination. This component is demagnetised over the range 350°-670°C with the majority of remanence removed between 650°-670°C (i.e. thermally discrete behaviour).

Site 14, positioned at an inferred stratigraphic level approximately two metres below site 15 (and some three metres eastward), showed a demagnetisation structure consistent with other Loch Lintrathen sites (Figure 7.6 d). Component (P) is notably thermally discrete at site 14 however comparable in property if not direction with site 15.

In order to further investigate this discrepancy, sites 14 and 15 were reoccupied and a traverse between them sampled for study. An abrupt change in the NRM orientation (and of the thermally discrete component) was found to occur between two samples along the traverse (L14 A.10 & L14 A.11). This proved coincident with a similarly abrupt swing in the attitude of the ignimbrite fabric/foliation identified in the recovered cores. The 'anomalous' results of site 15 are therefore explained as due to rotation about an originally undetected change in attitude of the ignimbrite foliation. Assuming this change to have a tectonic origin, it is seen as supporting evidence to the contention of a predeformational age for component (P); see (7.5.2). AF demagnetisation of samples from Sites 14, 15, and from the traverse produced little or no change in the direction or intensity of NRM. This accords with the high blocking temperatures (>600°C) encountered on thermal treatment and indicates hematite to be the remanence carrier for these sites.

7.5 FOLD TESTS.

The contrasting attitude of the 'Lintrathen Porphyry' at Loch Lintrathen and Glenbervie together with the identification of remanence components of equivalent properties, allows the performance of fold tests for components (S) and (P). Component (R) has been interpreted as a recent VRM and by implication, would fail a fold test. The fold test constrains the magnetisation age relative to the 'Acadian deformation' responsible for the differing tilt corrections at each locality (Soper *et al.* 1987).

7.5.1. COMPONENT (S).

The in situ and structurally corrected distributions of component (S) for both localities are shown in Figure 7.11 a, b. Evolving statistical parameters upon incremental tilt correction are graphically illustrated in Figure 7.11 c. Summarised Fisher statistics for individual and combined data are listed in Table 7.4 below:

Component (S) fails a palaeomagnetic fold test (McElhinny, 1964) at the 99% confidence level and is therefore concluded to postdate Acadian deformation.

Component (S) pole positions for Loch Lintrathen and Glenbervie are statistically indistinguishable at 95% confidence. They fall within the broad cluster of Group 'A' poles reported elsewhere in Scotland (see 6.6). In the context of the Storetvedt (1987) model recounting former Great Glen Fault (GGF) movements, the poles agree with determinations west of the GGF (Figure 7.10) and as such are in direct contradiction of the proposed model. At present the age of component (S) cannot be constrained beyond late Palaeozoic - early Mesozoic (see 6.6).

TABLE 7.4.

COMPONENT (S): IN SITU & STRUCTURALLY CORRECTED.

LOCATION	N	DEC	INC	k	α95	POLE POSN.		dP	dM
(IN SITU)	(Sample)					(Long)	(Lat)		
GLENBERVIE	24	177.8	-25.7	25.9	5.9	359.3E	46.7S	3.4	6.4
LINTRATHEN	11	175.4	-29.4	20.7	10.3	356.5E	49.0S	6.3	11.4
COMBINED	35	177.1	-26.9	24.5	5.0	357.9E	47.9S	3.0	5.4
(CORRECTED)									
GLENBERVIE	24	341.6	-79.9	25.9	5.9				
LINTRATHEN	11	180.4	-12.6	20.7	10.3				
COMBINED	35	192.0	-25.4	3.7	14.6				

GLENBERVIE STRIKE/DIP = 85.2/74.1(S)

LINTRATHEN STRIKE/DIP= 305.6/21.1(N)

TABLE 7.5

COMPONENT (P): IN SITU & STRUCTURALLY CORRECTED.

LOCATION	N	DEC	INC	k	α95	POLE POSN.		dP	dM
(IN SITU)	(Sample)					(Long)	(Lat)		
GLENBERVIE	36	134.6	-54.7	96.2	2.5				
LINTRATHEN	41	36.1	-24.4	28.5	4.3				
COMBINED	77	67.6	-49.6	4.4	8.7				
CORRECTED									
GLENBERVIE	36	24.7	-40.2	96.2	2.5	334.7E	7.6S	1.8	3.0
LINTRATHEN	41	36.1	-45.6	28.5	4.3	325.1E	1.0S	3.5	5.5
COMBINED	77	30.4	-43.2	37.1	2.7	329.9E	4.3S	2.1	3.3

	PALAEOLATITUDE	dP (Uncertainty on Palaeolatitude)
GLENBERVIE	22.9°S	1.82°
LINTRATHEN	27.0°S	3.48°
COMBINED	25.2°S	3.25°

STRIKE/DIP VALUES AS TABLE 7.4.

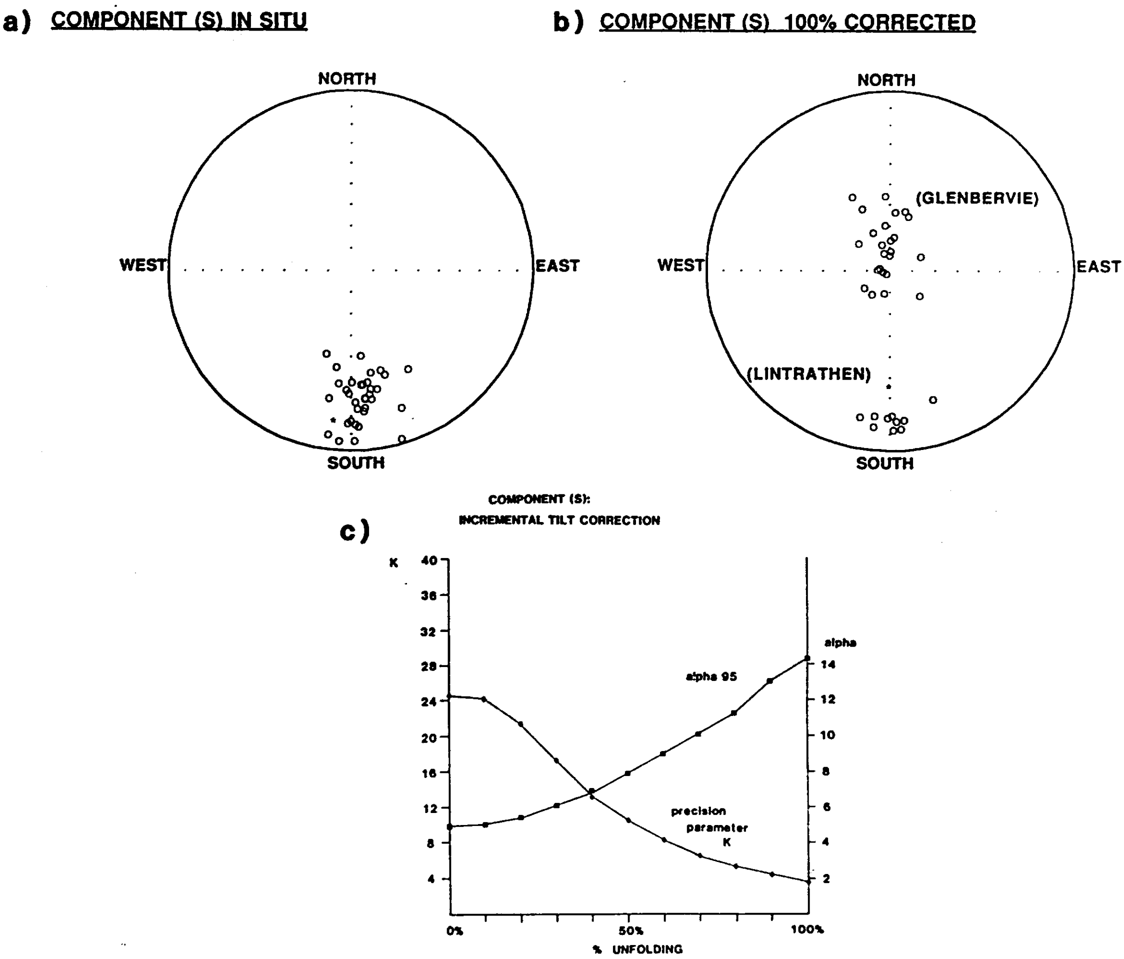


FIGURE 7.11: Palaeomagnetic fold test performed with respect to component (S).

(a,b): In situ and structurally corrected sample components from the Loch Lintrathen & Glenbervie porphyries.

(c): Evolving Fisher statistical parameters with incremental tilt correction at both sampling localities.

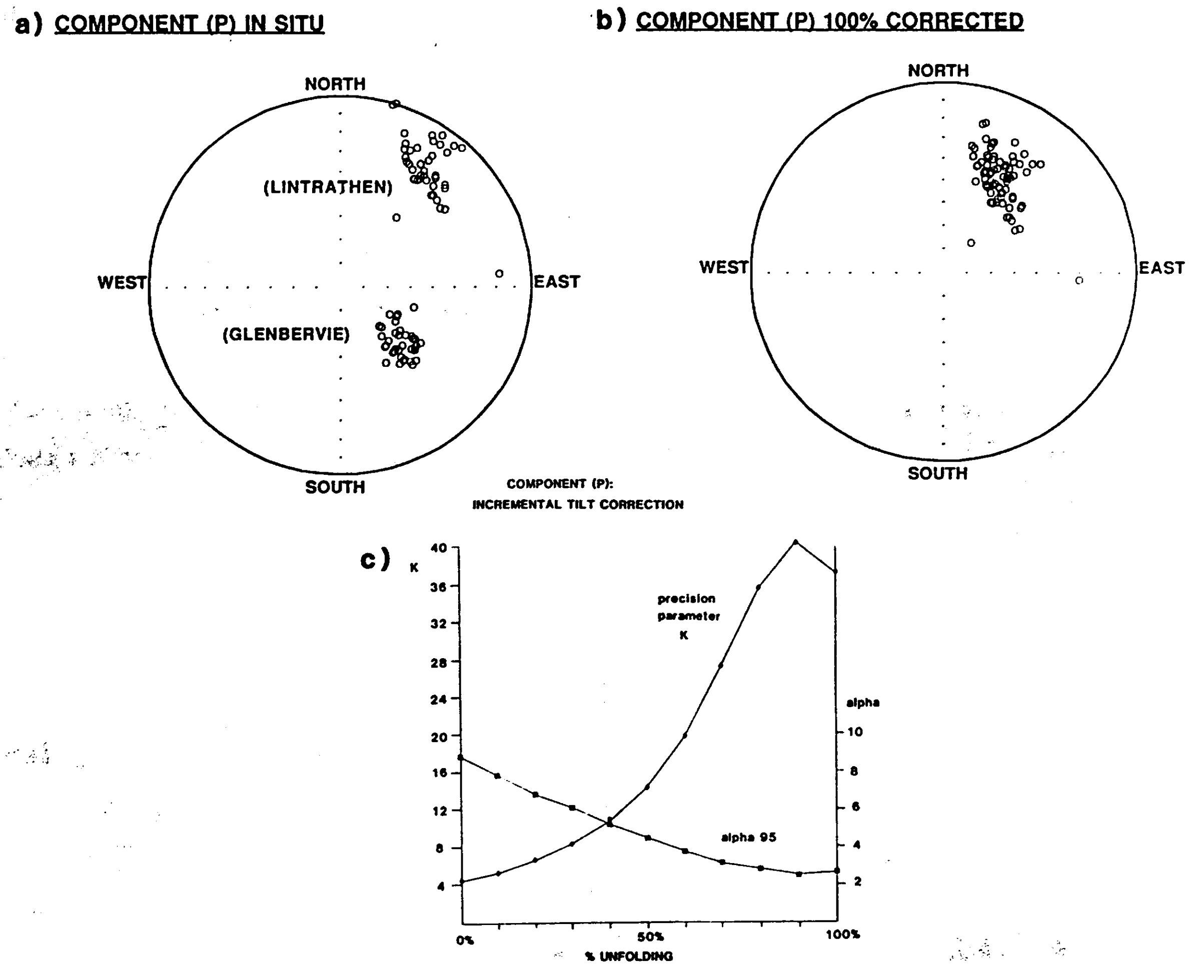


FIGURE 7.12: Palaeomagnetic fold test performed with respect to component (P).

(a,b) : In situ and corrected component (P) directions for the Loch Lintrathen & Glenbervie porphyries.

(c): Fisher statistics with incremental structural correction of the ignimbrite foliation at each locality.

7.5.2 COMPONENT (P).

In situ and corrected component (P) distributions for the Loch Lintrathen and Glenbervie porphyries are shown in Figure 7.12 a, b. Incrementally tilt corrected Fisher statistics are shown graphically in Figure 7.12 c and summarised in Table 7.5.

In contrast to component (S), the precision of component (P) increases significantly after structural correction. The component therefore passes the fold test at the 99% confidence level (McElhinny 1964) and is concluded to be of 'pre-Acadian' age. Component (P) is interpreted as representing a primary magnetisation acquired at or close to the time of ignimbrite emplacement.

A local peak in the precision parameter at 90% unfolding is recognised (Figure 7.12 c). Taken literally, this appears to indicate a syn-folding origin for the component. A pre-folding origin is favoured however considering the following; (1) the syn-folding peak does not approach statistical significance at the 95% confidence level when compared to the fully corrected data; and, (2) the problems of locating the palaeohorizontal within volcanic successions is well known in palaeomagnetic studies (6.5.4, 4.3.3). Greatest precision close to complete unfolding may therefore indicate the palaeohorizontal to have been incorrectly located by a few degrees at either locality. Determined palaeolatitudes calculated from component (P) are not distinguishable across the HBF (Table 7.5).

A contrast in precision between the respective component (P) distributions of each locality becomes evident from Table 7.5 (Loch Lintrathen, k=28.5., Glenbervie, k=96.7). This may result from the greater stratigraphic thickness available for sampling at Loch Lintrathen perhaps leading to the sampling of multiple flows. This being the case, the observed precision decrease could reflect a longer time averaging of the ambient field.

7.6 GYROREMANENT & ANHYSTERETIC REMANENT MAGNETISATION ACQUISITION.

Although static AF demagnetisation was used only occasionally during the study (7.2); the results obtained have particular bearing on the proposed correlation of the Loch Lintrathen and Glenbervie porphyries.

Standard laboratory cleaning of a sample at a given peak field proceeded as follows:
i) demagnetisation along each of the three orthogonal sample axes (X, Y, Z) in turn.
ii) measurement of the remaining total magnetic moment.
iii) incremental increase of the peak field.
iv) repetition of (i) for the new peak field but with a changed order of axis demagnetisation (e.g. Z, X, Y).

All specimens subjected to the above AF method (excepting those from sites 14

&15 at Loch Lintrathen; 7.4.2v) were found to acquire a 'spurious' magnetisation at treatments in excess of 35-40 mT. This was manifest as an 'oscillatory' or 'spiralling' movement of the demagnetisation trajectory when viewed in orthogonal projection (e.g. Figure 7.13 a, b). Furthermore, oscillation was found to vary systematically with the final demagnetisation axis; e.g. Figure 7.13 c (Glenbervie) & d (Loch Lintrathen).

The possible acquisition of spurious effects during AF treatment has been recognised for some time (e.g. Doell & Cox, 1967). An empirical method for the removal of the 'axis dependent' contamination described above was proposed by Dankers & Zijderveld (1981). A theoretical explanation for its generation was developed by Stephenson (1980 a, 1980 b, 1981) in terms of the gyroscopic properties of the sample moments: The acquired remanence being referred to as a Gyroremanent Magnetisation (GRM).

The Dankers & Zijderveld (1981) method for removal of the GRM was therefore adopted in the present study.

This is described briefly below:

(i) the conventional three axis cleaning described earlier was undertaken but no ensuing measurement made.

(ii) the sample was again demagnetised firstly with the X axis parallel to the solernoid coil and subsequently measured. This procedure was then repeated for axes Y and Z.

(iii) the true demagnetisation co-ordinates were calculated using the axis values determined when parallel to the coil. GRM is therefore removed as it is contained in a plane perpendicular to the coil axis (Stephenson, 1981., Roperch & Taylor, 1986).

This method proved successful in the present work although was not adopted extensively due both to the greater time required and the success of thermal treatment in separating components. A detailed example is given in Figure 7.14 for sample LP1.7 (Glenbervie Porphyry). The open symbols in each of the diagrams (a, b & c) give the intensities of magnetisation when measured parallel to the coil axis whereas the closed symbols refer to measurements perpendicular to the coil. If after each demagnetisation step the open symbols are used to calculate the true demagnetisation co-ordinates (Dankers & Zijderveld, 1981), the resulting orthogonal projection shows no 'oscillations' and the contaminant GRM has been removed (cf. Figures 7.14 d & 7.13 c).

It is notable in Figure 7.14 a-c that the open symbols are displaced from a central position with respect to the closed symbols. This indicates the acquisition of an Anhysteretic Remanence (ARM) during demagnetisation directed along the coil axis. The ARM originates either from a stray ambient field or may result from impurity of the sinusoidal waveform during treatment (Collinson, 1983).

By reversing the sample in the coil, (i.e. +X becomes -X etc.), an equal but opposite ARM can be imparted. The true axis value can then be calculated as half the algebraic sum of the positive and negative axis results. This procedure (which is actually a doubling of the Dankers & Zijderveld method) allows removal of both ARM and GRM. It was performed for a single sample from each porphyry (LP10.7, Loch Lintrathen., & LP6.1, Glenbervie) both of which procured comparable ARM and GRM. The effect of removing both ARM and GRM contaminants using this method is shown in Figure 7.15 a, b. The presence of GRM & ARM (oriented in the sample XY plane and along the sample Z axis respectively) is seen to displace the demagnetisation trajectory away from the origin (Figure 7.15 a). Removal of both remanences results in a trajectory which approaches the origin (Figure 7.15 b). These observations are confirmed using the LINEFIND algorithm (Kent *et al.* 1983).

With respect to the proposed correlation of the Loch Lintrathen and Glenbervie porphyries, the acquisition of GRM in both instances is thought to strongly favour this. In fact, Langereis (1979) notes " the introduction of disturbing remanences of this type (now termed GRM) in higher alternating fields very rarely occurs in palaeomagnetic research." A past lack of recognition no doubt accounts for some of its 'rarity' however. GRM has been linked to magnetically anisotropic single domain magnetite (Stephenson, 1981) which is inferred to be present at both porphyry localities. Anisotropy is likely to relate to the plane of ignimbrite foliation although this has not been directly investigated in the present study.

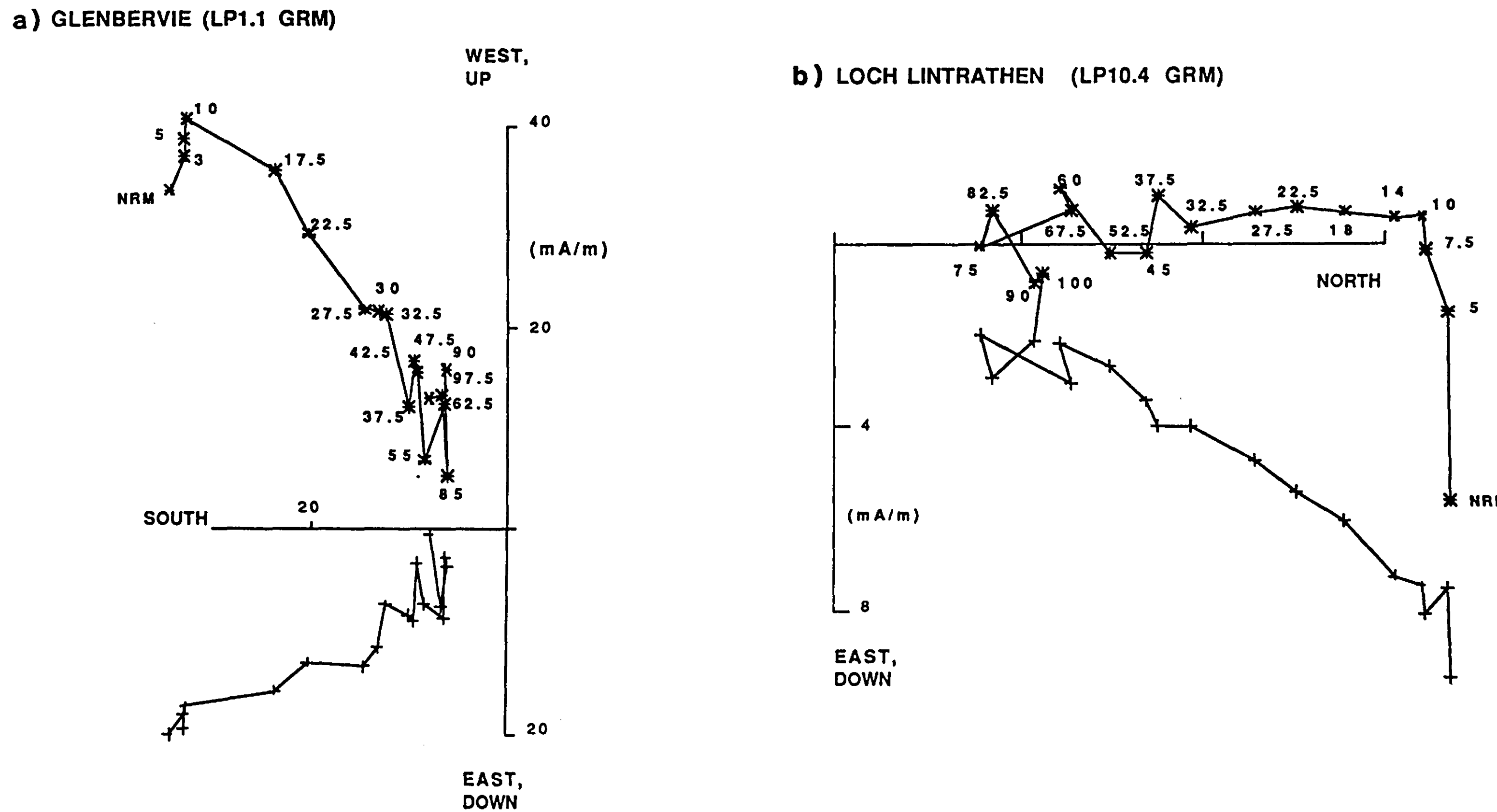


FIGURE 7.13: Orthogonal projections show the acquisition of Gyromagnetic Remanence (GRM) with static alternating field demagnetisation.
(a,b): 'Oscillatory' behaviour at treatment in excess of 35mT for the Glenbervie (a) and Loch Lintrathen (b) porphyries.

