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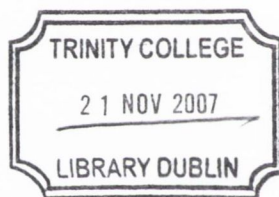
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**QUANTITATIVE STUDIES OF ROCK FABRICS AND TEXTURES
IN LAYERED MAFIC INTRUSIONS OF THE BRITISH TERTIARY
IGNEOUS PROVINCE: IMPLICATIONS FOR MAGMA SYSTEM
EMPLACEMENT AND EVOLUTION.**

Brian O'Driscoll

Submitted to the University of Dublin, Trinity College, for the degree of Doctor of
Philosophy

November 2006



THOS S
8289

DECLARATION

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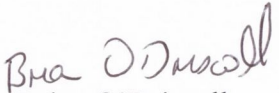

Brian O'Driscoll
November 2006

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Appendix B: Publications and conference contributions.

1. O'Driscoll, B., Troll, V.R., Reavy, R.J., and Turner, P. (2006). The Great Eucrite intrusion of Ardnamurchan, Scotland: re-evaluating the ring-dyke concept. *Geology*, **34** (3), 189-192.
2. **Abstract:** O'Driscoll, B., Hargraves, R.B., Emeleus, C.H., Troll, V.R., Donaldson, C.H., and Reavy, R.J. Magmatic lineations inferred from anisotropy of magnetic susceptibility fabrics in Units 8, 9, and 10 of the Rum Eastern Layered Series, Scotland. *Lithos* (in press).
3. **Abstract:** O'Driscoll, B., Troll, V. R., Donaldson, C.H., Jerram, D.A., and Emeleus, C.H. A crystal size distribution study of harrisitic and granular olivine from the Rum Layered Suite, NW Scotland. *Journal of Petrology* (in press).
4. **Abstract:** O'Driscoll, B. Magmatic layering and magnetic fabrics in the Palaeogene Carlingford Later Gabbros, Co. Louth, Ireland. *Irish Journal of Earth Sciences* (in press).
5. O'Driscoll, B., Troll, V.R., Reavy, R.J., and Turner, P. (2005). The Great Eucrite intrusion of Ardnamurchan, NW Scotland: re-evaluation of the ring-dyke concept. European Geosciences Union (EGU) annual meeting. Poster contribution.
6. 3. O'Driscoll, B., O'Dowd, K., McCourt, E., Troll, V. R., Donaldson, C.H., and Jerram, D.A. (2005). A textural study of harrisitic olivine: preliminary results from Crystal Size Distribution (CSD) analysis. Irish Geological Research Meeting. Poster contribution.
7. Complete publications and conference contributions list.

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SUMMARY

This thesis examines and considers the processes which led to magmatic layering and associated planar and linear fabrics in mafic and ultramafic rocks of four igneous centres of the British (and Irish) Palaeogene Igneous Province. The intrusions studied are the Ardnamurchan Centre 3 Gabbros, the Rum Layered Suite, the Skye Druim Hain Layered Gabbros (all in NW Scotland) and the Carlingford Later Gabbros (in NE Ireland). The interpretations of layer formation have important implications for magma chamber processes, and for intrusion geometries and emplacement mechanisms.

The study utilizes detailed field observations, modern methods of quantitative textural (Crystal Size Distribution; CSD) and rock microfabric (Anisotropy of Magnetic Susceptibility; AMS) analysis together with mineral-chemical data. AMS fabrics are typically carried by magnetite and are generally oriented parallel to visible macroscopic layer-parallel foliations. In the case of the Ardnamurchan and Rum intrusions, deformed structures in the layered rocks and consistently plunging orientations of magnetic lineations are interpreted as strong evidence for significant central subsidence of each body following initial emplacement. For the Ardnamurchan Centre 3 rocks, the combined evidence suggests that the intrusion is a composite lopolith and not a ring-dyke, as previously suggested. The close association of syn-magmatically deformed layering with inward-plunging magnetic lineations in parts of the Carlingford Later Gabbros suggests that this intrusion may also have undergone central subsidence, though less than at Ardnamurchan or Rum.

Magmatic layering at both Ardnamurchan and Rum is believed to have developed largely through the action of large and small-scale crystal-laden plumes or currents, possible driven by the central subsidence referred to above. At Druim Hain, the gabbros show evidence for central subsidence, but no evidence of magmatic flow is observed, and an *in situ* crystallization model of layer and fabric formation is advocated. Detailed quantitative textural evidence from parts of the Ardnamurchan laminated gabbros and the Druim Hain rocks suggests that postcumulus processes such as crystal ripening were locally very important in modifying primary cumulate textures and fabrics in both intrusions.

The data presented in this thesis have important implications for layered mafic and ultramafic rocks as they show that the textures and fabrics of cumulates may record magma chamber processes at different stages in the history of a cumulate pile. The data show that although the textures of mafic and

ultramafic rocks may be strongly influenced by postcumulus processes, primary (syn-cumulus) processes are probably responsible for initiation of layer and fabric acquisition in all of the intrusions studied. The conclusions drawn in this thesis also question some of the classic models for high-level magma emplacement and intrusion geometries in the British Palaeogene Igneous Province. For example, lopolithic central subsidence is shown to be an important process governing the late-stage development of each intrusion and suggests a need to re-evaluate other classic models for magma emplacement in the British Palaeogene Igneous Province, e.g. on the Isles of Mull and Arran, NW Scotland, and Slieve Gullion, Northern Ireland.

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CHAPTER 1. INTRODUCTION

1.1. Magmatic layering in mafic and ultramafic intrusions

Although mafic and ultramafic intrusions are often lithologically, texturally and compositionally layered at a variety of scales, considerable controversy surrounds the origin of such layering (see Irvine *et al.* 1998 for review). The variety of magmatic layer types may be described through a number of characteristics, such as variations of crystal size, crystal shape, crystal orientation (grain size or textural layering), mineral chemistry (cryptic layering), and varying modal proportions of minerals present in the rock (modal layering) (Irvine 1980). Modal layering may be termed rhythmic layering if there is cyclic repetition of this variation (Wager and Brown 1968). Combinations of any number of these layer types occur, and result in an almost infinite number of subtly different kinds of layering (Wager and Brown 1968). Variation of layering within the groups set out above can also occur through irregularities in the nature of the layer boundaries. Layer boundaries may be sharp or gradational and may be planar or undulatory. Layers may also be laterally continuous or discontinuous and may be conformable or unconformable with adjacent layers (Irvine *et al.* 1998).

Often closely associated with magmatic layering is a range of small-scale structures. Some of these, such as current bedding, modal and grain-size grading, magmatic lineations and slump structures, provide strong evidence for magmatic sedimentation (crystal settling) and current action as an important layer forming process (Wager and Brown 1968; Irvine *et al.* 1998). Others, such as planar mineral foliations (the layer parallel ‘igneous lamination’ of Wager and Brown (1968)) and folding of magmatic layering have origins that are less clear, and processes including *in-situ* crystallisation, mush rheomorphism (e.g. folding), post-cumulus compaction, metasomatism, and recrystallisation have all been held responsible (Wager and Brown 1968; McBirney and Noyes 1979; and Hunter 1987). It is obvious that the different varieties and scales of layering in mafic and ultramafic plutons represent a range of processes, and all of the features observed cannot be attributed to one single process (e.g. McBirney and Nicolas 1997; Boudreau and McBirney 1997; Irvine *et al.* 1998; O’Driscoll *et al.* 2005). Interpretations of magmatic layering and the structures that often accompany it have important implications for our understanding of the mechanisms by which layered intrusions are emplaced and evolve.

1.2. Fabric acquisition and textural evolution in layered cumulates

1.2.1. Introduction

Cumulus theory, proposed by Wager and Brown (1968), and refined by Irvine (1980), defined cumulus crystals as ‘the fractionated crystals’ that form a ‘cumulus framework of touching mineral crystals’. Different

(competing) processes in the magma chamber including *in situ* crystal growth and crystal transport are believed to be capable of forming such a primary, loose touching framework. However, postcumulus processes such as mechanical compaction may act on this framework to reduce its porosity and form a denser touching framework of crystals. The final stages of textural development may involve porous media convection, compositional convection, and growth of new crystals in the pore spaces of the framework as well as overgrowth (crystal ripening) on existing cumulus phases. Pore space may be reduced by compaction involving deformation of the crystals themselves, and/or alteration of crystal shape as a result of pressure solution. When porosity and permeability have decreased sufficiently to restrict fluid flow, a small fraction of intercumulus melt will be trapped in the pore spaces, and will ultimately crystallise to fully solidify the rock. Subsequent re-equilibration of both the mineral chemistry and textures may also occur.

1.2.2. Primary mechanisms of fabric development

There are many ways of initially concentrating crystals to produce a primary foliated or laminated crystal mush or framework. This framework will have different porosity and permeability characteristics depending on the way it was formed, and this will in turn control the operation of the secondary fabric/texture-forming processes, which contribute to the final fabric, texture and composition of the solidified rock. [Note that the term 'texture' is applied in this thesis to any arrangement of mineral grains, their sizes, shapes and relationships with each other. The term 'fabric, as used in this thesis, applies specifically to the linear and planar anisotropic distribution or alignments of grains in rocks.]

Crystals may nucleate and grow on an existing substrate or they may nucleate homogeneously in suspension and impinge to form a framework. This *in situ* development of layering and/or igneous lamination makes up the main kind of 'non-dynamic layering' of Boudreau and McBirney (1997). The characteristics of a silicate framework developed in this way will depend on nucleation density and growth rate. Layering may therefore develop through oscillations or fluctuations in the values of the latter two parameters through variation in liquid composition, pressure or oxygen fugacity. This might arise from injections of new magma (in open system magma chambers), convective overturn, or some other factor affecting liquidus conditions (McBirney and Noyes 1979). Fabrics in these rocks will generally be isotropic, but exceptions to this are crescumulate or harrisitic structure (Donaldson 1975a), in which crystals are frequently oriented perpendicular to magmatic layer

planes. McBirney and Noyes (1979) also describe an elegant theoretical model in which layer parallel igneous lamination may develop through *in situ* crystallization (see Chapter 5).

Crystals may also accumulate by means of crystal transport. Processes may range from simple gravitative crystal settling, to magmatic density currents and crystal-laden plumes (Wager and Brown 1968; Irvine *et al.* 1998; O'Driscoll 2003; O'Driscoll *et al.* 2005). There may be a range from dilute suspensions to high concentration, crystal rich regimes. A depositional fabric may result from the settling of inequant crystals; this will usually be a planar 'igneous lamination'. However, a well-defined magmatic flow regime is required in order to produce both igneous lamination and an associated magmatic lineation on lamination planes (the 'dynamic layering' mechanism of McBirney and Nicolas 1997). Additionally, it has been shown experimentally by Irvine (1980) that deposition from small density currents does not actually take place, particularly for very crystal-rich flows; rather the currents stop and become layers. It is also plausible, from studies on sedimentary rocks (e.g. Rust 1972; Davies and Walker 1974) as well as cumulates (Worral 2002), that crystal laden current action could lead to several different types of magmatic lineation as follows: 1) Gentle bedload transport (grains rolling and sliding) might produce a lineation (long axes normal to flow) in conjunction with imbricated crystals where direction of flow is given by the imbrication. 2) Stronger flows could lead to saltation, with the long axes oriented parallel to flow, and no imbrication. 3) Elongate grains in grain-flows and density flows could produce long-axes parallel to flow and might show imbrication.

1.2.3. Secondary mechanisms of fabric development

Secondary mechanisms of cumulate development encompass the processes that govern the transformation of the primary crystal framework into a solid rock and may overlap or operate synchronously with primary mechanisms. They typically involve chemical exchange between the cumulus crystals and interstitial melt and can occur during open or closed system regimes (Best and Christiansen 2001). The principal secondary magma chamber processes that act on the cumulate pile to develop igneous lamination are summarized below.

Compaction (through pure shear) operates initially by mechanical re-organisation of the crystal mush in order to attain closer packing. If compaction is to occur, melt must be able to escape from the local system, i.e. compaction is an implicitly open system process. Evidence for compaction is both textural and geochemical. The most obvious chemical effect is the exclusion of interstitial liquids as seen in lower concentrations of incompatible elements in cumulate rocks (e.g. Boudreau and McBirney 1997; Meurer and Boudreau 1998).

Petrographic evidence for compaction includes bent plagioclase grains, strained extinction and distorted twin planes, i.e. crystal-plastic strain. Although compaction of the crystal mush may cause some alignment of inequant grains, it is unlikely to produce a perfect planar alignment if it is the only process operating. Indeed, perfect or intense igneous lamination has been shown to develop without any element of compaction involved (McBirney and Hunter 1995). Lineation will generally be absent unless compaction is associated with a component of simple shear.

In addition to mechanical re-organisation or sorting, compaction may also result in igneous lamination development through differential (pressure) solution and reprecipitation (Boudreau and McBirney 1997). Because the excess free energy at the surface of a crystal increases with stress, points where stress is concentrated tend to dissolve, whereas those under smaller stress will grow preferentially. Boudreau and McBirney (1997) suggest that the large 010 faces of tabular plagioclase grains appear to be more resistant than other smaller faces. They propose that when the contacts bear stress, the latter tend to dissolve and the former grow, increasing the proportion of grains oriented with 010 normal to the direction of maximum stress (or pure shear).

The importance of textural equilibration of the crystal mush in layered intrusions has recently been highlighted by Hunter (1987), Elliott *et al.* (1997), Holness (2005), Holness *et al.* (2005) and O'Driscoll (2005). Textural equilibration operates in order to attain a lower-energy grain boundary configuration by reducing the surface energy of the system. The driving force for textural equilibration is differences in local grain boundary curvature. Thus, texturally equilibrated rocks have constant mean grain boundary curvature and constant dihedral angles between like mineral phases. Large grains have a lower mean grain-boundary curvature than smaller grains, therefore textural equilibrium results in an increase in size of the larger crystals at the expense of the smaller grains (Hunter 1987). This is termed grain growth or Ostwald ripening.

Ostwald ripening occurs through further growth into pore spaces within the framework. Closed system crystal overgrowth will produce normally zoned crystals, reflecting the evolution of the melt composition. Overgrowth within an open-system, where porous media convection can operate between the interconnected pore spaces, has the potential to produce high modal contents of a particular mineral. However, the permeability of the crystal framework will decrease as overgrowth continues, so the very final stages of crystallisation will probably take place under closed system conditions, when remaining pore spaces are no longer connected (Hunter 1987). Textural equilibrium may only be achieved on a local scale, the length of which is limited by diffusion/transport.

It is important to note that since textural equilibration is diffusion controlled, equilibration may operate above and below the solidus (Hunter 1987).

1.3. Geological setting of the intrusions studied

Magmatic layering and the small-scale features described above are well preserved in some of the deeply eroded central igneous complexes of the British and Irish Palaeogene Igneous Province (BPIP) in NW Scotland (Fig. 1.1; Bell and Williamson 2002), the site of intense igneous activity during the Palaeocene and early Eocene (ca. 63–52 Ma) due to continental separation and lithospheric attenuation during the early stages of the opening of the North Atlantic (Woodcock and Strachan 2000; Bell and Williamson 2002). Notable examples of layered intrusions in the BPIP include in particular the large mafic to ultramafic bodies on the Isles of Rum and Skye. Other well-known mafic intrusions (of the British and Irish Palaeogene Igneous Province central complexes) are the arcuate gabbroic intrusions of the Mull and Ardnamurchan igneous centres, NW Scotland and the Carlingford ‘Later Gabbros’ in Co. Louth, Ireland.

Whilst considerable research has been carried out on magmatic layering in the Rum Layered Suite (see Emeleus *et al.* 1996 for review), much less work has been done on layering and small-scale structures in the central igneous complexes of Skye, Ardnamurchan, and Carlingford (e.g. Harker 1904; Richey and Thomas 1930; Richey 1932; Le Bas 1960). Though layering in some of the mafic and ultramafic intrusions of Skye is comparable to that of Rum (e.g. the Druim Hain layered gabbro), a paucity of work carried out on these rocks in Skye can probably be attributed to remoteness and difficulty of terrain combining to make the area much less accessible. Unlike the Rum and Skye centres, the mafic annular intrusions of Mull, Ardnamurchan and Carlingford are not well-layered and are in general much less well understood (Wager and Brown 1968; Bell and Williamson 2002). The arcuate gabbro intrusions of Ardnamurchan have historically been interpreted as a sequence of ring-dykes, circular sheet intrusions that develop due to ascent of magma triggered by central block subsidence which, when fully formed, comprise a flat-lying roof as well as steeply outward-dipping walls on all sides (Richey and Thomas 1930; Anderson 1936; Roche *et al.* 2000). The Carlingford ‘Later Gabbros’ form a single annular mafic intrusion that has also been interpreted as a ring-dyke (Richey 1932), a model that was contested by Le Bas (1960) based on detailed field and petrological observations. Both the Ardnamurchan Centre 3 gabbros and the Carlingford ‘Later Gabbros’ have been interpreted as having steeply outward dipping contacts, but locally exhibit inward dipping magmatic layering and lamination (e.g. the Ardnamurchan Centre 3 ‘fluxion gabbros’), a phenomenon that still lacks a convincing

explanation in the context of their overall geometries and emplacement histories. Despite this, some of them, e.g. the Great Eucrite of Centre 3 in Ardnamurchan, have remained type examples for high level magma emplacement mechanisms, such as ring-dyking, since the original work by Richey in the 1930s without serious reinvestigation (Emeleus and Bell 2005).

1.4. Thesis Aims and Objectives.

The principal aims of this work are summarised as follows:

- To apply the Anisotropy of Magnetic Susceptibility (AMS) method to the comparatively poorly understood partially-layered Centre 3 Great Eucrite gabbro of Ardnamurchan and the Carlingford 'Later Gabbros' in an attempt to better understand their internal structure and geometry. The sensitivity of the AMS method means that magnetic fabrics extracted from these (generally) macroscopically isotropic gabbros may provide an insight into the above and hence clues to the overall emplacement mechanisms for each intrusion.
- To make detailed observations on the nature of AMS fabrics in strongly-laminated rocks from well layered intrusions. The objective here is to assess whether the magnetic foliation corresponds to the (planar) igneous lamination and whether a consistently oriented magnetic lineation (at an intrusion scale) can be observed on magnetic foliation planes. Superb examples of igneous lamination occur in the troctolites of the Rum Eastern Layered Series, the so-called 'fluxion gabbros' of Ardnamurchan and the layered gabbros of Druim Hain on the Isle of Skye. Detailed AMS datasets are compiled for each set of laminated rocks and in the case of Skye and Ardnamurchan, combined with quantitative textural (Crystal Size Distribution; CSD) datasets, with a view to discussing the implications for layer and lamination acquisition mechanisms and subsequent development in these mafic rocks. The implications of these observations for magma chamber processes and magma chamber evolution are discussed.
- To apply the AMS and CSD techniques to a magmatic fabric other than layer-parallel igneous lamination in mafic rocks, i.e. harrisitic structure from the Rum Western Layered Series. The objective here is to test the usefulness of both methods in providing quantitative fabric and textural data that can be used to derive a model for harrisite formation.

1.5. Thesis Outline.

Chapter 1 serves as an introduction to this study. It gives a broad overview of the important processes by which rock fabrics and textures in cumulate rocks are thought to form, and references important studies that have developed ideas in the field of layering in mafic and ultramafic intrusions, particularly in the BPIP. It also briefly describes the geological setting of the intrusions studied, summarises the principal aims of the study and provides a brief outline of each of the thesis chapters.

Chapter 2 introduces the important analytical techniques used in this work, and highlights their relevance to the study in general in the context of the thesis aims and objectives. These principally include the AMS and CSD techniques. Analytical conditions for the electron microprobe work carried out on feldspar from Ardnamurchan and Skye are also described.

Chapter 3 concerns the Centre 3 gabbros of the Ardnamurchan igneous complex. Detailed remapping and field observations of the petrological variation of Centre 3 is combined with a high resolution AMS dataset from the Great Eucrite and fluxion gabbros and quantitative textural analyses (CSD) and mineral-chemical data of the latter. The importance of localised development of magmatic layering and igneous lamination throughout the gabbros of Centre 3 is evaluated with respect to the AMS data and other field observations. A model for emplacement and subsequent central subsidence of the Centre 3 gabbros is suggested based on the combined approach outlined above. Some of the results of this study are published in the journal *Geology*; the article is included in the thesis as Appendix B1. This is a multi-author paper, to which my contribution is 80%.

Chapter 4 presents the results of two independent studies carried out on two types of cumulate fabric in layered rocks of the Rum Layered Suite:

- (1) The first of these is a detailed AMS study across Unit 10 of the Eastern Layered Series (ELS), together with less detailed background sampled sites from adjacent Units 8 and 9, all the NE of the area. The AMS data is coupled with field observations and structural measurements on layering, igneous lamination and associated small-scale structures in the field. The presence of a consistently oriented magnetic fabric (lineation and foliation) is discussed with reference to field observations made in this study and other work on the area. A model for fabric formation is proposed. This study constitutes an article submitted to

the journal *Lithos* in March 2006 (see abstract in Appendix B2), where it has been recently (June 2006) accepted for publication pending moderate revision. It is also a multi-author paper, to which my contribution is 60%. Sampling and data analyses were originally carried out by the late R.B. Hargraves (formerly of Princeton University (U.S.A.)), who died in March 2003. For this reason, it has not been possible to present this AMS data in exactly the same manner as for the other AMS studies in the thesis. However, two additional samples were selected from Unit 9 and 10 of the Eastern Layered Intrusion and measured in detail for their AMS fabrics using the same procedure as for the Ardnamurchan, Skye and Carlingford samples. These results are presented in Appendix A1 where they are compared with the data in Chapter 4 and with magmatic layering in the Eastern Layered Intrusion.

- (2) The second study on Rum is a CSD study of another type of fabric associated with layering on Rum, crescumulate or harrisitic structure at Ard Mheall in the Western Layered Series. The quantitative textural data are combined with field observations and AMS data from several sites to assess fabric/texture development in these rocks. The results of this study have important implications for layer formation in, and open system evolution of, the Rum magma chamber as a whole. This study was submitted to *Journal of Petrology* in March 2006 (see abstract in Appendix B3) and will be published there in early 2007. It is also a multi-author paper to which my contribution is 80%.

Chapter 5 presents results of a detailed AMS study of the exceptionally well-layered Druim Hain Gabbro, Skye, NW Scotland. The primary objective of this study is again to evaluate how magnetic fabrics in layered rocks behave with respect to the macroscopic well-developed layer parallel igneous lamination observed (and in particular to investigate the magnetic lineation). The AMS data are combined with field observations, detailed field structural measurements, crystal size distribution measurements and mineral-chemical data in order to suggest potential layer forming processes for this particular sequence of layers.

Chapter 6 presents the results of a detailed AMS study of the poorly layered Carlingford Later Gabbros, and interprets these in the context of several field observations and previous work on this central complex. The AMS studies on the Ardnamurchan Great Euclite of this study (in which magmatic layering is better preserved) are also considered for the interpretation of the Carlingford Later Gabbros. The results presented in this chapter have

recently been submitted (August 2006) and accepted (September 2006) for publication in the *Irish Journal of Earth Sciences* (see abstract in Appendix B4).

Chapter 7 is a short summary of the main findings of this work.

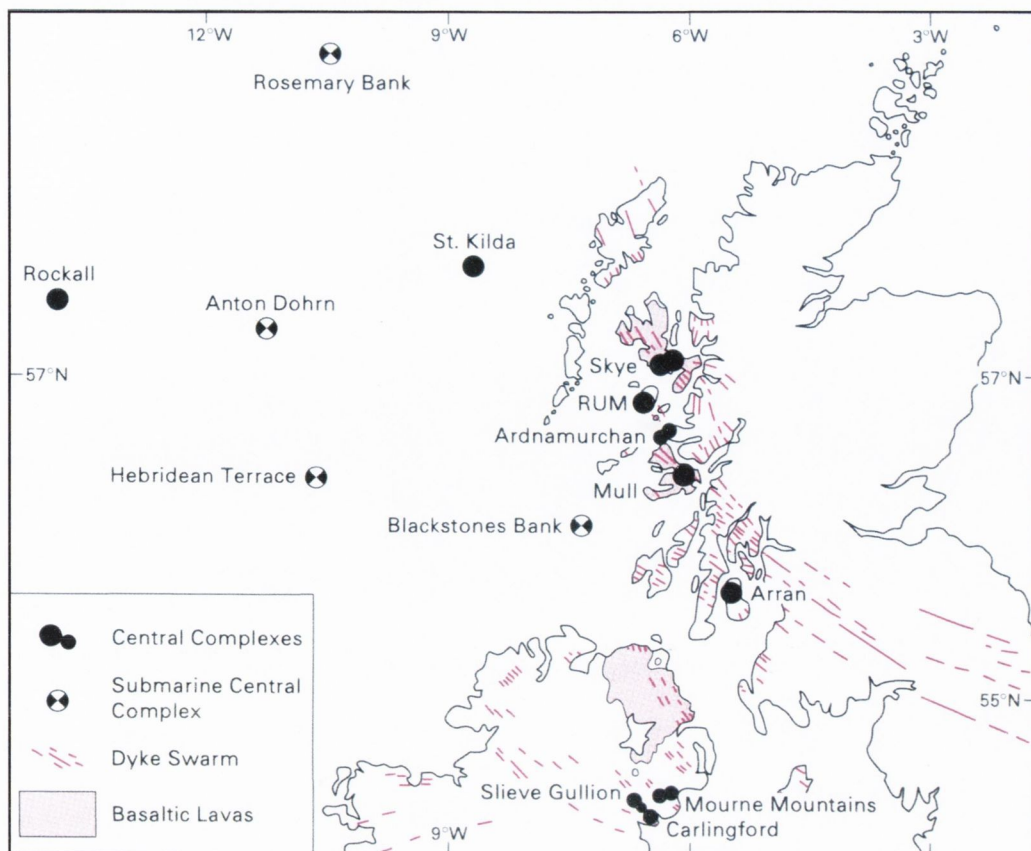


Figure 1.1. Sketch map of the Palaeogene central complexes of NW Scotland and NE Ireland (reproduced from Emeleus 1997).

CHAPTER 2. THEORY AND METHODOLOGIES

2.1. Introduction

Considerable controversy surrounds the development of magmatic layering and associated layer parallel igneous lamination observed in many mafic-ultramafic intrusions. In addition to the classic cumulus theory of Wager and Brown (1968) that attributed layering and lamination to crystal settling and magmatic sedimentation processes, an extensive array of models including monomineralic phase-precipitation, melt migration due to compaction, and in-situ crystallization (oscillatory nucleation and growth) have also been held responsible (e.g. Jackson 1961; McBirney and Noyes 1979; Hunter 1987; McBirney and Nicolas 1997; Boudreau and McBirney 1997; Irvine *et al.* 1998; O'Driscoll *et al.* 2005, see also Chapter 1). Even in cases where layering and igneous lamination are exceptionally well-developed, it is often difficult to unequivocally attribute layer development to any one of the models mentioned above. In many layered intrusions, e.g. the Rum Layered Suite, a variety of post-cumulus processes is envisaged to have modified the primary mineralogies and textures of layered rocks at a variety of scales (Butcher *et al.* 1985; Young *et al.* 1988; Emeleus *et al.* 1996; Holness 2005; Holness *et al.* 2005). These include compaction, liquid migration, channeled and infiltration metasomatism, and textural re-equilibration.

It is therefore often difficult to deduce magmatic layer forming processes from sequences of layered rocks in the absence of established current flow indicators such as macroscopic linear arrangements of crystals (magmatic lineations) or sedimentary structures (scour structures or cross bedding) that indicate current flow. Indeed, even where the latter field evidence is available, the possibility exists that subsequent postcumulus processes may enhance or accentuate magmatic layers (e.g. O'Driscoll *et al.* 2005).

This study combines two modern methods of igneous fabric (AMS) and quantitative textural (CSD) analysis to examine different examples of layered and partially layered intrusions. This integrated approach will demonstrate that it may be possible to elucidate and interpret the relative importance of competing primary and secondary processes of cumulate formation.

2.2. The Anisotropy of Magnetic Susceptibility (AMS) technique

2.2.1. Anisotropy of Magnetic Susceptibility

The anisotropy of magnetic susceptibility (AMS) of igneous rocks can be used as a magma flow indicator to a very high degree of accuracy, and for fabrics with anisotropies of only a few percent (Hargraves *et al.*, 1991; Rochette *et al.*, 1992; Canon-Tapia *et al.*, 1996). However, though the technique has greatly benefited

understanding of magma flow in dykes and lava flows of varying composition and intrusive granitoids, there is comparatively little AMS work reported in the literature on large laccolithic or lopolithic, layered, mafic-ultramafic intrusions (Ferré *et al.* 2002).

The differing magnetic susceptibilities of different minerals arise from atomic and molecular variations within the crystal lattice. The magnetic susceptibility (**K**) of a mineral refers to the susceptibility of that mineral or rock to become magnetised (i.e. how magnetisable it is) and is the relationship between the induced magnetisation of the material and the applied field strength (B). Thus the magnetisation (M) is given by:

$$M = KB$$

and **K** is dimensionless and measured in SI.

The susceptibility of rocks is anisotropic (Owens and Bamford, 1976). The susceptibility tensor (**K**) comprises a number of linked parameters; **K_{mean}**, **H**, **μ** (defined below) and the principal axis directions is one representation. **K₁** is the axis of maximum susceptibility, **K₂** is the axis of intermediate susceptibility and **K₃** is the axis of minimum susceptibility (**K_{mean}** is the average of these three). Thus the anisotropy of magnetic susceptibility (AMS) of a rock may be described as a 2nd order tensor (or susceptibility ellipsoid) with three orthogonal, unequal axes (Fig. 2.1). In the simple case where there is a simple mineralogy with grains that do not interact magnetically, the bulk susceptibility (**K_{mean}**) is a measure of the amount of magnetic carrier present (i.e. as a general rule for ferromagnetic rocks the value of **K_{mean}** is equal to three times the volume (%) of magnetic carrier; Balsley and Buddington 1958). **H** and **μ** are ratios which are normalised to a **K** of 1 therefore also for the amount of magnetic carrier. **H** is the anisotropy degree which is the strength of the magnetic anisotropy in percent and **μ** is the shape of the anisotropy. **H** is also the sum of the magnetic lineation [**L** = (**K₁**-**K₂**)/**K_{mean}**] and magnetic foliation [**F** = (**K₂**-**K₃**)/**K_{mean}**]. The **μ** value relates to such terms as oblate (0 < **μ** < 45) where **K₁** = **K₂** >> **K₃**, and prolate (45 < **μ** < 90) where **K₁** >> **K₂** = **K₃** (Fig. 2.4A-C).

Unless otherwise specified, AMS measurements in this study were carried out on 8-14 sub-samples drilled from field oriented block specimens using an AGICO KLY3 Kappabridge instrument, which measures specimen susceptibility axes to within ±2° (95% confidence limits). Magnetic fabric data are most often presented in this study as lower hemisphere equal area stereographic plots of the mean principal susceptibility axes for each

block sample, on a map of the relevant intrusion (e.g. Figs. 3.16; 3.21). This style of data presentation gives a good estimate of both the shape and the orientation of the mean susceptibility ellipsoid for each block sample. The mean shape of the ellipsoid is given by the shape of the confidence ellipses around each susceptibility axis. This is because the size of the ellipse semi-axis in each principal plane varies inversely as the difference between the two principal susceptibilities in that plane (Jelinek 1978; Owens 2000). Therefore, an oblate fabric will have a small circular confidence ellipse around the minimum susceptibility axis, with the other two confidence ellipses elongated in the foliation plane (e.g. Fig. 2.2A), whilst a triaxial fabric will have confidence ellipses around the maximum and minimum axes that are both elongated toward the intermediate axis. The confidence ellipse area around the intermediate axis in the case of the latter will be larger and more circular than the other two. The overall size of the confidence ellipses for the mean principal directions for a sample, if based on a constant number of sub-samples, gives a relative indication of the strength or scatter of specimen anisotropies within a block; the larger the ellipse, the greater the scatter and the weaker the fabric (Owens 2000; Fig. 2.2B). AMS ellipsoid shapes may also be estimated from an **L/F** plot, which plots the mean linear element of the magnetic fabric of a block against the mean planar element. **L/F** plots are also presented for each dataset studied. Simplified diagrams of AMS fabrics in terms of commonly used structural planar and linear fabric symbols are also presented for each dataset. Detailed representations of the magnetic susceptibility ellipsoids for each block specimen including individual sub-sample data are presented in Appendix A1.

2.2.2. Rock Magnetism

Above absolute zero, all minerals can be said to be magnetic if there is an orbital motion of charged particles, particularly of the negatively charged electrons, in a compound or molecule. The three major types of magnetization, diamagnetism, paramagnetism and ferromagnetism are summarized below and in Figure 2.3.

2.2.2.1. Diamagnetism and paramagnetism

Diamagnetic minerals have complete electron shells. All minerals exhibit diamagnetic properties when placed in a magnetic field, manifested by the acquisition of a very weak temperature independent induced magnetism in the opposite direction to the applied magnetic field (Dunlop and Özdemir 1997). Thus diamagnetic minerals have small negative susceptibilities ($\sim -1.4 \times 10^{-5}$ SI; Rochette 1987). This magnetism is reversible; upon removal of

the applied field, no remanent magnetization remains and the electron spins are once again randomised. Quartz and feldspar are examples of purely diamagnetic minerals.

The electron shells of paramagnetic minerals are incomplete. Minerals that react paramagnetically to an applied magnetic field acquire a weak, temperature dependent induced magnetization in the same direction as the applied field (Dunlop and Özdemir 1997). Thus paramagnetic minerals have positive (10^{-2} to 10^{-4} SI) susceptibilities. Whilst M (the induced magnetization) is still weak, it is a lot stronger than the diamagnetic response, which will be swamped by any paramagnetic behaviour. The induced magnetization is linear and reversible, i.e. paramagnetism is lost as soon as the external magnetizing field is removed. Biotite, hornblende and the pyroxene group are all examples of paramagnetic minerals.

2.2.2.2. Ferromagnetism (*sensu lato*)

Some minerals have very much stronger positive susceptibilities than paramagnetic substances and may also carry a strong remanent magnetization i.e. a magnetization remaining after the external magnetizing field is removed (O'Reilly 1984; Dunlop and Özdemir 1997). Such minerals are ferromagnetic (*sensu lato*). This magnetization occurs because electron spins are coupled so that all individual spin magnetizations (domains) are aligned even without the applied field. Elements that belong to the first transition series such as iron, nickel and cobalt often show this type of magnetization.

Ferromagnetism (*sensu lato*) can be further divided into ferromagnetism (*sensu stricto*), antiferromagnetism and ferrimagnetism as follows (and see Tarling and Hrouda 1993; Dunlop and Özdemir 1997 for a more comprehensive review):

1. Ferromagnetism (*sensu stricto*) occurs when there has been either form of quantum-mechanical coupling forces (exchange and super-exchange) linking the electron spins in ferromagnetic materials. In metallic substances such as iron, nickel and cobalt, the electron spins of adjacent cations are directly coupled so that the magnetic vectors are aligned in the same direction. Ferromagnetic minerals can thus acquire and retain a very strong magnetization (O'Reilly 1984).

2. Antiferromagnetic minerals have magnetic alignments that are not parallel and equally strongly magnetized. This results in a strong internal field but no net magnetization once an applied field is removed. However, some antiferromagnetic minerals, (e.g. haematite) can exhibit a magnetization that is weaker than ferromagnetism but

is stable. This is called parasitic magnetism and is the result of lattice imperfections that make the magnetic lattice antiparallel.

3. Ferrimagnetism occurs when a lattice is more strongly magnetized than another. The magnetic alignment is antiparallel but each couple is not of the same magnitude giving it a net magnetic field. It retains a weaker external field than ferromagnetic (*sensu stricto*). An example of such a mineral is magnetite.

2.2.3. Magnetic fabrics and Domain Theory

Magnetic fabrics in rocks arise from the preferred orientation of individually anisotropic magnetic grains (Rochette *et al.* 1992; Tarling and Hrouda 1993). In diamagnetic and paramagnetic minerals the grain anisotropy is crystallographically controlled; in a rock constructed of such grains a resultant anisotropy related to preferred orientation by grain shape will only arise if the grain habit is crystallographically determined (the link between grain shape and grain magnetic anisotropy is indirect). Haematite is also sufficiently weakly magnetic for its magnetic anisotropy to be dominated by crystallographic effects. Such crystallographically controlled anisotropy is widespread in silicate rocks (Rochette *et al.* 1992).

In strongly ferrimagnetic minerals (magnetite and maghemite) shape-related magnetic anisotropy or shape anisotropy is dominant (Rochette *et al.* 1992; Gregoire *et al.* 1998). In a strongly magnetic inequant grain, e.g. of magnetite or maghemite, the magnetization will lie preferentially parallel to the grain long axis. This can be understood in terms of minimization of energy of the external magnetic field caused by the magnetization, or alternatively in terms of the demagnetizing field within the grain caused by the distribution of north and south poles over the surface of the grain. When the grain is magnetized along its long axis, these poles are furthest apart and the demagnetizing field is therefore the weakest. In a weakly magnetic, e.g. paramagnetic grain these effects are insignificant. Within ferromagnetic grains magnetic domain structures determine the effect that grain shape has on anisotropy, giving rise to diametrically opposite effects in single- and multidomain grains. The influence of domain structure on low-field anisotropy is described below and in Figures 2.4 and 2.5.

2.2.3.1. Multidomain (MD) magnetic grains

These grains have $>20\ \mu\text{m}$ diameter and contain multiple domains which are separated by a Bloch wall (the boundary between magnetic domains). Across the Bloch wall the magnetic direction changes. In the absence of an external field the domains arrange themselves so that the magnetostatic forces are at a minimum (Fig. 2.4A)

but once a field is applied domain walls shift to enlarge those domains that are parallel to the direction of the net internal field (the resultant of the applied field and the shape-related demagnetizing field) at the expense of the others (Fig. 2.4B and 2.4C). In the case of initial low-field susceptibility the domain walls are elastic and partially reversible (Fig. 2.4D). Thus, in a MD grain, an applied field causes an induced magnetization and this magnetization is greatest when the field is applied parallel to the grain long axis. In this way, the susceptibility anisotropy is directly related to the grain shape.

2.2.3.2. *Single domain (SD) grains*

In small grains ($<1\ \mu\text{m}$ for elongate magnetite $<0.1\ \mu\text{m}$ for equant magnetite) it is energetically unfavourable for the grains to develop domain walls and a single domain grain exists (Fig. 2.5A). Whilst MD grains experience magnetisations relatively easily due to the translations of Bloch walls, SD grains require that the field overcomes the exchange energy. Thus, application of a magnetic field parallel to the long axes of SD grains will do nothing to alter the magnetization, as under low field susceptibility anisotropy the field is too weak to flip grain magnetization (Fig. 2.5B). By contrast, application of a field perpendicular to SD grain long-axes will cause a small deflection of grain magnetisation away from its preferred direction, giving a small net induced magnetization attributable to a finite, if small, anisotropy (Fig. 2.5C). In the case of SD grains therefore the susceptibility anisotropy is inversely related to grain shape (Borradaile 1987; Rochette *et al.* 1992).

2.2.3.3. *Pseudo-single domain grains*

These are similar to MD grains but the domains don't interact with one another due to lattice imperfections, i.e. due to small grain size, domain walls cannot shift when a magnetic field is applied and are effectively pinned in place (Dunlop and Özdemir 1997). They generally occur when grain volumes are between those of MD and SD ($1\text{--}20\ \mu\text{m}$).

2.2.4. Application of the AMS technique in this study

Magnetite is the major ferromagnetic mineral. It need only be present in very small amounts ($<1\%$ volume of rock) to dominate the susceptibility of a rock sample. In this study, where all of the samples studied are mafic and ultramafic rocks, it can be shown from the susceptibility measurements that magnetite is present in every sample analysed. It is therefore extremely important to know if the magnetite is dominated by MD, SD or

PSD grains. MD grains typically dominate in medium-coarse grained rocks (gabbro or granite), whilst SD and PSD grains become more important in fine-grained rocks such as basalts. In MD grains, the presence of domains means that the anisotropy of susceptibility is largely controlled by their shape, whereas their crystalline anisotropy is slight (Rochette *et al.* 1992). This makes MD grains very useful in AMS studies as the magnetic anisotropy of the crystal reflects the shape orientation of that crystal (or the shape-preferred orientation (SPO) of that phase). Thus, in a gabbroic rock in which the susceptibility is controlled predominantly by magnetite, the anisotropy of susceptibility is directly related to the shape preferred orientation of the magnetite grains. AMS data from SD grains, on the other hand, tend to be difficult to interpret as they often yield inverse fabrics (Borradaile 1987; Rochette *et al.* 1992).

2.3. Textural quantification: Crystal Size Distribution analysis

In recent years there has been a marked increase in the number of studies which look in detail at the quantification of crystal populations in rocks using advanced textural analysis techniques (Jerram and Kent 2006). The key elements of the quantification of crystals in a rock are: (1) the size distribution (e.g. Marsh 1998; Jerram 2001), (2) the spatial distribution (e.g. Jerram *et al.* 1996; Jerram and Cheadle 2000), and (3) the shape of crystals (e.g. Higgins 1994; Mock and Jerram 2005; Morgan and Jerram 2006). In this contribution we employ the study of Crystal Size Distributions (CSDs) in the quantification of harrisite and granular olivine textures. This requires the quantification of both the size and shape elements of the crystal population. Below we discuss CSD theory and its application to igneous systems, and then introduce the procedure by which CSDs were measured in this study.

2.3.1. CSD Theory

CSD analyses are a quantitative measure of the number of crystals of a mineral per unit volume within a series of defined size intervals. Crystal size in igneous rocks carries information on growth rate and nucleation, and thus CSDs have been used as a method of determining some of the crystallization kinetics of magmatic systems independent of experimental approaches and thermodynamic or kinetic models (e.g. Cashman and Marsh 1988; Resmini and Marsh 1995; Marsh 1998; Higgins 2002a; Boorman *et al.* 2004). A CSD plot is generally shown as a semi-logarithmic plot of population density (number of crystals per unit volume) against crystal size (maximum length).

Marsh (1988; 1998) suggested two end-member CSD models for igneous petrology; an open-system, or steady-state model and a closed-system (batch) model. Both of these studies derive conservation equations for CSDs in different geological systems and show how these may be used to extract information on crystal growth rates and nucleation rates from population densities. The first open-system model describes a steady-state population balance of crystals growing into and out of a specific size range (L), while at the same time physically circulating into and out of a system (Marsh 1988). Continuous crystallization results in a straight, or log-linear, CSD plot. This model is described by the equation:

$$n = n^0 \exp (-L / G\tau)$$

where n is the population density, n^0 is the nucleation density, the intercept of the curve on the Y-axis, G is the crystal growth rate, and τ is the magma chamber residence time or growth time of the crystals in the system. This steady-state model assumes that G is constant and independent of L and that nucleation rate is constant as well.

The second batch (Avrami-type) model of Marsh (1998) allows no input or output of crystals, and therefore cannot be described as a steady-state system. The volume of actively crystallizing magma decreases with time, conditions that might be satisfied by a lava lake (e.g. Cashman and Marsh 1988), but not a magma chamber (particularly an open-system magma reservoir). Marsh (1988; 1998) showed that under certain conditions (e.g. exponentially increasing nucleation rate with a constant growth rate), a batch system might also produce linear CSDs.

The texture produced in an open-system end-member model might be envisaged as resulting solely from the processes of nucleation and growth. The studies of Marsh (1988; 1998) suggest that the CSDs measured from such initial textures approximate a semi-logarithmic distribution, i.e. result in a log-linear plot (Fig. 2.6A). Such textures have been referred to as 'kinetic' in origin (e.g. Higgins 2006). Kinking or curvature in the CSD plot profile has been attributed to processes such as crystal accumulation and removal (Marsh 1998), compaction (Boorman *et al.* 2004), mixing of crystal populations (Jerram *et al.* 2003; Turner *et al.* 2003) and post-nucleation crystal ageing caused by annealing or Ostwald ripening (Figs. 2.6B-2.6G). Indeed, Higgins (2002a) and Boorman *et al.* (2004) have used CSD analysis to show that primary igneous textures may be strongly modified by both crystal coarsening and compaction-driven recrystallisation.

Marsh (1998) examined a range of CSDs from a number of intrusive and extrusive igneous settings and found that none of these systems showed CSDs typical of purely batch or open-system behaviour, each exhibiting instead a combination of the characteristics of each model. Although it is likely therefore that a given CSD reflects aspects of each end-member model, Marsh (1988; 1998) proposed generally applicable or *effective* values of crystal growth times for CSD interpretation based on the steady-state model:

$$\ln(n) = -(1/G\tau)L + \ln(n^0)$$

or

$$m = -1/G\tau$$

where **m** is the slope of the CSD curve. Nucleation rate (**J**) may also be extracted from the CSD plot through:

$$J = n^0 G$$

We will utilize the proposition of Marsh (1998) that initial (unmodified) ‘kinetic’ textures produce straight CSDs in our interpretation of the textural data presented here. Subsequent modification of the straight CSD is interpreted on the basis of hand specimen and thin section petrography, and also based on what is known of the magmatic system in question.

2.3.2 Procedure

CSDs of cumulates were measured in this thesis in the following way. Individual crystals were identified and outlined on hard-copy overlays of high-resolution photomicrographs of single thin sections with the aid of a microscope. This texture overlay was then edited into a simple bitmap format before being opened into the UTHSCSA ImageTool, a freeware image analysis software package (Fig. 2.7; ddsdx.uthscsa.edu/dig/itdesc.html). The image scale was set and the crystals were analysed for their area and the orientation and length of their long and short axes in a texture map of each sample (Fig. 2.7). The smallest crystals measured in this study were approximately 0.1mm in size. These were the smallest grains observed at 25 times magnification and were easily large enough to be counted in the analysis. As all of the samples measured are holocrystalline, it is considered that all crystals have been measured for each sample, and we therefore take the smallest grain size reported for

each sample as the limit for that sample. Initial CSD analysis was subsequently carried out as outlined by Higgins (2002a); the size distributions of the long axes of crystals were measured and corrected for 2D-3D effects using the method and software of Higgins (2000, *CSDCorrections* version 1.37). There are several steps involved in the (stereological) conversion of the 2-dimensional thin-section measurements to the 3-dimensional CSD. The first step is to calculate the frequency distribution of the area number density using logarithmic bin sizes. To do this the number of crystals in each bin is divided by the total area measured. This gives the number density for each size interval. Corrections are then made by the *CSDCorrections* software to account for stereological effects (after Higgins 2000). The CSD programme also requires input of crystal aspect ratios and roundness factors for each dataset analysed, and these were calculated following the method of Higgins (1994, 2000) and Morgan and Jerram (2006). Many recent quantitative textural studies have used the *CSDCorrections* program by Higgins (2000), including Coogan *et al.* (2002), Jerram *et al.* (2003) and Boorman *et al.* (2004).

Boorman *et al.* (2004) highlighted problems with the *CSDCorrections* software that affect CSDs calculated for plutonic rocks in particular. One is that the software assumes crystals of a given mineral will have euhedral shapes with fixed aspect ratios, an assumption that while accurate for crystals in many volcanic rocks, will certainly not always hold true for cumulates, especially the skeletal and dendritic olivine crystal morphologies in harrisite observed in this study (Chapter 4). The second problem is that CSDs calculated for samples containing crystals with high aspect ratios will produce flatter curves than samples with more equant grains, even though both samples may have an identical Volume Phase Proportion (Higgins 2002b; Boorman *et al.* 2004). Boorman *et al.* (2004) suggested an alternative means by which the *CSDCorrections* software may be used for plutonic rocks to avoid the above problem. Instead of taking major axis length as a grainsize parameter, Feret length, the length of a square with an area equal to the measured area of the grain, is used. This requires that aspect ratios for all crystals be 1:1:1 and that the roundness factor is 0. This approach gives a good correlation between measured volume phase proportions and those calculated by *CSDCorrections*. However, as stated by Boorman *et al.* (2004), 'uncertain error is introduced in the cut section and fabric correction by the assumption of cubic shape', causing CSD curves to have much steeper slopes. This is well illustrated in Figure 2.8, which shows two CSDs for sample R15 (a harrisite sample from Rum; see Chapter 3), one calculated using Feret length, the other using maximum crystal length. In addition, Mock and Jerram (2005) and Morgan and Jerram (2006) show that assumption of a spherical crystal shape (with a similar aspect ratio to a cube) gives a poor estimation of CSD slope. As calculation of crystal growth times is dependent on the slope of the CSD, we do not employ the Feret

length method in this study. To overcome the problems outlined by Boorman *et al.* (2004), the updated version of the *CSDCorrections* software is used (version 1.37 available at <http://www.dsa.uqac.quebec.ca/~mhiggins/csdcorrections.html>, Higgins 2000), which allows the correction of the CSD to the measured Volume Phase Proportion. In addition, we use the *CSDslice* spreadsheet of Morgan and Jerram (2006) to obtain better objective estimates of olivine crystal habits in the Rum samples and the other plagioclase and pyroxene cumulates studied. Finally, Mock and Jerram (2005) estimate that a minimum of two hundred crystals should be analysed to quantify the shape of a given CSD accurately. The number of crystals measured, therefore, is presented with each CSD in this study. In most cases this number is substantially above the minimum 200 crystals required, but in some cases is close to this threshold and in very few cases it is below 200 crystals. A *CSDCorrections* output file for each sample analysed that includes both the parameters input into the program and the plotted textural data is given in the Appendix A3.

2.3.3. Closure limits

Closure limits are calculated for the CSD data following the methods outlined and recommended by Higgins (2002b). In principle, closure limits do not allow the calculated crystal content of a rock to exceed 100%, though where chemical or thermal effects limit growth of a specific mineral phase, closure occurs at lower a volumetric phase proportion (Higgins 2002b). It follows that the calculation of volumetric phase proportions from CSD curves can be used to verify that the CSDs have been correctly determined from two-dimensional measurements using the equations:

$$m = -1/C_i$$

and

$$V_i = 6\sigma n_{i0} C_i^4$$

where C_i is the characteristic length, V_i is the volumetric phase proportion, σ is a shape factor, and n_{i0} is the final nucleation density. However, the equation for V_i above is for straight CSDs only, and for more complex curves, V_i may be calculated using:

$$V_i = \sigma \sum n_i (\bar{L}_j)^3 W_j$$

after Higgins (2002b). $\bar{L}_j$ is the mean size of the interval j , and W_j is its width. The shape factor (σ) is given by the equation:

$$\sigma = [1 - (1 - \bar{L}_j^3 / L^3)]^{1/3}$$

where $\bar{L}_j$ is a measure of crystal roundness and I , S , and L are the crystal short, intermediate and long axes respectively (Higgins 2002a).

Closure limits have thus been calculated for all of the CSD data in this study for 100% crystal content, the threshold above which the CSD may not go. This provides a measure of quality of the CSD data by illustrating, if the data fall above the 100% threshold, that the stereological conversion of textural data is not giving an accurate reflection of the volume crystal content of the sample. The plot may also indicate how far below the samples plot below the maximum allowed volume phase proportion, giving an approximate visual estimation for comparison with the volume phase proportion calculated by *CSDCorrections 1.37*. The threshold curve for 100% crystal content may be constructed using the parameters C_i and n_{i0} and σ , which may be calculated from the above equation for V_i . As linear regression analysis shows that all of the CSDs presented from Ardnamurchan, Rum and Skye in this study are approximately log linear at all but the smallest crystal size fractions, it is appropriate to use the simpler equation for V_i in all cases. Higgins (2002b) also recommends plotting CSD data on a C_i vs. V_i plot for comparison of a series of CSD datasets and to identify potential groups of samples. This diagram has the advantage of being completely accessible, i.e. there are no forbidden zones. This accessibility is because the two parameters are completely independent. These two plots are therefore presented with each CSD dataset in this thesis for the following reasons:

- (a) To test the quality of the data.
- (b) To examine each dataset for well-defined internal groups or subsets.

2.4. Electron microprobe analytical conditions

Mineral analyses were performed on a Cameca SX-50 electron microprobe at GEOMAR (www.ifm-geomar.de/index.php?id=home) applying the built-in PAP correction procedure (Pouchou and Pichoir 1984). Analytical conditions included an acceleration voltage of 15 kV, a beam current of 8-20 nA and counting times of

between 20 and 60 s on peaks. A rastered beam of $3\ \mu\text{m} \times 4\ \mu\text{m}$ $12\ \mu\text{m}^2$ was used for the feldspar to minimize Na loss. Na counts were continuously monitored during analysis and generally remained stable over at least twice the measurement time (see Troll and Schmincke 2002). Relative analytical precision [(standard deviation/mean) $\times$ 100] was <2% for Si, Al, and Ca, <3% for Na and K, <4% for Ti, <5% for Fe and <10% for Mg, based on repeated analysis of natural and synthetic mineral and glass standards. All electron microprobe data are tabulated and presented in Appendix A4.

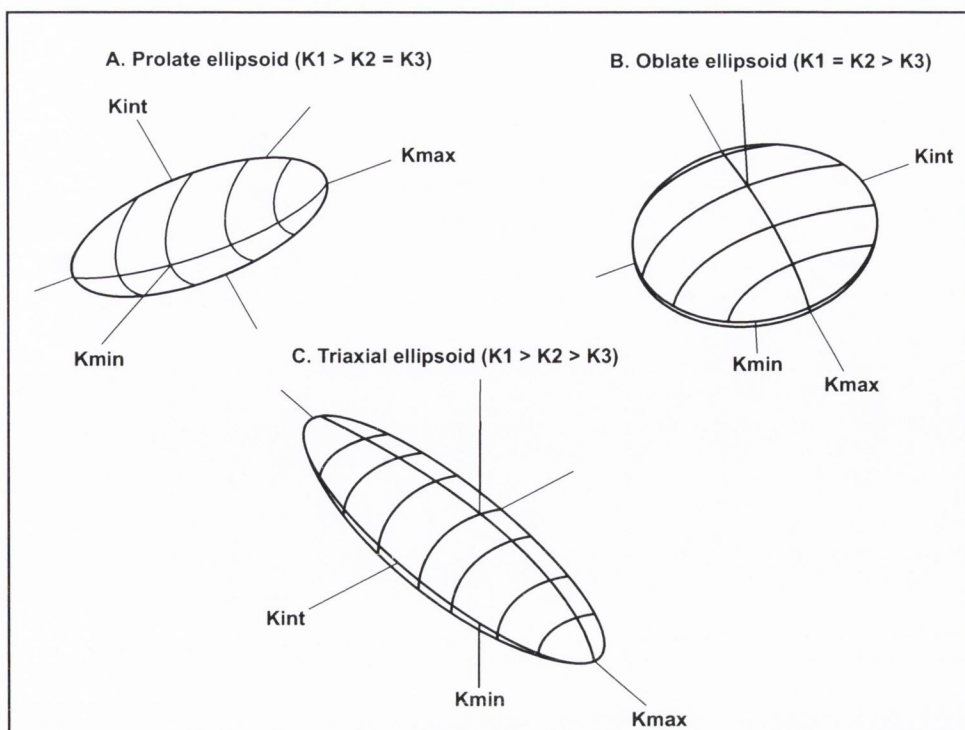


Figure 2.1. Schematic diagram showing the types of susceptibility ellipsoid. The three orthogonal axes correspond to the maximum (K_{max}), intermediate (K_{int}) and minimum (K_{min}) susceptibility values. A: Prolate ellipsoid. B: Oblate ellipsoid. C: Triaxial ellipsoid. (adapted from Tarling and Hrouda 1993).

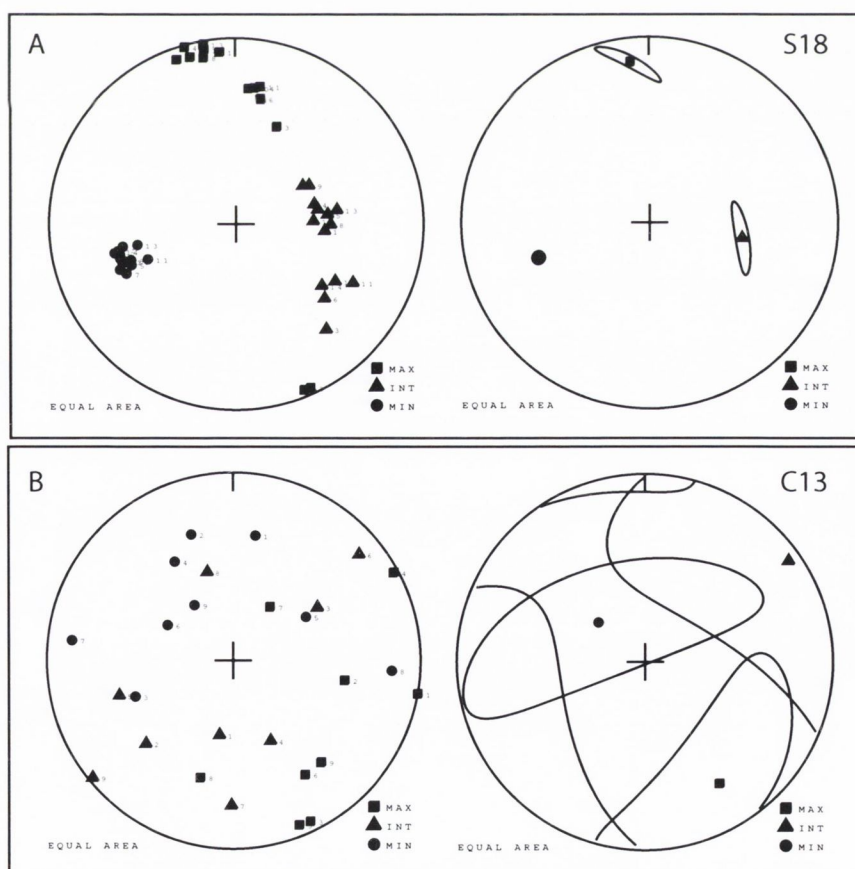


Figure 2.2. Equal-area lower hemisphere stereographic plots of individual sub-samples and block means with confidence ellipses of A: Sample S18 (Chapter 5) illustrating a highly oblate fabric and B: Sample C13 (Chapter 6) illustrating a more poorly defined fabric that can be accepted, but with caution.

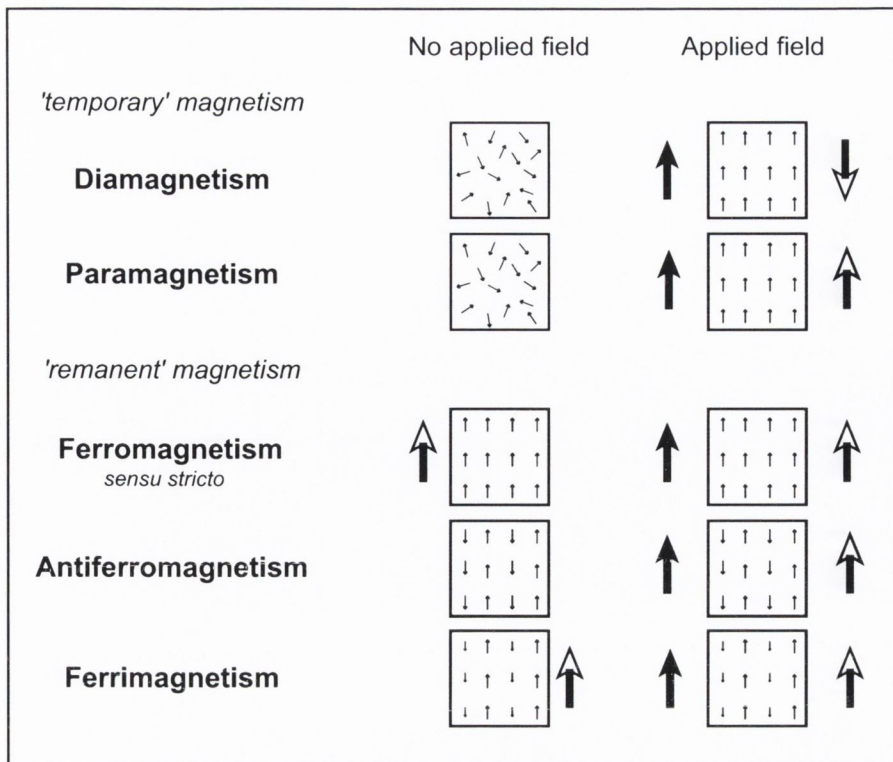


Figure 2.3. Schematic diagram summarizing the different types of rock magnetism. Hollow arrows represent the direction of net magnetization; bold arrows represent the direction of the applied field (adapted from Tarling and Hrouda 1993).

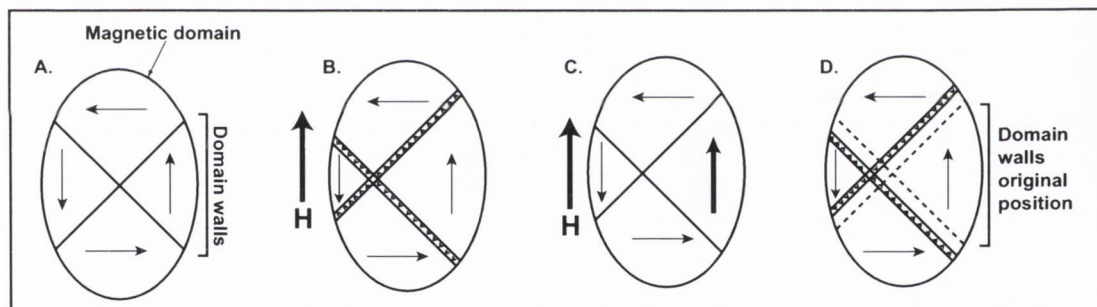


Figure 2.4. A: An MD ferromagnetic grain in a zero field. B: Upon application of a magnetic field, H , the domain walls shift. C: Favourably oriented domains will be enlarged. D: Upon removal of the magnetic field, domain walls shift back to their original position but stop short resulting in a remanent magnetization (redrawn from Dunlop and Özdemir 1997).

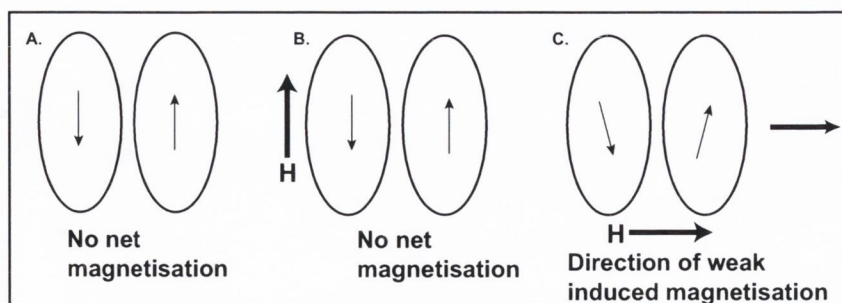


Figure 2.5. A: Two parallel elongate SD ferromagnetic grains in zero field. B: Application of a weak magnetic field, H , parallel to the elongation direction produces no net magnetization. C: Application of a weak magnetic field, H , perpendicular to the elongation direction produces a weak induced magnetization parallel to the field (redrawn from Dunlop and Özdemir 1997).

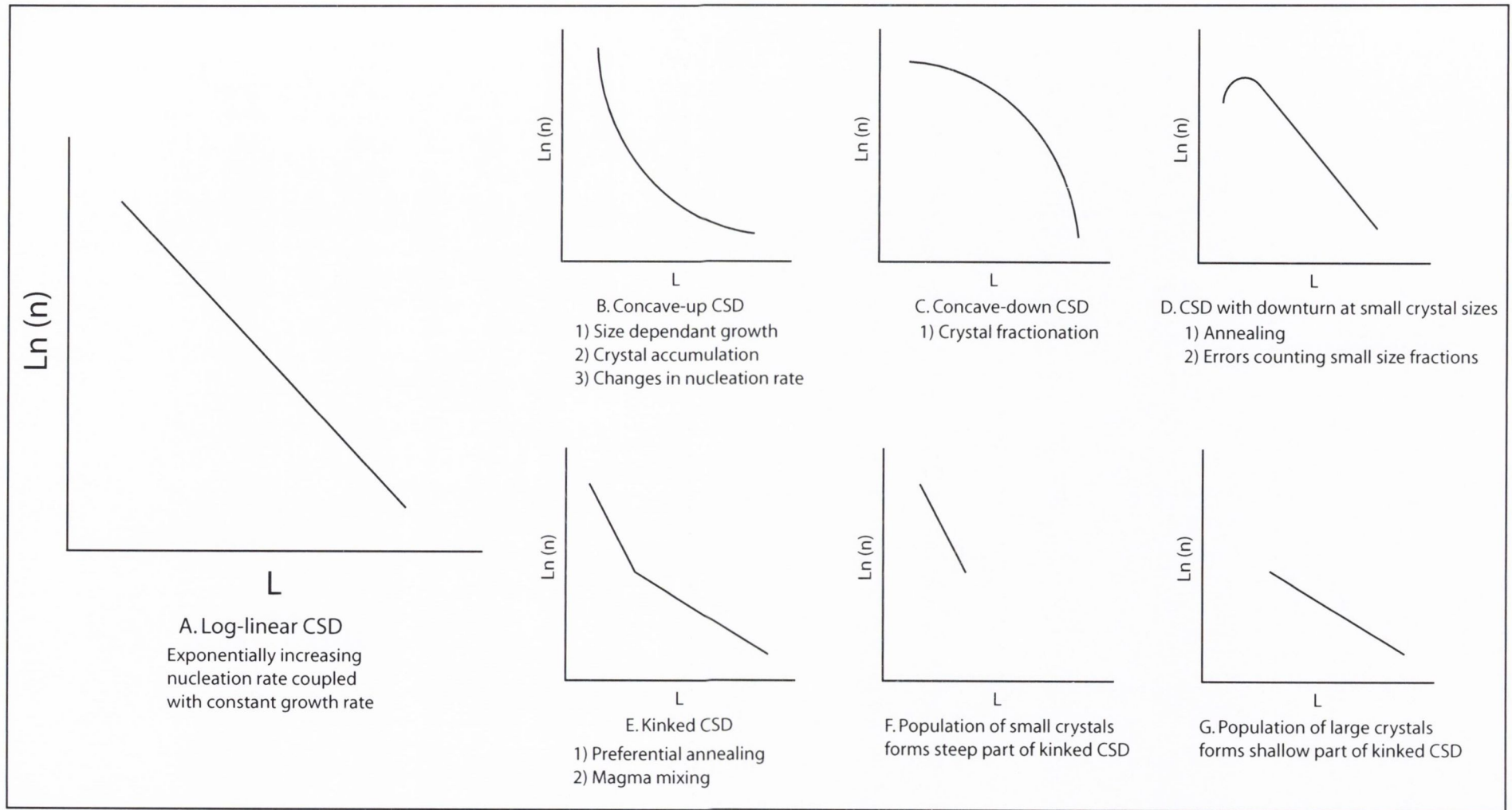


Figure 2.6. Summary diagram of differently shaped CSD curves together with possible interpretations (based on interpretations of CSD curves given in Marsh 1988 and Marsh 1998).

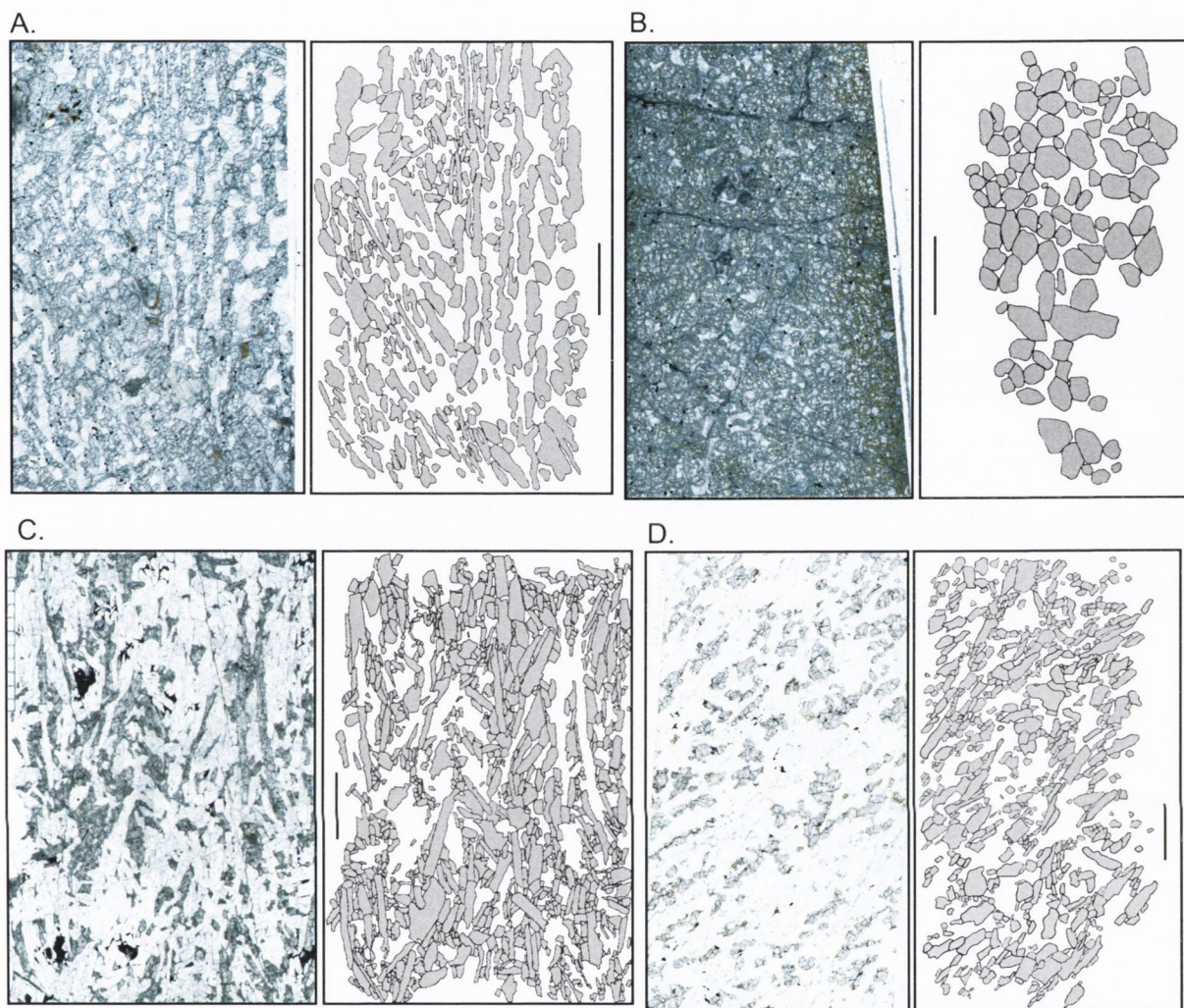


Figure 2.7. Examples of original thin-section images together with corresponding 'edited', greyscale texture maps. A: Skeletal olivine in Sample R15 (Chapter 4). B: Granular olivine in Sample R1 (Chapter 4). C: Tabular plagioclase in Sample S23 (Chapter 5). D: Tabular plagioclase in Sample 4 from the Ardnamurchan Achnaha laminated gabbro (Chapter 3). The small vertically oriented scalebar displayed in each edited texture map is 5 mm and corresponds to each photomicrograph/digitised image pair.

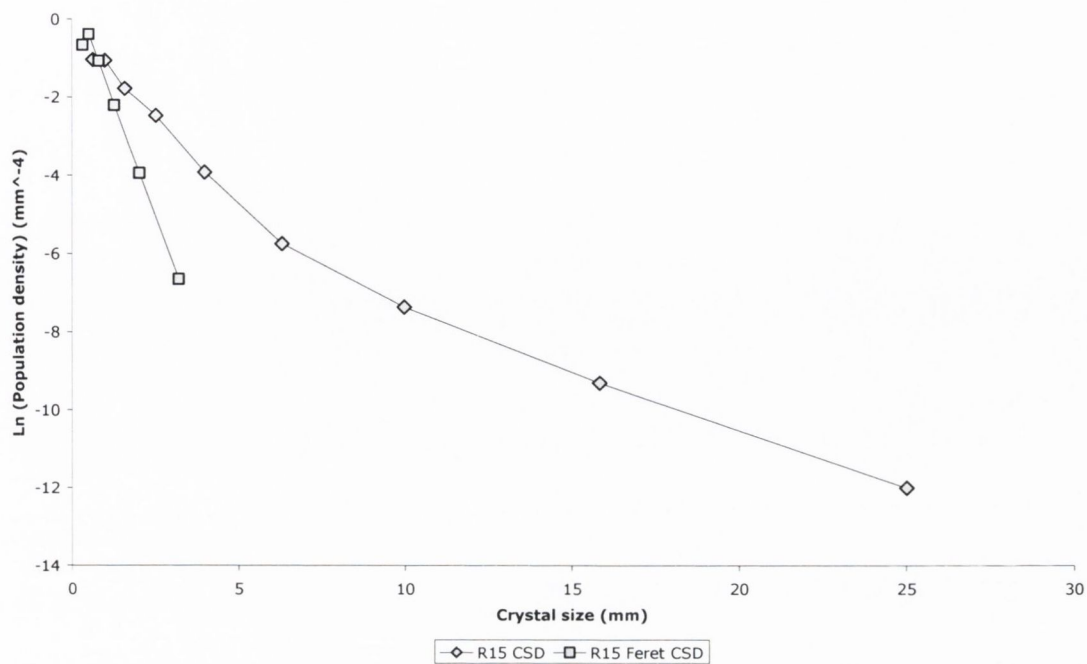


Figure 2.8. Two plots of CSD data for the same sample (R15; Chapter 4) from the Rum Layered Suite, illustrating the markedly different slope magnitudes returned by the CSDCorrections program for the different crystal size parameters: major axis length and Feret length (see discussion in text on Pages 29 and 30).

CHAPTER 3. THE ARDNAMURCHAN CENTRE 3 GABBROS

3.1 Introduction

The Palaeogene igneous complex of Ardnamurchan has been described as a superb example of an eroded section through a volcanic complex (Woodcock and Strachan 2000; Bell and Williamson 2002). Volcanic activity began with the eruption of basaltic lavas onto Mesozoic sediments and Moine basement (ca. 60 Ma; Chambers *et al.* 2005), followed by the establishment of distinct foci of sub-volcanic intrusive activity, of which three have been recognized in the Ardnamurchan complex (Centres 1, 2, and 3; Richey and Thomas 1930; Woodcock and Strachan 2000; Bell and Williamson 2002). Each of these centres is dominated by mafic intrusive rocks that were emplaced either as concentric, inward-dipping sets of cone sheets related to doming and extension, or as larger annular intrusions historically interpreted as outward-dipping ring-dykes associated with central subsidence (Richey and Thomas 1930; Anderson 1936). The Centre 3 intrusions are the focus of this study (Fig. 3.1), and are described in further detail below.

The third and youngest plutonic centre of the Ardnamurchan igneous complex forms the largest and most complete set of ring-intrusions in the British Palaeogene igneous province (Fig. 3.1). Centre 3 is dominated (up to 70% by area) by a gabbroic intrusion referred to as the Great Eucrite, historically referred to as *the* classic example of a wholly complete mafic ring-dyke (Richey and Thomas 1930; Wager and Brown 1968; Woodcock and Strachan 2000; Bell and Williamson 2002). The early ring-dyke models of Richey and Thomas (1930) and Anderson (1936) envisaged caldera ring-fault development and associated subsidence of a central block as the dominant structural processes that allowed the intrusion of the Great Eucrite. Ring-faults are widely considered to be steeply outward-dipping (reverse) structures, as models for ring-dyke development require that subsidence of the central block is accommodated during collapse (Roche *et al.* 2000; Walter and Troll 2001). Ring-dykes are therefore traditionally envisaged as having a bell-jar-like geometry, forming broadly cylindrical intrusions at shallow, sub-volcanic levels (Fig. 3.2).

The Great Eucrite wholly encompasses a suite of smaller, arcuate gabbro bodies, which have also been interpreted as partial ring-dykes. In particular these include two ‘fluxion-gabbro ring-dykes’ at Sithean Mor and Glendrian, and several other quartz-gabbro ring-dykes in the Achnaha area (see Fig. 3.1, fE and qE symbols represent fluxion and quartz gabbros respectively). A central tonalite body, containing a small (more evolved) quartz monzonite zone, is considered to be a late-stage intrusion into these arcuate gabbros (Richey and Thomas 1930; Walsh and Henderson 1977; Bell and Williamson 2002; Emeleus and Bell 2005). One final intrusion occurs in Centre 3; described by Richey and Thomas as a narrow ‘quartz-dolerite ring-dyke’ (extensively net-

veined with granophyre) and the type example of a ring-dyke intrusion on Ardnamurchan (Fig. 3.1). In the recent memoir on the Palaeogene rocks of Scotland, Emeleus and Bell (2005) also refer to this latter intrusion as a ring-dyke, suggesting that its arcuate outcrop pattern implies some form of rotational or trap-door collapse subsidence model for its emplacement.

As mentioned above, the igneous complexes of the British Palaeogene Igneous Province (BPIP) are where many of the original models for sub-volcanic intrusion of ring-dykes and cone-sheets emplacement were first developed (Richey and Thomas 1930; Anderson 1936). The arcuate mafic intrusions of Centre 3 on Ardnamurchan in particular have been used as type examples for high-level magma emplacement mechanisms for the past 70 years. This interpretation has never been seriously questioned for any of the Centre 3 intrusions since it was first proposed by Richey and Thomas (1930), though some workers (Bradshaw 1961; Wills 1970; Walsh 1975) noted that macroscopic inward-dipping igneous lamination (fluxion structure) occurs in the fluxion gabbros and sporadic inward-dipping layering is present in the Great Eucrite. These workers suggested that these features are inconsistent with a ring-dyke model for the Great Eucrite and the Sithean Mor and Glendrian laminated gabbro intrusions in particular, although convincing alternatives for emplacement of these Centre 3 gabbro bodies were not proposed. Emeleus & Bell (2005) summarise the observations of the workers above and go on to suggest that the Great Eucrite might possibly be a funnel-shaped intrusion. However, they refer to it as an intrusion 'largely devoid of internal structure' in which 'layering, mineral fabric, xenoliths and pegmatites are uncommon'.

The study outlined in this chapter combines detailed remapping and structural measurements on macroscopic primary magmatic features, textural analysis and quantification of magnetic (AMS) fabrics of several of the Centre 3 gabbro bodies (including the Great Eucrite). It is shown that magma emplacement was probably not parallel to outward-dipping ring-fractures in any of the intrusions referred to above, a key criterion in the identification of ring-dykes (Fig. 3.2; Anderson 1936; Roche *et al.* 2000). Instead, the Centre 3 gabbros have many of the petrological and structural features of a composite layered mafic lopolith.

3.2 Centre 3 lithological relationships

3.2.1 Introduction

The problems raised by previous workers (Bradshaw 1961; Wills 1970; Walsh 1975) with the ring-dyke model for the Centre 3 gabbros originated primarily from the presence of inward-dipping igneous lamination and

occasional inward-dipping layering in the 'fluxion gabbro' and the Great Eucrite intrusions respectively. This, together with an obvious need for an understanding of contact relations between both the various Centre 3 gabbros and also between the Great Eucrite and its country rocks provided the motivation for detailed remapping of the Centre 3 gabbros to be undertaken as part of this study. The specific objectives of this remapping of Centre 3 are as follows:

- (1) To characterize the intrusive contacts of the Centre 3 gabbros in the context of the ring-dyke model.
- (2) To map out the petrological variation of the various Centre 3 gabbros.
- (3) To record the structure and frequency of occurrence of magmatic layering, igneous lamination and associated small-scale magmatic structures.

A re-evaluation of the field relations of the Great Eucrite and other gabbro intrusions are presented below, together with a revised map for the Centre 3 gabbros (Fig. 3.3). Reference is made throughout this chapter to the lithological divisions of Richey and Thomas (1930) in order to highlight the similarities and differences between both maps (Fig. 3.1 and Fig. 3.3). The original study of Richey and Thomas (1930) contains superb and detailed petrographic descriptions of the different Centre 3 rock types in thin-section and it is not the aim of this study to replicate all of this work. However, where significant features are noted in thin-section analysis, or where the interpretations of this study differ to those of Richey and Thomas (1930) on the basis of thin-section evidence, detailed observations are presented. Magmatic layering and structural features of the Centre 3 gabbros are discussed in the next section.

3.2.2. *The Great Eucrite*

The term eucrite is given to gabbroic rocks containing plagioclase that is bytownitic to anorthitic in composition (An_{70} - An_{100}). Petrographically the Great Eucrite is typically a coarse-grained feldspathic rock dominated by plagioclase with varying amounts of olivine and clinopyroxene and minor opaques.

3.2.2.1 *Internal heterogeneity of the Great Eucrite*

Remapping suggests that the Great Eucrite comprises three distinct petrological facies of gabbro, separated from each other on textural and mineralogical grounds, and traceable around the full circumference of the intrusion (Fig. 3.3). The two most common lithologies are a dark grey, partially layered olivine gabbro (1) (Figs. 3.4A and 3.4B) that is surrounded by an extremely heterogeneous, brown-light grey, partially layered

olivine gabbro (2). Both of these rocks contain variably-sized xenoliths and rafts (from <1 m up to 1 km in length) of an olivine-glomerocrystic generally unlayered gabbro (3) (Figs. 3.5A and 3.5B). An unlayered, olivine-deficient gabbro (4) is typically found both around the margin of the Great Eucrite intrusion and at its interior. This gabbro corresponds to the 'quartz-gabbro' of Richey and Thomas (1930) based on comparison with their petrographic descriptions and the spatial occurrence of the rock as observed in this study. The 'Inner Eucrite' and 'Biotite Eucrite' intrusions of Richey and Thomas (1930; Fig. 3.1) cannot be separated from gabbro (1) of this study in the field.

Peridotite xenoliths are common in the Great Eucrite. These occur as two principal types:

- (1) Fine-grained peridotite xenoliths (Figs. 3.6A), composed dominantly of olivine and plagioclase, frequently occur concentrated in zones around the SE, E and NE parts the Great Eucrite. These are generally <1 m to several metres in size and are most abundant on the high areas of the Great Eucrite ridge (e.g. east of Meall an Fhir Eoin at GR 48900 69750 and south of Creag an Airgid at GR 47975 66407). The peridotite xenoliths often appear to be in various states of digestion or resorption by the host (Great Eucrite) gabbro (Fig. 3.6B). Superb relict magmatic layering and cumulate textures are sometimes observed in these and are described in the next section.
- (2) Three large coarse-grained feldspathic peridotite xenoliths (Fig. 3.6C) up to 120 m in diameter occur at GR 49058 69369, GR 49185 69184 and GR 49207 69273. These rocks typically have 60% olivine and coarse plagioclase glomerocrysts giving the rock a very distinctive appearance in the field (Fig. 3.6D). They also, in some cases, appear to have suffered considerable digestion by the gabbros in which they are incorporated (Fig. 3.6E). Examples of layering that are observed in this rock are again described in the next section.

3.2.2.2 *Great Eucrite outer contacts*

Poor exposure makes reliable contact data from around the outer margin of the Great Eucrite extremely rare. However, one boundary with Jurassic sediments in the north of the peninsula (south of Rubha Carrach; Fig. 3.2) is well preserved and can be traced laterally for ~15 m dipping inward at ~50° (Figs. 3.3 and 3.7A). The contact area (at GR 46316 70123) is marked by a zone of abundant net-veined dolerite and microgranite that outcrop between Jurassic sediments and Great Eucrite gabbro (Figs. 3.7B and 3.7C). Outcrops of Jurassic siltstones and mudstones commonly exhibit incipient partial melting and varying degrees of migmatisation. To

the east, the small intrusive 'Rubha Groulin gabbro' of Richey and Thomas (1930) is remapped as part of the Great Eucrite gabbro based on its very similar appearance in the field and in thin-section. The contact between the Great Eucrite in this area and finer-grained dolerite country rock also dips inward at about 40-50° (Fig. 3.7D). Outer contact relations of the Great Eucrite at other parts of the intrusion are not observed i.e. no clear lithological contacts are observed between the Great Eucrite and the following country rocks of Richey and Thomas (1930):

- (1) The Fluxion gabbro of Fascaidale
- (2) The Hypersthene Gabbro
- (3) Quartz-gabbros of Fascaidale and Meall an Tarmachain at the southern margin of the Great Eucrite
- (4) The Fluxion gabbro of Portuairk

Whilst the lack of control on contact relations must largely be attributed to poor exposure, almost complete coastline exposure at Portuairk means this is not the case for the so-called 'fluxion gabbro' intrusion that crops out in this area. Though Richey and Thomas (1930) describe a contact between the Great Eucrite and the Portuairk fluxion gabbro along the shoreline (GR 44055 68302), they also note that the Great Eucrite itself appears to be 'fluxioned' at its outer margin. Re-examination of this inferred contact and a full mapping traverse from the fluxion gabbro intrusion into the Great Eucrite along the shoreline revealed no evidence of an intrusive contact between these two gabbros anywhere along this stretch of coastline. Instead, field evidence suggests that both lithologies grade into one another eastward from Portuairk. This is supported by similar recent independent observations in this area (C.H. Emeleus, pers. comm.). In addition, although fieldwork carried out on the outer Centre 3 'quartz-gabbros of Fascaidale and Meall an Tarmachain' (Richey and Thomas 1930) was not extensive, it seems unlikely from their mineralogical and textural similarities in the field and in thin-section that both are separate intrusions. Whether the Great Eucrite is intrusive into these gabbros or not cannot be determined due to lack of outcrop evidence.

Evidence for contacts between the Great Eucrite and its country rock roof is present on some of the topographically high areas around the course of the Great Eucrite. Meall nan Con (GR 50389 68137) is the highest summit in the west of the Ardnamurchan peninsula at 437 m. Richey and Thomas (1930) referred to the rocks in this area as comprising a vertically sided 'country rock screen' between two ring-dykes (Fig. 3.1) and composed of three lithologies:

- (1) An altered porphyritic gabbro.

(2) Vent agglomerate.

(3) Basalt.

The porphyritic gabbro is included with gabbro (4) (quartz-gabbro) of this study based on the similarity of both in the field. Field observations carried out in this study and other independent observations (Brown *et al.* 2006) suggest that the lithology referred to as vent agglomerate by Richey and Thomas is actually a fine-grained dolerite that exhibits frequent microgranite net-veining, very similar in appearance to the net-veined dolerite at the Rubha Carrach contact in the north described above (Fig. 3.8A). In addition, areas of net-veined dolerite are also observed on the summit ridge of Beinn na hImeilte (GR 45816 67115; 215 m), above Coire na Rainich (e.g. at GR 49500 69700) and just south of Meall an Tarmachain (GR 49000 66600) (Fig. 3.3). Fine-grained highly-altered basalt is present just to the north of Meall nan Con summit (GR 50400 68500) and also south of Meall an Tarmachain (GR 49000 66600). Contacts between the net-veined dolerite of the so-called Meall nan Con screen and Great Eucrite gabbro are observed to be sub-horizontal at Coire Creagach (GR 50300 68300). This is supported by the manner in which these contacts traverse topographic contours at a very low angle around the Meall nan Con summit knoll (Fig. 3.8B). The manner in which the Meall nan Con exposures of net-veined dolerite together with altered basalt sit topographically above a flattish contact with the Great Eucrite gabbro suggests that the Meall nan Con mass represents country-rock roof to the Great Eucrite. Though no clear contacts are observed between net-veined dolerite and Great Eucrite gabbro on Beinn na hImeilte or below Meall an Tarmachain (Fig. 3.3), it is thought that, as with the Meall nan Con lithologies, they may represent pendants of roof rock.

3.2.3 The laminated gabbro

Four arcuate areas of a fifth olivine-deficient, plagioclase-rich gabbro are observed at the centre of the pluton, at Achnaha, Sithean Mor, Sgurr nan Gabhar and around Glendrian (Figs. 3.3 and 3.9A). This gabbro is characterized by a very common, sometimes intensely developed, igneous lamination defined by the planar arrangement of tabular plagioclase crystals (Figs. 3.9B and 3.9C). Clinopyroxene and opaques are also common constituent minerals of this rock. Earlier work (Richey and Thomas 1930) referred to the fabric in these rocks as 'fluxion structure', in particular the 'Sithean Mor' and 'Glendrian' laminated zones of this study, and interpreted them as distinct 'fluxion gabbro ring-dykes' (Fig. 3.9C). This chapter will continue to refer to this fluxion

structure as igneous lamination (cf. Wager and Brown 1968; Chapter 1 of this study), because of the unsuitable connotation of flow that the former implies.

No chilled margins or intrusive contacts are observed between these bodies and gabbro (1), and their lamination always strikes parallel to their outer margins and consistently dips toward the centre of the pluton (Fig. 3.10). Richey and Thomas (1930) considered these bodies to be very closely associated with the quartz-gabbros (gabbro 4) of this study, which are compositionally indistinguishable from the laminated gabbros (e.g. Walsh 1975). Indeed the pronounced planar foliation exhibited in the case of the laminated gabbro appears to be the principal difference between both. In addition, two further areas of this laminated gabbro are mapped in this study. The first of these crops out NW of the Achnaha area (GR 46300 68300), the second slightly south of Sgurr nan Gabhar (GR 46900 69900) (Fig. 3.3).

3.2.4 The central tonalite intrusion

Of the two late bodies that are considered to have intruded the Centre 3 gabbros (Fig. 3.3), the central tonalite has been accorded some significance as the most aerially extensive intermediate (in composition) intrusion in the British Palaeogene Igneous Province. Contact information with the surrounding quartz-gabbro and laminated gabbro is poor, but along its southern margin a steeply outward-dipping (79° SE) intrusive contact toward the laminated gabbro is observed (GR 47523 68048) (Fig. 3.11A). In addition, evidence that the tonalite body has a chilled margin is reflected by a coarsening of grain size in the rock inward from the southern margin of the body. No intrusive contacts are observed between the tonalite and the central quartz-monzonite and it is thought likely that since both are texturally and compositionally very similar, that one is a gradational variant of the other (Fig. 3.11B). The tonalite contains ortho- and clinopyroxene, hornblende, plagioclase, biotite, quartz and K-feldspar and up to 10 vol% opaques (Fig. 3.11C-3.11E). Accessory zircon and apatite are also abundant (1-2 vol%). Very (pleochroic) Fe-rich biotite occurs as large megacrysts (up to 1 cm in size) and is the only mineral phase (with the exception of the unusually large and fresh zircons) that appears not to have suffered significant alteration and resorption (Fig. 3.11C-3.11E). Some normal zoning of Ca-rich plagioclase grains is observed, though much of the feldspars tend to exhibit highly turbid crystal surfaces suggesting considerable alteration.

3.2.5 The quartz-dolerite ring-dyke

The second late intrusion associated with the Centre 3 gabbros is a thin, fine-grained, sheet-like dolerite intrusion frequently and extensively net-veined with microgranite (Fig. 3.1). However, remapping of this lithology reveals several lines of field evidence to suggest that this dolerite/microgranite may not actually form a separate intrusive body (see also Fig. 3.3):

- (1) The dolerite/microgranite does not outcrop extensively, and though it occurs at a consistent topographic height around the interior of the main Great Eucrite topographic scarp, single outcrops of no more than several metres in size separated by up to kilometers of no exposure are not convincing field evidence for its continuity (Fig. 3.3).
- (2) The dolerite/microgranite contains considerable lithological heterogeneity in appearance in the field. For example, one outcrop in the east (GR 48777 69500) consists of a microgranite intrusion approximately 1 m thick with abundant angular dolerite and gabbro fragments (Fig. 3.12A). Other outcrops (e.g. at GR 47025 66850) are dolerite outcrops (at least 7-8 m thick) with minor intricate microgranite net-veining (Fig. 3.12B). Fine-grained dolerite also frequently occurs in the area mapped as the quartz-dolerite ring-dyke with no apparent evidence of microgranite present (e.g. at GR 49290 68905).
- (3) The dolerite/microgranite has a very similar field appearance to the net-veined dolerite observed at the summit of Beinn na hMeilte, Meall nan Con and also at Rubha Carrach, as outlined earlier for the Great Eucrite outer contacts (Fig. 3.3). Dolerite outcrops are therefore not confined to the area mapped by Richey and Thomas as the quartz-dolerite ring-dyke. Further evidence of this is observed in the Sithean Mor laminated gabbro at GR 46648 67259.
- (4) Contact orientations for the dolerite/microgranite also make it seem unlikely that this lithology comprises a single continuous intrusion as suggested by Richey and Thomas (1930). For example, the microgranite intrusion described above from the east of the study area (GR 48777 69500) dips outward (E) at $\sim 65^\circ$ (Fig. 3.3; Fig. 3.12C), a similar contact to that measured by Richey and Thomas (1930). However, two outcrops in close proximity just to the south of Sithean Mor (e.g. at GR 46483 67250 and GR 46651 67010) dip inward (N) at 79° and 51° respectively (Fig. 3.3). In addition, two outcrops of the so-called dolerite/microgranite ring-dyke in a small area around GR

49347 68861 and GR 49287 68689 dip 80° inward (NW) and 80° outward (SE) respectively (Fig. 3.3).

- (5) Small microgranite sheets devoid of dolerite or gabbro fragments are commonly observed intruding the Great Eucrite (e.g. at GR 47550 66036, GR 47998 66705 and GR 45874 68978).

Thin-section examination reveals that the dolerite is dominated by small (~1 mm long) plagioclase feldspar laths and similarly sized rounded clinopyroxene grains. Though apparently quite fresh, these clinopyroxene crystals appear to have been completely annealed or recrystallised, i.e. the rock exhibits a very granular texture (Fig. 3.12D). In several cases, spherulitic growths of clinopyroxene are observed intergrown with the plagioclase. Rare interstitial biotite and quartz are also present, and opaque minerals are abundant (up to 15 vol%).

3.3 Magmatic layering and associated structures

Magmatic layering is common in gabbros (1) and (2) of the Great Eucrite, typically comprising thin sequences of plagioclase-rich layers alternating with olivine-rich layers and less commonly pyroxene-rich layers (Figs. 3.13A and 3.13B). Individual layer thicknesses rarely exceed 25 cm and the maximum thicknesses of sequences of layers is typically ~10 m. Layer planes consistently strike parallel to the outer margins of the Great Eucrite, and can be traced for up to 20 m laterally and generally dip inward toward the center of the intrusion at 40-60° (Fig 3.3; 3.13C). An exception to this is rare layering observed in the olivine glomerocrystic gabbro (3) where layering may dip either inward or outward. Magmatic sedimentary structures are present and often associated with layering, particularly in the inner gabbro (1). These include modally graded trough structures (Fig. 3.13D), fallen-blocks onto which layers onlap (Fig. 3.13E) and graded bedding (Fig. 3.13F). Layering also very frequently exhibits evidence for syn-magmatic deformation, such as slumping and folding of layers (Fig. 3.13G), syn-magmatic faulting and lateral variation in single layer thicknesses (Fig. 3.13H). Planar or linear alignments of crystals associated with magmatic layering are not observed in the Great Eucrite gabbros.

Igneous lamination is well-developed in four areas in the interior of Centre 3, as described above. These planar fabrics in the outer areas at Sithean Mor, Achnaha and Sgurr nan Gabhar typically dip inward at 50-80°. By contrast, dip values of 30-50° are characteristic of the extensive interior arcuate area of laminated gabbro around Glendrian (Fig. 3.9A). No evidence of shear or crystal-plastic deformation is observed with this planar fabric, nor can an associated macroscopic magmatic lineation be distinguished on planar lamination surfaces. However, subtle layering is frequently present associated with (and parallel to) the igneous lamination, and

evidence for syn-magmatic deformation in the laminated gabbros is common, e.g. slumped and intricately mixed-up 'crystal slurries' and 'boudined layer planes' (Fig. 3.14A and 3.14B). Sedimentary structures such as graded bedding and slumped layering are present in the laminated gabbros, although they are not common.

The fine-grained peridotite xenoliths observed in the Great Eucrite frequently exhibit excellent internal rhythmic layering characterised by alternating olivine and feldspar rich magmatic layers (Fig. 3.15A). Magmatic layer planes are generally oriented randomly with respect to the orientation of the outer contacts of the Great Eucrite. In addition, many of the xenoliths exhibit layer-parallel igneous lamination carried by fine-grained plagioclase laths (Fig. 3.15B). Fine-grained (<1 mm in size) olivine crystals often occur as glomerocrysts in the xenoliths and in one particularly olivine-rich sample (Fig. 3.15C), appear to show superb solid state textural equilibration with a very high percentage of dihedral angles at olivine-olivine-olivine triple-grain junctions approaching 120° (Elliot *et al.* 1997; Holness *et al.* 2005; O'Driscoll 2005). Olivine glomerocrysts in examples of peridotite xenoliths that display good lamination also frequently have triple junctions that appear to approach textural equilibrium, but the effect is not as pronounced as in Figure 3.15C as olivine is not as common a mineral component of these rocks. Layering is observed in the coarse-grained peridotite xenoliths at just one outcrop, but occurs as very coarse plagioclase rich bands several cm thick that may define planar layers or anastomose and define trough-like structures (Fig. 3.15D and 3.15E). Large equant olivine grains (up to 1 cm in size) are observed in thin-section. Plagioclase generally occurs as exceptionally large intercumulus grains, optically continuous in crossed polars for several cm in some cases.

3.4 Anisotropy of Magnetic Susceptibility (AMS) data

3.4.1 Sampling methodology

Block sampling for AMS analysis of the Great Eucrite was carried out at 80–100 m intervals along five radial traverses (6–10 sampled stations each) approximately perpendicular to the outer margin of the Great Eucrite (as mapped by Richey and Thomas 1930; Fig. 3.16). Samples for AMS analysis were also collected from around the course of the laminated gabbro zones as follows; four from the Achnaha area, eight from the Sithean Mor area and eleven from the Glendrian area (see below). Several sites were double sampled, to test for within-site variation. In all cases, nine to fourteen sub-samples were then drill-cored from each block, and site mean tensor data were calculated from the measurements (Owens 2000). In addition, four further tonalite blocks were collected at its contact with the Glendrian laminated gabbro at GR 47523 68048 (see below) in order to quantify

the AMS fabrics in this area. In this instance, only four sub-samples were drill-cored from each block as the tonalite is much finer-grained than either the Great Eucrite or laminated gabbros; again site means were calculated following Owens (2000).

3.4.2 AMS results

3.4.2.1 The Great Eucrite

Magnetic fabric data for the Great Eucrite gabbros is presented in Table 3.1. The data revealed a range of bulk susceptibilities (K_{mean}) of 7.9×10^{-3} to 3.3×10^{-2} SI in the Great Eucrite, suggesting that the susceptibility (and therefore the AMS) in these samples is overwhelmingly controlled by magnetite. As mentioned in Chapter 1, once sufficiently high ($> 10^{-3}$ SI), the bulk susceptibility may be taken as approximately three times the volume concentration of magnetite in a rock (Balsley and Buddington 1958). The values of K_{mean} quoted above thus suggest that magnetite is present in the Great Eucrite gabbros in volume concentrations of up to ~1%. However, because the lower value of K_{mean} is close to the minimum value that this assumption can be made for ($\sim 10^{-3}$ SI), the presence of magnetite in these rocks has been corroborated by measurement using an AGICO CS-3 furnace, of the temperature dependence of susceptibility of four Great Eucrite samples. The results also show the dominance of magnetite with Curie temperatures of 575–580 °C (Fig. 3.17). Reflected and transmitted light microscopy carried out on selected thin-sections indicates that magnetite occurs as large (generally >100 microns) anhedral-subhedral grains throughout the rock (Fig. 3.18). This is in close agreement with the work of Bradshaw (1961), who also found magnetite in maximum quantities of 0.5–1 vol% in his petrological study of over 300 thin sections of the Great Eucrite gabbros. Bradshaw (1961) suggested that magnetite occurred as interstitial grains, similar to the large subhedral grains observed in this study, and as alteration grains rimming olivine crystals.

In magnetite-bearing rocks susceptibility anisotropy normally arises from the shape preferred orientation of inequant grains (with the maximum susceptibility in the direction of maximum long axis concentration) as described in detail in Chapter 1. The anisotropic distribution (or 3-dimensional arrangement) of grains may also influence the AMS if the magnetite concentration is sufficiently high and the distribution of magnetite sufficiently non-uniform (W.H. Owens, pers. comm.; Hargraves *et al.* 1991; Bouchez 1997; Launeau and Cruden 1998), i.e. a highly ordered (anisotropic) packing of grains. However, the volume concentration of magnetite in

rocks of the Great Eucrite, for which **H** is typically 5% (range 2 - 9%), is sufficiently low so that it is unlikely distribution anisotropy is a significant contributor to the fabric.

The AMS results for the Great Eucrite gabbros are summarized in Figure 3.16, 3.19 and 3.20. For all but one of the blocks sampled the susceptibility ellipsoids are triaxial to prolate in shape (Fig. 3.19) indicating that the magnetic lineation (**K₁**) is the most clearly defined component of the magnetic fabric overall. The directions of this axis are remarkably consistent, typically plunging toward a focal point at the center of the intrusion at 40–70° in all traverses (Figs. 3.16 and 3.19). The magnetic foliation also generally dips inwards, though the strikes are not as consistent trending either parallel or obliquely to the outer margins of the intrusion at different stations (Figs. 3.16 and 3.19). Double-sampled sites are also quite consistent (Fig. 3.16).

3.4.2.2 *The laminated gabbros*

Magnetic fabric data for the laminated gabbros (for sampled sites see Fig. 3.21) is presented in Table 3.2. Bulk susceptibility values for the laminated gabbros are extremely high, ranging between 4.5×10^{-3} and 2.8×10^{-1} SI. The Glendrian laminated gabbro exhibits the highest values of **K_{mean}** with an average of 2.3×10^{-1} SI; average **K_{mean}** values for the Achnaha and Sithean Mor areas are 9.7×10^{-3} and 1.4×10^{-1} SI respectively. **K_{mean}** values are up to two orders of magnitude greater for these rocks than for the Great Eucrite gabbros, and also seem to increase inward with the highest susceptibilities in the innermost laminated gabbro zone (the Glendrian laminated gabbro). This increase in **K_{mean}** toward the centre of the intrusion may have implications for the crystallization history of the Great Eucrite gabbros and is discussed in more detail later. Bulk susceptibilities also indicate that magnetite is present in the laminated gabbros in volume concentrations of up to 9% (Balsley and Buddington 1958). These values are sufficiently high for it to be unnecessary to carry out thermomagnetic analyses to show that magnetite controls the susceptibility (and hence the anisotropy) in these rocks as well. Reflected and transmitted light microscopy carried out on these rocks indicates that magnetite commonly occurs as large (generally >150 microns) subhedral grains throughout the rock. This is supported by the petrological work of Richey and Thomas (1930), who describe magnetite in these rocks as occurring as ‘abundant irregular grains’ and ‘plentiful equi-dimensional crystals’ for the Sithean Mor and Glendrian areas respectively.

Total anisotropy values (**H**) range between 8 and 15% indicating that magnetic fabrics in the laminated gabbros are quite strong and probably reflect the existing fabric carried by the plagioclase. This is supported by the fact that the magnetic foliation is very similar in orientation to the igneous lamination at all of the AMS

sampled sites in the three laminated gabbros. Together with the presence of relatively large quantities of magnetite in these rocks, it is possible that the AMS fabrics in this instance are controlled to some degree by an existing (very anisotropic) silicate template (distribution anisotropy; e.g. Launeau and Cruden 1998), as opposed to being completely controlled by the maximum orientation of magnetite grain long axes. The reason for this is that it is envisaged in this study that with increasing volume of magnetite and strength of anisotropy (as reflected by both **H** values and by the intensity of the fabric in the field), the potential for the distribution of grains throughout the rock sample to contribute to the AMS fabric increases (W.H. Owens, pers. comm.). The potential implications of this are considered in the discussion section below.

The susceptibility ellipsoids (Figs. 3.21 and 3.22A) for all of the laminated gabbros are typically triaxial and **K₁** axes for the Achnaha and Glendrian laminated gabbros are very consistently oriented suggesting that both linear and planar components of the AMS fabric in these instances may be used as valid structural elements. These magnetic lineations usually plunge down-dip on magnetic foliation planes toward a focal point at the centre of the Centre 3 gabbros, in a manner similar to that of the Great Eucrite magnetic lineations (Figs. 3.19 and 3.21). The magnitude of these inward plunges is a good reflection of the magnitude of igneous lamination/magnetic foliation plane dips in all cases, i.e. the mean lineation plunge in the Achnaha laminated gabbro is 50° and in the Glendrian laminated gabbro is 28°. This is further evidence that the AMS fabric is closely related to the macroscopic igneous lamination. In the case of the Sithean Mor laminated gabbro, magnetic lineations are less consistently oriented (Figs. 3.19 and 3.22A); several samples exhibit lineations that plunge down-dip and several exhibit lineations that are oblique or sub-parallel to strike of magnetic foliation planes. Double sampled sites for the laminated gabbros are generally very consistent in terms of magnetic fabric shape and orientation (Fig. 3.21).

3.4.2.3 *The tonalite/laminated gabbro contact*

Magnetic fabric data for the tonalite are presented in Table 3.3 (sampled sites are illustrated in Figure 3.16). AMS analysis of the central tonalite at its outer contact with the Glendrian laminated gabbro reveals **K_{mean}** values that range between 2.4×10^{-2} and 2.7×10^{-2} SI. It is likely therefore that, as with the samples described above, these relatively high susceptibilities suggest that magnetite again carries the AMS fabric in this rock. Magnetic susceptibility ellipsoids are triaxial to oblate suggesting a strong planar component to the fabric (Fig 3.22B). This magnetic foliation dips steeply outward with a similar orientation to that of the contact (Figs. 3.16

and 3.19). Although the magnetic lineation is the weaker component of the AMS fabric, it is consistent for all four samples, plunging steeply outward (approximately) down-dip on magnetic foliation planes (Fig. 3.16 and 3.19).

3.5 Crystal size distribution data

3.5.1 Sampling methodology

Several samples of the Sithean Mor, Achnaha and Glendrian laminated gabbro zones were selected for CSD analysis in order to extract quantitative information on the textural development of this rock. Thin-sections for CSD analysis were taken from AMS samples so that the textural information acquired could be combined with magnetic fabric data and an integrated approach to understanding the development of the laminated gabbros could be taken. Of particular interest is the development of the planar igneous lamination and for this reason CSD analysis focused on the principal mineral carrying this fabric in the laminated gabbros: plagioclase feldspar. In any case, the other common constituent mineral in the rock, clinopyroxene, typically exhibits alteration features and poorly defined crystal boundaries, making it unsuitable for crystal size distribution analysis. All analyses were carried out on thin-sections cut normal to the foliation plane, again because plagioclase crystals in the plane of lamination often had poorly-defined crystal boundaries and had been subject to alteration. Additionally, though carrying out CSD analysis on magnetite grains would provide an ideal multi-disciplinary AMS/CSD study, magnetite grains are generally not common enough, at large enough grainsizes in the rock for this to be undertaken, and sometimes have poorly defined anhedral crystal shapes or occur as glomerocrysts, making single crystal identification for CSD work difficult or impossible¹. Six samples were collected from the Sithean Mor laminated gabbro, two from the Achnaha laminated gabbro and five from the Glendrian laminated gabbro. The field locations of these CSD samples are illustrated together with their corresponding AMS sample in Figure 3.21.

¹ Note that plagioclase makes up about 50-60% of these rocks, and a thin-section usually yields in the range 200-400 relatively coarse-grained crystals. The maximum volume of magnetite is, as calculated from the bulk susceptibility measurements, ~7-8%, and magnetite crystals are also usually much finer grained.

3.5.2 CSD Results

3.5.2.1 CSD Plots

The CSD data together with the number of crystals analysed for each sample is presented in Table 3.4 and CSD plots are illustrated in Figure 3.23. Although there is some subtle variation in these plots for different samples (discussed below), all of the CSD curves are approximately log linear for larger crystal size fractions. Linear regression analysis carried out on the log linear portion of each plot to calculate slope and intercept data for each reveal that none of the curves has an R^2 value of less than 0.94. Measured slope values for the CSDs are generally consistent, with most of the samples falling in a relatively steep slope range (-0.8 to -1.9). The exceptions to this include Samples 1, 6, 11 and 13 with measured slope values falling in the range -0.25 to -0.7. The CSD curves can be sub-divided into two groups on the basis of plot shape. One group (includes Samples 4, 5, 7, 13, 15A, 17A, 19 and 22A) displays only very poorly developed convex-upward or 'humped' profiles at smaller size fractions or none at all. The other group of CSD curves (Samples 1, 6, 9, 10 and 11) has more complex shapes at smaller size fractions, generally given by pronounced convex-upward profiles at small crystal sizes (i.e. Samples 6, 9, 10 and 11). Sample 1 also has a complex shape at small size fractions, and is discussed in detail below.

Closure limits were calculated for the CSD plots to assess the quality of the CSD data, as outlined in Chapter 2 (after Higgins 2002a; 2002b; Boorman *et al.* 2004). Figure 3.24A shows characteristic grain length plotted against intercepts together with empirically calculated closure limits using an average aspect ratio of 1:2.5:4 for the Ardnamurchan laminated gabbros. With the exception of Sample 11, all sample data fall well within permitted range, i.e. below the curve for 100% volume illustrated by the dashed line. In the case of Sample 11, a second closure curve is constructed employing its actual aspect ratio (1:1.15:9) rather than the average used for the other samples, showing that Sample 11 does indeed satisfy closure, but that it is not well described by the average aspect ratio for tabular plagioclase grains initially used. A plot of CSD characteristic grain length against volume phase proportion (c.f. Higgins 2002a) shows most of the samples (again with the exception of Sample 11) falling within the same broad group of characteristic grain length (Fig. 3.24B).

3.5.2.2 Crystal growth times and nucleation rates

Crystal growth times have been calculated for plagioclase crystal populations in each sample using the CSD slope data presented above and a growth rate for plagioclase of $1 \times 10^{-10} \text{ mm.s}^{-1}$ (Cashman and Marsh 1988;

Higgins 1996; Marsh 1998). These times are generally quite consistent (266-561 years) for 10 of the 13 samples measured (Table 3.4). Again Sample 11 does not conform and exhibits an unusually long crystal growth time of approximately 1280 years.

Nucleation densities (n^0) have been calculated from the Y-axis intercepts on the CSD curves and are shown in Table 3.4. CSD intercepts ($\text{Ln } [n^0]$) range from -3.3 to 2.1 mm^{-4} ($n^0 = 4 \times 10^{-2}$ to 8.4 mm^{-4}). These values are very low compared with published values on plagioclase nucleation densities (Cashman and Marsh 1988). Consequently, values of nucleation rate (J) for the laminated gabbros are also very low, ranging from 3.8×10^{-12} to $8.4 \times 10^{-10} \text{ mm}^{-3} \cdot \text{s}^{-1}$.

However, as noted by Marsh (1998) and Higgins (2002a) coarsening or ripening of cumulate textures might lead to a rotation of CSD slopes to shallower sizes. The results presented above are thus treated with caution, as it is plausible that the calculations have produced greatest values of n^0 and least values of J .

3.6 Electron microprobe data

3.6.1 Introduction

Four plagioclase crystals from a sample of well-laminated gabbro were selected to test for major element zonation in order to constrain the textural and AMS data described above. Analysis was carried out under the laboratory and instrumental conditions outlined in Chapter 2. Sample 5 was selected as it is the only sample of the AMS/CSD sample set from the Sithean Mor laminated gabbro that exhibits visible magmatic layering as well as a strongly developed layer-parallel igneous lamination. Indeed the locality from which Sample 5 was collected exhibits the best layering in the Sithean Mor laminated gabbro. Analysis of 200 points per crystal along a rim-to-rim traverse (of the length of each crystal) with spot distances of between 22 and 34 μm was carried out.

3.6.2 Microprobe data

Figure 3.25 is a summary of the microprobe data for plagioclase from Sample 5. The graphs illustrate $\text{An}\%$, FeO_t , BaO and SrO plotted against distance for each of the crystals analysed. The K_2O - CaO - Na_2O feldspar triangles for each crystal also shown in Figure 3.25 illustrate that they are all very similar in composition. Anorthite contents for the four crystals typically range between 70 and 85%. However, characteristic of all of the crystals, i.e. Traverses 1, 2 and 4 is the distinctly-zoned profiles revealed by the $\text{An}\%$ content data for each of the plagioclase crystals. The trend shown by each of these three plagioclase crystals, and to a lesser extent by

Traverse 3, is one that defines a relatively low An core, with four more narrow well-defined overgrowth zones, ending at each rim with relatively low An concentrations (Fig. 3.25). Typical $\Delta\text{An}\%$ values between any two given data points defining these regular zones is 7-15%, indicating quite marked changes in chemical composition. All four crystals have quite similar FeO , SrO and BaO contents, with relatively uniform plots across each of the four crystal lengths in all cases, showing that the zoning illustrated by the An% plots is only weakly reflected in other elemental traverses

3.7 Discussion

3.7.1 The Great Eucrite intrusion

The presence of inward-dipping intrusive contacts along the northern margin of the Great Eucrite strongly suggests that the intrusion does not have the classic 'bell-jar' geometry of a ring-dyke. The well-developed magmatic layering in gabbros (1) and (2) exhibits sedimentary structures that suggest layering developed due to magmatic flow and associated fluid-dynamic processes. Such localized, gravity-controlled layering is generally considered to form due to the action of crystal-laden density currents on horizontal to gently-sloping magma-mush interfaces that are often parallel or sub-parallel to the outer walls of the intrusion (Wager and Brown 1968). The fact that layering typically dips comparatively steeply toward a central focal point in the intrusion and often exhibits evidence for syn-magmatic deformation as outlined above, suggests a significant degree of syn-to post-depositional tilting of basal surfaces toward the centre of the pluton.

Magnetic fabrics in the Great Eucrite are dominantly triaxial to prolate, with a clearly defined K_1 axis in the direction of flow described above. These fabrics are unusual as flow fabrics in that they are not oblate (cf. Rochette *et al.* 1999) and the magnetic foliation is not always coincident with layering. This inconsistency may result from 'abnormal' or complex fabrics in the sense of Rochette *et al.* (1999) because of the strongly prolate nature of some of the susceptibility ellipsoids. However, the consistent inward plunge of the magnetic lineation at 40–70° (approximately down-dip on layer-planes) in the Great Eucrite suggests that it may be validly used as a structural element. It is suggested therefore that the magnetic lineation may also have developed due to the sedimentation processes described above, and was tilted inwards simultaneously with layering. Another possibility is that the magnetic lineation represents a strain fabric resulting from subsidence of the lopolith, i.e. a sub-vertical stretching lineation. This might also explain the dominantly triaxial-prolate trend of the AMS ellipsoids. Importantly, as subsidence is envisaged in this study to be the main driving mechanism behind radially

directed flow, then flow/particle displacement should be parallel to any strain fabric, so both might be treated as representing the same process. This observation is supported by the way in which even the syn-magmatically deformed layers are also oriented confocally.

Evidence from contact relations, magmatic layering, and magnetic fabrics therefore suggests that the Great Eucrite gabbros comprise a lopolithic, composite pluton (Fig. 3.26). This is in agreement with one of the principal findings of Wager and Brown (1968) that layered mafic and ultramafic intrusions are pre-dominantly 'funnel-shaped' lopoliths. Rotation of originally sub-horizontal, magnetic lineations has been described by Cowan (1999) in the Sudbury Igneous Complex, where it may have been related to a cantilever-type, syn-to post-emplacement, inward-tilting of the intrusion floor (Cruden 1998). Indeed such centrally directed 'sagging', and inward-dipping magmatic layering is well documented for layered mafic-ultramafic lopoliths worldwide, e.g., the Bushveld Complex (Carr *et al.* 1994), the Rum Layered Suite (Emeleus *et al.* 1996), and the Skaergaard intrusion (McBirney and Nicolas 1997). In addition, the weakly developed steepening-inward trends observed in the northern and southern traverses bear similarities to documented examples of inward-steepening structures attributed to central-sagging in a number of mafic-felsic complexes (Wiebe and Collins 1998).

Following on from this, in one of the very first studies of central subsidence and its effects on layering in mafic intrusions, Skelhorn and Elwell (1971) describe pronounced steepening inward trends in layer-planes from the Hypersthene Gabbro of Centre 2 on Ardnamurchan. However, though a model for central subsidence was proposed by this study, little was done with the structural data to interpret the overall geometry of the intrusion as either a lopolith or a ring-dyke. However, in a concurrent palaeomagnetic study at the time, Wells and McRae (1969) showed that magnetic poles from throughout the Hypersthene Gabbro clustered very closely together, suggesting that little or none of the inward tilting had occurred after cooling below the Curie temperature of $\sim 570^\circ$. This provides some constraint on the timing of such tilting with respect to the rheology of the partially layered mush, and has obvious implications for central subsidence in the Great Eucrite as well. For example, the Hypersthene Gabbro palaeomagnetic data support the inference in this study that the Great Eucrite layers may also have been quite hot and capable of being syn-magmatically deformed by central subsidence. However, well defined steepening inwards trends of magmatic layering are not observed in the Great Eucrite.

It is also worth commenting on the textural and compositional nature of the peridotite xenoliths in the Great Eucrite gabbros. These rocks bear a remarkable similarity to the feldspathic peridotites of both Rum and Skye in which olivine and plagioclase are the dominant mineral constituents. In the case of the smaller (m-scale)

fine-grained xenoliths, it is clear that these have been transported to some extent by the Great Eucrite gabbros in which they are incorporated. This is deduced on the basis of the magmatic layering and igneous lamination the xenoliths contain, being discordant to layering in the Great Eucrite gabbros. Also a factor in this conclusion is the manner in which these xenoliths, both coarse and fine-grained, are clearly completely out of compositional equilibrium with the Great Eucrite gabbro as they are often observed undergoing extensive resorption/disgestion in the field as illustrated in Figs. 3.6B and 3.6E. It is uncertain whether the frequently texturally equilibrated nature of the fine-grained peridotite xenoliths is a result of early postcumulus magma chamber processes or a result of protracted thermal and chemical interaction with their host gabbro.

The implication of the recognition of these xenoliths as peridotitic for the Ardnamurchan igneous centre is evident. Superb layering preserved in these xenoliths, and particularly the presence of the very coarse-grained nature of the large peridotite xenoliths (also layered) suggests that there may be a large ultrabasic component to the Ardnamurchan gabbros at depth. In addition, previous work on both Rum and Skye igneous centres have shown that emplacement of picritic magmas had a significant part to play in the construction of the basic-ultrabasic components of each igneous centre (Gibb 1976; Upton *et al.* 2002). Given the Rum and Skye cases, these olivine-rich xenoliths may represent indirect evidence for the presence of picrite magma on Ardnamurchan also.

3.7.2 Development of the laminated gabbro zones

3.7.2.1 Introduction

Richey and Thomas (1930) suggested that the planar lamination or 'fluxion structure' of the Centre 3 laminated gabbros resulted from flow of a crystal mush into a ring-cavity, a theory supported by Bradshaw (1961), Wills (1970) and Fortey (1980). All three workers tentatively suggested that a likely implication of this was that the 'fluxion gabbro intrusions' were in fact inward dipping bodies. Field evidence in this study suggests the four mapped areas of laminated gabbro in Centre 3 are layered bodies and that layer planes have a similar (inward-dipping) orientation to those in the Great Eucrite. In addition, similar (and typically more intense) syn-magmatic deformation of layering to that in the Great Eucrite is also often observed in the laminated gabbros. However, no contacts or chilled margins with the surrounding gabbro (1) are observed. Despite both the evidence for magmatic layer forming processes and the erection of previous models as outlined above, the author feels that no clear origin for the pervasive layer-parallel lamination can be determined in the field. This is because the

absence of a macroscopic magmatic lineation and rarity of sedimentary structures in the field precludes any interpretation of flow being based on field evidence alone. Indeed, the development of planar igneous lamination in mafic and ultramafic rocks has recently been attributed to a wide range of primary and secondary magma chamber processes (Chapter 1 and see also Irvine *et al.* (1998) for review). The implication of this is that primary flow mechanisms cannot be held exclusively responsible for igneous lamination development in layered rocks.

3.7.2.2 Magnetic fabrics

Magnetic foliations in the laminated gabbros are well-developed and consistently parallel to the macroscopic lamination observed in the field, suggesting that the AMS foliations are an accurate reflection of the planar silicate fabric (igneous lamination) in the rock. It may also suggest that the aligned plagioclase laths may be forming a silicate template, into the interstices of which magnetite grains crystallized resulting in a distribution anisotropy (magnetite would be expected to nucleate and grow relatively late in the crystallization histories of many silicate melts). As the AMS foliation often mimics the igneous lamination (the potential distribution anisotropy referred to above), it may be that the magnetic lineations for the laminated gabbros reflect a subtle macroscopic lineation of plagioclase on lamination plane surfaces. These magnetic lineations (L values) are also strong and in almost all samples from the Glendrian and Achnaha laminated zones plunge consistently downdip (inward) on magnetic foliation planes. In these cases, the lineations indicate that the lamination of the 'fluxion gabbros' may indeed reflect primary flow, as suggested by Richey and Thomas (1930), Bradshaw (1961), Wills (1970). Fortey (1980) measured the orientations of plagioclase grains on igneous lamination planes in two samples from the Sithean Mor body and two samples from the Glendrian body using the Universal Stage [in a similar technique to that developed by Brothers (1964) for the Eastern Layered Series troctolites of Rum (see Chapter 4)]. Fortey (1980) found that in three samples, the plagioclase lineations were oriented downdip on igneous lamination planes, and in one Glendrian sample, oriented parallel to strike of the lamination. Although comprising a very limited number of samples, Fortey's results led him to concur with the previous studies that lamination development was a result of emplacement-related flow of a crystal mush.

This study considers it highly unlikely that the lamination represents original flow planes developed on emplacement of a crystal mush as proposed by the workers above. The reason for this is that magmatic layering is understood to develop after, rather than upon, magma emplacement (Wager and Brown 1968; McBirney and Noyes 1979; Irvine *et al.* 1998) through the various magma chamber processes summarised in Chapter 1. It is

more likely that the development and subsequent syn-magmatic deformation of magmatic layering would completely postdate the original emplacement of the magma and therefore would be likely to obliterate any *a priori* flow fabrics (linear or planar) developed through the original intrusion of the magma that crystallized to form the laminated gabbros. The parallelism of the planes of magnetic foliation, macroscopic lamination and magmatic layering, together with the syn-magmatic deformation of this layering, suggests instead that layering had already developed and that it is more likely that the centrally directed AMS lineations formed as layering was being tilted and rotated into the centre of the intrusion, in a manner similar to that proposed for the layering and AMS lineations in the Great Eucrite gabbros above.

As with the Great Eucrite magnetic fabrics, it is difficult to ascertain whether the inward-plunging AMS lineations represent a strain fabric related to central subsidence rather than a flow fabric, though the evidence from deformed layering in the field is equally convincing for the fluxion gabbros (as for the Great Eucrite above) that both would again have similar orientations, and may be considered together. Finally, although most of the samples from the Sithean Mor laminated gabbro do not have similarly oriented inward plunging magnetic lineations to those described above, it is interesting to note that Sample 5, the only sample from a well-layered locality on Sithean Mor, has a centrally plunging magnetic lineation.

3.7.2.3 CSD Data

Eight of the thirteen CSD plots presented above exhibit quite straight (log linear) CSDs for most crystal size fractions suggesting a simple, open-system crystallization history of just one crystal population (Cashman and Marsh 1988; Marsh 1998; Chapter 2 of this study). This interpretation is supported by the similar crystal growth times quoted above and in Table 3.4 for the majority of the samples. The nucleation densities calculated from the CSDs (and consequently the nucleation rates) are exceptionally low compared with nucleation densities ($2.07\text{--}4.55 \times 10^7 \text{ mm}^{-4}$) reported by Cashman and Marsh (1988) for plagioclase from the Makaopuhi lava lake (Hawaii). However, it might be expected that cumulates such as the Ardnamurchan laminated gabbros, with very high crystal content, and close to the final solid texture, would have significantly lower nucleation densities (and nucleation rates) compared with volcanic rocks.

Five of the eight relatively 'simple' CSD plots are from the Glendrian laminated gabbro, two are from the Sithean Mor laminated gabbro, and one is from the Achnaha laminated gabbro. The other four of the six CSD plots from the Sithean Mor laminated gabbro (i.e. Samples 6, 9, and 10 and 11) exhibit evidence for a distinct

convex-upward profile at small crystal sizes that might suggest the textures of the laminated gabbros have undergone some postcumulus ‘Ostwald’ ripening, i.e. growth of large crystals at the expense of small ones (Marsh 1998; Boorman *et al.* 2004). In cumulates such as these rocks, this type of profile might also suggest a significant loss of nuclei (small size fractions) by expulsion of liquid through the crystal mush. However, the latter scenario might not account for the fact that in the case of three of these CSD plots (Samples 9, 10 and 11), the corresponding AMS sample data have by far the lowest **L/F** ratios observed in the Sithean Mor gabbros (Table 3.2). If it is assumed that these rocks had **L** and **F** values closer to the average of the rest of the laminated gabbro samples measured at one stage, then it might be that some intensification of the foliation at the expense of the lineation has occurred. Though all of the CSD plots have been described as being approximately log linear, most display subtle kinks at varying larger size fractions, in most cases to shallower slopes (e.g. Samples 5, 7, 9 and 11). This suggests that the population deviates to a proportionally greater number of larger size fractions than predicted by a log linear distribution. These kinks are not substantial enough to indicate the presence of a wholly different crystal population, but may be sufficient evidence for slight ripening of crystals to somewhat larger sizes in addition to the convex-upward profiles.

The ‘crystal ripening’ hypothesis may explain the inconsistency in orientation of some of the magnetic lineations of Sithean Mor with respect to the other laminated gabbro zones, and indeed the rest of the Great Euclidite. It seems unlikely that such consistently oriented magnetic lineations should develop everywhere except the gabbro body that exhibits the steepest inward dipping lamination, where such a lineation might be most expected. Late-stage compaction and pure shear of the crystal mush might be a potentially viable mechanism to explain such a process, whereby the plagioclase grains in the crystal mush were allowed to ripen in the plane of lamination only, obscuring any linear fabric present. This situation might arise as compaction could result in interstitial melt pockets being preferentially located laterally around the edges of crystals, rather than above and below them. This might restrict the late growth of crystals by pressure solution (see Chapter 1) to orientations perpendicular to the principal stress associated with compaction, i.e. within the plane of lamination. Crystal plastic strain features such as deformed twin lamellae in plagioclase are generally not observed in the Centre 3 laminated gabbros, so there is no evidence of substantial mechanical compaction. In addition, crystal aspect ratios calculated for input into the *CSDCorrections* program typically have markedly long major axes lengths for those CSDs that display slight kinks to shallower slopes at large size fractions (Fig. 3.23 and Table 3.4; Samples 7, 11, 13 and 22A). This could be interpreted as further evidence that textural ripening in the plane of lamination for

some CSDs is associated with intensifying the planar element of the rock fabric at the expense of the linear component.

The CSD for Sample 5 exhibits a slight upward kink at the largest size fraction, suggesting some ripening. This correlates well with the microprobe data for this sample, which shows good evidence of internal compositional zoning in the largest crystals in the rock (four of which have been studied). It should also be emphasized that Sample 5 comes from a well-layered locality and also has an AMS lineation oriented down-dip on igneous lamination planes. It might be that as this locality is well-layered, it preserves some evidence of the primary subsidence related flow referred to above, but also displays a CSD curve, which together with the mineral-chemical evidence for distinct oscillatory compositional zoning, indicate some textural modification. Indeed, significant flow of the crystal mush would plausibly promote mobility of the interstitial melt, bringing the crystals into contact with liquids of significantly different composition (changes of >10 mol% observed in some feldspars; Fig. 3.25).

The Achnaha CSD represented by the concave-upward shape (Sample 1) at smaller size fractions might be interpreted as indicating that the crystal population underwent a stage of postcumulus ripening, as above, followed by a final event which introduced finer crystals into the system before final textural lock-up. This could be explained by either a very late nucleation episode in the interstices of the cumulate framework or the incorporation mixing of smaller crystal sizes from the country rock into the crystal mush. Sample 1 comes from an outcrop at Achnaha (GR 46183 68844) that displays the best examples of slumped and mixed 'crystal slurries' in Centre 3 (Fig. 3.14A), representing syn-magmatically deformed layers due to central subsidence of the Centre 3 laminated gabbros. A more plausible interpretation for the concave-upward CSD profile at this outcrop therefore might be that thorough mechanical mixing of crystal mushes as is suggested by field evidence would have the effect of juxtaposing different crystal populations from different magmatic layers in a given sequence. This might explain why this CSD appears to have gained crystals of a very small size.

It should be noted that the model involving mixing of crystal populations in the above paragraph might also be considered a possible explanation for those CSDs displaying convex-upward profiles. Random mixing of mineral phases from different magmatic layers could just as easily result in a loss of smaller crystals from the system as a gain. However, given that the AMS data for Samples 9, 10 and 11 show unusually low L/F ratios (as described above), it is believed (and re-emphasised) that crystal ripening has been at least partially responsible for the textural development of the particular samples (from Sithean Mor) in question. The link made in this

study between the AMS and CSD studies here requires that the magnetic mineralogies have texturally matured or ripened, reflecting the textural ripening of plagioclase that is suggested by the CSD data (especially in Samples 9, 10 and 11 where the lowest L/F ratios occur). Such ripening of magnetite in lamination planes is considered to be quite possible as magnetite is a primary (abundant) magmatic mineral in this rock. Given that the final composition of the interstitial melt of the cumulus framework (at a late-stage in the mush-pile's history) should have the approximate composition of the cotectic, overgrowth on magnetite crystals as well as plagioclase in the plane of lamination should also be possible.

The second Achnaha CSD plot (Sample 4) is a remarkably straight plot, with the slightest evidence of a downturn in small crystal sizes. The CSDs from the Glendrian laminated gabbro exhibit approximately simple profiles at small size fractions, with the 'humped' profile described from many of the Sithean Mor samples being quite poorly developed or absent. Some kinking of larger size fractions (without damaging the approximately log linear profile of the curves) might be interpreted in a similar manner to those of Sithean Mor, i.e. slight textural ripening may have also occurred here. Sample 13 exhibits a more pronounced shallowing-upward kink that might suggest more substantial textural ripening.

The simple 'straight' CSD plots at most crystal size fractions and relatively consistently oriented AMS fabrics of the Glendrian and Achnaha laminated gabbros indicates that they underwent a simpler textural evolution than the Sithean Mor laminated gabbro zone. As well as the good correlation between complex CSD shape and lowest L/F ratio, the Sithean Mor laminated gabbros also have igneous lamination planes that dip inward at far greater (70-80°) magnitudes than the Glendrian and Achnaha laminated gabbros (20-30° and 50-55° respectively). Together with their exterior position, this might suggest they may be the older body and hence show evidence for a more protracted textural (postcumulus) history than the inner Glendrian and Achnaha bodies. This interpretation is favored in this study because it simplifies the link between the textural evidence and the AMS fabric data so that both can be explained by one process that is demonstrable in the field.

This study concludes that the arcuate zones of laminated 'fluxion' gabbro of Centre 3 are not distinct intrusions, but represent one or more upper laminated 'facies' of gabbro in the Great Eucrite lopolith. It is envisaged that an originally horizontal to sub-horizontal igneous lamination, developed synchronously with localized small-scale magmatic layering, was rotated progressively inwards giving rise to the syn-magmatic deformation observed and the consistent centrally-plunging AMS lineations on lamination planes (Fig. 3.26). The consistency of this magnetic lineation in two of the bodies and its similarity to that observed in the Great Eucrite,

as well as the presence (though rare) of sedimentary structures suggests that magmatic flow was the initial primary process responsible for lamination and layer formation. Thus, flow, probably subsequently enhanced by stretching accompanying subsidence, is thought to be responsible for creating the inward plunging magnetic lineations and syn-magmatically deformed layering. Combined magnetic fabric and CSD evidence indicates (in general) a more protracted and complex crystallization history and textural evolution for the rocks of the (probably older) outer Sithean Mor laminated gabbros resulting in late-stage postcumulus modification of crystal shapes and fabrics within the plane of igneous lamination.

3.7.3 *The late tonalite and quartz-dolerite intrusions*

An important line of evidence used by Richey and Thomas (1930) for their ring-dyke model was the reported outward-dipping nature of the late quartz-dolerite intrusion. Highly irregular contact data measured for the dolerite sheet in this study combined with other field observations outlined above indicate that it does not have the form of a single coherent intrusion. Thin-section petrography suggests that the dolerite has the texture of a baked (thermally metamorphosed) rock rather than that of a late-stage intrusion that was emplaced into all of the surrounding rocks. Combining this with the observation that net-veining of dolerite (or gabbro) by microgranite appears to consistently occur wherever the contacts can be closely narrowed down, it is proposed here that the net-veined dolerite 'intrusion' is actually an annularly arranged series of xenolithic roof slabs or pendants that have been back-injected with anatectic country-rock melts (Wells 1954b; Dunham 1965). Their position immediately just interior to the break in slope of the Great Eucrite may indicate the presence of an annular fault located there, perhaps associated with central subsidence of the proposed lopolith, which controlled their downthrow.

The central tonalite body contains significant amounts of K-feldspar and quartz (modally up to 20% of both combined in a given sample), and is therefore (technically) incorrectly referred to as tonalite. Instead it plots in the granodioritic or granitic field on a Streckeisen diagram. However, the significant range of minerals and textural nature of this rock (described above) suggests that it has not cooled and solidified from an equilibrium melt, but rather from a relatively rapidly cooled mixed magma. The presence of reasonably fresh orthopyroxene, clinopyroxene and Ca-rich plagioclase strongly suggests that a basic melt was involved in the rock's crystallization history. However, significant Na-rich rims on more calcic plagioclase grains, quartz and K-spar suggest a magma of more felsic composition. The presence of abundant accessory zircon supports this,

suggesting that parts of this rock cooled from a highly evolved melt (given the highly incompatible nature of zirconium in most mafic and intermediate silicate melts). The rock is considered in this study to have crystallized from a mixture of crystal mushes of very different composition. The large fresh biotite plates may be the only mineral which crystallized in equilibrium with the intermediate melt produced from the mixing process.

It is concluded that the Centre 3 'tonalite' is not in fact a separate intrusion. Given its position at the centre of the Great Euclite intrusion where the effects of the central subsidence proposed here are likely to have been most pronounced (Fig. 3.26), it is suggested that the so-called tonalite represents a preserved zone of gabbro-felsic country rock (roof) interaction. It may therefore, together with the rocks of the Meall nan Con area (described above), the best evidence of the presence of the roof of the Great Euclite lopolith. The geochemical work of Walsh (1975) and Walsh and Henderson (1977) support this to some extent as they indicate the tonalite derived from country rock contamination rather than fractional crystallization of the gabbros. Magnetic fabric data from samples taken at the tonalite contact with laminated gabbro are somewhat equivocal, and do not confirm or cast doubt on the above interpretation. Magnetic foliations are parallel to the contact itself and magnetic lineations plunge steeply outward (downdip) on the contact plane, and could therefore describe an emplacement related upward flow fabric of a separate late felsic intrusion or a downward strain fabric related to subsidence of a central roof block as a response to overall lopolithic subsidence of the Great Euclite.

3.7.4 Broad implications

The interpretation of the Centre 3 gabbros as a composite layered mafic lopolith fed from a central source in this study has significant implications for the presence of the three temporally and spatially distinct 'foci of activity', purported to have shifted throughout the evolution of the Ardnamurchan complex (Richey and Thomas 1930). K-Ar age studies carried out on the gabbro intrusions of Centres 2 and 3 show that very little time (gabbros may actually be younger than the Centre 3 intrusions (Mitchell and Reen 1973). For example, the Hypersthene Gabbro of Centre 2 is dated as 59.7 ± 2.3 Ma whilst the Centre 3 Tonalite (previously interpreted as one of the youngest intrusions on Ardnamurchan) is dated at 60.8 ± 1.0 Ma (Mitchell and Reen 1973). If the layered gabbros of Centre 2 are also lopolithic in geometry, then the concept of migrating centers of activity may be seriously flawed. In that case, the geometry of the Ardnamurchan intrusions would be best envisaged as a

vertical stack of offset ‘funnel-shaped’ bodies, with the gabbros of Centre 2 possibly representing a younger intrusive episode underlying the older Centre 3 rocks.

The historical importance of the British Paleocene igneous complexes in laying the foundation for understanding the emplacement mechanisms of shallow crustal-level intrusions elsewhere is well-documented (see Woodcock and Strachan 2000; Bell and Williamson 2002 for reviews). In particular, the concept of ring-dyke intrusion and central subsidence of caldera volcanoes has been applied to sub-volcanic geological problems worldwide for decades (Anderson 1936; Wager and Brown 1968; Roche *et al.* 2000) as they provide critical information regarding the way magma system emplacement and evolution occurs, in particular the physical and chemical interaction between the subsiding central block and the underlying magma chamber. However, even though ring-dykes are emplaced at shallow (2–3 km) crustal levels (Saunders 2004), good examples are rarely well exposed as they tend to be obscured by sedimentary volcanic caldera infill and other intrusive bodies with different emplacement mechanisms and three-dimensional geometries, e.g., cone-sheets, laccoliths, and lopoliths.

The work described here comprises the first magnetic fabric, textural and structural study of one of the classic BPIP mafic ring-dykes together with associated intrusions, and proposes instead that it has the geometry of a lopolith or ‘funnel-shape’ intrusion. This raises the prospect that the layered, mafic-ultramafic ‘ring-dykes’ of the other Palaeogene igneous complexes such as Carlingford (NE Ireland) and the Isles of Mull and Skye (Scotland) may be lopoliths as well (see Chapter 5). The implication for the BPIP igneous complexes is that a re-appraisal of the mechanisms of emplacement and structural architecture of their intrusive elements is now required employing modern methods of igneous fabric analysis together with other advanced geophysical techniques e.g., three-dimensional seismic modeling (cf. Malthe-Sørenssen *et al.* 2004). To be identified as ring-dykes in the sense of Richey and Thomas (1930) and Anderson (1936), in the BPIP and elsewhere, intrusions *must be shown* to have intruded along a vertical to outward-dipping concentric ring-fracture and to have been accompanied by block subsidence related to caldera collapse.

3.7.5 Outlook

Most of the conclusions reached in the study of the Ardnamurchan gabbros are supported by field, AMS, textural and mineral-chemical data. However, there are several instances in particular where the author feels that further work would substantially improve the ideas presented here. These are outlined as follows:

- (1) The idea that microgranite (granophyre) in the Centre 3 gabbros is largely a product of melting of shallow-level country rock with subsequent back-injection into the gabbros is highly testable. All of the Mesozoic and older rocks are chemically very distinctive and highly refractory, so should therefore readily contribute a strong isotopic signature to the microgranite if the latter has developed through melting of near-surface wall rock sequences (the only other possible country-rocks of sedimentary origin are Moine metasediments). Detailed and isotopic studies might provide evidence to support or refute the interpretation from the field observations made in this study that microgranite generally occurs close to the Great Eucrite contacts and is a locally derived melt, so that any interpretation of the Centre 3 'Meall nan Con screen' and the 'quartz-dolerite ring-dyke' must take account of this.
- (2) The presence of transported feldspathic peridotite xenoliths (similar to peridotite observed in other igneous centres of the BPIP) of varying sizes and all containing primary magmatic layering and textures has been used here to suggest that there may be a large layered ultrabasic body at depth and also that picrite magma may have been available on Ardnamurchan. This interpretation could be supported by measurement of the MgO and Ni contents of olivine crystals contained within these peridotites for comparison with rocks in other Palaeogene Central Complexes (e.g. Rum and Skye). For example, olivine crystals in peridotites on Rum have been shown to contain up to 20% Mg, which, if could be demonstrated for Ardnamurchan, might support the hypotheses reached above.
- (3) Forceful emplacement of the so-called 'quartz-dolerite ring-dyke', if the model of Richey and Thomas (1930) is correct, is likely to have produced strong emplacement-related flow fabrics that could potentially be analysed using AMS. A detailed magnetic fabric dataset could either lend strong support or rule out the suggestion made in this study (based largely on field evidence and thin-section petrography) that the quartz-dolerite has been misinterpreted as a single coherent intrusion.
- (4) Finally, preliminary mapping in the so-called Centre 2 gabbros suggests that many of the 'quartz-gabbros' exterior to the Great Eucrite ring-intrusions could be part of the same intrusion. In fact, this might be extended to include the outer Hypersthene Gabbro intrusion, so that all of the mafic plutonic bodies of the Ardnamurchan igneous centre form part of one large partially-layered mafic intrusion (probably of lopolithic form). Detailed remapping of the Centre 2 gabbros could again

confirm or rule out these suggestions. In addition, the observations made in this study should be combined with kinematic studies of wall-rock deformation for the country rocks of the Great Eucrite and other Ardnamurchan gabbros. For example, where measurable, bedding in sedimentary units typically dips away from a focal point at the centre of the complex, suggesting an early period of doming (laccolithic?) style of emplacement of the gabbros on Ardnamurchan. However, within the Great Eucrite (and also, for example, the Hypersthene Gabbro; Skelhorn and Elwell 1971) intrusions primary magmatic structures strongly indicate considerable central (lopolithic) subsidence. A move away from describing single plutons in terms of simple intrusion geometries might be advised and description of intrusions in terms of end-member 'laccolithic' and 'lopolithic' processes, whereby a given intrusion may exhibit evidence of each mechanism, proposed instead.

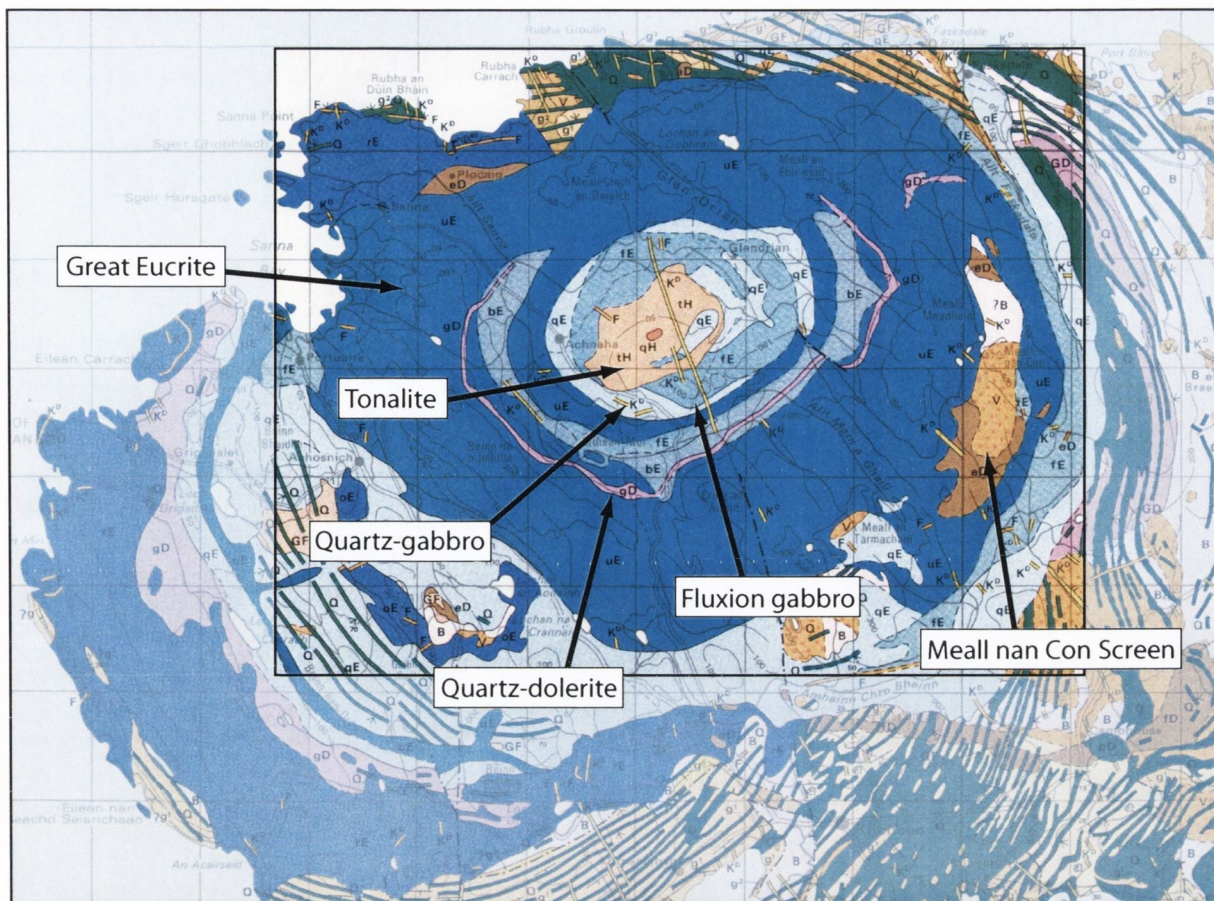


Figure 3.1. Map of Ardnamurchan peninsula with the main intrusive components of the Centre 3 gabbros labelled (reproduced from Richey and Thomas 1930). The principal lithologies on map are represented by the following symbols: uE: Great Eucrite, qE: Quartz Gabbro, bE: Biotite Eucrite, fE: Fluxion Gabbro, gD: Quartz-dolerite (net-veined with granophyre), th: Tonalite, qH: Quartz Monzonite, eD: Other Gabbro, V: Vent Agglomerate, and B: Basalt.

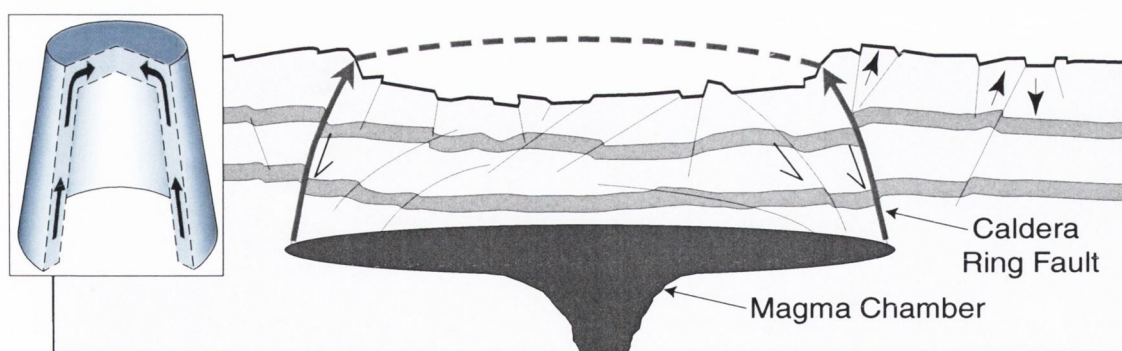


Figure 3.2. Schematic diagram showing the subvolcanic level and ring-fault system along which ring-dykes are emplaced (adapted from Walter and Troll 2001). Inset: Bell-jar geometry of a typical ring-dike intrusion and expected magma flow directions during emplacement.

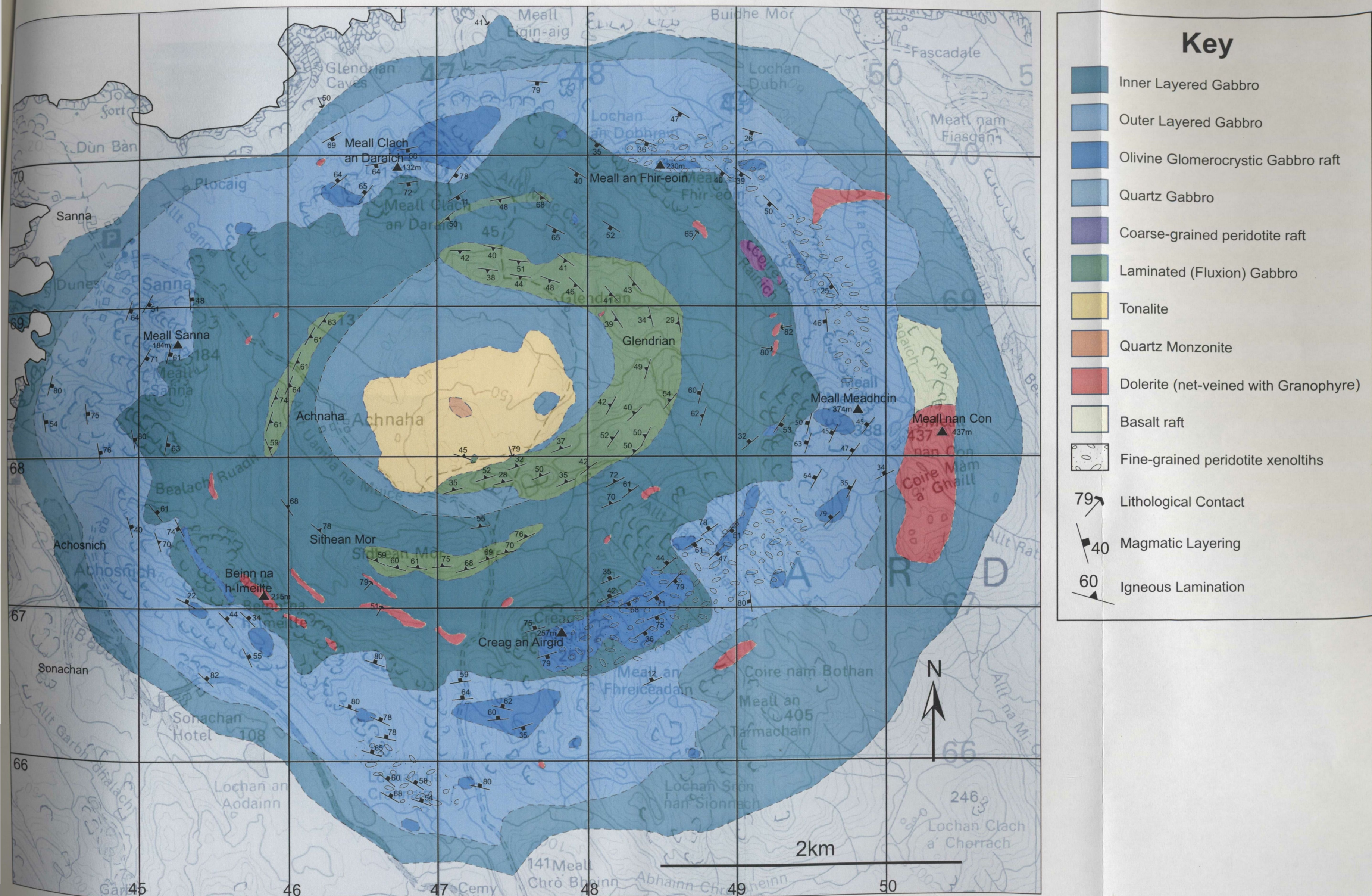


Figure 3.3. Revised map of the Great Eucrite and other Centre 3 gabbros as presented in the text.

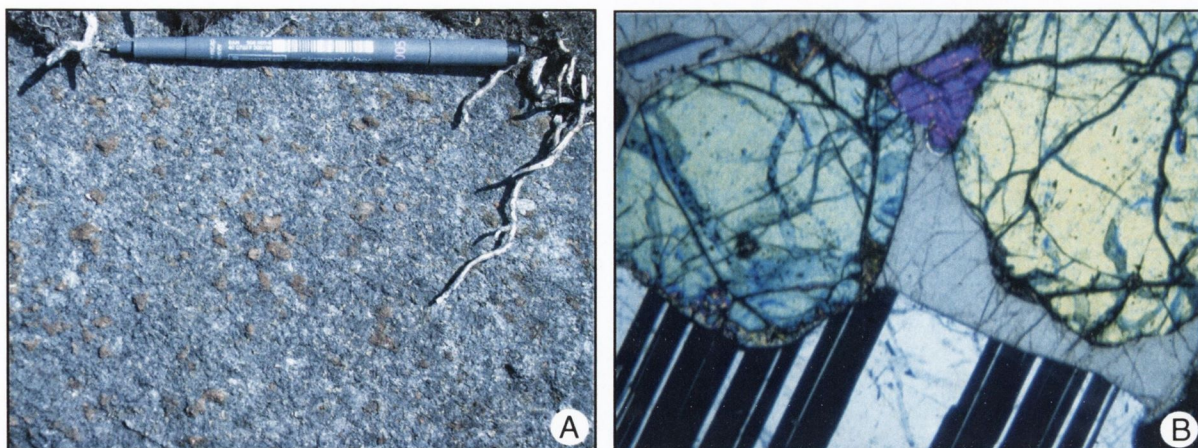


Figure 3.4. A: Typical outcrop appearance of the Great Eucrite gabbro (1). B: Thin-section of the Great Eucrite gabbro (1) in crossed polars. This lithology is characterized by dominant plagioclase, rounded olivine grains and rare interstitial clinopyroxene as shown in the photomicrograph. The width of the field of view in 4B is 5mm.



Figure 3.5. A: Typical outcrop appearance of olivine glomerocrystic gabbro (3). B: Block of olivine glomerocrystic gabbro (3) in gabbro (1). Pen at the centre of the image gives scale.

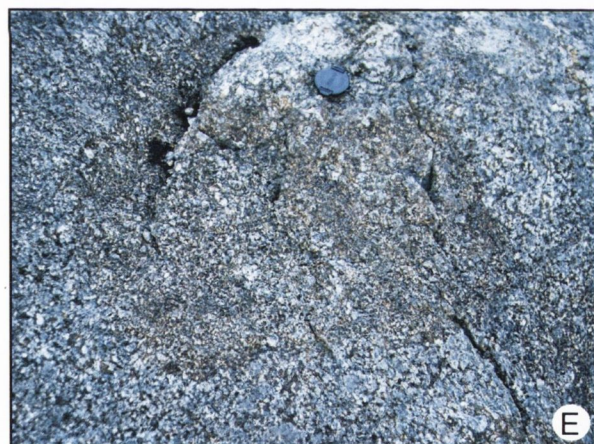


Figure 3.6. A: Fine-grained peridotite xenoliths in the Great Eucrite gabbros. B: Resorption of fine-grained peridotite xenoliths in gabbro (2). C: Large coarse-grained peridotite raft (highlighted), approximately 120 m long, in the Great Eucrite gabbro. D: Coarse-grained olivine in peridotite in the Great Eucrite gabbro. E: Resorption of small coarse-grained peridotite xenoliths.