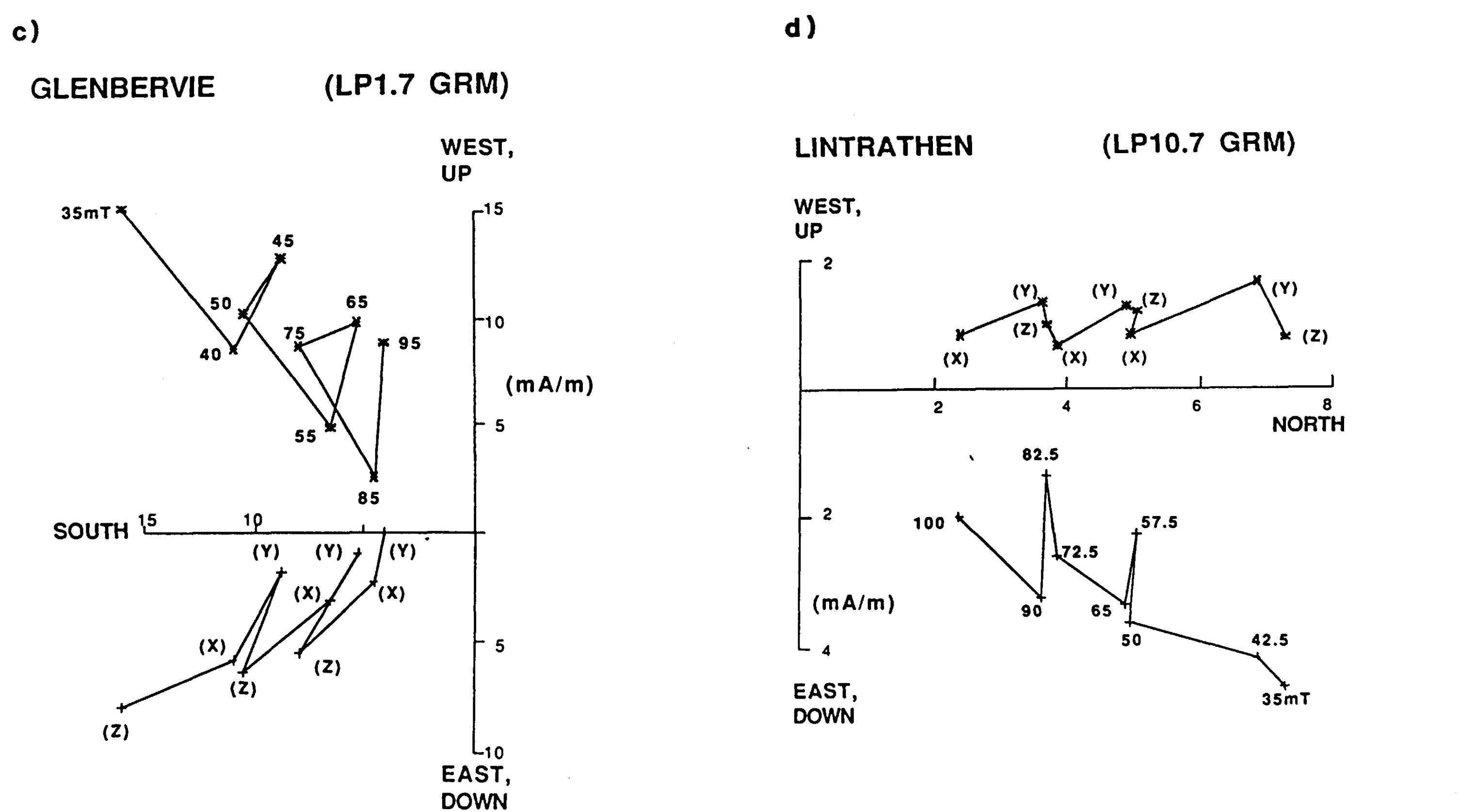


FIGURE 7.13: (c,d) Orthogonal projections expanded in the range 35-100 mT show the 'oscillation' or 'spiralling' during demagnetisation and the dependence of this upon the final demagnetisation axis (labelled X, Y or Z).

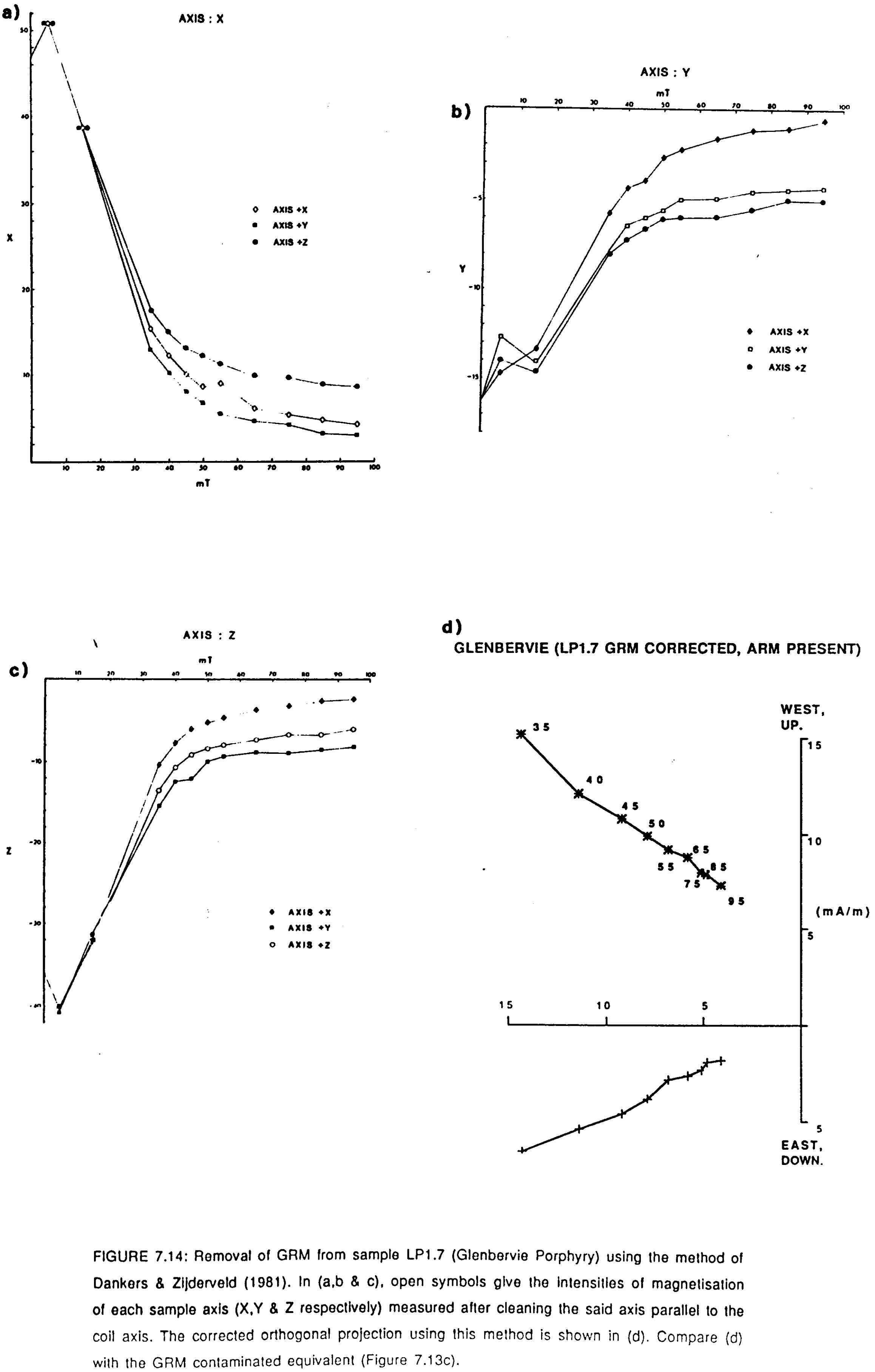


FIGURE 7.14: Removal of GRM from sample LP1.7 (Glenbervie Porphyry) using the method of Dankers & Zijderveld (1981). In (a,b & c), open symbols give the intensities of magnetisation of each sample axis (X,Y & Z respectively) measured after cleaning the said axis parallel to the coil axis. The corrected orthogonal projection using this method is shown in (d). Compare (d) with the GRM contaminated equivalent (Figure 7.13c).

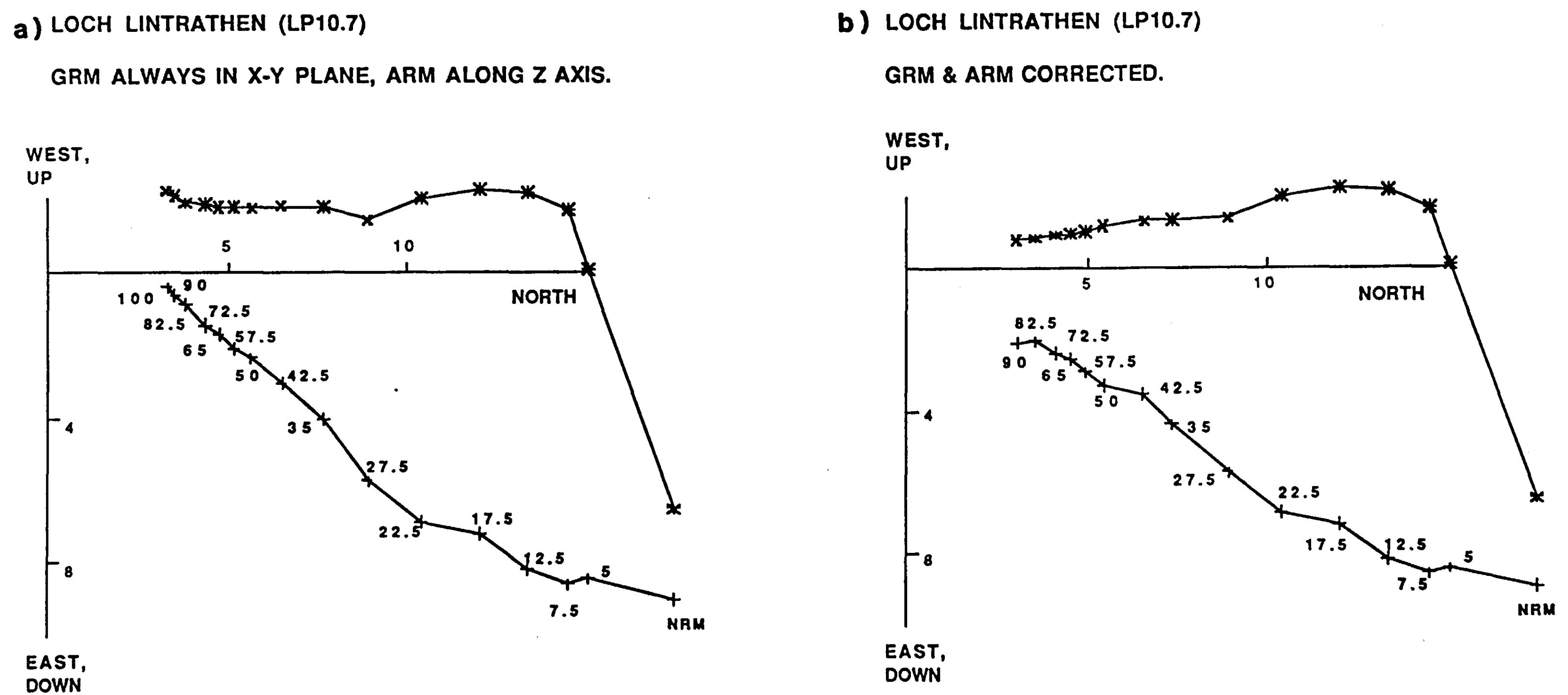


FIGURE 7.15: The removal of both ARM & GRM from sample LP10.7 (Loch Lintrathen Porphyry) is demonstrated using a 'doubling' of the original Dankers & Zijderveld (1981) method. In (a), the GRM always resides in the X-Y sample plane and the ARM is directed along the Z axis. Both effects have been removed to leave a 'cleaned' magnetisation decay approaching the origin in (b).

7.7 SUMMARY, TECTONIC IMPLICATIONS & CONCLUSIONS.

Statistically equivalent palaeolatitudes determined for the Loch Lintrathen and Glenbervie porphyries positioned on either side of the Highland Border requires that any subsequent net translation (e.g. during the Acadian orogeny) along the HBF must not exceed the palaeomagnetic errors (Table 7.5). This places particular constraint on strike-slip movement given the similarity of the palaeo-azimuth with the present trend of the HBF. We can therefore consider the Grampian Highlands and Midland Valley terranes to have docked (to within the measured errors) by late Silurian time (415Ma).

This confirms the previously noted equivalence of late-Silurian to early Devonian data across the terrane boundary (Harte *et al.* 1984). The poles from either porphyry are marginally statistically separated due to a declination difference (11.4°) between sampling localities. This may reflect either true tectonic rotation or result from an incorrect assumption that tilting took place about the line of strike (see Macdonald, 1980).

Additionally, several demagnetisation properties of the Loch Lintrathen and Glenbervie porphyries are found to be unusual but directly comparable. These are notably the occurrence of component (S) within both porphyries and their similar acquisition of GRM during AF treatment. These observations strongly support the correlation of the porphyries as follows:

i) Component (S) 'type' magnetisations were not revealed during the detailed demagnetisation of surrounding volcanics of the Crawton and Arbuthnott groups (Torsvik, 1985).

ii) GRM acquisition has been reported only occasionally upon routine AF demagnetisation of rocks.

Conversely, significant differences exist in the initial magnetic properties (i.e. NRM Intensity, susceptibilty) which require explanation if a common volcanic source is to be accepted. Also, component (D) is not located at Glenbervie although as its limited local occurrence has been demonstrated at Loch Lintrathen; 'absence' at Glenbervie may therefore result from insufficient sampling to date.

We conclude the palaeomagnetic evidence to favour the proposed correlation of the units. In this light (accepting correlation), movements along the HBF which postdate ignimbrite emplacement cannot have exceeded its former geometry.

For example, taking a single volcanic source centred at Loch Lintrathen; relative displacements would not be expected to exceed the mean distance travelled from source by a 'typical' ignimbrite and at most be slightly in excess of the maximum distance travelled. Possible reconstructions using this example (and distance data from Cas & Wright, 1987) relative to an arbitrary fixed Grampian Highlands are shown in Figure 7.16. Recently determined geological constraints (Bluck, 1985., Haughton, 1986) are also illustrated.

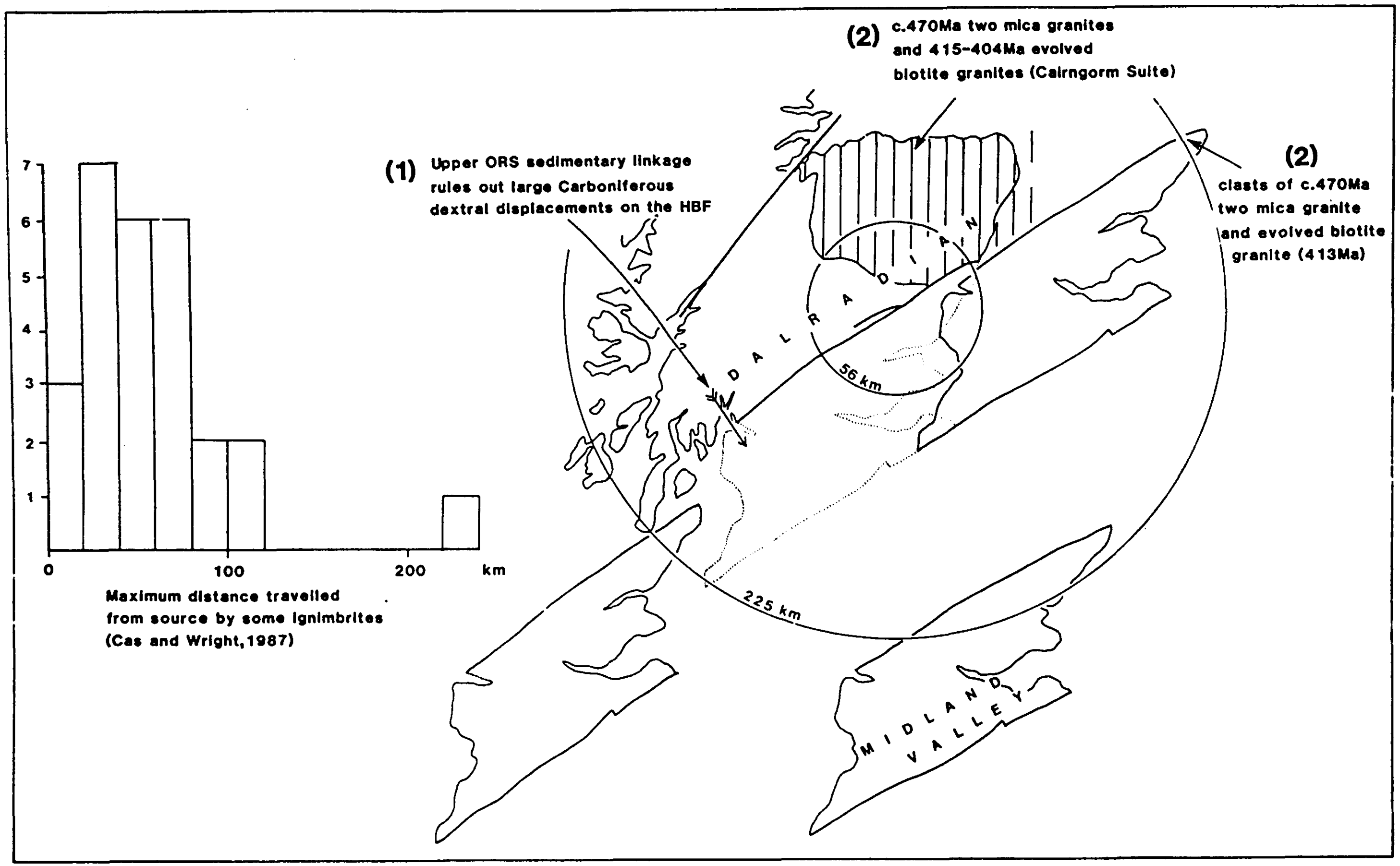


FIGURE 7.16: An example of possible movements of the Midland valley with respect to the Grampian Highlands given accepted correlation of the 'Lintrathen Porphyry' between terranes. Geological constraints from Bluck (1985): (1) and Haughton (1987): (2) are indicated. A histogram of distances travelled from source by some ignimbrites is shown constructed from data quoted in Cas & Wright (1987). Mean distance (56kms) and maximum distance (225kms) have been used to control the possible reconstructions. Note that the present day configuration of the terranes is compatible with porphyry correlation.

CHAPTER 7 : REFERENCES.

Allan, D.A. 1928. The geology of the Highland Border from Tayside to Noranside. *Transactions of the Royal Society of Edinburgh,* 56, 57-87.

Armstrong, M. & Paterson, I.B. 1970. The Lower Old Red Sandstone of the Strathmore Region. *Report of the Institute of Geological Sciences,* 70/12.

Bluck, B.J. 1985. The Scottish paratectonic Caledonides. *Scottish Journal of Geology,* 21, 437-464.

Campbell, R. 1913. The geology of south-eastern Kincardineshire. *Transactions of the Royal Society of Edinburgh.* 48, 923-960.

Dankers, P.H.M. & Zijderveld, J.D.A. 1981. Alternating field demagnetisation of rocks, and the problem of gyromagnetic remanence. *Earth & Planetary Science Letters.* 53, 89-92.

Doell, R.R. & Cox, A. 1967. Analysis of alternating field demagnetization equipment, in *Methods in Palaeomagnetism* (eds. D.W. Collinson, K.M.Creer and S.K. Runcorn), Elsevier, Amsterdam.

Geikie, A. 1897. *The Ancient Volcanoes of Great Britain (2 vols.).* London: MacMillan.

Haughton, P.D.W. 1986. *The sedimentology and provenance of the Dunottar and Crawton Groups, Lower Old Red Sandstone, Kincardineshire,* Scotland. PhD Thesis, University of Glasgow.

Langereis, C.G. 1979. An attempt to correlate two adjacent Tortonian marine clay sections in western Crete using magnetostratigraphic methods. *Utrecht Micropalaeontological Bulletin,* 21, 193-214.

McElhinny, M.W. 1964. Statistical significance of the fold test in palaeomagnetism. *Geophysical Journal of the Royal Astronomical Society,* 8, 338-374.

Miller J.D. and Kent, D.V. 1986. Synfolding and pre-folding magnetizations in the Upper Devonian Catskill Formation of eastern Pennsylvania. *Journal of Geophysical Research,* 91, 12791-12803.

Molyneux, L. 1971. A complete results magnetometer for measuring the remanent magnetisation of rocks. *Geophysical Journal of the Royal Astronomical Society* , 24, 429-434.

Paterson, I.B. & Harris, A.L. 1969. Lower Old Red Sandstone Ignimbrites from Dunkeld, Perthshire. *Report of the Institute of Geological Sciences.* 69/7.

Reynolds, R.L. 1977. Palaeomagnetism of Welded Tuffs of the Yellowstone Group. *Journal of Geophysical Research,* 82, 3677-3693.

Roperch, P. & Taylor, G.K. 1986. The importance of gyromagnetic remanence in alternating field demagnetization. Some new data and experiments on G.R.M. and R.R.M. *Geophysical Journal of the Royal Astronomical Society,* 87, 949-965.