Figure 3.7. A: Great Eucrite gabbro in sharp intrusive contact with melted country rock. B and C: Gabbro net-veined with microgranite at Rubha Carrach contact, camera lenscap for scale in each instance. D: Great Eucrite gabbro contact (highlighted) with dolerite dipping south at Rubha Groulin.

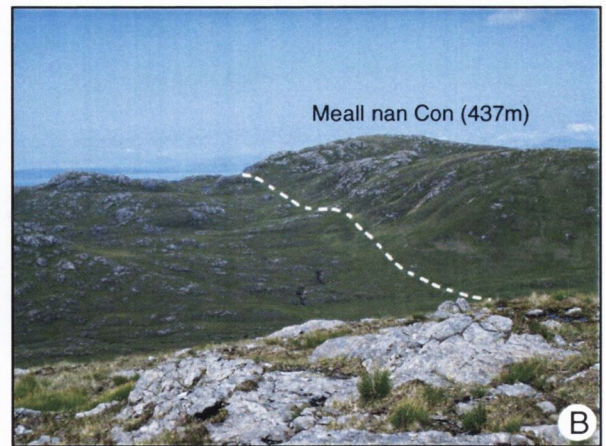


Figure 3.8. A: Net-veined dolerites at Meall nan Con. Lens cap at the centre of the image gives scale. B: The topographic position of the Meall nan Con ridge above the Great Eucrite.

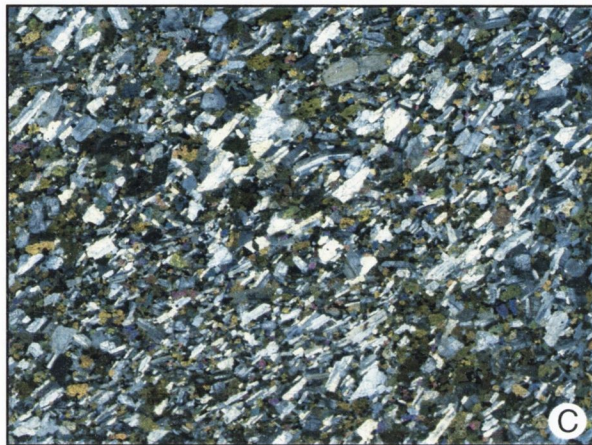
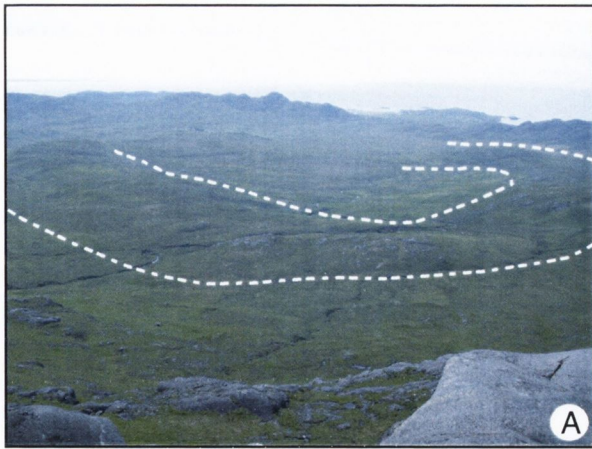


Figure 3.9. A: Annular topographic expression of the Glendrian laminated gabbro from Meall Meadhoin. B: Close-up of igneous lamination in field. C: Photomicrograph of igneous lamination in crossed polars. Planar foliation defined by plagioclase laths trends NE-SW across image. The field of view is 5mm in width.

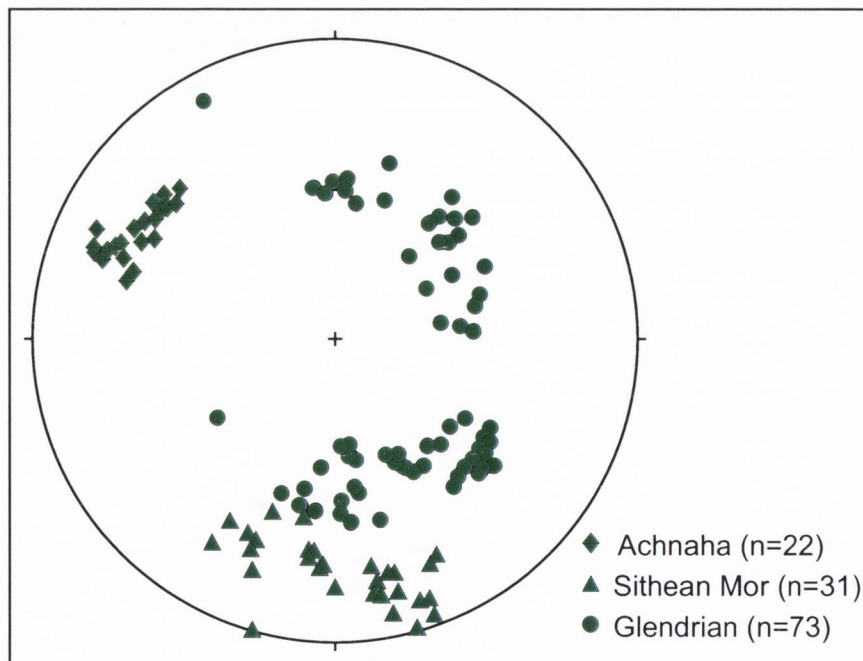


Figure 3.10: Equal area stereograms of lamination data (plotted as poles to planes) for the Achnaha, Sithean Mor, and Glendrian laminated gabbros.

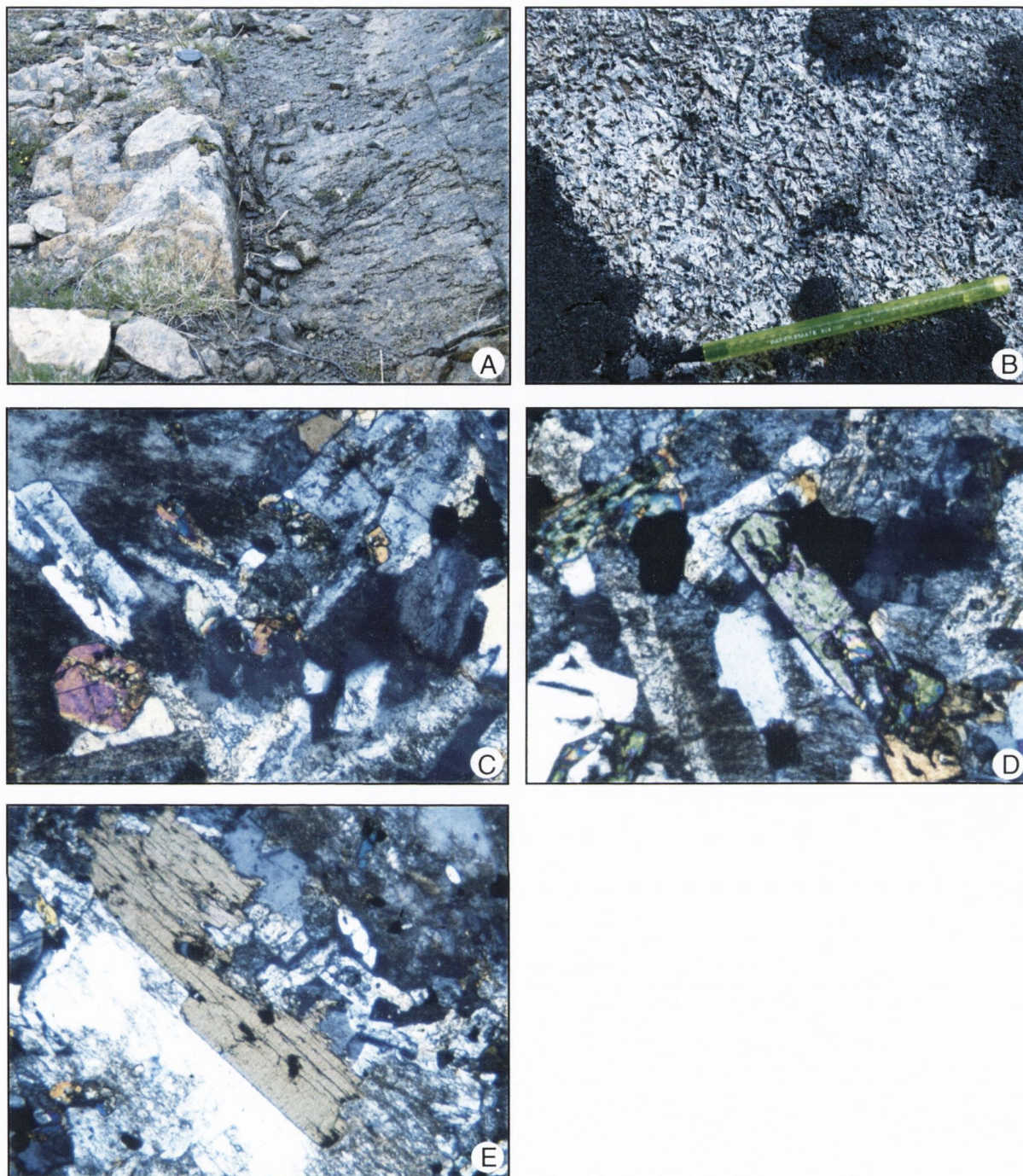


Figure 3.11. A: Tonalite (left of image) contact with the Glendrian laminated gabbro that dips SE. Lens cap at top of image gives scale. B: Field appearance of the tonalite. C, D and E: Thin-section appearance of the tonalite highlighting significant mineralogical and textural features. All photomicrographs are taken between crossed polars; the width of the field of view in C and E is 5mm and in D is 2mm. C shows an orthopyroxene crystal at the bottom left of the image and highly altered zones of plagioclase feldspar. D shows a large highly birefringent zircon crystal in the centre of the image, and an altered K-feldspar crystal exhibiting Carlsbad twinning just to the left of centre. E shows an example of the large fresh biotite megacrysts that are very characteristic of both the tonalite and quartz monzonite bodies.

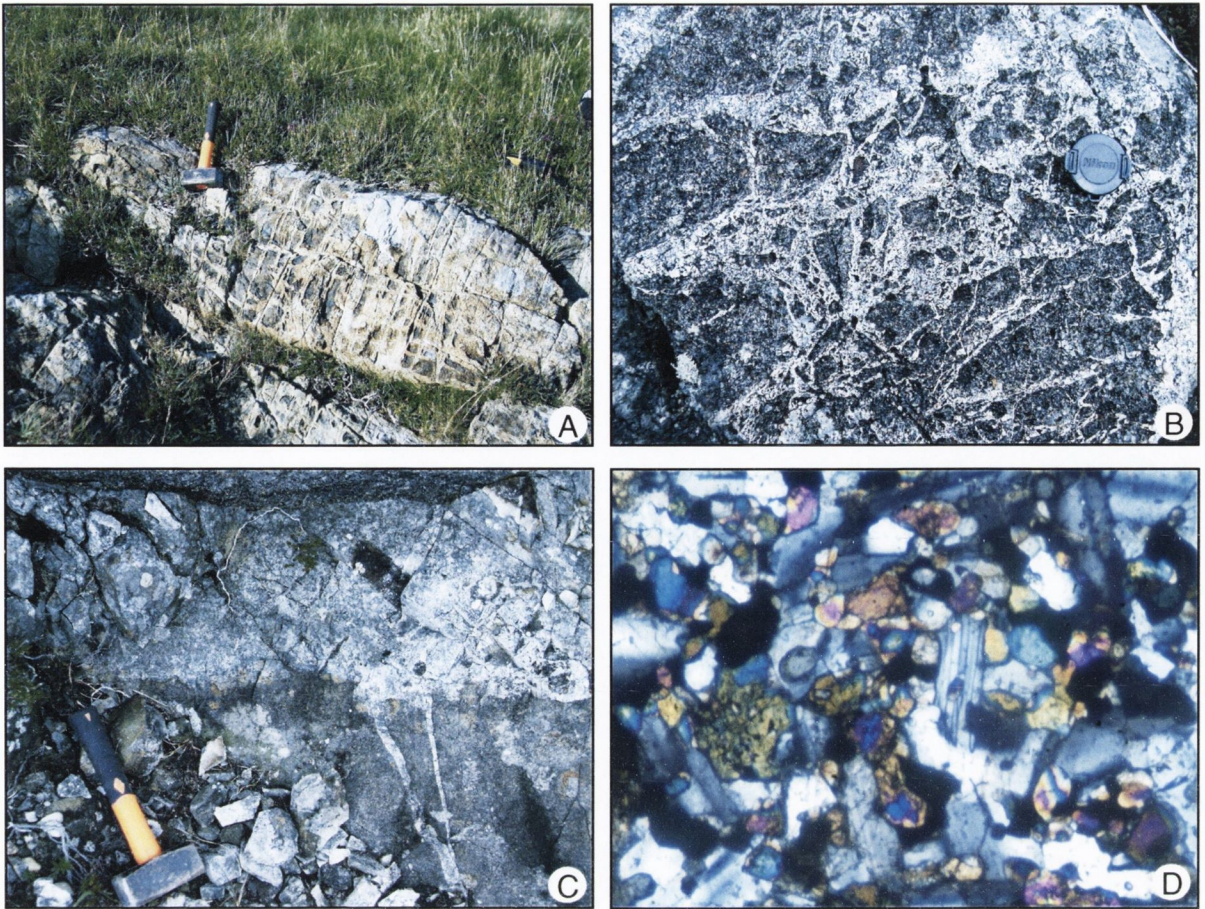


Figure 3.12. A: Microgranite containing gabbro and dolerite fragments. B: Intricate net-veining of dolerite by microgranite. C: Contact (outward (NE)-dipping) of microgranite intrusion at GR 48777 69500 at very top of image. D: Granular appearance of the quartz-dolerite in thin-section. Image is taken in crossed polars, and the field of view is 2mm in width.

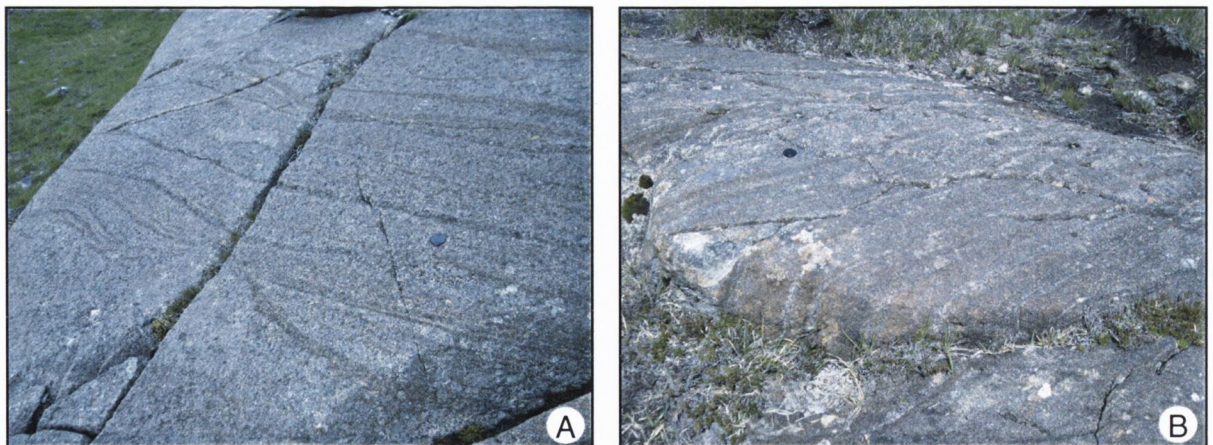


Figure 3.13. A and B: Sequences of magmatic layering in the Great Eucrite (see text for discussion). In both cases a lens cap is present on the outcrop for scale.

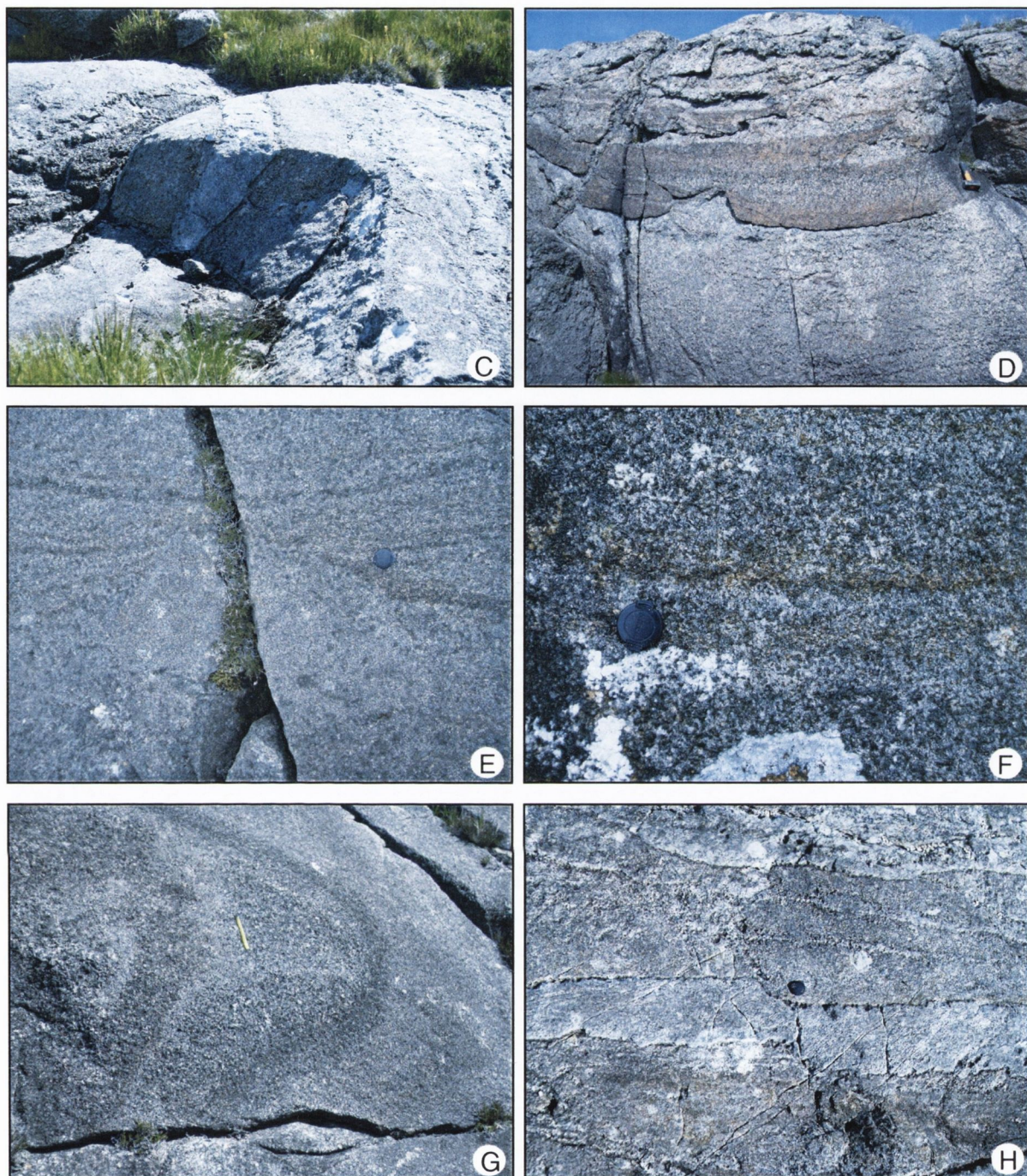


Figure 3.13. C: Inward dip of plagioclase-rich layer toward the centre of the Great Eucrite. Lens cap on outcrop left of centre gives scale. D: Trough structure (with modal graded bedding of olivine). Hammer to the right of centre gives scale. E: Layering draped over and lapping onto gabbro dropstone. F: Modal grading of olivine in magmatic layers. G: Syn-magmatic folding of pyroxene-rich layers. H: Syn-magmatic deformation of layering: lateral variation of layer thickness, and in the centre of the image below the lens cap, a small syn-magmatic normal fault.

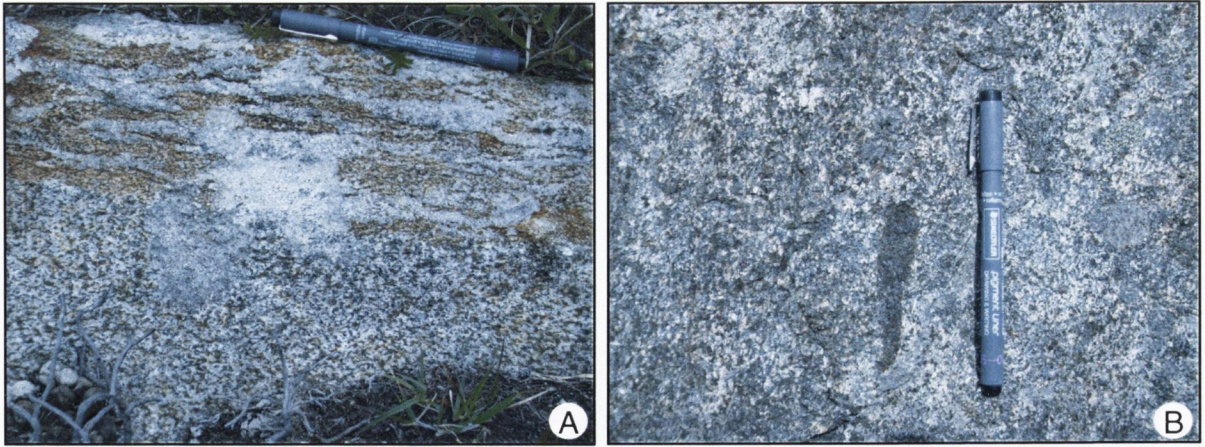


Figure 3.14. A: Crystal slurry (syn-magmatic deformation at Achnaha). B: Boudined pyroxene layer (Sithean Mor). The igneous lamination is parallel to the plane of deformed layering/boudinage here, i.e. approximately parallel to the orientation of the pen.

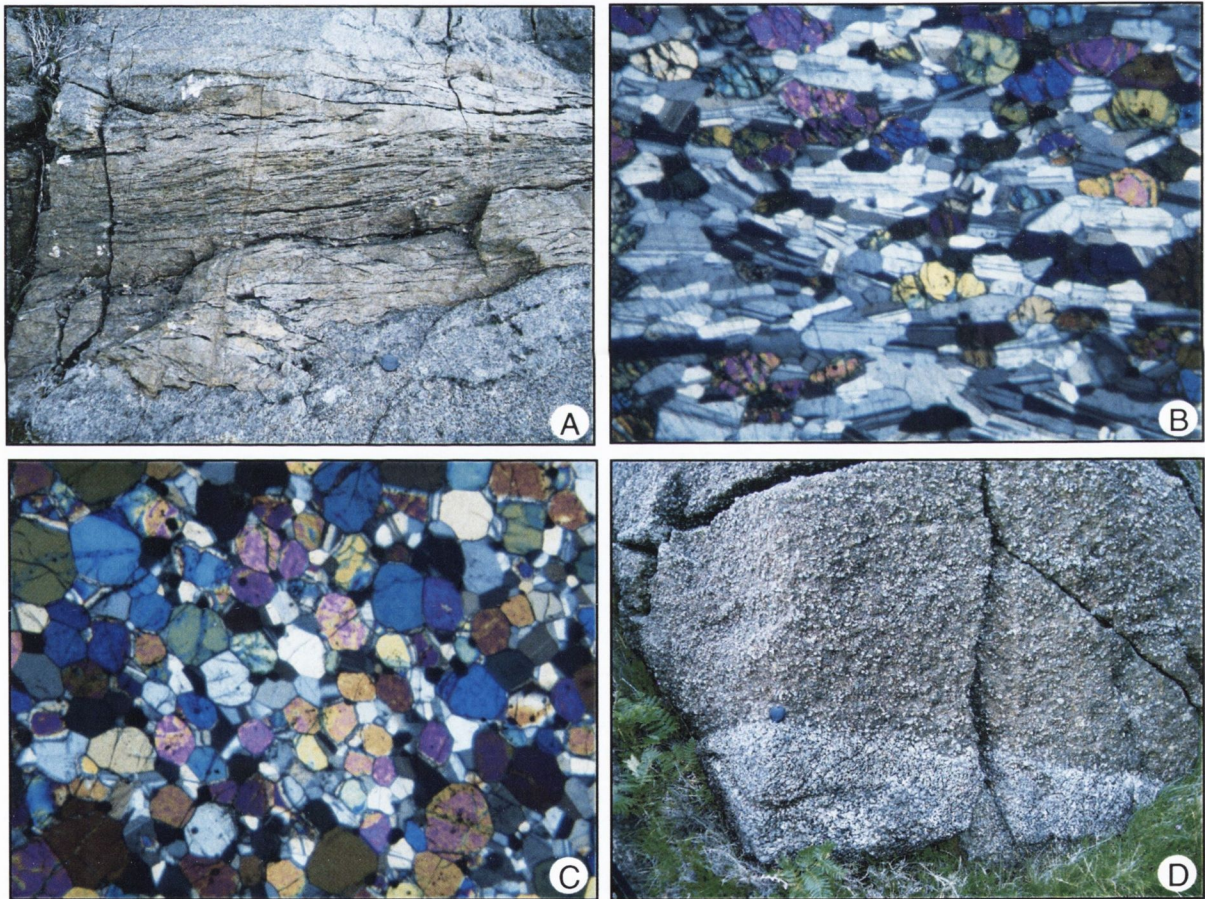


Figure 3.15. A: Magmatic layering in fine-grained peridotite xenolith. B: Photomicrograph of well-developed plagioclase igneous lamination from fine-grained peridotite xenolith. Image is taken in crossed polars and field of view is 3mm in width. C: Olivine dihedral angle relationships in fine-grained peridotite sample. Image is taken in crossed polars and field of view is 3mm. D: Magmatic layering in coarse-grained peridotite layers.

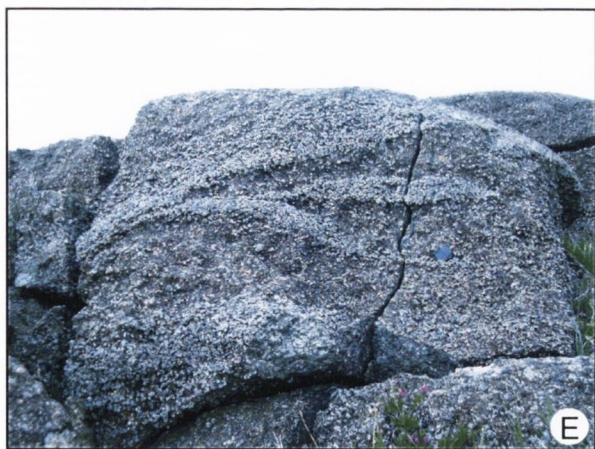


Figure 3.15. E: Magmatic layering in coarse-grained peridotite layers.

Figures 3.16 and 3.17: See overleaf.

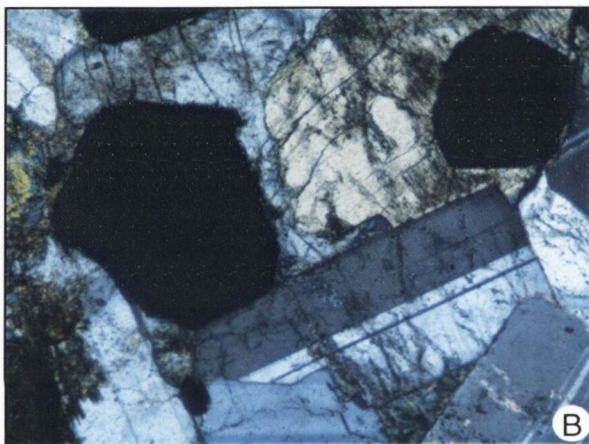
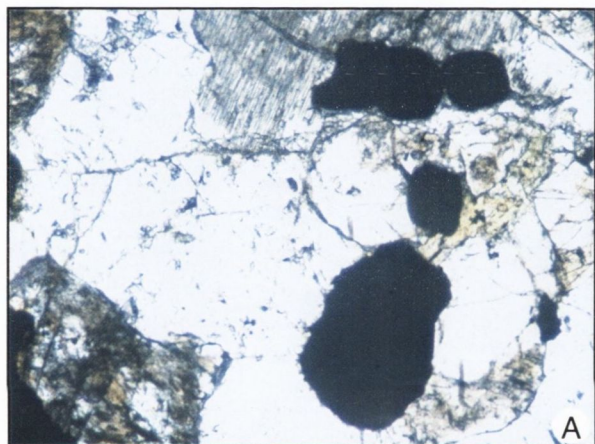
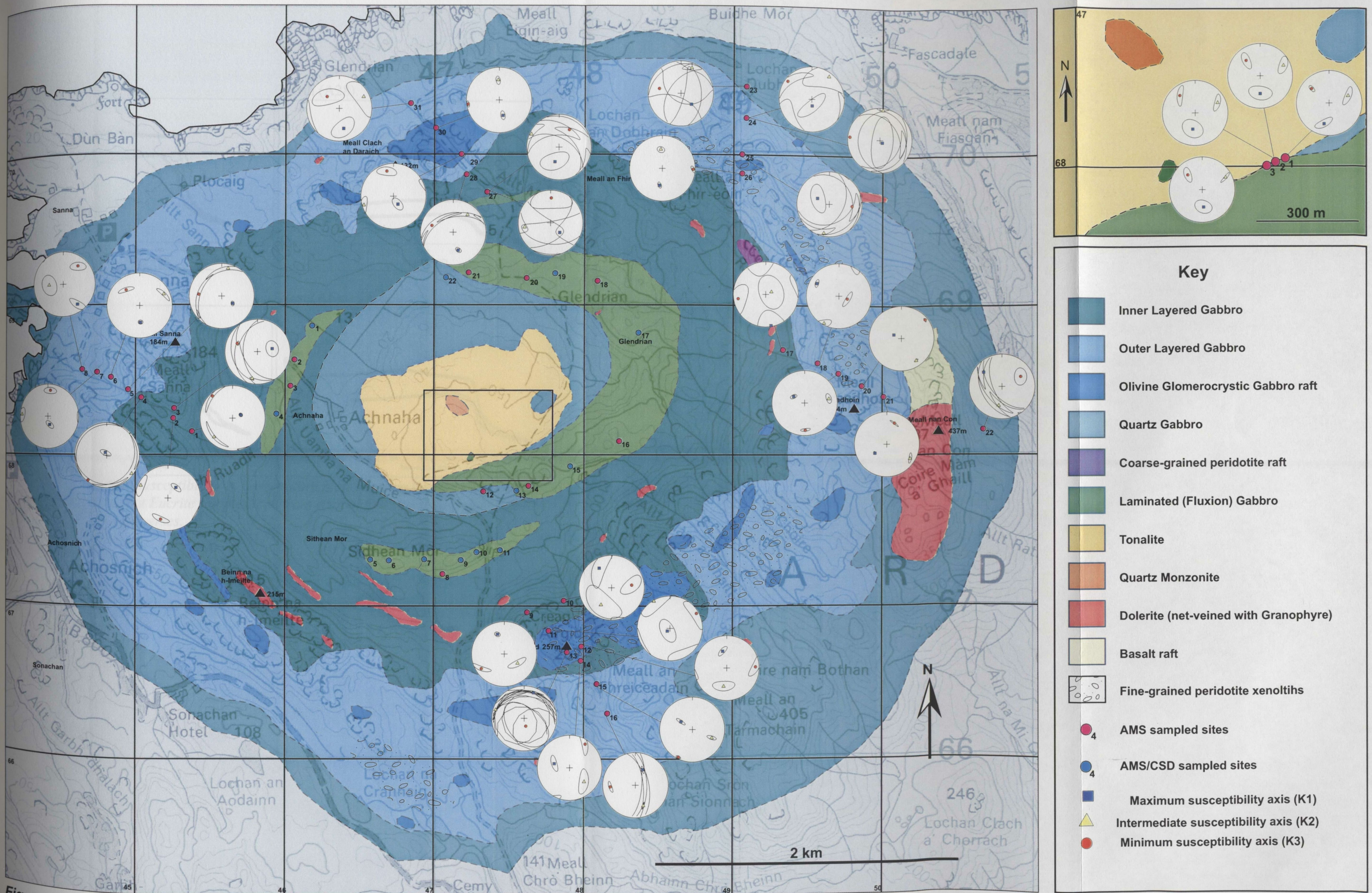
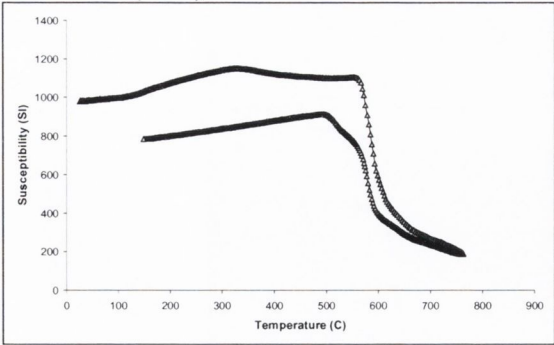


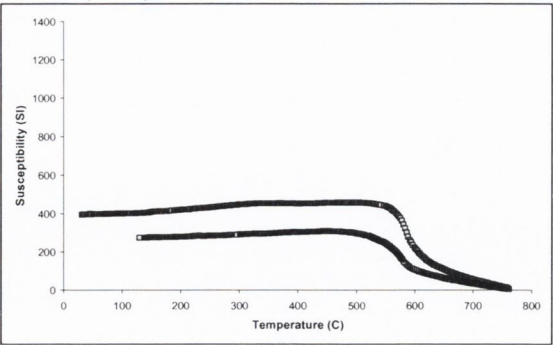
Figure 3.18. A and B: Large subhedrad magnetite grains in the Great Eucrite gabbro. Field of view in both images is approximately 1mm. A is taken in plane polarized light, B in crossed polars.



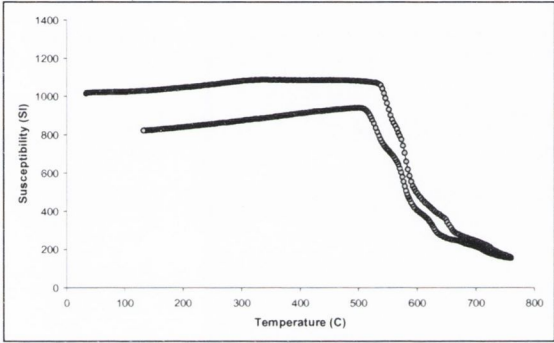
Northeast (A23).



North (A28).



South (A9).



West (A6).

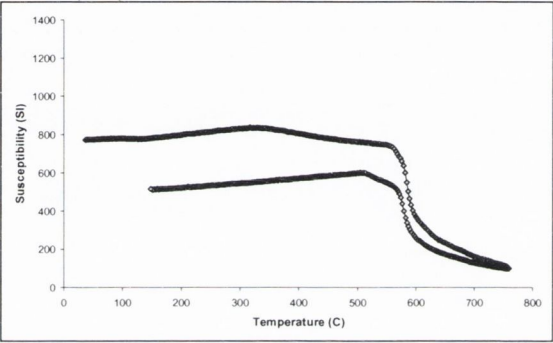


Figure 3.17. Labelled susceptibility vs. temperature plots showing heating and cooling paths for selected Great Eucrite samples, one from each of four, northeast, north, south and west, of the five traverses.

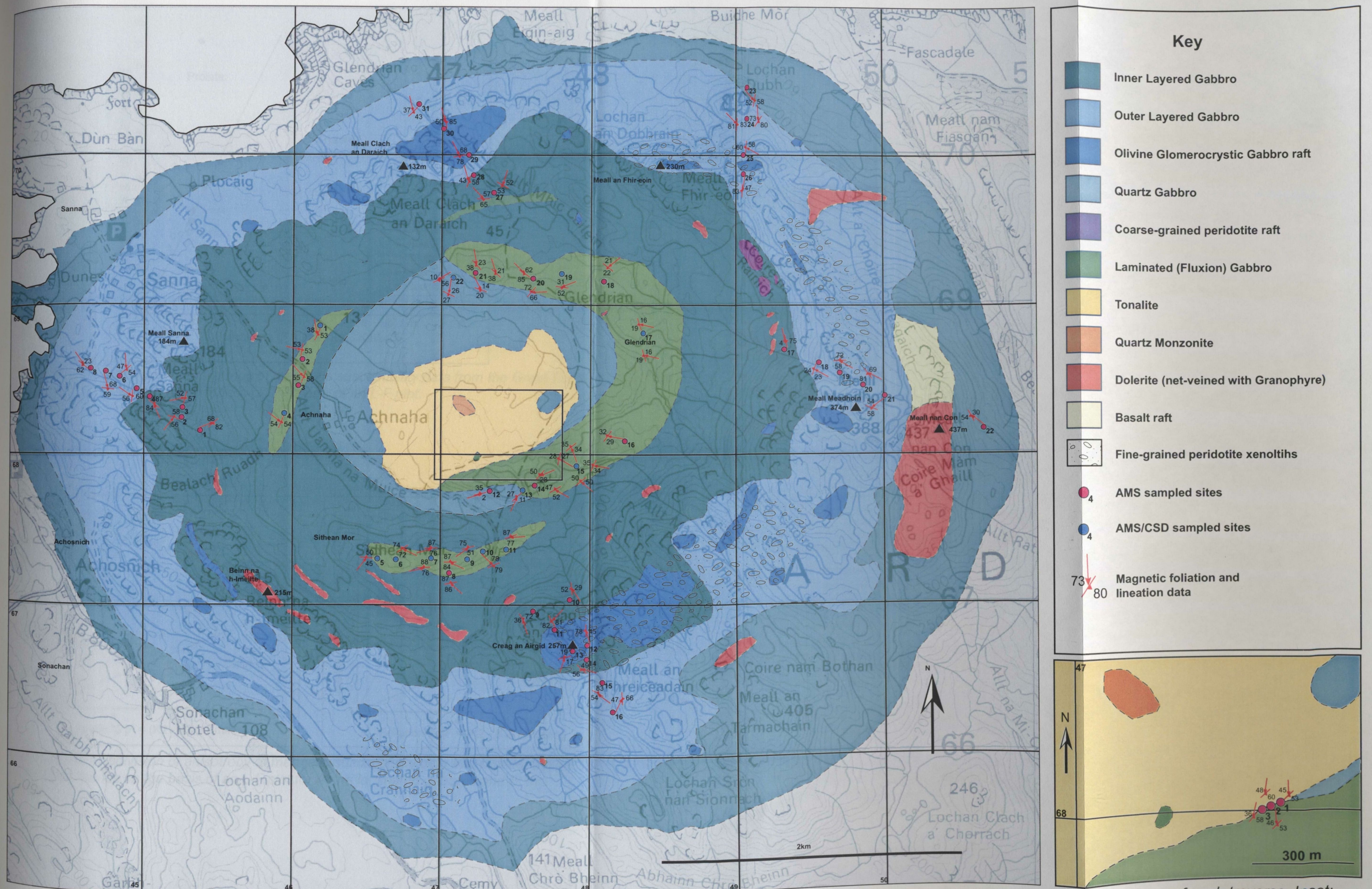


Figure 3.19. Simplified presentation of AMS data with magnetic lineations and foliations of the Great Eucrite, the laminated gabbros and the tonalite on a structural map of each traverse. Inset: AMS data presented in the same way for the tonalite contact.

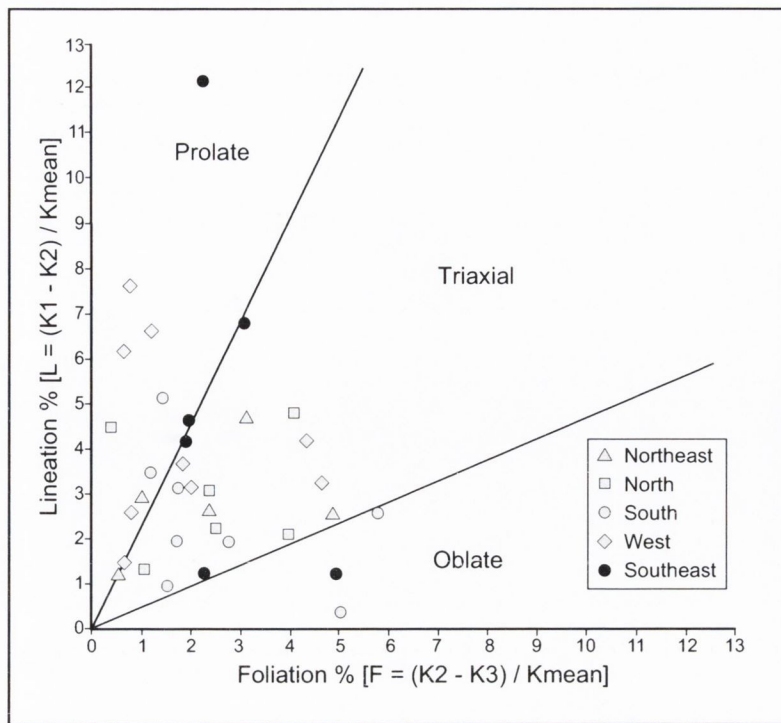


Figure 3.20. Subdivision of anisotropy of magnetic susceptibility data from the Great Eucrite into prolate, triaxial and oblate fabrics on the basis of an L-F plot.

Figure 3.21. See overleaf.

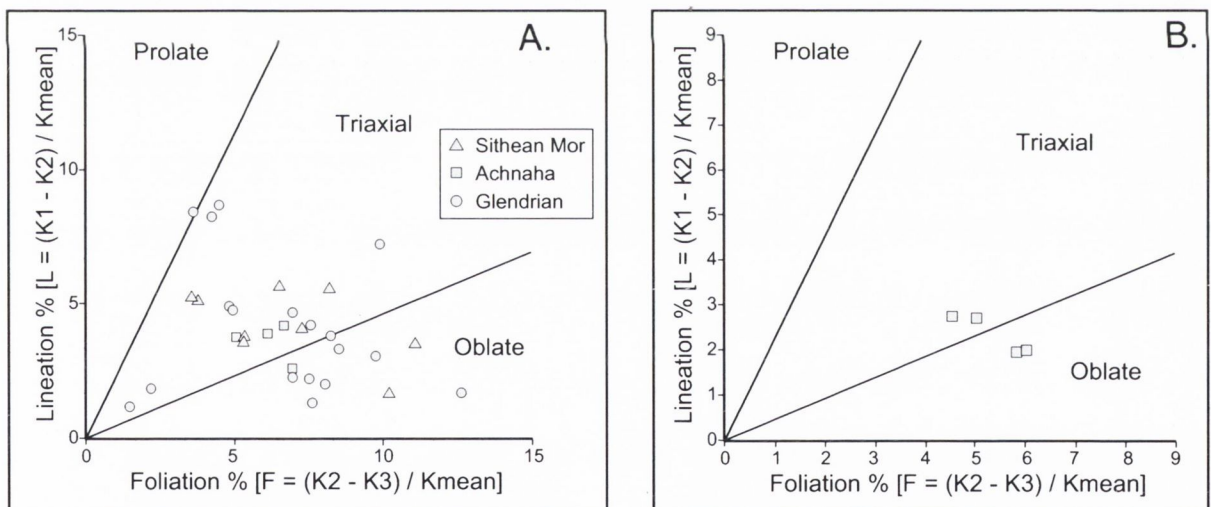
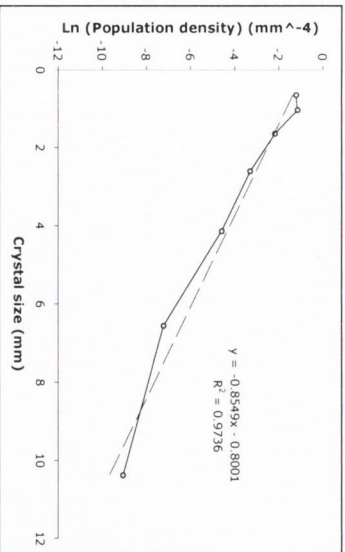


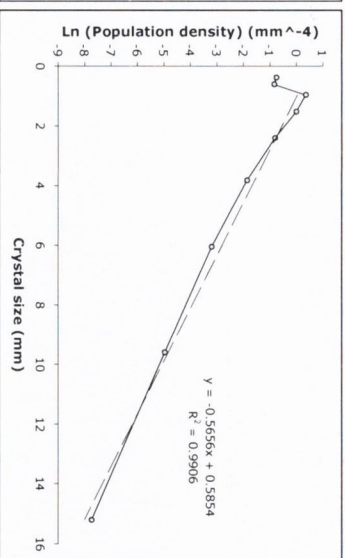
Figure 3.22. Subdivision of anisotropy of magnetic susceptibility data into prolate, triaxial and oblate fabrics on the basis of an L-F plot for A: the laminated gabbros and B: the tonalite.

A.

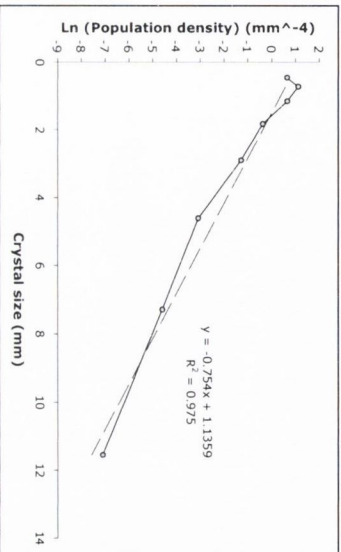
A5.



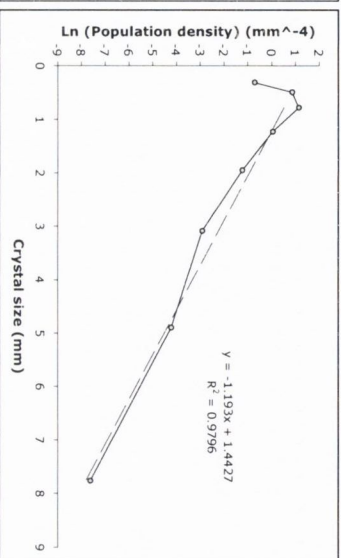
A6.



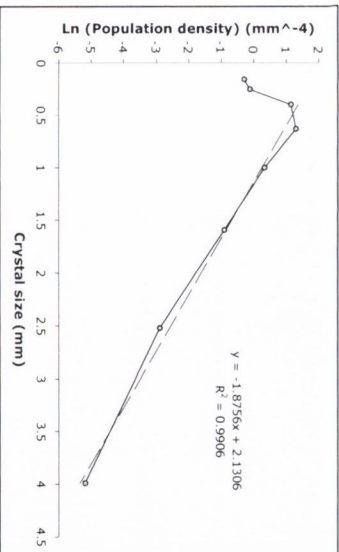
A7.



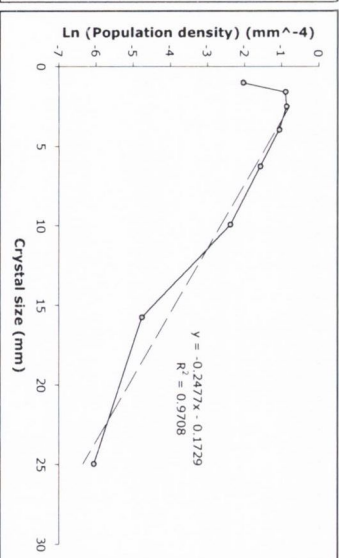
A9.



A10.

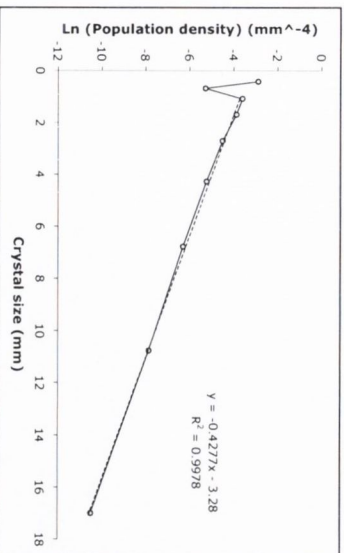


A11.

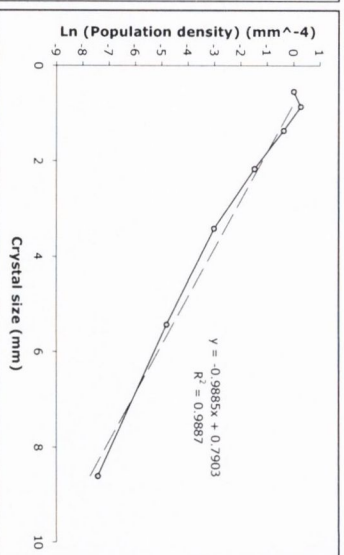


B.

A1.

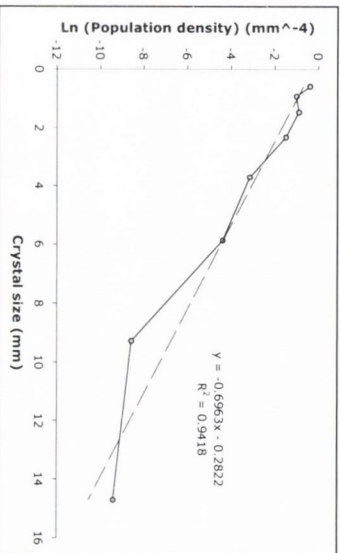


A4.

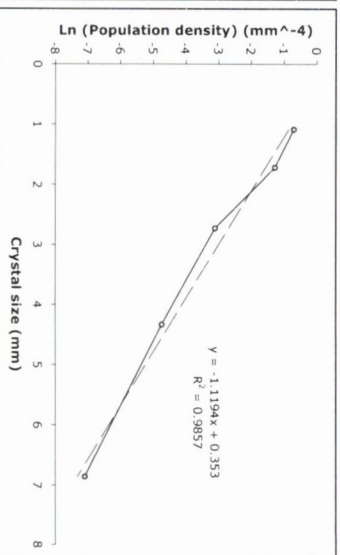


C.

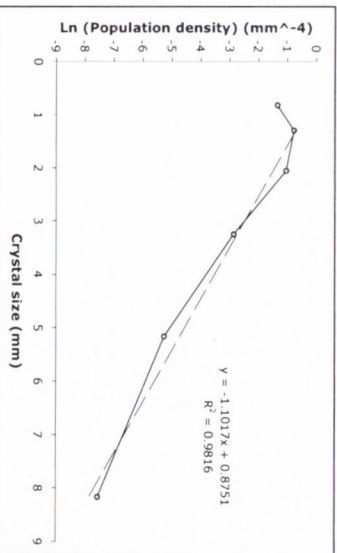
A13.



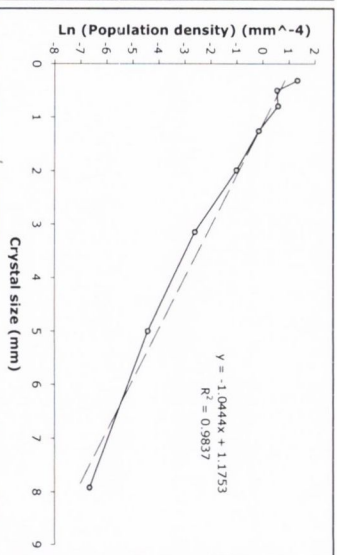
A15.



A17.



A19.



A22.

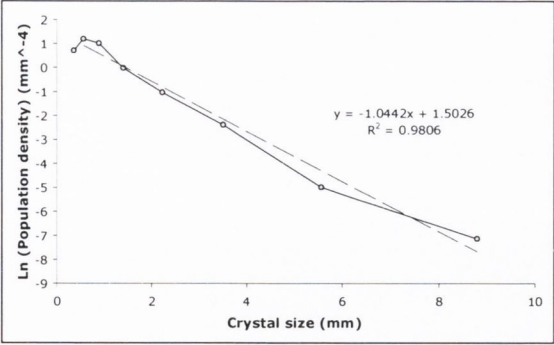
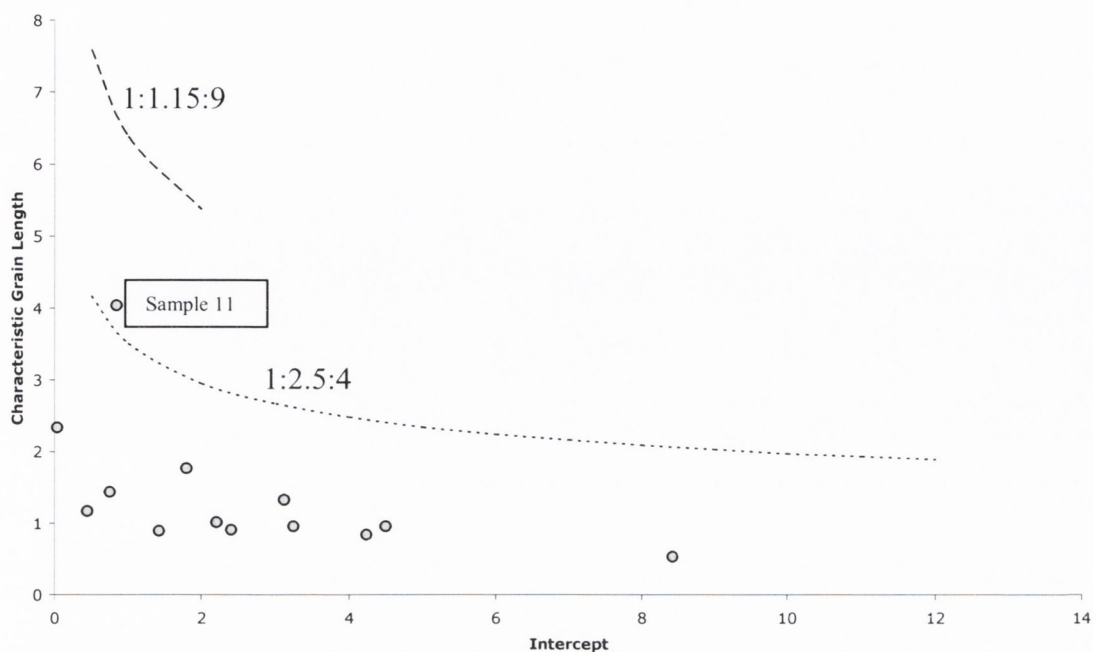


Figure 3.23. Labelled CSD plots for the laminated gabbros: A: Sithean Mor samples. B: Achnaha samples. C: Glendrian samples. The results of linear regression analysis carried out on each and the slope of the line in each case are shown.

A.



B.

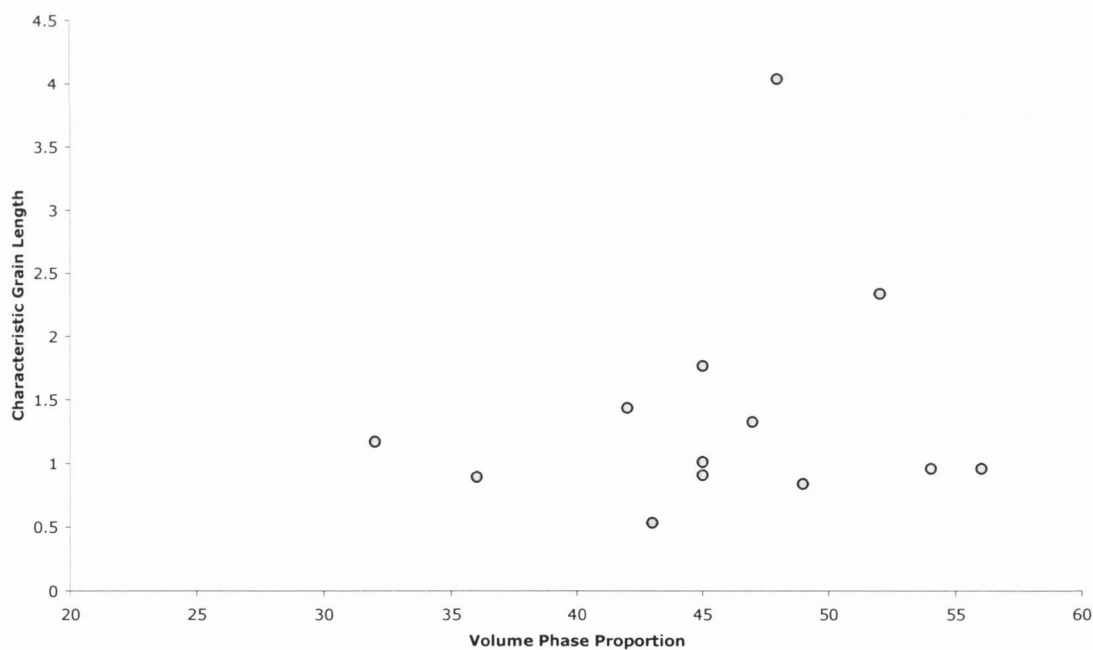
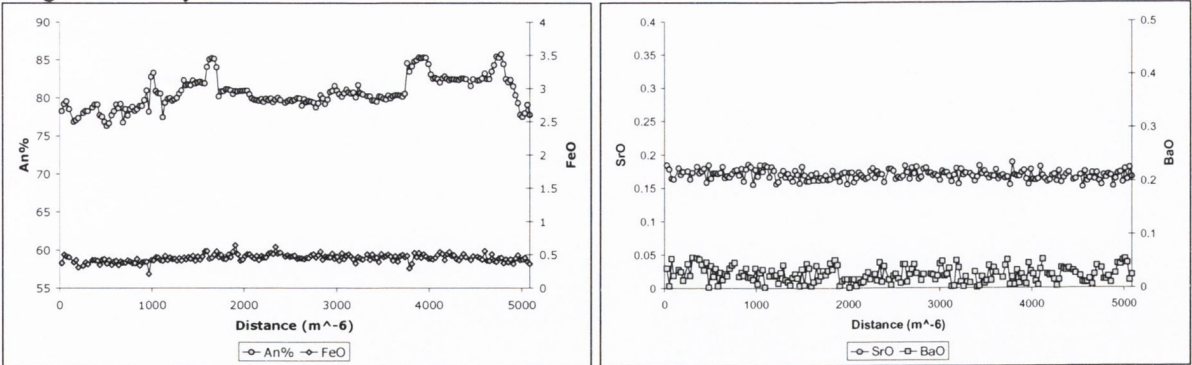
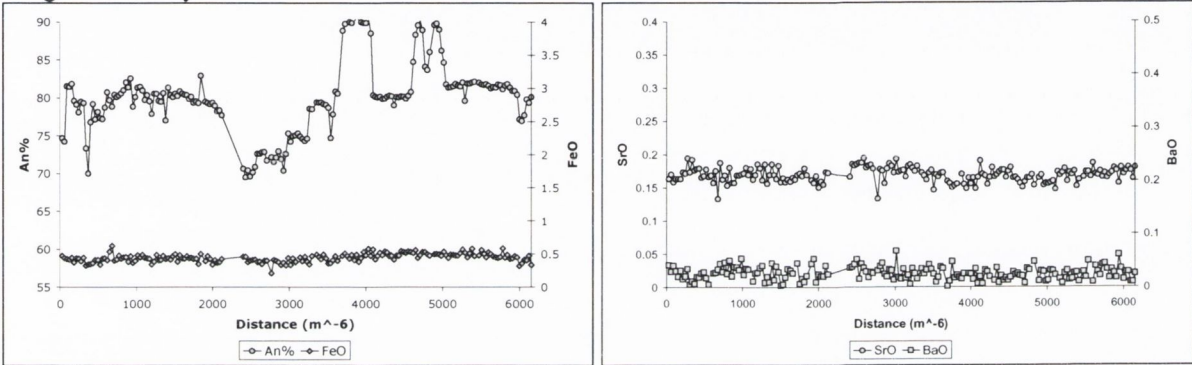


Figure 3.24. Closure plots for CSD data. A: Characteristic length vs. intercepts for the laminated gabbros. Each of the two curves for 100% crystal volume has the aspect ratio used to calculate it labeled, as described in text. Sample 11, discussed in the text, is also labeled. B: Subdivision of the CSD data on the basis of a characteristic length vs. volume phase proportion plot.

Plagioclase Crystal 1.



Plagioclase Crystal 2.



Plagioclase Crystal 3.

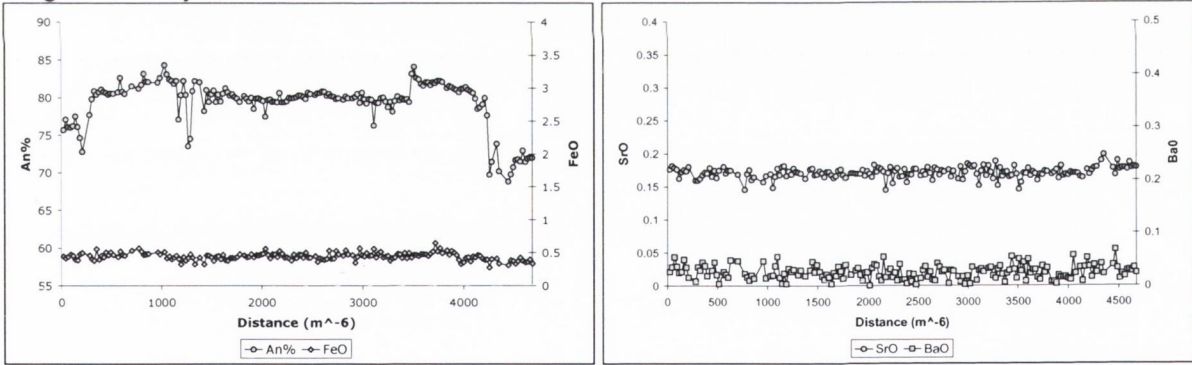


Figure 3.25. Mineral chemical data for Plagioclase Crystal Traverses 1-3 from Sample 5 of the Sithean Mor laminated gabbro. Rim-to-rim traverses along the length of each crystal for An mol%, FeO_t wt%, SrO wt%, and BaO wt% vs. distance are illustrated for each.

Plagioclase Crystal 4.

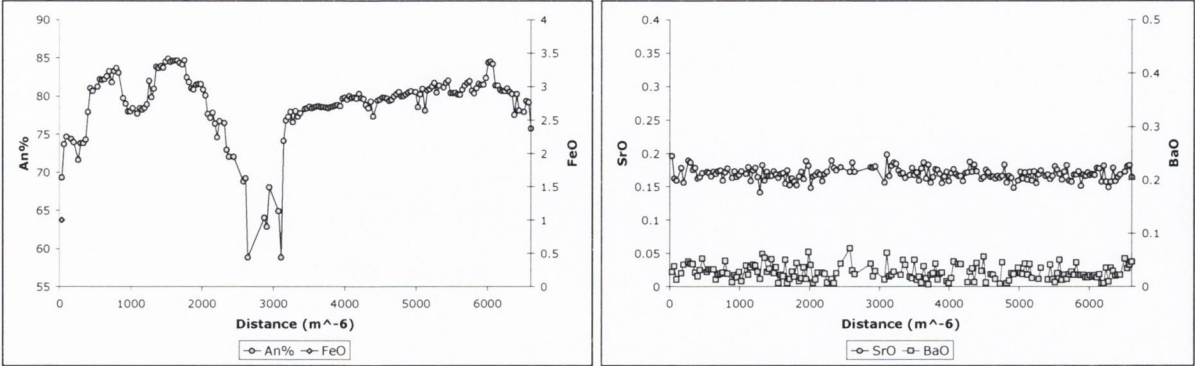


Figure 3.25. Mineral chemical data for Plagioclase Crystal Traverse 4 from Sample 5 of the Sithean Mor laminated gabbro. Rim-to-rim traverses along the length of each crystal for An mol%, FeO_t wt%, SrO wt%, and BaO wt% vs. distance are illustrated for each.

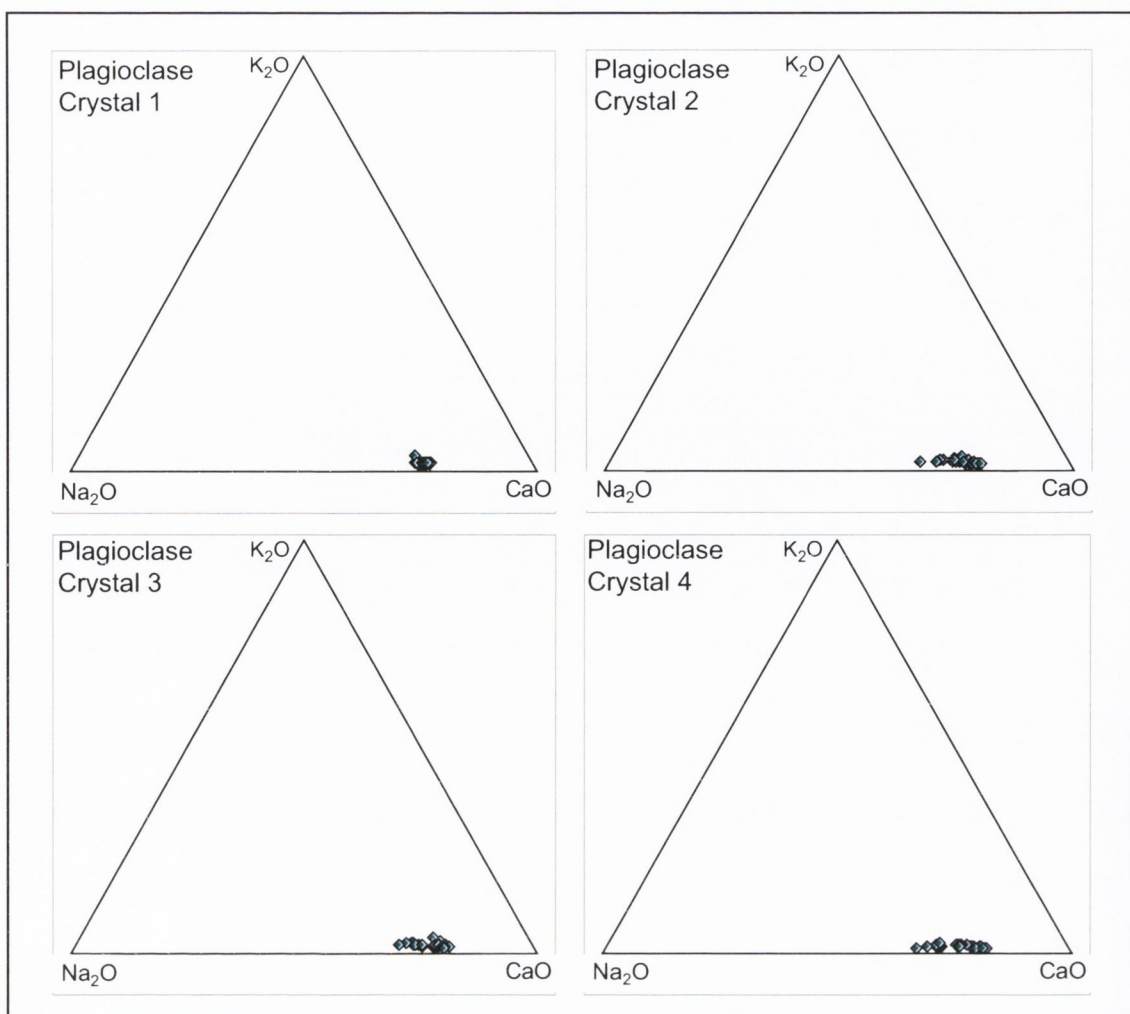


Figure 3.25. B: Ternary ($K_2O/CaO/Na_2O$) plots for all Sample 5 mineral-chemical data.

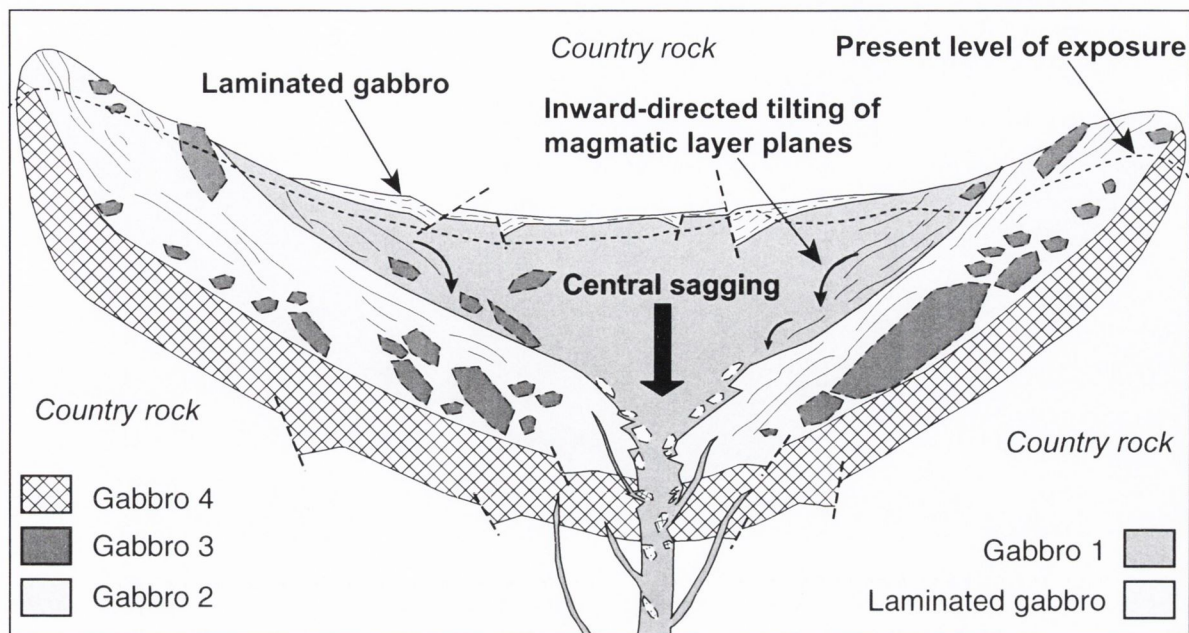


Figure 3.26. Schematic diagram showing the proposed pre-tonalite form of the Ardnamurchan Centre 3 gabbros and primary magma flow planes as suggested by field observations, structural data and magnetic fabric results. The suggested position of each of the component gabbros of the Great Euclite is shown.

Table 3.1. AMS data for the Ardnamurchan Great Eucrite gabbros

Sample	Kmean	K1	Dec	Inc	K2	Dec	Inc	K3	Dec	Inc	L	F	H	Mu
West														
1	7903.62	1.053	248.7	-68	0.977	44.4	-20.2	0.97	317.5	8.3	7.56	0.76	8.32	84.3
2	12899.12	1.042	218.4	-56.4	1	114.9	-8.8	0.958	19.4	-32.1	4.16	4.29	8.45	44.1
3	13936.54	1.02	78.3	51.8	0.994	10.9	-16.8	0.986	112.3	-33.1	2.61	0.82	3.43	72.5
4	12920.35	1.043	154.8	-83.9	0.982	126.8	5.4	0.975	37.1	-2.9	6.12	0.67	6.79	83.7
5	14122.22	1.048	124.1	56.3	0.982	12.9	13.5	0.97	94.8	-30.2	6.58	1.19	7.77	79.8
6	11962.73	1.03	356.7	-47.4	0.994	64.3	19.3	0.976	319.5	36.2	3.65	1.83	5.48	63.4
7	14365	1.028	345.6	-68.1	0.996	93.3	-7	0.976	6	20.7	3.16	1.99	5.15	57.8
8A	16126.19	1.037	144.5	23.2	1.005	266.9	51.3	0.959	40.7	29	3.24	4.61	7.84	35.1
8B	15991.33	1.012	299.6	74.2	0.997	347.6	-10.7	0.991	75.4	11.5	1.46	0.65	2.12	65.9
South														
9	15363.62	1.027	160.7	-35.7	0.992	125.5	48.7	0.981	57.2	-18	3.44	1.18	4.61	71.1
10	16700.37	1.022	147.4	-29.3	1.003	210.9	38.5	0.975	83.1	37.7	1.9	2.74	4.65	34.7
11	15517.23	1.019	223.4	81.3	0.999	329.7	2.5	0.982	60	8.3	1.93	1.72	3.65	48.3
12	32839.09	1.039	346.3	45	0.988	9.4	-42.6	0.974	88.3	11.8	5.1	1.41	6.51	74.5
13	25302.57	1.011	19	17.1	1.002	106.1	-9.2	0.987	168.9	70.5	0.92	1.51	2.43	31.5
14	18954.56	1.027	105.7	-48.7	0.995	134.5	37.6	0.978	32.9	14.6	3.13	1.71	4.83	61.4
15	17065.82	1.036	124.6	-54.4	1.01	112.8	35	0.954	26.8	-5.6	2.54	5.67	8.21	24.1
16	24063.61	1.019	24.8	47.1	1.015	339.1	-33	0.966	86	-24.1	0.35	4.97	5.33	4.1
Southeast														
17	14531.61	1.016	169.7	4	1.003	65.5	74.1	0.981	80.8	-15.3	1.24	2.28	3.52	28.5
18	9437.74	1.034	300	23.3	0.992	28.3	-4	0.974	109.1	66.3	4.13	1.84	5.97	66
19	12875.52	1.037	120.1	-57.8	0.991	79	25.4	0.972	358.1	-18.4	4.6	1.97	6.57	66.8
20	15971.43	1.055	297.1	69	0.988	325.8	-18.6	0.957	52.6	9.4	6.78	3.04	9.82	65.9
21	26439.04	1.089	53.9	-53.4	0.967	120.5	16.4	0.944	20	31.6	12.15	2.26	14.41	79.5
22	22145.37	1.024	308.1	29.5	1.012	9.5	-40.3	0.964	62	35.7	1.23	4.86	6.09	14.2
Northeast														
23	13944.28	1.01	136.1	52.4	0.998	23.7	16.4	0.992	102.7	-32.8	1.19	0.56	1.75	64.6
24A	7856.96	1.025	134.4	81.3	0.999	5.9	5.4	0.976	95.3	-6.8	2.58	2.37	4.95	47.4
24B	8624.75	1.041	177.2	72.9	0.995	37.6	13.2	0.964	125.1	-10.7	4.67	3.09	7.76	56.5
25	20179.96	1.023	295.9	57.8	0.994	10.5	-9.5	0.984	94.8	30.5	2.89	1.03	3.92	70.5
26	15347.33	1.033	188.9	47.1	1.008	355.5	42.1	0.959	91.6	6.7	2.51	4.84	7.35	27.4
North														
27A	19947.74	1.045	16.6	-51.7	0.998	115	-6.6	0.957	30.1	37.5	4.74	4.02	8.77	49.7
27B	15221.6	1.028	315.5	-56.5	0.998	81.3	-21.2	0.974	1.5	24.7	3.04	2.34	5.38	52.3
28	9853.92	1.031	163.3	42.7	0.987	39.8	30.9	0.982	108	-31.7	4.45	0.44	4.89	84.3
29	22412.53	1.023	331.6	-67.6	1.001	73.3	-4.8	0.976	345.2	21.8	2.2	2.52	4.72	41.2
30	8803	1.027	166.7	50.2	1.006	356.2	39.4	0.967	82.4	-4.7	2.09	3.97	6.06	27.8
31	24501.79	1.012	347.7	-37.4	0.999	63.9	17.3	0.989	314	47.5	1.3	1.06	2.36	50.9

Table 3.2. AMS data for the Ardnamurchan laminated gabbros

Sample	Kmean	K1	Dec	Inc	K2	Dec	Inc	K3	Dec	Inc	L	F	H	Mu
Achnaha														
1	4518.3	1.041	170	37.8	1.005	52.5	30.7	0.954	115.8	-37.1	3.64	5.11	8.75	35.5
2	12094	1.049	102.7	52.5	1.009	10.5	1.7	0.942	99.2	-37.4	4.07	6.65	10.72	31.5
3	9903.22	1.039	139.5	54.5	1.015	29.9	13.4	0.946	111.3	-32.1	2.38	6.97	9.35	18.8
4	12395.15	1.046	127.9	53.5	1.008	28.3	7	0.946	113.2	-35.6	3.79	6.14	9.93	31.7
Sithean Mor														
5	18055.72	1.042	218.5	-44.5	1.005	110.5	-17.5	0.953	5	-40.3	3.63	5.22	8.86	34.8
6	101696.643	1.041	116.2	-71.8	1.006	54.5	8.9	0.953	327	-15.8	3.55	5.27	8.82	34
7A	92892.96	1.046	258.9	-76.1	0.996	89.5	-13.6	0.958	358.9	-2.4	5.06	3.72	8.78	53.7
7B	93699.42	1.046	255.2	-75.7	0.995	88.4	-13.9	0.959	357.6	-3.1	5.1	3.61	8.71	54.8
8A	160837.755	1.064	114.7	-83.7	1.009	89.5	5.7	0.927	359.7	-2.7	5.47	8.21	13.68	33.7
8B	150725.396	1.059	132.3	-85.7	1.003	79.8	2.6	0.938	350	-3.4	5.57	6.54	12.11	40.4
9	143007.646	1.044	235.7	-51.1	1.029	85.1	-35.1	0.927	344.6	-14.6	1.58	10.17	11.75	8.8
10	249728.042	1.06	314.9	-78.2	1.025	66.7	-4.4	0.915	337.6	10.9	3.44	11.04	14.47	17.3
11	208637.51	1.051	86.3	-76.8	1.011	71	12.8	0.938	341.7	-3.4	3.99	7.28	11.27	28.7
Glendrian														
12	252279.375	1.081	254.9	-2.2	1.009	343.4	34.5	0.91	168.1	55.5	7.15	9.86	17.01	35.9
13	238158.516	1.054	26.7	10.6	1.008	111.9	-24.3	0.938	138.5	63.2	4.58	6.98	11.56	33.3
14A	239626.385	1.052	67.9	-27.5	1.037	1.4	37.4	0.911	311.8	-40.3	1.57	12.6	14.17	7.1
14B	221733.39	1.072	118.7	-41.7	0.986	44.4	16.9	0.941	331.1	-43.4	8.61	4.51	13.11	62.4
15A	245076.833	1.04	339.8	33.5	1.02	64.4	-8.2	0.94	142.4	55.3	1.93	8.06	9.98	13.5
15B	251361.339	1.052	300.6	27.1	1.023	26.7	-7.6	0.925	102.4	61.7	2.96	9.72	12.68	16.9
15C	243665.162	1.039	130.5	-50	1.018	46.7	5.1	0.943	320.9	-39.6	2.1	7.53	9.64	15.6
15D	224396.333	1.05	279.6	33.6	1.018	14.7	7.6	0.933	115.8	55.3	3.24	8.5	11.73	20.8
16	227044.359	1.052	280.1	29	1.015	16.7	11.8	0.933	126.5	58.2	3.73	8.24	11.97	24.4
17A	217781.474	1.048	282.9	16.1	1	10.1	-9.6	0.952	70.5	71.1	4.8	4.85	9.64	44.7
17B	217442.276	1.048	283.3	16	1.001	10.5	-9.4	0.951	71.2	71.3	4.68	4.94	9.63	43.4
18	207494.104	1.038	52.8	-21.2	1.016	140.8	5	0.946	38.1	68.1	2.28	6.98	9.26	18.1
19	210906.005	1.034	69.9	-31	1.021	133.7	36.4	0.945	8.2	38.3	1.25	7.61	8.86	9.4
20A	214762.448	1.012	313.8	-62.4	1.002	121.7	-27	0.986	34.3	5	1.06	1.52	2.58	34.8
20B	276420.036	1.053	267.9	66	1.012	35.9	15.3	0.936	131	18	4.09	7.58	11.67	28.4
21A	261919.927	1.068	349.9	-22.8	0.984	93.1	-28.6	0.948	47.3	52	8.36	3.62	11.98	66.6
21B	239691.989	1.044	332	-14.3	1.018	65.7	-14.2	0.939	18.8	69.6				
21C	257751.37	1.069	343.5	-21	0.987	86.1	-29.5	0.944	43.5	52.4	8.18	4.26	12.44	62.5
22A	119547.435	1.019	8.7	-25.8	1.002	102	-6.8	0.979	25.6	63.2	1.75	2.22	3.97	38.2
22B	271199.005	1.045	60.5	9.6	1.011	316.9	54.2	0.944	337.1	-34.1				

Table 3.3. AMS data for the Ardnamurchan tonalite

Sample		Kmean	K1	Dec	Inc	K2	Dec	Inc	K3	Dec	Inc	L	F	H	Mu	
2A	1	27025.22	1.033	359.6	-44.9	1.013	65.5		22.3	0.954	317.7	36.7	1.98	5.84	7.82	18.7
		25102.58	1.033	9.5	-48.4	1.006	65.8		26.3	0.961	319.4	29.7	2.72	4.56	7.27	30.8
	2B	26984.99	1.033	356.3	-45.8	1.013	62.9		21.1	0.954	316.2	36.6	1.95	5.99	7.94	18
	4	23655.01	1.035	194	35.5	1.008	69.9		38.1	0.957	130.5	-32	2.71	5.02	7.73	28.3

Table 3.4. CSD data for samples from the Ardnamurchan laminated gabbros

Sample	Vol. Phase Prop.	Aspect Ratio	Slope	Ln(n0)	n0	τ_1 (Years)	J1 (mm ⁻³ s ⁻¹)	No. of Crystals
1	52	1:1.5:2.7	-0.4277	-3.28	0.0376	741	3.76283E-12	189
15A	36	1:1.6:2.9	-1.1194	0.353	1.4233	283.3	1.42333E-10	187
17A	45	1:1.3:2.9	-1.1017	0.8751	2.3991	287.8	2.39912E-10	313
4	45	1:1.6:3.6	-0.9885	0.7903	2.2041	320.8	2.20406E-10	692
7	47	1;2.7;8	-0.754	1.1359	3.114	420.6	3.11397E-10	350
9	49	1:1.9:3.8	-1.193	1.4427	4.2321	265.8	4.23211E-10	248
11	48	1:1.15;9	-0.2477	-0.1729	0.8412	1280.2	8.41222E-11	135
10	43	1:1.7:2.8	-1.8756	2.1306	8.4199	169.1	8.41992E-10	338
13	42	1:1.5;4	-0.6963	-0.2822	0.7541	455.4	7.54123E-11	241
19	54	1:1.6:3.6	-1.0444	1.1753	3.2391	303.6	3.23911E-10	606
22A	56	1:2;4.5	-1.0442	1.5026	4.4934	303.7	4.49336E-10	326
6	45	1:2.3;9	-0.5656	0.5854	1.7957	560.6	1.79571E-10	377
5	32	1:2.3:3.6	-0.8549	-0.8001	0.4493	370.9	4.49284E-11	379

CHAPTER 4. THE RUM LAYERED SUITE

4.1. Magmatic lineations inferred from anisotropy of magnetic susceptibility fabrics in Units 8, 9, and 10 of the Rum Eastern Layered Intrusion, Scotland

4.1.1. Introduction

The Rum Layered Suite is part of the Rum Igneous Centre and is a superb example of a layered, mafic-ultramafic intrusion (Emeleus 1987; Emeleus *et al.* 1996; Bell and Williamson 2002). The first study in this chapter focuses on the origin and significance of AMS fabrics in Units 8, 9, and 10 in a small area in the north of the well-studied Eastern Layered Intrusion of the Rum Layered Suite. The results are combined with field observations and structural measurements on magmatic layering and associated small-scale structures to assess the importance of flow and magmatic sedimentation on magmatic layer and fabric formation in the Rum cumulate pile.

4.1.2. Geological Setting

The Layered Suite of the Palaeogene Rum Igneous Centre forms an upstanding area of about 30km² in the central and eastern part of the island. It has been divided into three separate parts, the Eastern Layered Intrusion, Western Layered Intrusion, and the Central Intrusion (Fig. 4.1). Age relations of the Eastern Layered Intrusion and Western Layered Intrusion are uncertain; although the Western Layered Intrusion is structurally lower, it is separated from the Eastern Layered Intrusion by the younger Central Intrusion (Emeleus *et al.* 1996). The subject of this study, the Eastern Layered Intrusion, comprises a cyclic sequence of coupled peridotite-troctolite macro-units, in which peridotite is always overlain by rhythmically layered troctolite (historically termed allivalite). The exposed sequence of the Eastern Layered Intrusion has been divided into sixteen such units (Brown 1956; Volker and Upton 1990; Emeleus *et al.* 1996), whose thicknesses range from a few tens of metres to ~100m (Fig. 4.2A). This stratigraphy has been shown to be overly simplistic by Bédard *et al.* (1988) and Holness (2005) who present strong evidence that the Unit 9 peridotite is likely to be a late layer-parallel intrusive body. However, Holness (2005) has also demonstrated that Unit 9 is likely to be the only major intrusive peridotite body in the Eastern Layered Intrusion.

The peridotite bases of units are generally sharp, and are occasionally marked by the development of thin chrome-spinel seams, as are the upper parts of many of the troctolites by the appearance of cumulus clinopyroxene (Brown 1956). These large-scale layers of the Eastern Layered Intrusion typically dip inward towards a central focal point in Atlantic Corrie (Fig. 4.1), giving the Eastern Layered Intrusion an apparently

lopolithic geometry, analogous to a series of saucers stacked one upon the other. Dip values for these units are generally 10°-15°, but may locally be as much as 40° or more (e.g. in the Trollaval region; Volker and Upton 1990). Macro-units of the Eastern Layered Intrusion are thought to have developed through cyclic replenishments of picritic liquids ponding in thin sill-like bodies at the Lewisian gneiss-Torridonian sandstone unconformity, each contributing incrementally to the layered cumulate sequence (Emeleus *et al.* 1996).

Magmatic layering of minerals on the scale of millimeters to tens of centimeters is commonly observed within units of the Eastern Layered Intrusion (Brown 1956; Fig. 4.2B). In particular, the upper troctolitic sections of each unit are associated with small-scale phase and rhythmic layering, resulting from numerous mm-to-cm thick peridotite bodies interleaved with the troctolite. These thin peridotite bodies are mineralogically and texturally similar in appearance to the much thicker peridotites that make up the lower portion of each unit. Many of the upper troctolitic parts of each unit are also associated with a strong layer-parallel igneous lamination, generally defined by the planar arrangement of tabular plagioclase crystals, and frequently exhibiting compactional draping around olivine or clinopyroxene oikocrysts (Emeleus *et al.* 1996). They also exhibit syn-magmatic (soft-sediment) deformation features, such as slumping, load and scour structures, and syn-sedimentary folding/faulting. Although individual layers are sometimes modally graded, graded bedding caused by mineral size variation in the Eastern Layered Intrusion is uncommon. All of the small-scale layering observed has the same orientation as the macro-units that define the geometry of the Eastern Layered Intrusion, dipping toward the centre of the intrusion. Alignments of minerals on layer and lamination planes (magmatic lineation) are rarely observed in the field or in thin section.

4.1.3. Anisotropy of Magnetic Susceptibility analysis

4.1.3.1 Sampling methodology

Samples were collected at 11 sites from Units 8, 9, 10 and 11 of the Eastern Layered Intrusion, in a relatively small area extending across the northern slopes of Hallival and Barkeval (Fig. 4.1; Table 4.1). Samples were generally taken from the troctolites of each unit, so that AMS fabric data could be compared or contrasted with measurements carried out on small-scale structures that are much more common in the troctolite portions of units. Samples for each of these traverses were collected as oriented field blocks and all samples were collected away from faults and fractures and were precisely positioned using GPS. An average of 6-8 specimens were analysed for each site.

In addition, two detailed traverses were sampled through both the peridotite and troctolite sections of Unit 10 (the type unit of the Eastern Layered Intrusion) on the north side of Hallival, so that the importance of within-unit fabric variation could be determined. One of these (A) comprises a comprehensive traverse of 34 sites through Unit 10, and the other (B) a traverse of 10 sites also through Unit 10, located about 500m east of traverse A (Fig. 4.1). Traverse A was approximately 150m long, whilst Traverse B was approximately 130m long. Samples for both traverses were collected as oriented drilled cores; 458 specimens from traverse A, and 35 specimens from traverse B. AMS measurements were carried out at Princeton University, USA, using a Sapphire Instruments SI2 low-field susceptibility apparatus. Detailed analyses were also carried out on two samples from Unit 9 and Unit 10 using a KLY3 Kappabridge (the instrument used in all of the other studies presented in this thesis), in order to test for any variation of fabric orientation. These results are presented in Appendix A1.

4.1.3.2 Magnetic mineralogy of the Eastern Layered Intrusion rocks

The most common primary oxide accessory mineral reported in previous studies of the Rum Eastern Layered Intrusion layered rocks is chromite (Brown 1956), although Faithfull (1985) also reported Fe-Ti oxides as being the predominant opaque phase in troctolite layers of some of the lower Units. However, Dagley and Musset (1981) found that near-pure magnetite was the only ubiquitous ferrimagnetic mineral present, and the sole carrier of remanent magnetism. Additionally, three independent studies carried out by Putnis (1979), Moseley (1984) and Housden *et al.* (1996) each report that magnetite in Eastern Layered Intrusion rocks typically occurs as crystallographically constrained dark brown symplectic magnetite dendrites and platelets. The magnetite dendrites are between 30 and 50 microns in size, frequently intergrown with clinopyroxene and believed to have formed at high temperatures by oxidation and exsolution from olivine (Putnis 1979; Moseley 1984). Rare occurrences of magnetite as a by-product of low-temperature alteration (serpentinisation) of the olivine are also observed (Housden *et al.* 1996). Although the bulk susceptibilities in the Eastern Layered Intrusion rocks (reported below) are generally sufficiently high for it to be inferred magnetite is present (i.e. $>10^{-3}$ SI), it is extremely useful for the understanding of the AMS fabrics to have a grasp of the nature of its occurrence in this way.

4.1.4. Results

4.1.4.1 Macroscopic magmatic structures

Small-scale magmatic layering of peridotite and troctolite in the upper parts of Units 8, 9, and 10 consistently strikes parallel to the outer contacts of the Eastern Layered Intrusion, and dips gently ($<20^\circ$) toward the centre of Atlantic Corrie (Emeleus *et al.* 1996). A planar igneous lamination defined by tabular plagioclase crystals is frequently observed in the upper troctolite parts of each of the units (Fig. 4.3A), in contrast to the underlying, associated peridotite layers in which it is rarely observed. Structural measurements of the lamination show that it is generally oriented parallel to the magmatic layering. Where small-scale layering of peridotite and troctolite is well developed, inferred sedimentary structures are frequently observed at layer interfaces (Fig. 4.3B). Of these, rare scour structures and smeared-out slump and load structures provide limited measurable current direction data. These current flow data exhibit a consistent radial attitude, generally plunging down-dip on the planes of magmatic layering and igneous lamination toward the centre of the intrusion in Atlantic Corrie (Fig. 1; Fig. 4.4).

4.1.4.2 Magnetic Susceptibility

Magnetic susceptibility data for all samples of the Eastern Layered Intrusion rocks are given in Table 4.1, together with the other principal magnetic features measured. Bulk magnetic susceptibilities of individual stations throughout the Eastern Layered Intrusion range between 0.01 and 15.4×10^{-3} SI. K_{mean} variation between specific units appears to bear no relation to stratigraphic height (Unit 8: $5.32\text{--}15.4 \times 10^{-3}$ SI, Unit 9: $1.38\text{--}6.09 \times 10^{-3}$ SI, Unit 10: $1.5\text{--}3.75 \times 10^{-3}$ SI and Unit 11: 0.63×10^{-3} SI). Both of the detailed traverses of Unit 10 in the north of the Eastern Layered Intrusion have comparatively low susceptibilities: Traverse A: $0.01\text{--}3.96 \times 10^{-3}$ SI, and Traverse B: $1.94\text{--}12.6 \times 10^{-3}$ SI. No correlation of K_{mean} variation with height is observed within either traverse.

4.1.4.3 Magnetic fabrics

The degree of anisotropy (H) measured for the Eastern Layered Intrusion rocks varies between 2–35.1%, and averages at 6.8% (Table 4.1). It is therefore moderate in strength, between 4–9% for 60% of samples. H values average at 4.4% for Unit 8, 14.9% for Unit 9, and 7.9% for Unit 10, suggesting a slight positive correlation upwards with height of the intrusion. H averages for traverses A and B are similar to those already observed for

Unit 10; 6.3% and 5.3% respectively. No lateral variations of **H** are apparent throughout the Eastern Layered Intrusion. Plots of **L** vs. **F** show that the shape of the AMS ellipsoid ranges between triaxial and strongly-oblate, indicating that the planar element of the magnetic fabric is dominant (Fig. 4.5).

However, both linear and planar components of the AMS fabrics are very consistent over the area of the Eastern Layered Intrusion, both across and within different units. Magnetic foliations consistently strike NW-SE, and usually dip shallowly to the SW (Fig. 4.5; Fig. 4.6A). Magnetic lineations for traverses carried out over Units 8, 9, and 10 typically exhibit a NW-SE trend, with bimodal, very shallow plunges (usually $<8^\circ$; Fig. 4.5; Fig. 4.6B). Both of the detailed traverses A and B yield magnetic fabric orientations comparable to those already described throughout their respective thicknesses, i.e. lineations and foliations throughout Unit 10 are characterized by similar trends to those described above for Sites 1-11 (Fig. 4.5; Fig. 4.6A and 4.6B). A second subordinate (SW) trend of the magnetic lineation is observed towards the middle of Unit 10 in both traverses. In these cases, the magnetic foliations generally remain oriented parallel to layering, so that the magnetic lineations trend down-dip rather than parallel to the strike of magnetic foliation planes (Fig. 4.6A and 4.6B).

4.1.5. Discussion

AMS fabrics from the top of the troctolites of Units 8, 9, and 10 are overall consistent throughout the northern part of the Eastern Layered Intrusion, though minor within-unit variation occurs in Unit 10 (traverses A and B) and is discussed later. Magnetic foliations generally strike NW/SE and dip shallowly to the SW, and magnetic lineations show a broadly NW/SE trend with extremely shallow bimodal plunges. The magnetic foliations are thus typically parallel to the macroscopic magmatic layering at both the macro-rhythmic unit scale and at smaller scales. Magnetic lineations trend parallel to the strike of these planes with remarkable consistency, and may plunge gently in either direction. Although AMS ellipsoid shapes in the Eastern Layered Intrusion are mainly triaxial to strongly-oblate, the consistency of the magnetic lineations throughout Units 8, 9, and 10 indicate that they may also (in addition to the magnetic foliations) be interpreted as valid linear structural elements.

Importantly, measurements of magnetic lineation data from Units 8, 9, 10 and 11 are consistent with a detailed petrofabric analysis of feldspar orientation in the troctolites of Units 8, 9, and 10 carried out by Brothers (1964). His study on field-oriented thin-sections mapped out the presence of linear arrangements of feldspar crystals on igneous lamination planes by assuming that the grain tabularity and elongation approximately

coincide with crystallographic axes (e.g. Fig. 4.7). His work highlighted well-defined linear arrangements of crystals that consistently trend parallel to strike of the pervasive igneous lamination, plunging gently ($0-5^\circ$) on the lamination planes. Although he also carried out a similar study on cumulus olivine crystals in both the troctolites and the peridotites (in the latter olivine is the dominant phase $\sim 70\%$) of Units 8, 9, and 10, his method was not sufficiently sensitive to pick up a lineation carried by this mineral.

Bulk susceptibilities suggest that AMS fabrics in the Eastern Layered Intrusion are typically given by magnetite, which occurs primarily as rodlets (dendrites) enclosed in olivine grains, and as interstitial magnetite that surrounds olivine crystals (Housden *et al.* 1996). For this reason it is thought that the AMS fabric effectively mimics the orientation of an olivine fabric (as olivine has exerted a crystallographic control on the growth of magnetite). The consistency of the AMS fabric data throughout the troctolites of Units 8, 9, 10, and 11 (and the uniformity of AMS fabrics through the peridotite and troctolite portions of Unit 10 in traverses A and B) suggests a common acquisition mechanism for the magnetic fabrics of each of the units. The validity of the AMS fabrics as a proxy for the olivine crystal fabric is reinforced by two lines of evidence: the first is that magnetic foliations parallel magmatic layering and igneous lamination at all scales throughout the studied area, and the second is the study of Brothers (1964) that described plagioclase crystals throughout Units 8, 9 and 10 displaying a similarly oriented lineation.

Brothers (1964) suggested that lineation on the surface of the well-developed igneous lamination planes represented the preferred orientation adopted by the crystals during flow. Magma flow orientations measured in this study, from structures such as asymmetric slump and scour structures on troctolite layer planes in the Eastern Layered Intrusion, consistently plunge toward the centre of Atlantic Corrie. Such structures provide strong evidence for the action of both large-and small-scale currents operating in this case, on magma-crystal mush interface planes that dip with the same magnitude toward this focal point. These currents are envisaged as moving across a magma-mush interface that they may deform somewhat, creating scours and deformed load structures. However, AMS lineations inferred in this study to be a proxy for olivine orientation, together with the lineations of Brothers (1964), do not, in general, parallel these current directions. Instead, they are both oriented transverse to the supposed direction of current flow in the northern part of the Eastern Layered Intrusion. Any model attempting to interpret these lineations as flow fabrics must rule out that they could have been imposed at a later stage in the history of the cumulate pile, and also propose a plausible scenario by which grains are aligned transverse to, instead of parallel to current flow at the magma-mush interface, or perhaps within the mush pile.

Although planar fabrics such as igneous laminations in cumulates have been ascribed to processes ranging from primary deposition of crystals from density currents and plumes to compaction-related solid-state recrystallisation (see Irvine *et al.* 1998 for review), consistent lineation data in such rocks are widely accepted as reliable evidence for flow. It is important to note that crystallographically constrained magnetite dendrites (and also crystallographic axes in plagioclase in the case of Brothers 1964) reveal crystallographic preferred orientations (CPO) rather than shape-preferred orientations (SPO) of the respective mineral grains. It is the SPO that determines the character and extent of fabric development, be it developed through either primary flow processes or through secondary postcumulus processes, but significant deviation of the CPO from the SPO may only occur during the latter (Benn and Allard 1989; Ildefonse *et al.* 1992; Meurer and Boudreau 1998). In the case of the Rum Eastern Layered Intrusion, complex isotopic zoning (Sr) of plagioclase grains (Tepley and Davidson 2003), the preservation of magmatic twins, and the coincident nature of the CPO and SPO argue against extensive compaction and solid-state recrystallisation (LoRe *et al.* 2003). In addition, further recent textural work on Units 8, 9 and 10 by Holness (2005) have shown that with the exception of textures modified locally by the Unit 9 intrusive peridotite, these cumulates have not undergone significant postcumulus modification or ripening. It is likely, therefore, that the magnetic foliation of this study (parallel to the planar igneous lamination of the Eastern Layered Intrusion) represents a primary deposition fabric of olivine grains, and the magnetic lineation (parallel to that of Brothers plagioclase lineation) represents the orientation of crystals within a flow plane.

The macro-rhythmic units of the Eastern Layered Intrusion are widely regarded as one of the most significant lines of evidence for major (separate) replenishment events in the Rum magmatic system (e.g. Renner & Palacz 1987). Emeleus *et al.* (1996) envisaged emplacement of each of these units as major pulses of magma flowing out across the floor of a 'persistently reconstituted, thin, sill like magma chamber'. Furthermore, they suggest that the body of magma in the intrusion at any given time may have been no more than several tens to hundreds of meters thick. Although some debate persists as to the mode of construction of units of the Eastern Layered Intrusion, it is generally accepted that the Rum magma chamber is lopolitic (saucer-shaped) in form, as defined by the geometry of magmatic layering at all scales. There is a substantial body of evidence to suggest that a significant degree of central subsidence down toward Atlantic Corrie and the Long Loch Fault (Fig. 4.1) occurred. This includes steepening of dips of magmatic layering and igneous lamination (e.g. at least 40° in the Trollaval region; Volker and Upton 1990) and evidence of mass slumping of cumulate mush and large-scale

deformation structures such as folding and syn-magmatic faulting in cumulate adjacent to the Long Loch Fault (Emeleus *et al.* 1996). It is likely that this deformation occurred during emplacement of the macro-rhythmic units, so that shortly after a unit was emplaced it began to undergo central subsidence as it cooled. Emplacement of successive units of the Eastern Layered Intrusion would have the effect of intensifying this deformation, so that central sagging became more pronounced as the sequence of units grew thicker. We propose a model in which central sagging throughout development of the Eastern Layered Intrusion caused progressive reshuffling, sliding and rotation of grains *along* and *within* the magma-mush interface plane as or just after deposition of the crystals occurred (Fig. 4.8A and 4.8B). Gentle bedload transport and interaction with other grains at the magma-mush interface produced the layer-parallel planar fabrics (igneous lamination and magnetic foliation). We believe it likely that the magmatic lineation (magnetic lineation and Brothers plagioclase CPO fabric) with grain long-axis orientation perpendicular to flow direction (rather than parallel) may have initiated through this primary sedimentary mechanism. Indeed, clast orientation perpendicular to current direction is well documented in sedimentary rocks (e.g. Rust 1972; Davies and Walker 1974; and see also Section 1.2.2 in Chapter 1). The lineation carried by olivine and plagioclase in the Eastern Layered Intrusion rocks may have been subsequently intensified through incremental reshuffling and sliding of grains as downward creep of the crystal mush occurred on and within magmatic layer-planes during central subsidence (Fig. 4.8A and 4.8B), as described above. The magnetic lineation variation observed in several samples of Unit 10 might indicate fabrics caused by more abrupt slumping of crystal mushes, or fast flowing localized density currents, overprinting the effect of the more pervasive fabric.

4.1.6. Conclusions

- (1) Magnetic susceptibilities in the northern part of the Eastern Layered Intrusion are high and AMS fabrics are carried by olivine-bearing magnetite rodlets. The magnetic total anisotropy (**H**) is moderate to strong and the shape of the AMS susceptibility ellipsoids are typically triaxial to strongly oblate. Both magnetic foliations and lineations are consistent throughout the Eastern Layered Intrusion, the former are oriented NW-SE, parallel to magmatic layering and igneous lamination, and dip shallowly to the SW, the latter trend approximately NW or SE parallel to strike of the magnetic foliation planes, and plunge very shallowly in either direction. Two detailed AMS traverses carried out through Unit 10 north of Hallival confirm the consistency of the magnetic fabric measurements.

- (2) Small-scale, sedimentary structures and macroscopic lineations carried by tabular plagioclase crystals suggest that density currents operated locally in unconsolidated cumulates of Units 8, 9, and 10 of the Eastern Layered Intrusion. Measurements carried out on these structures give centrally directed flow orientations, plunging down dip on magmatic layering and igneous lamination planes towards Atlantic Corrie.
- (3) A model is suggested in which the pervasive magnetic lineation (carried by olivine), together with the plagioclase lineation of Brothers (1964) are developed through initial gentle transport and rolling of cumulus grains at the magma-mush interface during central sagging of the Rum lopolith. This lineation is intensified by subtle reorientation of grains in a crystal mush as shallowly dipping magmatic layer planes continue to tilt inwards. Evidence for more abrupt or faster flowing, periodic slumps of the crystal mush as a result of this sagging might be present in several sites where magnetic lineations trend parallel to the macroscopic current direction.

4.2. A crystal size distribution study of harrisitic and granular olivine from the Rum Layered Suite, NW Scotland.

4.2.1. Introduction

Harrisite is a term applied to a facies of coarse-grained basic or ultrabasic rock in the Rum Palaeogene layered intrusion (Fig. 4.9), NW Scotland. Both gabbroic and feldspathic peridotite varieties are found. Harrisite comprises >25% olivine crystals that have a dendritic or skeletal habit (Figs. 4.10A and 4.10B; Harker 1908; Wadsworth 1961; Wager and Brown 1968; Donaldson 1975a; 1977). Elongated olivines may be oriented at high-angles to layers, a fact that led Wager *et al.* (1960) to describe the rock as a 'crescumulate' in their categorisation of cumulate rocks. Such an arrangement of crystals resembles that of comb layering (e.g. Taubeneck and Poldervaart 1960; Lofgren and Donaldson 1975). However, examples of harrisite in which the olivines are oriented parallel or even obliquely to the layering are also observed, as are stellate olivines, implying some downward growth (Donaldson 1977). Harrisitic texture is remarkably similar to skeletal olivine crystal forms observed in ultramafic Archean hypabyssal and volcanic 'spinfex' rocks found in greenstone belts. Donaldson (1974) discussed the link between harrisite and spinifex, proposing a crystal morphological classification scheme that characterised the similarities between both.

Harrisite generally occurs interlayered with granular textured gabbro or feldspathic peridotite on Rum. Olivines in the latter rocks show a marked morphological and size contrast to harrisitic olivines. As well as being considerably smaller (<2mm versus 2-1000mm), olivine crystals in gabbro and feldspathic peridotite are typically subhedral in shape and are generally interpreted as cumulus in origin (Brown 1956; Wadsworth 1961; Emeleus *et al.* 1996). Donaldson (1977) described a cyclic stratigraphy from gabbro/feldspathic peridotite up into harrisite in which small equant granular olivines are overlain by progressively larger and more deeply indented skeletal 'hopper' olivines (Figs. 4.10C and 4.11). The main morphological changes within the harrisite are from subequant hopper and tabular hopper olivines to dendritic, branching crystal morphologies (Figs. 4.10B and 4.11A). This change involves a 1500-fold decrease in the number of olivine crystals and grain-size increases of up to 1000 or more times (Donaldson 1977). The upper contact of a harrisite layer with cumulate gabbro or peridotite is typically abrupt in both texture and grain size, an observation that led Wadsworth (1961) to suggest that it was recommencement of the settling of cumulus crystals that caused termination of harrisitic olivine formation.

Though it has been suggested that harrisitic olivine grew rapidly (Donaldson 1974; Hort 1998) and estimated growth rates (e.g. Henderson and Williams 1979; $6.4 \times 10^{-5} \text{ mm.s}^{-1}$) are four orders of magnitude greater than normal olivine crystal growth rates (e.g. Marsh 1988; $10^{-9} \text{ mm.s}^{-1}$), no quantification of the actual crystal growth times has previously been presented for harrisite. In addition, no link has been proposed between the cyclic interlayering of harrisite and feldspathic peridotite with the inferred open system behaviour (frequent replenishment by picrite magmas) of the Rum magma chamber. This study combines published growth rates for harrisite and other examples of skeletal olivines with crystal size distribution (CSD) analyses, to estimate crystal growth times on the order of several hours to several hundred days for harrisitic olivine. A model is proposed in which very fast bursts of olivine growth accompanied repeated influxes of thin sheets of crystal-poor picrite magma. This style of growth resulted from enhanced undercooling of the picrite at the base of the Rum intrusion and consequent enhanced olivine supersaturation of each sheet of new magma, before nucleation could set in. This model supports the view that the Rum magma chamber acted as an open or 'leaky' system (Brown 1956; Tait 1985; Emeleus *et al.* 1996, Troll *et al.* 2004).

4.2.2. Sampling methodology and CSD analysis

4.2.2.1 Sampling methodology

Harrisite occurs throughout the Rum layered intrusion but is most abundant in the western part of the Layered Suite at Ard Mheall and Harris Bay (Fig. 4.10), the latter being the type locality for the rock (Harker 1908). The Layered Suite comprises the Eastern and Western Layered Intrusion, considered to be lateral equivalents of one another, though at different structural levels (Emeleus *et al.* 1996), subsequently intruded and separated by the younger Central Intrusion (Fig. 4.10). Whereas the Eastern Layered Intrusion is dominated by feldspathic peridotite and troctolite, the Central Intrusion is mostly feldspathic peridotite, and the Western Layered Intrusion is feldspathic peridotite in its upper reaches (Ard Mheall) and bytownite-bearing gabbro in its lower reaches (Harris Bay).

Sampling focused on the Western Layered Intrusion, where a vertical traverse of ten samples was collected through the sequence of feldspathic peridotite layers in the Ard Mheall area (Fig. 4.10). In addition, two samples were collected from Harris Bay and seven from the Eastern Layered Intrusion; of the latter, four are from Units 10-13 on Askival and three are from Units 13-15 on Hallival (Fig. 4.10). A variety of olivine crystal morphologies were sampled, including granular grains from feldspathic peridotite to skeletal hopper and simple branching grains in harrisite. Sample numbers are given together with characteristic crystal morphologies in Table 4.2. Note that very large, complex harrisitic olivines (larger than several centimetres in size) were not studied for reasons discussed in the next section.

4.2.2.2 CSD analysis of harrisitic olivine

The intricate morphologies of some of the more complex harrisitic olivine crystal groups are far removed from the ideal crystal habit groupings assumed by the *CSDCorrections* program. These include the 'parallel-linked', 'chain-like', and 'radiate' morphologies of Donaldson (1975a), amongst others. A cut through such skeletal crystals could give the false impression in a thin section of many more (smaller) crystals than in reality. To avoid this problem, only samples with comparatively simple skeletal olivine morphologies were selected for study. Samples HB1, HB2, R15, and ARH6 contained simple branching skeletal olivine crystals, generally not greater than 1.5 cm in length. Thin-sections of these crystals were studied to ensure that groups of apparently distinct crystals were not in optical continuity, i.e. were not linked in three-dimensions, and hence did not mis-represent the CSD's of the rock. An average of 430 crystals were studied per sample and none had less

than 200 crystals measured, as recommended by Mock and Jerram (2005) to accurately quantify the CSD (see Chapter 2 also). This required that several sections be measured per sample for most of the harrisite samples. In such cases, the grainsize data were then integrated and analysed together. Many samples are isotropic, but some of the harrisite samples exhibit a well-defined layer-parallel planar foliation defined by the alignment of elongate olivine crystals. In such cases this was taken into account by the *CSD Corrections* software (Higgins 2000).

4.2.3. Olivine growth rates

As described above, the slope of a CSD gives a measure of $G\tau$, and if a value for G is known, crystal growth time in the magma chamber can be estimated. Although typical crystal growth rates for minerals, both silicates and oxides, have been quoted as being between 10^{-10} and 10^{-9} mm.s⁻¹ (Marsh 1988; 1996; Cashman 1993; Higgins 1996), studies carried out on crystals that have grown in a melt supersaturated with respect to their constituent elements show that these crystals may have grown considerably faster. In particular, a sizeable body of work has been carried out on anhedral (hopper, skeletal, and dendritic) olivine crystals (Donaldson 1975a; 1975b; Donaldson 1976; Donaldson 1977; Jambon *et al.* 1992; Roggensack 2001; Faure 2003; Kohut and Nielson 2004; Zieg and Lofgren 2006), which suggests that crystal growth rates in the range 10^{-5} - 10^{-7} mm.s⁻¹ are more typical of these crystals.

An independent estimate of olivine growth rates in the Rum cumulates was obtained by Henderson and Williams (1979) from the distribution of uranium between crystals and magma. They measured the uranium contents of olivines of different shapes and found that the more skeletal the shape, the greater the content (Table 4.3). Using the estimate of Henderson *et al.* (1971) of the magma's uranium content, Henderson and Williams (1979) employed the Burton and Slichter (1953) model of diffusion-controlled crystal growth to compute model growth rates for the Rum olivines (Table 4.3). These show that the branching olivines grew at least five times faster than the granular crystals in interlayered cumulate. [The calculations required insertion of a value for the uranium diffusion coefficient in basaltic magma. In the absence of this information, they used a figure of 10^{-8} cm².s⁻¹ measured by Seitz (1974) for Th diffusion in a synthetic melt of diopside, albite and anorthite. This figure differs little from an estimate of the diffusion coefficient of uranium in basalt melt at 1300 °C ($10^{-7.7}$ cm².s⁻¹) obtained by using Hoffman's (1980) empirical relationship between diffusion coefficient and ionic radius of the diffusing species.]

Although cooling rate, and hence growth rate, may be arbitrarily imposed in experimental systems to create skeletal crystal and dendritic morphologies, it is believed here that it is likely the complex Rum harrisite textures crystallised in response to a cooling regime not typical of plutonic environments. Given the experimental evidence outlined above for very fast growth rates of skeletal and dendritic crystal morphologies, it is considered that the calculated growth rates of Henderson and Williams for harrisitic olivine are likely to be accurate. In particular, values of $2\text{--}6 \times 10^{-6} \text{ mm.s}^{-1}$ (Donaldson 1975b), $1.25\text{--}34.9 \times 10^{-6} \text{ mm.s}^{-1}$ (Kohut and Nielsen 2004) and $1\text{--}6000 \times 10^{-7} \text{ mm.s}^{-1}$ (Jambon *et al.* 1992) compare favourably with Henderson and Williams' computed value of $6.4 \times 10^{-5} \text{ mm.s}^{-1}$. We estimate a range of crystal growth times from our CSD plots for olivines in harrisite and feldspathic peridotite on Rum using the growth rates described above. The growth rates of Henderson and Williams give the shortest crystal growth times, so these are compared with the slowest growth rate quoted above, that of Jambon *et al.* (1992; $1 \times 10^{-7} \text{ mm.s}^{-1}$) for skeletal crystal growth and the implications for harrisite formation are discussed.

In addition, though the model growth rates of Henderson and Williams (1979) are consistent with those produced in laboratory experiments on skeletal crystals (Donaldson 1975b; Jambon *et al.* 1992; Kohut and Nielson, 2004), not all of the crystals studied here are as complex. As typical growth rates for olivine are approximately $10^{-9} \text{ mm.s}^{-1}$ we believe that the growth rates suggested by (Henderson and Williams 1979) for granular (cumulus) olivine in the Rum magma chamber (e.g. samples R1, P1, R31B, R36A and R37) are likely to be too fast. In order to calculate realistic crystal growth times for granular olivine in the Rum magma chamber, the estimated value of Marsh (1988; $10^{-9} \text{ mm.s}^{-1}$) is employed as a lower limit of growth rate for granular peridotite samples.

4.2.4. Results

4.2.4.1 CSD Plots

The CSD results for all the samples are given in Table 4.2 and CSD plots for each sample are contained in Fig. 4.12. Data for different olivine crystal morphologies and sizes are generally consistent over the different sampled sites. All the curves are approximately log-linear for the larger size fractions and several have a well-developed 'humped', convex-up profile at smaller size fractions. Regression analysis was carried out on these curves in Microsoft Excel for a best-fit line through the log-linear portion of the plot in order to calculate slope and intercept data from each. Although a minority of samples have slightly kinked CSDs (HB1, R15, R16, R17,

R31A, and ARH3), characterised by changes to shallower slopes at the larger size intervals, these are also well described by one best-fit line through the whole curve; none has an R^2 value of less than 0.89. CSD slopes for feldspathic peridotite samples with simple non-skeletal granular or polyhedral olivine morphologies (R1, P1, R31B, R36A and R37) display the most pronounced ‘humped’ profiles at small crystal size fractions and have consistently relatively steep slopes between -1.78 and -1.15. Consistency (-0.54 to -0.31) is also observed in the shallower slopes of the most complex skeletal branching morphologies studied (R15, HB1, HB2, R34 and ARH6). However, samples that contain hopper crystal morphologies (R2, ARH1, ARH2, ARH3, R16, R17, R31A, R32, R33, and R36B) span a wider range of slope values (-0.89 to -0.48).

The lower size limit of our CSDs has been defined at 0.1 mm and the data is interpreted based on the observation that there are no crystals in these rocks smaller than this size. The CSDs for harrisitic olivines are typically straight on semi-logarithmic plots of population density vs. crystal size, especially at the larger size fractions. These disequilibrium textures are interpreted as ‘kinetic’ textures, i.e. formed through nucleation and growth alone without significant postcumulus ripening or coarsening, though such textures may not be common in plutonic igneous rocks (see discussion below). This interpretation may not extend completely to the samples containing granular olivine crystals, some of which exhibit a ‘humped’ profile as outlined above. This issue and its bearing on the values of CSD slope obtained (and consequently the crystal growth times calculated) is also discussed in more detail in the section on the CSD data below.

The quality of the CSD data has been assessed using closure limits (after Higgins 2002a; 2002b; Boorman *et al.* 2004). A plot of characteristic grain length against intercepts, together with empirically calculated closure limits for harrisitic, hopper, and granular olivine crystals illustrates that our data fall well within permitted range (Fig. 4.13A). A plot of CSD characteristic grain length against volume phase proportion (c.f. Higgins 2002a) highlights three distinct zones for each of the three crystal morphological groups (Fig. 4.13B) and is discussed further below.

4.2.4.2 Crystal growth times

Crystal growth times have been calculated for the crystal populations of each sample (Table 4.2), using the slope of each CSD curve and the crystal growth rates for harrisitic olivine computed by Henderson and Williams (1979; Table 4.3). The times are exceptionally short, ranging from 7 hours to 20 hours (τ_1 in Table 4.2). In general, the shortest times are given by the more complex olivine crystal geometries such as the skeletal

branching and hopper morphological groups, even though these are larger in size than the granular olivines. Granular crystal morphologies typically give longer crystal growth times. Maximum crystal growth times have also been calculated for skeletal olivine morphologies using the upper growth rate limit of Jambon *et al.* (1992) as quoted above (τ_2 in Table 4.2). Though it is likely that these values are overestimates, they are still very short, ranging between 137 and 369 days. A set of crystal growth times for granular olivines are also presented in Table 4.2 (τ_3), based on a growth rate of $10^{-9} \text{ mm.s}^{-1}$ as quoted above (Marsh 1988; Cashman 1993). The calculated times are again quite short, ranging between 18 and 28 years, particularly when compared with values based on published growth rates (Marsh 1988; Cashman 1993; Higgins 1996) that are three or four times higher (e.g. 50-80 years). [However, see below on the discussion of crystal growth times for granular olivine crystals.]

4.2.4.3 Nucleation rates

Nucleation densities (n^0) have been calculated from the Y-axis intercepts on the CSDs, and are presented in Table 4.2. CSD intercepts ($\text{Ln } [n^0]$) range from -2.6 to 1.9 mm^{-4} , ($n^0 = 7.4 \times 10^{-2}$ to 6.7 mm^{-4}), values that are exceptionally low compared to nucleation densities ($2.07\text{-}4.55 \times 10^7 \text{ mm}^{-4}$) reported by Cashman and Marsh (1988) for plagioclase from the Makaopuhi lava lake (Hawaii). Values of nucleation rate calculated using the growth rates of Henderson and Williams (1979) range from $0.37\text{-}8.1 \times 10^{-5} \text{ mm}^{-3}.\text{s}^{-1}$ (J_1 in Table 4.2). In general, the largest values of n^0 , and consequently the largest values of J , are given by feldspathic peridotite samples containing granular olivines (R1, P1, R31B, R36A and R37). Conversely, samples containing complex harrisitic morphologies (HB2, ARH1, ARH3, and R2) give the smallest values of n^0 and much smaller values of J respectively.

However, the use of the growth rates above create calculated nucleation rates (J_1) that are **maxima** for the Rum harrisites and the feldspathic peridotites containing granular olivine morphologies. As suggested above, the granular olivine crystals are unlikely to have growth rates as high as predicted by Henderson and Williams (1979). Therefore, the slowest likely growth rate ($10^{-7} \text{ mm.s}^{-1}$) for harrisitic olivine together with the slowest growth rate for granular olivine ($10^{-9} \text{ mm.s}^{-1}$) are used to give **minimum** nucleation rates (J_2 and J_3 ; Table 4.2). These values of J range between $1.1\text{-}6.7 \times 10^{-9} \text{ mm}^{-3}.\text{s}^{-1}$ for olivine in the feldspathic peridotite and $9.9\text{-}130 \times 10^{-9} \text{ mm}^{-3}.\text{s}^{-1}$ for hopper and harrisitic olivine. Notably, values of J for harrisite are now higher than those for granular textured peridotite, despite the fact that values of n^0 remain the same.

4.2.5. Reworked harrisitic olivine at Ard Mheall as indicator of magmatic flow

Harrisite layers at Ard Mheall in the Western Layered Intrusion are frequently interlayered with rhythmically layered feldspathic peridotite (Figs. 4.10C and 4.14A) that exhibit evidence for deposition as cumulate 'sediments'. This includes sedimentary structures such as scour structures and slumping at layer interfaces. In addition, there is evidence in this area for periodic disruption of harrisite growth by small-scale, crystal-rich 'density' currents. Large fragmented harrisitic olivines have been incorporated into peridotitic cumulate overlying the harrisite layers, in which they exhibit structures that indicate they were re-worked as single crystal clasts and as crystal clusters in flowing currents. These structures include linear trains (Fig. 4.14B) and imbricated fragments of broken olivines (Fig. 4.14C), and well-developed crystal lineations on layer planes. Based on their larger size than the equant (cumulus) olivine crystals native to the peridotite, these crystals are interpreted as fragments of harrisitic olivine. Their repeated occurrence throughout the sequence at Ard Mheall points to intervals of vigorous magmatic flow across the tops of harrisite layers, breaking the tops off crystals and terminating or suffocating harrisite development. These field observations are supported by quantitative textural data from Worral (2002) on the Western Layered Intrusion, which suggest that olivine accumulation occurred through crystal transport, with the possible involvement of current activity.

4.2.6. Discussion

4.2.6.1 Harrisite petrogenesis

Wager *et al.* (1960) regarded harrisite as a type of cumulate texture in which skeletal and dendritic olivine grew upwards from previously 'deposited' cumulus crystals (crescumulate). Precipitation of olivine from a supercooled basaltic melt occurred onto those cumulus grains with upward-oriented c-axes; these olivines grew into a nuclei-deficient melt under tranquil conditions, following temporary cessation of convection of the magma. Donaldson (1974; 1977) pointed out that while this model explains the preferred upward olivine growth in most harrisite layers, it doesn't account for those olivines in some harrisite layers that are inferred to have grown downwards, horizontally, or in stellate arrangement. He also showed that some harrisite layers are in fact intrusive into the layers above and below them (Donaldson 1982). In addition, Greenwood *et al.* (1990) and Upton *et al.* (2002) have presented evidence that picrite melts with 25-30 wt% MgO, rather than the basaltic melts envisaged by Wager *et al.* (1960), were involved on Rum.

Experimental studies suggest that skeletal hopper and branching crystals grow relatively rapidly under conditions of strong supersaturation/magmatic undercooling (e.g. Lofgren and Donaldson 1975; Donaldson 1976;

Lofgren 1980). Donaldson (1974; 1977) attributed harrisite development to *in situ* crystallisation under conditions of enhanced supersaturation of the magma in olivine. This he speculated might arise from two possible, alternative mechanisms; one is a sudden decrease in the water content of a water-undersaturated feldspathic peridotitic liquid, and the other the transition of a water-saturated peridotitic magma to an unsaturated state by exsolution of volatiles. Hort (1998) referred to harrisite as a disequilibrium texture developed through successive bursts of rapid crystallisation as a result of periodic “perturbations” of the liquidus temperature. He too suggested that exsolution of volatiles from magma could induce such an increase in undercooling, giving rise to the dendritic and skeletal crystal morphologies observed in harrisite texture. This he suggested could occur as a result of depressurisation of a batch of magma during its ascent through the crust and would be most effective in shallow-level intrusions. Hort (1998) also pointed out that degassing of magma can occur where a more primitive melt enters a chamber and cools due to magma mixing with a more evolved melt.

4.2.6.2 CSD data

The Rum CSD data are generally consistent throughout the localities studied. The CSD plots fall into three groups based on slope and intercept data calculated from regression analysis of each. This is well illustrated in Fig. 4.13B, which gives three groups of crystal morphology based on characteristic grain length vs. volume phase proportion. The plot reflects decreasing crystal growth times and nucleation densities with increasing crystal morphological complexity. The majority of the granular peridotite CSD plots in Figure 4.12 (e.g. R1, P1, R31B, R37) display pronounced convex-upward shapes at small size fractions as well as log-linear shapes at larger size fractions. Boorman *et al.* (2004) discussed the danger that cumulus textures may be strongly modified by crystal-ageing and compaction-driven recrystallisation. It is thought a downturn at small crystal sizes may indicate the consumption of smaller crystals at the expense of larger ones to minimise free energy as the primary cumulus textural arrangement equilibrated following deposition or *in situ* crystallisation (Hunter 1987; Waters and Boudreau 1996; Higgins 1998; 2002a; Park and Hanson 1999). In addition to creating this ‘humped’ profile at small crystal sizes, this type of coarsening or ripening of primary igneous textures results in rotation of CSD plots to progressively shallower slopes (Marsh 1998; Higgins 2002a; 2006). For this reason, we feel that the crystal growth times calculated from the granular peridotite CSDs in this study may be useful only insofar as they might indicate possible greatest values of τ . Worrall’s (2002) study provides support for this data and

interpretation; she observed similar 'humped' profiles in Western Layered Intrusion peridotite CSDs, which she attributed to textural ripening processes.

By contrast, harrisitic olivines are a disequilibrium texture in which the olivines have large or very large surface areas and hence surface energy, yet in many cases appear to have escaped subsequent textural equilibration or other postcumulus processes. For example, it is unlikely that compaction had a significant role to play in the development of the textures observed in harrisite, as thin-section petrography reveals a large (~50%) melt fraction in all of the samples (even those bearing an alignment of olivine crystals), represented by interstitial (intercumulus) unzoned plagioclase or clinopyroxene, which was apparently not expelled into the overlying magma. In addition, it might be expected that layers comprising vertically oriented harrisitic olivines would form a scaffold-like crystal arrangement that would be strongly resistant to compaction. Neither is there evidence of compaction-related processes such as compaction fractures or draping of olivine crystals around plagioclase or clinopyroxene oikocrysts as reported from other parts of the intrusion (Emeleus *et al.* 1996). Another argument against significant recrystallisation of harrisite is the cyclic nature of the sequences of magmatic layers they are confined within. The sequential change in olivine shape reported by Donaldson (1977; Figs. 4.10C and 4.11) from simple granular forms to more complex crystal morphologies is observed in all areas where harrisite occurs. In these, particular types of olivine crystal morphology are often confined to certain layers, i.e. there is a clear relationship between primary magmatic layering and crystal morphology, whereas significant recrystallisation might have disrupted this relationship by causing complex crystal morphologies to grow towards simpler forms. It is concluded that harrisite represents a primary magmatic, disequilibrium texture, essentially unmodified by recrystallisation or textural equilibration and the values of τ calculated for harrisitic olivine are taken as reliable estimates for crystal growth times in this instance.

The extraordinarily short crystal growth times estimated from the CSDs are a function of the input growth rates used. There is experimental evidence to suggest that these rates are realistic (Lofgren and Donaldson 1975; Lofgren 1980). If the range of estimated crystal growth times presented is an accurate reflection of harrisite growth rates, then of particular interest is the rate at which individual harrisite layers crystallised. If an average crystal growth time of 8 hours is taken for hopper olivines 10-20 mm in size (e.g. τ_1 in Table 4.2), then an average-sized layer, 500 mm thick, would crystallise in 8-17 days. Similar rates of crystallisation (approximately 15 days) are achieved by branching olivine layers of the same size. It is difficult to calculate a rate of thickening of layers containing granular olivines in the Rum cumulate pile, as it is very unlikely that granular olivines grew

wholly *in situ*; i.e. evidence described earlier suggests that peridotite layers accumulated by current deposition and magmatic flow processes. However, assuming rates of crystal accumulation similar to those for thickening of layers in the Skaergaard intrusion (0.6 mm/day; Wager and Brown 1968) harrisite layers may have formed up to 160 times faster than normal cumulate layers.

Another indication of how rapidly harrisite layers formed can be obtained from a simple conductive cooling estimate of the time (t) taken to cool a sheet of crystal mush/melt of half-thickness (L) is:

$$t \sim L^2/K$$

where K is the thermal diffusivity which is $1 \times 10^{-2} \text{ cm}^2.\text{s}^{-1}$ (Jaeger 1968). Given that harrisite layers range in thickness from 7 cm to 10 m (Donaldson 1975a), a range of cooling times for harrisite layers are calculated and presented in Figure 4.15. [The effect of taking latent heat of crystallisation into account is to reduce each calculated layer thickness for a given time in Figure 4.15 by approximately 30%]. The calculations are consistent with the crystal growth times estimated from the CSDs, and suggest that the thinnest layers cooled fastest (e.g. approximately 11 hours for a 40 cm thick layer of harrisite). However, thicker layers are also shown to have cooled relatively rapidly, with values of 72 days and 290 days for 5 m and 10 m thick layers respectively.

4.2.6.3 Open system behaviour of the Rum magma chamber during harrisite growth

A substantial body of evidence exists to suggest that open system processes were a major influence in the history of the Rum magmatic system (Brown 1956; Tait 1985; Emeleus *et al.* 1996; Troll *et al.* 2004). Much recent study on the ultrabasic and basic rocks of Rum has focused on the Eastern Layered Intrusion, built of 16 macro-rhythmic peridotite-troctolite units (e.g. Tepley and Davidson 2003; Holness 2005). Although some debate persists as to the mode of construction of these units, it is generally accepted that most if not all of them represent major magma replenishment events (Emeleus *et al.* 1996; Holness 2005). Magmatic layering of minerals on the scale of millimetres to tens of centimetres is commonly observed within units of the Eastern Layered Intrusion. In particular, the upper troctolitic section of each unit is associated with small-scale phase and rhythmic layering, resulting from numerous mm-to-cm-thick peridotite bodies interleaved with the troctolite. These thin peridotite bodies are mineralogically and texturally very similar in appearance to the much thicker peridotites that make up the lower portion of each unit, and suggest that replenishment may have involved both continual small influxes of magma, as well as intermittent large influxes of magma launching a new unit (Butcher *et al.* 1985; Faithfull 1985;

Renner and Palacz 1987). It is generally accepted that the Western Layered Intrusion represents a deeper structural level of the Rum magma chamber, despite relations between the two being obscured by the younger Central Intrusion. The Western Layered Intrusion is also considered to have grown through periodic large volume influxes as well as smaller more frequent ones. Emeleus *et al.* (1996) point to the major N-S-trending Long Loch Fault, active throughout growth of the Rum Layered Suite, as the conduit for these magma influxes.

It is argued here that the approximately log-linear profiles and range of short crystal growth times given by the harrisitic olivine CSDs, combined with the nature of olivine growth in repeated sequences of magmatic layers, are additional strong evidence for open system behavior in the Western Layered Intrusion. This leads to a petrogenetic model for harrisite layers in which the information supplied by the textural data on nucleation and growth of olivine in harrisite is applied to periodic small influxes of hot picrite magma over the floor of the Rum reservoir (Fig. 4.16).

Prior to harrisite formation a major batch of magma nucleated and grew olivine at the base of the intrusion, with magmatic sedimentation and crystal accumulation through small-scale density current action giving rise to magmatic layering of feldspathic peridotite with associated sedimentary structures (Fig. 4.16A). The chamber was then replenished by a small batch of hotter, denser picrite magma that spread thinly along the bottom of the chamber and cooled against the colder magma above (Fig. 4.16B). It is assumed that the inflowing magma contained very sparse or no olivine crystals, so that for solidification to commence homogeneous, rather than heterogeneous, nucleation of olivine was necessary (Fig. 4.16C). Thus there was a delay in nucleation during which the melt undercooled (Donaldson 1979), creating the necessary enhanced olivine supersaturation for homogenous olivine nucleation as well as promoting skeletal growth (Fig. 4.16C). Upon nucleation, fast bursts of *in situ* skeletal olivine growth occurred throughout the batch of picrite magma, occasionally producing stellate or 'starburst' crystals. It is also envisaged that sometimes rapid precipitation of olivine occurred from the picrite melt onto the crystal mush below triggering harrisite growth from the substrate, where cumulus crystals with their c-axes oriented sub-vertically outgrew their neighbours (Fig. 4.16C; cf. Wadsworth, 1961). A recent experimental study of olivine growth suggests that such constrained growth may require the presence of a significant vertical temperature gradient (Faure *et al.*, 2006).

It is considered that sheets of picrite magma containing significant amounts of crystals and nuclei might not have developed harrisitic texture, as the crystals would have provided sites for heterogeneous nucleation and thus precluded intense supersaturation of olivine.

Cessation of harrisite development may have resulted from the complete crystallisation of a thin batch of picrite magma as outlined above. Alternatively, the passage of crystal-laden density currents over the top of the growing layer of harrisite crystals, as inferred from evidence at Ard Mheall (Figs. 4.14B and 4.14C; Fig. 4.16D) may have occasionally terminated harrisite formation. Convective overturn when the density of the picrite magma approached that of the overlying magma and attendant crystals could also have terminated skeletal crystal growth. It is proposed here that continual periodic influxes of crystal-poor picrite produced the sequence of harrisite layers of variable thickness observed at Harris Bay and Ard Mheall in the Western Layered Intrusion. The presence of minor harrisite layers high up in the Eastern Layered Intrusion (i.e. Units 13-15) suggests that crystal-poor picrite magma was still available at this later stage in the development of the Rum Layered Suite, though possibly in much smaller quantities (see also Upton *et al.* 2002).

Recognition that the open-system behaviour of magma emplacement in the Rum magma chamber included small volume crystal-poor magma inputs, which experienced enhanced cooling rate as they spread across the floor, removes the need to invoke supersaturation effects arising from decompression of large influxes of H₂O-saturated magma or repeated exsolution of H₂O once the magma entered the chamber (Donaldson 1974; Hort 1998). Absence of rocks in the Rum Layered Suite that show the effects of explosions and retention of the delicate dendritic olivines in many harrisite layers are consistent with this inference.

4.2.7. Conclusion

This study has employed detailed textural quantification using CSD analysis, incorporating published olivine growth rates and experimental data, to fully evaluate the formation of harrisite and granular olivine textures in the Rum intrusion, NW Scotland, with the following conclusions:

1. Influxing batches of crystal-poor picrite magma at the base of the Rum magma chamber undercooled upon contact with the cooler magma already in place.
2. The delay in homogeneous nucleation of olivine and consequent elevated supersaturation of the picrite in an olivine component gave rise to harrisitic texture.
3. Periods of rapid crystal growth lasted on the order of hours to days. Using the textural data available at present, our estimates range from several hours to several hundreds of days.
4. The repeated occurrence of harrisite throughout the Western Layered Intrusion, and to a lesser degree the Eastern Layered Intrusion, is consistent with the concept of 'leaky' open system behavior of the Rum magma chamber.

4.3 Magnetic fabrics in the Ard Mheall harrisite and harrisitic peridotite

4.3.1 Sampling methodology and localities

Three samples of harrisite were selected for AMS analysis to quantify magnetic fabrics for comparison with magmatic layering and the so-called crescumulate fabric defined by harrisitic olivine. All of the block samples were collected in the Ard Mheall area and each sample represents a different type of harrisitic olivine occurrence (Fig. 4.17). As described in an earlier section in this chapter, the Ard Mheall area is characterized by spectacular interlayering of harrisitic and feldspathic peridotite, with layering at all scales dipping gently E-SE at 10-30° (Fig. 4.17A and 4.17B). Sample HB1 contains large branching crystals approximately 10 cm in length, oriented both perpendicular and obliquely to magmatic layering (Fig. 4.17C.3). The second sample (HB2) is feldspathic peridotite, but contains broken or fragmented elongate clasts of harrisitic olivine (1-3 cm long) and has been described already in Section 3.2.5 of this chapter. These crystals, together with normal granular olivines, define a planar fabric in this rock. Evidence of a magmatic lineation is observed at the hand-specimen scale as the fragmented harrisitic olivine grains often are often imbricated or form linear trains of crystals as also described in Section 3.2.5 above (Fig. 4.17D.3). This magmatic lineation plunges gently down-dip on magmatic layer planes, i.e. SE at 5-10°. Sample HB3 contains of one large (15 cm) tabular and branching olivine crystal oriented approximately perpendicular to layering, i.e. defining a crescumulate fabric (Fig. 4.17E.3). Again, no macroscopic lineation is observed in this rock.

4.3.2 Anisotropy of Magnetic Susceptibility Data

Magnetic fabric data for the three Ard Mheall harrisite samples are presented in Table 4.4 and illustrated in Figure 4.17C, 4.17D and 4.17E. Samples HB1 and HB3 reveal the highest bulk susceptibilities (8.1 and 13.8×10^{-3} SI, respectively). K_{mean} for the laminated harrisitic peridotite (Sample HB2) is 3.7×10^{-3} SI, a value that together with those for Samples HB1 and HB2 indicate that magnetite is the dominant mineral controlling the susceptibility and hence the anisotropy in these rocks. Thin-section analysis reveals that some of the harrisitic olivine crystals in all three samples contain similar magnetite dendrites to those described above in Section 4.1.3.2 of this chapter. Indeed, the work carried out by Moseley (1984) encompassed analyses of Western Layered Intrusion olivines, within which he recognised similar magnetite dendrites. Where present, the magnetite dendrites appear to be well-aligned within individual crystals and can be traced across different crystals in a given thin-section, provided the olivine host crystals are also aligned. However, this feature usually more

pronounced in the peridotites and troctolites of the Eastern Layered Intrusion. Magnetite also occurs with rare serpentine as anhedral grains altering olivine grain boundaries.

Samples HB1 and HB2 each reveal a relatively low degree of anisotropy (**H**), 1.4 and 4.4 respectively. The consistency of orientation of **L** for Sample HB2 with magmatic lineation observed in the field and approximate parallelism of **F** with magmatic layering, together with a triaxial ellipsoid shape, suggest that both the magnetic foliation and lineation can be treated as reliable. The relatively low value of **H**, despite the fact that the rock has both a planar and linear foliation that are observable in the field, may be due to the very fine-grained nature (olivine grains <1 mm in diameter) of the rock. However, note that the latter statement does not include the large fragmented olivine clasts that Sample HB2 contains, which may contribute significantly to the AMS of the rock. Both **F** and **L** for Sample HB1 are inconsistent and weak, which might be expected given that the macroscopic rock fabric is carried by branching harrisitic olivine crystals that are oriented anywhere between sub-vertical and highly obliquely to magmatic layer planes. Sample HB3 has a high **H** value (12.9%), with both a strong **F** and **L** component (8.8% and 4.1% respectively). Given that this sample comprises one crystal with a broad branching tabular morphology and appears to have its long axis oriented perpendicular to layering, the orientation of the magnetic foliation approximately perpendicular to layering is not unusual. The reasonably well-defined magnetic lineation that is oriented approximately down-dip on the plane of **F** is discussed with reference to olivine crystal morphology below.

4.3.3 Discussion and Conclusions

The AMS study outlined in this section is very short and hence does not merit substantial discussion. However, several concluding remarks pertinent to the development of harrisitic fabrics in the context of their magnetic fabrics and in relation to the harrisite study in the previous section (4.2) are noted as follows:

1. The very poor magnetic fabric in Sample HB1 (in which tabular dendritic harrisitic olivines are oriented vertically and obliquely on magmatic layer planes) indicates that there is a lack of aligned magnetite grains in this rock. As described above, magnetite may occur as either within-crystal dendrites or extra-crystal alteration products (either of which might be expected to provide a magnetic fabric that reflects olivine crystal shape). Given its discordance with magmatic layering and low **H** value, the poor AMS fabric in Sample HB1 might therefore be considered to support the interpretation that there is no consistent planar or linear arrangement of olivine crystals in this rock.

2. Though relatively weak, the AMS fabric revealed by the data for Sample HB2 is consistent with the planar igneous lamination and magmatic lineation observed in the field as described above. Magnetite typically occurs in this rock as sporadic dendrites lying parallel to olivine crystal long-axes. It is difficult to suggest whether the magnetic lineation measured is purely a function of the large harrisite crystal fragments or whether the much finer-grained granular olivine grains carry a lineation as well. The similarity of the magnetic lineation to observed flow directions in the field (and magnetic foliation to igneous lamination and magmatic layering) suggests that the AMS data for this sample supports the conclusion reached in Section 4.2.5 that regards these rocks as representing periodic turbulent flow of crystal mushes over harrisite layers. Such currents, possibly driven by simultaneous central subsidence of the Rum lopolith as discussed earlier, fragmented and reworked the large harrisite clasts, imposing on them the lineation described above. If this scenario is accepted, then it is likely that the smaller olivine crystals contribute to the magnetic lineation as well.
3. The AMS data for Sample HB3 describes a well-developed magnetic foliation with a fairly well-defined magnetic lineation. The magnetic foliation is approximately perpendicular to magmatic layering at the outcrop scale and the magnetic lineation is oriented down-dip on the magnetic foliation plane. Taking into account that the single harrisite crystal measured in this sample is approximately perpendicular to layering and that Donaldson (1974; 1975a; 1976) frequently finds that harrisitic olivine crystals may have a well-defined tabular or plate-like form, the AMS data for this sample is interpreted as follows. The magnetic foliation defines a tabular planar form of the olivine crystal, growing perpendicular to layering as observed in the field and outlined earlier. In a tabular crystal form, the short axis is well distinguished relative to the intermediate and maximum axes. The K_3 axis of the magnetic susceptibility ellipsoid may thus be tracking this well-defined plane (Fig. 4.18). As the maximum and intermediate axes of a well-developed tabular crystal form are approximately equal, the harrisite crystal in this instance may not actually be tabular, but somewhat longer in the orientation not observed in the hand specimen, i.e. its long and short axes are actually parallel to the plane of layering and the intermediate axis is perpendicular to the plane of layering (Fig. 4.18). [Note that the AMS ellipsoid for Sample HB3 has three susceptibility ellipsoid axes 1: 1.1: 1.14]. This interpretation derives from the magnetic lineation which is oriented parallel to strike of magmatic layer planes. The implication of the interpretation is that as well as harrisite growth in orientations relative to magmatic layering already

known from the field (shown in Fig. 4.18; Donaldson 1975a; 1977), growth of harrisitic olivine in the orientation as illustrated in Figure 4.18 may also be possible.

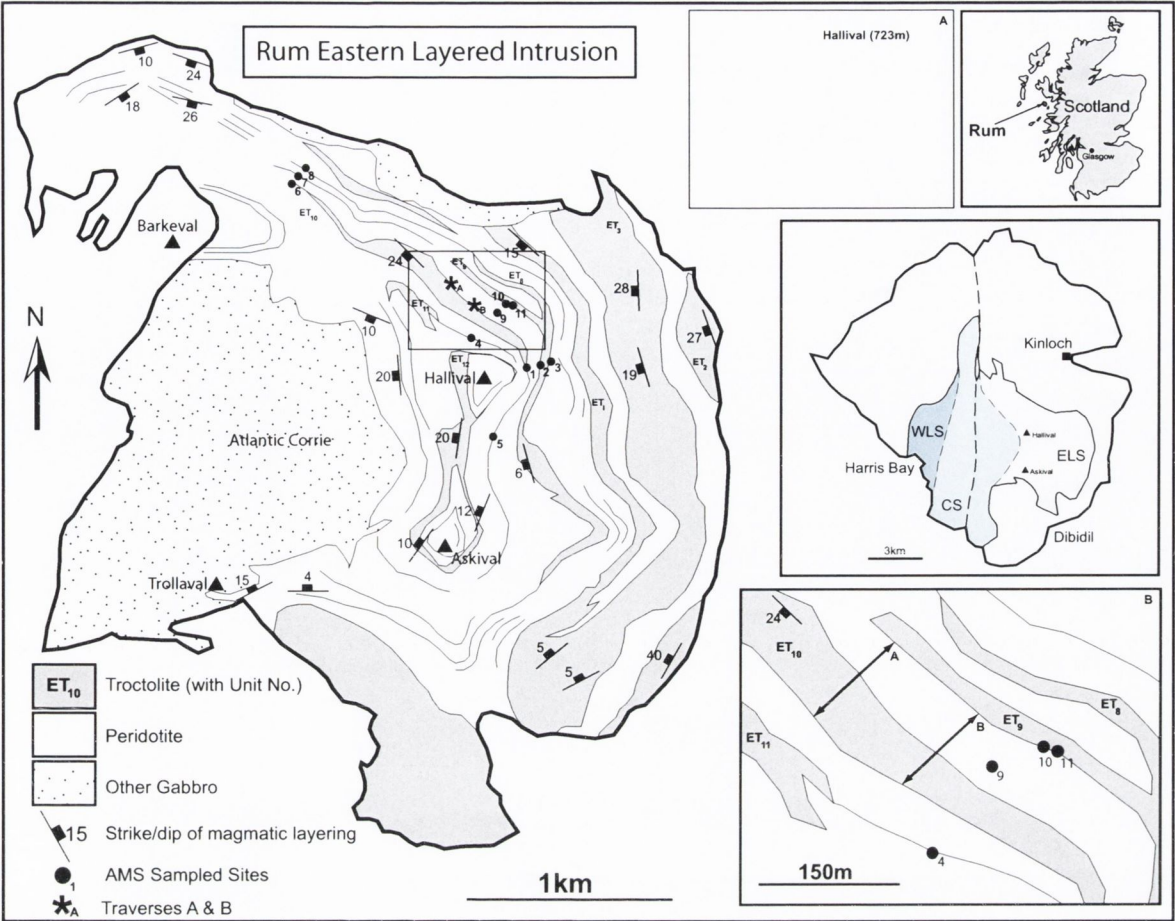


Figure 4.1. Map of the Eastern Layered Intrusion in the Rum Layered Suite, AMS sampling localities, and structural data measured from large-scale magmatic layering (the latter after Emeleus et al. 1996). Inset A: Northern slopes of Hallival, the resistant pale rock steps are the upper troctolite parts of each Unit, and the intervening slack ground the lower peridotites. Inset B: The positions of the detailed traverses carried out on the northern slopes of Hallival.

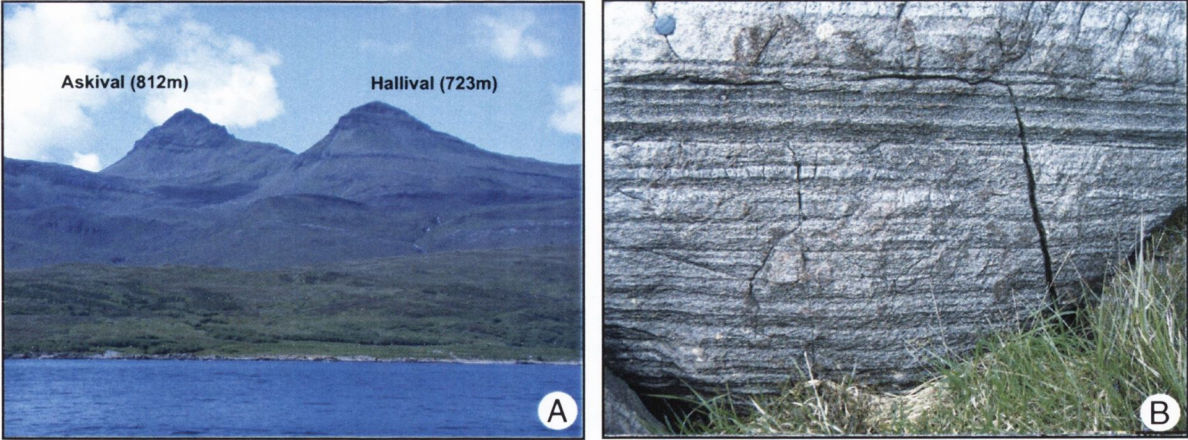


Figure 4.2. A. The macro units of the Eastern Layered Intrusion give the hills of Askival and Hallival their stepped topographical appearance viewed from the NE. B. Small-scale magmatic layering of peridotite and troctolite from the upper part of Unit 10, northern face of Hallival (lens cap in upper left of photo is 4cm in diameter).

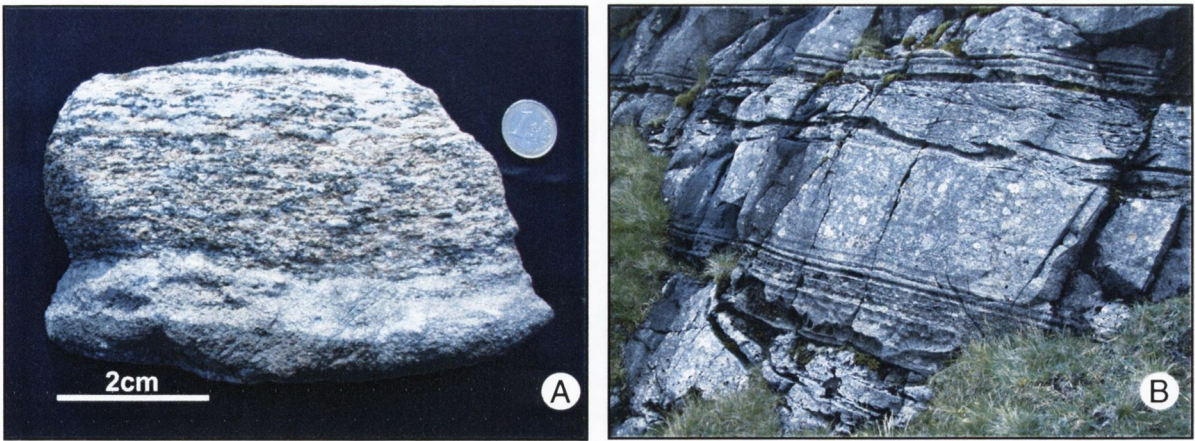


Figure 4.3. A. Pervasive igneous lamination defined by tabular plagioclase crystals observed throughout the Eastern Layered Intrusion troctolites. B. Magmatic slumping and folding of small-scale layering in Unit 10 troctolites, southern side of Hallival (sequence is ~4m thick).

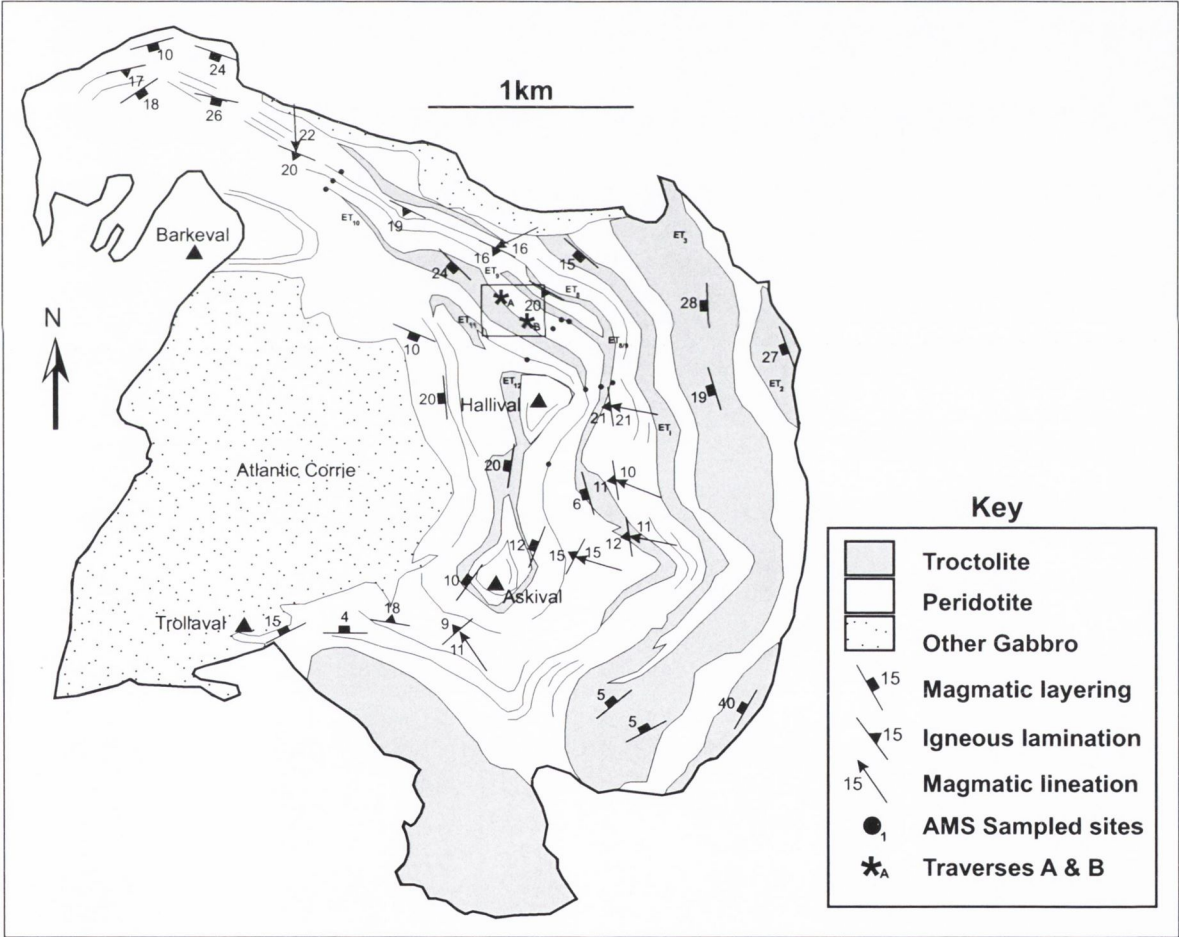


Figure 4.4. Map of the Eastern Layered Intrusion illustrating field measurements of the pervasive igneous lamination together with radial current directions deduced from macroscopic sedimentary structures.