Sallomy, J.T. and 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.

Soper, N.J., Webb, B.C. and Woodcock, N.H. 1987. Late Caledonian (Acadian) transpression in north-west England: timing, geometry and geotectonic significance. *Proceedings of the Yorkshire Geological Society,* 46, 175-192.

Stephenson, A. 1980a. Gyromagnetism and the remanence acquired by a rotating rock in an alternating field. *Nature,* 284, 48.

Stephenson, A. 1980b. A gyroremanent magnetisation .in anisotropic magnetic material. *Nature,* 284, 49.

Stephenson, A. 1981. Gyroremanent magnetization in in a weakly anisotropy rock sample. *Physics of the Earth & Planetary Interiors,* 25, 163-166.

Storetvedt, K.M. and Torsvik, T.H. 1983. Palaeomagnetic re-examination of the basal Caithness Old Red Sandstone; aspects of local and regional tectonics. *Tectonophysics,* 98, 151-164.

Storetvedt, K.M. and Torsvik, T.H. 1985. Palaeomagnetic results from the Esha Ness Ignimbrites, Shetland. *Physics of the Earth & Planetary Interiors,* 31, 169-173.

Teall. 1888. *British Petrography,* pp.267.

Thirlwall, M.F. 1988. Geochronology of Old Red Sandstone Magmatism in Northern Britain. *Journal of the Geological Society, London.* in press.

Torsvik, T.H. 1985. Magnetic properties of the Lower Old Red Sandstone lavas in the Midland Valley, Scotland; palaeomagnetic and tectonic considerations. *Physics of the Earth & Planetary Interiors,* 39, 194-207.

Torsvik, T.H., Lyse, O., Atteras, G., & Bluck, B.J. 1988. Palaeozoic palaeomagnetic results from Scotland and their bearing on the British apparent polar wander path. *Physics of the Earth & Planetary Interiors,* in press.

CHAPTER 8 : CONCLUSIONS & RECOMMENDATIONS FOR FUTURE WORK.

8.1 GENERAL.

The three studies of Palaeozoic rocks from central and southern Scotland described in this thesis contribute significantly to the available palaeomagnetic dataset for the region.

A compilation of these data with previously published results allows the construction of preliminary Apparent Polar Wander Paths (APWP's) for the Grampian Highlands, Midland Valley and Southern Uplands tectonostratigraphic terranes. A considerable dataset now exists for the Grampian Highlands but fewer studies are available for the Midland valley and Southern Uplands blocks.

Study areas from which data are obtained are shown in Figure 8.1 and resulting poles listed in Table 8.1. APWP's for each of the terranes form Figures 8.2, 8.3, & 8.4. Each of the determined paths is now briefly discussed:-

8.2 GRAMPIAN BLOCK.

The Grampian APWP (Figure 8.2) shows a broad east-west polar tracking between Ordovician and late Silurian to early Devonian times. Superimposed upon this is an approximate 15°S-25°S-equatorial latitudinal polar wander accommodating particular Newer Granite data (Torsvik 1984, 1985 a).

The Ordovician APW segment is delineated by results from the Aberdeenshire gabbros (Watts and Briden, 1984), Dalradian schists (Watts, 1985) and Port Askaig Tillite (Stupavsky *et al.* 1982). Relative magnetisation ages are constrained by K-Ar chrontours (gabbros) and D3-D4 fold tests (schists). A negative palaeomagnetic conglomerate test attests to the secondary nature of the tillite remanence.

Estimates of absolute magnetisation age are hampered by uncertainty in the mechanism of remanence acquisition in each case. For example, in considering the Aberdeenshire gabbros, a purely thermo-remanence blocking (TRM), carries the implication of a magnetisation age somewhat older than the respective K-Ar chrontour ages (Harte *et al.* 1984). Conversely, either a thermo-chemical (TCRM) or chemical (CRM) acquisition might take place at temperatures similar to or below that of argon blocking in biotite. The range in potential acquisition temperature is therefore accompanied by a corresponding uncertainty in absolute magnetisation age.

Briden *et al.* (1986) suggest a CRM mechanism to predominate in the reported studies from the Grampian and northwest highlands and by implication support comparatively 'young' magnetisation ages.

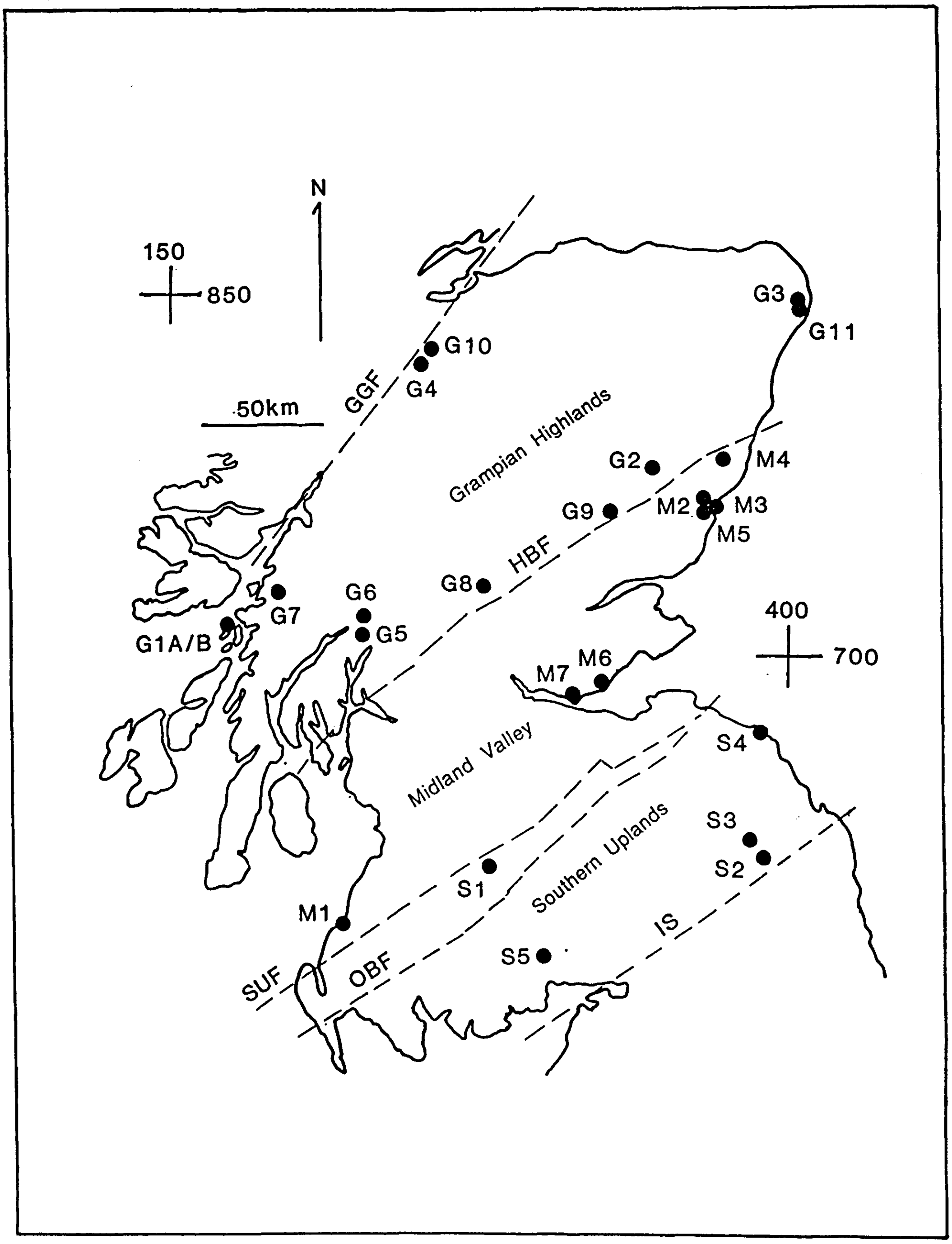


FIGURE 8.1 : LOCATION OF PALAEOMAGNETIC STUDY AREAS.

Numbers attributed to study areas correspond with those listed in Table 8.1. Grampian poles are prefixed (G)., Midland Valley poles, (M) and Southern Uplands poles, (S).

PALAEOMAGNETIC POLE POSITIONS USED IN THE COMPILATION OF THE GRAMPIAN, MIDLAND VALLEY & SOUTHERN UPLANDS PALAEOZOIC APPARENT POLAR WANDER PATHS.

No.	LITHOLOGY/FORMATION	POLE LAT.	LONG.	REFS.
GRAMPIAN HIGHLANDS.				
1A	PORT ASKAIG TILLITE (MATRIX)	14°S	16.6°E	Stupansky et al.1982. (re-interpreted).
1B	PORT ASKAIG TILLITE (CLASTS)	6.8°S	25.5°E	As above.
2	DALRADIAN SCHISTS	3°S	22°E	Watts, 1985.
3	PETERHEAD GRANITE	20.9°S	357.8°E	Torsvik, 1984.
4	FOYERS GRANITE	27.2°S	346.5°E	Torsvik, 1985a.
5	ARROCHAR COMPLEX	7.4°S	323°E	Briden, 1970.
6	GARABAL HILL - GLEN FYNE	4.6°S	326.2°E	Briden, 1970.
7	LORNE PLATEAU LAVAS	2°N	321°E	Latham & Briden,1975.
8	COMRIE INTRUSION	6.2°S	287.1°E	Turnell, 1985.
9	LOCH LINTRATHEN PORPHYRY	1.0°S	325.1°E	This study.
10	FOYERS SANDSTONE (recalc)	30°S	327°E	Kneen, 1973.
11	PETERHEAD DOLERITE	41°S	342°E	Torsvik, 1985a.

Site means from the Aberdeenshire Gabbros (Watts & Briden, 1984) are indicated by stars, inverted triangles or upright triangles dependent on whether K-Ar cooling ages are >463, 463-443 or <443Ma respectively.

No.	LITHOLOGY/FORMATION	POLE LAT.	LONG.	REFS.
MIDLAND VALLEY.				
1	BALLANTRAE SERPENTINITE	12.3°S	26.5°E	Piper,1978.
2	STRATHMORE LAVAS (Dunottar-Strathmore Groups)	4°S	320°E	Sallomy & Piper, 1973. (incorp. previous work)
3	STRATHMORE LAVAS (Crawton & Arbuthnott Groups)	2°N	318°E	Torsvik, 1985b.
4	GLENBERVIE PORPHYRY	7.6°S	334.7°E	This study.
5	STRATHMORE OVERPRINT	20°S	315°E	Torsvik, 1985b.
6	KINGHORN - BURNTISLAND LAVAS	15°S	332°E	Torsvik et al.1988.
7	QUEENSFERRY SILL	38°S	354°E	As above.

Stonehaven Group site means (31 ,32., Sallomy & Piper, 1973) are indicated by encircled stars.

No.	LITHOLOGY/FORMATION	POLE LAT.	LONG.	REFS.
SOUTHERN UPLANDS.				
1	BAIL HILL VOLCANICS	32.5°S	347.5°E	Piper, 1978.
2	CHEVIOT GRANITE	4°N	337°E	Thorning,1974.
3	CHEVIOT VOLCANICS	11°N	320°E	As above.
4	ST.ABBS HEAD LAMPROPHYRE	28.6°N	316°E	This study.
5	DUMFRIES RED SANDSTONES	27°S	355°E	Maslanyj & Collinson, 1988.

NRM data from Nairn (1960) has been omitted as no cleaning was performed.

N.B. POLE NUMBERS DO NOT STRICTLY IMPLY RELATIVE MAGNETISATION AGES.

TABLE 8.1 : PALAEOMAGNETIC POLES USED IN THE COMPILATION OF THE GRAMPIAN, MIDLAND VALLEY & SOUTHERN UPLANDS PALAEOZOIC APPARENT POLAR WANDER PATHS.

Storetvedt and Deutsch (1986) offer a reappraisal of Scottish Ordovician palaeomagnetism (incorporating data from the Grampian block) which contrasts with the APWP depicted in Figure 8.2. Aspects of their interpretation have been criticised both in section 3.2.2 and by Briden *et al.* (1986). Notably, the results from the Port Askaig Tillite (Stupavsky *et al.* 1982) are here regarded as being post-deformational (see Figure 3.5).

Whether the Grampian APWP tracks through the Foyers-Peterhead Newer granite poles (Torsvik, 1984., 1985 a) during Silurian time is not yet proven. A later back tracking of the APWP in Lower Carboniferous time (Figure 8.2) allows for the possibility of their remagnetisation (see Tarling, 1985). The observed discordancy of these results with other data from the Newer granite suite (cf. Briden, 1970., Turnell, 1985) has no obvious explanation in terms of differing magnetic age given available radiometric determinations (Stephens and Halliday, 1984., Thirlwall, 1983., Turnell, 1985). This might in itself favour their subsequent remagnetisation. Consideration of the Foyers-Peterhead data also has importance outwith the Scottish terranes with its acceptance as an original palaeo-field indicating that Iapetus was still palaeomagnetically detectable into Silurian times (Briden *et al.* 1986).

The Lorne Plateau volcanics (Latham and Briden, 1975), Arrochar Complex, Glen Fyne - Garabal Hill Complex (Briden, 1970), Comrie Intrusion (Turnell, 1985) and Loch Lintrathen Porphyry (Chapter 7) all yield equatorial south poles and form a late Silurian-early Devonian "corner" of the Grampian APWP. Younger poles from the block are reported from the Foyers Old Red Sandstone (recalculated from Kneen, 1973) and Peterhead dolerite (Torsvik, 1985 a) and are attributed Lower Carboniferous and Permo - Carboniferous magnetic ages respectively (see Torsvik *et al.* 1988).

GRAMPIAN HIGHLANDS.

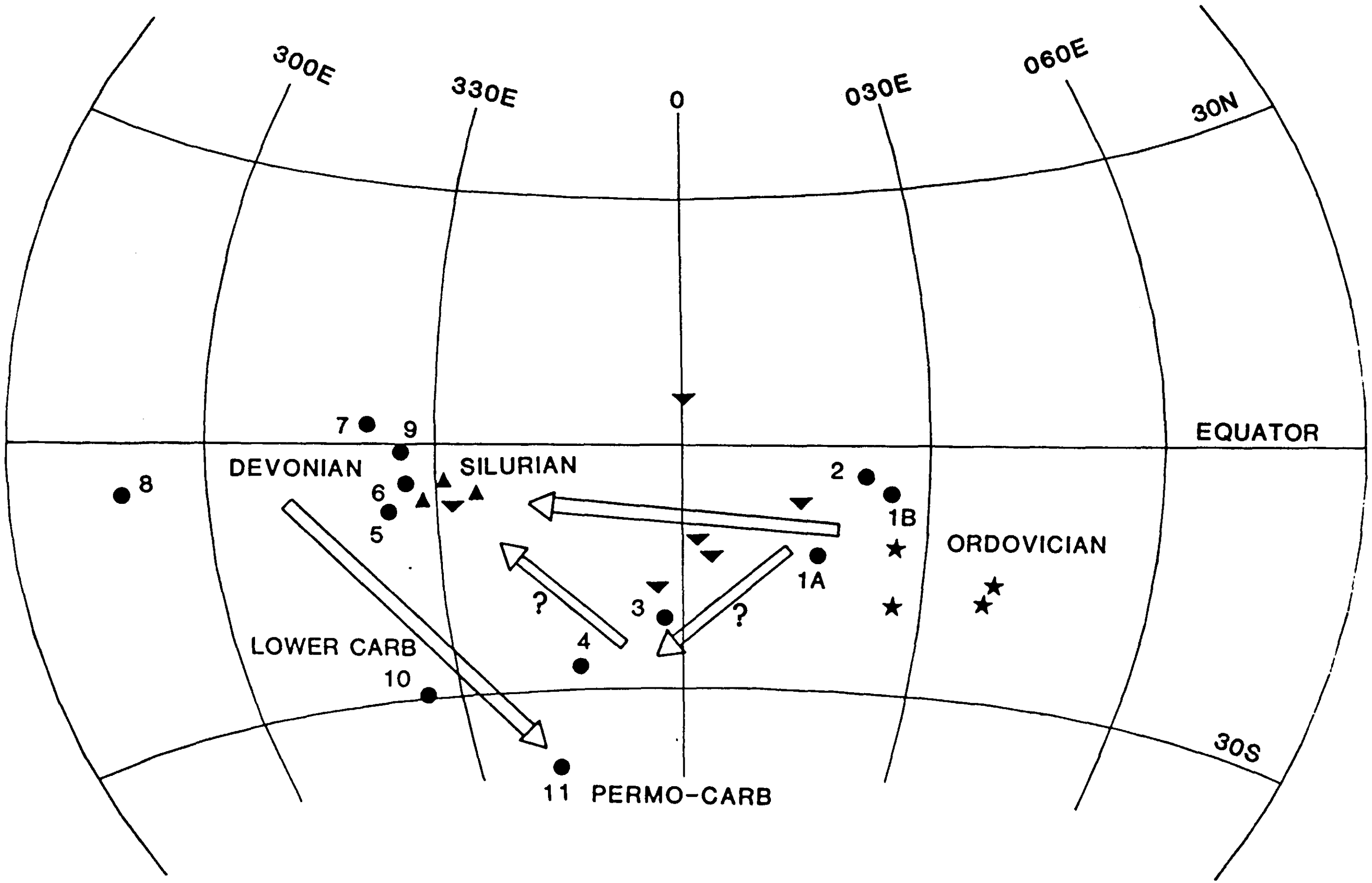


FIGURE 8.2 : GRAMPIAN TERRANE APWP.

All poles are listed numerically in Table 8.1. Poles are plotted in Lambert equal area projection.

Site means from the Aberdeenshire gabbros (Watts & Briden, 1984) are indicated by stars, inverted triangles or upright triangles dependent on whether K-Ar cooling ages are >463, 463-443 or <443 Ma respectively.

8.3 MIDLAND VALLEY.

Palaeozoic palaeomagnetic data for the Midland Valley are plotted in Figure 8.3. The majority of studies come from Devonian and Carboniferous strata which outcrop over most of the region.

The Ordovician segment of the APWP relies exclusively on data from the Arenig Ballantrae Ophiolite Complex exposed in the southwest of the Midland Valley. Nesbitt (1967) and Piper (1978) first reported remanence data from the Slockenray Lavas, Byne Hill Gabbro and serpentinites of the complex, recovered magnetisations being interpreted to post-date obduction.

The Slockenray Lavas have here been shown to actually possess a pre-obduction remanence (Chapter 4). This is fortuitously aligned, in situ, close to what was presumed an Ordovician field direction by the previous workers. The lava data cannot constrain the post-docking history of the Ballantrae and Midland Valley blocks but in itself defines the complex as a terrane element in palaeomagnetic terms.

The non-Fisherian remanence distribution from the Byne Hill Gabbro (Piper, 1978., Figure 4.14) has been noted and accordingly questioned as recording a single palaeo-field. (The gabbro pole is therefore omitted from Figure 8.3).

The results from the Ballantrae serpentinite (Piper, 1978) form a Fisherian distribution, yield consistent directions over several kilometres of outcrop, and therefore do not appear internally deformed by Caledonian deformation. The remanence most probably dates from magnetite generation upon serpentinisation. This took place during late syn- to post-obduction of the ophiolite (Holub *et al.* 1984), and hence the serpentinites are tentatively interpreted to record an Ordovician field.

As for the Grampian data, a late Silurian - early Devonian "corner" in the APWP can be recognised. The "corner" is defined by results from the Strathmore Lavas (Crawton and Arbuthnott Groups., Torsvik, 1985b., Dunottar -Strathmore Groups., Sallomy and Piper, 1973) and Glenbervie Porphyry (Chapter 7).

Poles plotting along the Ordovician to Siluro-Devonian swathe are yielded by two sites in the basal Stonehaven Group (numbers 31 and 32, Figure 8.3) originally regarded as anomalous by Sallomy and Piper (1973) but proving broadly consistent between lava and enclosing sediment. Whether these results actually record a segment of APW, reflect intra-basin tectonic rotation or record subsequent remagnetisation is as yet unclear. The results should be presently be treated cautiously particularly given the accepted levels of laboratory treatment prevailing at the time of their original study.