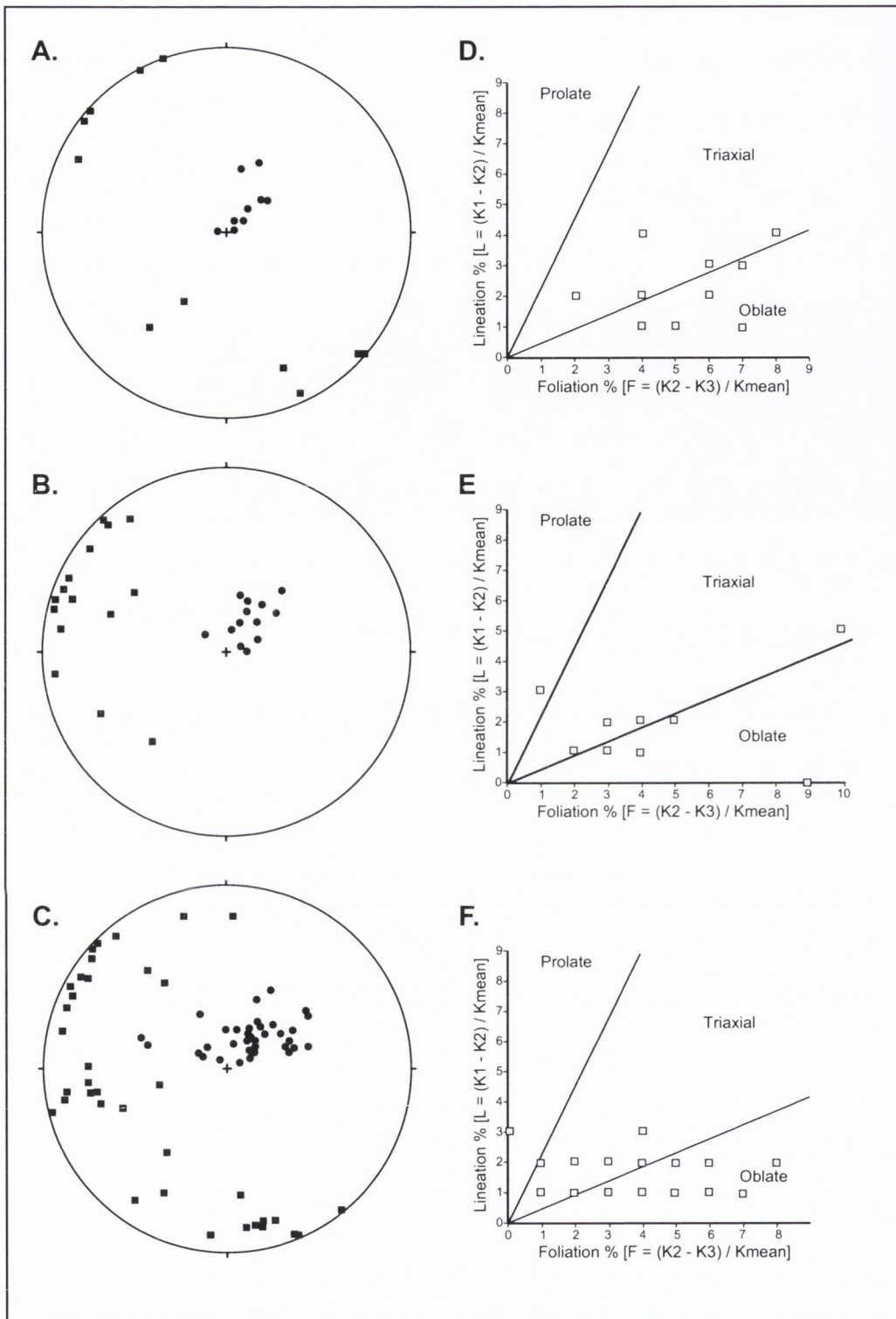


Figure 4.5. Anisotropy of Magnetic Susceptibility data. A-C: Poles to magnetic foliation planes (circles) and magnetic lineations (squares) for Sites 1-11, Traverse A, and Traverse B respectively. D-F: Lineation vs. foliation plots for AMS data for Sites 1-11, Traverse A, and Traverse B respectively.

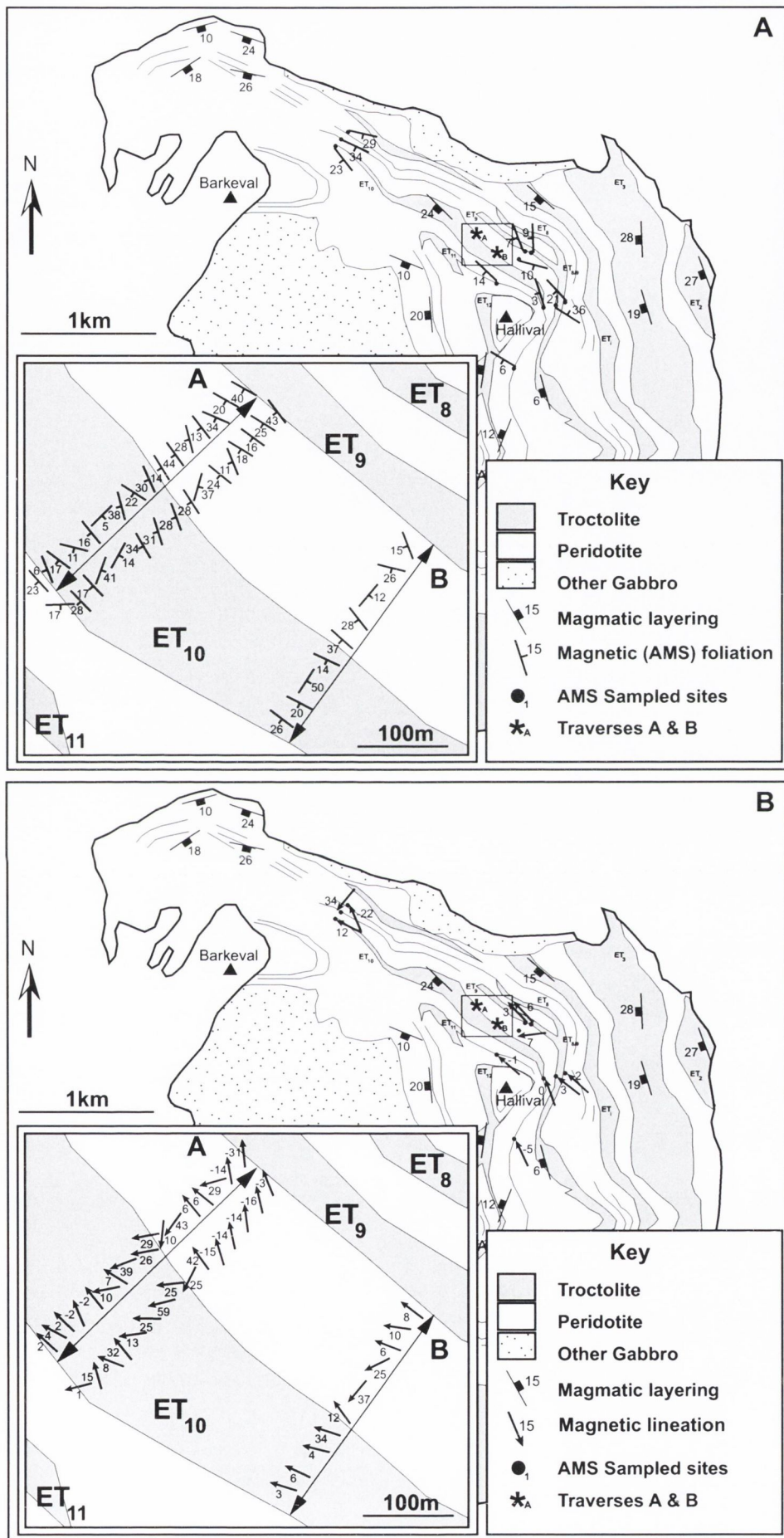


Figure 4.6. A: Magnetic foliation data for the Eastern Layered Intrusion. B: Magnetic lineation data for the Eastern Layered Intrusion.

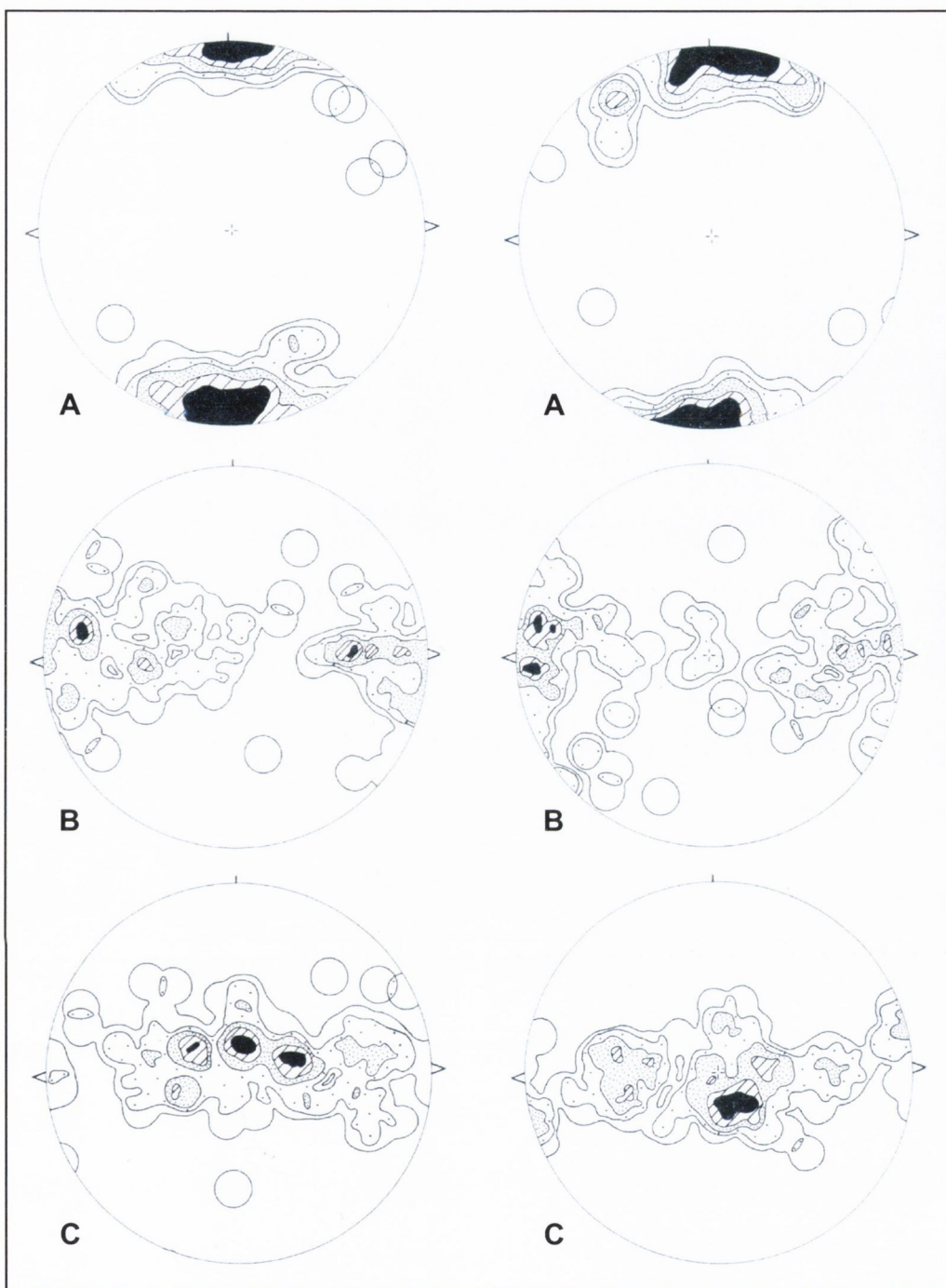


Figure 4.7. Crystallographic orientations of feldspar (A-C, left), measured on a U-stage, from Unit 9 of the Eastern Layered Intrusion (East face of Hallival), and (A-C, right) from south side of Barkeval reproduced from Brothers (1964). Layer plane is oriented E-W in all cases, and B in both cases gives the orientation of feldspar grain long axes. Both samples show a pronounced feldspar lineation parallel to strike of magmatic layering.

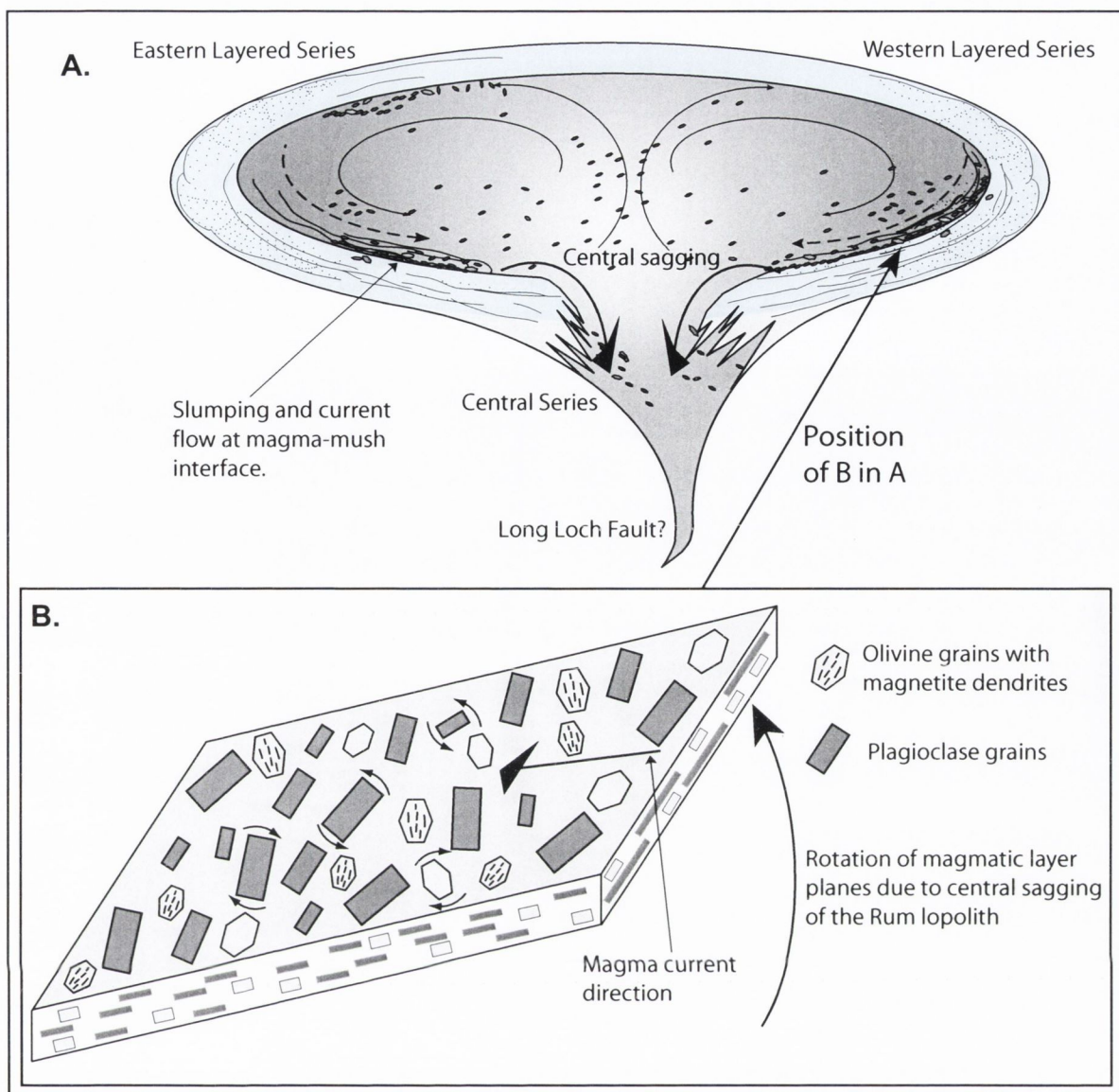


Figure 4.8. A: Diagram of the Rum intrusion illustrating magma chamber sedimentation processes and overall subsidence of the body at a central feeder system along the Long Loch Fault. B: Schematic sketch of a magmatic layer plane illustrating the development of the dominant 'strike-parallel' lineation carried by cumulus olivine bearing magnetite dendrites and plagioclase aligned transverse to magma current flow directions as indicated by AMS data in this study and the crystallographic study of Brothers (1964). Arrows are drawn on some crystals to show how reorientation may continue to occur through reshuffling and sliding of grains in the crystal mush pile.

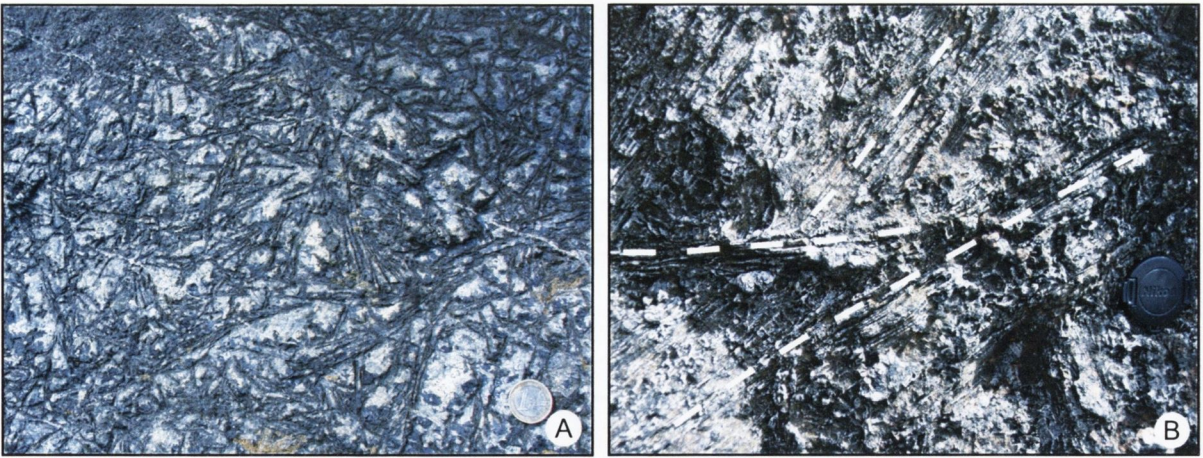


Figure 4.9. A: Olivine 'dendrites' in harrisite, Harris Bay (coin for scale). B: Intersecting skeletal olivine crystals in harrisite Harris Bay (crystal orientations highlighted; lenscap for scale).

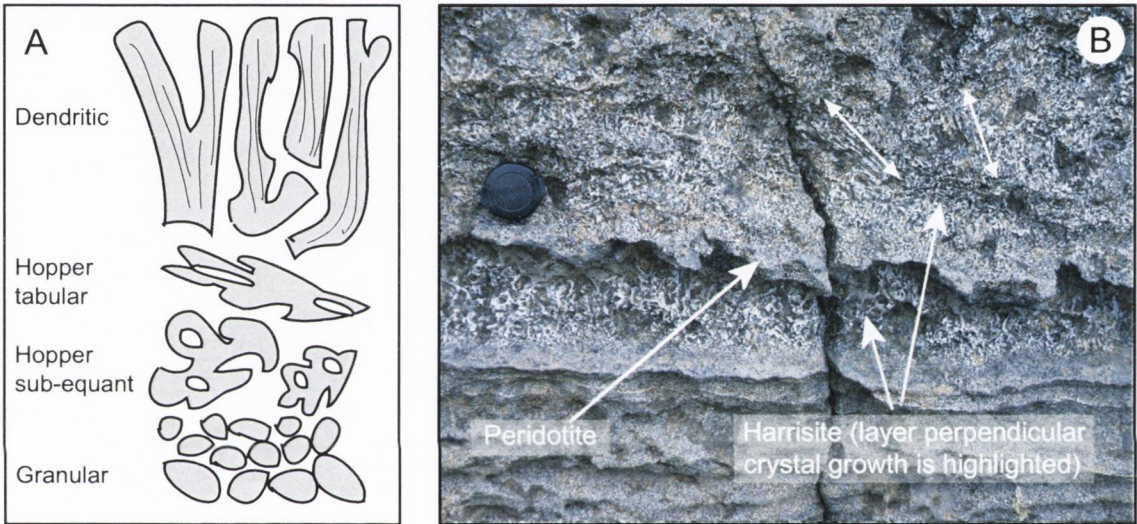


Figure 4.10. A: Schematic cross-section through a sequence of layers (granular peridotite at base into overlying harrisitic feldspathic peridotite) illustrating the upwards increase in size and complexity of olivine crystal morphology (after Donaldson 1977). B: Field photograph illustrating harrisite and granular textured peridotite layers.

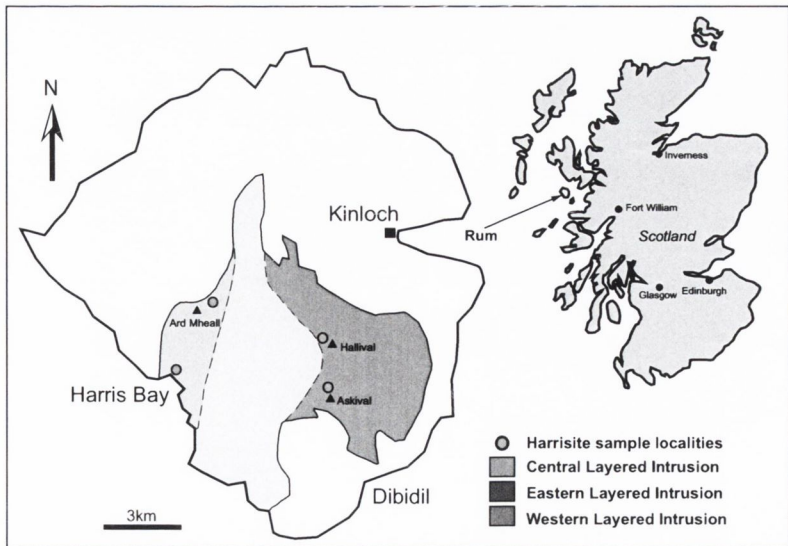
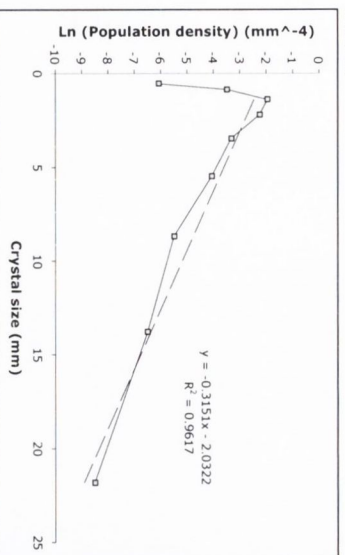


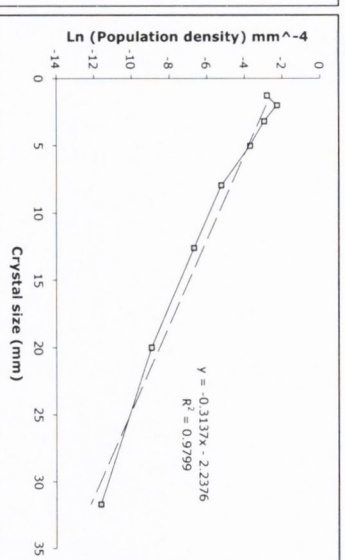
Figure 4.11. Map of the Rum Layered Suite illustrating the occurrence of harrisite throughout the Eastern, Western, and Central Layered Intrusions. Harrisite sampling localities at Harris Bay, Ard Mheall, Hallival and Askival are also shown.

A.

HB1.

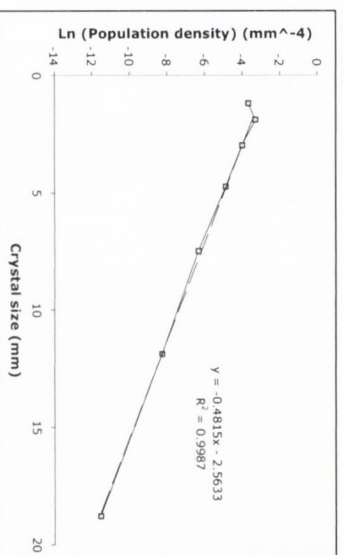


HB2.

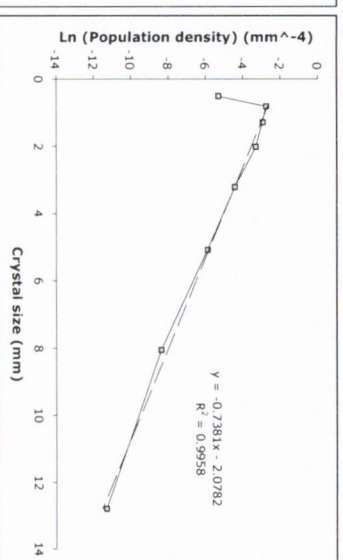


B.

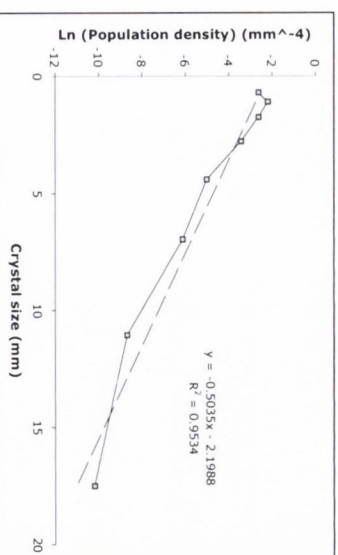
ARH1.



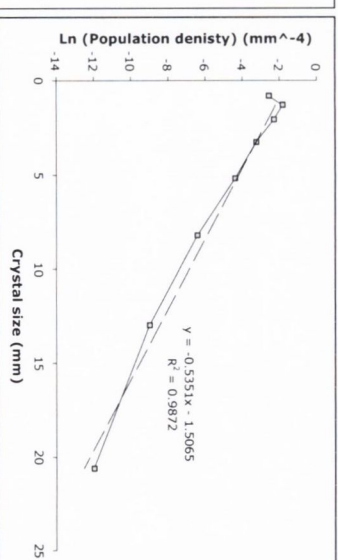
ARH2.



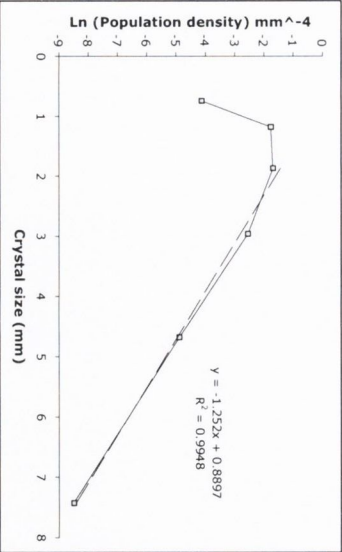
ARH3.



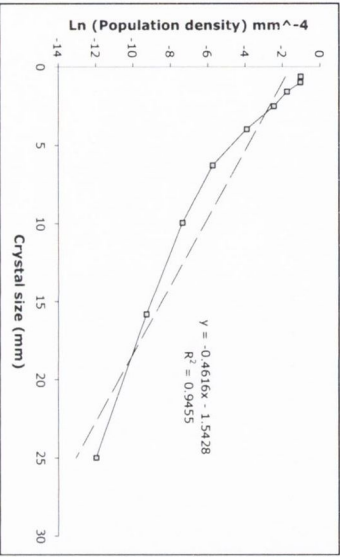
ARH6.



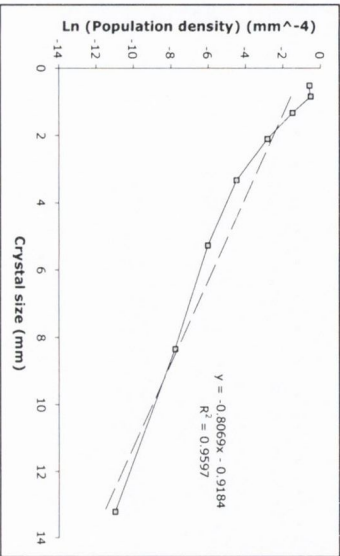
P1.



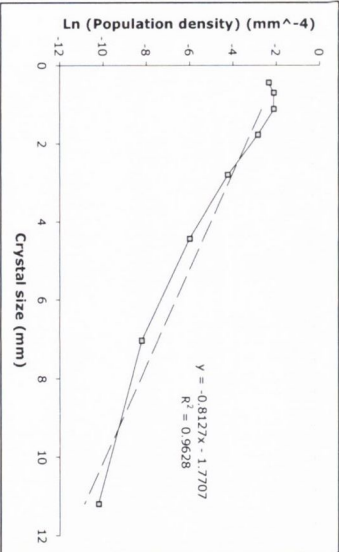
C.
R15.



R16.

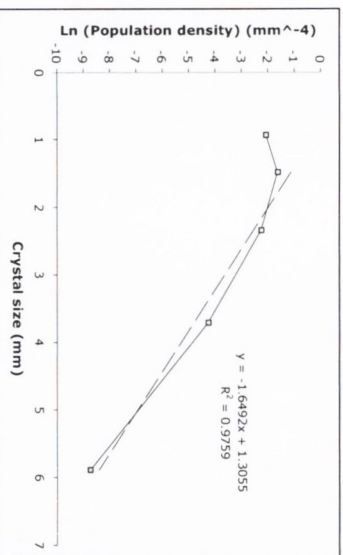


R17.

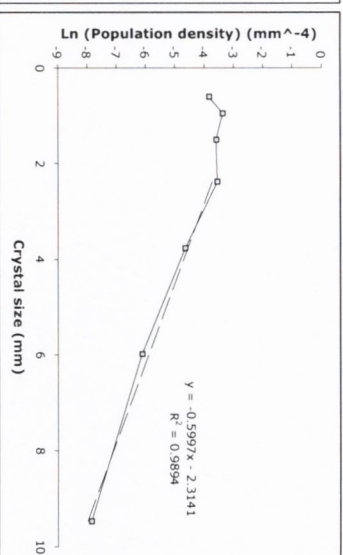


D.

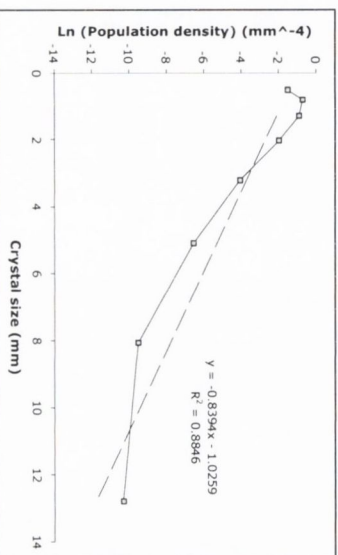
R1.



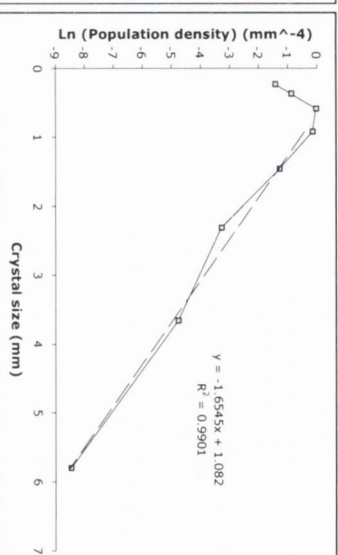
R2.



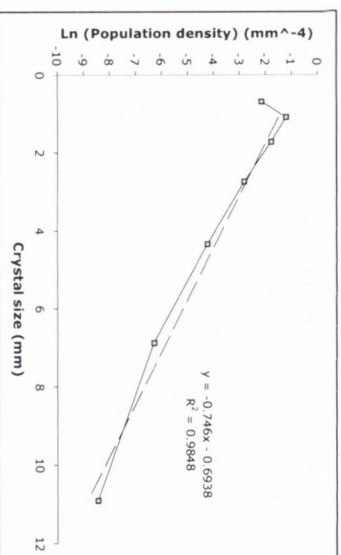
R31A.



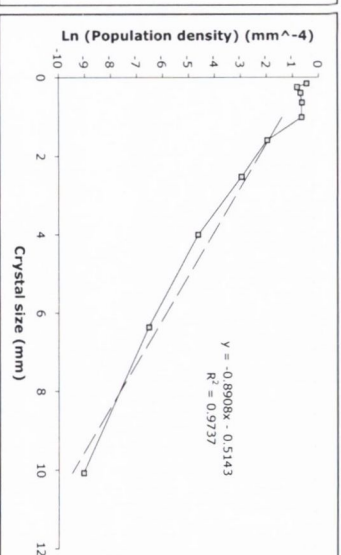
R31B.



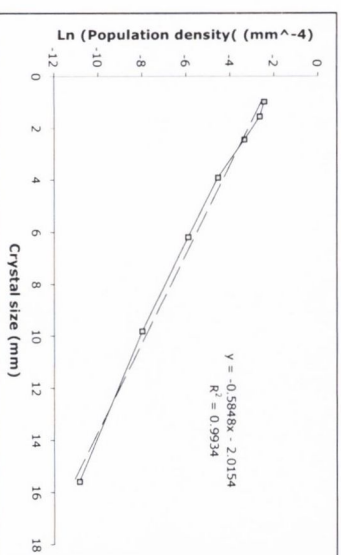
R32.



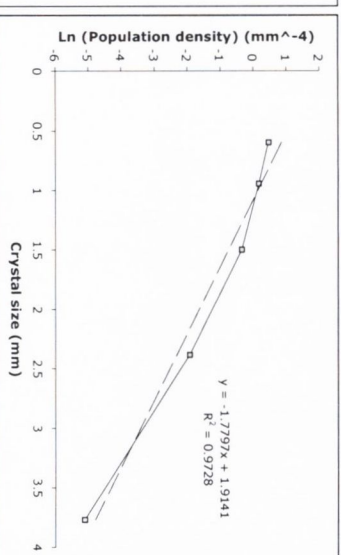
R33.



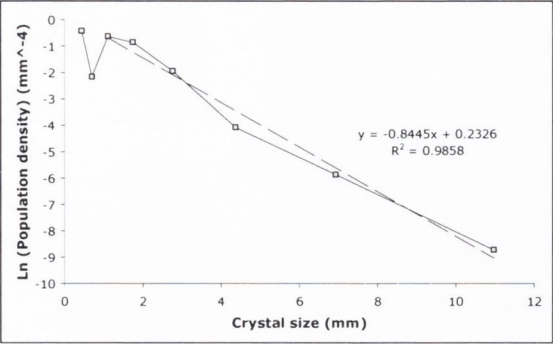
R34.



R36A.



R36B.



R37.

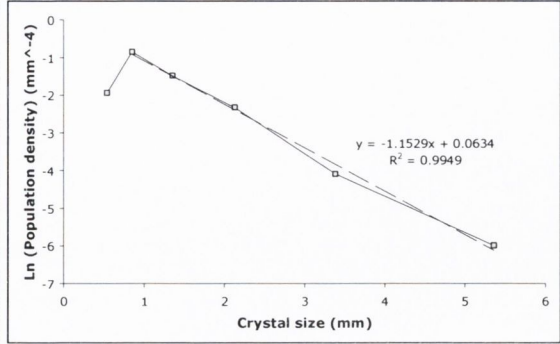


Figure 4.12. Labelled CSD curves for samples from: A- Harris Bay; B- Askival; C- Hallival; D- Ard Mheall.

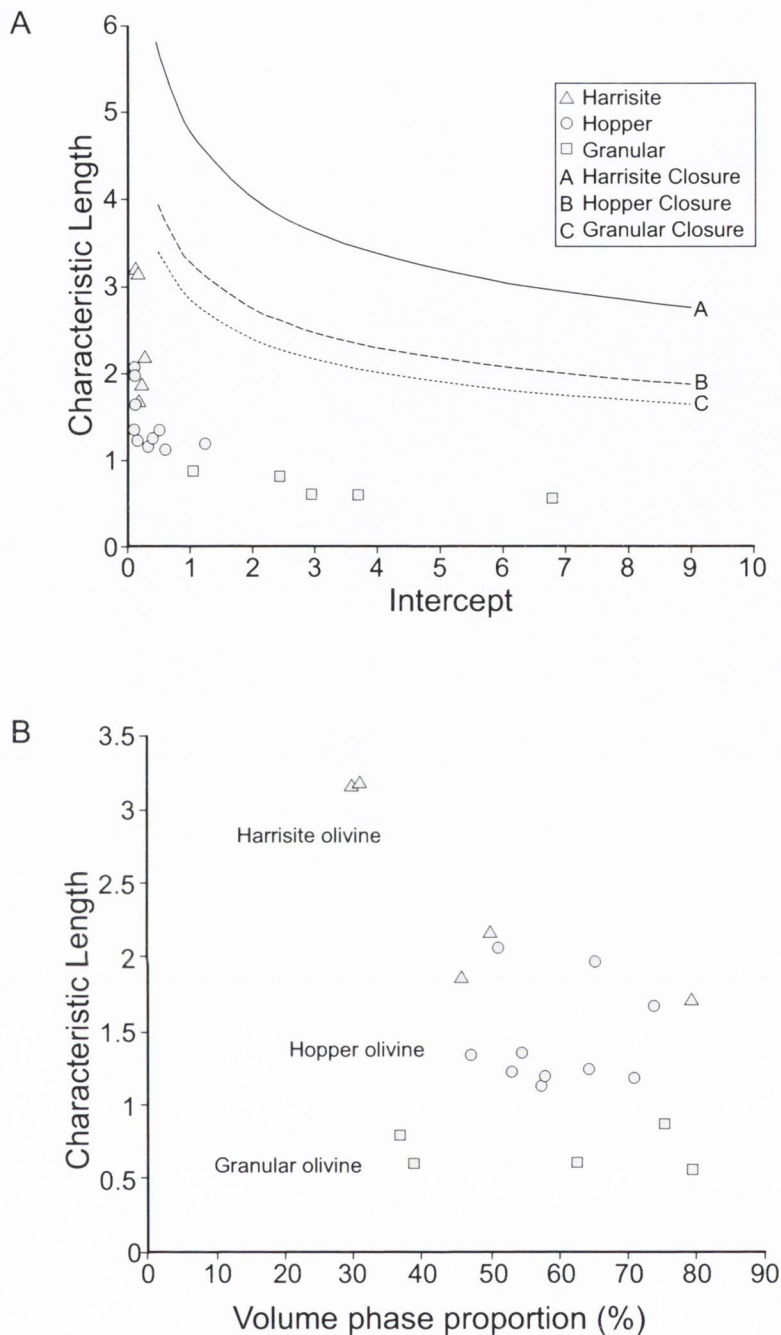


Figure 4.13. A: Plot of characteristic grain length vs. intercept together with closure limits for all CSD data. Curves for 100% crystal volume are labeled in legend, together with aspect ratios used to calculate each. B: Plot of characteristic grain shape vs. volume phase proportion for harrisitic, hopper, and granular olivine crystal morphologies. Closure limits are calculated with approximate characteristic aspect ratios for each crystal morphology (after Morgan and Jerram 2006).

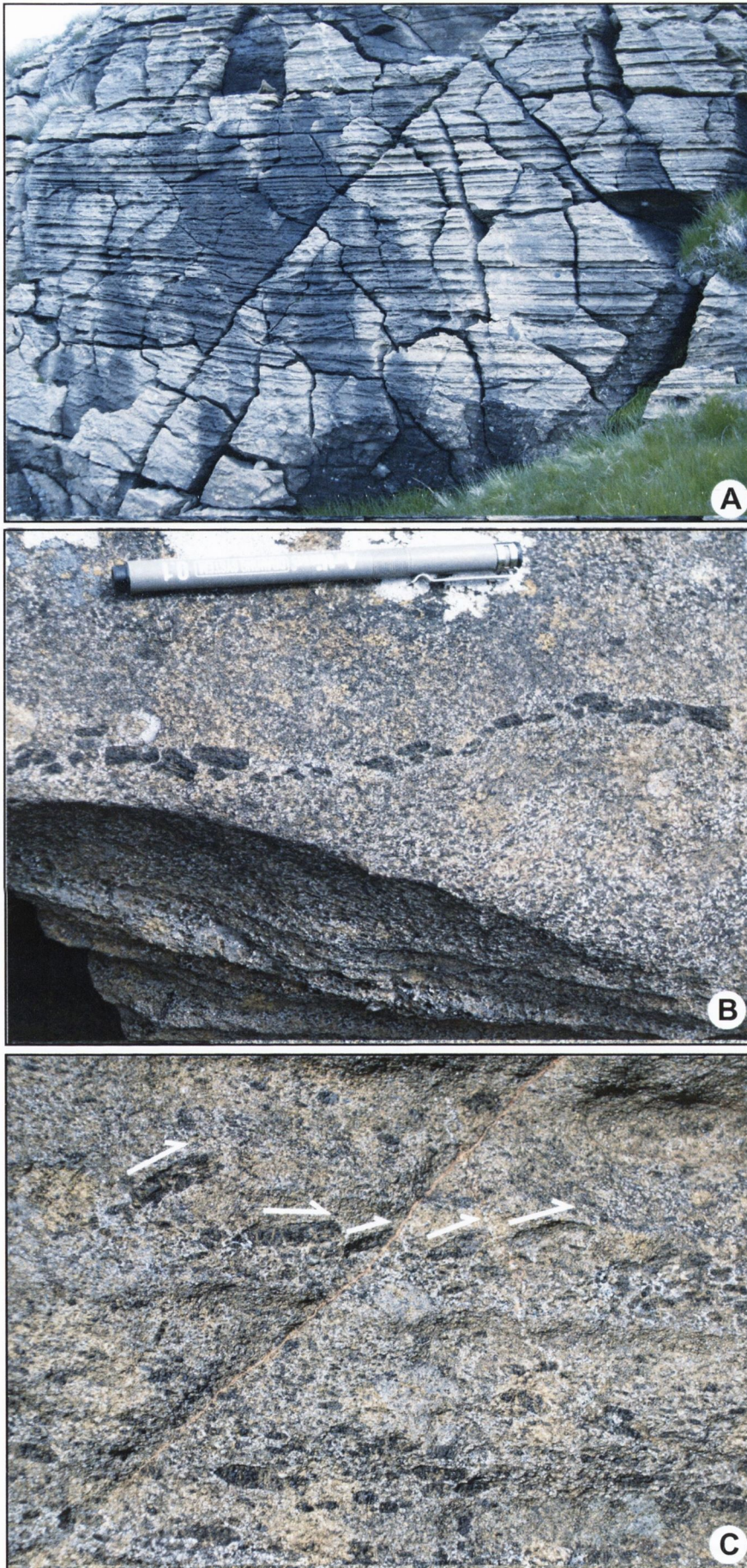


Figure 4.14. A: Rhythmically layered feldspathic peridotite at Ard Mheall. B: Linear train of fragmented olivine crystals in feldspathic peridotite. C: Imbrication (highlighted) of fragmented harrisitic olivine crystals in feldspathic peridotite.

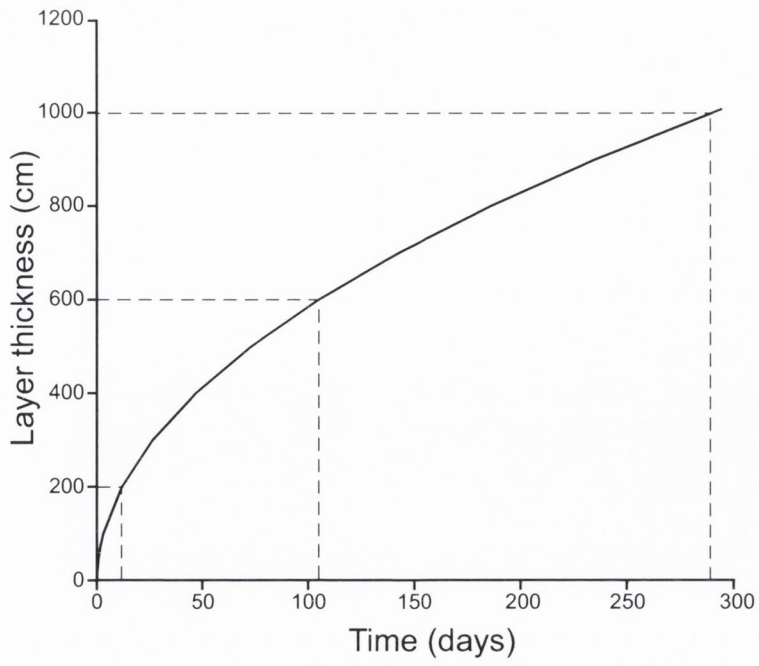


Figure 4.15. Plot of cooling estimates of the time taken for harrisite layers to crystallize based on a range of values of layer thickness between a minimum of 7 cm and a maximum of 10 m (Donaldson 1975a).

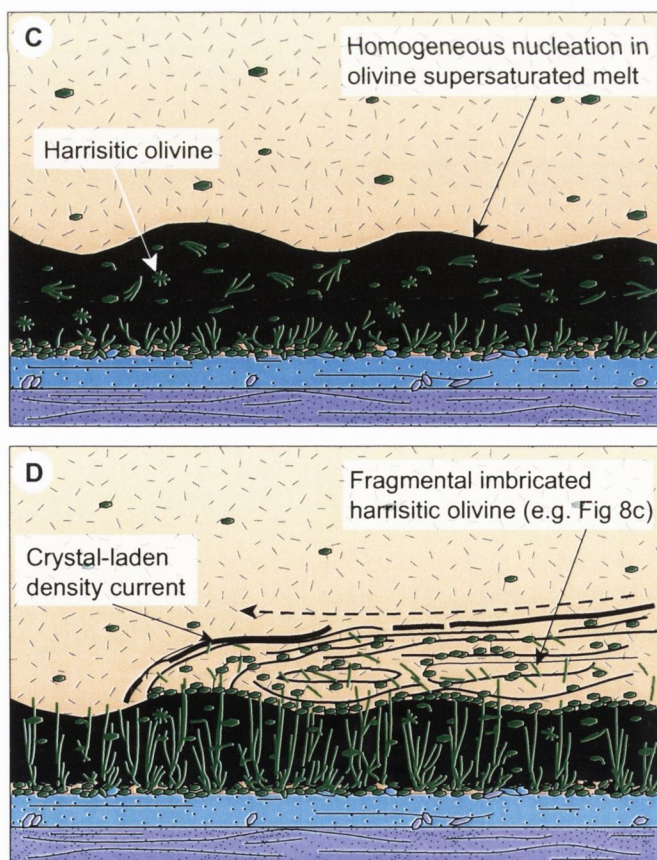
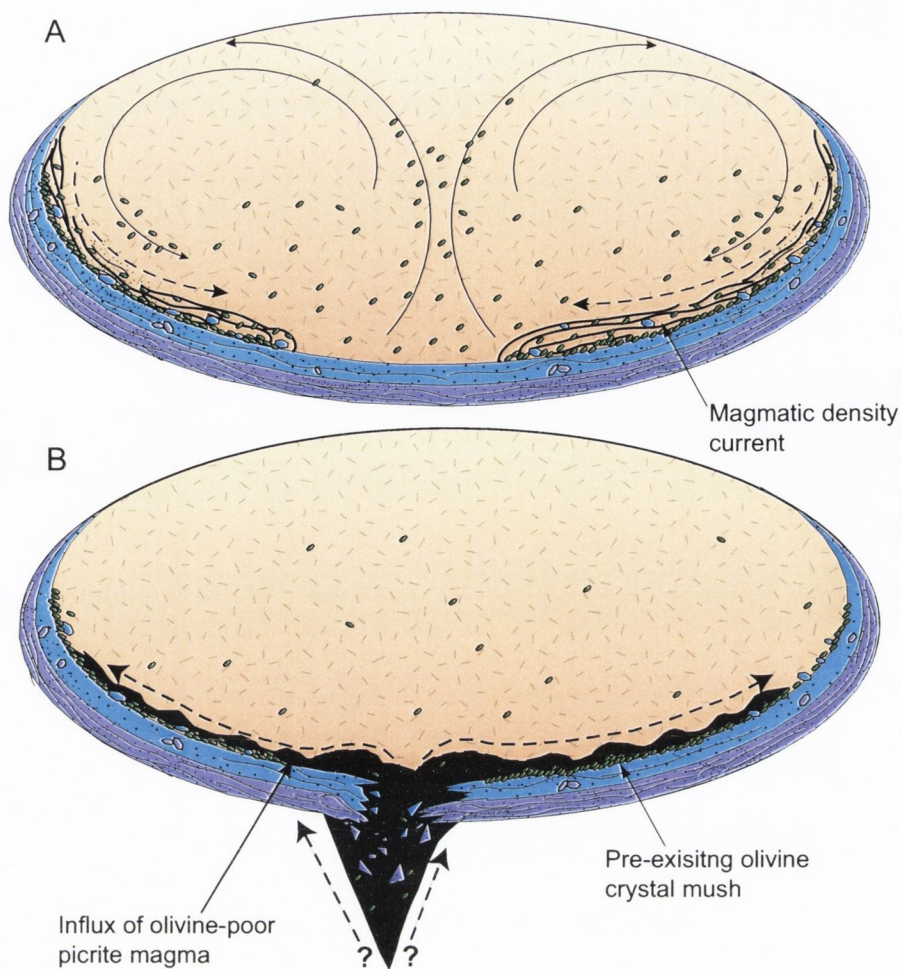


Figure 4.16. A-D: Schematic diagram of the Rum magma chamber throughout development of a harrisite layer (see text for description).

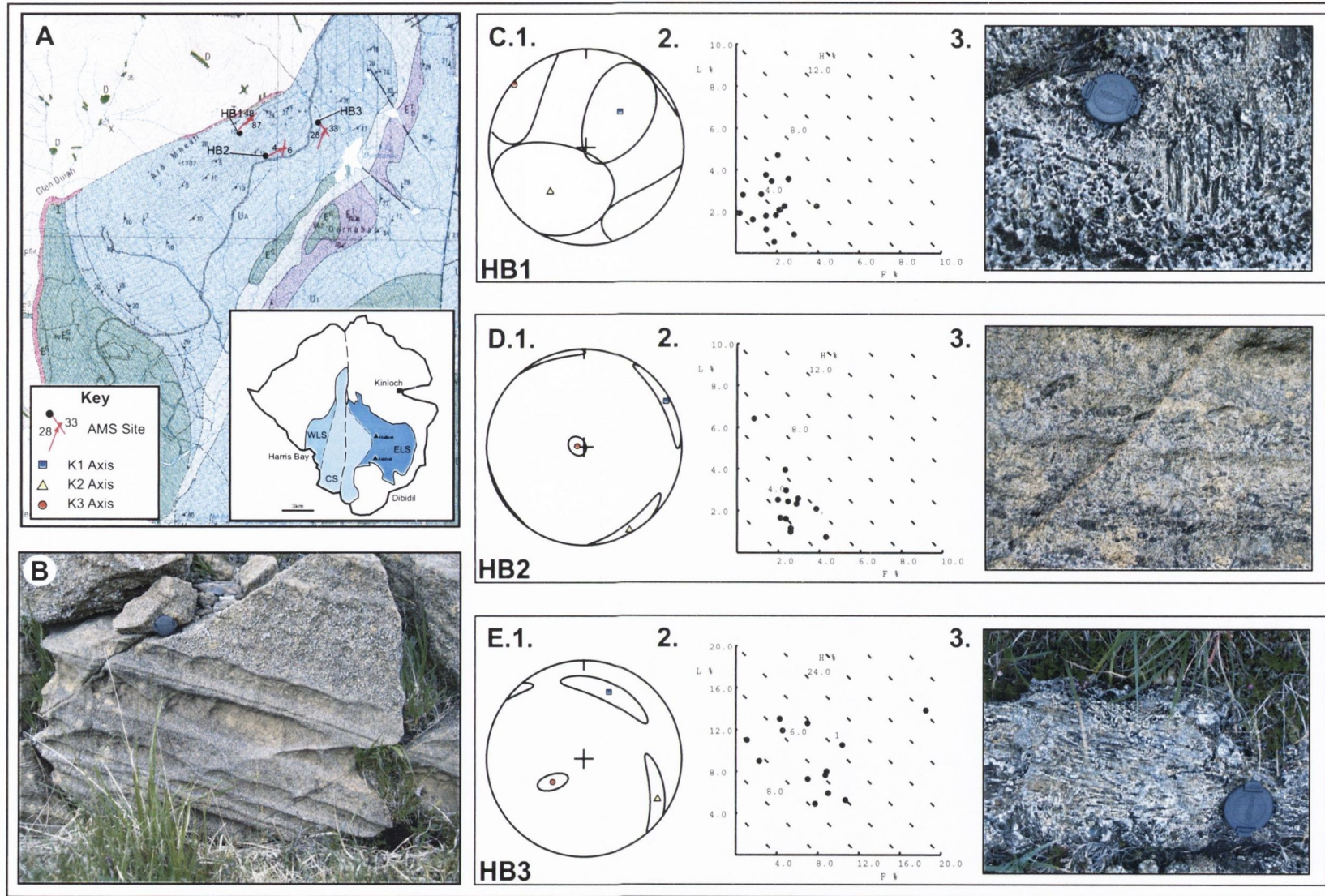


Figure 4.17. A: Map of the three sampled sites at Ard Mheall with AMS foliation and lineation orientations (from Emeleus 1997). B: Rhythmically layered harrisite and feldspathic peridotite at Ard Mheall. C, D and E: AMS data with field photographs of Samples HB1, HB2 and HB3 (see text for

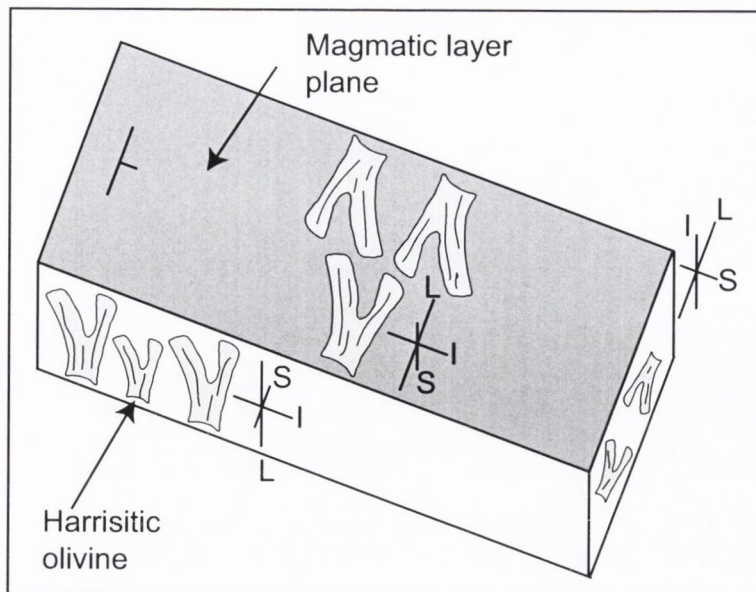


Figure 4.18. Schematic model diagram illustrating the interpretation of previous field observations of harrisite crystal orientation in the field and that reached from the AMS fabrics revealed by Sample HB3 in this study.

Table 4.1. AMS data for rocks of the Eastern Layered Intrusion

Site	Unit No	Km (E-6)	Magnetic Foliation	Magnetic Lineation	H %	F%	L%
Sites 1-11							
1	10	3.75E+03	162/3 SW	0	340	12.1	8 4
2	9	5.88E+03	122/36 SW	3	308	7.7	4 4
3	8	1.54E+04	137/21 SW	2	312	3.9	2 2
4	11	6.30E+02	133/14 SW	-1	311	4.9	4 1
5	10	1.50E+03	121/6 SW	-5	335	5.8	5 1
6	10	2.82E+03	142/23 SW	12	296	7.7	4 4
7	9	3.28E+03	115/34 SW	34	219	5.8	4 2
8	8	5.32E+03	103/29 SW	-22	337	4.9	4 1
9	10	3.40E+02	105/10 SW	7	263	5.8	4 2
10	9	1.38E+03	159/7 SW	3	317	14.7	10 5
11	9	6.09E+03	178/9 SW	6	317	31.5	26 5
Traverse A Unit 10							
1		6.80E+02	147/43 SW	-3	338	3.9	3 1
2		2.64E+03	119/40 SW	-31	354	3.0	2 1
3		1.40E+03	122/25 SW	-16	347	5.8	5 1
4		2.58E+03	119/20 SW	-14	350	5.8	4 2
5		2.38E+03	126/16 SW	-14	353	3.9	3 1
6		1.87E+03	113/34 SW	29	254	3.0	2 1
7		2.91E+03	121/18 SW	-14	348	7.6	7 1
8		2.91E+03	142/13 SW	6	309	5.8	5 1
9		2.06E+03	158/11 SW	8	295	3.9	3 1
10		9.50E+02	165/28 SW	6	320	3.0	2 1
11		1.60E+03	129/24 SW	-15	343	4.9	4 1
12		2.84E+03	144/44 SW	43	216	3.9	3 1
13		2.96E+03	16/37 SW	42	324	3.0	1 2
14		3.96E+03	148/14 SW	10	186	6.7	6 1
15		2.96E+03	147/28 SW	25	207	5.8	4 2
16		2.81E+03	156/30 SW	29	260	6.7	5 2
17		3.48E+03	160/28 SW	25	264	6.8	4 3
18		2.65E+03	122/25 SW	26	260	10.3	8 2
19		2.15E+03	163/31 SW	59	256	6.8	4 3
20		2.87E+03	165/38 SW	39	249	7.6	6 2
21		3.29E+03	150/34 SW	25	271	4.9	4 1
22		1.88E+03	48/5 SW	7	302	6.7	5 2
23		1.28E+03	29/14 SW	13	262	4.9	4 1
24		1.26E+03	29/14 SW	10	259	8.5	7 1
25		1.76E+03	64/27 SW	32	321	2.0	1 1
26		4.40E+02	141/16 SW	-2	321	7.6	7 1
27		3.70E+02	20/41 SW	13	215	4.9	3 2
28		1.20E+03	104/11 SW	-2	337	4.9	3 2
29		2.00E+01	137/17 SW	8	291	3.0	0 3
30		2.00E+01	127/17 SW	2	314	4.9	4 1
31		1.04E+03	136/28 SW	15	344	35.1	31 4
32		1.00E+01	158/6 SW	4	298	5.8	4 2
33		1.04E+03	88/17 SW	1	256	3.9	2 2
34		3.70E+02	138/23 SW	2	312	8.5	7 1
Traverse B Unit 10							
1		2.05E+03	159/15 SW	8	307	3.9	3 1
2		5.07E+03	104/26 SW	10	278	3.9	3 1
3		2.95E+03	40/12 SE	6	291	4.9	3 2
4		1.26E+04	142/28 SW	25	244	6.7	5 2
5		7.59E+03	132/37 SW	37	220	6.7	5 2
6		2.58E+03	115/14 SW	12	324	3.9	1 3
7		4.45E+03	33/50 SE	34	288	3.0	2 1
8		2.06E+03	117/20 SW	4	284	5.8	4 2
9		1.94E+03	127/26 SW	6	295	4.9	4 1
10		4.17E+03	113/24 SW	3	287	9.4	9 0

Table 4.2. Model growth rates of olivines of different shapes (Henderson and Williams (1979)

Morphology	Mean U (ng-g-1)	Growth Rate (mm sec-1)
Granular	5	1.2 x 10-5
Hopper	5.99	4.8 x 10-5
Harrisitic	8.34	6.4 x 10-5

Table 4.3. Sample numbers and CSD data for harrisitic and granular olivines from the Rum Layered Suite

Sample	Crystal morphology	Slope	Ln(n0)	Crystal-melt contact time			Nucleation rate		
				$\tau 1$ (Hours)	$\tau 2$ (days)	$\tau 3$ (years)	J1 (mm ⁻³ s ⁻¹)	J2 (mm ⁻³ s ⁻¹)	J3 (mm ⁻³ s ⁻¹)
R1	Granular (1:1.2:1.7)	-1.6492	1.3055	14		19.2	4.4 x 10 ⁻⁵	3.7 x 10 ⁻⁹	
R2	Skeletal Hopper (1:1.25:1.9)	-0.5997	-2.3141	9.7	193		4.8 x 10 ⁻⁶		9.9 x 10 ⁻⁹
ARH1	Skeletal Hopper (1:1.4:2.8)	-0.4815	-2.5633	12	240.4		3.7 x 10 ⁻⁶		7.7 x 10 ⁻⁹
ARH2	Skeletal Hopper (1:1.5:1.9)	-0.7381	-2.0782	7.8	156.8		6 x 10 ⁻⁶		1.3 x 10 ⁻⁸
ARH3	Skeletal Hopper (1:1.3:2.4)	-0.5035	-2.1988	11.5	229.9		5.3 x 10 ⁻⁶		1.1 x 10 ⁻⁸
ARH6	Skeletal Branching (1:1.5:3.6)	-0.5351	-1.5065	8.1	216.3		1.4 x 10 ⁻⁵		2.2 x 10 ⁻⁸
P1	Granular (1:1.4:2.8)	-1.252	0.8897	18.5		25.3	2.9 x 10 ⁻⁵	2.4 x 10 ⁻⁹	
HB1	Skeletal Branching (1:2:10)	-0.3151	-2.0322	13.8	367.3		8.4 x 10 ⁻⁶		1.3 x 10 ⁻⁸
HB2	Skeletal Branching (1:2.5:9)	-0.3137	-2.2376	13.8	369		6.8 x 10 ⁻⁶		1.1 x 10 ⁻⁸
R15	Skeletal Branching (1:2.5:5)	-0.4616	-1.5428	9.4	250.7		1.4 x 10 ⁻⁵		2.1 x 10 ⁻⁸
R16	Skeletal Hopper (1:1.25:1.8)	-0.8069	-0.9184	7.2	143.4		1.9 x 10 ⁻⁵		4 x 10 ⁻⁸
R17	Skeletal Hopper (1:1.4:1.7)	-0.8127	-1.7707	7.1	142.4		8.2 x 10 ⁻⁶		1.7 x 10 ⁻⁸
R31A	Skeletal Hopper (1:1.7:2.3)	-0.8394	-1.0259	6.9	137.9		1.7 x 10 ⁻⁵		3.6 x 10 ⁻⁸
R31B	Granular (1:1.25:1.8)	-1.6545	1.082	14		19.2	3.5 x 10 ⁻⁵	3 x 10 ⁻⁹	
R32	Skeletal Hopper (1:1.6:3.2)	-0.746	-0.6938	7.8	155.2		2.4 x 10 ⁻⁵		5 x 10 ⁻⁸
R33	Skeletal Hopper (1:1.25:2)	-0.8908	-0.5143	6.5	129.9		2.9 x 10 ⁻⁵		6 x 10 ⁻⁸
R34	Skeletal Branching (1:1.2:1.9)	-0.5848	-2.0154	9.9	197.9		8.5 x 10 ⁻⁶		1.3 x 10 ⁻⁸
R36A	Granular (1:1.2:1.8)	-1.7797	1.9141	13		17.8	8.1 x 10 ⁻⁵	6.7 x 10 ⁻⁹	
R36B	Skeletal Hopper (1:1.6:3.2)	-0.8445	0.2326	6.9	137.1		6.1 x 10 ⁻⁵		1.3 x 10 ⁻⁷
R37	Granular (1:1.25:1.7)	-1.1529	0.0634	20.1		27.5	1.3 x 10 ⁻⁵	1.1 x 10 ⁻⁹	

Table 4.4. AMS data for Ard Mheall harrisite samples

Sample	Kmean	K1	Dec	Inc	K2	Dec	Inc	K3	Dec	Inc	L	F	H	Mu	
HB1	8077.55		1.007	44.1	48.5	1.001	38.8	-41.4	0.992	131.1	-2.6	0.62	0.82	1.43	36.9
HB2	3645.77		1.02	241.1	-4.4	1.004	331.4	-3.3	0.976	277.9	84.5	1.65	2.75	4.4	31
HB3	13839.7		1.056	20.6	28.2	1.016	118.8	15	0.928	233.6	57.4	4.05	8.81	12.86	24.7

CHAPTER 5. THE SKYE DRUIM HAIN LAYERED GABBROS

5.1 Introduction

The Cuillin Complex is the oldest major plutonic suite of rocks of Palaeogene age preserved on the Isle of Skye and is dominated by coarse-grained partially-layered mafic and ultramafic lithologies (Bell and Williamson 2002). The complex is approximately 8 km in diameter, and where present, magmatic layering generally dips toward a focal point below Meall Dearg, at the southern end of Glen Sligachan (Fig. 5.1). The NE portion of the complex has been intruded by the later granites of the Srath na Creitheach and Western Red Hills Centres. Elsewhere, the complex is intruded into plateau lavas.

The Cuillin gabbro complex has been sub-divided into three major groups as follows (and see Fig. 5.1; Emeleus 1991; Bell and Williamson 2002): (i) the Outer Gabbros (oldest); (ii) the Outer Layered Suite; and, (iii) the Inner Layered Suite (youngest). The Outer Gabbros comprise a heterogeneous group of structureless (generally unlayered) gabbro and bytownite gabbro extending in an arc from Loch Scavaig in the south to Sgurr nan Gillean in the north. The Outer Layered Series comprises an extensive and sometimes exceptionally well-layered group of troctolites, feldspathic-olivine-rich peridotites and bytownite gabbros. The Inner Layered Series is separated from the Outer Layered Series by the strongly transgressive unlayered Druim na Ramh Ring Euclite, interpreted as the type example of a mafic ring-dyke in the Skye central complex. The Inner Layered Series consists of a number of distinct masses of layered and unlayered gabbro, bytownite gabbro and bytownite troctolite. Of these, the Inner Gabbros, also referred to as the Druim Hain layered gabbros (Fig. 5.1), exhibit the best examples of magmatic layering and more importantly for this study (intimately associated with the layering), some of the best and most extensive known examples of layer-parallel igneous lamination (cf. Harker 1904; Wager and Brown 1968; Bell and Williamson 2002) in the entire British Palaeogene Igneous Province. The relatively small (and comparatively poorly studied) area covered by the Druim Hain layered gabbros was chosen in this study for a detailed examination of the relationship between magmatic layering, igneous lamination, magnetic (AMS) fabrics and crystal size distributions on the basis of three criteria:

- (1) The E-NE dipping rhythmically layered cumulate sequence of Druim Hain are superbly exposed on west dipping slabs and *almost always* displays an exceptionally well-developed layer-parallel igneous lamination (Harker 1904; Wager and Brown 1968). This macroscopic foliation is carried by a variety of different mineral grains, depending on the mineral composition of the laminated magmatic layer.

- (2) Both magmatic layer and igneous lamination planes display a marked 90° 'strike-swing', from an E-W north-dipping orientation in the south to a N-S east-dipping orientation in the north of the intrusion. The AMS data, if closely related to these macroscopic fabrics, might be expected to parallel them.
- (3) Several previous studies (e.g. Geikie and Teall 1894; Wager and Brown 1968) have made reference to the presence of abundant primary cumulus and intercumulus magnetite in the Druim Hain layered gabbros. As described already in this study, the presence of this mineral is useful for AMS fabric measurement as magnetite dominates the susceptibility and hence the AMS of any rock it occurs in (Chapter 2). Therefore, the fabric measured will be homogenous, i.e. controlled by only one mineral phase.

5.2 Magmatic layering and internal structure

The layered gabbros exposed on the Druim Hain ridge comprise a sequence of layered cumulates approximately 700 m thick. Layering is typically poorly developed with no evidence of an associated lamination observed at the base of (the W and NW) of the intrusion (lowermost 250 m of stratigraphy). Above this is approximately 400 m of layered gabbro, comprising olivine, plagioclase, magnetite and clinopyroxene-rich layers. These are rarely monomineralic, but are typified by layers rich in one or two of the mineral components listed. Magmatic layering generally occurs at a small-scale (cm to m) (Figs. 5.2A and 5.2B). Wager and Brown (1968) reported an upward change of An_{69} to An_{58} in plagioclase feldspar compositions and from Fo_{66} to Fo_{58} in olivine compositions. No evidence is observed for cyclic repetition of sequences or packages of magmatic layers up sequence, although the layered sequence described above is punctuated on 5 (observed) occasions by thin plagioclase-rich layered packages approximately 3 m thick. Magmatic layering here is typically monomineralic with layers of anorthosite or magnetite dominating (Fig. 5.3A and 5.3B). These packages often anastomose slightly, paralleled by layering and igneous lamination, as if they have been syn-magmatically deformed. The eastern side (top of sequence) of the intrusion is characterized by containing a host of xenoliths of varying composition. These include in particular fragments of Lewisian gneiss, fine-grained mafic xenoliths and greenish highly-altered blocks of basalt. The gabbros at this easternmost side of the intrusion are not well-layered, but highly-altered and veined with felsic and mafic pegmatites and dykes.

Layering in the Druim Hain gabbros strikes parallel to the outer contacts of the intrusion and dips inward without exception toward a focal point beneath the Meall Dearg granophyre of the Srath na Creitheach Centre (Fig. 5.4), whose intrusive contacts bound the eastern side of the gabbros. Mapping of magmatic layering and igneous lamination has revealed a distinct steepening-inward trend in both (30-70°) as this focal point is approached. Field observations suggest that the igneous lamination varies in intensity. Though this may in part be attributed to some minerals (e.g. olivine) being less suited to carrying such a fabric than plagioclase, variation in intensity of lamination is also observed in plagioclase cumulate throughout the intrusion (Fig. 5.5). With the exception of the igneous lamination, little evidence has been observed in the Druim Hain gabbros for small-scale structures (such as slumping or trough layers) often observed in association with other layered gabbro sequences in this study and in layered mafic intrusions elsewhere, e.g. the Skaergaard intrusion (Wager and Brown 1968; Irvine *et al.* 1998). Toward the eastern side (roof) of the intrusion however, sporadic fine-grained mafic blocks (dropstones) are sometimes observed deforming the layered sequence beneath them as illustrated in Figure 5.6A and in two cases are very large, measuring 4.5 m and 2 m in diameter (e.g. Fig. 5.6B). On one occasion graded bedding is observed in an olivine-rich gabbro at the centre of the Druim Hain layered gabbro. This corresponds with Wager and Browns (1968) assertion that such structures were also 'rare' through out the layered sequence.

5.3 Anisotropy of Magnetic Susceptibility Data

5.3.1 Sampling methodology

Block sampling was carried out exclusively on 23 sites in the well-layered upper portion of the Druim Hain gabbros (the lower poorly-layered 100-200 m were not considered). Two sites were double-sampled to test for within-site variation. Eight to twelve sub-samples were drill-cored from each block and site mean tensor data were calculated from the measurements (Owens 2000). All of the sampled sites exhibit well-developed layering together with a good layer-parallel igneous lamination, both of which were measured at each locality for comparison with the AMS data. The AMS sampled sites are illustrated in Figure 5.7. It is important to note that completely monomineralic magnetite layers were not selected for AMS analysis, as they typically did not carry a

discernible igneous lamination in the field. In addition, it is anticipated that it would be impossible to measure such rocks with the KLY3 Kappabridge because of expected very high K_{mean} values¹.

5.3.2 AMS Results

AMS data for the Druim Hain layered gabbros is presented in Table 5.1 and illustrated in Figures 5.7 and 5.8. Bulk susceptibilities (K_{mean}) are quite high, ranging between 6 and 166×10^{-3} SI, suggesting volume concentrations of magnetite of up to 6-7% (Balsley and Buddington 1958). This is supported by reflected and transmitted light microscopy that indicates magnetite typically occurs as subhedral and anhedral grains (the latter occurring as interstitial grains to other equant grains such as olivine or plagioclase; see Fig. 5.9A). Magnetite may also be enriched in magmatic layers, occasionally forming monomineralic bands (Fig. 5.9B). The Druim Hain gabbros therefore contain primary magmatic magnetite cumulus or intercumulus grains in well-developed cumulate textures (cf. Wager and Brown 1968). It is also worth noting that Geikie and Teall (1894), in the only detailed published petrological study of these rocks, express no doubt that the magnetite in these rocks crystallized from the original Druim Hain magmas.

Total anisotropy degree (**H**) values are also very high, ranging between 7 and 25% for the Druim Hain rocks. In the vast majority of cases, the magnetic foliation (**F**) completely dominates the AMS fabric over the magnetic lineation (**L**) (Table 1). Except for Sample 11, the orientations of the magnetic foliation planes are very consistent, and as with the laminated ('fluxion') gabbros of Ardnamurchan (Chapter 3) and the laminated troctolites of the Rum Eastern Layered Series (Chapter 4), parallel the macroscopic layering/igneous lamination (Fig. 5.7 and 5.8). Again, this is a good indication that the AMS fabrics reflect the fabric observed in the field, and may suggest, as with the laminated gabbros on Ardnamurchan, that the AMS (magnetite fabric) is being controlled to some extent by the existing silicate template or framework. This may be particularly true of those samples in which magnetite is a very common interstitial (intercumulus) component, rather than as subhedral cumulus grains. Taking the above into consideration, it is probable that an error occurred in either the field orientation or the laboratory reorientation of Sample 11 to produce the anomalous AMS fabric it exhibits (Fig. 5.7).

¹ The upper limit of bulk susceptibility that the KLY3 instrument was capable of measuring was found to be 3×10^{-1} SI in this study (corresponding to approximately 10 vol% magnetite), measured for a sample from Skye that has not been included in the dataset presented (as analysis could not be completed).

However, as the L/F ratios might suggest, the susceptibility ellipsoids are dominantly very oblate in shape (Fig. 5.10). The principal (K_1) axes of the Druim Hain ellipsoids are very inconsistent in terms of their orientations and trend in different orientations on magnetic foliation planes (unlike the dominant intrusion-scale magnetic lineation trends observed in both the laminated gabbros of Ardnamurchan and the laminated troctolites of the Rum Eastern Layered Series; Chapters 3 and 4). When considered in conjunction with the ellipsoid shapes, which indicate that L is quite weak, it is reasonable to assume that the magnetic lineation is both statistically and directionally too weak to be relied on as a valid petrofabric indicator at an intrusion scale in this instance.

5.4 CSD Analysis

5.4.1 Sampling methodology

Crystal size distribution analysis was carried out on six of the AMS samples described above, in a manner consistent with CSD analysis on the Ardnamurchan laminated gabbro samples (Chapter 3), i.e. in order to gain an insight into the textural evolution of the widespread igneous lamination. As plagioclase and pyroxene are quite abundant in the Druim Hain cumulates and often form subhedral-euhedral crystals, it was possible to carry out CSD analysis on both mineral phases as follows:

- (1) Plagioclase in Samples 6, 8 and 23.
- (2) Pyroxene in Samples 4 and 15.
- (3) Plagioclase and pyroxene in two sections [parallel (S18A) and perpendicular (S18B) to the igneous lamination] in Sample 18.

5.4.2 CSD Results

5.4.2.1 CSD Plots

CSD data for the Druim Hain samples is presented in Table 5.2 and CSD plots are illustrated in Figure 5.11. The plots exhibit considerable variation in shape depending on two factors; the mineral phase analysed and the strength of the igneous lamination in the sample. Although some samples exhibit an apparent deviation from a log-linear profile (e.g. 4, 15, 23), linear regression analysis reveals that none have an R^2 value of less than 0.91. Measured slope values for the CSD curves are quite consistent (-1.1 to -1.9), with the exception of Samples 4 and 23, whose curves have much shallower slopes (-0.5 and -0.8 respectively).

Two groups are recognized in the CSD curves on the basis of plot shape and slope value. The first group of CSDs contains plots that exhibit generally steeper slope values and simple, relatively straight curve shapes (Samples 6, 8 and 18 [nos. 1-4]). The CSDs from Sample 18 seem to be better separated by slope on the basis of whether they have been cut perpendicular or parallel to the igneous lamination, rather than by mineral phase measured. The plagioclase and pyroxene CSDs derived from thin-sections cut parallel (S18A) to the igneous lamination have somewhat steeper slopes (-1.7 and -1.9 respectively) than those cut perpendicular (S18B) to the igneous lamination (-1.1 and -1.1 respectively). However, Figure 5.11 shows that, despite this, the four CSDs from Sample 18 appear very similar, indicating that the CSD data is accurate as the *CSDCorrections* program is required to take the foliation and crystal shape parameters of a sample into account.

The second group of CSD plots is characterized by more complex plot shapes (Sample 15) or more complex plot shapes and much shallower slopes (Sample 4 and 23). Samples 15 and 23 are both characterized by plots that display gently concave-upward shapes at larger size fractions, though Sample 15 has a much steeper slope value (-1.8 and -0.8 respectively). Sample 4 has both a complex shape (pronounced 'humped' profile at smaller crystal size fractions and broad concave-upward shape at larger size fractions) and a very shallow slope (-0.5).

Closure limits were again calculated to assess the quality of the CSD data as outlined in previous chapters following Higgins (2002a; 2002b) and Boorman *et al.* (2004). Figure 5.12A shows characteristic grain length plotted against intercepts together with empirically calculated closure limits using an average aspect ratio of 1:2.3:4.5 for the Druim Hain laminated gabbros and shows that all sample data falls well within permitted range, i.e. below the line representing 100% crystallinity. A plot of CSD characteristic grain length against volume phase proportion (cf. Higgins 2002a) shows that with the exception of Samples 4 and 23, all samples fall within a fairly well-constrained group of characteristic grain length (Fig. 5.12B).

5.4.2.2 Crystal growth times and nucleation rates

Crystal growth times have been calculated for plagioclase and pyroxene crystal populations in each sample using slope data and a growth rate for both of $1 \times 10^{-10} \text{ mm.s}^{-1}$ (Cashman and Marsh 1988; Higgins 1996; Marsh 1998). These times are generally quite consistent (163-289 years) for 4 of the 6 samples measured (Table 5.2). Samples 4 and 23 fall outside this range of crystal growth times with results of 417 and 676 years

respectively. Plagioclase and pyroxene from Sample 18 have crystal growth times of 175-289 years and 186-281 years respectively, giving only a range of time of crystal growth for each in the cumulate pile.

Nucleation densities (n^0) have been calculated from the Y-axis intercepts on the CSD curves and are shown in Table 5.2. CSD intercepts ($\text{Ln}[n^0]$) range from -1.4 to 2.9 mm^{-4} ($n^0 = 2.4 \times 10^{-1}$ to 19.8 mm^{-4}). These values are very low compared with published values on plagioclase nucleation densities (Cashman and Marsh 1988), but are similar to values of n^0 presented for the Ardnamurchan laminated gabbros (Chapter 3). Consequently, values of nucleation rate (J) are also comparable to nucleation rates obtained for the Ardnamurchan laminated gabbros, ranging from 2.4×10^{-11} to $1.9 \times 10^{-9} \text{ mm}^{-3} \text{ s}^{-1}$.

As with the Ardnamurchan laminated gabbros, it may be that coarsening or ripening of cumulate textures has led to a rotation of CSD slopes to shallower sizes (cf. Marsh 1998; Higgins 2002a). The results presented above are thus also treated with caution, as it is plausible that the calculations have produced greatest values of n^0 and least values of J .

5.5 Electron Microprobe Data

5.5.1 Introduction

Four plagioclase crystals from a sample of laminated gabbro were selected for major element analysis of sub-crystal zonation for comparison with the textural and AMS data described above. As with Chapter 3, analysis was carried out under the laboratory and instrumental conditions given in Chapter 2. Sample 18, a well-laminated plagioclase and clinopyroxene-bearing cumulate, was selected for microprobe analysis of approximately one hundred points per crystal at between 43 and 54 μm spacing.

5.5.2 Microprobe data

Figure 5.13 is a summary of the microprobe data for plagioclase from Sample 18. The graphs illustrate $\text{An}\%$ and FeO_t plotted against (rim-to-rim) distance for each of the crystals analysed. The $\text{K}_2\text{O}-\text{CaO}-\text{Na}_2\text{O}$ composition of each crystal is plotted in the feldspar ternary diagram in Figure 5.13, illustrating that all four are very similar in composition. Anorthite contents for the four crystals range between approximately 70 and 80%, typically with less than 5% An variation between any two data points. [The maximum $\Delta\text{An}\%$ between any two given data points is $\sim 7\%$]. However, although a degree of rim-to-rim variation is observed in each crystal, no evidence of distinct compositional zones are present, in direct contrast to Sample 5 described from Sithean Mor,

Ardnamurchan in Chapter 3. All four crystals have quite similar FeO_t contents, with relatively uniform compositions across crystal lengths in all four cases.

5.6 Discussion

Magmatic layering at all scales on Druim Hain appears to define a saucer-like internal structure to the layered gabbros similar to the layering trends observed in the Ardnamurchan and Rum intrusions (Chapters 3 and 4). However, the Druim Hain gabbros comprise only a small part of the Skye mafic-ultramafic pluton, and it would be unreasonable to draw conclusions regarding the geometry of the intrusion as a whole from this localized, though detailed, study. Indeed, it is not even certain that the gabbros of the Cuillin Complex can realistically be considered as a single intrusion, or whether perhaps a suite of nested (lopoliths?) might be a more likely alternative. This study will therefore use the field observations, AMS and textural data presented above to make inferences on the development of magmatic layering and the pervasive layer-parallel igneous lamination at Druim Hain alone, without extensive speculation on the emplacement of the whole Cuillin Complex.

Though rhythmic layering is exceptionally well-developed at Druim Hain, associated small-scale structures that might give an insight into layer-development are conspicuous by their rarity. Though the ubiquitous layer-parallel igneous lamination is an exception to this, the usefulness of the latter on its own in aiding determination of magma chamber processes is limited, as has been discussed in previous chapters. Indeed, it would be highly unreasonable to invoke a separate density current to account for every single well-laminated and/or monomineralic layer in the Druim Hain layered sequence, particularly as almost all of them are well-laminated. This means that there is little or no direct field evidence for or against primary ‘sedimentary’ processes being a significant mechanism in the development of layering at Druim Hain. However, the consistent steepening-inward (eastward) from $\sim 30^\circ$ to $\sim 70^\circ$ of layering and lamination planes is compelling evidence that central subsidence, such as interpreted for Rum and Ardnamurchan, may have been an important process in the development of the Druim Hain intrusion too. Whether this reflects central subsidence of the Cuillin Complex as a whole, or a separate younger Druim Hain intrusion is again beyond the scope of this study to discuss.

Magnetic fabric susceptibility ellipsoids are dominantly very oblate and as with laminated gabbros from elsewhere described in this thesis, the magnetic foliation planes consistently parallel the igneous lamination. However, the magnetic lineation (L) is very weak and despite the sensitivity of the AMS technique, very inconsistently oriented, giving no evidence for a consistent flow pattern or syn-magmatic deformation fabric

throughout the Druim Hain gabbros. As the magnetic foliation traces out the igneous lamination very well, it might be assumed that were there a consistent macroscopic magmatic lineation present in these rocks, it would be reflected by the magnetic lineation. It must be noted that though no consistency is revealed from the magnetic lineation data between different sites, many samples have very well-defined (well-oriented) magnetic lineations. However, of the two double-sampled sites (2 and 13), considerable within-site magnetic lineation variation is also observed, suggesting that the magnetic lineation cannot be treated as a reliable rock fabric indicator to any degree whatsoever. It may thus be reasoned that there is very little evidence in the Druim Hain rocks for either magmatic flow or sedimentation processes as an important process in magnetic fabric development.

Crystal size distribution data from Druim Hain suggest that although secondary (postcumulus) processes may have been significant in some samples (e.g. 4, 15 and 23), lamination development cannot be solely attributed to late-stage 'Ostwald ripening' or 'crystal-ageing'. The reason for this is that many of the laminated samples measured for CSD, i.e. Sample 6, 8 and 18 (nos. 1-4), that include both plagioclase and pyroxene CSDs, are quite straight at the larger size-fraction portions of the curves. This indicates (as suggested for other similar CSDs at Glendrian and Achnaha on Ardnamurchan in Chapter 3) that crystallization was relatively simple without the addition of foreign crystal/nuclei populations or significant crystal ripening in the late-stage crystallisation history of the cumulate pile. A relatively consistent range of crystal growth times for Samples 6, 8 and 18 (nos. 1-4) (i.e. 163-289 years) supports this. Microprobe analyses for Sample 18 also substantiate the CSD data and the interpretation above, by giving little evidence of distinct growth and/or ripening events in the cumulate pile during crystallisation, as all feldspars analysed maintain quite consistent compositions across their respective lengths.

It is therefore tentatively suggested that primary magma chamber processes are responsible for the initial development of the igneous lamination (without any formation of a lineation) at Druim Hain. One such process is simple gravitative settling of tabular plagioclase and tabular-acicular pyroxene grains (see Wager and Brown 1968), which would probably result in crystals falling into position on their broad (flattish) faces forming a strong planar fabric. Such a mechanism would not produce a linear arrangement of crystals within the planes of lamination consistent with the field and AMS observations in this study. However, many studies (McBirney and Noyes 1979; Morse 1979; Boudreau and McBirney 1997) have questioned the ability of plagioclase crystals, which have demonstrably lower densities than mafic silicate melts, to settle, referring to the 'plagioclase flotation problem'. The crystal settling hypothesis cannot be ruled out entirely for the Druim Hain gabbros, even for

plagioclase, as Irvine *et al.* (1998) outlines a number of processes by which plagioclase may accumulate to form layers at the base or sidewalls of a magma chamber. These include the tiling or 'sticking' of plagioclase to more mafic phases for periods during settling and the sinking/settling of plagioclase crystals in large 'rafts' or 'mats' instead of as single crystal grains. However, it is not certain that the above scenarios would produce the ubiquitous lamination observed throughout the whole of the Druim Hain layered sequence. In any case, Irvine *et al.* (1998) also states that the above mechanisms are important only in overcoming the buoyancy of plagioclase; magmatic currents are required in order to separate crystals into monomineralic layers and to create lamination. Additionally, crystal-settling theory requires the presence of a magma-crystal mush interface, where crystals may accumulate. It might be expected that the presence of such an interface would give rise to small-scale 'sedimentary' structures associated with layering. These need not necessarily develop through flow, but might include features such as slumping of denser layers into less dense, i.e. soft sediment deformation or modal grading of individual layers. It should be emphasized again that evidence for magmatic currents and such small-scale structures are rare to absent throughout the whole of the Druim Hain sequence.

McBirney and Noyes (1979) and Boudreau and McBirney (1997) suggested that magmatic layering and consequently the very closely associated igneous lamination of some layered intrusions could form through *in situ* crystallization. They envisaged examples of planar crystal fabrics developing simultaneously with layering along slow-moving gradients or chemical equi-potential at inward moving solidification fronts as an intrusion cooled. McBirney and Noyes (1979) presented convincing evidence for this process in the Skaergaard intrusion. This mechanism (giving rise to non-dynamic layering as defined by Boudreau and McBirney 1997) explains why strong planar fabrics might arise without any evidence for a linear component within the lamination plane and without any development of small-scale structures associated with layering. The position and diameter of the Druim Hain gabbros at the uppermost part of the Cuillin Complex strongly indicates that they developed quite close to the roof of the intrusion. This suggestion is supported by the comparatively large number of Lewisian and basaltic country-rock xenoliths along the crest of the Druim Hain ridge (the easternmost extent of the intrusion) as described above and by the extensive alteration (metasomatism) that seems to have occurred there. If the Druim Hain gabbros are indeed close to the roof of the intrusion as inferred, then it might be suggested that an inward/downward moving solidification front developed the rhythmic cumulate sequence at Druim Hain from the top to the bottom. However, this possibility may be ruled out as several roof or upper wall blocks have clearly

fallen downward to deform the layered rocks high up in the sequence (Figs. 6A and 6B), suggesting instead that the crystal mush/solidification front built/moved from the bottom upward.

It is considered that the effect of this solidification front on diffusive and thermal gradients may have controlled the direction of crystal growth at the melt-crystal mush interface in a manner suggested by McBirney and Noyes (1979). For example, where the thermal gradient falls below the liquidus curve, the liquid may become constitutionally undercooled, leading to crystal growth perpendicular to the direction of movement of the solidification front (e.g. certain types of harrisitic olivine growth described in Chapter 3). However, where solidification is slower, the diffusion gradient will be less steep and crystals may grow with their broad faces parallel to the direction of the advancing solidification front. Although Boudreau and McBirney (1997) seem to have subsequently abandoned this model, it is believed that the oscillatory nucleation and growth of layers together with a solidification-front control on foliation development can explain two features in the Druim Hain rocks not explained by any other model:

- (1) The occurrence of up to ~400 m of continuously well-layered cumulate, whose layering is often at a scale of several centimeters and can be laterally extensive on scales up to 150 m, and which is difficult to reconcile with continuous magmatic flow and sedimentation.
- (2) The presence of a ubiquitous layer-parallel igneous lamination of many of the mineral phases (throughout almost all of this 400 m of cumulate), the initial stage of formation of which is inferred, largely from CSD evidence, to have been related to primary magma chamber processes.

This process may be explained as follows: Slow rates of chemical diffusion may lead to the production of a chemical boundary layer adjacent to the crystal face that is depleted in the crystal's components and enriched in the incompatible components. As it is the chemical potential adjacent to the crystal face that controls the rates of growth of the different faces of the crystal, replacement of the depleted liquid by more enriched magma through, for example, magma stirring or movement, changes the chemical potential at the crystal face and hence the growth rate and crystal habit. Crystal faces with the fastest growth rates are most strongly affected by this process, as they are the most depleted in the compatible components. Therefore, minerals such as plagioclase will have long and intermediate axes accentuated relative to the short axis during this process.

Oscillatory nucleation and growth of layers as mentioned above is responsible for the mineral phase growing in a magmatic layer where the proportions of simultaneously nucleating and precipitating minerals are

varied at the solidification front through, e.g. convective overturn, input of new magma, loss of volatiles, and/or contamination (Boudreau and McBirney 1997). However, any model erected must also explain the lack of substantial (or consistent) compositional (An% and FeO_i) variation (e.g. ΔAn is always $\pm 7\%$) in rim-to-rim traverses of the plagioclase in Sample 18. If significant postcumulus processes were responsible for this lack of variation, even minor (<5%) variation might not be observed, i.e. the feldspars might be expected to have completely equilibrated. It seems more likely that, despite the magma chamber processes leading to changes in the proportions of nucleating and crystallizing mineral phases at the solidification front, the feldspars grew in a melt that did not change dramatically in composition. This has notable similarities to the adcumulus growth mechanism advocated by Wager and Brown (1968), where diffusion and convective fractionation through a mobile intercumulus liquid act to supply cumulus crystals with chemical components of a similar composition at the mushy crystal mush-liquid interface. The final interstitial fluid expelled from the crystal mush into the main body of melt is rich in incompatibles (i.e. highly evolved) and leaves behind cumulus crystals that exhibit little or no zoning.

It has also been noted however that several of the CSD curves have profiles that are somewhat more complex than a simple straight-line plot, i.e. 4, 15 and 23. It is interesting to note that these plots come from samples that exhibit the most pronounced and well-developed fabrics in the field. These three samples are also characterized by the lowest L/F ratios of the Druim Hain AMS dataset (Table 5.1), a characteristic shared by those complex CSDs described from Sithean Mor in Chapter 3. It therefore seems reasonable to suggest a similar mechanism of intensification of the planar fabric at a late-stage in the textural history of the cumulate pile as for the Sithean Mor cumulates.

Additionally, Samples 4, 15 and 23 contain very elongate (up to 1.5 cm long) plagioclase and pyroxene crystals that display notable evidence of crystal-plastic strain (cf. Nicolas 1992; McBirney and Nicolas 1997), including intra-crystal dislocation structures and mechanical twinning (e.g. Fig. 5.14). Some plagioclase crystals in Sample 23 even exhibit well-developed strain shadows. This, together with the combined evidence above, suggests that pure shear or compaction of the crystal pile were significant processes in causing intensification of the planar fabric at Druim Hain. However, as only three of six CSD samples show evidence for textural ripening, it must be deduced that it was a locally variable process restricted to certain parts of the cumulate pile. It should be noted also that aspect ratios for two of these three samples (S23 and S4) have amongst the largest calculated long axes (as measured by *CSDSlice*). Again this is suggestive that crystal shapes have been enhanced in a

particular orientation, accentuating or intensifying the existing planar foliation. It is not certain from the existing sample-set whether the apparent CSD trend for the pyroxene cumulate (Samples 4 and 15) to be texturally more ripened (i.e. slightly more accentuated 'humped-profiles' at small size fractions) relative to the plagioclase profiles is significant.

As with the Ardnamurchan cumulates, the implication of linking the AMS and CSD datasets for certain samples is that magnetite has undergone crystal ripening as well as plagioclase and pyroxene (in the plane of lamination) to give the significantly lower L/F ratios. Although convincing evidence of this cannot easily be observed at a thin-section scale for magnetite in any of the six combined AMS/CSD sample datasets, some samples (e.g. Sample 16; Fig. 5.9A and 5.15) show that intercumulus melt, now completely pseudomorphed by opaque minerals (most of which is deduced to be magnetite from the bulk susceptibility measurements) has caused significant damage to the preexisting pyroxene-plagioclase framework in the process. This has principally occurred through thorough resorption and corrosion of mineral grains (Fig. 5.15). This petrological observation is not unique in studies of British Palaeogene layered gabbros: Wells (1954a) refers to the 'corrosive relationship of the late-formed iron ore to feldspar' in describing the effects of a late-stage aggressive intercumulus liquid on the plagioclase feldspar framework in layered gabbros of the Centre 2 Hypersthene Gabbro of Ardnamurchan.

As the magnetic foliation in Sample 16 (and in all other AMS samples) consistently parallel the igneous lamination, it must be assumed that this resorption was restricted to within lamination planes. This effect is probably far more pronounced in some samples than in others, and as with the Ardnamurchan laminated gabbros (Chapter 3) can be correlated from the most ripened CSDs to the lowest L/F ratios. However, though the simple straight CSDs of many Druim Hain samples suggest this ripening process is often not important, even small degrees of ripening of minor quantities of magnetite (~1 vol%), could substantially affect the AMS fabric, given that this fabric is dominantly carried by magnetite. It is plausible therefore that this mechanism might be responsible for the inconsistent magnetic lineations observed throughout the complete sample set.

Finally, it should be highlighted that the evidence from either the AMS or CSD datasets alone to suggest that layering and initial igneous lamination development was not formed by primary 'magmatic sedimentation' is not strong. Primary AMS lineations subjected to the intense grain ripening such as observed in Sample 16 (described above) might easily have been completely obliterated. This would be expected to leave little evidence for the initial stages of fabric development, even within individual AMS block samples (leading to the within-site magnetic lineation discrepancies observed in Samples 2 and 13) and also within those samples containing small

amounts of magnetite, as discussed above. Therefore, the most important reason for attributing primary magmatic layer formation to *in situ* crystallization processes rather than to magmatic currents in this study is the marked lack of field evidence for the latter, and not the lack of a consistent magnetic lineation, as this feature may have been imposed at a postcumulus stage. In addition, as mentioned earlier, to invoke sedimentation for every well-laminated layer at Druim Hain is wholly unrealistic, as it requires a single density current be held to account for every individual layer formed.

It is also envisaged that a 400 m thick sequence of layers such as at Druim Hain would have acted as excellent deformation marker horizons, were there fluid dynamic processes or syn-magmatic deformation operating at layer boundaries such as has been inferred for the Ardnamurchan layered gabbros (Chapter 3). Indeed, the Druim Hain cumulates illustrate this in part by picking out the steepening inward of magmatic layer and lamination planes eastward, suggesting that some form of central subsidence may have occurred. However, this central subsidence must have affected relatively coherent layer planes capable of undergoing such rotation without disaggregating or deforming syn-magmatically.

5.7 Conclusion

Field observations suggest that early magmatic layering and igneous lamination of the Druim Hain Gabbros formed through *in situ* crystallization at the solidification front of a crystal mush crystallizing upward. A lack of evidence of primary flow structures that might be associated with 'magmatic sedimentation' at a crystal mush/magma interface indicates that such processes may have had a limited role in the development of the layering and igneous lamination. A combination of magnetic fabric data, textural (CSD) analysis and crystal compositional analysis provide evidence for postcumulus processes involving compaction and mobilization of a late-stage intercumulus melt, which led to locally intense ripening and maturing of textures in the crystal mush pile. This is believed to have had: a) the effect of intensifying the planar elements of the fabric, i.e. the igneous lamination and magnetic foliation, b) imposed crystal-plastic strain features on the textures of some samples, and c) possibly resulted in the ubiquitous inconsistently oriented magnetic lineations. Late-stage central subsidence, evidenced by the steepening inward (eastward) of the magmatic layering and igneous lamination, seems to have affected a relatively cohesive cumulate pile, i.e. one cooled and already largely solidified to too great an extent for syn-magmatic deformation to occur, thus markedly contrasting the situation in the Ardnamurchan Great Eucrite (Chapter 3) and the Rum Layered Suite (Chapter 4).

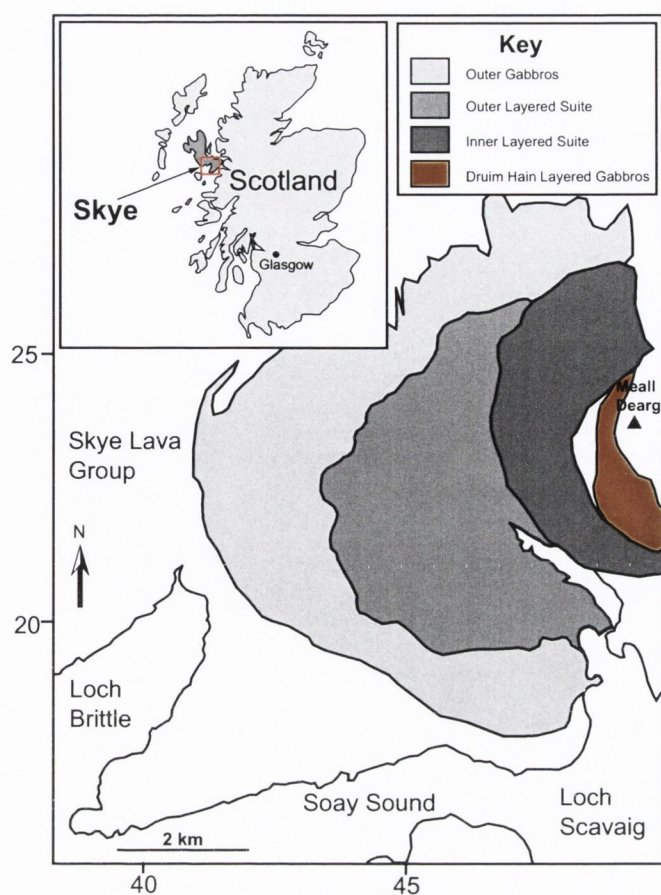


Figure 5.1. Location map showing the Isle of Skye and the position of the Cuillin Complex and the Drumm Hain layered gabbros.

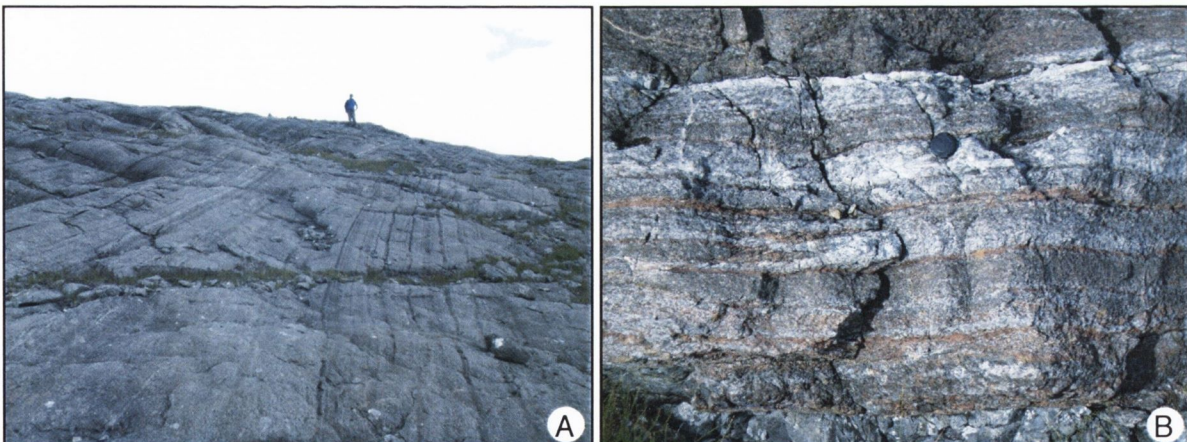


Figure 5.2. A and B: Small-scale rhythmic layering at Drumm Hain.

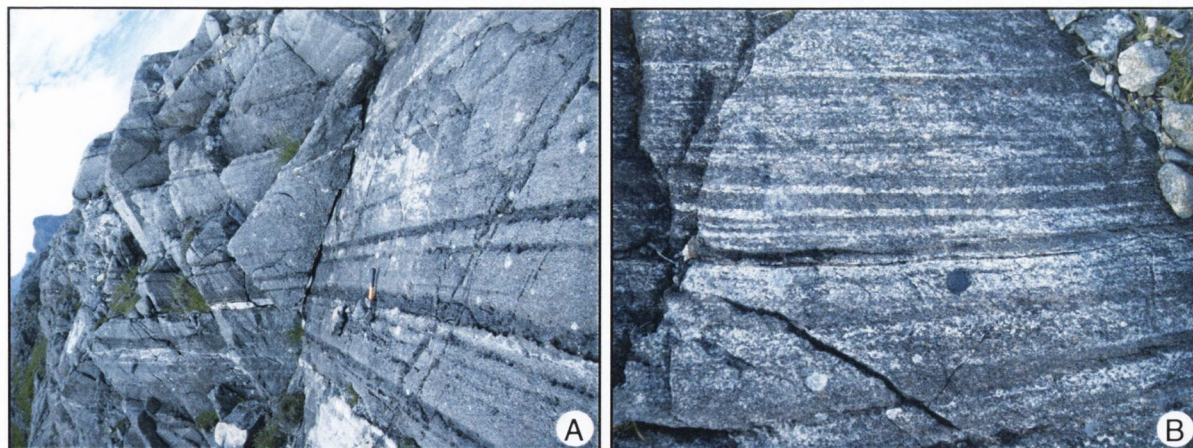


Figure 5.3. A and B: Plagioclase-magnetite rich sequences of rhythmic layers. In 3A, the dark coloured bands are composed of = 80% magnetite.

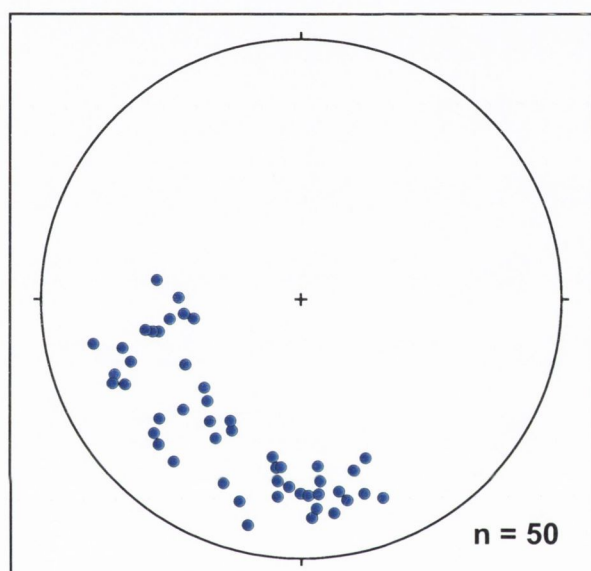


Figure 5.4. Equal-area stereoplot illustrating poles to magmatic layer planes at Druim Hain. The 90° strike-swing of layer planes is well shown.

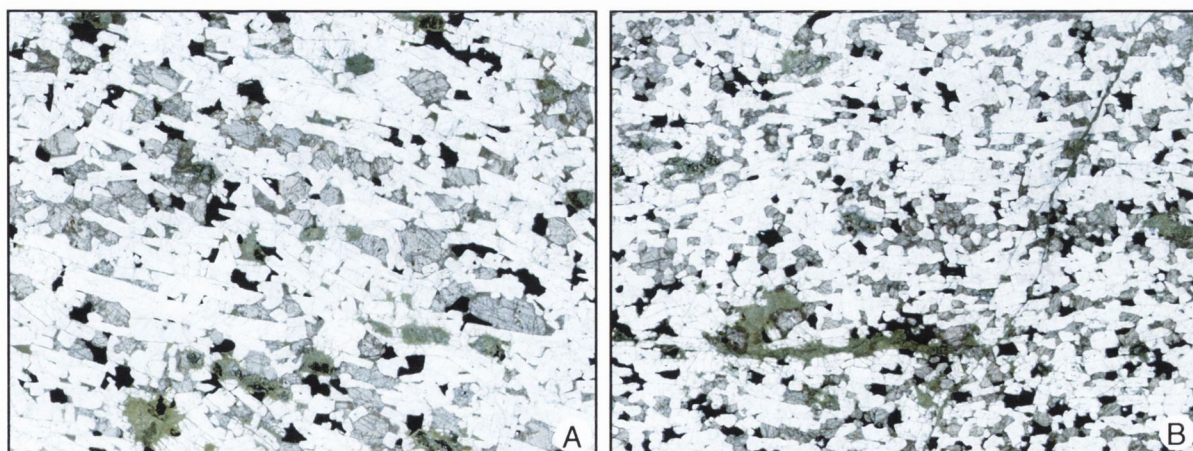


Figure 5.5. Plagioclase lamination in two Druim Hain cumulate samples (Samples 23 and 6). Note that the fabric illustrated in 5A is more intense than that in 5B, due to a combination of better aligned grains and larger crystal size. Both images are taken in plane-polarised light and the width of the field of view is 2 cm in each case.

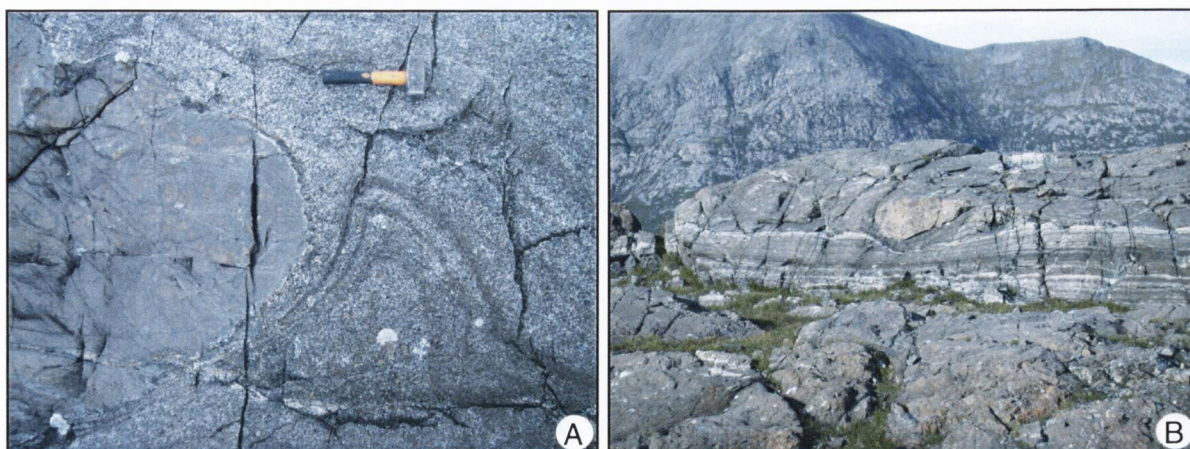


Figure 5.6. Two rare examples of dropstones deforming magmatic layers close to the eastern margin of the Druim Hain gabbros. A: Fine-grained mafic dropstone creates a syn-magmatic folded structure in olivine-rich layers. B: Block of basalt (2 m in length) depresses a sequence of magnetite and plagioclase rich cumulates.

Figure 5.7. See overleaf.

Figure 5.8. See overleaf.

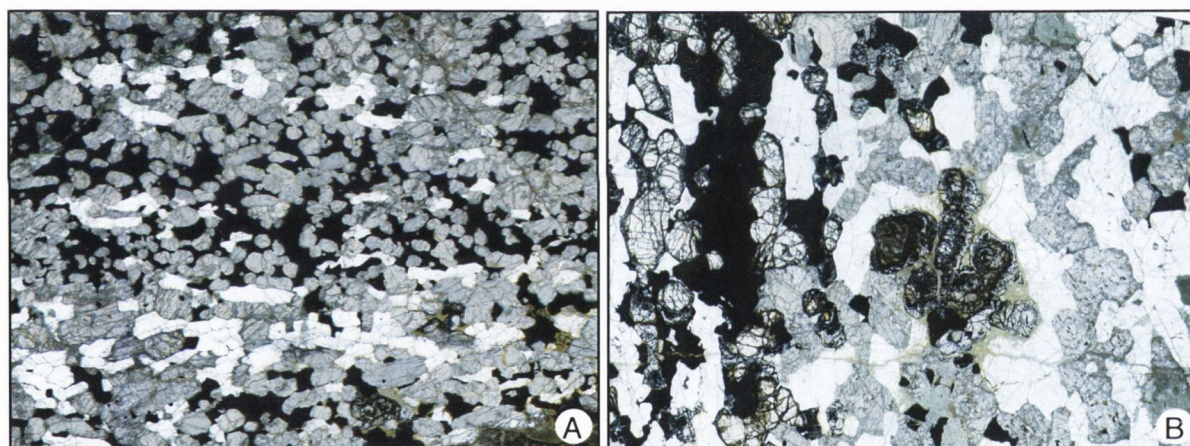


Figure 5.9. A: Magnetite in Sample 16 typically occurs as interstitial grains to pyroxene crystals. Note igneous lamination oriented approximately E-W across photomicrograph and plagioclase-rich magmatic layer in the same orientation. B: Layering and igneous lamination, including a magnetite-rich magmatic layer, trend N-S across the photomicrograph (note that this image is not of Sample 16, nor any other sample analysed for AMS or CSD). Both images are taken in plane-polarised light and the width of the field of view is 1 cm in each case.

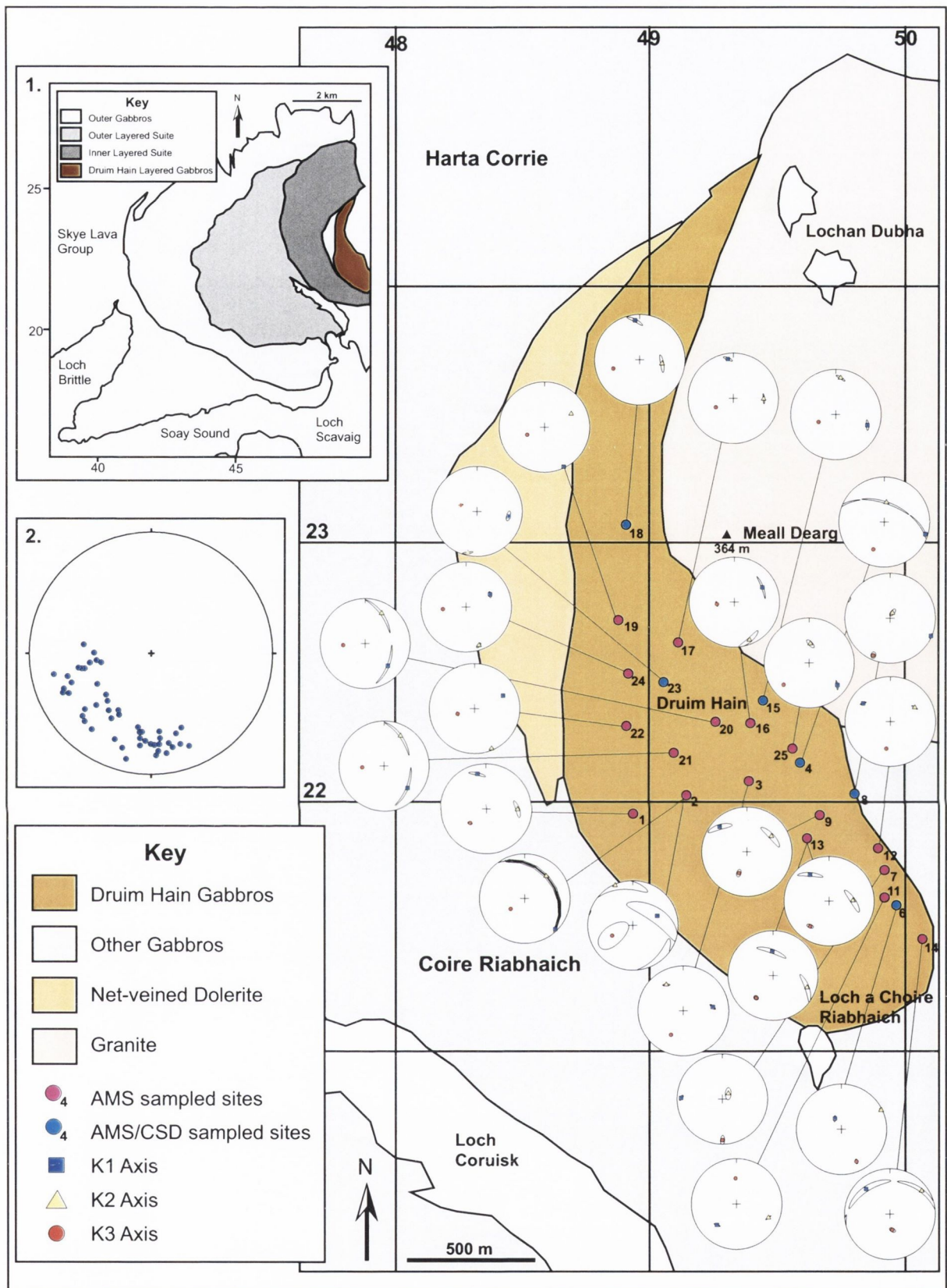


Figure 5.7. Summary diagram of AMS data showing equal-area stereoplots plotting K1, K2 and K3 axes with their respective confidence ellipses. Inset. 1: Regional locational map of Skye for reference. 2: Magmatic layer field data for reference and comparison with the AMS data.

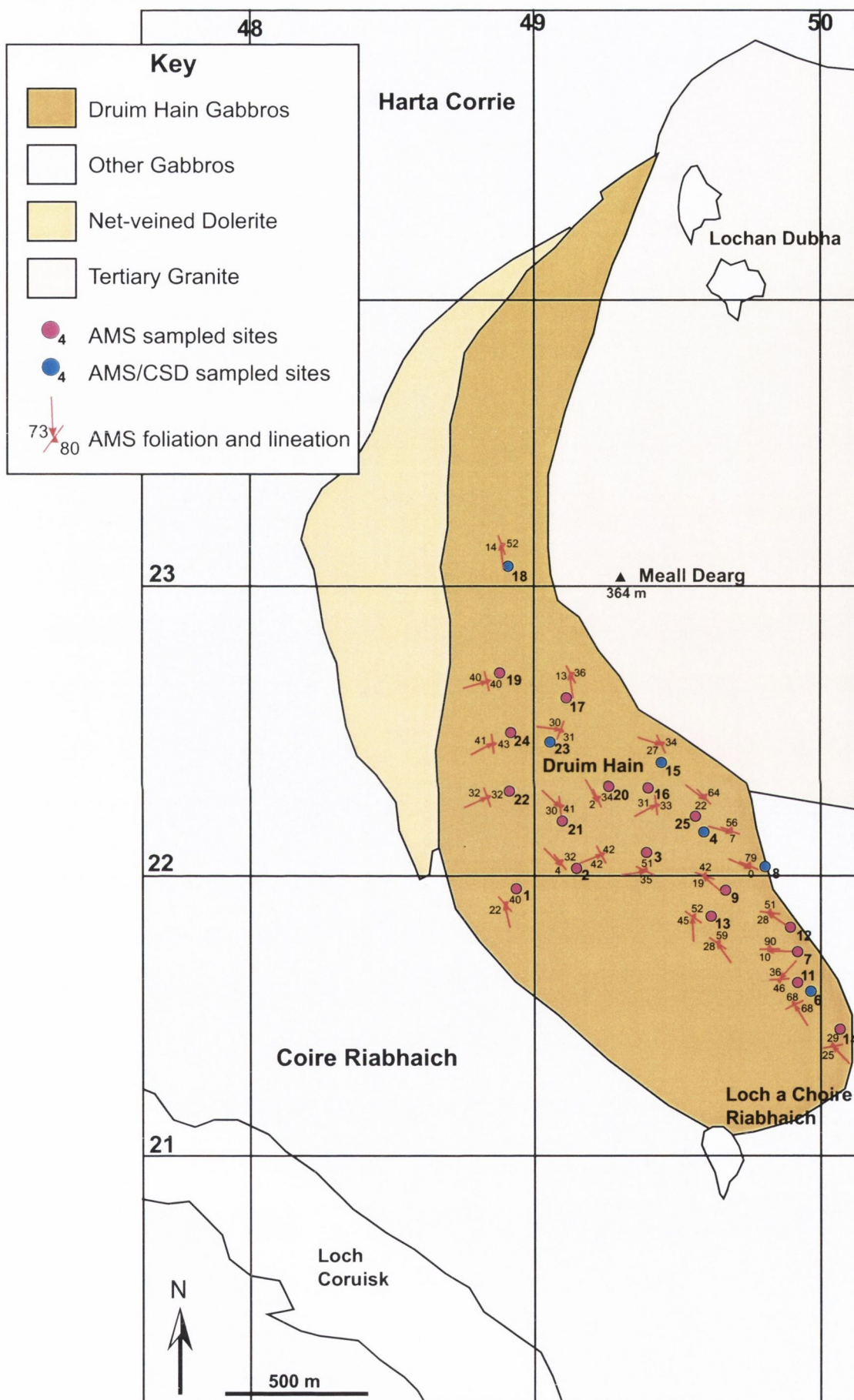


Figure 5.8. Schematic structural map of the Druim Hain gabbros illustrating the orientations of the AMS foliations and lineations.

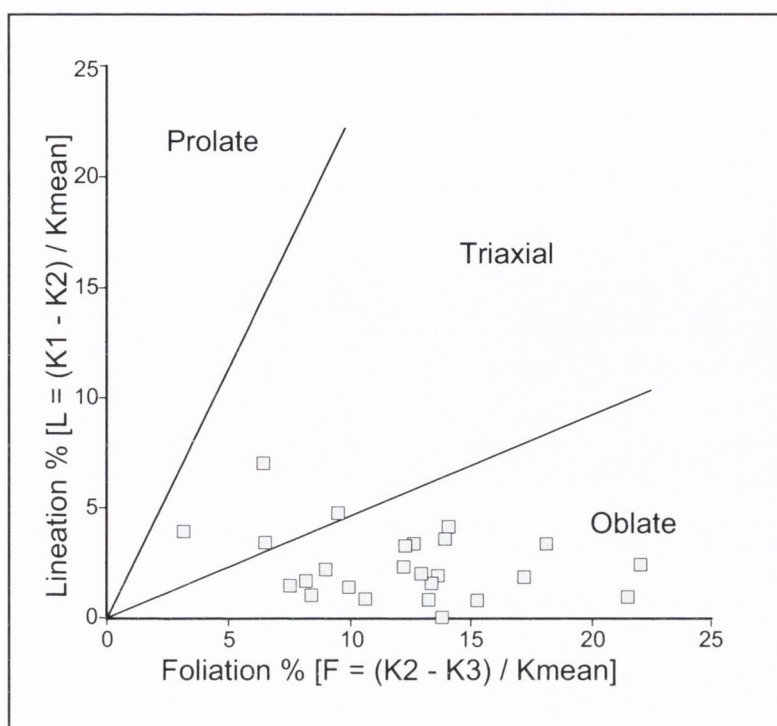
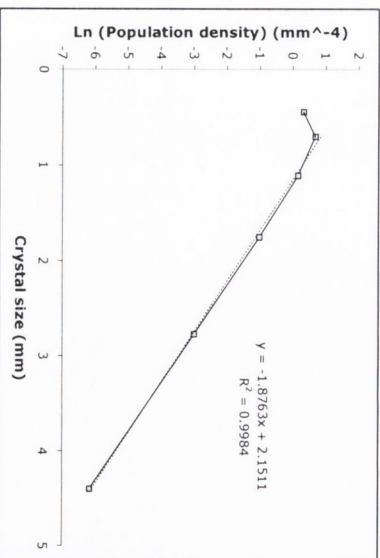
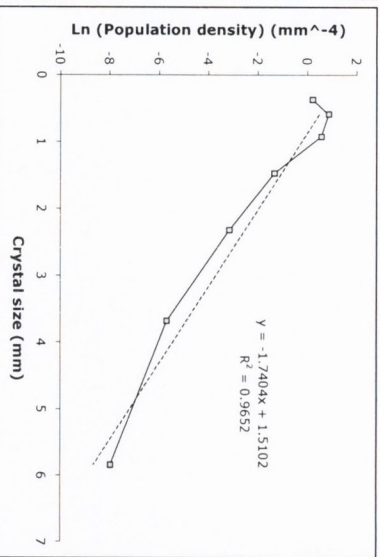


Figure 5.10. Subdivision of the Druim Hain magnetic susceptibility ellipsoids on the basis of an L/F plot into oblate, triaxial and prolate fabric shapes.

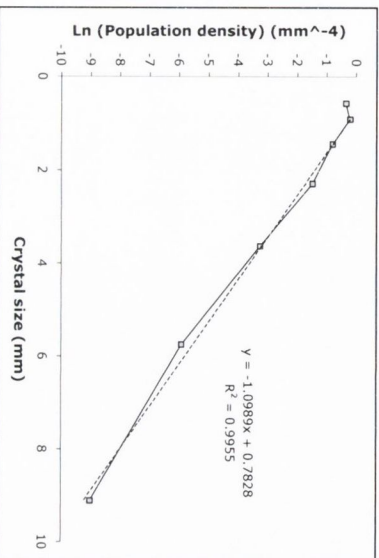
S18AP.



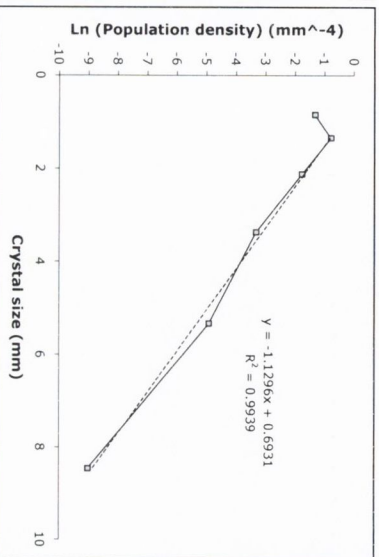
S18APY.



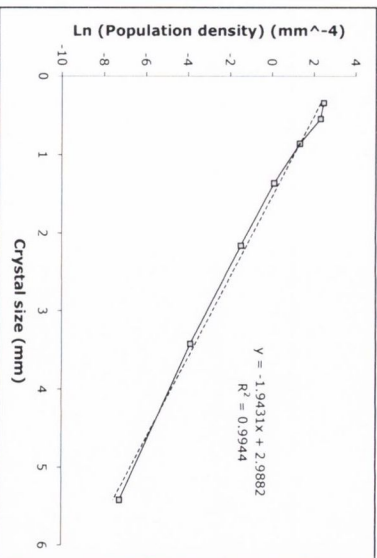
S18BP.



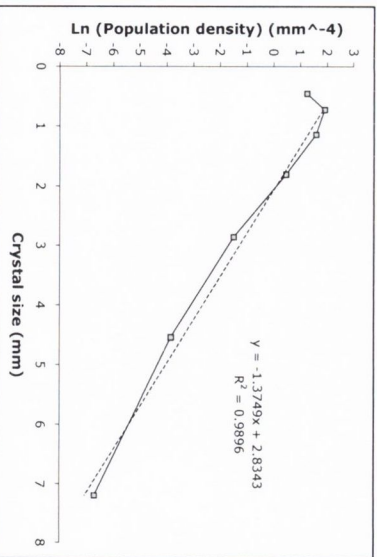
S18BPY.



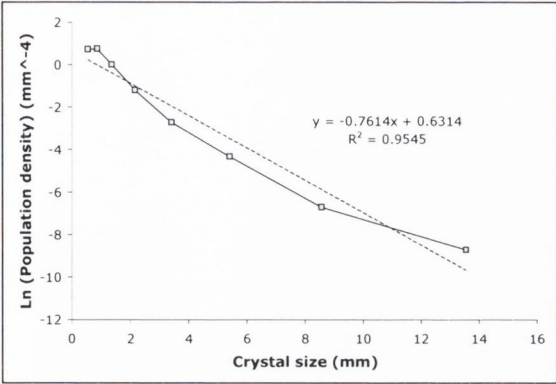
S6.



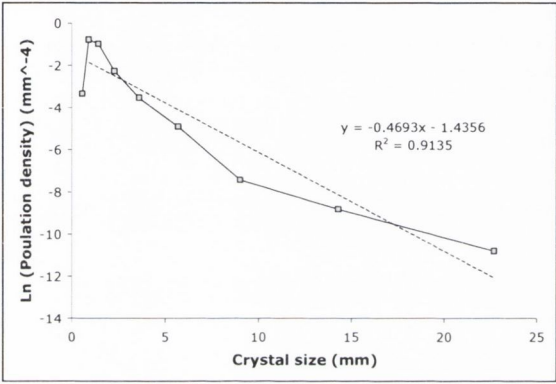
S8.



S23.



S4.



S15.

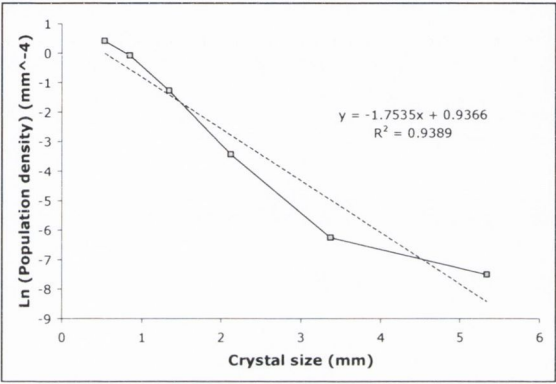
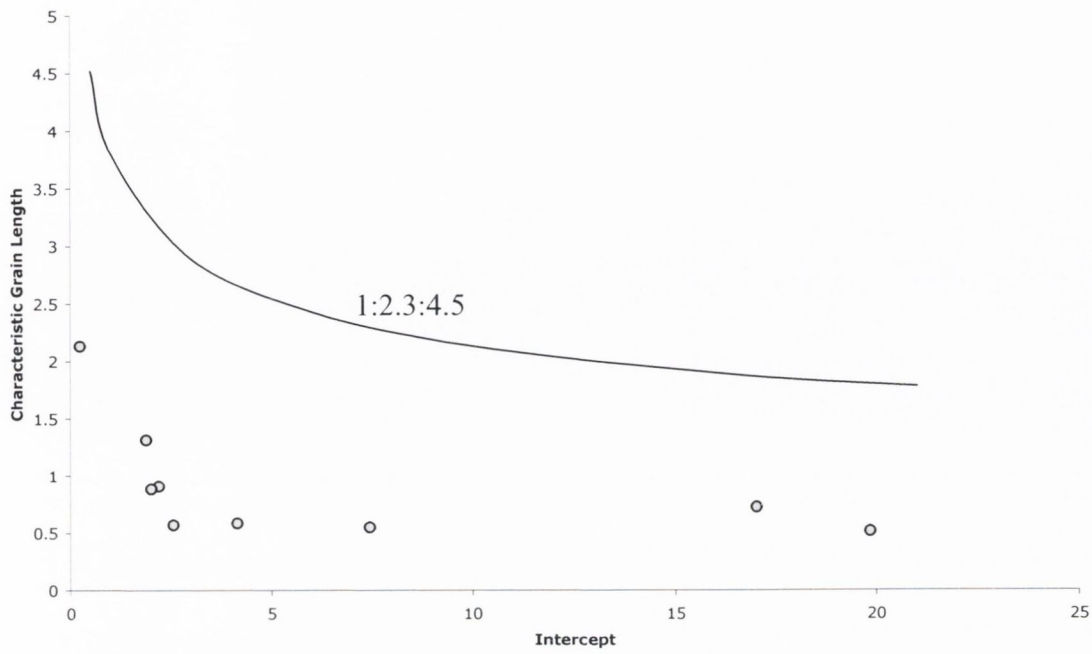


Figure 5.11. Labelled CSD plots for Samples 18, 6, 8, 23, 4 and 15 (see text for description and discussion).

A.



B.

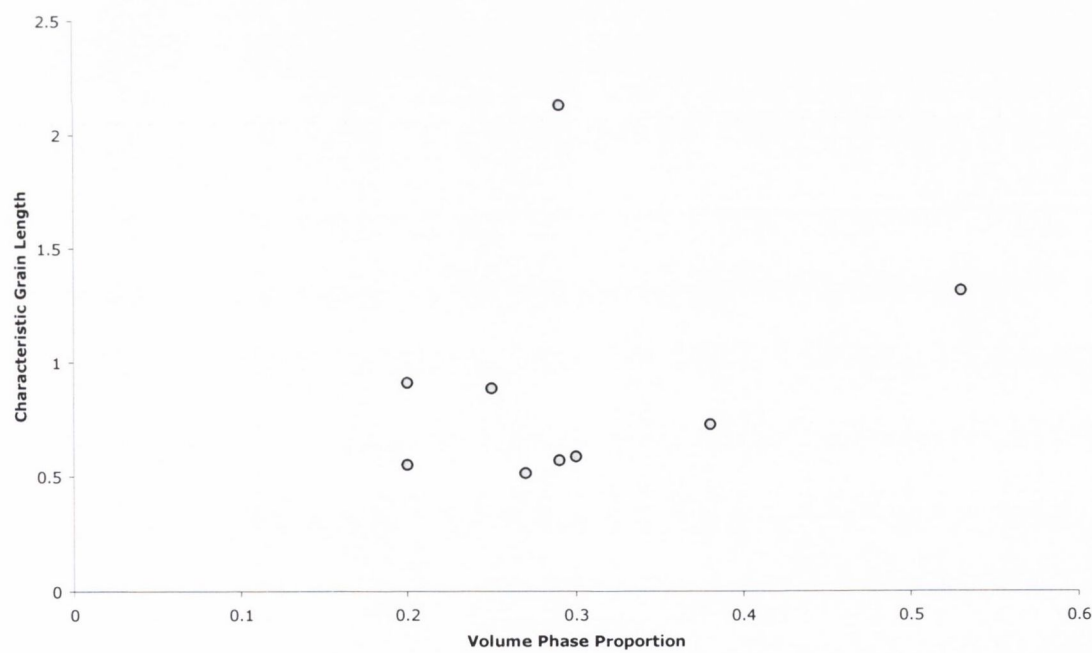
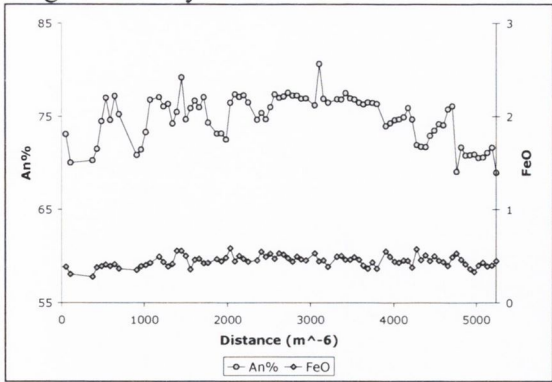
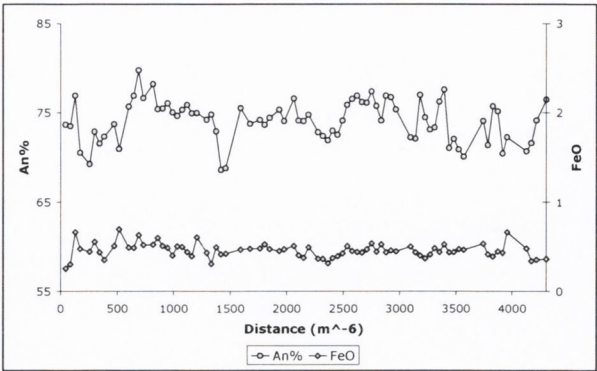


Figure 5.12. Closure plots for CSD data. A: Characteristic length vs. intercepts for the laminated gabbros CSD data. The curve for 100% crystal volume is labeled with the aspect ratio used to calculate it, see text for discussion. B: Subdivision of the CSD data on the basis of a characteristic length vs. volume phase proportion plot.

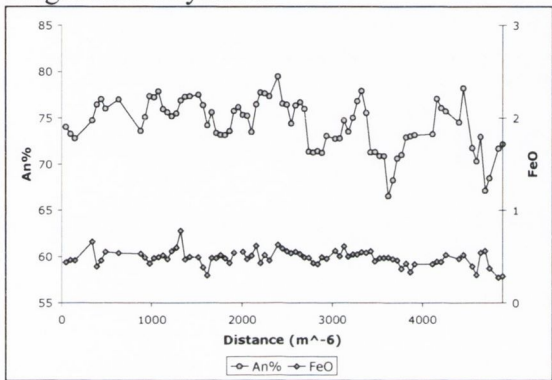
Plagioclase Crystal 1.



Plagioclase Crystal 2.



Plagioclase Crystal 3.



Plagioclase Crystal 4.

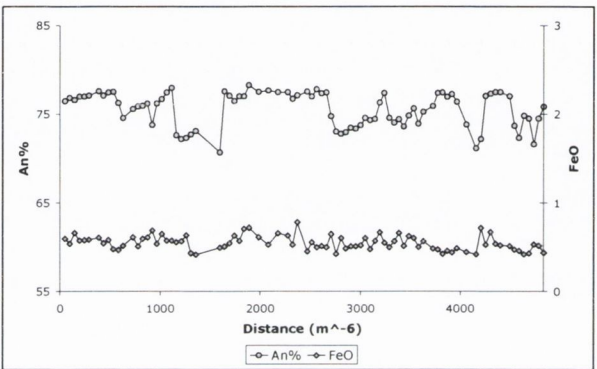


Figure 5.13. A: Mineral chemical data for four plagioclase crystals from Sample 18 of the Druim Hain layered gabbros. Rim-to-rim traverses along the length of each crystal for An mol% and FeO wt% vs. distance are illustrated for each.

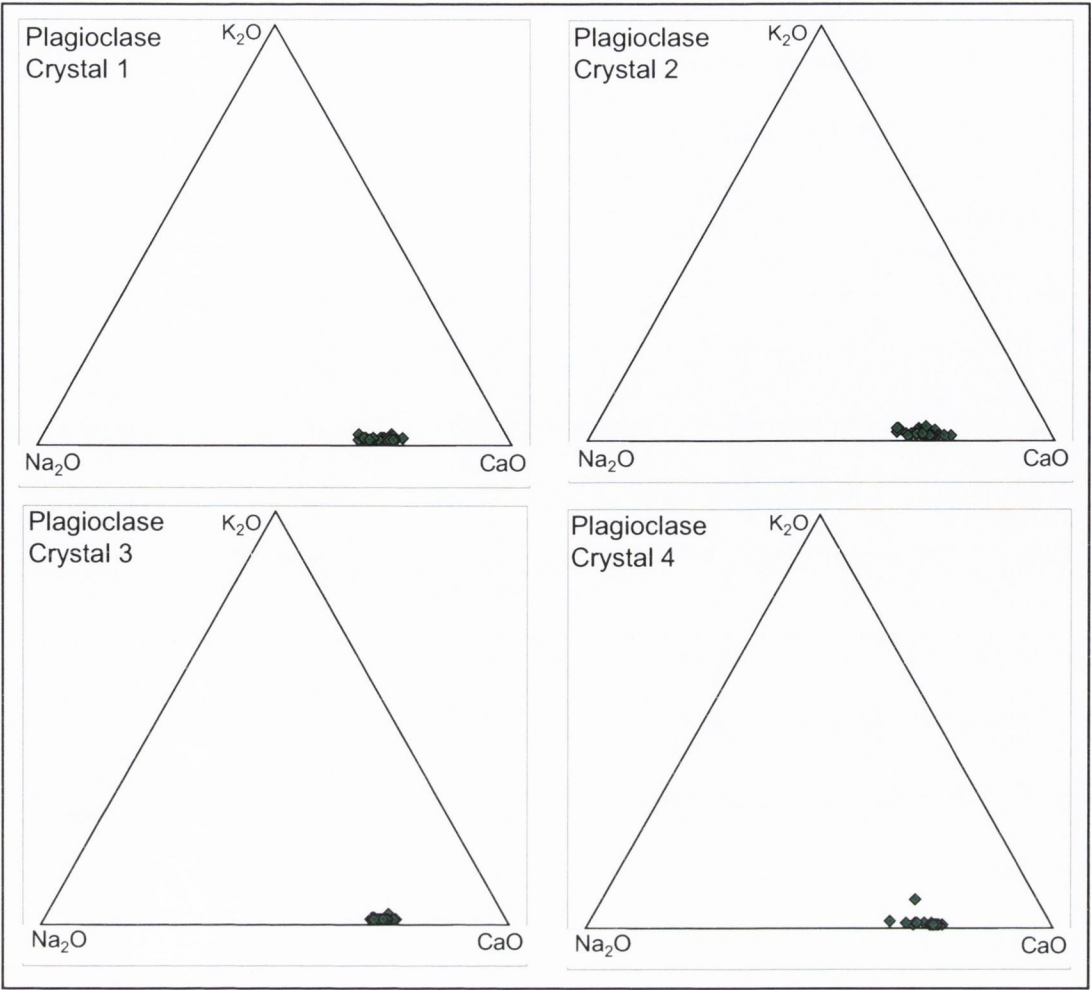


Figure 5.13. B: Ternary ($K_2O/CaO/Na_2O$) plots for all Sample 18 mineral-chemical data.

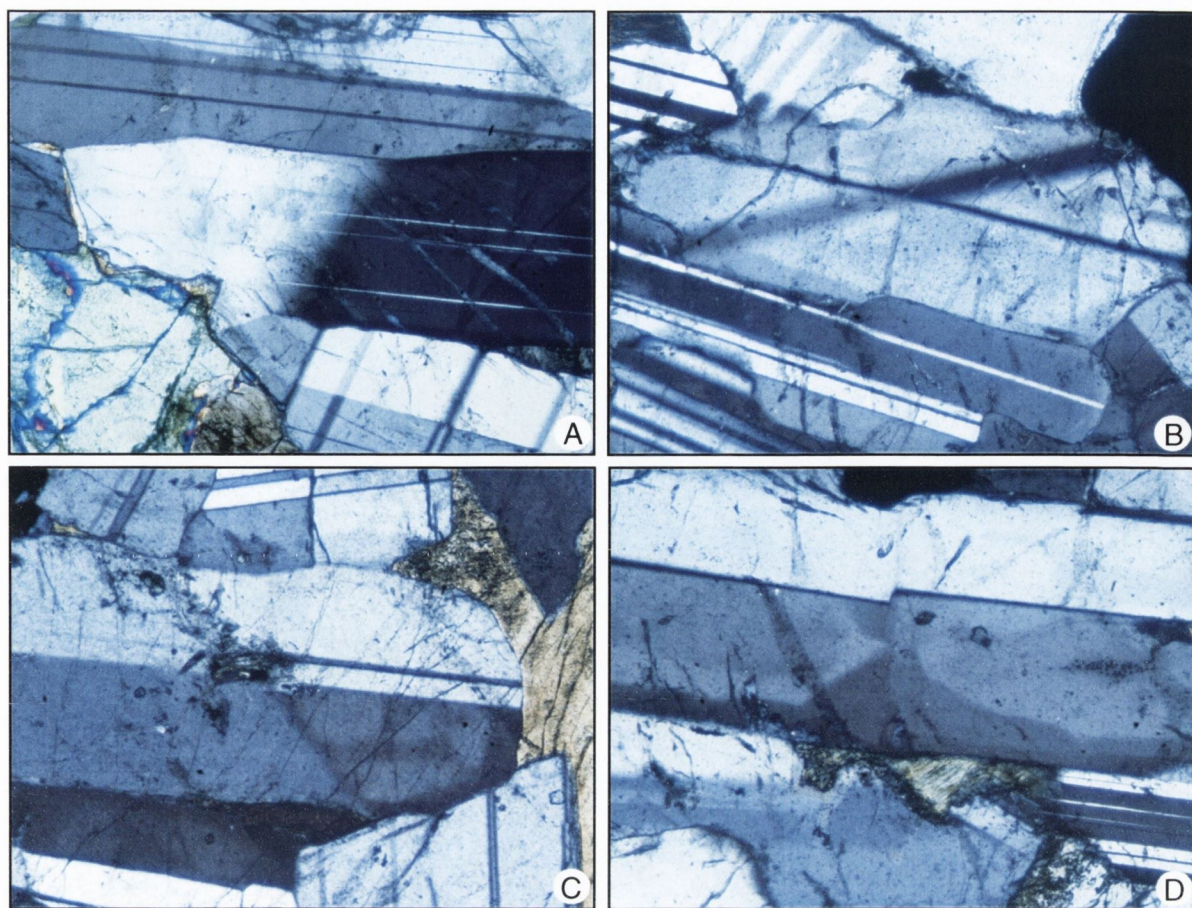


Figure 5.14. A and B: Plagioclase crystals from Sample 23 illustrating mechanical twinning imposed on previous multiple twins. C: Broken/bent plagioclase crystal from Sample 4. D: Intra-crystal dislocation structures highlighted by 'offset multiple twins' from Sample 23. All images are taken in crossed polars and the width of the field of view in each is 3 mm.

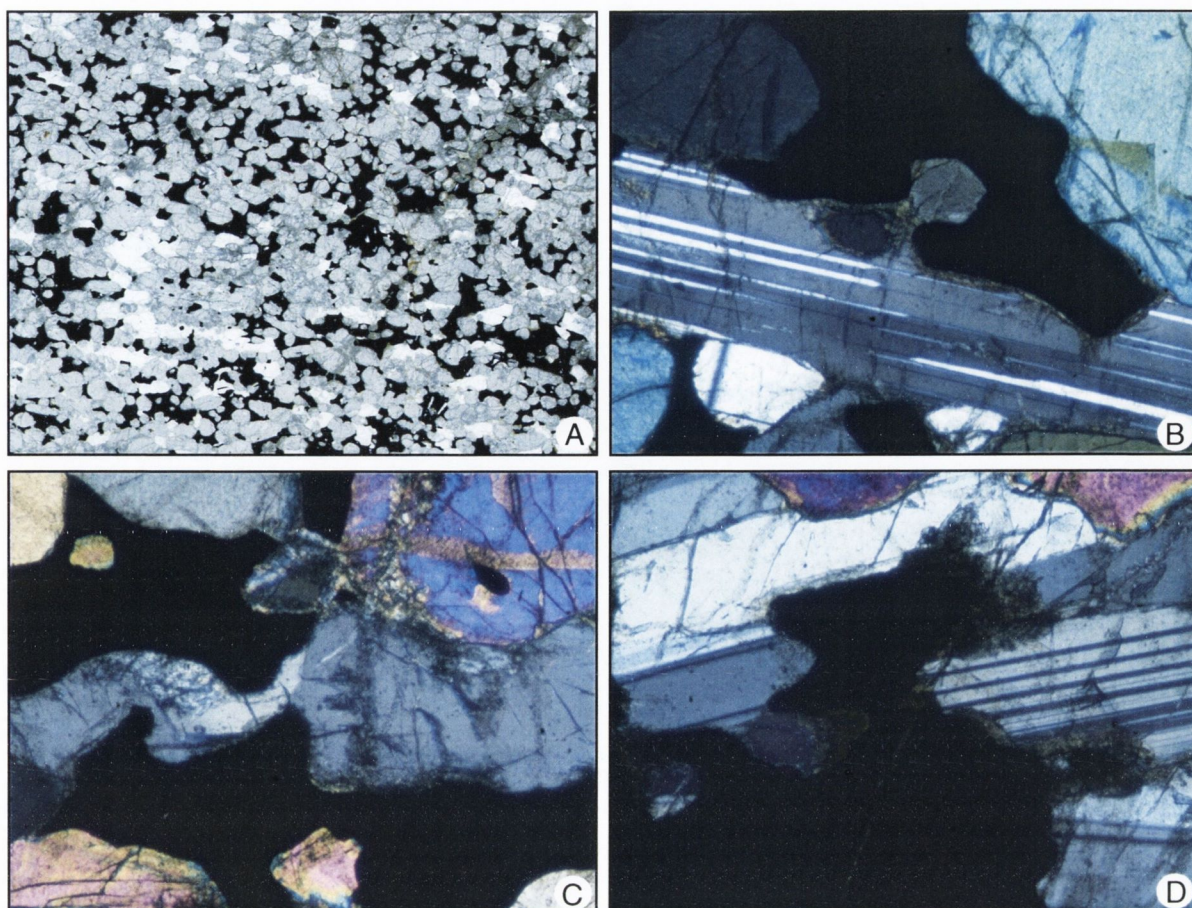


Figure 5.15. A: Similar image of Sample 16 as in Figure 9A illustrating nature of magnetite occurrence in the rock. Image is taken in plane-polarised light and width of field of view is 1.2 cm. B-D: Close-ups of Fig. 15A show resorption of pyroxene and particularly plagioclase grains by a late melt. This late melt is now completely pseudomorphed by opaque minerals. From the bulk susceptibility of this sample, it is likely that most of these opaque minerals by volume are magnetite. Images (B-D) are taken in crossed polars and the width of the field of view in each is 3 mm.

Table 5.1. AMS data for the Druim Hain layered gabbros

Sample	Kmean	K1	Dec	Inc	K2	Dec	Inc	K3	Dec	Inc	L	F	H	Mu
S1	6014.61	1.036	346.8	21.6	1.024	90.7	31.3	0.94	228.1	50.5	1.23	8.4	9.62	8.3
S2A	51782.64	1.047	316.3	-4.3	1.046	43.7	31.5	0.907	233.3	58.2	0.13	13.92	14.05	0.5
S2B	65077.54	1.036	248.6	-41.6	1.019	336.3	2.6	0.945	243.4	48.3	1.64	7.48	9.12	12.3
S3	137971.45	1.072	82.2	35	1.034	326.9	31.4	0.894	27	-39.2	3.8	13.98	17.79	15.2
S4	25285.18	1.08	106.5	7.2	1.068	6.3	54.6	0.852	21.4	-34.5	1.13	21.64	22.77	3
S6	148278.23	1.064	148.4	-67.4	1.015	63.9	2.3	0.92	334.8	-22.4	4.93	9.48	14.41	27.5
S7	84003.47	1.045	91.7	-10.2	1.009	47.3	75.9	0.945	360	-9.7	3.59	6.42	10.02	29.2
S8	146023.69	1.037	114.1	0.4	0.996	22.1	78.7	0.967	24.1	-11.3	4.06	2.96	7.02	53.8
S9	6590.49	1.065	312.5	19.2	1.03	57.2	36.1	0.904	200.2	47.6	3.51	12.6	16.11	15.6
S11	166042.07	1.059	43.1	-36.4	1.039	113.5	24.4	0.902	357.8	43.7	2.02	13.64	15.66	8.4
S12	73891.7	1.064	124.3	-28.4	1.03	59.6	38.2	0.906	8.7	-38.7	3.44	12.41	15.85	15.5
S13A	44882.79	1.084	177.5	-44.9	1.049	109.8	20.9	0.867	37	-37.8	3.52	18.21	21.73	10.9
S13B	99780.05	1.058	145.1	-28.1	1.036	88.8	46.1	0.905	36.7	-30.6	2.18	13.12	15.3	9.4
S14	18090.88	1.051	316.9	24.7	1.041	53.6	14.3	0.908	170.8	60.9	0.99	13.33	14.32	4.2
S15	51133.93	1.071	288.3	-27	1.051	7.8	19.6	0.878	246.4	55.6	2.01	17.26	19.27	6.6
S16	104609.58	1.057	241.7	-30.6	1.039	337.8	-10.3	0.904	264.3	57.4	1.87	13.5	15.38	7.9
S17	12185.79	1.044	352.2	12.8	1.028	90.7	33.1	0.928	244	53.9	1.56	9.98	11.54	8.9
S18	64093.18	1.039	173.4	-13.9	1.021	99.7	48.5	0.94	72.2	-38.1	1.85	8.11	9.96	12.9
S19	59703.02	1.042	254.5	-40.2	1.032	345.9	-1.7	0.926	257.9	49.8	1.01	10.61	11.62	5.4
S20	127467.09	1.069	334.6	-1.7	0.997	63.4	34.4	0.934	247.1	55.6	7.13	6.36	13.49	48.3
S21	72599.21	1.057	314	-29.5	1.048	28.7	25	0.895	265.6	49.5	0.94	15.29	16.23	3.5
S22	51038.64	1.046	245.5	-31.7	1.022	337.4	-3.2	0.932	252.6	58.1	2.33	9.01	11.34	14.5
S23	32285.37	1.091	278.4	-30.3	1.065	12	-6.2	0.844	292.3	58.9	2.59	22.17	24.76	6.7
S24	76536.21	1.057	242.1	-40.5	1.033	342.1	-11.4	0.91	264.7	47.2	2.48	12.28	14.76	11.4
S25	94029.02	1.076	128.4	21.8	1.033	3.9	54.7	0.891	49.7	-26.3	4.29	14.17	18.46	16.8

Table 5.2. CSD data for samples from the Druim Hain layered gabbros

Sample	Vol. Phase	Aspect Ratio	Slope	Ln(n0)	n0	t1 (Years)	J1 (mm ⁻³ s ⁻¹)	No. of crystals
S8	0.38	1:1.4:4.5	-1.3749	2.8343	17.01848	230.6	1.70185E-09	642
S15	0.29	1:1.15:1.6	-1.7535	0.9366	2.551292	180.8	2.55129E-10	270
S23	0.53	1:2.1;5	-0.7614	0.6314	1.880241	416.5	1.88024E-10	1028
S4	0.29	1:2.4;6	-0.4693	-1.4356	0.237973	675.7	2.37973E-11	278
S18A P	0.2	1:3.2:5.5	-1.8763	2.1511	8.594307	174.9	8.59431E-10	628
S18A PY	0.3	1:1.3:2.1	-1.7404	1.5102	4.527636	186.2	4.52764E-10	688
S18BP	0.2	1:3.2;7	-1.0989	0.7828	2.187589	288.6	2.18759E-10	449
S18B PY	0.25	1:1.8:4.5	-1.1296	0.6931	1.999906	280.7	1.99991E-10	305
S6	0.27	1:1.6:3.6	-1.9431	2.9882	19.84992	163.2	1.98499E-09	1191

CHAPTER 6. THE CARLINGFORD LATER GABBROS

6.1 Introduction

The Carlingford Igneous Complex is the oldest of three closely associated Palaeogene intrusive centres in NE Ireland dated (U-Pb zircon age) at 61.4 ± 0.8 Ma; the others are the Slieve Gullion Complex and the Mourne Mountains Complex (Gamble *et al.* 1999; Cooper and Johnston 2004 and references therein); Fig. 6.1. An early series of basalt lavas exposed on the southern margin of the complex is believed to mark the earliest Palaeogene activity in the area. Two separate phases of gabbro are believed to have intruded into these basalts, the earlier represented by several isolated outcrops in the SW of the complex around Trumpet Hill (Fig. 6.2). The later suite of gabbros (the Carlingford 'Later Gabbros') form the prominent ring of hills around the Carlingford peninsula including the main Slieve Foye Ridge in the NE of the complex, Barnavave (SE), Round Mountain (SW) and Carnavaddy in the north. These gabbros are the focus of the study outlined in this chapter. Breccias that have been interpreted as vent agglomerate (Richey 1932; Le Bas 1960) are associated with a stage of explosive volcanic activity. These also contain xenoliths of an early granophyre, suggesting a prior phase of felsic magmatism. An extensive body of granophyre that outcrops throughout the centre of the complex is interpreted as the final major intrusive episode in the complex and is believed to have the geometry of a ring-dyke with a laccolithic top (Richey 1932; Le Bas 1967). Late-stage basic magmatism is represented by the emplacement of cone-sheet and linear dyke swarms.

The Carlingford Later Gabbros (Fig. 6.2) have been previously interpreted as a ring-dyke (Richey 1932) or a small lopolithic sheet (Le Bas 1960). Though Richey described a critical vertical contact between gabbro and Silurian sediments just to the NW of Two Mile River, Le Bas' (1960) mapping of the Slieve Foye-Ballintreskin ridge showed that this supposed contact actually cut across the large-scale layers described above and is thus more likely to be a post-gabbro emplacement fault. Le Bas suggested that the Later Gabbros had the form of a horizontal layered sheet-like structure instead, describing several basal contacts between gabbro and country rock sediment that dip sub-horizontally to 20° inward towards the interior of the complex at Spellickanee (Fig. 6.2).

The Later Gabbros exposed on the Slieve Foye-Ballintreskin ridge exhibit the only evidence of well-preserved primary magmatic layering in the Carlingford complex. This occurs at two scales of outcrop as follows:

- (1) The Slieve Foye-Ballintreskin ridge is constructed of four large-scale conformable cryptic gabbroic layers, each varying from 60 to 150 m in thickness. Each layer is principally defined by the modal decrease upward of olivine and accompanying increase in plagioclase. Le Bas (1960) showed that

the Fe content of the olivine increased dramatically toward the upper part of the lowest unit (Layer 1), the top 100 m of which is almost completely devoid of olivine. The other layers show similar trends, if not so well pronounced. Contacts between these units are seldom observed but Le Bas (1960) suggested that they were undulose and dipped gently to moderately inward at 0-50° toward the centre of the complex. Le Bas also suggested that as all of the four layers comprise similar gabbro types, it is likely that they were fed from the same magma reservoir and each represents a sharply defined pulse or intrusion event.

- (2) Within the large-scale units described above, magmatic layering of olivine, plagioclase or pyroxene is also present at a small-scale (up to 7 m lateral extent). Le Bas (1960) noted that where present, these were oriented in a similar manner to the large-scale units. Le Bas (1960) also described saucer-shaped or trough-shaped layers and asymmetrically folded layers from the Ballintreskin area (Figs. 6.2 and 6.3). This he attributed to slumping of a crystal mush, and/or the disturbance of a crystal mush by gravity driven density currents. Le Bas measured small-scale magmatic layer plane dips and recorded a dominant orientation NNE-SSW strike and dips inward toward Spellickane of 20-50°. Additionally, Le Bas attempted to measure 'direction of movement' from the magmatic slump structures and found that the prevalent orientation was down-dip on layer planes, again towards Spellickane at the centre of the complex. Finally, Le Bas noted that small-scale layering is best preserved on the northern side of the Slieve Foye-Ballintreskin ridge, in Layers 2 and 3 around the Ballintreskin area. The southern side of this ridge, at the summit of Slieve Foye, also exhibits magmatic layering.

6.2 Field observations

The primary goal of fieldwork carried out in the Carlingford Later Gabbros in this study was, in addition to assembling a detailed AMS sample set, to re-assess the degree to which the intrusion is layered and, if possible, to gain a further measure of control on its outer and inner contacts. This study does not therefore attempt to remap the internal petrological variation of the gabbros in any great detail, and for the most part accepts the mapping carried out by Le Bas (1960). Though some of the field observations made in this study (described below) have also been made by Le Bas [1960; e.g. (2) below], they are emphasized again here so that the Carlingford Later Gabbros may be considered in the context of other layered mafic intrusions described in

earlier chapters. Other field observations described here have not been reported in previous work and the importance of these is also later discussed with reference to the emplacement and post emplacement history of the Later Gabbros.