Younger palaeomagnetic poles for the Midland Valley are derived from the extensive Lower Carboniferous Lavas (Wilson and Everitt, 1963., Torsvik *et al.* 1988),

MIDLAND VALLEY

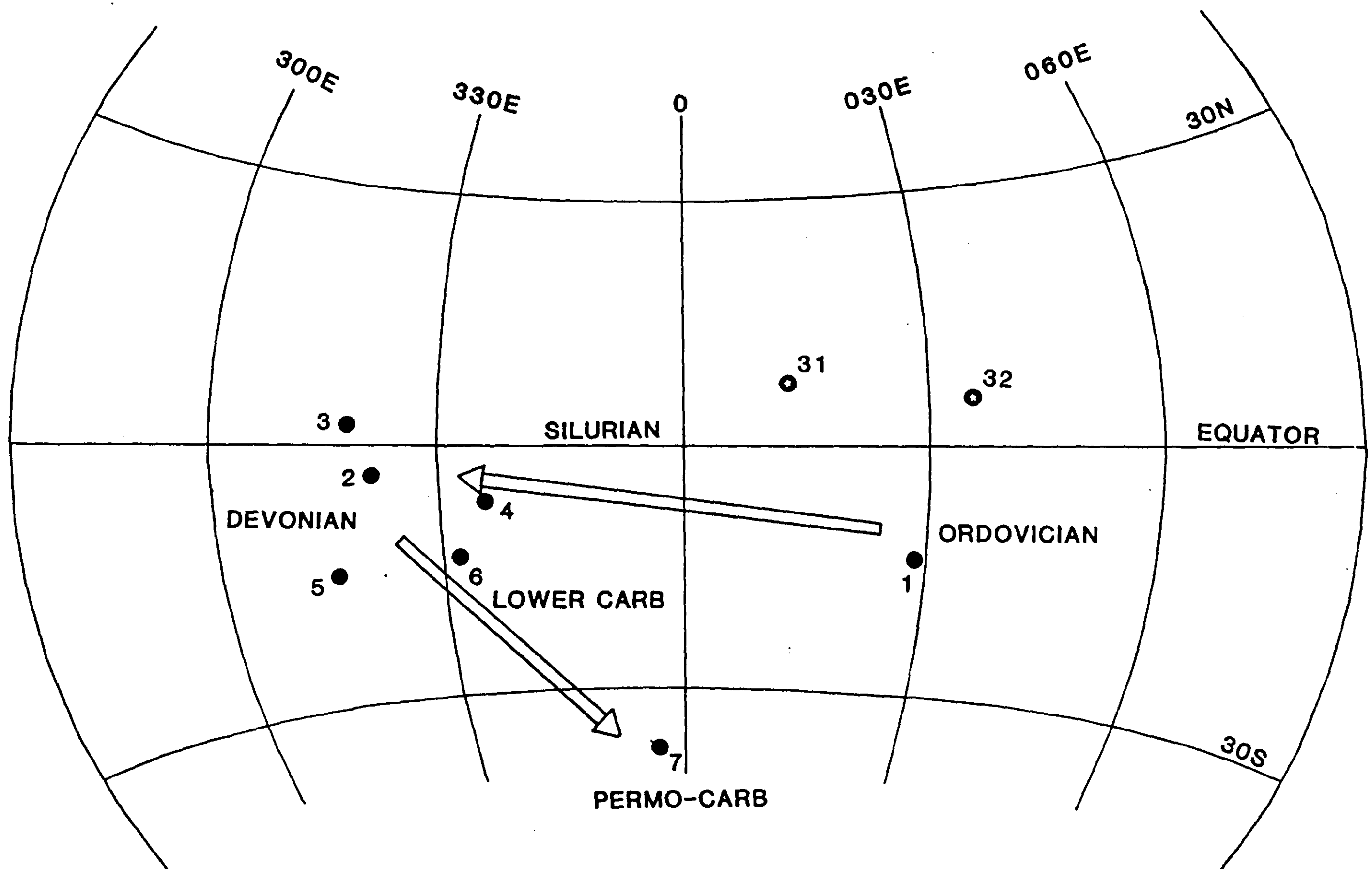


FIGURE 8.3 : MIDLAND VALLEY TERRANE APWP.
Stonehaven Group site means (31 & 32 of Sallomy & Piper, 1973) are indicated by encircled stars.

remagnetisations from the Strathmore Basin (Torsvik, 1985b), and the Permo-Carboniferous Queensferry sill (Torsvik *et al.* 1988).

8.4 SOUTHERN UPLANDS.

Palaeomagnetic coverage of the Southern Uplands block is particularly poor and hence its APWP is accordingly only loosely constrained (Figure 8.4). Data are insufficient to attempt further subdivision of the block as has been suggested on geological grounds (Anderson and Oliver, 1986).

The single Ordovician determination comes from five sites in the Caradocian Bail Hill Volcanics (Piper, 1978) which yield a palaeomagnetic pole at 347.5°E, 32.5°S after tectonic correction. Elsewhere in the northern belt,greywackes have thus far failed to reveal the presence of a stable remanence (Floyd and Trench, 1988). The corrected Bail Hill result plots close to the Carboniferous-Permian "back tracking" of the Midland Valley and Grampian paths but is precluded from representing an Upper Palaeozoic overprint due to the Lower Palaeozoic deformation age. The in-situ Bail Hill site means lie close to a present day field however, and recent field overprinting cannot be excluded.

If the Bail Hill remanence is Ordovician in age, then a near equatorial palaeo-latitude is implied for the Southern Uplands terrane contrasted with (?) coeval low southerly latitudes for the Grampian Highlands and Midland Valley. Given the errors within the datasets, this may be explained by a strike-slip shuffling of terranes along the southern Laurentian margin. Further work is required before a suggestion of this type could be adopted with any certainty.

The late Silurian-early Devonian "corner" to the APWP is again evident delineated by results from a Siluro-Devonian lamprophyre intruding the St Abbs Head Volcanics (Chapter 6), the Cheviot Granite and the Cheviot Lavas (Thorning, 1974). The Cheviot Lavas can be regarded as an overstep sequence and thus constrain the timing of collision across the Iapetus Suture (Soper *et al.* 1987). A younger pole from the Permian red beds of Dumfries (Manlanyj and Collinson, 1988) is also plotted to again illustrate the back tracking of the APWP.

SOUTHERN UPLANDS.

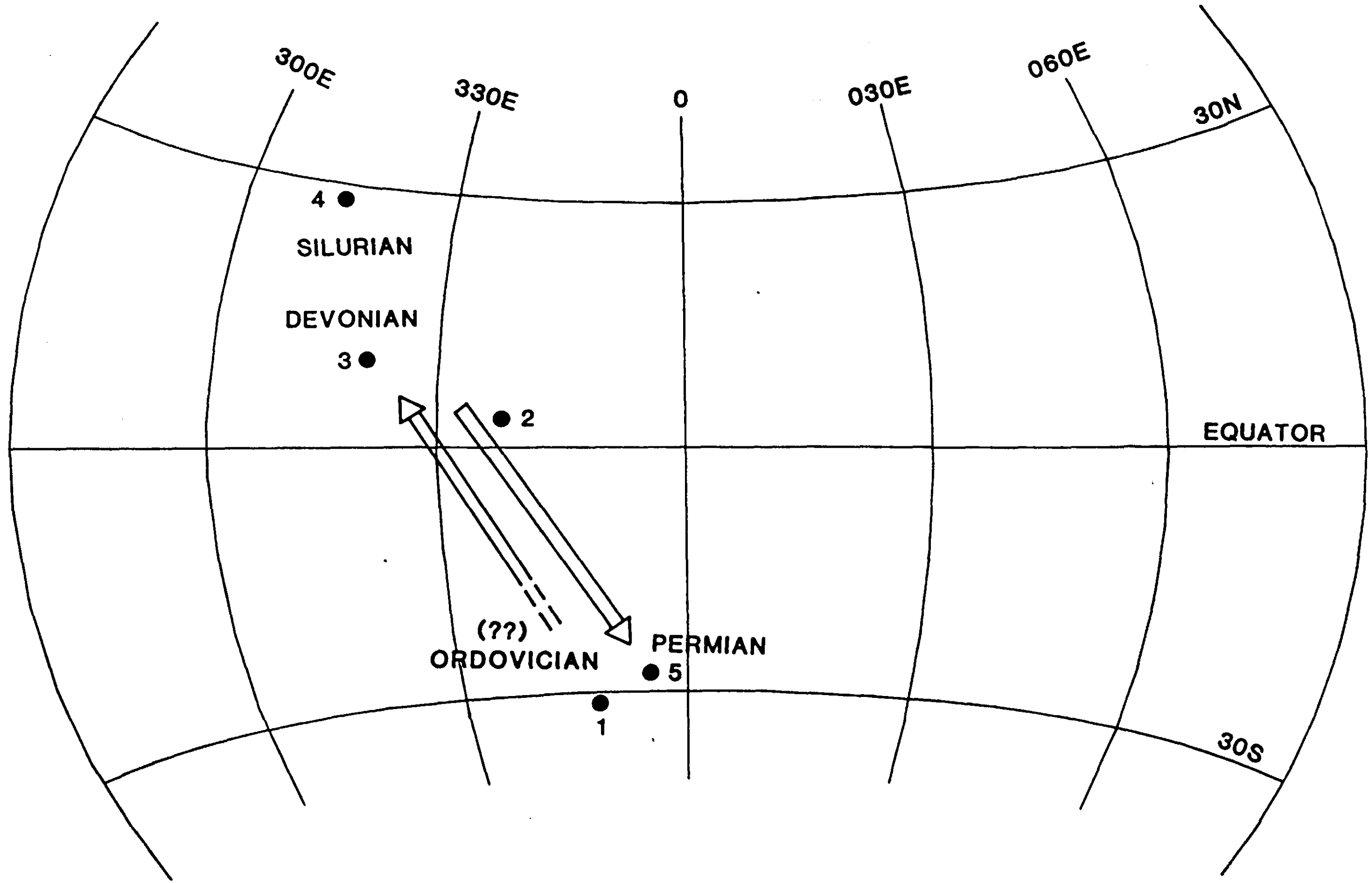


FIGURE 8.4 : SOUTHERN UPLANDS TERRANE APWP.

NRM data from Nairn (1960) has been omitted as no cleaning was performed but is consistent with the described path.

8.5 DISCUSSION & CONCLUSIONS.

The proposal of Piper (1987, p. 259-270) that northern Britain was sited (along with southern Britain and Armorica) close to the magnetic pole during late Ordovician times has not been commented upon. This is because there is as yet no palaeomagnetic evidence from either the Grampian, Midland Valley or Southern Uplands in support of this hypothesis, the only "steep" inclination result north of the Iapetus Suture being an overprint magnetisation from the Unst Ophiolite in Shetland (Taylor, 1988). It remains to be seen whether evidence will accrue in later studies and at present it is regarded as speculative.

Due to the construction of APWP's on terrane rather than continental scale, a paucity of available data results in some instances (notably for the Southern Uplands). With this in mind, every effort to outline the assumptions and limitations of the arguments presented here has been made. Particularly, since the errors in the locations of the palaeomagnetic poles are usually in the order of several hundred kilometres, the APWP cannot constrain small relative movements between terranes.

Despite this, several important conclusions result from inspection of the determined terrane APWP's (Figures 8.2, 8.3, 8.4):

1) The Grampian Highlands, Midland Valley and (?) Southern Uplands terranes were all positioned at low southerly latitudes in Ordovician times. This accords with a tectonic position at or close to the southern Laurentian margin (see Figure 4.16). There is at present no evidence to support any movement of northern British terranes into higher latitudes. Relative movement between terranes suggested by both geological (Bluck, 1985), and geophysical evidence (Dentith *et al.* 1988) must have occurred predominantly in palaeolongitude; i.e. approximately parallel to the Laurentian margin.

2), The Grampian, Midland Valley and possibly Southern Uplands share a broadly similar anti-clockwise rotation history about local axes prior to late Silurian times (although absolute time constraints on this are presently poor). The elucidation of terrane rotation histories adjacent to Laurentia may yield important information concerning the sense of oblique closure of Iapetus (cf. Beck, 1976., 1980., for the Western Cordilleran margin). Better age calibration of the paths is required before reliable net rotations with respect to the craton can be calculated but recent studies attest at least to the presence of rotated blocks (e.g. Chapter 4., Smethurst & Briden, 1988).

3), The identification of the late Silurian-early Devonian "corner" in the APWP of each terrane suggests that they had impinged upon each other by this time (to within the individual errors of the palaeomagnetic poles). The similarity of palaeo-declination with the trend of the Highland Boundary and Southern Uplands Faults tightens this constraint. For the Grampian and Midland Valley blocks, consistency in palaeo-latitude determinations from the Loch Lintrathen and Glenbervie Porphyries (Chapter 7) supports their proposed correlation. Relative translation and/or shortening across the Highland Border during the Acadian Orogeny cannot therefore exceed the former geometry of the ignimbrite(s).

4), A common 'back tracking' of the APWP's confirms the terranes to have behaved as essentially a single unit from Carboniferous times. Overprint magnetisations recovered both at St.Abbs Head (Chapter 6) and from the Loch Lintrathen and Glenbervie porphyries (Chapter 7) are consistent with the 'back tracking' of the now singular APWP.

8.6 RECOMMENDATIONS FOR FUTURE WORK.

Funding is available from the Natural Environment Research Council (NERC) to conduct a two year project aimed at the elucidation of terrane rotation histories within the Scottish paratectonic Caledonides (see conclusion 2 of 8.5). Research work will be centred within the Ordovician Highland Border Complex terrane (HBC) particularly for sections at Stonehaven, North Esk and Arran. Emphasis will be placed on the performance of field stability tests wherever possible. Central aims of the research are presently seen as follows:

i) To record rotational events affecting both primary and overprint magnetisation components identified for each terrane section. These will then be evaluated by use of structural models to explain detected block rotations.

ii) Determination of the number of separate terrane elements presently preserved in the Highland Border region. To document the nature and timing of overprinting for each section and to ascertain whether tectonic elements acquired a common overprint record.

iii) Provision of palaeolatitudinal information for each of the tectonostratigraphic elements of the HBC. There is presently a paucity of stratigraphically constrained Ordovician results to the north of the Solway Line and the work should make a valuable contribution in this context.

iv) Inferences from (i) to (iii) will be combined to create a quantitative palaeotectonic model for the evolution of the HBC both with respect to other 'British' terranes and as an indicator of former tectonic processes operating both within and marginal to the Iapetus Ocean.

CHAPTER 8 : REFERENCES.

Anderson, T.B. and Oliver, G.J.H. 1986. The Orlock Bridge Fault: A major Late Caledonian sinistral fault in the Southern Uplands Terrane, British Isles. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* 77, 203-222.

Bluck, B.J. 1985. The Scottish paratectonic Caledonides. *Scottish Journal of Geology,* 21, 437-464.

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, 457-470.

Briden, J.C., Turnell, H.B. and Watts, D.R. 1984. British palaeomagnetism, Iapetus Ocean and the Great Glen fault. *Geology* , 12, 428-431.

Briden, J.C., Turnell, H.B. and Watts, D.R. 1986. Reappraisal of Scottish Ordovician palaeomagnetism: Reply to Storetvedt and Deutsch. *Geophysical Journal of the Royal Astronomical Society.* 87, 1207-1213.

Dentith, M.C., Trench, A., Bluck, B.J. and Floyd, J.D. 1988. Geophysical Constraints on terrane models of the Scottish Caledonides : (I), Deep Structure. (submitted to *Journal of the Geological Society, London*).

Dewey, J.F. and Pankhurst, R.J. 1970. The evolution of the Scottish Caledonides in relation to their isotopic age pattern. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* 68, 351-389.

Floyd, J.D. and Trench, A. 1988. Magnetic susceptibility contrasts in Ordovician greywackes of the Southern Uplands of Scotland. *Journal of the Geological Society, London.* in press.

Harte, B., Booth, J.E., Dempster, T.J., Fettes, D.J., Mendum, J.R. and Watts, D. 1984. Aspects of post-depositional evolution of Dalradian and Highland Border Complex rocks in the Southern Highlands of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* 75, 151-163.

Holub, F.V., Klapova,H., Bluck, B.J. and Bowes,D.R. 1984. Petrology and geochemistry of post-obduction dykes of the Ballantrae Complex, SW Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* 75, 211-223.

Kneen, S., 1973. The palaeomagnetism of the Foyers Plutonic Complex, Inverness-shire. *Geophysical Journal of the Royal Astronomical Society,* 32, 53-63.

Latham, A.G. and Briden, J.C. 1975. Palaemagnetic field directions in the Siluro-Devonian lavas of the Lorne Plateau, Scotland and their regional significance. *Geophysical Journal of the Royal Astronomical Society.* 43, 243-252.

Maslanyj, P.M. and Collinson, D.W. 1988. A magnetic and petrological study of some Permian aeolian red sandstones. *Geophysical Journal,* 92, 421-430.

Nairn, A.E.N. 1960. Palaeomagnetic results from Europe. *Journal of Geology,* 68, 285-306.

Nesbitt, J.D., 1967. Palaeomagnetic evidence for the Ordovician geomagnetic pole position, *Nature* , 216, 49-50.

Piper, J.D.A. 1978. Palaeomagnetism and palaeogeography of the Southern Uplands block in Ordovician times. *Scottish Journal of Geology.* 14, 93-107.

Piper, J.D.A., 1987. *Palaeomagnetism and the Continental Crust,* Open University Press, Milton Keynes.

Sallomy, J.T. and 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.

Soper, N.J., Webb, B.C. and Woodcock, N.H. 1987. Late Caledonian (Acadian) transpression in north-west England: timing, geometry and geotectonic significance. *Proceedings of the Yorkshire Geological Society.* 46, 175-192.

Stephens, W.E. and Halliday, A.N. 1984. Geochemical contrasts between the late Caledonian granitoid plutons of northern, central and southern Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* 75, 259-273.

Storetvedt, K.M. and Deutsch, E.R. 1986. Reappraisal of Scottish Ordovician palaeomagnetism, *Geophysical Journal of the Royal Astromonical Society.* 87, 1193-1206.

Stupavsky, M., Symons, D.T.A. and Gravenor, C.P. 1982. Evidence for metamorphic remagnetisation of Upper Precambrian tillite in the Dalradian Supergroup of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* 73, 59-65.

Tarling, D.H. 1974. A palaeomagnetic study of Eocambrian tillites in Scotland. *Journal of the Geological Society, London.* 130, 163-177.

Tarling, D.H. 1985. Palaeomagnetic studies of the Orcadian Basin. *Scottish Journal of Geology.* 21, 261-273.

Taylor, G.K. 1988. A palaeomagnetic study of a Caledonian ophiolite. *Geophysical Journal.* 94, 157-167.

Thirlwall, M.F. 1983. Isotope geochemistry and origin of calc-alkaline lavas from a Caledonian continental margin volcanic arc. *Journal of Volcanology and Geothermal research,* 18, 589-631.

Thorning, L. 1974. Palaeomagnetic results from the Lower Devonian rocks of the Cheviot Hills. Northern England. *Geophysical Journal of the Royal Astronomical Society.* 36, 487-496.

Torsvik, T.H. 1984. Palaeomagnetism of the Foyers and Strontian granites, Scotland. *Physics of the Earth & Planetary Interiors.* 36, 163-177.

Torsvik, T.H. 1985a. Palaeomagnetic results from the Peterhead granite, Scotland; implication for regional late Caledonian magnetic overprinting. *Physics of the Earth & Planetary Interiors.* 39, 108-117.

Torsvik, T.H. 1985b. Magnetic properties of the Lower Old Red Sandstone lavas in the Midland Valley, Scotland; palaeomagnetic and tectonic considerations. *Physics of the Earth & Planetary Interiors.* 39, 194-207.

Torsvik, T.H., Lyse, O., Atteras, G., and Bluck, B. 1988. Palaeozoic palaeomagnetic results from Scotland and their bearing on the British apparent polar wander path. *Physics of the Earth & Planetary Interiors,* in press.

Turnell, H.B. 1985. Palaeomagnetism and Rb-Sr ages of the Ratagan and Comrie intrusions. *Geophysical Journal of the Royal Astronomical Society,* 83, 363-78.

Watts, D.R. 1985. Palaeomagnetic resetting in the Barrovian zones of Scotland and its relationship to the late structural history. *Earth & Planetary Science Letters,* 75, 258-264.

Watts, D.R. and Briden, J.C. 1984. Palaeomagnetic signature of slow post-orogenic cooling of the north-east Highlands of Scotland recorded in the Newer Gabbros of Aberdeenshire. *Geophysical Journal of the Royal Astronomical Society.* 77,775-788.

Wilson, R.L. and Everitt, C.W.F. 1963. Thermal demagnetization of Carboniferous lavas for palaeomagnetic purposes. *Geophysical Journal of the Royal Astronomical Society.* 8, 149-164.

APPENDIX A : LINEFIND DETERMINATIONS.

EXPLANATION OF APPENDIX A TABLE FORMAT.

LINEFIND (Kent *et al.* 1983) determinations have been grouped under the appropriate chapter headings with subheadings having been used to delineate either a particular group of sites or a stated magnetisation component.

Column headings are as follows from left to right hand side of the tabled pages.

1) Palaeomagnetic sampling site names.
2) Sample number.
3/4) Strike and dip of strata used in the tectonic correction of a given site. Dip directions are always given 90° clockwise of the strike azimuth.
5) Laboratory treatment. A; Alternating Field., T; Thermal., AT; Combined.
6/7) Treatment interval over which LINEFIND segment is 'picked'. Treatments are given in degrees Celcius (T) or millaTesla (A). The point at the origin is denoted as 999. dashes in the case of the Slockenray and Benan Conglomerates indicate combination of samples from a given clast to give a 'clast mean' which is quoted.
8/10) Declination/Inclination of the LINEFIND determination.
9/11) Determined errors of 8 & 10 respectively.
12) RHO parameter used in the LINEFIND computation.

APPENDIX A: LINEFIND DETERMINATIONS.

CHAPTER 4: BALLANTRAE OPHIOLITE.

SLOCKENRAY FORMATION. COMPONENT (M) IN SITU.