- (1) Very subtle magmatic layering, mostly involving changes in the modal proportions of plagioclase and pyroxene, is observed in several outcrops at the Round Mountain Later Gabbro (e.g. at GR 11239 10289; Fig. 6.2). These layers typically strike N-S and dip E or strike NNW-SSE and dip NNE at between 20 and 45°.
- (2) As noted by Le Bas (1960), small-scale (rhythmic) magmatic layering is best preserved on the northern portion of the Slieve Foye-Ballinteskine ridge, around Ballinteskine (Fig. 6.3A). Layers are typically enriched in olivine and clinopyroxene with interstitial pyroxene, though no monomineralic layers are observed (Figs. 6.3B and 6.3C). These rocks therefore exhibit orthocumulate textures [*sensu* Wager and Brown (1968): loosely defined as a rock in which a late-crystallising phase pseudomorphs the pore spaces between earlier, framework-forming (cumulus) phases]. Folding and slumping of layers is sporadically observed (Fig. 6.3D) and layers often have a 'trough-like' form (Figs. 6.3E and 6.3F). At outcrops on Ballinteskine (around GR 14116 14485) where layer planes are sufficiently distinguishable for measurement to be carried out, orientations of 104 11SW are typical. Unfortunately, extensive weathering and lichen cover on outcrop surfaces often make it difficult to carry out detailed petrological observations or measurements on layer orientations. This includes re-checking the 'flow orientations' of Le Bas (1960) mentioned above.
- (3) A contact between the Carlingford granophyre and the Later Gabbros is observed at Barnavave (GR 17758 10180). At this locality, the gabbro clearly overlies the Carlingford granophyre and the contact between both is oriented 058 20NW (Fig. 6.4A and 6.4B). Towards the contact, the gabbro appears to become finer-grained in the manner of a chilled margin.
- (4) Several outcrops described as vent agglomerate have been mapped in the Carlingford Complex. These include a zone along the SW margin of the Slieve Foye-Ballinteskine ridge and several in the centre of the complex, around Spellickanee. The small zone along SW margin of the Slieve Foye-Ballinteskine ridge, together with another unmapped zone along the inner margin of the Barnavave gabbro (immediately west of AMS sites 2 and 4 of this study) comprise relatively coarse-grained

angular gabbro blocks extensively net-veined with microgranite (Figs. 6.5A and 6.5B). No contact relations are evident here with the Later Gabbros or the Silurian sediments.

- (5) A contact zone along the NE of the Slieve Foye-Ballintreskin ridge (e.g. at GR 16849 13010) exhibits extensive melting and migmatization of Silurian country rock. Figure 6.6A and 6.6B exhibit the sedimentary country rocks being segregated into felsic leucosome and darker coloured 'restitite' (sometimes folded) mesosomes. Here, the contact of the Later Gabbros with Silurian sediments can be narrowed down to within 5 m. By examination of the manner in which this contact traverses topography, it is estimated that it dips inward (SW) shallowly ($\sim 25^\circ$) toward the centre of the pluton.

6.3 Anisotropy of Magnetic Susceptibility (AMS) data

6.3.1 Sampling methodology

Block sampling for AMS analysis of the Carlingford Later Gabbros was carried out as follows (Fig. 6.2). The Slieve Foye-Ballintreskin portion of the intrusion was sampled at 50–200 m intervals along four traverses (5–7 sampled stations each) approximately perpendicular to the outer margin of the body as mapped by Le Bas (1960). From north to south, these are the Ballintreskin, Split Rock, Eagles Rock and Slieve Foye traverses respectively. Samples for AMS analysis were also collected from other parts of the Later Gabbros as follows: five from Barnavave, five from the Round Mountain and five from Carnavaddy hill. Three sites (15, 23 and 24) were double-sampled for within-site variation. In all cases, nine to sixteen sub-samples were then drill-cored from each block, and site mean tensor data were calculated from the measurements as outlined in previous Chapters (3 and 5) and by Owens (2000).

6.3.2 AMS results

Magnetic fabric data for the Carlingford Later Gabbros are summarised in Table 6.1. The data reveals a wide range of bulk susceptibilities (K_{mean}) from 0.4×10^{-3} to 101.9×10^{-3} SI in the Later Gabbro intrusions, indicating again the dominance of magnetite (up to ~ 3 vol%; see Balsley and Buddington 1958) in controlling the susceptibility ($< 10^{-3}$ SI for just 5 of 38 samples measured). However, in order to verify the dominance of magnetite, measurements of the temperature dependence of susceptibility of two Later Gabbro samples (Samples 34 and 38) from the Slieve Foye traverse have been carried out using an AGICO CS-3 furnace. The data give

Curie temperatures of 575–580 °C (Fig. 6.7) for each sample supporting the conclusion that magnetite controls the AMS. Le Bas (1960) has given a petrological description of the occurrence of magnetite in the Later Gabbros and notes that magnetite grains are present in two general modes of occurrence. The first is as small grains associated with alteration of olivine, typically around the rims of olivine crystals. Le Bas (1960) suggested that these magnetite grains crystallized in the later and oxidizing stages of the magma mush. The second type of magnetite occurrence is usually distinct from the first, where it can be found as interstitial crystals associated with ilmenite.

The AMS results for the Later Gabbros are summarized in Figures 6.8 and 6.9. The L/F plot (Fig. 6.8) shows that the susceptibility ellipsoids for the Later Gabbros range in shape from highly oblate to prolate. There is little obvious consistency within individual sections of the Later Gabbros with respect to ellipsoid shape, apart from within the Round Mountain section, which shows several very highly oblate fabrics and the Ballintreskin area, the samples from which all exhibit triaxial magnetic fabrics. In addition to this, AMS fabric strengths (**H**%) are quite weak,

Magnetic fabric orientations are also inconsistent over the scale of the intrusion and often within individual sections of the intrusion as well (Figs. 6.8 and 6.9). For example, the Round Mountain, Carnavaddy, Split Rock and Eagles Rock sampled sections of the intrusion have a high degree of inconsistency in fabric orientation within the set of five AMS samples from each. Thus they may range from being oblate through triaxial to prolate with no consistent orientation of the AMS fabric for any shape of susceptibility ellipsoid. Magnetic foliation planes dip inward or outward and the magnetic lineation may have any trend on the plane of foliation plane (e.g. the Eagles Rock sample set). The three double sampled sites (i.e. 15, 23 and 24) also show considerable within-site variation (Fig. 6.8).

However, the Barnavave, Ballintreskin and Slieve Foye traverses each have somewhat better defined consistently oriented AMS fabrics. Magnetic foliation planes for all of these fabrics, with no exceptions, strike approximately parallel-slightly obliquely to outer contacts and dip inwards toward the centre of the complex at Spellickanee. Dip values for these planes may be sub-horizontal to very steeply dipping. With the exception of the Ballintreskin traverse, no consistency in magnetic lineation orientation is observed. In the case of the former, a well-developed (susceptibility ellipsoids for this traverse are all triaxial) inward plunging magnetic lineation down-dip on magnetic foliation planes is ubiquitous (Figs. 6.8 and 6.9).

6.4 Discussion

The approximately annular outcrop of the Carlingford Later Gabbros is strikingly similar to the classic Great Eucrite intrusion of Ardnamurchan in terms of the topographic expression the intrusion creates on the surrounding area. However, at 6 km, the diameter of the Later Gabbro 'ring-intrusion' is about 2 km greater than that of the Great Eucrite and is imperfectly exposed around its circumference compared to the latter intrusion. The Later Gabbros comprise seven large gabbro segments, the largest of which outcrops along the main Slieve Foye-Ballintreskin ridge. From detailed field mapping and petrological observations (particularly on the Slieve Foye part of the Later Gabbros), Le Bas (1960) revised the assertions of Richey (1932) that the Later Gabbros comprised a ring-dyke intrusion, suggesting instead a sheet-like or lopolithic form.

Beyond some additional field observations on inward-dipping field contacts with the central granophyre and Silurian sediments and the presence of previously unreported magmatic layering from the opposite side of the complex at the Round Mountain (as outlined above), this study can do little to confirm or refute the model of Le Bas (1960). The reason for this is that the magnetic fabrics are, in many parts of the Later Gabbros, inconsistently oriented to the point of being of little use at an intrusion scale. Consistently oriented AMS fabrics occur in just three sample sets: those of Barnavave, Slieve Foye and Ballintreskin. The Barnavave and Slieve Foye sample sets are characterized by oblate-triaxial susceptibility ellipsoids, with magnetic foliations that typically dip inward. Magnetic lineations are not consistently oriented. However, the Ballintreskin magnetic fabric sample set, all of which are represented by triaxial AMS fabrics, have consistently oriented inward-dipping magnetic foliations and magnetic lineations that typically plunge down-dip on foliation planes.

The implications of the above observations on the magnetic fabric data become clear when the distribution of layered gabbro throughout the Later Gabbros is considered. Magmatic layering is observed in the area around Slieve Foye summit, but is best exposed at Ballintreskin. Le Bas (1960) and this study show that the latter area also exhibits occasional evidence for small-scale slumping and deformation of layers that is not preserved elsewhere throughout the Later Gabbros. Given these field observations and the evidence presented for a strong link between magmatic layering and magnetic fabrics for the Ardnamurchan Great Eucrite in Chapter 3, it seems reasonable to link the occurrence of layering at Ballintreskin with the consistent magnetic fabrics there. It may therefore be inferred that similar processes are responsible for both layer formation (and/or syn-magmatic layer deformation) and the consistent AMS fabrics. Additionally, though layering is inconsistent at the Round Mountain, the outcrops that exhibit layering exhibit a magnetic foliation that dips inward and a magnetic

lineation that plunges shallowly down-dip on the foliation plane (Sample 30). Both magnetic foliation and magnetic lineation therefore have dip and plunge values (23° and 19°) that are of similar shallow magnitude to layering (24°).

The combination of field observations and the magnetic fabric dataset for the Great Eucrite led to the interpretation of the intrusion as a lopolithic body that underwent considerable central subsidence and inward rotation of originally horizontal to sub-horizontal features (layering frequently dips inwards at $>50^\circ$ and magnetic lineations plunge inward). The evidence for this is not convincing in the Carlingford Later Gabbros. Indeed, for the most part, the origin of the AMS fabrics is obscure, reflecting a complexity that is not interpretable with the current dataset resolution and field evidence available. The relatively shallow dip of magmatic layering (at both a large and small scale) together with shallowly dipping intrusion contacts suggests that if central subsidence occurred, as might be interpreted from the ubiquitous inward dipping nature of layering and contacts (however shallow), then its effects are not as pronounced in the Later Gabbros as they are in the Great Eucrite. It may be therefore that though central subsidence occurred at Carlingford, it was insufficient to imprint an intrusion-wide AMS fabric on the rocks. This means that the complexity observed in both the orientation and the shape of the magnetic fabrics (susceptibility ellipsoids) may represent primary flow of a basaltic magma in the intrusion. However, the complexly oriented AMS fabrics could also quite easily represent two conflicting magnetite fabrics, were mineral grains of both modes of occurrence as described above from Le Bas (1960) oriented differently. These complexly oriented fabrics also have implications for an issue raised regarding the nature of the AMS fabrics at Ardnamurchan, i.e. whether they represent flow fabrics *sensu stricto* (particle displacement in a particular direction) or whether they in fact represent strain fabrics imposed on the rock in a magmatic state. This is discussed as follows.

Notably, the layers on Ballinteskinn that are correlated with AMS fabrics in this study are those where Le Bas (1960) extracted linear 'flow' or 'slumping direction' data, orientations which coincide with the magnetic lineations reported here. Though it is uncertain to what degree flow or strain each contribute to the AMS fabric here (as it is likely both parallel each other as in the Great Eucrite), it must be concluded that increasing strain will have the effect of increasing the intensity of the fabric. As the central subsidence mechanism proposed for Ardnamurchan (and now Carlingford) has an approximately vertically oriented stretching direction, increasing strain and fabric intensity would also result in strengthening of the linear element of the fabric, as is observed in

the highly prolate AMS fabrics of Ardnamurchan. This might also be suggested for the consistent AMS lineations on Ballinteskine, as they correlate well with syn-magmatically deformed layering.

Finally, several of the other field observations made in this study may have important implications for previous interpretations of the Carlingford Complex and are now briefly discussed. In particular, the extensive late granophyre has long been considered to postdate the Later Gabbros and to represent the laccolithic top of a ring-dyke intrusion. The presence of a shallowly inward dipping contact between the gabbros and the granophyre, very similar in orientation to the contact between the gabbros and the Silurian sedimentary country rock described by Le Bas (1960) and by this study, might suggest that the granophyre represents earlier country rock to the gabbro. Although it is possible to narrow down the contact between the Carnavaddy gabbro and granophyre in the north to a minimum of approximately 10 m in several places, little can be said of its nature, i.e. whether it is intrusive or faulted. The presence of gabbro blocks net-veined with granophyre was used by both Richey (1932) and Le Bas (1967) to suggest the gabbros were earlier. However, the same argument can be used to suggest that the granophyre predates the Later Gabbros, as contact melting of the granophyre and ensuing back-veining of gabbro by mobilized felsic melts would be a thermal metamorphic effect, leading to the rocks observed and illustrated in Figure 6.5. These rocks do not therefore provide sufficient evidence to assign relative ages to both intrusions. These rocks, frequently described as 'vent agglomerate' by Richey (1932) and Le Bas (1960) are probably not correctly identified thus, but better referred to as 'net-veined gabbro' or 'agmatite'. It is concluded that the evidence previously used to support the interpretation of the intrusion of the granophyre body as the latest event may be flawed and that there exists at present no grounds for interpreting the granophyre as the later intrusive episode.

6.5 Summary

Magnetic fabric data for the Carlingford Later Gabbros are, with some exceptions, obscure. However, consistency in orientation of the magnetic fabrics is observed at Slieve Foye, Barnavave and in particular, the Ballinteskine area in the north of the complex, where both the AMS foliations and lineations are consistent and exhibit a close spatial relationship with magmatic layering. This observation is used to suggest that a similar central subsidence mechanism as proposed for the Great Euclite of Ardnamurchan may have been important in the evolution of the Later Gabbros, though its effects are nowhere nearly as well preserved. As with the Great Euclite, this may indicate that the AMS lineation is in fact a strain fabric reflecting a stretching lineation rather

than an *a priori* flow fabric. Field observations indicate that there is insufficient evidence for models to suggest that the large granophyre is the youngest body in the complex, and it might be that the Later Gabbros actually represent the youngest intrusive event there. Similar sequences of magma emplacement, i.e. early episodes of felsic magmatism with later intrusion of large mafic bodies are reported from other Palaeogene igneous centres (e.g. Rum; Emeleus 1997).

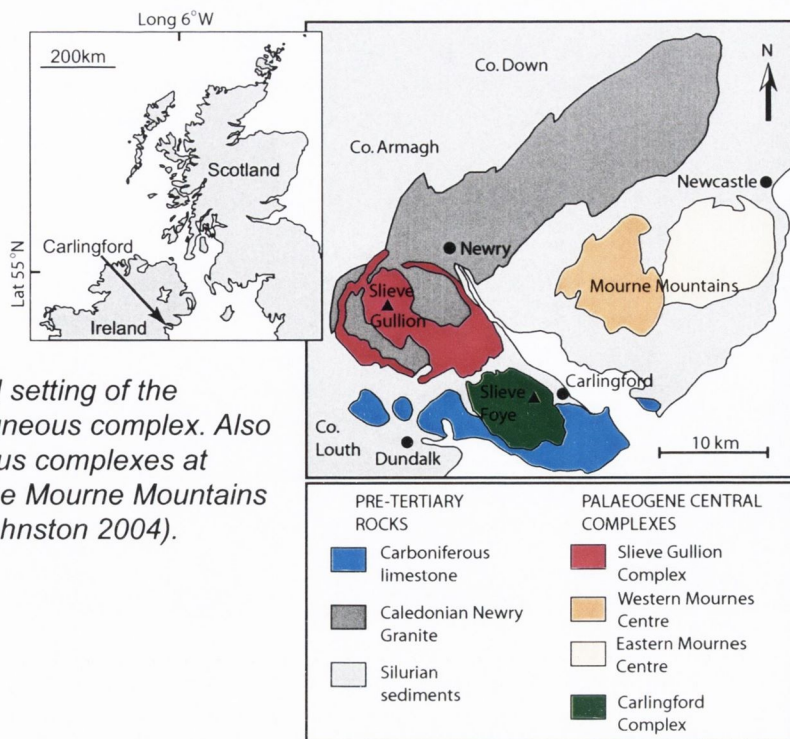


Figure 6.1. Regional setting of the Carlingford central igneous complex. Also shown are the igneous complexes at Slieve Gullion and the Mourne Mountains (from Cooper and Johnston 2004).

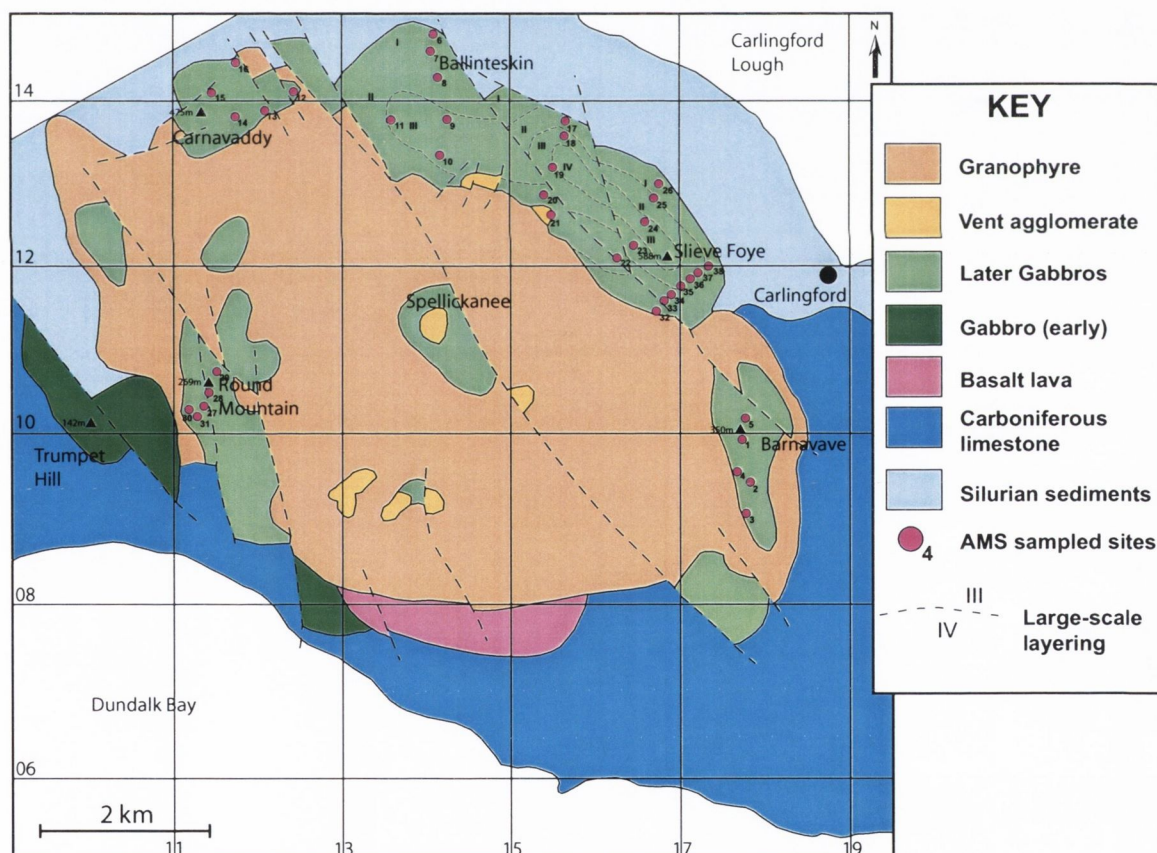


Figure 6.2. The position of the Later Gabbros within the Carlingford central complex. Also shown are the AMS sampled sites (adapted from Cooper and Johnston 2004).



Figure 6.3. A: Small-scale rhythmic layering of pyroxene-rich gabbro at Ballintreskin. B and C: Orthocumulate texture in layered Later Gabbros from Ballintreskin as described in text. Photomicrograph images are both taken in cross polars and the field of view is 4 mm in width. D: Slumped and deformed layers (highlighted) at same locality. E and F: Small-scale layering at Ballintreskin also often exhibits layers with a 'trough-like' form.

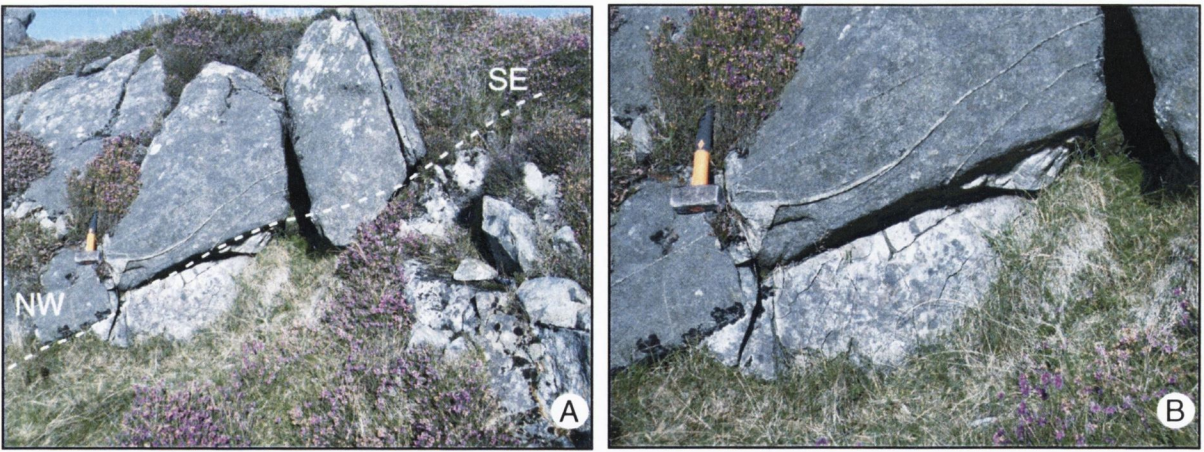


Figure 6.4. A and B: Shallowly NW dipping granophyre (below) contact with Later Gabbro (above).

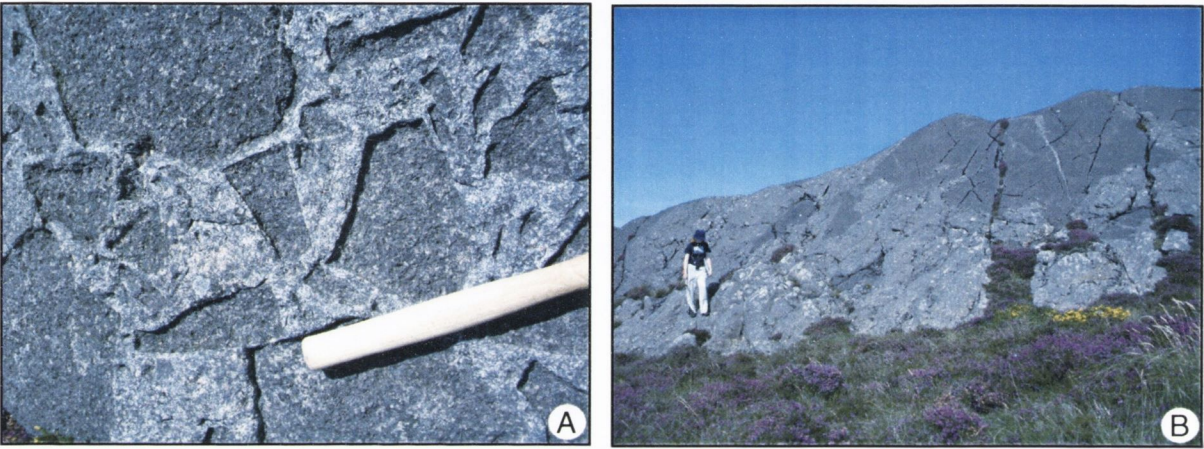


Figure 6.5. A and B: Microgranite-net-veined frequently angular blocks of gabbro close to the NW margin of the Barnavave gabbro. Both photographs courtesy of Fiona Meade, Trinity College Dublin (Ireland).

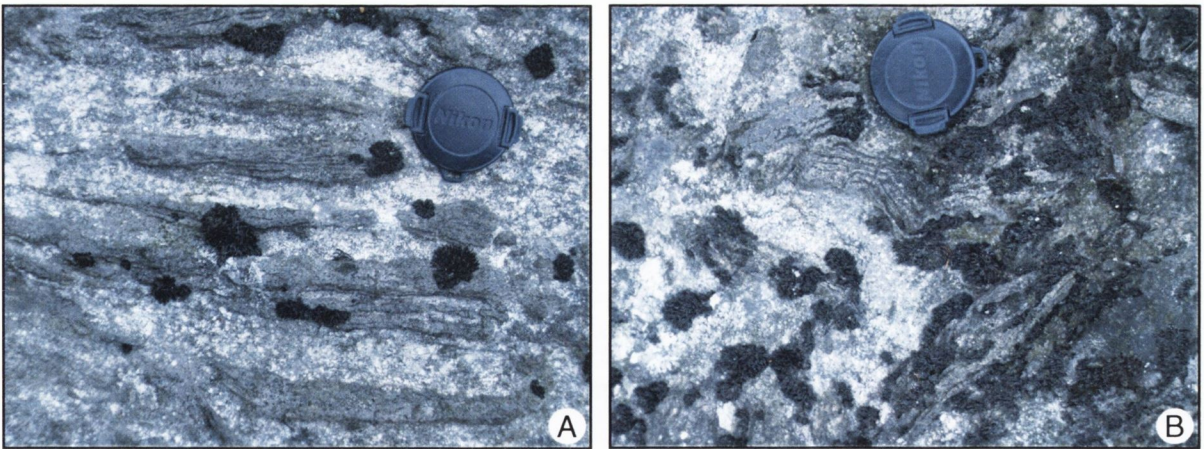
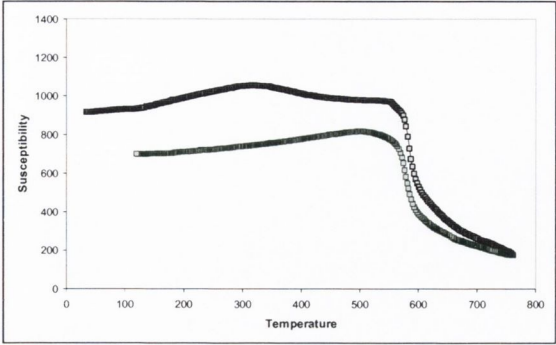


Figure 6.6. Incipient melting and migmatisation of Silurian sediment with the formation of dark mesosome (restitic) lenses (A) that retain bedding/cleavage which is frequently complexly folded (B).

C34.



C38.

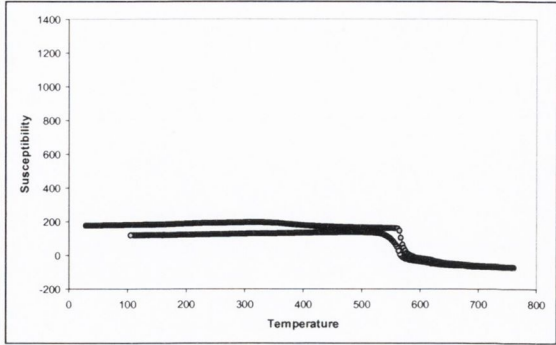


Figure 6.7. Labelled susceptibility vs. temperature plots showing heating and cooling paths for selected Carlingford samples (two from the Slieve Foye traverse).

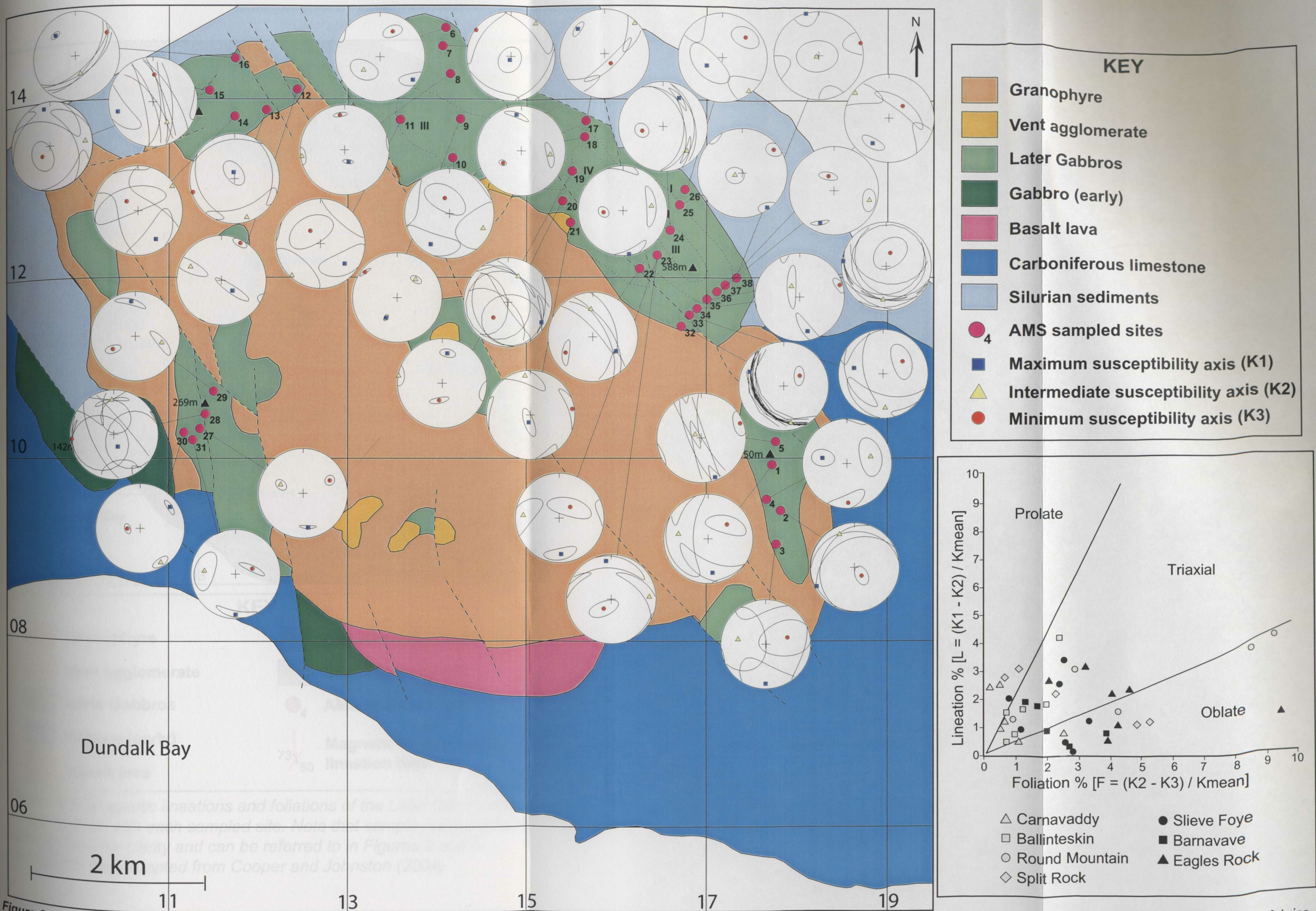


Figure 6.8. AMS data shown on equal-area stereoplots with confidence ellipses for each of the Later Gabbro samples. Inset: Subdivision of AMS data from the Later Gabbros into prolate, triaxial and oblate fabrics on the basis of an L-F plot.

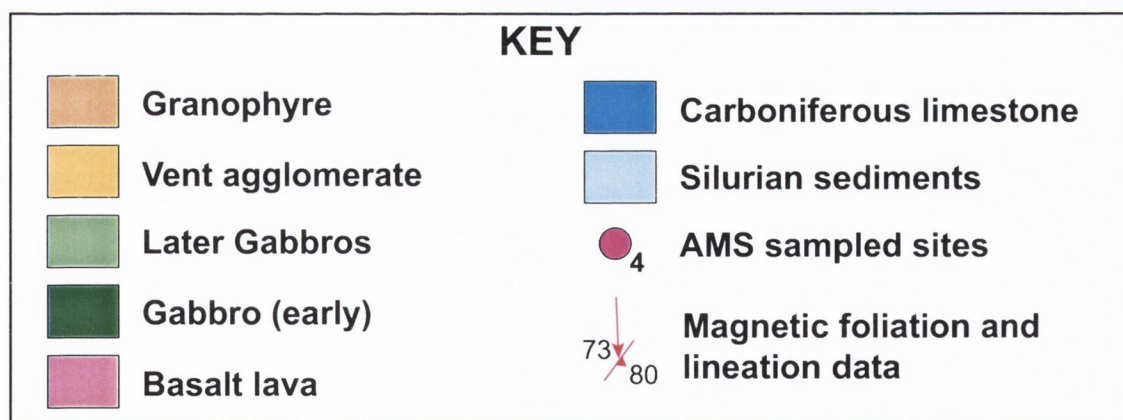
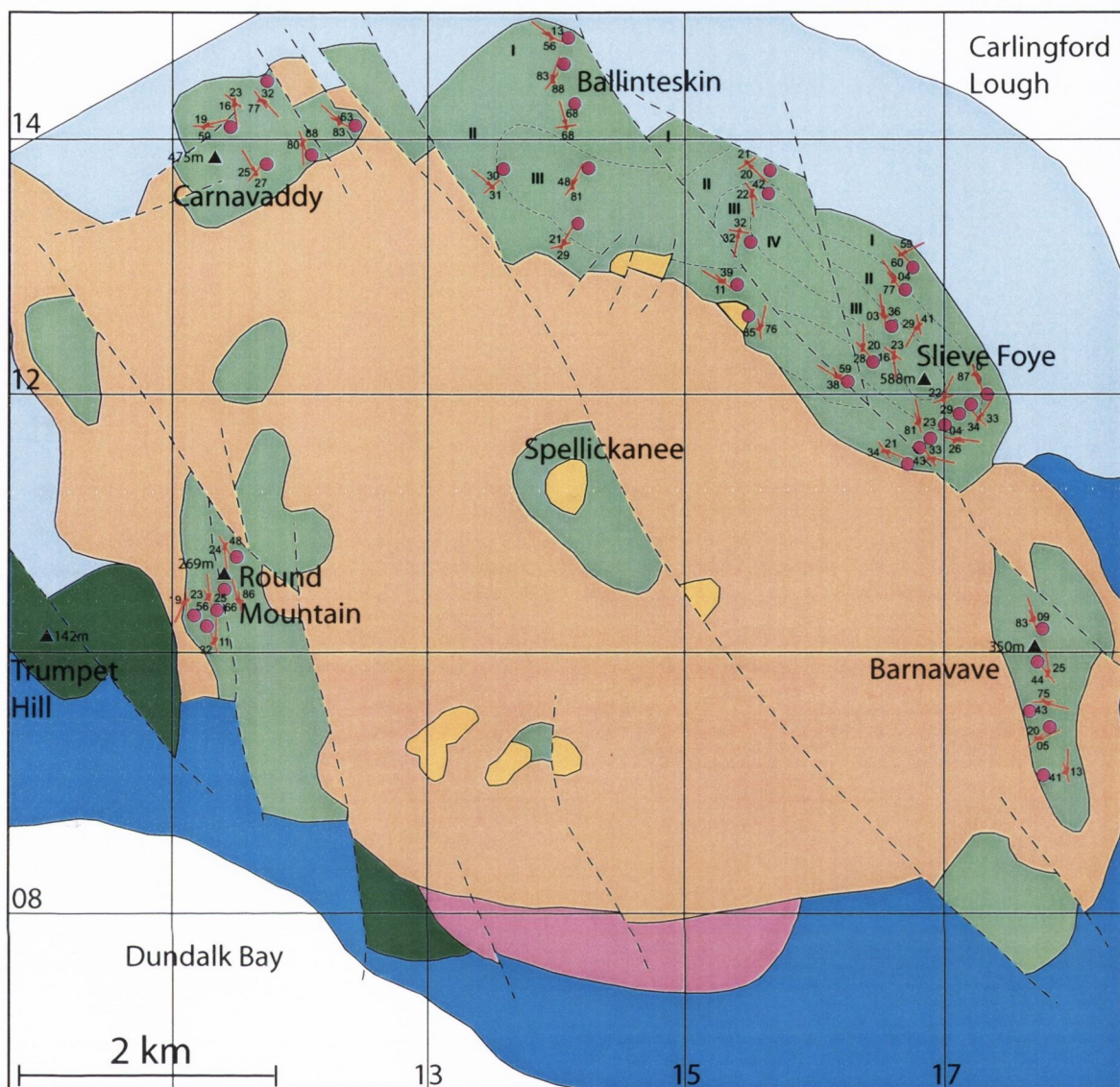


Figure 6.9. Magnetic lineations and foliations of the Later Gabbros on a structural map with each sampled site. Note that sample numbers have been omitted for clarity and can be referred to in Figures 2 and 8. Lithological map adapted from Cooper and Johnston (2004).

Table 6.1. AMS data for the Carlingford Later Gabbros

Sample No.	Kmean	K1	Dec	Inc	K2	Dec	Inc	K3	Dec	Inc	L	F	H	Mu	
Barnavave	1	17889.06	1.018	351.7	-25.3	1	99.7	-33.3	0.983	52.5	46	1.81	1.7	3.51	46.7
	2	15612.53	1.018	243.9	5.4	1.01	335.8	19.1	0.972	138.8	70.1	0.78	3.89	4.66	11.3
	3	10525.7	1.013	359.7	-12.9	1.004	99.9	-37.8	0.984	74.2	49.3	0.9	2	2.9	24.3
	4	8149.81	1.017	103.2	-43.1	0.998	74.1	43	0.985	358.7	-15.1	1.86	1.32	3.18	54.7
	5	7247.39	1.011	160.7	9.4	1.008	301.6	77.9	0.981	69.5	7.5	0.3	2.72	3.01	6.3
Ballinteskin	6	18228.8	1.019	125.1	12.6	1	231.1	50.8	0.981	25.7	36.3	1.84	1.98	3.81	42.9
	7	13972.96	1.013	197.9	83	0.997	36.9	6.7	0.99	126.6	-2.3	1.55	0.73	2.28	64.7
	8	12462.86	1.036	343.2	-67.6	0.994	81.6	-3.5	0.97	353.1	22.1	4.18	2.39	6.57	60.3
	9	7101.65	1.015	209	47.5	0.999	46.4	41.2	0.986	128.7	-8.8	1.66	1.24	2.9	53.3
	10	3215.35	1.006	30.4	-20.9	1.001	112.9	18.8	0.993	344.5	61.3	0.51	0.75	1.26	34.2
	11	11610.72	1.009	308.9	-30	1.001	41.9	-5.2	0.991	320.9	59.5	0.78	1	1.78	38
Carnavaddy	12	3739.99	1.014	311.1	-62.8	1.006	112.9	-26	0.98	26.5	7.3	0.8	2.56	3.36	17.4
	13	3812.88	1.008	355.2	79.7	0.999	341.8	-10	0.993	72.2	-2.3	0.97	0.56	1.53	60.3
	14	1387.77	1.01	328.4	-25.3	0.998	55	7.3	0.991	310.2	63.5	1.22	0.68	1.9	60.9
	15A	24166.24	1.007	350.3	15.6	1.002	85.1	16.7	0.991	219.6	66.9	0.51	1.12	1.63	24.5
	15B	24390.08	1.019	75.8	-19.4	0.993	145.9	44	0.988	2.8	39.6	2.54	0.54	3.09	77.9
	16	36098.75	1.017	137.2	-32.1	0.993	165	54.7	0.99	55.7	13.2	2.45	0.22	2.67	84.8
	Split Rock	17	14275.26	1.021	313.2	19.7	0.993	44.8	4.7	0.986	147.7	69.7	2.78	0.69	3.47
18		7585.14	1.026	353	21.6	1.014	98.3	33.6	0.961	236.6	48.4	1.21	5.27	6.48	12.9
19		12696.9	1.022	10.2	32	1	100	-0.2	0.977	189.7	58	2.22	2.3	4.52	44.1
20		587.82	1.024	300.6	-10.8	1.013	22.2	37.1	0.964	224.1	50.8	1.12	4.9	6.02	12.8
21		3161.3	1.024	191	75.6	0.993	351.4	13.6	0.982	82.5	4.7	3.09	1.13	4.21	69.9
Eagles Rock	22	700.45	1.041	122.2	37.9	1.027	356.3	37	0.932	59.7	-30.7	1.37	9.47	10.84	8.2
	23A	828.42	1.028	357.6	-19.8	1.006	94.7	-19.1	0.966	45.2	61.9	2.17	4.06	6.23	28.1
	23B	421.38	1.031	351.9	16.1	1.008	86.4	15.3	0.961	217.8	67.5	2.34	4.63	6.97	26.8
	24A	4463.66	1.021	352.7	-2.6	1.011	80.9	35.6	0.968	266.3	54.3	1.07	4.25	5.33	14.2
	24B	5275.3	1.017	29	29.1	1.011	134.7	25.9	0.972	258.9	49.2	0.55	3.95	4.5	8
	25	11614.56	1.025	144.1	4.3	0.998	251.9	76.1	0.977	53.1	13.2	2.68	2.08	4.76	52.2
	26	10827.88	1.032	242.4	59.1	1	321	-6.7	0.968	47.1	30	3.14	3.21	6.34	44.4
Round Mountain	27	64180.33	1.053	172.1	24.9	1.016	290.8	46	0.931	64.1	33.6	3.7	8.51	12.21	23.5
	28	40487.7	1.012	164.2	66.2	0.999	356.3	23.3	0.99	84.3	-4.5	1.33	0.91	2.24	55.8
	29	62297.2	1.025	173	-23.5	1.009	103.6	39.1	0.966	60.1	-41.8	1.59	4.3	5.88	20.3
	30	45851.97	1.03	234.6	-19.4	0.999	328.9	-11.9	0.97	268.7	67	3.08	2.9	5.97	46.7
	31	101896.58	1.058	360	-11	1.017	96.5	-30.1	0.925	72.2	57.6	4.16	9.2	13.36	24.3
Slieve Foye	32	1311.62	1.01	292.5	20.6	1.009	12	-25.7	0.981	56.4	56	0.15	2.83	2.99	3.1
	33	1397.7	1.01	281.8	32.8	1.001	355.3	-23.8	0.989	56.6	47.5	0.94	1.19	2.12	38.2
	34	16971.33	1.019	167.1	22.8	1.007	322.8	65.2	0.974	73.2	9.1	1.25	3.33	4.58	20.5
	35	714.25	1.012	277.1	4.4	1.007	5	-25.7	0.981	16.2	63.9	0.48	2.59	3.07	10.5
	36	5713.35	1.031	23.1	-21.7	0.997	105.4	18.6	0.972	338.5	60.7	3.4	2.55	5.94	53.1
	37	5898.57	1.016	32.3	-32.6	0.996	126.8	-7.1	0.988	47.6	56.5	2.01	0.82	2.83	67.7
	38	4970.2	1.025	163	-0.3	1	247.2	87	0.975	73	3	2.55	2.41	4.97	46.6

CHAPTER 7. SUMMARY OF CONCLUSIONS

7.1. Introduction

The primary objectives of this thesis, as outlined in Chapter 1, are to investigate the textures and fabrics of some of the well-known layered and partially-layered mafic and ultramafic intrusions of the British Palaeogene Igneous Province (i.e. the Ardnamurchan Centre 3 Gabbros, the Rum Layered Suite, the Skye Druim Hain Gabbros, and the Carlingford Later Gabbros). This was carried out by combining detailed field observations and structural measurements with modern quantitative methods of textural and igneous rock fabric analysis, such as the Crystal Size Distribution (CSD) technique and Anisotropy of Magnetic Susceptibility (AMS) analysis. The resulting data has been considered in the context of existing models for the respective intrusions studied, and where necessary, new interpretations have been proposed based on discrepancies between the findings of this thesis and the published interpretations.

Each of the four results chapters (3-6 inclusive) is self-contained, and distinct conclusions have been drawn in each after detailed discussion. Therefore, this final chapter is a simple summary list of the principal conclusions drawn in each chapter.

7.2. The Ardnamurchan Centre 3 Gabbros.

A combined field, magnetic fabrics and quantitative textural study of the Centre 3 gabbros of Ardnamurchan has led to a complete re-evaluation of their intrusion geometry and emplacement history. Inward-dipping contacts between gabbro and Jurassic sediments are observed in the NW of the peninsula, and used to rule out the ring-dyke hypothesis for the Great Eucrite intrusion. Consistently inward-dipping, frequently syn-magmatically deformed layering, together with inward-plunging strongly-prolate AMS susceptibility ellipsoids are interpreted as suggesting that significant central subsidence of the Great Eucrite, together with the interior laminated gabbros have been of considerable importance at a late-stage in the history of Centre 3. The Centre 3 gabbros are therefore re-interpreted as a composite lopolithic intrusion, containing different petrological facies of gabbro. The late-stage quartz-dolerite intrusion is re-interpreted as an annular series of anatectically melted roof blocks above the Great Eucrite, and the central tonalite intrusion is suggested to represent the original subsided zone of country-rock interaction with the top of the Centre 3 magma chamber, i.e. the chamber roof. The Meall nan Con screen is re-interpreted as roof to the Great Eucrite, rather than as a screen, based on flattish contacts seen in the field with the gabbro rather than steep contacts, as previously described (Richey and Thomas 1930).

The presence of sedimentary structures and strongly linear AMS fabrics suggests that magmatic flow was an important process in layer development. Similar observations, together with detailed quantitative textural analysis, suggest a primary cumulus mechanism of formation of layering and igneous lamination for the Glendrian and Achnaha laminated gabbros. The Sithean Mor body displays evidence for a more complex textural history, possibly including postcumulus processes, such as compaction induced pressure solution, leading to crystal ripening and lamination intensification. The latter is supported by the AMS data for the Sithean Mor samples. Microprobe data for feldspar crystals from a Sithean Mor sample show significant zoning of up to 10 mol%, possibly supporting the idea of enhanced mobility of one or more interstitial fluids through magmatic flow. This is interpreted as having been driven by central subsidence in the Centre 3 Gabbros.

7.3. The Rum Layered Suite.

The work carried out on the Rum Layered Suite presented in this thesis comprises two independent studies on two different types of cumulate that occur there.

The first of these focuses on field observations and magnetic fabric data of a sequence of interlayered peridotite and troctolite [Units 8, 9 and particularly Unit 10] in a small area north of Hallival in the Eastern Layered Intrusion. Macro-rhythmic layering, small-scale layering and igneous lamination strike parallel to the outer margins of the intrusion and consistently dip inward. Measurements on sedimentary structures suggest that magmatic flow was toward a focal point in Atlantic Corrie at the centre of the Eastern Layered Intrusion. Previous work (several independent studies: Putnis 1979; Moseley 1984; Housden *et al.* 1996) suggests that magnetite occurs in these rocks as crystallographically constrained dendrites in olivine crystals.

The magnetic fabrics are probably carried by these magnetite grains (from susceptibility measurements), and exhibit a very dominant trend, where magnetic foliation planes are always oriented parallel to the pervasive igneous lamination, and magnetic lineations normally trend parallel to the strike of magnetic foliation planes. In some instances, magnetic lineations are oriented down-dip on magnetic foliation planes. The magnetic fabrics are interpreted to reflect olivine crystal fabrics, and the data described above are supported by independent work by Brothers (1964), which found that plagioclase crystals also display a well-defined lineation parallel to strike of igneous lamination planes. A model is proposed where the alignment of tabular grains parallel to flow directions (measured from field evidence) is a result of reshuffling and re-orientation of grains in the cumulate pile. It is proposed that this process is also driven by central subsidence of the Rum magma chamber.

The second study undertaken is a detailed crystal size distribution study of granular and harrisitic olivine crystal morphologies from the Rum Layered Suite. Most samples are from Ard Mheall in the Western Layered Intrusion, but samples are also taken from Harris Bay and the Eastern Layered Intrusion. Resulting CSD plots are generally quite log linear and give exceptionally fast crystal growth times for harrisite growth. Formation of harrisite layers is estimated to be approximately 160 times faster than layer formation in the Skaergaard based on rates published by Wager and Brown (1968).

A model incorporating these very fast crystal growth times, together with low calculated nucleation rates and field observations of extensive interlayering of harrisitic peridotite with 'normal' peridotite composed of granular olivine grains is proposed. A link between the cyclic development of harrisite as a disequilibrium texture and repeated influxes (of varying size) of picrite magma at the base of the Rum chamber is made. Harrisite is envisaged as developing through bursts of crystal growth in response to regularly induced 'perturbations' of the liquidus temperature of the magma chamber by influxing batches of picrite. Field evidence suggests that magmatic sedimentation and syn-magmatic deformation, perhaps also related to the central subsidence of the Rum chamber, halted or terminated harrisite growth. This study therefore supports the view of the Rum intrusion as an open magmatic system as previously proposed (Emeleus *et al.* 1996 and references therein).

7.4. The Skye Druim Hain Gabbro.

This study combines detailed field observations and structural measurements on magmatic layering with magnetic fabric and quantitative textural studies. Layering and a ubiquitous layer-parallel lamination dip inward, toward a central focal point to the NE, and display a marked steepening inward ($\sim 30\text{--}70^\circ$) trend. Sedimentary structures are typically absent, i.e. one example of modally graded bedding is observed in a section of ~ 450 m thickness of layered cumulate. Magnetic fabrics are similar to the other studies (Ardnamurchan and Rum) in that the magnetic foliation plane always parallels layering and lamination. However, the magnetic lineation is highly inconsistent: even double sampled sites show no consistency in lineation orientation. Magnetic fabrics are also highly oblate, indicating that the planar element of the fabric is proportionally much stronger than the linear one.

Textural evidence suggests that the samples with the most intense planar foliations are those with the most complex textural histories, i.e. have undergone some ripening of mineral grains. This is in agreement with AMS fabric evidence that suggests, in a similar manner to the laminated cumulates of Ardnamurchan, late-stage intensification of the foliation at the expense of the lineation. However, even those samples that appear, from

textural evidence, to have relatively simple crystallization histories are laminated. This indicates that some primary mechanism of fabric acquisition must be invoked to account for the initial stage of lamination development. Given the lack of evidence for flow throughout the Skye cumulates, even though a potential driving mechanism, i.e. central subsidence, appears likely to have occurred, *in situ* crystallization in the manner of McBirney and Noyes (1979) is suggested to be responsible. It is proposed here that localized postcumulus compaction caused textural ripening in parts of the cumulate pile. Late-stage subsidence leading to the steepening-inward trend observed in layering affected a relatively coherent almost fully-crystallized mush, incapable of being syn-magmatically deformed.

7.5. The Carlingford Later Gabbros.

A detailed magnetic fabric study of the annular partially-layered Carlingford Later Gabbros is combined with new field observations and existing knowledge to test the ideas proposed in earlier chapters in this study and also to constrain existing emplacement models for the Later Gabbros. Fieldwork shows that the mapping of Le Bas (1960) of four distinct petrological facies within the Later Gabbros is very accurate. Layering is best preserved in the north of the intrusion at Ballintreskin. Syn-magmatic deformation of layering is often seen in this area and includes deformed slump structures and varying thicknesses of layering. However, AMS fabrics are very inconsistent. Only in three of seven traverses is consistency observed, suggesting that little can be drawn from the magnetic fabric data by way of interpretation. However, the traverse in the north of the intrusion, at Ballintreskin, corresponds to the area where deformed layering is present and magnetic fabrics here exhibit consistently oriented inward dipping and inward plunging magnetic foliations and lineations respectively.

A comparison of this data with that from the Great Eucrite of Ardnamurchan suggests that though central subsidence may have occurred in the Later Gabbros too, it was neither as important nor as extensive as in Ardnamurchan. This is supported to some degree by the presence of a very shallowly-dipping ($\sim 20^\circ$) intrusive contact between the Later Gabbros and an extensive granophyre intrusion (note that outer contacts between the Great Eucrite and country rock dip inward at 50°). The presence of the above contact also has implications for age relations between the granophyre and the Later Gabbros, suggesting that the granophyre may not be the younger intrusion, as previously thought (Le Bas 1960; 1967).

REFERENCES

- Anderson, E.M. (1936). The dynamics of the formation of cone-sheets, ring-dykes, and cauldron-subsidence. *Proceedings of the Royal Society of Edinburgh*, **56**, 128-156.
- Balsley, J.R. and Buddington, A.F. (1958). Iron-titanium oxide minerals, rocks and aeromagnetic anomalies of the Adirondack area, New York. *Economic Geology*, **53**, 777-805.
- Bédard, J.H., Sparks, R.S.J., Renner, R., Cheadle, M.J., & Hallworth, M.A. (1988). Peridotite sills and metasomatic gabbros in the Eastern Layered Series of the Rhum complex. *Journal of the Geological Society*, **145**, 207-224.
- Bell, B.R. & Williamson, I.T. (2002). Tertiary Igneous Activity. In: Trewin, N.H. (ed.), *The Geology of Scotland*. Geological Society, London, **4th Edition**, 371-408.
- Benn, K. & Allard, B. (1989). Preferred Mineral Orientations related to Magmatic Flow in Ophiolite Layered Gabbros. *Journal of Petrology*, **30**, 925-946.
- Best, M.G. & Christiansen, E.H. (2001). *Igneous Petrology*. Oxford, Blackwell Science. 458p.
- Boorman, S., Boudreau, A., & Kruger, F.J. (2004). The Lower Zone-Critical Zone Transition of the Bushveld Complex: a Quantitative Textural Study. *Journal of Petrology*, **45**, 1209-1235.
- Borradaile, G.J. (1987). Anisotropy of magnetic susceptibility: rock composition versus strain. *Tectonophysics*, **138**, 327-329.
- Bouchez, J.-L. (1997). Granite is never isotropic: an introduction to AMS studies of granitic rocks, in Bouchez, J.L., Hutton, D.H.W., and Stephens, W.E., eds., *Granite: from segregation of melt to emplacement fabrics*. Kluwer Academic Publishers, Dordrecht, p. 95-112.
- Boudreau, A.E. & McBirney, A.R. (1997). The Skaergaard Layered Series. Part III. Non-dynamic layering. *Journal of Petrology*, **38**, 1003-1020.
- Bradshaw, N. (1961). *The mineralogy and petrology of the eucrites of the Centre 3 igneous complex, Ardnamurchan, Scotland*. Unpublished Ph.D thesis, University of Manchester.
- Brothers, R.N. (1964). Petrofabric analysis of Rhum and Skaergaard Layered Rocks. *Journal of Petrology*, **5**, 255-274.
- Brown, D.J., Bell, B.R. & McLeod, G.W. A re-interpretation of the "Centre 3 screens" of Ardnamurchan, NW Scotland. *Scottish Journal of Geology*, **42 (1)**, 83-85.
- Brown, G.M. (1956). The layered ultrabasic rocks of Rhum, Inner Hebrides. *Philosophical Transactions of the Royal Society*, **B, 240**, 1-53.
- Burton, J.A., Prim, R.C., & Slichter, W.P. (1953). The distribution of solute from crystals grown from the melt. Part 1: Theoretical Journal of Chemical Physics, **21**, 1987-1999.
- Butcher, A.R., Young, I.M., & Faithfull, J.W. (1985). Finger structures in the Rhum Complex. *Geological Magazine*, **122**, 503-518.
- Canon-Tapia, E. (1996). Single-grain versus distribution anisotropy: a simple three dimensional model. *Physics of the Earth and Planetary Interior*, **94**, 149-158.
- Canon-Tapia, E., Walker, G.P.L., & Herrero-Bervera, E. (1995). Magnetic fabric and flow direction in basaltic pahoehoe lava of Xitle, Mexico. *Journal of Volcanology and Geothermal Research*, **65**, 249-263.

- Carr, H.W., Groves, D.I., & Cawthorne, R.G. (1994). The importance of synmagmatic deformation in the formation of Merensky Reef potholes in the Bushveld Complex. *Economic Geology*, **89**, 1398-1410.
- Cashman, K.V. (1993). Relationship between plagioclase crystallization and cooling rate in basaltic melts. *Contributions to Mineralogy and Petrology*, **113**, 126-142.
- Cashman, K.V. & Marsh, B.D. (1988). Crystal size distribution (CSD) in rocks and the kinetics and dynamics of crystallisation II: Makaopuhi lava lake. *Contributions to Mineralogy and Petrology*, **99**, 292-305.
- Chambers, L.M., Pringle, M.S., and Parrish, R.R. (2005). Rapid formation of the Small Isles Tertiary centre constrained by precise $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb ages. *Lithos*, **79**, 367-384.
- Coogan, L.A., Thompson, G., & MacLeod, C.J. (2002). A textural and geochemical investigation of high level gabbros from the Oman ophiolite: implications for the role of the axial magma chamber at fast spreading ridges. *Lithos*, **63**, 67-82.
- Cooper, M.R. & Johnston, T.P. (2004). Chapter 15, Palaeogene Intrusive Igneous Rocks. In: Mitchell, W.I. (ed.), *The Geology of Northern Ireland*, Belfast, pp179-198.
- Cowan, E.J. (1999). Magnetic fabric constraints on the initial geometry of the Sudbury Igneous Complex: a folded sheet or basin shaped igneous body? *Tectonophysics*, **307**, 135-162.
- Cruden, A.R. (1998). On the emplacement of tabular granites. *Journal of the Geological Society [London]*, **155**, 853-862.
- Dagley, P. & Musset, A.E. (1981). Palaeomagnetism of the British Tertiary Igneous Province: Rhum and Canna. *Journal of the Royal Astronomical Society*, **65**, 475-491.
- Davies, I.C., Walker, R.G. (1974). Transport and deposition of resedimented conglomerates: The Cap Enrage Formation, Cambro-Ordovician, Gaspé, Quebec. *Journal of Sedimentary Petrology*, **44**, 1200-1216.
- Donaldson, C.H. (1974). Olivine crystal types in harrisitic rocks of the Rhum pluton and in Archean spinifex rocks. *Geological Society of America Bulletin*, **85**, 1721-1726.
- Donaldson, C.H. (1975a). *A petrogenetic study of harrisite in the Isle of Rhum pluton, Scotland*. Unpublished Ph.D. thesis, University of St Andrews, Scotland, 138 p.
- Donaldson, C.H. (1975b). Calculated diffusion coefficients and the growth rate of olivine in a basalt magma. *Lithos*, **8**, 163-174.
- Donaldson, C.H. (1976). An experimental investigation of olivine morphology. *Contributions to Mineralogy and Petrology*, **57**, 187-213.
- Donaldson, C.H. (1977). Laboratory duplication of comb layering in the Rhum pluton. *Mineralogical Magazine*, **41**, 323-336.
- Donaldson, C.H. (1982). Origin of some of the Rhum harrisite by segregation of intercumulus liquid. *Mineralogical Magazine*, **45**, 201-209.
- Dunham, A.C. (1965). The nature and origin of groundmass textures in felsites and granophyres from Rhum, Inverness-shire. *Geological Magazine*, **102**, 8-23.
- Dunlop, D.J. & Ozdemir, O. (1997). *Rock Magnetism, Fundamentals and frontiers*. Cambridge University Press, 573 p.
- Elliot, M.T., Cheadle, M.J., & Jerram, D.A. (1997). On the identification of textural equilibrium in rocks using dihedral angle measurements. *Geology*, **25**, 355-358.

- Emeleus, C.H. (1987). The Rhum Layered Complex, Inner Hebrides, Scotland. *In*: Parsons, I. (ed.), *Origins of Igneous Layering*. (D. Reidel Publishing Company), 263-286.
- Emeleus, C.H. (1991). Tertiary Igneous Activity. *In*: Craig, G. (ed.), *The Geology of Scotland*. Geological Society, London, **3rd Edition**, 455-502.
- Emeleus, C.H, Cheadle, M.J, Hunter, R.H, Upton, B.G.J, & Wadsworth, W.J. (1996). The Rum Layered Suite. *In*: Cawthorn, R.G (ed.), *Layered igneous rocks*. (Amsterdam: Elsevier), 403-440.
- Emeleus, C.H. (1997). *Geology of Rum and the adjacent islands*. Memoir of the British Geological Survey, 497. Sheet 60 (Scotland). pp.170. 498.
- Emeleus, C.H. & Bell, B.R. (2005). British regional geology: the Palaeogene volcanic districts of Scotland (Fourth edition). British Geological Survey, Nottingham.
- Faithfull, J.W. (1985). The Lower Eastern Layered Series of Rhum. *Geological Magazine*, **122**, 459-468.
- Faure, F., Trolliard, G., Nicollet, C., & Montel, J.M. (2003). A developmental model of olivine morphology as a function of the cooling rate and the degree of undercooling, *Contributions to Mineralogy and Petrology*, **145**, 251-263.
- Ferré, E.C., Bordarier, C. & Marsh, J.S. (2002). Magma flow inferred from AMS fabrics in a layered mafic sill, Insizwa, South Africa. *Tectonophysics*, **354**, 1-23.
- Fortey, N.J. (1980). Petrofabrics of laminated gabbros from the Centre 3 igneous complex, Ardnamurchan, Scotland. *Mineralogical Magazine*, **43**, 989-994.
- Gamble, J.A., Wysoczanski, R.J. & Meighan, I.G. (1999). Constraints on the age of the British Tertiary Volcanic Province from ion microprobe U–Pb (SHRIMP) ages for the acid igneous rocks from NE Ireland. *Journal of the Geological Society, London* **156**, 291–299.
- Geikie, A. & Teall, J.J.H. (1894). On the banded structure of some Tertiary gabbros in the Isle of Skye. *Quarterly Journal of the Geological Society*, **1**, 645-659.
- Gibb, F.G.F. (1976). Ultrabasic rocks of Rhum and Skye: the nature of the parent magma. *Journal of the Geological Society, London*, **132**, 209-222.
- Greenwood, R.C., Donaldson, C.H., & Emeleus, C.H. (1990). The contact zone of the Rhum ultrabasic intrusion: evidence of peridotite formation from magnesian magmas. *Journal of the Geological Society, London*, **147**, 209-212.
- Gregoire, V., Darrozes, J., Gaillot, P., Nedelec, A. & Launeau, P. (1998). Magnetite grain fabric and distribution anisotropy vs. rock magnetic fabric: a three dimensional case study. *Journal of Structural Geology*, **20**, 937-944.
- Hargraves, R.B., Chan, C.Y. & Johnson, D. (1991). Distribution anisotropy: The cause of AMS in igneous rocks? *Geophysical Research Letters*, **18**, 2193-2196.
- Harker, A. (1904). *The Tertiary Igneous Rocks of Skye*. Memoir of the Geological Survey of the United Kingdom.
- Harker, A. (1908). *The Geology of the Small Isles of Inverness-shire*. Memoir of the Geological Survey of Scotland.
- Henderson, P., MacKinnon, A., & Gale, N.H. (1971). The distribution of uranium in some basic igneous cumulates and its petrological significance. *Geochimica et Cosmochimica Acta*, **35**, 917-925.

- Henderson, P., & Williams, C.T. (1979). Variation in trace element partition (crystal/magma) as a function of crystal growth rate. In: Ahrens, L. H., (ed.), *Origin and Distribution of the Elements*. Pergamon, 191-198.
- Higgins, M.D. (1994). Numerical modelling of crystal shapes in thin-sections; estimation of crystal habit and true size. *American Mineralogist*, **79**, 113-119.
- Higgins, M.D. (1996). Crystal size distribution and other quantitative textural measurements in lavas and tuffs from Egmon volcano (Mt. Taranaki), New Zealand. *Bulletin of Volcanology*, **58**, 194-204.
- Higgins, M.D. (1998). Origin of anorthosite by textural coarsening: quantitative measurements of a natural sequence of textural development. *Journal of Petrology*, **39**, 1307-1323.
- Higgins, M.D. (2000). Measurement of crystal size distributions. *American Mineralogist*, **85**, 1105-1116.
- Higgins, M.D. (2002a). The role of textural coarsening in the development of the Kigaplaik layered mafic intrusion, Labrador, Canada: a crystal size distribution study. *Contributions to Mineralogy and Petrology*, **144**, 314-330.
- Higgins, M.D. (2002b). Closure in crystal size distributions (CSD), verification of CSD calculations, and the significance of CSD fans. *American Mineralogist*, **87**, 171-175.
- Hoffmann, A.W. (1980). Diffusion in nature; silicate melts: a critical review. Chapter 9 in: Hargraves, R.B. (ed.), *Physics of Magmatic Processes* (Princeton University Press), 385-417.
- Holness, M.B. (2005). Spatial constraints on magma chamber replenishment events from textural observations of cumulates: the Rum Layered Intrusion, Scotland. *Journal of Petrology*, **46**, 1585-1600.
- Holness, M.B., Cheadle, M.J. & McKenzie, D. (2005). On the use of changes in dihedral angle to decode late-stage textural evolution in cumulates. *Journal of Petrology*, **46**, 1565-1583.
- Hort, M. (1998). Abrupt Change in Magma Liquidus Temperature because of Volatile Loss or Magma Mixing: Effects on Nucleation, Crystal Growth and Thermal History of the Magma. *Journal of Petrology*, **39**, 1064-1076.
- Housden, J., O'Reilly, W., & Day, S.J. (1996). Variations in magnetic properties of Unit 10, Eastern Layered Intrusion, Isle of Rum, Scotland: implications for patterns of High temperature hydrothermal alteration. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **86**, 91-112.
- Hunter, R.H. (1987). Textural equilibrium in layered igneous rocks. In: Parsons, I. (ed.) *Origins of Igneous Layering*. Dordrecht: Reidel, 473-503.
- Ildefonse, B., Launeau, P., Bouchez, J-L. & Fernandez, A. (1992). Effect of mechanical interactions on the development of shape preferred orientations: a two dimensional experimental approach. *Journal of Structural Geology*, **14**, 73-84.
- Irvine, T.N. (1980). Magmatic Density Currents and Cumulus Processes. *American Journal of Science*, **280A**, 1-58.
- Irvine, T.N., Anderson, J.C., Brooks, C.K. (1998). Included blocks (and blocks within blocks) in the Skaergaard intrusion: Geologic relations and the origins of rhythmic modally graded layers. *Geological Society of America Bulletin*, **110**, 1398-1447.
- Jackson, E.D. (1961). *Primary textures and mineral associations in the Ultramafic Zone of the Stillwater Complex, Montana*. U.S. Geological Survey Professional Paper 358, 106p.
- Jambon, A., Lussiez, P., Clocchiatti, R., Weisz, J., & Hernandez, J. (1992). Olivine growth rates in a tholeiitic basalt: An experimental study of melt inclusions in plagioclase. *Chemical Geology*, **96**, 277-287.

- Jelinek, V. (1978). Statistical processing of anisotropy of magnetic susceptibility measured on groups of specimens. *Studia Geophysica et Geodætica*, **22**, 50-62.
- Jerram, D. A., Cheadle, M. J., Hunter, R. H., & Elliott, M. T., (1996). The spatial distribution of grains and crystals in rocks. *Contributions to Mineralogy & Petrology*, **125** (1), 60-74.
- Jerram, D. A. & Cheadle, M. J. (2000). On the cluster analysis of rocks. *American Mineralogist* **84** (1), 47-67.
- Jerram, D. A. (2001). Visual comparators for degree of sorting in 2-D and 3-D. *Computers and Geoscience* **27**, 485-492.
- Jerram, D.A., Cheadle, M.J., & Philpotts, A.R. (2003). Quantifying the Building Blocks of Igneous Rocks: Are Clustered Crystal Frameworks the Foundation? *Journal of Petrology*, **44**, 2033-2051.
- Jerram, D. A. & Kent, A. J. R. (2006). An overview of modern trends in petrography: Textural and microanalysis of igneous rocks. *Journal of Volcanology and Geothermal Research*, **154**, 7-9.
- Kohut, E.J. & Nielsen, R.L. (2004). Melt inclusion formation mechanisms and compositional effects in high-An feldspar and high-Fo olivine in anhydrous mafic silicate liquids. *Contributions to Mineralogy and Petrology*, **147**, 684-704.
- Launeau, P. & Cruden, A.R. (1998). Magmatic fabric acquisition mechanisms in a syenite: Results of a combined anisotropy of magnetic susceptibility and image analysis study. *Journal of Geophysical Research*, **103**, 5067-5089.
- Le Bas, M.J. (1960). The petrology of the layered basic rocks of the Carlingford Complex, County Louth. *Transactions of the Royal Society of Edinburgh*, **64**, 169-200.
- Le Bas, M.J. (1967). On the origin of the Tertiary granophyres of the Carlingford Complex, Ireland. *Proceedings of the Royal Irish Academy*, **65B**, 325-338.
- Lofgren, G.E. (1980). Experimental studies on the dynamic crystallization of silicate melts. In Hargraves, R.B. ed., *Physics of Magmatic Processes*. Princeton University Press, 487-551.
- Lofgren, G.E. & Donaldson, C.H. (1975). Curved branching crystals and differentiation in comb-layered rocks. *Contributions to Mineralogy and Petrology*, **49**, 309-319.
- LoRe, F.C., Cheadle, M.J., Swapp, S.M. & Coogan, L.A. Eos Transactions. AGU, **84** (46), Fall Meeting. Supplement, Abstract V12A-0558, 2003.
- Malthe-Sørensen, A., Planke, S., Svensen, H., and Jamtveit, B. (2004). Formation of saucer-shaped sills, in Breikreuz, C. and Petford, N., eds., *Physical Geology of High-Level Magmatic Systems*. *Geological Society [London], Special Publication*, **234**, 215-227.
- Marsh, B.D. (1988). Crystal size distribution (CSD) in rocks and the kinetics and dynamics of crystallisation I: Theory. *Contributions to Mineralogy and Petrology*, **99**, 277-291.
- Marsh, B.D. (1996). Solidification fronts and magmatic evolution. *Mineralogical Magazine*, **60**, 5-40.
- Marsh, B.D. (1998). On the interpretation of crystal size distributions in magmatic systems. *Journal of Petrology*, **39**, 553-599.
- McBirney, A.R. & Noyes, R.M. (1979). Crystallisation and layering in the Skaergaard intrusion. *Journal of Petrology*, **38**, 487-554.
- McBirney, A.R. & Hunter, R.H. (1995). The cumulate paradigm reconsidered. *Journal of Geology*, **103**, 114-122.

- McBirney, A.R. & Nicolas, A., (1997). The Skaergaard Layered Series: Part II. Dynamic layering: *Journal of Petrology*, **38**, 569-580.
- McKenzie, D.P. (1984). The generation and compaction of partially molten rock. *Journal of Petrology*, **25**, 713-766.
- Meurer, W.P. & Boudreau, A.E. (1998). Compaction of igneous cumulates. Part II: Compaction and the development of igneous foliations. *Journal of Geology*, **106**, 293-304.
- Mitchell, J.G., and Reen, K.P. (1973). Potassium-argon ages from the Tertiary Ring Complexes of the Ardnamurchan Peninsula, Western Scotland. *Geological Magazine*, **110** (4), 331-340.
- Mock, A. & Jerram, D.A. (2005). Crystal size distributions (CSD) in three dimensions: insights from the 3D reconstruction of a highly porphyritic rhyolite. *Journal of Petrology*, **46** (8), 1525-1541.
- Morgan, D.J. & Jerram, D.A. (2006). On estimating crystal shape for crystal size distribution analysis. *Journal of Volcanology and Geothermal Research*, **154**, 1-7.
- Morse, S.A. (1979). Kigaplaits geochemistry I: Systematics, sampling and density. *Journal of Petrology*, **20**, 555-590.
- Moseley, D. (1984). Symplectic exsolution in olivine. *American Mineralogist*, **69**, 139-153.
- Nicolas, A. (1992). Kinematics in magmatic rocks with special reference to gabbros. *Journal of Petrology*, **33**, 891-915.
- O'Driscoll, B. (2003). *The Geology of Dawros Peninsula and Hinterland*. Unpublished Undergraduate Thesis, University College Cork, 120p.
- O'Driscoll, B. (2005). Textural equilibrium in magmatic layers of the syn-tectonic Lough Fee ultramafic intrusion, NW Connemara: implications for adcumulus mineral growth. *Irish Journal of Earth Sciences*, **23**, 39-45.
- O'Driscoll, B., Powell, D.G.R., & Reavy, R.J. (2005). Constraints on the development of magmatic layering in a syntectonic mafic-ultramafic suite, NW Connemara, Ireland. *Scottish Journal of Geology*, **41** (2), 119-128.
- O'Reilly, W. (1984). *Rock and Mineral Magnetism*. Blackie, 220 p.
- Owens, W.H. (2000). Statistical applications to second-rank tensors in magnetic fabric analysis. *Geophysical Journal International*, **142**, 115-131.
- Owens, W.H. & Bamford, D. (1976). Magnetic, seismic and other anisotropic properties of rock fabrics. *Philosophical Transactions of the Royal Society of London, A*, **283**, 55-68.
- Park, Y. & Hanson, B. (1999). Experimental investigation of Ostwald-ripening rates of forsterite in the haplobasaltic system. *Journal of Volcanology and Geothermal Research*, **90**, 103-113.
- Pouchou, J.L. & Pichoir, F. (1984). A new model for quantitative X-ray microanalysis, Part I. Application to the analysis of homogenous samples. *Recherche Aerospatiale*, **3**, 13-38.
- Putnis, A. (1979). Electron petrography of high-temperature oxidation in olivine from the Rhum layered intrusion. *Mineralogical Magazine*, **43**, 293-297.
- Renner, R., & Palacz, Z.A. (1987). Basaltic replenishment of the Rhum magma chamber: evidence from unit 14. *Journal of the Geological Society of London*, **144**, 961-970.

- Richey, J.E. & Thomas, H.H. (1930). *The Geology of Ardnamurchan, North-west Mull and Coll*. Memoir Geol. Surv. Scotland, HMSO.
- Richey, J.E. (1932). Tertiary Ring Structures in Britain. *The Transactions of the Geological Society of Glasgow*, **19**, Part 1, 45-61.
- Roche, O., Druitt, T.H., & Merle, O. (2000). Experimental study of caldera formation: *Journal of Geophysical Research*, **105**, 395-416.
- Rochette, P. (1987). Magnetic susceptibility of the rock matrix related to magnetic fabric studies. *Journal of Structural Geology*, **9** No. 8, 1015-1020.
- Rochette, P., Jackson, M. & Aubourg, C. (1992). Rock magnetism and the interpretation of anisotropy of magnetic susceptibility. *Reviews in Geophysics*, **30**, 209-226.
- Rochette, P., Aubourg, C., & Perrin, M. (1999). Is this magnetic fabric normal? A review and case studies in volcanic formations. *Tectonophysics*, **307**, 219-234.
- Roggensack, K. (2001). Sizing up crystals and their melt inclusions: a new approach to crystallisation studies. *Earth and Planetary Science Letters*, **187**, 221-237.
- Rust, B.R. (1972). Pebble orientation in fluvial sediments. *Journal of Sedimentary Petrology*, **42**, 384-388.
- Saunders, S.J. (2004). The possible contribution of circumferential fault intrusion to caldera resurgence. *Bulletin of Volcanology*, **67**, 57-71.
- Seitz, M.G. (1974). Promotion of kinetic disequilibrium of trace thorium. *Carnegie Institute of Washington Year Book*, **73**, 551-553.
- Skelhorn, R.R. & Elwell, R.W.D. (1971). Central subsidence in the layered hypersthene-gabbro of Centre 2, Ardnamurchan, Argyllshire. *Journal of the Geological Society, London*, **127**, 535-551.
- Tarling, D. H., & Hrouda, F. (1993). *The Magnetic Anisotropy of Rocks*. Chapman and Hall, London.
- Taubeneck, W.H. & Poldevaart, A. (1960). Geology of the Elkhorn mountains, Northeastern Oregon: Part 2. Willow Lake intrusion. *Bulletin of the Geological Society of America*, **71**, 1295-1322.
- Tait, S.R. (1985). Fluid dynamic and geochemical evolution of cyclic unit 10, Rhum, Eastern Layered Series. *Geological Magazine*, **122**, 555-568.
- Tepley, F.J. & Davidson, J.P. (2003). Mineral-scale Sr-isotope constraints on magma evolution and chamber dynamics in the Rum layered intrusion, Scotland. *Contributions to Mineralogy and Petrology*, **145**, 628-641.
- Troll V.R. & Schmincke H.-U. (2002). Magma mixing and crustal recycling recorded in ternary feldspar from compositionally zoned peralkaline ignimbrite 'A', Gran Canaria, Canary Islands. *Journal of Petrology*, **43**, 243-270.
- Troll V.R., Donaldson C.H., & Emeleus C.H. (2004). Pre-eruptive magma mixing in intra- caldera ash-flow deposits of the Rum Igneous Centre, Scotland. *Contributions to Mineralogy and Petrology*, **147**, 722-739.
- Turner, S., George, R., Jerram, D.A., Hawkesworth C., & Carpenter N. (2003). Case studies of plagioclase growth and residence times in island arc lavas from Tonga and the Lesser Antilles and a model to reconcile discordant age information. *Earth and Planetary Science Letters*, **214**, 279-294.
- Upton, B.G.J., Skovgaard, A.C., McClurg, J., Kirstein, L., Cheadle, M., Emeleus, C.H., Wadsworth, W.J., & Fallick, A.E. (2002). Picritic magmas and the Rum ultramafic complex, Scotland. *Geological Magazine*, **139** (4), 437-452.