TSR1	TSR1.1	226.5	86.0	T	207	999	156.9	1.4	56.3	0.8	0
TSR1	TSR1.2	226.5	86.0	T	214	999	149.2	1.0	29.5	0.9	0
TSR1	TSR1.3	226.5	86.0	T	333	999	150.5	5.2	45.8	3.6	0
TSR1	TSR1.4	226.5	86.0	T	50	900	152.7	5.2	41.6	3.9	0
TSR1	TSR1.5	226.5	86.0	T	200	1000	142.8	7.2	44.1	5.2	0
TSR2	TSR2.1	226.5	86.0	T	207	999	156.6	1.3	37.4	1.0	0
TSR2	TSR2.2	226.5	86.0	T	214	999	163.7	0.8	9.4	0.8	0
TSR2	TSR2.3	226.5	86.0	T	214	999	159.1	0.8	20.8	0.7	0
TSR2	TSR2.4	226.5	86.0	T	333	999	149.4	1.9	31.2	1.6	0
TSR2	TSR2.5	226.5	86.0	A	0	999	150.4	2.6	35.7	2.1	0
TSR2	TSR2.6	226.5	86.0	A	100	1000	153.2	2.9	26.0	2.6	0
TSR3	TSR3.1	226.5	86.0	T	291	560	141.0	5.5	42.0	4.1	0
TSR3	TSR3.2	226.5	86.0	T	214	559	147.5	2.6	35.4	2.1	0
TSR3	TSR3.3	226.5	86.0	T	333	559	146.2	2.8	34.6	2.3	0
TSR3	TSR3.4	226.5	86.0	T	333	559	149.6	4.7	30.5	4.1	0
TSR3	TSR3.5	226.5	86.0	A	200	800	139.3	6.9	48.1	4.6	0
TSR3	TSR3.6	226.5	86.0	A	100	1000	141.2	5.9	50.0	3.8	0
TSR5	TSR5.1	256.0	83.0	T	207	560	210.1	2.7	-5.8	2.6	0
TSR5	TSR5.2	256.0	83.0	T	359	545	216.0	2.5	21.4	2.4	0
TSR5	TSR5.3	256.0	83.0	T	243	534	198.4	3.0	-0.3	3.0	0
TSR5	TSR5.4	256.0	83.0	T	243	500	198.3	3.3	-12.7	3.2	0
TSR5	TSR5.5	256.0	83.0	A	50	400	198.4	5.6	5.3	5.5	0
TSR6	TSR6.1	260.5	87.0	T	207	496	205.9	4.1	-4.6	4.0	1.0
TSR6	TSR6.2	260.5	87.0	T	181	534	225.9	3.7	-14.9	3.6	0.8
TSR6	TSR6.3	260.5	87.0	T	359	500	219.6	10.7	35.9	8.6	1.0
TSR6	TSR6.4	260.5	87.0	A	85	999	209.2	2.1	-0.2	2.1	1.0
TSR6	TSR6.5	260.5	87.0	A	50	999	206.3	4.0	20.5	3.8	0.3
TSR6	TSR6.6	260.5	87.0	A	175	300	193.3	8.4	30.5	7.2	0.2
TSR7	TSR7.1	207.5	72.5	T	207	496	155.9	3.6	10.2	3.5	0.6
TSR7	TSR7.2	207.5	72.5	T	181	534	169.7	3.2	21.9	3.0	1.0
TSR7	TSR7.3	207.5	72.5	T	359	534	161.0	2.3	20.0	2.1	0.4
TSR7	TSR7.4	207.5	72.5	T	359	534	156.6	4.1	8.1	4.1	1.0
TSR7	TSR7.5	207.5	72.5	A	100	500	176.6	5.3	23.0	4.9	1.0
TSR7	TSR7.6	207.5	72.5	A	100	325	170.3	3.5	8.4	3.5	0.6
TSR8	TSR8.1	213.5	80.0	T	131	999	187.3	3.0	-10.2	3.0	1.0
TSR8	TSR8.2	213.5	80.0	T	131	505	174.1	2.4	-13.0	2.3	1.0
TSR8	TSR8.3	213.5	80.0	T	131	445	173.8	3.5	-5.6	3.4	1.0
TSR8	TSR8.4	213.5	80.0	T	131	445	161.6	5.6	0.0	5.6	0.4
TSR8	TSR8.5	213.5	80.0	A	225	700	175.0	10.1	16.8	9.7	1.0
TSR8	TSR8.6	213.5	80.0	A	225	650	185.9	7.2	-1.4	7.2	1.0
PILLOW1	PL1	224.0	68.0	T	0	548	161.8	1.0	10.6	1.0	0.4
PILLOW1	PL2	224.0	68.0	A	75	999	161.1	5.0	8.2	4.9	1.2
PILLOW1	PL3	224.0	68.0	A	50	900	173.2	5.7	9.3	5.6	1.6

APPENDIX A: LINEFIND DETERMINATIONS.

PILLOW1	PL4	224.0	68.0	T	174	503	170.6	7.1	-4.3	7.1	0.8
PILLOW1	PL5	224.0	68.0	T	174	531	164.1	8.9	-0.8	8.9	1.2
PILLOW1	PL6	224.0	68.0	T	239	517	173.6	4.8	12.5	4.6	0.8
PILLOW1	PL7	224.0	68.0	T	164	999	169.4	2.5	8.8	2.5	1.0
PILLOW1	PL8	224.0	68.0	A	175	450	168.2	7.6	21.5	7.1	1.8
PILLOW1	PL9	224.0	68.0	T	468	531	146.1	5.3	21.3	4.9	0.6
PILLOW1	PL10T	224.0	68.0	A	100	500	166.3	6.9	17.9	6.6	1.0
PILLOW1	PL10B	224.0	68.0	T	164	520	183.5	5.1	7.6	5.1	0.8
PILLOW2	PL11	224.0	68.0	T	381	552	176.6	2.5	10.7	2.4	0.9
PILLOW2	PL12	224.0	68.0	A	100	350	175.1	3.0	15.4	2.9	0.2
PILLOW2	PL13	224.0	68.0	T	164	999	178.3	2.6	13.9	2.5	0.8
PILLOW2	PL14	224.0	68.0	T	164	481	189.5	5.3	6.5	5.2	0.6
PILLOW2	PL15	224.0	68.0	T	164	520	174.2	5.8	2.8	5.8	0.6
PILLOW2	PL16	224.0	68.0	A	100	999	174.3	3.6	10.2	3.6	0.6
PILLOW2	PL17	224.0	68.0	T	164	520	161.6	1.6	15.3	1.5	0.6
PILLOW2	PL18	224.0	68.0	T	0	520	166.3	2.3	13.2	2.2	0.8
PILLOW3	PL19	217.5	74.5	T	392	503	165.4	7.5	18.5	7.1	0.6
PILLOW3	PL20	217.5	74.5	A	50	400	186.0	3.6	-3.5	3.6	0.8
PILLOW3	PL21	217.5	74.5	T	174	503	185.9	6.4	17.9	6.1	1.0
PILLOW3	PL22	217.5	74.5	T	174	531	203.6	1.7	1.2	1.7	0.4
PILLOW3	PL23	217.5	74.5	A	150	450	183.3	2.0	1.6	2.0	0.8
PILLOW3	PL24	217.5	74.5	T	392	531	199.4	1.9	2.3	1.9	1.0
PILLOW3	PL25	217.5	74.5	T	174	999	192.0	1.3	-7.3	1.3	0.6
BOL1	BOL1.1	214.5	80.0	T	608	636	187.4	10.6	4.8	10.5	1.0
BOL1	BOL1.2	214.5	80.0	T	158	636	216.1	1.6	18.4	1.5	0.8
BOL1	BOL1.3	214.5	80.0	T	158	608	220.7	1.6	-6.9	1.6	1.0
BOL1	BOL1.4	214.5	80.0	T	158	562	208.4	4.0	12.5	4.0	1.0
BOL1	BOL1.5	214.5	80.0	A	100	999	209.7	2.2	12.1	2.2	0.8
BOL1	BOL1.6	214.5	80.0	A	400	999	197.5	3.5	15.6	3.4	1.0
BOL2	BOL2.1	201.5	95.0	A	200	999	92.4	2.4	36.6	1.9	1.0
BOL2	BOL2.2	201.5	95.0	T	0	596	134.8	2.3	20.5	2.2	1.0
BOL2	BOL2.3	201.5	95.0	T	182	999	156.2	2.4	-5.1	2.4	0.8
BOL2	BOL2.4	201.5	95.0	T	216	999	139.5	1.1	29.4	1.0	0.6
BOL2	BOL2.5	201.5	95.0	T	177	999	128.6	1.5	29.5	1.3	1.2
BOL2	BOL2.6	201.5	95.0	T	323	999	110.3	1.1	44.2	0.8	1.0
BOL2	BOL2.7	201.5	95.0	T	0	999	125.6	0.7	29.0	0.6	0.6
BOL3	BOL3.1	201.5	90.0	T	323	999	132.5	1.8	40.0	1.4	1.0
BOL3	BOL3.2	201.5	90.0	T	637	999	110.3	106.6	85.8	7.8	1.2
BOL3	BOL3.3	201.5	90.0	T	394	999	149.3	3.9	40.6	3.0	1.0
BOL3	BOL3.4	201.5	85.0	T	276	999	119.5	2.0	44.9	1.4	0.7
BOL3	BOL3.5	201.5	85.0	T	216	999	125.6	2.2	47.7	1.5	0.6
BOL3	BOL3.6	201.5	85.0	A	100	1000	116.3	3.4	51.3	2.1	0.8
BOL3	BOL3.8	201.5	85.0	A	100	999	115.1	1.5	48.4	1.0	0.4
BOL4	BOL4.1	201.5	85.0	T	395	596	173.8	13.9	79.5	2.5	1.0
BOL4	BOL4.2	201.5	85.0	T	475	596	152.2	11.5	69.4	4.1	1.0
BOL4	BOL4.3	201.5	85.0	T	345	596	139.2	15.4	79.3	2.9	1.2
BOL4	BOL4.4	201.5	85.0	T	395	596	145.1	14.9	75.5	3.7	1.4

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BOL4	BOL4.5	201.5	85.0	T	395	596	142.1	6.4	79.3	1.2	0.8
BOL4	BOL4.6	201.5	85.0	A	1000	999	130.2	15.0	65.6	6.2	1.4
BOL4	BOL4.7	201.5	85.0	A	1000	999	130.2	15.0	65.6	6.2	1.4

SLOCKENRAY CONGLOMERATE CLAST MEANS IN SITU.

TCC	TCC2.1	225.5	95.0	T	245	999	156.3	1.6	13.9	1.6	0.4
TCC	TCC3.6	226.0	64.0	A	50	400	175.7	1.2	-5.8	1.2	0.8
TCC	TCC4.1	225.5	95.0	A	125	350	143.6	3.7	21.5	3.4	0.6
TCC	TCC4.3	225.5	95.0	T	230	500	167.8	1.8	-2.4	1.8	0.8
TCC	TCC7.1	171.5	64.0	T	275	551	174.0	1.5	14.3	1.5	1.0
TCC	TCC7.2	171.5	64.0	A	85	425	157.7	1.7	47.6	1.2	0.4
TCC	TCC8.1	200.0	53.5	T	274	999	163.9	2.1	23.6	2.0	0.8
TCC	TCC8.3	200.0	53.5	A	50	500	169.8	2.8	57.9	1.5	0.6
TCC	TCC8.4	200.0	53.5	T	149	509	150.8	2.4	14.1	2.3	1.0
TCC	TCC8.5	200.0	53.5	A	75	500	144.9	3.1	31.9	2.6	1.2
TCC	TCC8.7	200.0	53.5	T	274	509	174.1	2.2	31.4	1.9	1.0
TCC	TSR4.1	211.5	52.0	T	207	496	153.8	2.1	8.3	2.0	0.0
TCC	TSR4.2	211.5	52.0	T	254	999	156.9	2.0	1.5	2.0	0.0
TCC	TCC1.10	225.5	95.0	A	350	585	197.7	11.1	44.9	7.9	0.0
TCC	TCC3/1	---	---	-	-	-	190.7	---	15.4	---	---
TCC	TCC3/2	---	---	-	-	-	189.8	---	14.7	---	---
TCC	TCC3/3	---	---	-	-	-	192.7	---	5.8	---	---
TCC	TCC5	---	---	-	-	-	157.2	---	5.2	---	---
TCC	TCC6	---	---	-	-	-	182.3	---	52.0	---	---

BENAN CONGLOMERATE CLAST MEANS IN SITU.

BCT	BCT1	---	---	-	-	-	69.4	---	23.6	---	---
BCT	BCT10.2	0.	0.	A	225	1000	317.1	6.0	-8.0	6.0	1.0
BCT	BCT11.1	0.	0.	A	0	400	110.1	7.6	57.4	4.1	1.8
BCT	BCT13.1	0.	0.	T	478	999	18.6	7.9	40.7	6.0	1.2
BCT	BCT14.2	0.	0.	T	0	478	87.6	25.2	70.6	8.4	0.8
BCT	BCT16	---	---	-	-	-	338.9	---	28.9	---	---
BCT	BCT17.1	0.	0.	A	0	825	339.9	17.7	73.0	5.2	1.4
BCT	BCT18.2	0.	0.	A	85	850	167.2	27.7	59.3	14.2	2.4
BCT	BCT19	---	---	-	-	-	344.1	---	62.1	---	---
BCT	BCT2	---	---	-	-	-	153.6	---	40.1	---	---
BCT	BCT20.1	0.	0.	A	50	575	278.6	4.8	39.3	3.7	0.8
BCT	BCT21	---	---	-	-	-	288.0	---	77.1	---	---
BCT	BCT22.1	0.	0.	A	50	999	26.5	9.1	70.0	3.1	0.8
BCT	BCT23	---	---	-	-	-	71.5	---	-16.5	---	---
BCT	BCT24	---	---	-	-	-	329.3	---	64.4	---	---
BCT	BCT3	---	---	-	-	-	311.4	---	-6.5	---	---
BCT	BCT4	---	---	-	-	-	322.9	---	63.0	---	---
BCT	BCT5	---	---	-	-	-	297.5	---	-5.9	---	---
BCT	BCT6	---	---	-	-	-	253.2	---	-14.5	---	---
BCT	BCT7	---	---	-	-	-	53.5	---	43.9	---	---

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BCT	BCT8.3	0.	0.	T	478	550	32.0	21.3	-20.3	20.0	0.6

CHAPTER 6: ST.ABBS HEAD VOLCANICS & SEDIMENTS.

FOLD TEST: COMPONENT (I) IN SITU. (SOUTH LIMB)

FDS3	FDS3.1	253.5	50.0	T	240	999	201.1	3.0	-39.8	2.3	1.0
FDS3	FDS3.10	253.5	50.0	T	370	686	204.9	3.5	-54.2	2.0	1.0
FDS3	FDS3.11	253.5	50.0	T	238	670	206.5	4.5	-55.3	2.5	1.0
FDS3	FDS3.2	253.5	50.0	T	326	670	210.1	3.9	-33.6	3.2	1.0
FDS3	FDS3.3	253.5	50.0	T	325	670	225.3	4.6	-50.2	2.9	1.0
FDS3	FDS3.4	253.5	50.0	T	236	999	206.7	5.1	-44.6	3.7	1.0
FDS3	FDS3.5	253.5	50.0	T	182	999	207.6	2.1	-57.3	1.1	0.5
FDS3	FDS3.6	253.5	50.0	T	238	999	209.8	3.0	-49.4	1.9	1.0
FDS3	FDS3.7	253.5	50.0	T	274	999	212.9	2.1	-47.8	1.4	0.8
FDS3	FDS3.8	253.5	50.0	T	236	999	212.7	3.3	-43.7	2.4	1.0
FDS3	FDS3.9	253.5	50.0	T	238	999	200.4	2.2	-46.2	1.5	1.0
FDS4	FDS4.1	253.5	50.0	T	0	999	190.6	2.5	-46.1	1.7	1.0
FDS4	FDS4.2	253.5	50.0	T	0	657	186.3	2.3	-48.9	1.5	1.0
FDS4	FDS4.3	253.5	50.0	T	0	999	176.0	2.0	-41.2	1.5	1.0
FDS4	FDS4.4	253.5	50.0	T	0	999	170.4	2.4	-46.8	1.7	1.0
FDS4	FDS4.5	253.5	50.0	T	0	999	204.0	4.1	-52.2	2.5	1.0
FDS4	FDS4.6	253.5	50.0	T	0	670	195.9	1.9	-51.3	1.2	1.0
FDS4	FDS4.7	253.5	50.0	T	603	670	184.1	5.0	-47.2	3.4	1.0
FDS5	FDS5.1	253.5	50.0	T	0	999	208.1	1.7	-32.2	1.4	0.8
FDS5	FDS5.2	253.5	50.0	T	0	999	207.3	5.1	-31.2	4.4	1.0
FDS5	FDS5.3	253.5	50.0	T	0	999	202.6	1.8	-44.0	1.3	1.0
FDS5	FDS5.4	253.5	50.0	T	0	637	206.7	1.5	-42.4	1.1	1.0
FDS5	FDS5.5	253.5	50.0	T	0	999	204.0	1.4	-41.1	1.0	1.0
FDS5	FDS5.6	253.5	50.0	T	0	999	206.0	2.6	-42.2	1.9	1.0
FTS1	FTS1.2	239.0	72.0	T	555	999	197.9	3.3	-43.4	2.4	0.9
FTS1	FTS1.3	239.0	72.0	T	493	999	196.9	5.0	-43.4	3.6	0.6
FTS1	FTS1.4	239.0	72.0	T	338	999	184.0	4.2	-43.4	3.1	1.0
FTS1	FTS1.5	239.0	72.0	T	609	999	194.4	4.2	-40.4	3.2	1.0
FTS1	FTS1.6	239.0	72.0	T	410	657	178.4	5.2	-44.8	3.7	1.0
FTS2	FTS2.2	239.0	72.0	T	598	999	191.0	5.5	-40.2	4.2	1.0
FTS2	FTS2.3	239.0	72.0	T	268	649	191.9	3.8	-34.8	3.1	1.2
FTS2	FTS2.4	239.0	72.0	T	598	670	191.2	3.0	-38.6	2.4	1.0
FTS2	FTS2.5	239.0	72.0	T	550	670	190.8	5.2	-22.0	4.8	1.0
FTS2	FTS2.6	239.0	72.0	T	550	670	184.9	3.8	-44.5	2.7	0.6

FOLD TEST: COMPONENT (I) IN SITU. (NORTH LIMB)

LHL1	LHL1.1	32.0	30.5	T	556	999	208.4	3.3	-27.8	2.9	1.0
LHL1	LHL1.2	32.0	30.5	T	200	999	212.6	1.9	-23.8	1.7	1.0

APPENDIX A: LINEFIND DETERMINATIONS.

LHL1	LHL1.3	32.0	30.5	T	572	999	214.7	2.8	-24.6	2.5	1.0
LHL1	LHL1.4	32.0	30.5	T	572	999	215.2	2.1	-30.0	1.9	0.8
LHL1	LHL1.5	32.0	30.5	T	575	999	214.9	1.7	-28.8	1.5	0.4
LHL2	LHL2.1	32.0	30.5	T	308	664	208.6	1.4	-28.2	1.2	0.8
LHL2	LHL2.2	32.0	30.5	T	245	999	206.2	1.0	-29.1	0.9	0.6
LHL2	LHL2.3	32.0	30.5	T	307	664	212.1	1.5	-29.8	1.3	0.8
LHL2	LHL2.5	32.0	30.5	T	306	999	237.4	1.4	-36.1	1.2	0.6
LHL2	LHL2.6	32.0	30.5	T	370	999	210.1	1.0	-30.1	0.8	0.6
LHL2	LHL2.7	32.0	30.5	T	325	999	225.8	1.0	-24.7	0.9	0.6
LHL3	LHL3.1	32.0	30.5	T	239	999	209.1	0.9	-29.2	0.8	0.6
LHL3	LHL3.2	32.0	30.5	T	0	999	216.9	1.2	-26.1	1.0	0.6
LHL3	LHL3.3	32.0	30.5	T	316	664	203.3	1.1	-31.3	0.9	0.6
LHL3	LHL3.4	32.0	30.5	A	1000	999	212.7	1.4	-26.3	1.3	0.4
LHL3	LHL3.5	32.0	30.5	T	311	999	214.9	1.6	-30.3	1.4	1.0
LHL3	LHL3.6	32.0	30.5	T	425	999	219.6	2.0	-27.9	1.7	1.0
LHL3	LHL3.7	32.0	30.5	T	240	999	222.0	1.4	-28.7	1.2	1.0
LHL4	LHL4.1	32.0	30.5	T	438	664	217.6	1.5	-33.9	1.2	0.8
LHL4	LHL4.2	32.0	30.5	T	312	999	213.5	1.6	-35.2	1.3	0.8
LHL4	LHL4.3	32.0	30.5	T	485	999	216.8	1.9	-34.9	1.5	0.8
LHL4	LHL4.4	32.0	30.5	T	242	999	218.8	1.8	-34.8	1.5	1.0
LHL4	LHL4.5	32.0	30.5	T	488	999	215.3	2.1	-32.5	1.8	1.0
LHL4	LHL4.6	32.0	30.5	A	0	999	218.5	1.6	-40.5	1.2	1.0
LHL4	LHL4.7	32.0	30.5	T	490	655	219.7	3.4	-39.8	2.6	1.0
LHL4	LHL4.8	32.0	30.5	T	270	999	218.0	2.1	-41.6	1.6	0.8

SITE LHS1: ANOMALOUS COMPONENT, IN SITU.

LHS1	LHS1.1	32.0	30.5	T	75	525	159.4	4.5	-47.2	3.1	1.0
LHS1	LHS1.2	32.0	30.5	T	176	999	129.5	3.3	-44.7	2.4	1.0
LHS1	LHS1.3	32.0	30.5	T	0	999	154.6	11.9	-42.8	8.7	0.6
LHS1	LHS1.4	32.0	30.5	T	176	999	135.8	2.0	-41.9	1.5	1.0
LHS1	LHS1.5	32.0	30.5	A	0	775	132.2	5.7	-28.3	5.0	1.0
LHS1	LHS1.6	32.0	30.5	T	212	999	132.2	8.4	-45.8	5.8	0.4

VOLCANIC CONGLOMERATE: COMPONENT (I) IN SITU.

SAH10	SAH10.1	29.5	27.0	T	283	999	205.0	2.2	-36.4	1.7	0.4
SAH10	SAH10.2	29.5	27.0	T	284	999	245.3	1.1	-41.7	0.8	0.8
SAH11	SAH11.1	29.5	27.0	T	184	999	219.2	1.9	-35.0	1.6	1.0
SAH11	SAH11.2	29.5	27.0	T	377	999	219.2	1.8	-38.4	1.4	0.8
SAH12	SAH12.1	29.5	27.0	T	466	650	209.0	2.5	-38.9	2.0	1.0
SAH12	SAH12.3	29.5	27.0	T	176	999	206.4	2.1	-43.4	1.5	1.4
SAH13	SAH13.1	29.5	27.0	T	524	662	214.3	3.3	-34.3	2.8	1.0
SAH13	SAH13.2	29.5	27.0	T	540	999	210.3	1.0	-33.7	0.8	0.4

APPENDIX A: LINEFIND DETERMINATIONS.

SAH13	SAH13.3	29.5	27.0	T	283	656	209.6	2.1	-33.6	1.7	0.8
SAH14	SAH14.1	29.5	27.0	T	284	999	205.6	2.2	-34.4	1.8	1.0
SAH14	SAH14.2	29.5	27.0	T	283	999	199.2	2.7	-29.6	2.3	1.2
SAH15	SAH15.1	29.5	27.0	T	632	999	202.8	1.3	-40.6	1.0	0.6
SAH15	SAH15.2	29.5	27.0	T	475	999	195.1	2.6	-38.8	2.0	1.0
SAH16	SAH16.1	29.5	27.0	T	339	662	203.8	2.0	-40.7	1.5	0.8
SAH16	SAH16.2	29.5	27.0	T	377	999	202.3	1.7	-46.4	1.2	0.6
SAH17	SAH17.1	29.5	27.0	T	579	662	207.3	4.0	-45.4	2.8	1.0
SAH17	SAH17.2	29.5	27.0	T	283	999	207.9	1.5	-47.7	1.0	0.8
SAH5	SAH5.1	29.5	27.0	AT	150	750	199.2	4.7	-22.3	4.4	0.8
SAH5	SAH5.2	37.5	33.0	T	176	656	193.0	1.3	-26.7	1.2	0.6
SAH5	SAH5.3	37.5	33.0	AT	175	431	192.0	4.6	-25.2	4.1	1.4
SAH6	SAH6.1	37.5	33.0	T	176	999	196.6	2.4	-30.4	2.1	1.0
SAH6	SAH6.2	37.5	33.0	AT	150	525	200.9	7.1	-25.2	6.4	1.0
SAH7	SAH7.1	37.5	33.0	AT	100	999	196.1	9.6	-31.4	8.2	1.0
SAH7	SAH7.2	37.5	33.0	A	120	999	199.9	1.1	-31.1	0.9	0.6
SAH8	SAH8.1	37.5	33.0	AT	130	999	187.4	2.0	-23.8	1.8	1.2
SAH8	SAH8.2	37.5	33.0	AT	150	800	178.2	14.6	-19.1	13.8	1.2
SAH9	SAH9.1	37.5	33.0	A	100	999	191.5	3.3	-29.3	2.9	1.0

LAMPROPHYRE DYKE & MARGINS: COMPONENT (I) IN SITU.

KZ71	KZ71.1	29.5	27.0	AT	900	630	199.8	5.0	-36.5	4.0	0.8
KZ71	KZ71.10	29.5	27.0	T	278	649	201.1	7.7	-30.2	6.6	1.0
KZ71	KZ71.11	29.5	27.0	T	343	441	160.4	31.3	-52.5	19.0	0.6
Kz71	KZ71.12	29.5	27.0	T	597	999	200.6	18.2	-41.1	13.7	1.2
KZ71	KZ71.13	29.5	27.0	T	343	648	191.5	7.3	-37.9	5.7	0.8
KZ71	KZ71.14	29.5	27.0	T	272	648	198.8	4.0	-25.5	3.6	0.6
KZ71	KZ71.2	29.5	27.0	T	276	597	201.9	5.2	-46.0	3.6	0.8
KZ71	KZ71.3	29.5	27.0	T	275	648	193.0	3.0	-48.9	1.9	0.8
KZ71	KZ71.4	29.5	27.0	T	50	548	199.0	3.5	-37.9	2.7	1.0
KZ71	KZ71.6	29.5	27.0	AT	200	493	208.5	11.8	-26.7	10.5	1.0
KZ71	KZ71.7	29.5	27.0	AT	300	595	184.7	7.7	-39.7	5.9	1.0
KZ71	KZ71.8	29.5	27.0	T	407	650	187.1	4.9	-43.9	3.5	0.8
KZ72	KZ72.1	29.5	27.0	T	272	648	203.1	11.2	-24.6	10.2	1.4
KZ72	KZ72.2	29.5	27.0	T	238	650	187.3	5.4	-30.6	4.6	1.0
KZ72	KZ72.3	29.5	27.0	T	278	663	188.1	2.2	-38.8	1.7	0.8
KZ72	KZ72.4	29.5	27.0	T	276	500	187.4	7.9	-20.7	7.4	0.4
KZ72	KZ72.5	29.5	27.0	T	617	999	221.2	3.2	-48.6	2.1	1.0
KZ72	KZ72.6	29.5	27.0	T	546	999	197.3	3.0	-38.7	2.3	0.8
KZ72	KZ72.7	29.5	27.0	T	238	999	221.0	1.3	-35.7	1.1	0.6
KZ72	KZ72.8	29.5	27.0	T	0	999	210.0	1.2	-43.9	0.9	0.6
KZ72	KZ72.9	29.5	27.0	T	297	999	212.3	1.2	-42.1	0.9	0.8

APPENDIX A: LINEFIND DETERMINATIONS.

HORSECASTLE BAY LITHIC TUFFS: COMPONENT (I) IN SITU.

SAH1	SAH1.1	37.5	33.0	T	252	414	166.5	17.2	-36.1	13.9	0.8
SAH1	SAH1.5	37.5	33.0	T	312	609	139.7	7.4	-55.6	4.2	1.4
SAH1	SAH1.6	37.5	33.0	T	252	432	173.2	8.5	-31.3	7.2	0.8
SAH2	SAH2.1	37.5	33.0	T	269	484	203.2	7.6	-40.7	5.7	0.8
SAH2	SAH2.2	37.5	33.0	T	176	429	173.8	5.8	-30.5	5.0	0.8
SAH2	SAH2.3	37.5	33.0	AT	625	490	197.4	7.8	-33.9	6.5	1.2
SAH2	SAH2.4	37.5	33.0	T	366	551	167.8	13.4	-51.2	8.4	1.4
SAH2	SAH2.5	37.5	33.0	T	264	418	190.6	7.5	-34.3	6.2	1.0
SAH2	SAH2.6	37.5	33.0	T	252	338	192.8	17.6	-25.2	15.9	1.0
SAH2	SAH2.7	37.5	33.0	T	176	333	192.8	15.4	-27.6	13.6	1.4
SAH3	SAH3.1	37.5	33.0	A	200	625	188.2	12.7	-60.4	6.3	1.0
SAH3	SAH3.2	37.5	33.0	T	252	385	195.8	6.8	-29.1	5.9	1.0
SAH3	SAH3.3	37.5	33.0	T	252	385	184.6	7.5	-35.5	6.1	1.0
SAH3	SAH3.4	37.5	33.0	T	252	432	183.5	8.3	-45.3	5.8	1.0
SAH3	SAH3.5	37.5	33.0	T	252	470	181.8	8.3	-36.5	6.7	1.7
SAH3	SAH3.6	37.5	33.0	T	176	483	158.9	7.4	-16.1	7.1	1.5
SAH3	SAH3.7	37.5	33.0	T	265	485	225.0	9.1	-39.9	6.9	1.2
SAH4a	SAH4A.1	37.5	33.0	T	125	652	179.4	5.8	-43.2	4.2	1.4
SAH4	SAH4.2	37.5	33.0	T	302	385	186.3	28.0	-55.8	15.7	1.0
SAH4	SAH4.5	37.5	33.0	T	200	630	166.6	10.0	-55.2	5.7	1.4
SAH4	SAH4.6	37.5	33.0	T	252	338	187.5	22.0	-41.9	16.4	0.8

LAMPROPHYRE DYKE & MARGINS: COMPONENT (H) IN SITU.

KZ71	KZ71.1	29.5	27.0	AT	670	999	76.0	11.8	-30.6	10.2	0.8
KZ71	KZ71.11	29.5	27.0	T	371	999	103.8	4.3	-55.7	2.4	0.8
KZ71	KZ71.12	29.5	27.0	T	0	504	110.9	5.7	-47.7	3.9	1.2
KZ71	KZ71.13	29.5	27.0	T	648	999	108.0	9.4	-21.6	8.7	0.8
KZ71	KZ71.2	29.5	27.0	T	597	670	113.4	14.3	-60.8	7.0	0.8
KZ71	KZ71.3	29.5	27.0	T	648	999	106.6	14.3	-42.8	10.5	0.8
KZ71	KZ71.4	29.5	27.0	T	652	999	99.9	13.1	-40.9	9.9	1.0
KZ71	KZ71.6	29.5	27.0	AT	493	999	80.6	4.2	-49.1	2.8	1.0
KZ71	KZ71.7	29.5	27.0	AT	595	670	93.4	6.8	-49.0	4.5	1.0
KZ71	KZ71.8	29.5	27.0	T	730	999	33.6	19.3	-30.1	16.7	0.4
KZ72	KZ72.3	29.5	27.0	T	663	999	99.4	23.3	-50.2	14.9	0.8

HORSECASTLE BAY LITHIC TUFFS: COMPONENT (H) IN SITU.

SAH1	SAH1.1	37.5	33.0	T	414	657	105.7	4.9	-54.7	2.8	0.8
SAH1	SAH1.2	37.5	33.0	AT	1000	670	129.2	7.9	-46.0	5.5	0.8
SAH1	SAH1.6	37.5	33.0	T	470	613	123.8	4.8	-58.9	2.5	0.8
SAH2	SAH2.1	37.5	33.0	T	484	609	127.8	13.3	-55.8	7.5	0.8

APPENDIX A: LINEFIND DETERMINATIONS.

SAH2	SAH2.2	37.5	33.0	T	483	569	100.5	9.8	-44.1	7.1	0.8
SAH2	SAH2.3	37.5	33.0	AT	490	666	136.1	10.1	-55.6	5.7	1.2
SAH2	SAH2.4	37.5	33.0	T	551	999	116.4	6.4	-40.1	4.9	1.4
SAH2	SAH2.5	37.5	33.0	T	657	999	126.3	21.9	-58.5	11.4	1.0
SAH2	SAH2.6	37.5	33.0	T	338	540	146.4	9.1	-50.5	5.8	1.0
SAH2	SAH2.7	37.5	33.0	T	533	999	107.7	5.2	-46.8	3.6	1.4
SAH3	SAH3.2	37.5	33.0	T	385	584	162.4	6.5	-50.1	4.2	1.0
SAH3	SAH3.3	37.5	33.0	T	470	613	108.7	9.3	-50.8	5.9	1.0
SAH3	SAH3.4	37.5	33.0	T	613	665	82.6	14.0	-30.9	12.0	1.0
SAH3	SAH3.5	37.5	33.0	T	470	665	115.8	11.0	-51.1	6.9	1.7
SAH3	SAH3.6	37.5	33.0	T	483	604	92.1	12.8	-31.6	10.9	1.5
SAH3	SAH3.7	37.5	33.0	T	485	670	148.4	12.9	-56.1	7.2	1.2
SAH4a	SAH4A.1	37.5	33.0	T	652	670	103.6	25.5	-58.4	13.4	1.4
SAH4	SAH4.2	37.5	33.0	T	385	560	129.7	9.1	-57.2	4.9	1.0
SAH4	SAH4.6	37.5	33.0	T	338	504	118.9	13.1	-57.0	7.1	0.8

CHAPTER 7: LOCH LINTRATHEN & GLENBERVIE PORPHYRIES.

LOCH LINTRATHEN PORPHYRY: COMPONENT (S) IN SITU.

LP	L12a.10	305.6	21.1	T	206	456	169.0	22.7	-32.5	19.2	0.8
LP	L12a.2	305.6	21.1	T	279	408	180.9	46.6	-37.0	37.2	1.0
LP	L12a.4	305.6	21.1	T	232	435	182.4	21.1	-31.0	18.1	0.8
LP	L12a.6	305.6	21.1	T	203	435	173.2	15.8	-36.3	12.8	0.8
LP	L12a.7	305.6	21.1	T	203	408	175.5	29.5	-35.4	24.1	0.8
LP	L12a.8	305.6	21.1	T	178	408	171.9	33.2	-27.9	29.4	1.0
LP	L12a.9	305.6	21.1	T	203	435	172.0	25.1	-32.9	21.1	1.0
LP	LP12.1	305.6	21.1	T	209	450	187.5	14.5	-36.1	11.7	0.8
LP	LP12.2	305.6	21.1	T	182	426	175.0	14.4	-28.2	12.7	0.8
LP	LP17.3	305.6	21.1	T	224	429	187.7	24.7	18.9	23.3	0.8
LP	LP17.7	305.6	21.1	T	288	510	152.1	33.6	-36.5	27.0	1.0

LOCH LINTRATHEN PORPHYRY: COMPONENT (P) IN SITU.

LP	L12a.10	305.6	21.1	T	456	999	26.2	3.3	-26.4	2.9	0.8
LP	L12a.2	305.6	21.1	T	408	634	27.7	4.9	-28.3	4.3	1.0
LP	L12a.3	305.6	21.1	T	408	656	34.6	3.8	-22.2	3.5	0.6
LP	L12a.4	305.6	21.1	T	435	646	41.0	3.5	-26.9	3.1	0.8
LP	L12a.6	305.6	21.1	T	435	617	31.4	2.7	-30.6	2.4	0.8
LP	L12a.7	305.6	21.1	T	477	656	32.9	3.6	-26.3	3.2	0.8
LP	L12a.8	305.6	21.1	T	408	646	36.2	4.3	-32.2	3.7	1.0
LP	L12a.9	305.6	21.1	T	435	682	26.8	3.3	-22.3	3.0	1.0
LP	LP10.1	305.6	21.1	T	334	700	36.6	1.8	-9.9	1.8	0.8
LP	LP10.10	305.6	21.1	T	471	646	15.5	2.3	-2.0	2.3	0.6
LP	LP10.2	305.6	21.1	T	292	603	36.9	2.2	-29.6	1.9	1.0

APPENDIX A: LINEFIND DETERMINATIONS.

LP	LP10.3	305.6	21.1	T	379	664	16.5	1.4	-0.9	1.4	0.4
LP	LP10.4	305.6	21.1	A	100	525	33.7	5.8	-6.4	5.8	0.8
LP	LP10.5	305.6	21.1	T	379	664	28.6	3.0	-19.4	2.8	0.6
LP	LP10.6	305.6	21.1	T	540	999	24.6	2.7	-23.1	2.5	0.4
LP	LP10.7	305.6	21.1	A	125	999	30.8	0.9	-10.1	0.9	1.0
LP	LP10.8	305.6	21.1	T	525	629	40.6	2.8	-20.7	2.6	0.8
LP	LP10.9	305.6	21.1	T	379	640	35.3	3.6	-33.6	3.0	1.0
LP	LP11.1	305.6	21.1	T	510	670	22.0	2.7	-15.8	2.6	1.0
LP	LP12.1	305.6	21.1	T	511	640	40.5	4.0	-26.0	3.6	0.8
LP	LP12.2	305.6	21.1	T	510	670	35.5	3.4	-27.9	3.0	0.8
LP	LP12.3	305.6	21.1	T	559	999	46.6	3.0	-27.4	2.7	0.8
LP	LP13.1	305.6	21.1	T	581	679	28.8	3.0	-28.7	2.7	0.6
LP	LP14.1	305.6	21.1	T	510	670	47.8	3.2	-34.3	2.6	0.4
LP	LP14.2	305.6	21.1	T	589	999	42.5	2.6	-30.8	2.2	0.4
LP	LP14.3	305.6	21.1	T	603	683	45.5	3.4	-33.8	2.8	0.6
LP	LP14.4	305.6	21.1	T	450	999	34.0	2.4	-34.0	2.0	0.8
LP	LP14.5	305.6	21.1	A	225	999	34.2	0.5	-33.7	0.4	0.2
LP	LP14.6	305.6	21.1	T	559	999	44.6	2.7	-34.8	2.2	0.8
LP	LP14.7	305.6	21.1	T	581	700	38.7	3.2	-31.0	2.8	0.6
LP	LP16.1	305.6	21.1	T	559	999	85.8	6.7	-19.2	6.3	0.8
LP	LP16.3	305.6	21.1	T	600	999	34.9	3.4	-19.5	3.2	0.8
LP	LP16.4	305.6	21.1	T	600	999	38.6	3.1	-8.0	3.1	0.8
LP	LP17.2	305.6	21.1	T	460	999	24.0	2.1	-20.2	2.0	0.6
LP	LP17.3	305.6	21.1	T	525	680	32.1	5.2	-12.3	5.0	0.8
LP	LP17.5	305.6	21.1	T	540	679	34.6	2.8	-11.7	2.7	0.6
LP	LP17.7	305.6	21.1	T	510	999	38.8	5.5	-53.1	3.3	1.0
LP	LP18.1	305.6	21.1	T	540	999	53.4	5.4	-34.0	4.4	0.6
LP	LP18.2	305.6	21.1	T	540	999	52.0	6.8	-35.7	5.5	1.0
LP	LP18.4	305.6	21.1	T	209	999	45.8	2.1	-26.3	1.9	0.8
LP	LP19.1	305.6	21.1	T	581	999	35.6	3.9	-31.0	3.3	0.6

LOCH LINTRATHEN PORPHYRY: SITE 15 ANOMALOUS COMPONENT (P) IN SITU.

LP15	LP15.1	?????	????	T	212	679	145.5	1.2	-38.5	0.9	0.8
LP15	LP15.2	?????	????	T	281	999	148.4	1.0	-41.1	0.8	0.6
LP15	LP15.3	?????	????	T	460	670	146.3	3.3	-47.7	2.2	0.8
LP15	LP15.4	?????	????	A	1000	999	146.2	1.6	-46.0	1.1	0.2
LP15	LP15.5	?????	????	T	422	679	171.7	4.5	-60.1	2.3	0.6

LOCH LINTRATHEN PORPHYRY: COMPONENT (D) IN SITU.

LP	L12a.2	305.6	21.1	T	656	999	10.0	11.4	13.5	11.1	1.0
LP	L12a.3	305.6	21.1	T	656	999	30.9	10.6	17.1	10.1	0.6

APPENDIX A: LINEFIND DETERMINATIONS.

LP	L12a.4	305.6	21.1	T	646	999	29.0	7.7	12.9	7.5	0.8
LP	L12a.6	305.6	21.1	T	656	682	39.3	9.0	8.4	8.9	0.8
LP	L12a.7	305.6	21.1	T	656	999	17.5	12.2	14.8	11.8	0.8
LP	L12a.8	305.6	21.1	T	646	999	12.1	9.1	7.9	9.0	1.0
LP	LP12.1	305.6	21.1	T	640	999	24.0	10.1	7.1	10.0	0.8
LP	LP12.2	305.6	21.1	T	670	999	29.8	12.9	-4.7	12.9	0.8

GLENBERVIE PORPHYRY: COMPONENT (S) IN SITU

LP	LP1.2	85.2	74.1	T	204	376	176.7	22.5	-35.7	18.3	0.8
LP	LP1.3	85.2	74.1	T	207	376	165.3	20.1	-41.2	15.1	0.8
LP	LP1.4	85.2	74.1	T	205	376	171.0	17.7	-41.2	13.3	0.6
LP	LP2.1	85.2	74.1	T	274	425	178.3	19.1	-13.7	18.6	0.4
LP	LP2.2	85.2	74.1	T	173	432	179.1	20.8	-26.9	18.5	0.6
LP	LP2.3	85.2	74.1	T	209	456	175.5	19.9	-49.4	13.0	0.6
LP	LP2.5	85.2	74.1	T	182	351	183.4	23.7	-32.7	20.0	0.6
LP	LP2.6	85.2	74.1	T	274	425	197.1	29.6	-48.7	19.6	0.8
LP	LP3.4	85.2	74.1	T	198	482	163.7	15.6	-38.5	12.2	0.6
LP	LP3.5	85.2	74.1	T	155	363	190.7	21.5	-27.6	19.0	0.6
LP	LP4.1	85.2	74.1	T	211	379	188.6	20.0	-7.8	19.9	0.6
LP	LP4.2	85.2	74.1	T	208	452	182.1	18.5	-15.6	17.9	0.8
LP	LP4.3	85.2	74.1	T	139	363	164.3	16.9	-2.5	16.9	0.6
LP	LP4.5	85.2	74.1	T	198	434	173.0	21.9	-30.0	19.0	0.8
LP	LP4.6	85.2	74.1	T	123	363	185.0	13.5	-4.6	13.5	0.4
LP	LP5.1	85.2	74.1	T	204	376	176.0	13.7	-21.6	12.7	1.0
LP	LP5.2	85.2	74.1	T	182	351	179.8	17.2	-4.9	17.1	0.4
LP	LP5.3	85.2	74.1	T	276	432	175.3	19.6	-23.5	18.0	0.4
LP	LP6.4	85.2	74.1	T	285	380	161.2	16.2	-19.6	15.2	0.4
LP	LP8.1	85.2	74.1	T	198	482	189.7	10.0	-43.7	7.2	1.0
LP	LP8.3	85.2	74.1	T	198	434	179.5	12.5	-14.5	12.1	0.8
LP	LP8.4	85.2	74.1	T	276	484	178.4	15.7	-22.9	14.5	0.6
LP	LP8.5	85.2	74.1	T	272	482	181.0	11.1	-16.4	10.6	0.6
LP	LP9.2	85.2	74.1	T	284	468	174.9	17.6	-28.6	15.5	0.4

GLENBERVIE PORPHYRY: COMPONENT (P) IN SITU

LP	LP1.2	85.2	74.1	T	557	625	126.3	5.4	-51.2	3.4	0.8
LP	LP1.3	85.2	74.1	T	452	999	128.4	3.4	-58.7	1.8	1.0
LP	LP1.4	85.2	74.1	T	500	625	132.6	5.9	-59.5	3.0	1.0
LP	LP1.5	85.2	74.1	T	432	637	138.8	1.8	-43.7	1.3	0.4
LP	LP1.6	85.2	74.1	T	482	637	139.3	5.7	-53.1	3.4	1.0
LP	LP1.8	85.2	74.1	T	531	612	122.3	21.1	-66.4	8.5	0.6
LP	LP2.1	85.2	74.1	T	531	999	138.7	2.8	-45.4	2.0	0.4
LP	LP2.2	85.2	74.1	T	484	999	144.3	3.8	-47.8	2.6	0.6
LP	LP2.3	85.2	74.1	T	558	999	137.6	5.3	-65.5	2.2	0.6

APPENDIX A: LINEFIND DETERMINATIONS.

LP	LP2.4	85.2	74.1	T	459	654	124.5	6.3	-62.6	2.9	0.8
LP	LP2.5	85.2	74.1	T	425	612	142.9	5.2	-62.5	2.4	0.8
LP	LP2.6	85.2	74.1	T	425	999	138.3	6.0	-66.8	2.4	0.8
LP	LP3.2	85.2	74.1	T	434	999	140.6	6.4	-58.8	3.3	1.0
LP	LP3.3	85.2	74.1	T	535	637	145.6	9.5	-57.6	5.1	1.0
LP	LP3.4	85.2	74.1	T	482	637	107.1	4.5	-58.0	2.4	0.6
LP	LP3.5	85.2	74.1	T	484	999	140.8	3.5	-54.5	2.1	0.6
LP	LP4.1	85.2	74.1	T	502	625	143.7	3.2	-53.8	1.9	0.6
LP	LP4.2	85.2	74.1	T	557	654	128.2	7.7	-55.4	4.4	1.2
LP	LP4.3	85.2	74.1	T	484	637	133.1	3.5	-49.3	2.3	0.6
LP	LP4.4	85.2	74.1	T	531	626	144.2	6.3	-58.1	3.3	1.0
LP	LP4.5	85.2	74.1	T	482	637	131.2	4.6	-48.3	3.0	1.0
LP	LP4.6	85.2	74.1	T	484	637	135.7	6.1	-53.6	3.6	1.0
LP	LP5.1	85.2	74.1	T	500	625	126.8	2.7	-53.0	1.7	1.0
LP	LP5.2	85.2	74.1	T	531	612	142.3	8.7	-53.6	5.1	1.0
LP	LP5.3	85.2	74.1	T	484	637	131.5	9.2	-57.6	4.9	1.0
LP	LP6.2	85.2	74.1	T	468	580	140.0	5.7	-48.1	3.8	1.0
LP	LP6.3	85.2	74.1	T	500	654	129.8	3.3	-48.8	2.1	1.0
LP	LP6.4	85.2	74.1	T	503	999	131.8	4.1	-47.9	2.7	1.0
LP	LP7.1	85.2	74.1	T	432	637	127.8	4.4	-52.2	2.7	1.0
LP	LP7.2	85.2	74.1	T	425	999	118.4	10.7	-63.3	4.8	1.0
LP	LP8.1	85.2	74.1	T	482	637	120.9	4.8	-63.5	2.1	1.0
LP	LP8.3	85.2	74.1	T	482	592	141.6	5.1	-49.8	3.3	0.8
LP	LP8.4	85.2	74.1	T	542	637	151.1	7.9	-51.6	4.9	0.6
LP	LP8.5	85.2	74.1	T	535	999	141.6	2.4	-48.0	1.6	0.6
LP	LP9.2	85.2	74.1	T	531	626	135.9	4.0	-44.0	2.9	0.4
LP	LP8.2	85.2	74.1	T	391	626	126.6	8.3	-47.9	5.6	1.0

APPENDIX B : ROCKS FOUND TO BE UNSUITABLE FOR PALAEOMAGNETIC STUDY & DISCONTINUED STUDIES.

During the course of this study, various other work was attempted which has not been recounted in the body of this thesis. The reason for this is due either to the poor response of the sampled units to the palaeomagnetic method or to the constraint of time available for the completion of the research. A brief summary is given here:-

i) Caradocian sediments and volcanics; Capel Curig Volcanic Group, North Wales.

Several sites were sampled in coarse lithic wackes, acidic ash flow tuffs and mudstone near to Llyn Ogwen. The lithic wackes contain abundant heavy minerals including magnetite and accordingly yield high magnetic susceptibilities (see Cwm Eigiau Formation; Figure 4 of Evans & Greenwood, 1988). NRM directions proved widely dispersed both within and between sites. Intensities of magnetisation were in the range 0.1 - 1 A/m for the wackes but generally less than 1 mA/m for the tuffs. No stable magnetic component was isolated upon thermal demagnetisation of either rock type and the palaeomagnetic investigation was subsequently discontinued.

Five samples from the Llyn Ogwen microgranite (NRM intensities 1.4 - 16.6 mA/m) produced consistent directions close to the present Earth's field at the site:

(N = 5, Mean Dec. = 340.1., Mean Inc. = 68.6., $\alpha 95$ = 12.6., k = 37.8).

On thermal demagnetisation of two samples, a single component, thermally distributed magnetisation was observed unblocking at temperatures of up to 400°C. It is unclear whether this represents either a recent or palaeofield for the granite; steep magnetisations (of opposite polarity) having been reported for several members of the North Wales Ordovician intrusive suite by Thomas & Briden, (1976).

Refs;

Evans, R.B. and Greenwood, P.G. 1988. Outcrop magnetic susceptibility measurements as a means of differentiating rock types and their mineralisation, with examples from UK and overseas, including SE Asia. *Asian Mining '88* , 45 -57. Institute of Mining & Metallurgy.

Thomas, C. and Briden, J.C. 1976. Anomalous geomagnetic field during the late Ordovician. *Nature,* 259, 380-382.

ii) Bail Hill, (Northern belt of the Southern Uplands).

Two hand specimens were collected for test analysis from bedded tuffs associated with the Caradocian Bail Hill Volcanic centre. Magnetic moments of 0.35 and 0.67 mA/m were measured and found to have large associated errors (15° & 16° respectively). The two sample directions were separated by greater than 90° of arc. No further sampling was performed at Bail Hill due partially to problems in locating reliable bedding indicators within areas of limited exposure.

iii) Byne Hill Gabbro; Ballantrae Ophiolite.

Five sites were sampled systematically through the differentiated Byne Hill Gabbro (see Bloxham, 1968) in order to employ more sophisticated demagnetisation techniques than used in their original study (Piper, 1978). Sites were found to have uniformly low intensity (predominantly , 1 mA/m), large measurement errors (generally > 10°) and to cluster around a present day field direction. Time constraints precluded further sampling given that the initial collection did not appear promising.

Refs;

Bloxham, T.W. 1968. The petrology of Byne Hill, Ayrshire. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 68, 105-123.

Piper, J.D.A. 1978. Palaeomagnetism and palaeogeography of the Southern Uplands block in Ordovician times. *Scottish Journal of Geology,* 14, 93-107.

iv) Ardwell Flags, Upper Ordovician cover succession, Girvan.

Several oriented hand specimens were collected from the Ardwell Flags (greywackes) exposed above the Ballantrae Ophiolite at Girvan. NRM intensities proved uniformly weak (< 5 mA/m) and were directionally dispersed both within and between particular hand specimens. Test thermal demagnetisation of samples produced an order of magnitude drop in intensity following initial treatment in the range 100° - 200°C. This was regarded as unpromising and study was therefore discontinued.

v) Campsie Lavas, Lower Carboniferous.

Four sites were sampled within Lower Carboniferous lavas at Campsie Glen for use mainly in total field magnetic modelling (with M.C.Dentith, unpublished data). Magnetic intensities were of the order 0.5 - 2.0 A/m grouping either with southerly declination and approximately horizontal inclination or southerly declination and moderate positive inclination. Thermal demagnetisation revealed single component trajectories unblocking in the magnetite range.

APPENDIX C : ADDITIONAL WORK COMPLETED DURING THE COURSE OF Ph.D STUDY.

MAGNETIC SUSCEPTIBILITY CONTRASTS IN ORDOVICIAN GREYWACKES OF THE SOUTHERN UPLANDS OF SCOTLAND.

J.D.FLOYD^ & A.TRENCH.#

^British Geological Survey, West Mains Road, Edinburgh.
#Department of Geology, University of Glasgow.

Magnetic susceptibility contrasts in Ordovician greywackes of the Southern Uplands of Scotland

by J D FLOYD[1] and A TRENCH[2]

1. British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA, UK

2. Department of Geology, The University, Glasgow, G12 8QQ, UK

Abstract: Ordovician greywacke formations of the Southern Uplands are demonstrated to have consistent differences in magnetic susceptibility, which parallel differences in petrography. The observed susceptibilities range from a minimum of 0.16 x 10^{-3} SI for the quartz-rich, feldspar-poor Glenwhargen Formation to a maximum of 13.81 x 10^{-3} SI for the quartz-poor, feldspar-rich Marchburn Formation, and is considered to be directly related to variation in the amount of detrital magnetite in the greywackes. Rapid measurement of magnetic susceptibility is demonstrated to be a valuable field technique for distinguishing otherwise uniform sedimentary sequences on the basis of differing magnetite content. Detailed field observations illustrate considerable variation in susceptibility within metre-scale sections perpendicular to bedding through graded sedimentary units, which may be caused by density and/or grain-size effects. Laboratory measurements of the intensity of natural remanent magnetisation in the petrographically contrasting Kirkcolm and Galdenoch formations show a similar variation to that observed in susceptibility. Thermally distributed, scattered magnetisation directions indicate that no primary remanence has survived the low-grade burial metamorphic event in the Southern Uplands.

Key Words: magnetic susceptibility; field technique; greywacke; Ordovician; Southern Uplands.

In the Northern Belt of the Southern Uplands (Fig. 1a), greywacke formations established on the basis of petrography (Kelling 1961; Floyd 1982) are difficult to distinguish in the field. Their dramatic petrographic contrasts broadly indicate provenance within either cratonic or volcanic terrains, giving rise to quartz-rich (and feldspar/pyroxene-poor) or quartz-poor (and feldspar/pyroxene-rich) greywackes respectively.

The magnetic susceptibility of a material is the dimensionless ratio of the induced magnetisation to the magnetic intensity (M/H). It is a well established physical property of rocks (Clark 1983) where it is principally due to the mineral magnetite. There is an approximately linear relationship between magnetic susceptibility and the modal percentage of magnetite for low concentrations of the mineral (Nettleton 1971). The development of small portable susceptibility meters has allowed susceptibility to be measured in the field rather than in the laboratory, and recent work by the BGS in North Wales, as part of the Snowdonia Regional Geological Survey, has proved a good correlation between field and laboratory measurements (Evans & Greenwood 1988).

This paper documents the first set of detailed magnetic susceptibility measurements for the greywackes of the Southern Uplands and demonstrates that they form the basis of a valuable field technique for distinguishing sedimentary formations of uniform appearance but with differing magnetite content.

Parallel laboratory measurements were made of Koenigsberger Ratio (Q) (Koenigsberger 1938) and the intensity of natural remanent magnetism (NRM) for greywackes from two formations (of contrasting petrography and susceptibility) in order to investigate any similar inter-formational differences in these parameters.

Stratigraphic framework

The Northern Belt of the Southern Uplands consists of thick, Ordovician marine greywacke successions resting on thin sequences of black shale, chert and volcanic rocks. Beds are usually steeply inclined and strike consistently NE-SW. At least 4 well-defined lithostratigraphic greywacke formations have been described and can be traced for considerable distances along strike (Floyd 1982). These formations are in the most part separated by major strike-parallel faults (Fig. 1a) although some sedimentary interdigitation can be demonstrated. Their likely stratigraphical relationships (Fig. 1b) are based on palaeontological evidence, principally derived from the graptolite-bearing shales.

Field methods

The magnetic susceptibility was measured with a Microkappa Kappameter Model KT-5 field rock susceptibility meter weighing 350g and about the size and appearance of a hand torch. It should be noted that the Kappameter measures <u>apparent</u> susceptibility but in practice this differs little (<5%) from <u>true</u> susceptibility in the range of values encountered, when measurements are taken on a flat, magnetically isotropic and homogenous rock surface (Kappameter Model KT-5 Users Manual 1980). Every effort was made to take measurements on as flat and unweathered a rock surface as possible to minimise the negative effects of surface roughness. No account was taken of the orientation of the rock surfaces since Hamilton and Loveland (1967) and Janak (1972) have demonstrated that susceptibility anisotropy in greywackes is generally less than 7%, which is less than the variation usually found at each site.

The Kappameter includes a memory facility which was used to take the mean of 12 separate measurements in the close vicinity of the sample site. In order to minimise the effects of grain-size variation in graded beds, measurements were taken where possible on sand-grade intervals, avoiding pebbly bases or fine-grained tops.

The magnetic susceptibility of natural rock formations has been shown to display a log-normal (geometric) distribution (Irving et al. 1966; Tarling 1966) and therefore all field susceptibility measurements were converted to their logarithmic values for the calculation of a mean, standard deviation and coefficient of variation for each formation studied.

Field measurements were made at 351 sample sites chosen to be representative of the lithologies and succession. Most sites were in quarries or good natural exposures such as stream sections where flat and relatively unweathered rock surfaces were readily available for measurement. A thin section of greywacke was also available from each site to allow allocation within the existing petrographic lithostratigraphy (Floyd 1982), so all sites were assigned to their particular formations on the basis of normal field and petrographic parameters, with no reference to their magnetic properties. Histograms of outcrop magnetic susceptibility for the five formations studied are shown in Figure 2 along with detailed results in Table 1.

Detailed results

Marchburn Formation (Floyd 1982)

This formation was sampled at Craigburn Quarry, Leadburn [NT 2376 5448], Coulter Craigs Quarry, Coulter [NT 0286 3328] and in the type area of March Burn, New Cumnock [NS 6729 1298]. The greywackes are rich in feldspar and a variety of rock fragments. Quartz content is generally low (mean 14%, Table 2) with ferromagnesian minerals present only occasionally and in small amounts: Haggis Rock, a distinctive colourful pebbly greywacke (Floyd 1982), is closely associated with the greywackes at all 3 localities. Volcanic rocks were obviously an important feature of the source area for the Marchburn Formation as indicated by the relatively high content of acid, intermediate and basic lava clasts, especially prominent in the pebble fraction of the Haggis Rock. This formation has by far the highest susceptibility of those measured, with a mean of 13.81 x 10^{-3} SI units, and is a likely contributing source to the NE trending 150nT aeromagnetic anomaly shown between Leadburn and Coulter (Fig. 1) on the Borders Aeromagnetic Anomaly Map (BGS 1980). The Marchburn

Formation has been correlated, on stratigraphical, petrological and lithological criteria (Floyd 1982), with the Traboyack Division of the Tappins Group (Williams 1962) cropping out in the area between Girvan and Barrhill (Fig. 1). This correlation is further supported by the similarity in magnetic properties between the two formations, with the red and purple Traboyack greywackes reported by Powell (1970 p355) to have a susceptibility of P = 0.0015 cgs units (equivalent to 37.70 x 10^{-3} SI units). This is of a similar magnitude to that of the Marchburn Formation, which ranges up to a maximum of 31.83 x 10^{-3} SI units (Table 1), and 130 times greater than the mean of the adjacent Kirkcolm Formation.

Kirkcolm Formation (Kelling 1961)

Greywackes of the Kirkcolm Formation are characterised by moderate amounts of quartz (mean 45%, Table 2), less feldspar than the Marchburn Formation and with ferromagnesian minerals rare or absent. This indicates a provenance within a relatively mature low-grade metamorphic and cratonic terrain with little contemporary volcanic activity. The mean susceptibility of 0.29 x 10^{-3} SI is relatively low and considerably less than that for the adjacent Marchburn Formation. Sampling sites for the Kirkcolm Formation were all in the Barrhill area (Fig. 1).

Galdenoch Formation (Kelling 1961)

The greywackes of this formation are characterised by a variable content (up to 29%) of detrital grains of pyroxene and/or hornblende, with quartz (mean 18%, Table 2) generally less than in the Kirkcolm Formation. Lithic clasts of pyroxene/hornblende andesite are commonly present, generally in considerable amounts (up to 20%). The quantity and freshness of the original igneous material indicates derivation from an active volcanic region such as that postulated (Stone et al 1987) to form part of a contemporary calc-alkaline volcanic island arc.

Greywackes of the Galdenoch Formation have low to moderate susceptibilities (mean 0.65 x 10^{-3} SI), generally higher than those of the Kirkcolm Formation (Table 1). In keeping with its variable petrography, the Galdenoch Formation also shows considerable variation in susceptibility. Within the formation, those greywackes which are richest in detrital pyroxene/hornblende grains generally have the highest susceptibilities. This effect is probably due to a complementary variation in detrital magnetite. The Galdenoch Formation was studied in the Barrhill area where it appears to interfinger with the Kirkcolm Formation (Fig. 1, Stone et al. 1987).

Portpatrick Formation (Kelling 1961)

The Portpatrick Formation is dominated by medium- to thick-bedded greywackes which are usually poor in quartz (13%, Kelling 1962; 15%, Table 2) and rich in feldspar, ferromagnesian minerals and andesite lithoclasts. Though about 3 graptolite zones younger in age than the Galdenoch Formation (Fig. 1b), the greywackes have a broadly similar petrography and are thought to have a comparable calc-alkaline volcanic island-arc provenance (Stone et al. 1987).

The Portpatrick Formation was studied in the type area at Portpatrick as well as between Barrhill and Newton Stewart (Fig. 1a). The greywackes have a mean susceptibility of 0.42 x 10^{-3} SI and a fairly restricted range, which partly overlaps with that of the Galdenoch Formation greywackes (Table 1).

Glenwhargen Formation

In the description of the Scar Formation (now a junior synonym of the Portpatrick Formation) by Floyd (1982), associated quartz-rich greywackes were recorded near Glenwhargen Farm in the Scaur Water. Exposure was inadequate to distinguish whether the quartz-rich greywackes (Glenwhargen Formation) were repeated by interfingering or faulting (Floyd 1975, 1982, fig. 4b). However, recent work in the Rhinns of Galloway has established that equivalent quartz-rich greywackes are there interbedded with the greywackes of the Portpatrick Formation (Stone et al. 1987, fig. 2b; Kelling et al. 1987, p794).

The Glenwhargen Formation (here defined) consists of highly quartzose greywackes repeatedly interbedded with the strongly contrasting quartz-poor greywackes of the Portpatrick Formation (Fig. 1 and Table 2). The type section is along the Scaur Water near Glenwhargen from [NS 7681 0217] to [NS 7622 0261]. Other typical sections are at Killantringan, 1.6 km NW of Portpatrick [NW 9850 5550] (Stone et al. 1987, fig. 2b), and in the Clachaneasy area [NX 3626 7480], 10 km NW of Newton Stewart (Table 1).

In the Scaur Water and at Killantringan, the greywackes are commonly thin-bedded and tend to be associated with sequences of laminated siltstone. However, bed thickness locally ranges up to more than 1 metre, with well-developed internal turbidite structures, discounting any possibility that they represent contourites or otherwise reworked Portpatrick Formation greywackes. From coarser-grained specimens, it is evident that much of the quartz is of low-grade metamorphic origin, mostly from quartzites. In the Clachaneasy area, the formation consists of medium- to coarse-grained, often pebbly (mostly quartzite and vein quartz) greywackes in packets up to 400m thick.

As might be expected in a relatively mature quartz-rich formation (67%, Table 2), magnetic susceptibility is very low with a mean of 0.16×10^{-3} SI, the lowest of any of the Ordovician formations studied, and only one-third that of the enclosing Portpatrick Formation (Fig. 3 and Table 1).

Polished sections

Polished thin sections of greywackes from the Marchburn and Galdenoch formations were examined by reflected light to determine whether there were any visible differences in the amount of detrital magnetite and other opaque minerals between the two formations. Assuming the samples to be representative, the results (Table 3) indicate that the Marchburn Formation contains more than 20 times as much magnetite as the Galdenoch Formation. This is of a similar order to the ratio of the mean susceptibilities of the two formations (Table 1), supporting the view that detrital magnetite is the source of the observed magnetic susceptibility variation in the greywackes.

Bed-scale susceptibility studies

In order to investigate variation on bed-scale of the susceptibility of the greywackes, a detailed series of measurements were made at 7.5cm intervals through a measured section in the Galdenoch Formation in a Forestry Commission quarry near Barrhill [NX 2075 8069]. The resulting histogram (Fig. 3) characteristically shows a susceptibility peak at or just above the base of each graded bed, with a gradual decrease towards the top of the bed. This effect is interpreted as a combination of two independent factors operating together during sedimentation. Firstly, a density stratification involving a downward concentration of the relatively dense magnetite grains (as well as other heavy minerals which might be potential precursors of magnetite; S.G. magnetite = 5.18), and secondly, a grain-size stratification (graded bedding) tending to concentrate the larger (and multidomain) magnetite grains towards the base of the bedforms.

Natural Remanent Magnetisation (NRM) studies

Parallel field and laboratory investigations were carried out on greywackes from two formations to determine whether the susceptibility contrasts were accompanied by systematic differences in NRM intensity and to ascertain whether a stable remanence was recoverable from the greywackes. A total of 51 samples from 8 sites in the Kirkcolm and Galdenoch formations were cored in the field using a portable drill. The 2.5cm diameter cores were oriented using both magnetic and sun compasses and then trimmed into cylinders of 2.3cm length for laboratory measurement. Magnetic moments were measured with a fluxgate magnetometer (Molyneux 1971). Thermal demagnetisation of several samples from each site was also undertaken to test the thermal stability of the NRM. Combination of intensity data with equivalent susceptibility results enabled calculation of the Koenigsberger Ratio (Q), indicating the predominance of either induced or remanent magnetisation.

NRM and demagnetisation results

NRM intensities were generally weak (1–10 mAm^{-1}) and the directional distribution of NRM showed a high degree of within-site scatter for both the Kirkcolm and Galdenoch formations. Although weak, intensities were generally higher for the Galdenoch Formation (1.0 – 12.7 mAm^{-1}) than the Kirkcolm Formation (0.4 – 3.8 mAm^{-1}). A histogram of the intensity results from both formations is shown in Figure 4. Mean NRM intensity and mean Koenigsberger Ratios for both formations are given in Table 4.

Thermal demagnetisation did not result in the isolation of a stable component of magnetisation or reduce the within-site scatter for either formation. Blocking temperature spectra were thermally distributed (Irving and Opdyke 1965), the blocking temperatures ranging between 250 and 400°C.

Discussion of laboratory results

A systematic variation of NRM intensity is identified between the Galdenoch and Kirkcolm formations, the immature Galdenoch Formation having the higher intensities. This variation parallels that observed in magnetic susceptibility and is similarly attributed to a variation in magnetite content. Koenigsberger Ratios considerably less than unity indicate the predominance of the induced magnetisation component for both formations (the similarity in the calculated ratios is due to sympathetic variation in both intensity and susceptibility).

The low blocking temperatures of remanence and their thermally distributed nature are consistent with a remanence held by multidomain magnetite possibly as discrete detrital grains. Although the remanence may be carried by original detrital magnetite, its instability to thermal demagnetisation confirms that no primary remanence has survived the prehnite-pumpellyite facies metamorphism (Oliver et al. 1984) to which the Northern Belt has been subjected.

Discussion and conclusions

It has been demonstrated that established differences in bulk petrography of Ordovician greywacke formations in the Southern Uplands are paralleled by consistent variation in magnetic susceptibility. The variation is considered to reflect differences in the content of magnetite, the source of which may be as original detrital material or as an alteration product of ferromagnesian minerals. Although the susceptibilities are usually low to moderate by comparison with many basic igneous rocks or magnetic sandstones, variation by nearly two orders of magnitude has been noted (Table 1). Broadly, as might be expected, the susceptibility is highest in those formations which are rich in ferromagnesian minerals and were derived from an immature volcanic source area, and lowest in the more mature quartz-rich formations of more continental provenance.

Susceptibility contrasts were successfully used in the Barrhill area to define the Kirkcolm/Galdenoch interformational boundary in the field. Measurements were made on exposures in the general vicinity of the boundary, with susceptibilities of 0.50×10^{-3} SI or over implying Galdenoch, and 0.35×10^{-3} SI or less implying Kirkcolm (Table 1). The accuracy of this line was confirmed by microscope study of thin sections.

Susceptibility contrasts are accompanied by a similar variation in laboratory-measured NRM for two formations. Observed blocking temperatures are consistent with a remanence carried by multidomain detrital magnetite.

The close integration of geophysical and geological studies on well-documented detailed measured sections allows valuable correlation to be made between the physical, petrological and sedimentological characteristics of these otherwise uniform greywacke sequences. Such comparisons could ultimately provide a susceptibility-related stratigraphy for at least part of the Southern Uplands. This technique of rapid measurement of magnetic susceptibility shows promise as a very useful tool for field mapping, especially at a reconnaissance level and in areas of uniform rock types. The light weight and ease of use of the Kappameter imposes no significant extra logistical or workload burdens and it has been demonstrated to provide an excellent additional field method for characterising the rocks of an area, given sufficient magnetic contrasts.

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References

________ 1980. Kappameter Model KT-5 Users Manual. Geofyzica Brno, Czechoslovakia.

BRITISH GEOLOGICAL SURVEY. 1980. 1:250,000 Sheet 55°N 04°W, Borders (Aeromagnetic Anomaly). Institute of Geological Sciences.

CLARK, D.A. 1983. Comments on Magnetic Petrophysics. Bulletin of the Australian Society of Exploration Geophysicists, **14**, 49-62.

EVANS, R.B. and GREENWOOD, P.G. 1988. Outcrop magnetic susceptibility measurements as a means of differentiating rock types and their mineralisation, with examples from UK and overseas, including SE Asia. Asian Mining '88, 45-57. Institute of Mining and Metallurgy.

FLOYD, J.D. 1975. The Ordovician Rocks of West Nithsdale. Unpublished PhD Thesis, St Andrews University.

-------- 1982. Stratigraphy of a flysch succession: the Ordovician of W. Nithsdale, SW Scotland. Transactions of the Royal Society of Edinburgh: Earth Sciences, **73**, 1-9.

HAMILTON, N. and LOVELAND, P.J. 1967. Some preliminary susceptibility anisotropy measurements on greywackes from the Trinity Peninsula Series of Graham Land. British Antarctic Survey Bulletin, **11**, 59-71.

IRVING, E. and OPDYKE, N.D. 1965. The palaeomagnetism of the Bloomsburg redbeds and its probable application to the tectonic history of the Appalachians. Geophysical Journal of the Royal Astronomical Society, **9**, 153-167.

--------, MOLYNEUX, L. and RUNCORN, S.K. 1966. The analysis of remanent intensities and susceptibilities of rocks. Geophysical Journal of the Royal Astronomical Society, **10**, 451-464.

JANAK, F. 1972. Magnetic susceptibility anisotropy of various rock types and its significance for geophysics and geology. Geophysical Prospecting, **20**, 375-384.

KELLING, G. 1961. The stratigraphy and structure of the Ordovician rocks of the Rhinns of Galloway. Quarterly Journal of the Geological Society of London, **117**, 37-75.

------- 1962. The petrology and sedimentation of Upper Ordovician rocks in the Rhinns of Galloway, South-West Scotland. Transactions of the Royal Society of Edinburgh, **65**, 107-137.

-------, DAVIES, P. and HOLROYD, J. 1987. Style, scale and significance of sand bodies in the Northern and Central Belts, southwest Southern Uplands. Journal of the Geological Society, London, **144**, 787-805.

KOENIGSBERGER, J.G. 1938. Natural residual magnetism of eruptive rocks. Terrestrial Magnetism and Atmospheric Electricity, **43**, 119-127.

MOLYNEUX, L. 1971. A complete result magnetometer for measuring the remanent magnetisation of rocks. Geophysical Journal of the Royal Astronomical Society, **24**, 429-433.

NETTLETON, L.L. 1971. Elementary gravity and magnetics for geologists and seismologists. Monograph: Society of Exploration Geophysicists. Tulsa.

OLIVER, G.J.H., SMELLIE, J.L., THOMAS, L.J., CASEY, D.M., KEMP, A.E.S., EVANS, L.J., BALDWIN, J.R. and HEPWORTH, B.C. 1984 Early Palaeozoic metamorphic history of the Midland Valley, Southern Uplands - Longford-Down Massif and the Lake District, British Isles. Transactions of the Royal Society of Edinburgh: Earth Sciences, **75**, 245-258.

POWELL, D.W. 1970. Magnetised rocks within the Lewisian of Western Scotland and under the Southern Uplands. Scottish Journal of Geology, **6**, 353-369.

STONE, P., FLOYD, J.D., BARNES, R.P. and LINTERN, B.C. 1987. A sequential back-arc and foreland basin thrust duplex model for the Southern Uplands of Scotland. Journal of the Geological Society, London, **144**, 753-764.

TARLING, D.H. 1966. The magnetic intensity and susceptibility distributions of some Cenozoic and Jurassic basalts. Geophysical Journal of the Royal Astronomical Society, **11**, 423-432.

WILLIAMS, A. 1962. The Barr and Lower Ardmillan Series (Caradoc) of the Girvan District, south-west Ayrshire. Memoirs of the Geological Society of London, **3**.

Figure captions

<u>Figure 1a</u> Map showing location of study areas, major faults and formation boundaries. Numbers in circles refer to stratigraphic columns in Fig. 1b. Abbreviations: MCHB = Marchburn Formation, KKF = Kirkcolm Formation, GDF = Galdenoch Formation (stippled ornament), PPF = Portpatrick Formation, GWH = Glenwhargen Formation (cross hatched ornament), CF = Carcow Fault, LHF = Leadhills Fault, FF = Fardingmullach Fault, LD = Loch Doon Pluton.

<u>Figure 1b</u> Time stratigraphic diagram showing likely age relations of formations in the Northern Belt of the Southern Uplands between the Southern Upland Fault and the Fardingmullach Fault. A stratigraphic column is shown for each fault-bounded block.

<u>Figure 2</u> Histograms of magnetic susceptibility values for Ordovician greywackes in the Southern Uplands (logarithmic scale). Horizontal bar above each histogram indicates range, tall vertical line indicates mean, box indicates standard deviation. n = 351

<u>Figure 3</u> Detailed measured section in Forestry Commission quarry at [NX 2075 8069] near Barrhill. Lithology log indicates sandstone (no ornament) and siltstone/mudstone (black ornament) along with an indication of grain size variation. Susceptibility histogram shows mean of 12 measurements for each 7.5cm band throughout the section. Very thin mudstone units were impossible to measure accurately.

<u>Figure 4</u> Histograms of the NRM intensity for the Galdenoch and Kirkcolm formations.

Table captions

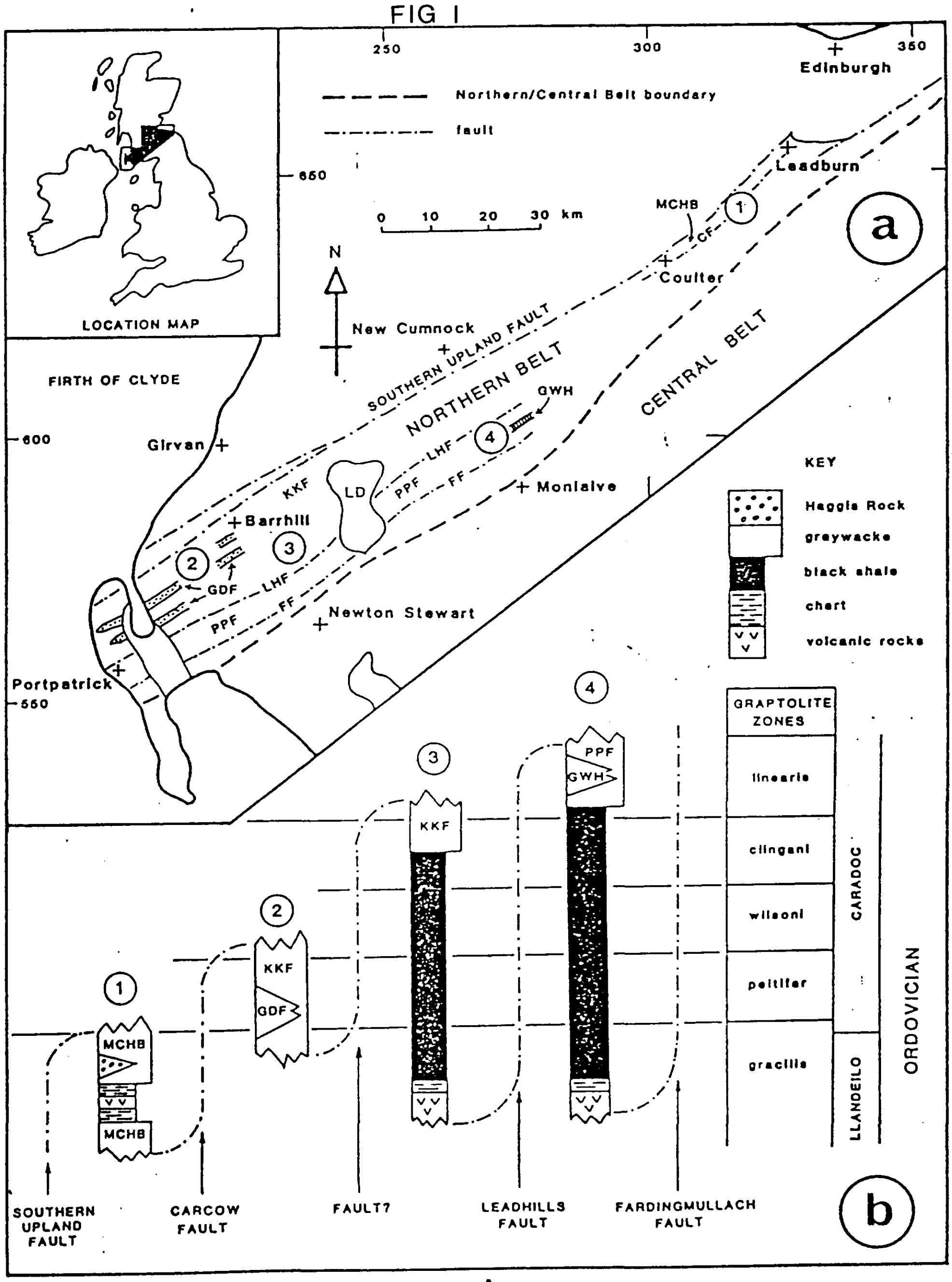
Table 1 Statistical details of magnetic susceptibility measurements on Ordovician greywacke formations in the Southern Uplands. Each sample is the mean of 12 measurements. For each formation, the magnetite content is approximate and is derived by calculation from the mean susceptibility (Nettleton 1971).

Table 2 Point count modal analysis details for Ordovician formations in the Northern Belt of the Southern Uplands. 1000 points counted in each sample. Based largely on Floyd 1975, Appendix 2, supplemented by new data. Figures are percentages.

Table 3 Ratios of magnetite and other opaque ore minerals between the Marchburn and Galdenoch formations. 100 grains were counted in one thin section from each formation and the total traverse length necessary to count the 100 grains was measured. Note that this table refers only to number of grains and not their volume.

Table 4 Statistical details of NRM intensity measurements for greywackes from the Kirkcolm and Galdenoch formations.

FIG I



250
300
350
Edinburgh
Northern/Central Belt boundary
fault
650
600
550
0 10 20 30 km
N
LOCATION MAP
Leadburn
MCHB
CF
1
a
Coulter
New Cumnock
SOUTHERN UPLAND FAULT
NORTHERN BELT
CENTRAL BELT
FIRTH OF CLYDE
GWH
Girvan
4
LHF
KKF
LD
PPF
FF
Moniaive
Barrhill
2
3
GDF
Newton Stewart
Portpatrick
KEY
Haggis Rock
greywacke
black shale
chert
volcanic rocks
GRAPTOLITE ZONES
linearis
clingani
wilsoni
peltifer
gracilis
CARADOC
LLANDEILO
ORDOVICIAN
MCHB
KKF
GDF
PPF
GWH
SOUTHERN UPLAND FAULT
CARCOW FAULT
FAULT?
LEADHILLS FAULT
FARDINGMULLACH FAULT
b

FIG 2

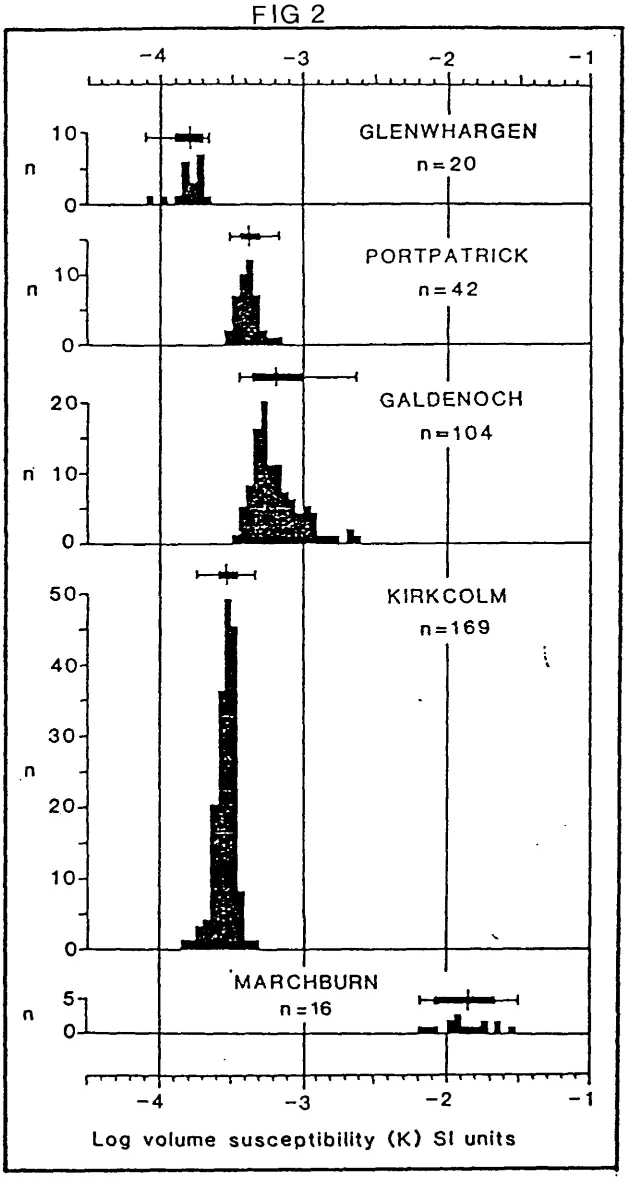

-4
-3
-2
-1
GLENWHARGEN
n=20
PORTPATRICK
n=42
GALDENOCH
n=104
KIRKCOLM
n=169
MARCHBURN
n=16
n
0
5
10
20
30
40
50
Log volume susceptibility (K) SI units

FIG 3

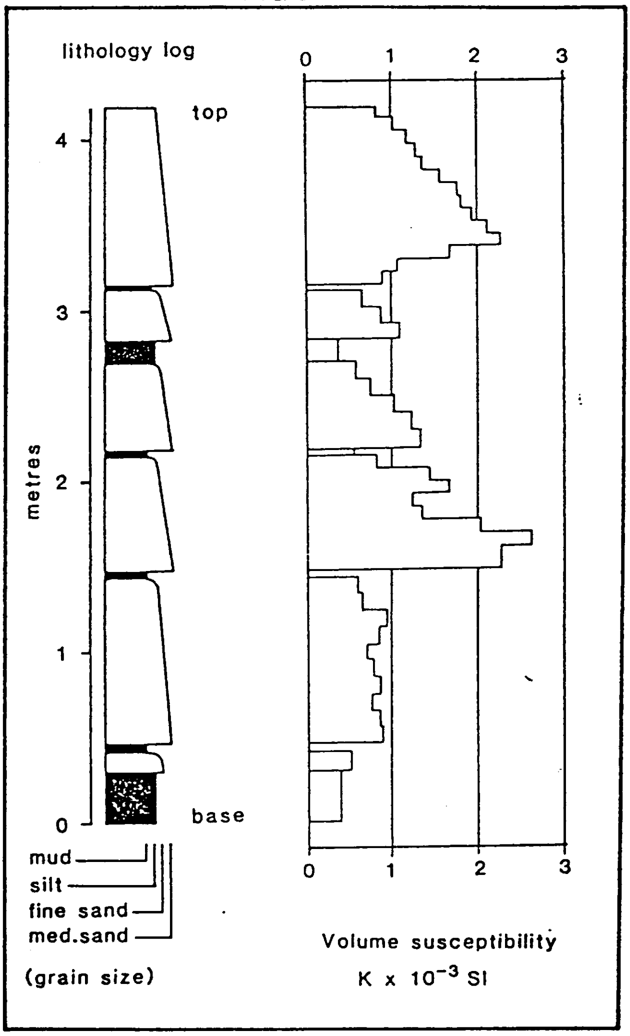

lithology log
top
base
metres
4
3
2
1
0
mud
silt
fine sand
med.sand
(grain size)
0
1
2
3
Volume susceptibility
K x 10^{-3} SI

FIG4

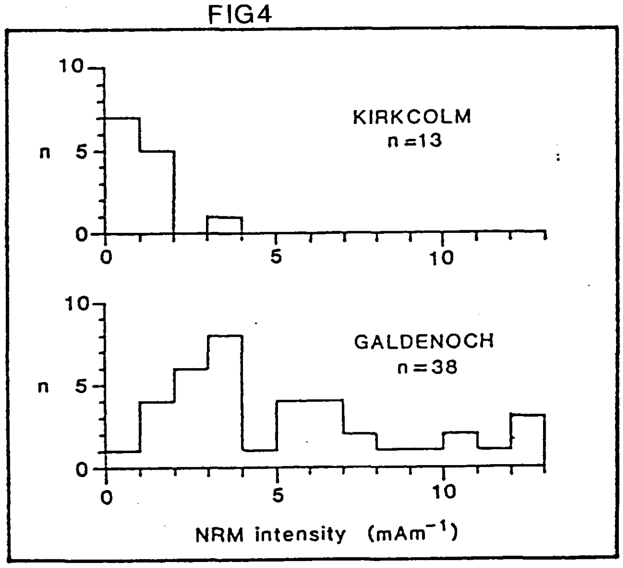


Table 1

Formation	Marchburn	Kirkcolm	Galdenoch	Portpatrick	Glenwhargen
Sample size (n)	16	169	104	42	20
Mean ($\bar{x}$) ($\times 10^{-3}$ SI)	13.81	0.29	0.65	0.42	0.16
Std. Dev. range (σ_n) ($\times 10^{-3}$ SI)	8.93-21.36	0.25-0.34	0.43-0.96	0.35-0.49	0.13-0.20
Total range ($x_1 - x_n$) ($\times 10^{-3}$ SI)	6.45-31.83	0.18-0.47	0.36-2.28	0.30-0.67	0.08-0.22
Coefficient of variation (V%)	45	16	41	17	22
Magnetite content (ppm)	3667	77	173	111	42

Table 2

Formation	Marchburn	Kirkcolm	Galdenoch	Portpatrick	Glenwhargen
Sample size n	25	80	5	80	5
Quartz	14.0	45.3	18.1	15.3	67.0
Feldspar	39.4	12.7	18.1	34.2	5.5
Basic igneous rock fragments	10.6	5.1	23.6	16.7	2.7
Acid igneous rock fragments	4.5	1.5	1.7	2.7	0.5
Metamorphic rock fragments	0.9	2.0	1.2	0.8	1.4
Sedimentary rock fragments	1.4	1.2	0.8	1.2	0.9
Ferromagnesian minerals	1.4	0.1	16.5	2.7	0.2
Matrix	27.8	32.1	20.0	26.4	21.8

Table 3

(Mean grains per 100mm traverse)	Marchburn Formation	Galdenoch Formation	Ratio Marchburn:Galdenoch
MAGNETITE	113.1	4.7	23.7 : 1
ILMENITE	6.2	0.5	12.4 : 1
PYRITE	7.5	19.8	1 : 2.6
TOTAL OPAQUES	125	25	5 : 1

FLOYD & TRENCH

Table 4

Formation	Kirkcolm	Galdenoch
Sample size (n)	13	38
mean NRM intensity (mAm^{-1})	0.84	5.41
Std. Dev. range (mAm^{-1})	0.41 - 1.46	3.49 - 8.38
Total range (mAm^{-1})	0.37 - 3.83	0.96 -12.70
mean Koenigsberger Ratio	0.11	0.21