- Volker, J.A., & Upton, B.G.J. (1990). The structure and petrogenesis of the Trallval and Ruinsival areas of the Rhum ultrabasic complex. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **81**, 69-88.
- Wadsworth, W.J. (1961). The layered ultrabasic rocks of south-west Rhum, Inner Hebrides. *Philosophical Transactions of the Royal Society, London*, **244B**, 21-64.
- Wager, L.R., Brown, G.M., & Wadsworth, W.J. (1960). Types of igneous cumulates. *Journal of Petrology*, **1**, 73-85.
- Wager, L.R. & Brown, G.M. (1968). *Layered igneous rocks*. Edinburgh, Oliver and Boyd, 588p.
- Walsh, J.N. (1975). Clinopyroxenes and biotites from the Centre 3 igneous complex, Ardnamurchan, Argyllshire. *Mineralogical Magazine*, **40**, 335-345.
- Walsh, J.N. & Henderson, P. (1977). Rare earth patterns of rocks from the Centre 3 Igneous Complex, Ardnamurchan, Argyllshire. *Contributions to Mineralogy and Petrology*, **60**, 31-38.
- Walter, T.R. and Troll, V.R. (2001). Formation of caldera periphery faults: an experimental study. *Bulletin of Volcanology*, **63**, 191-203.
- Waters, C. & Boudreau, A.E. (1996). A reevaluation of crystal size distributions in chromite cumulates. *American Mineralogist*, **81**, 1452-1459.
- Wells, M.K. (1954a). The structure and petrology of the hypersthene-gabbro intrusion, Ardnamurchan, Argyllshire. *Quarterly Journal of the Geological Society*, **109**, 367-397.
- Wells, M.K. (1954b). The structure of the granophyric quartz-dolerite intrusion of Centre 2, Ardnamurchan, and the problem of net-veining. *Geological Magazine*, **91**, 293-307.
- Wells, M.K. & McRae, D.G. (1969). Palaeomagnetism of the hypersthene-gabbro intrusion, Ardnamurchan, Scotland. *Nature, London*, **223**, 608-609.
- Wiebe, R.A. & Collins, W.J. (1998). Depositional features and stratigraphic sections in granite plutons: implications for the emplacement and crystallization of granite magma. *Journal of Structural Geology*, **20**, 1273-1289.
- Wills, K.J.A. (1970). *The inner complex of Centre 3, Ardnamurchan*. Unpublished B.Sc thesis, Royal School of Mines, University of London.
- Woodcock, N. and Strachan, R., 2000, *Geological History of Britain and Ireland*: Blackwell Science, 423 p.
- Worral, L.M. (2002). *The origin of igneous cumulates: integrated studies of peridotites from the Western Layered Series of the Rum Layered Intrusion*. Unpublished Ph.D thesis, University of Liverpool.
- Young, I.M., Greenwood, R.C. & Donaldson, C.H. (1988). Formation of the Eastern Layered Series of the Rhum Complex, northwest Scotland. *Canadian Mineralogist*, **26**, 225-233.
- Zieg, M.J. and Lofgren, G.E. (2006). An experimental investigation of texture evolution during continuous cooling. *Journal of Volcanology and Geothermal Research*, **154**, 74-88.

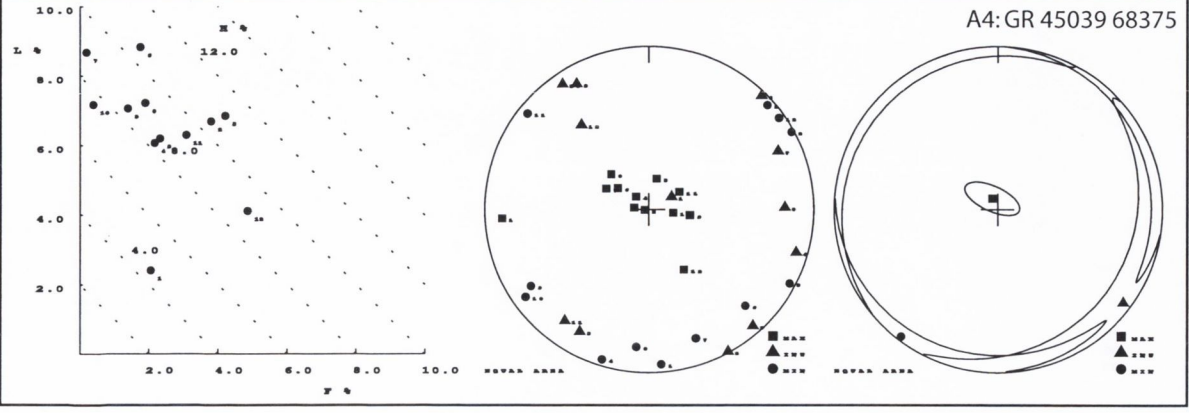
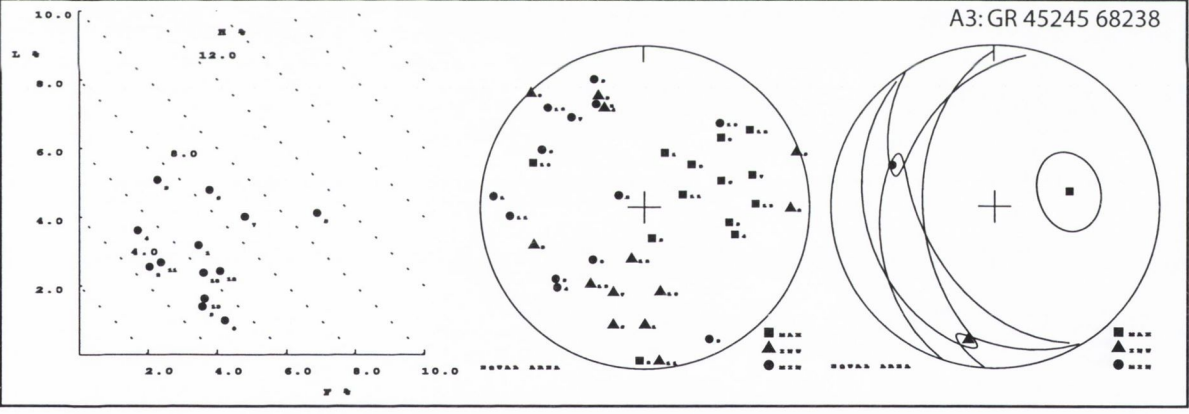
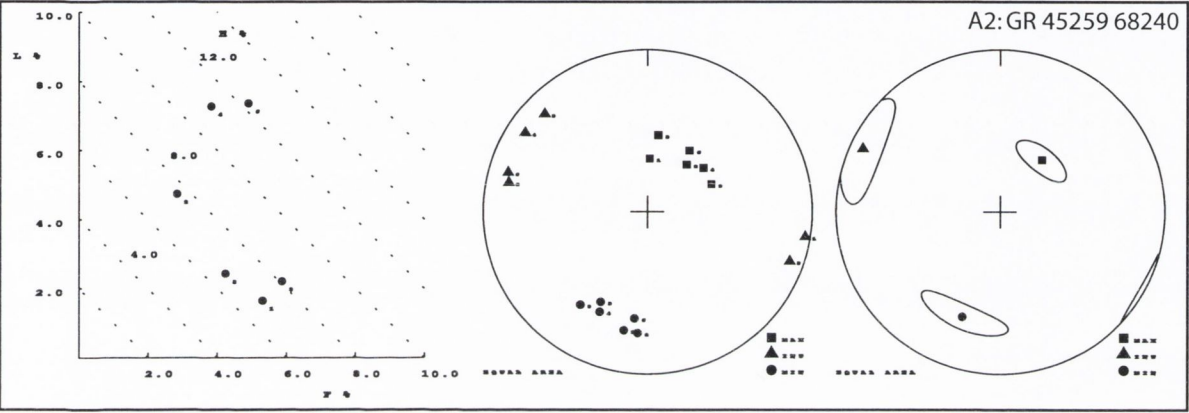
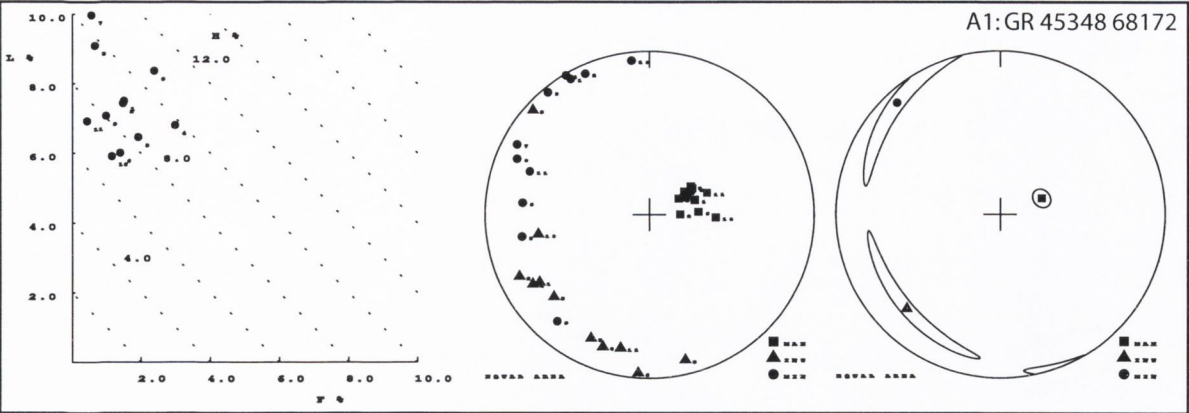
APPENDICES

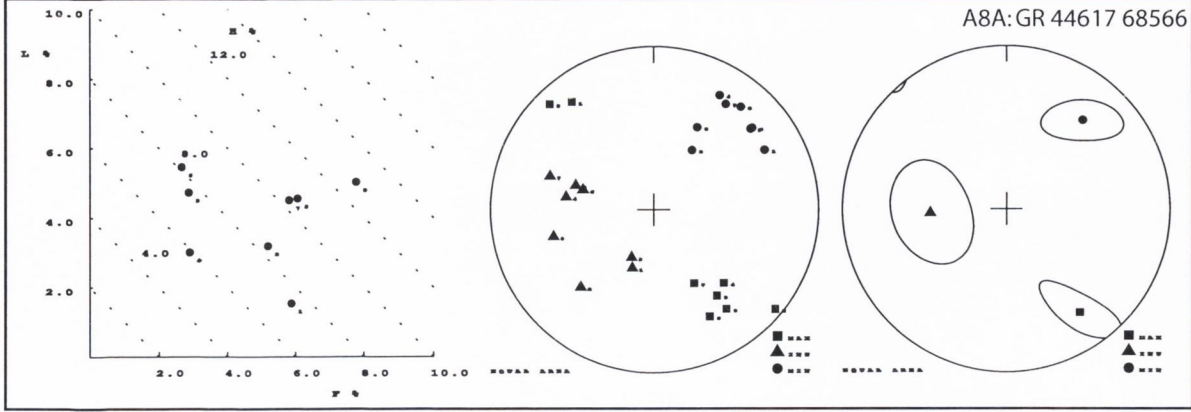
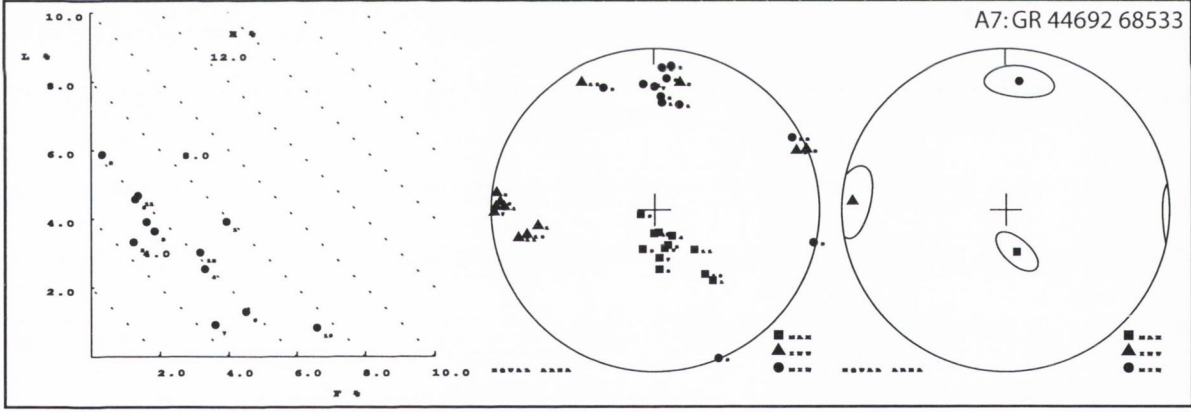
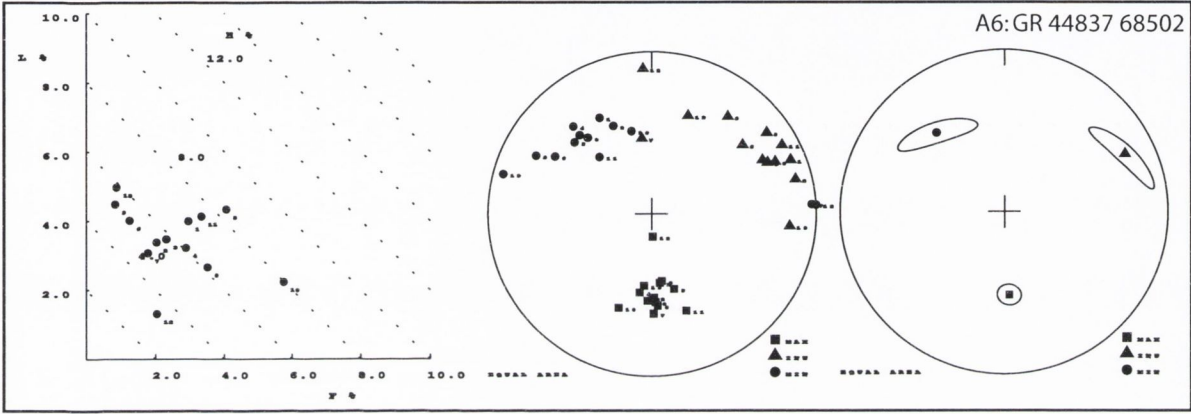
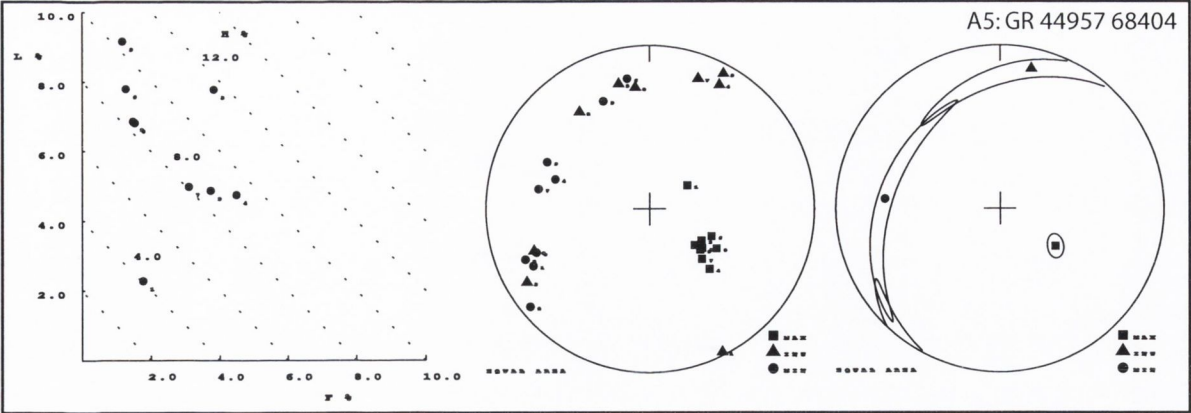
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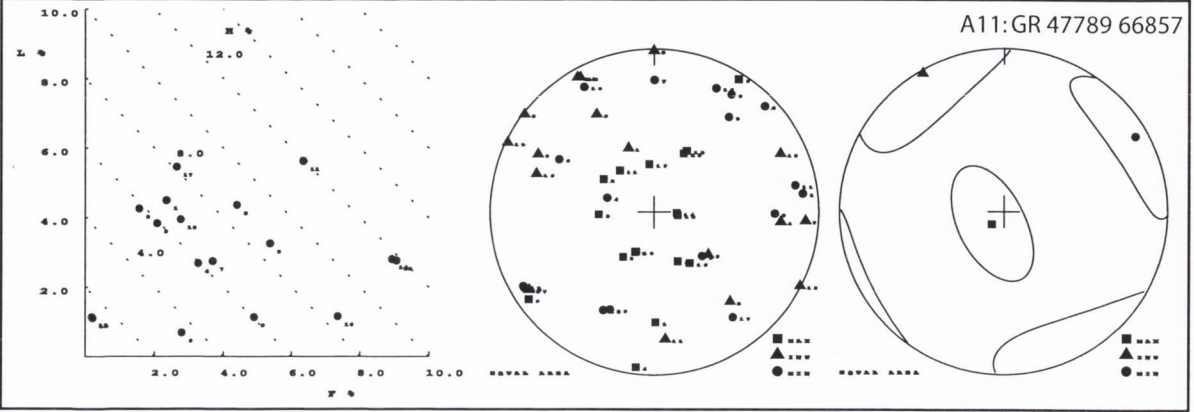
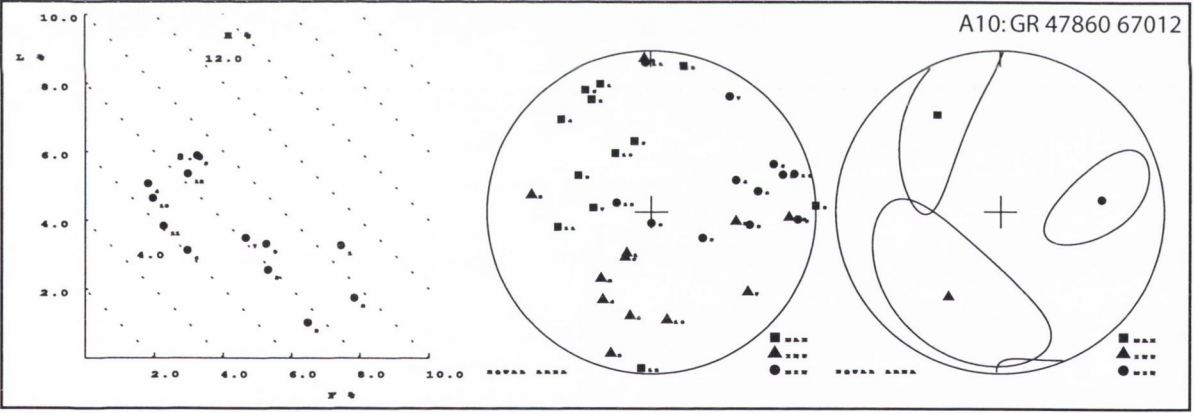
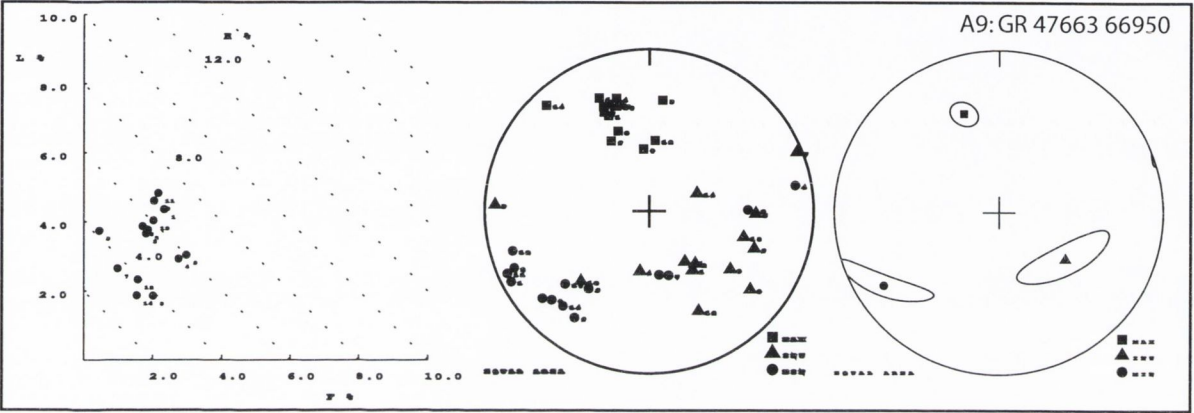
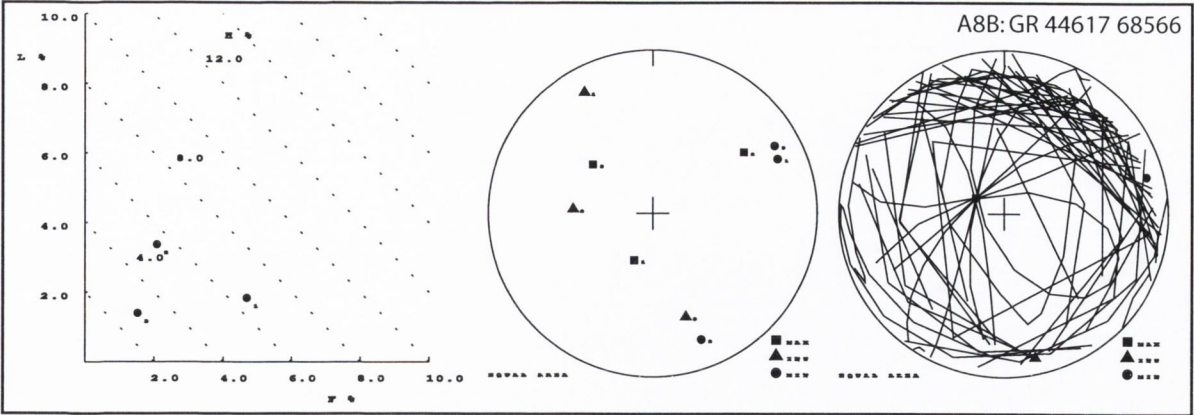
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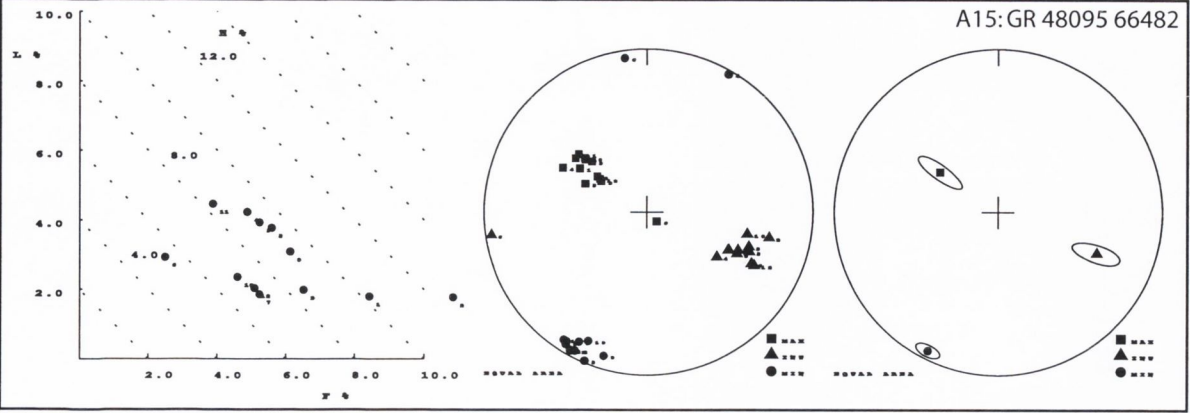
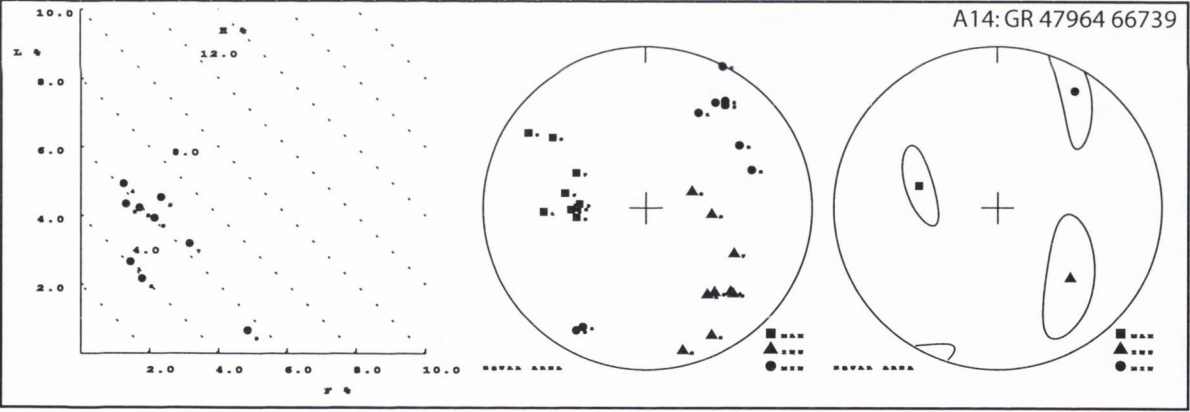
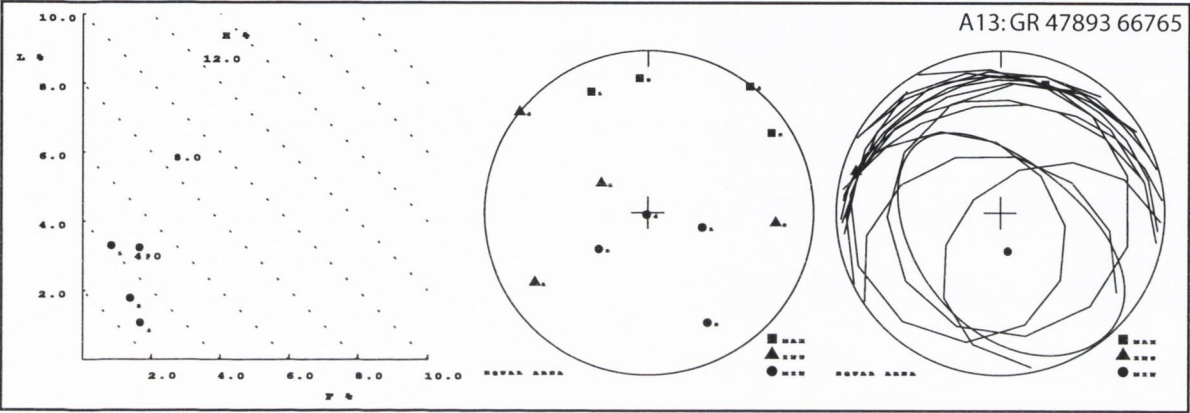
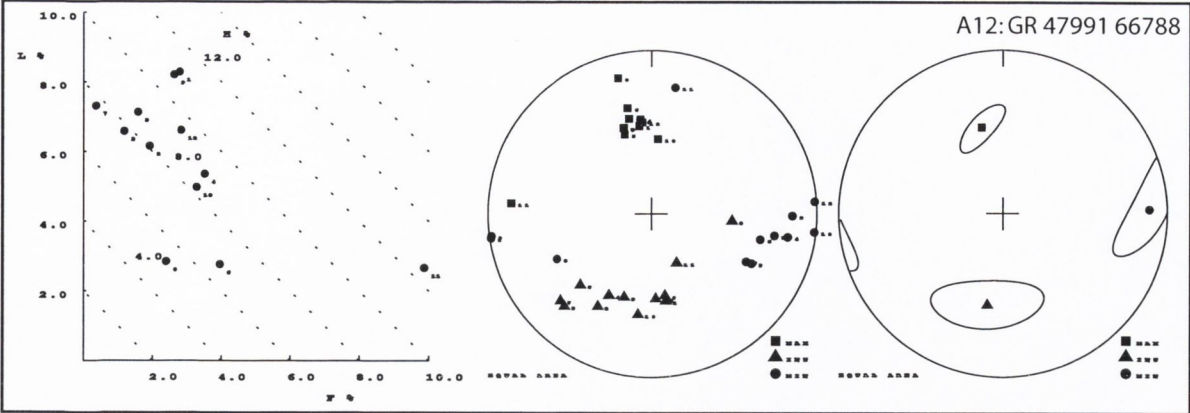
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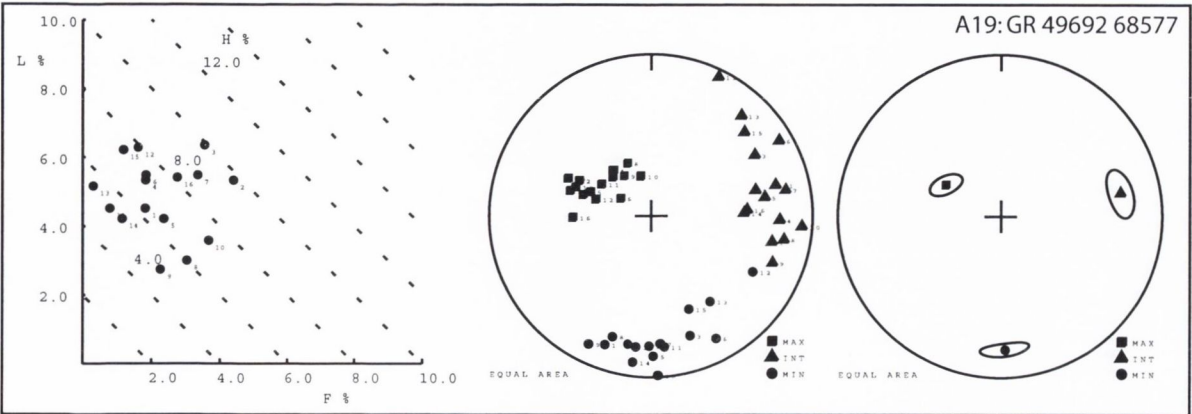
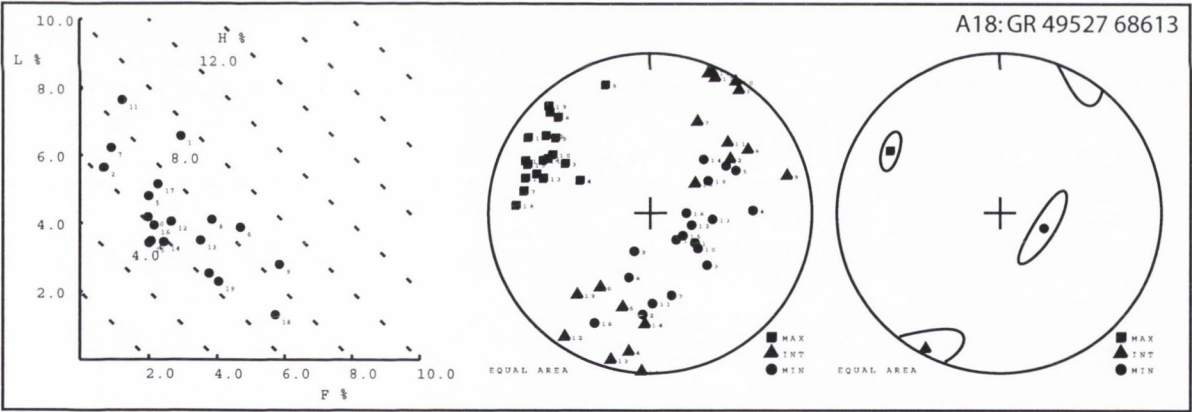
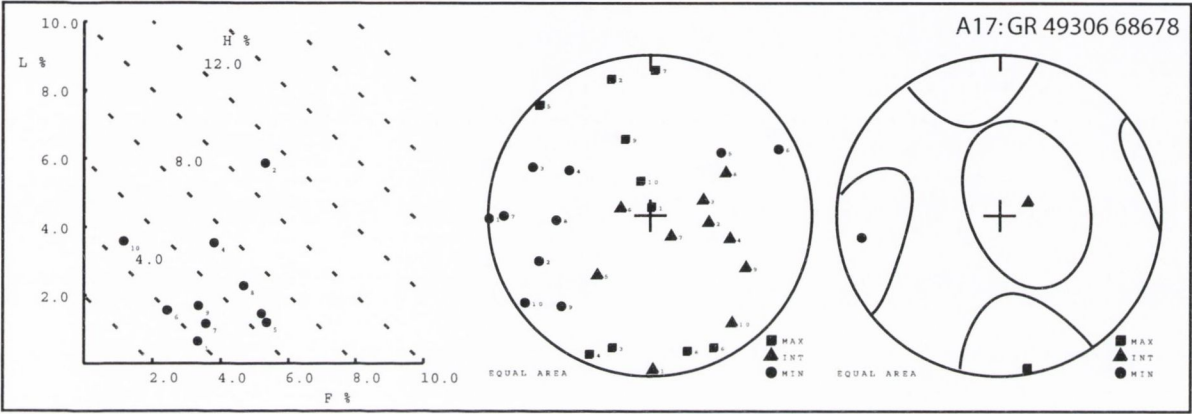
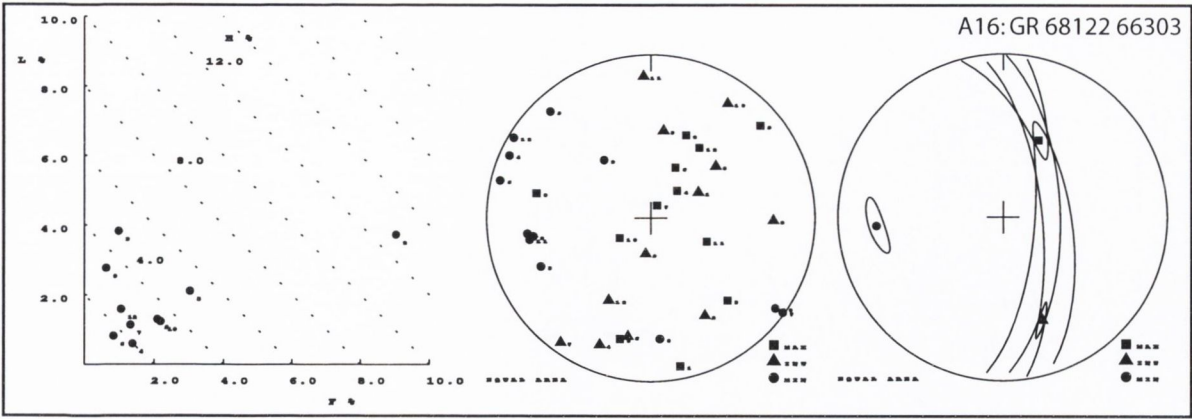
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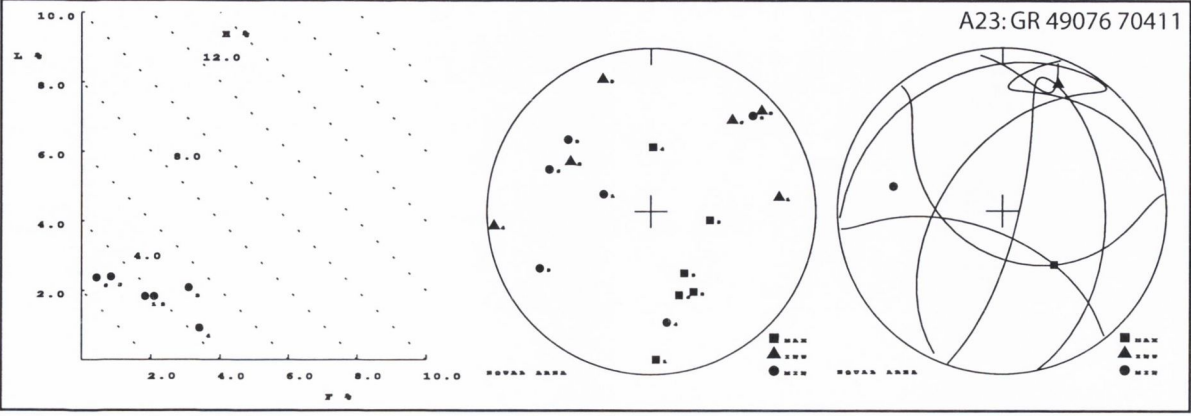
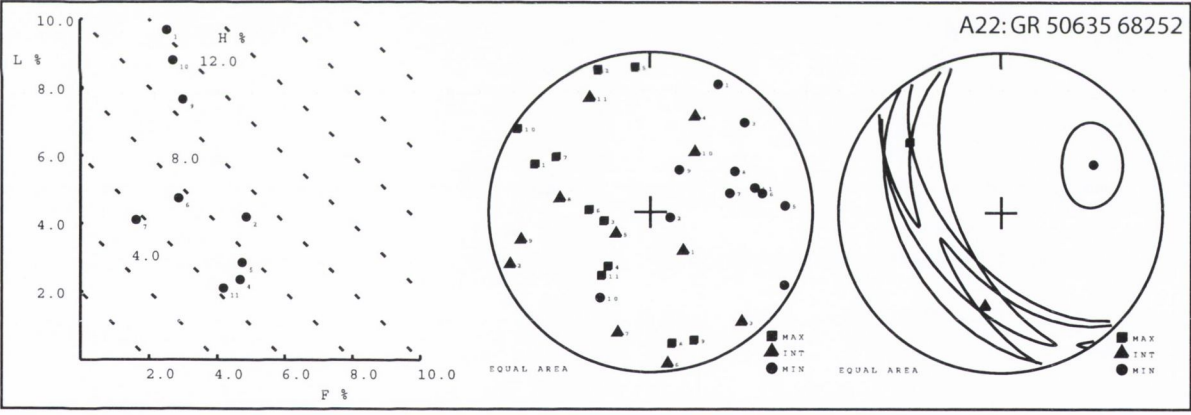
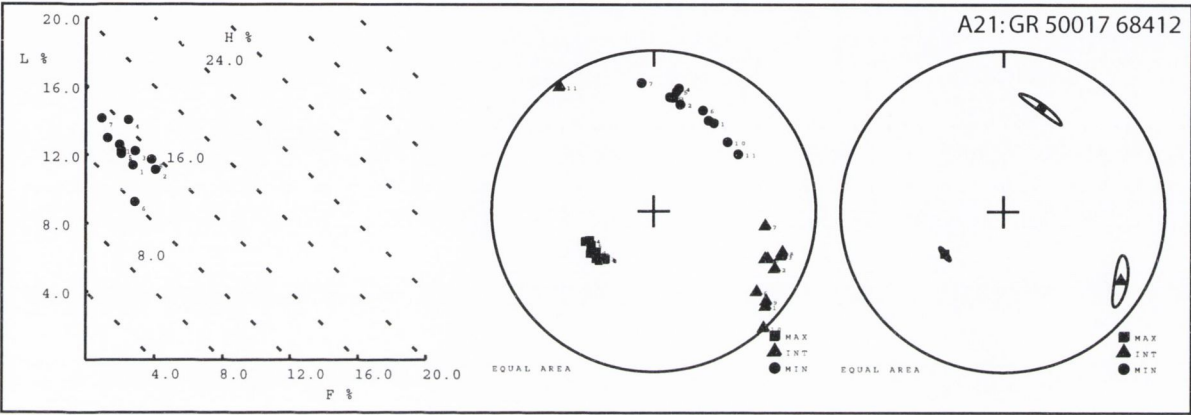
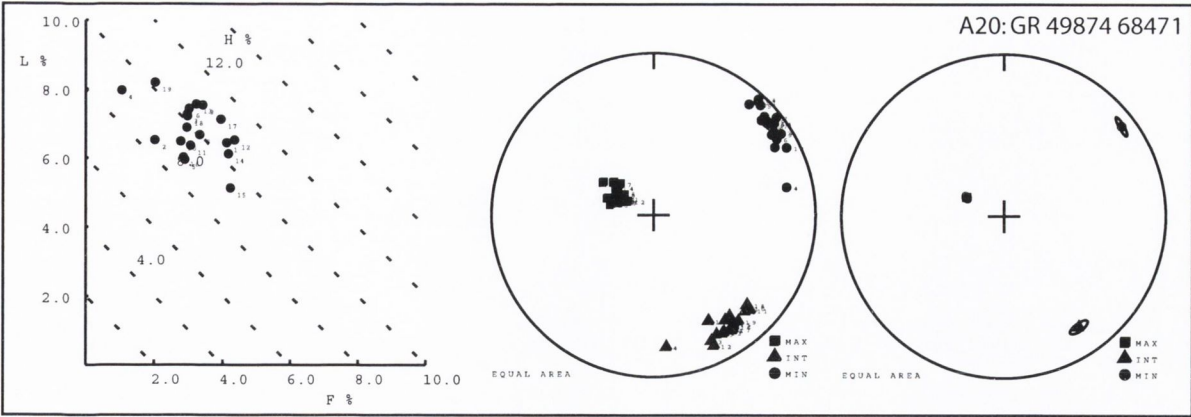


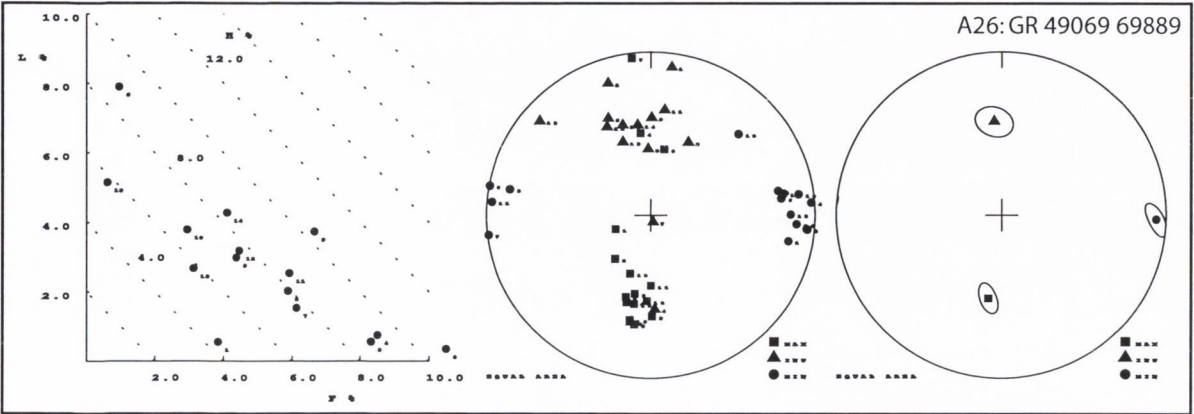
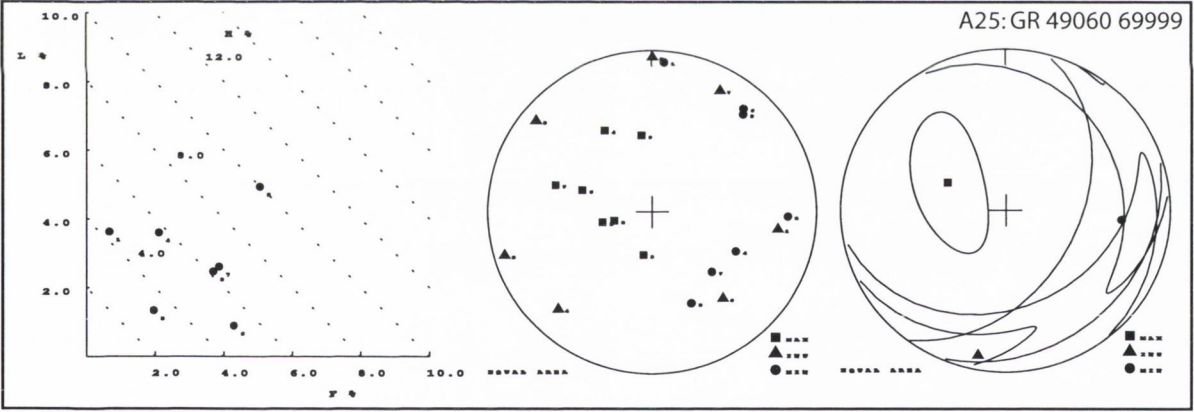
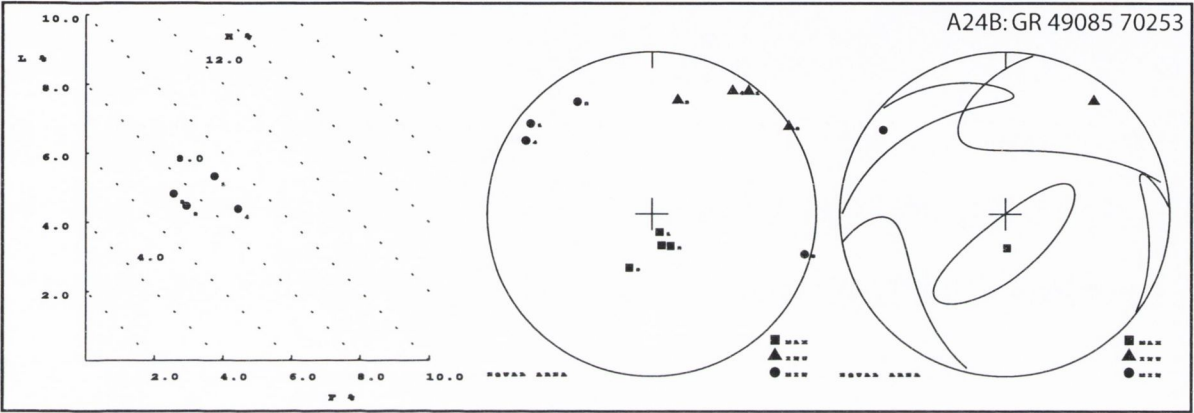
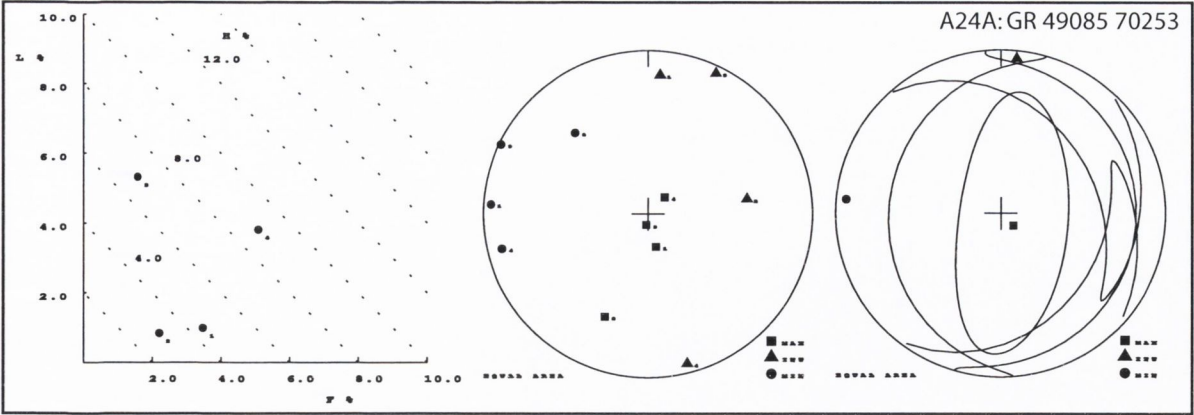


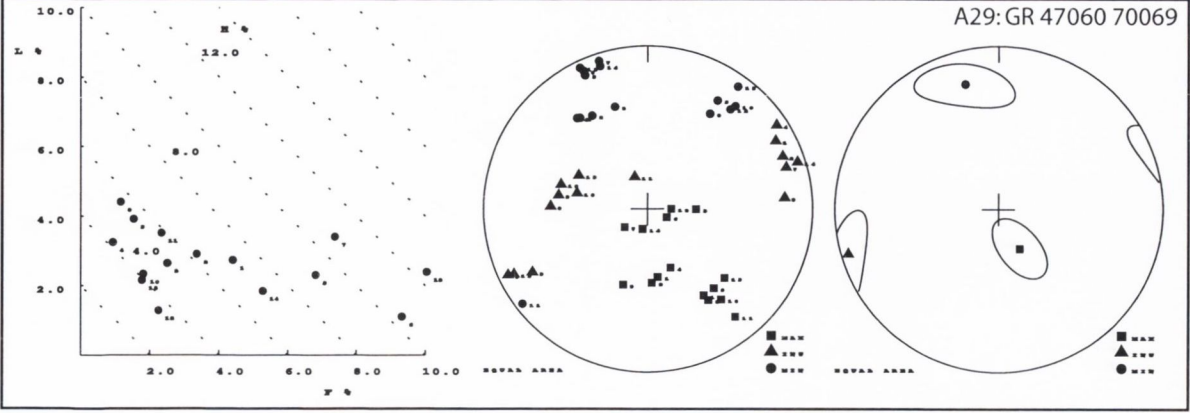
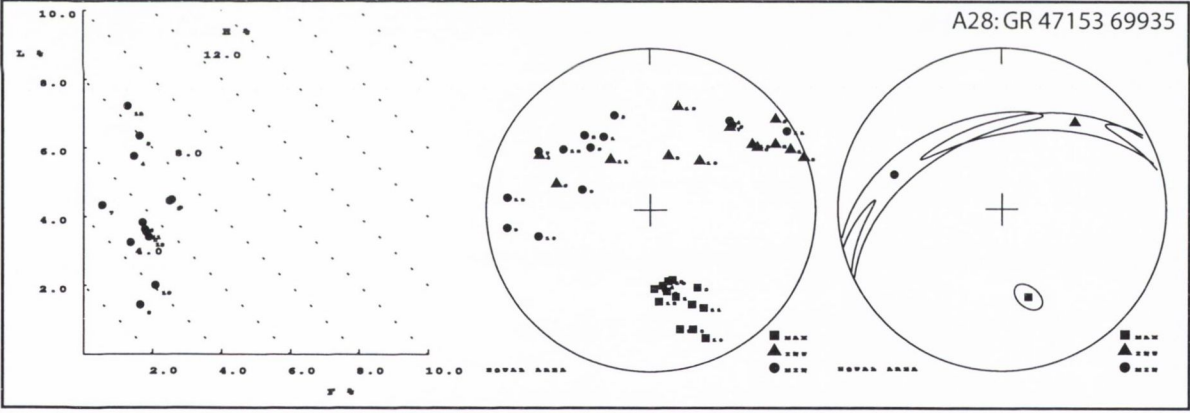
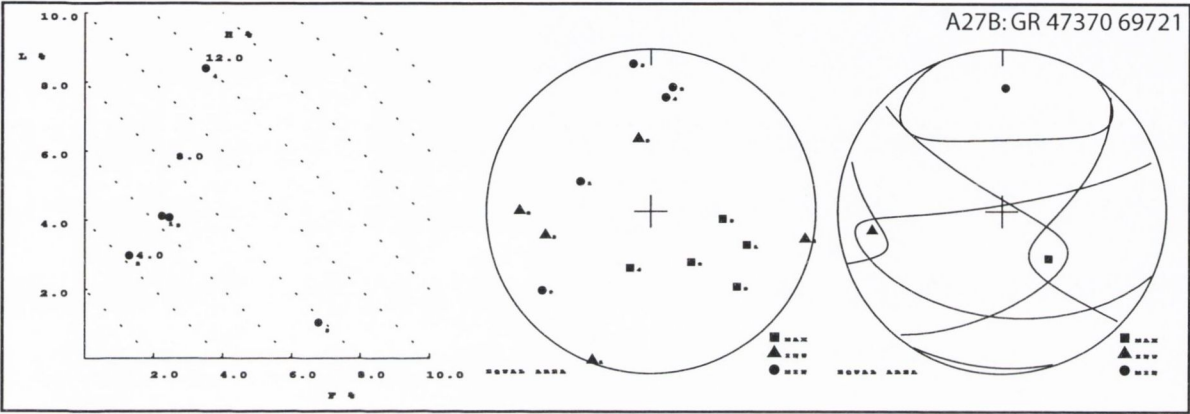
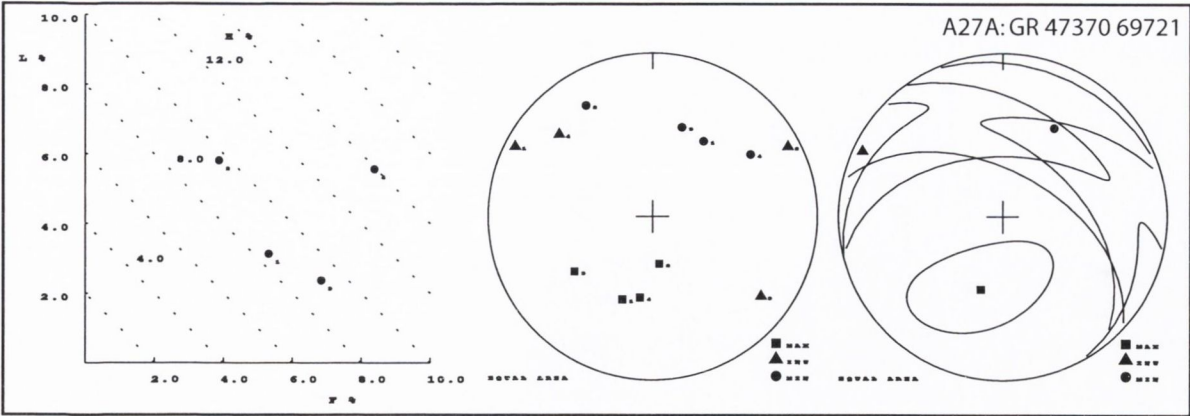


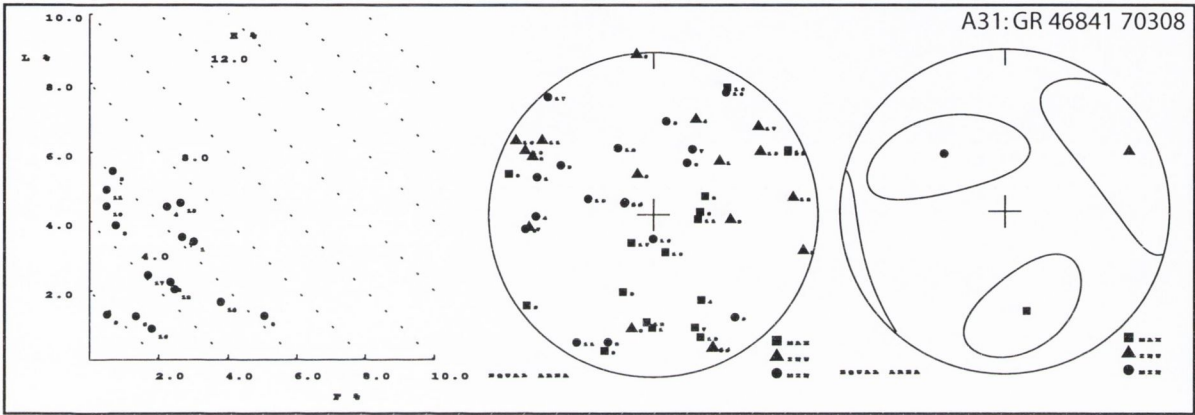
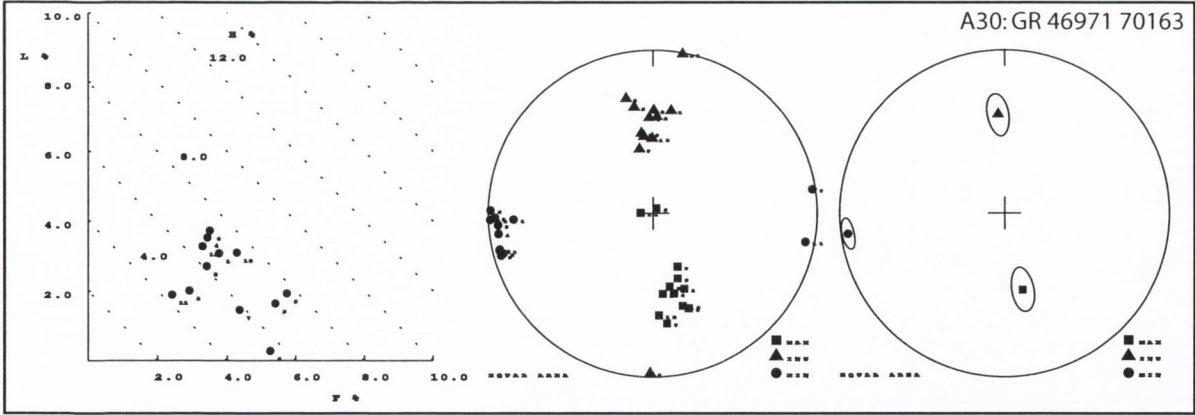




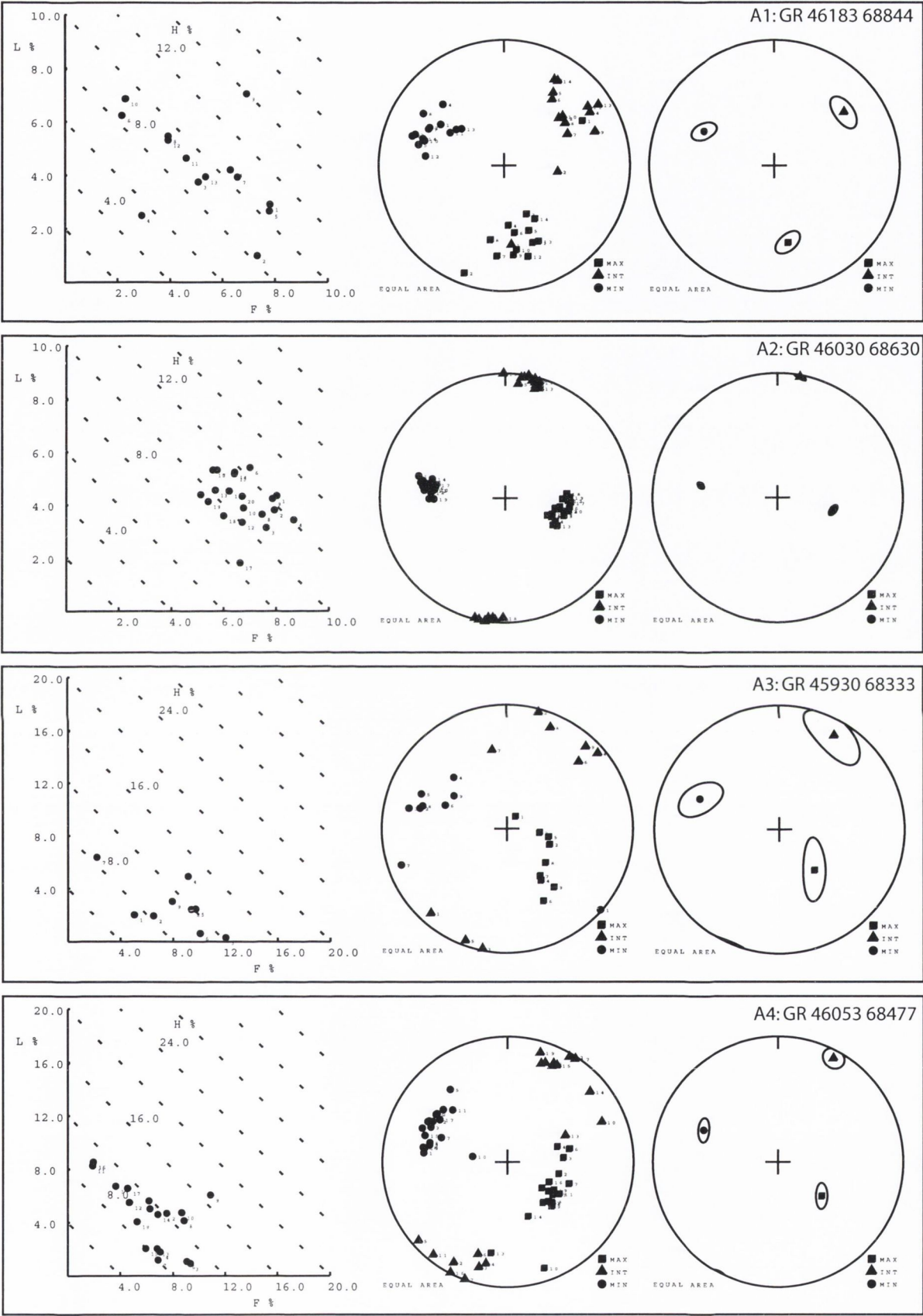


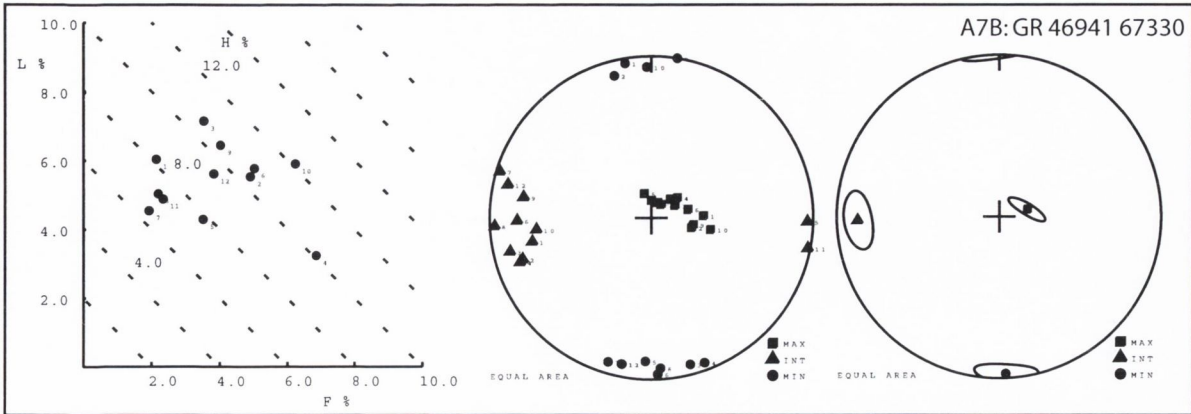
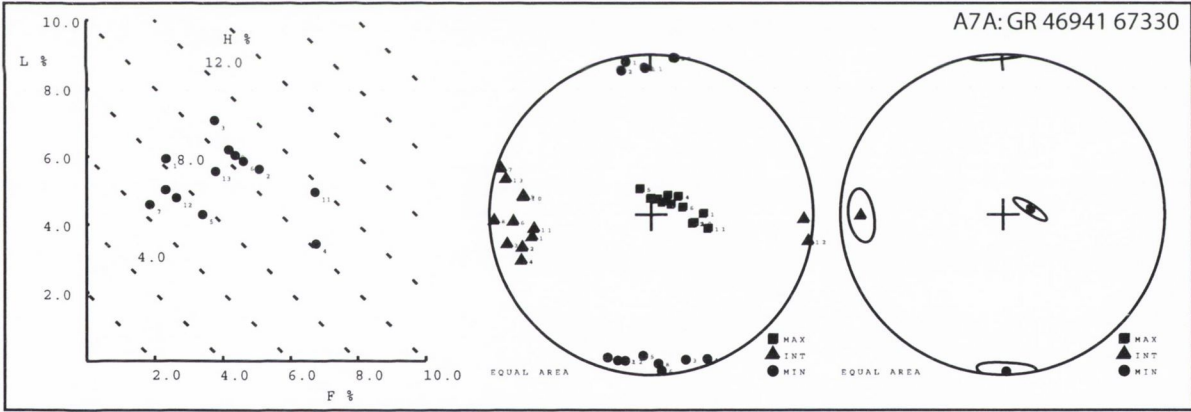
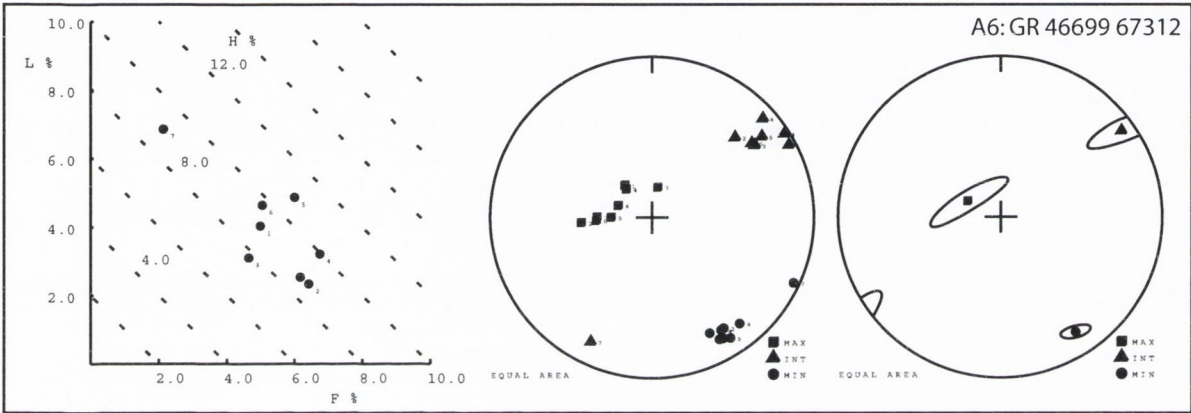
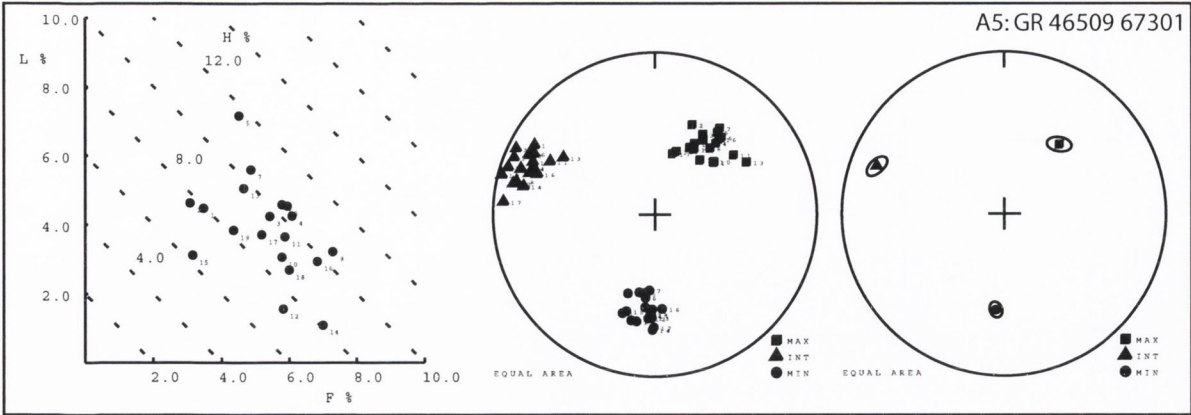


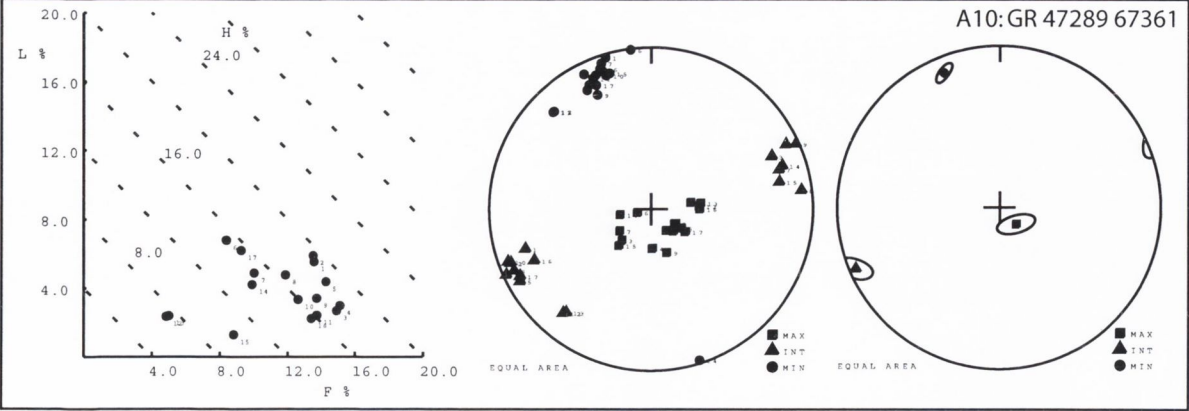
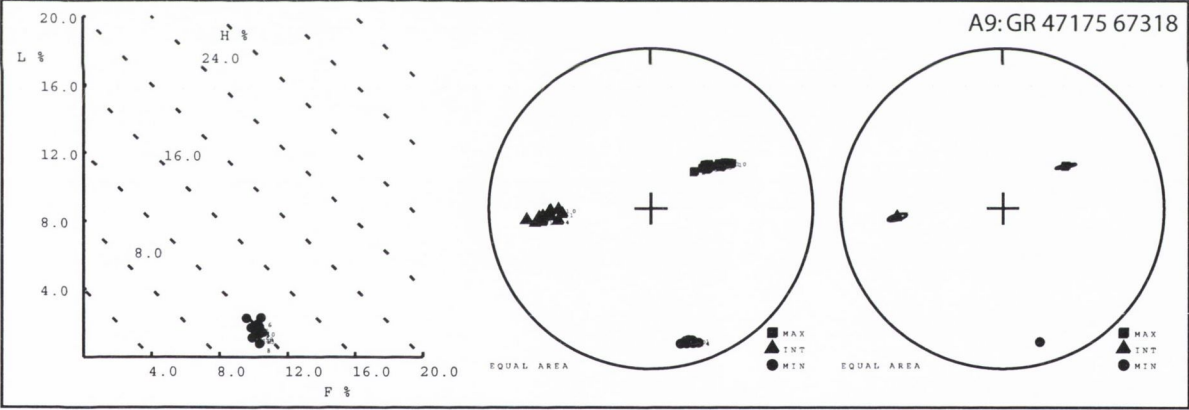
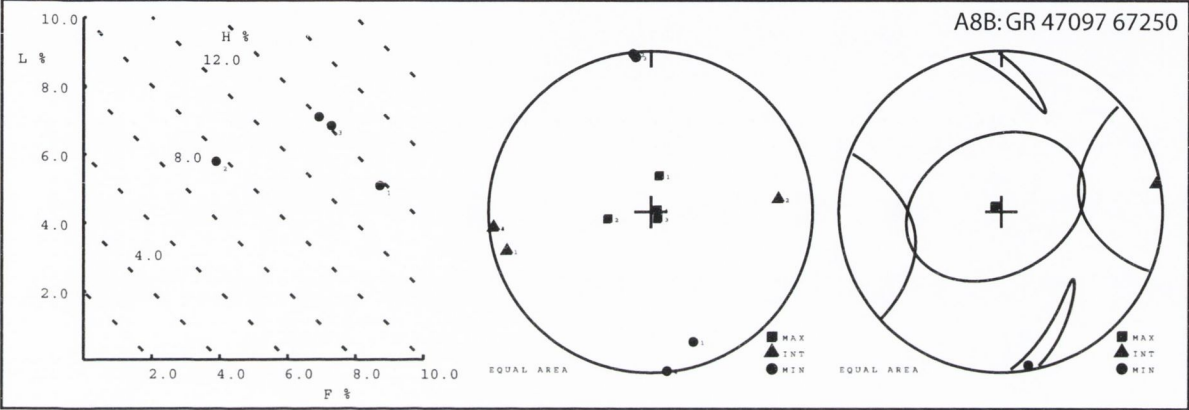
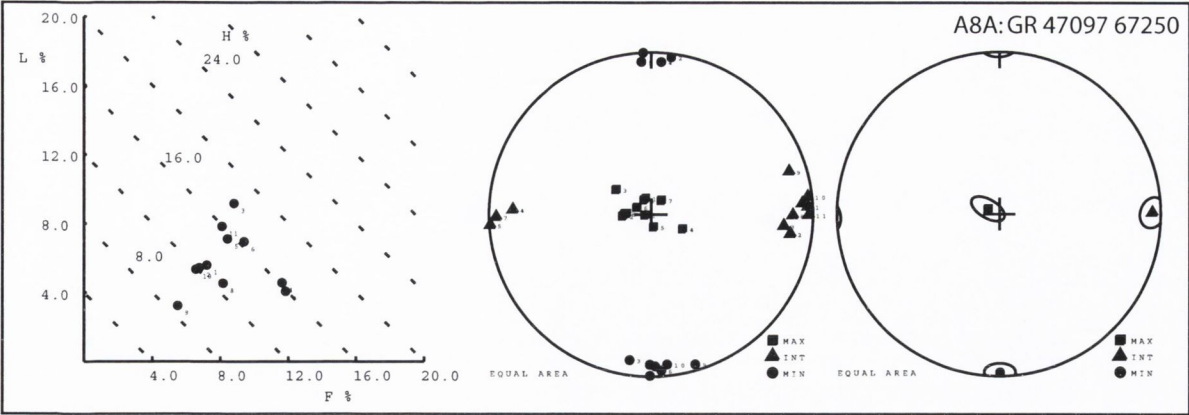


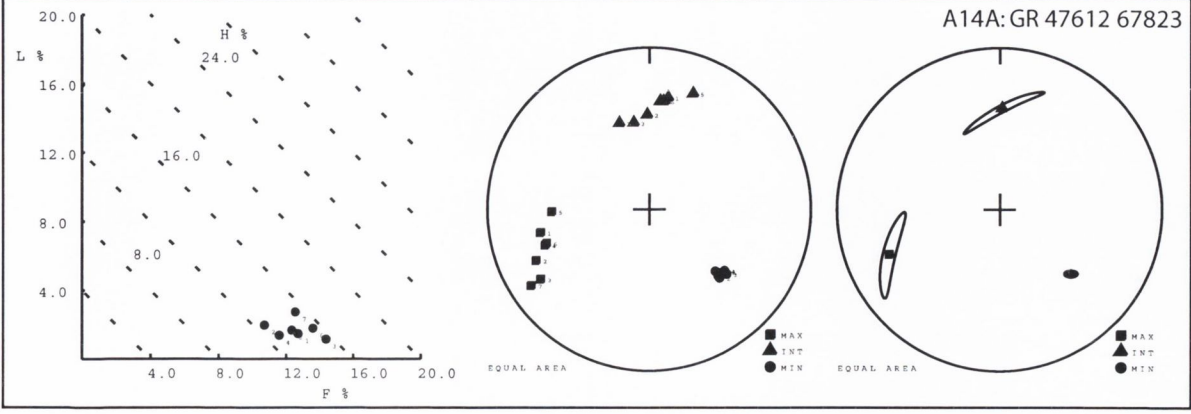
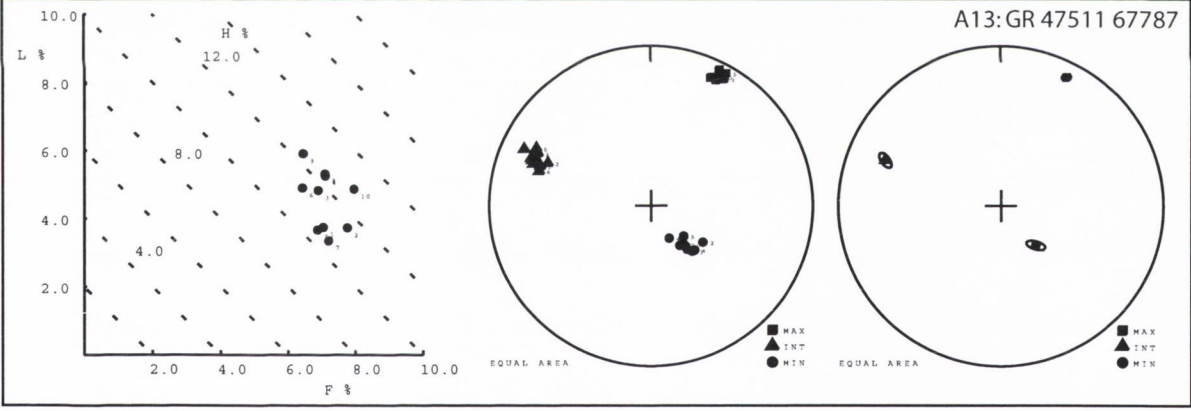
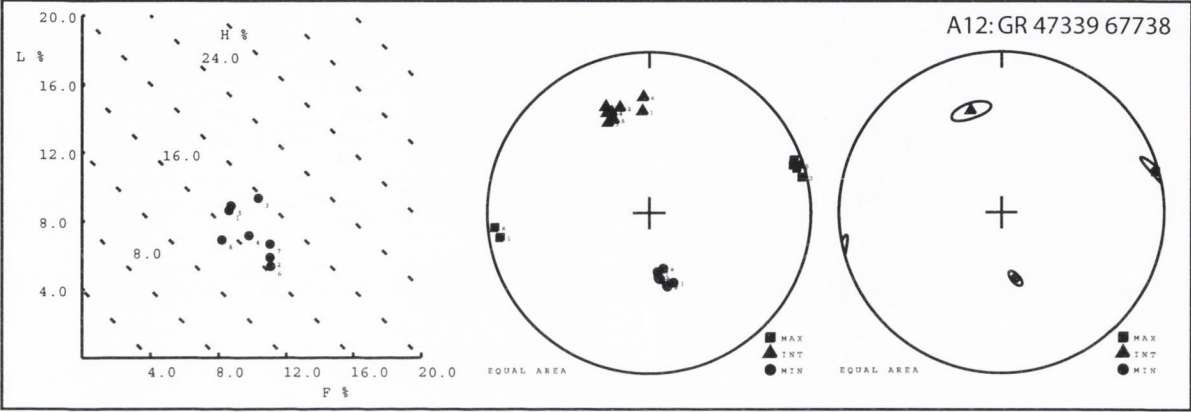
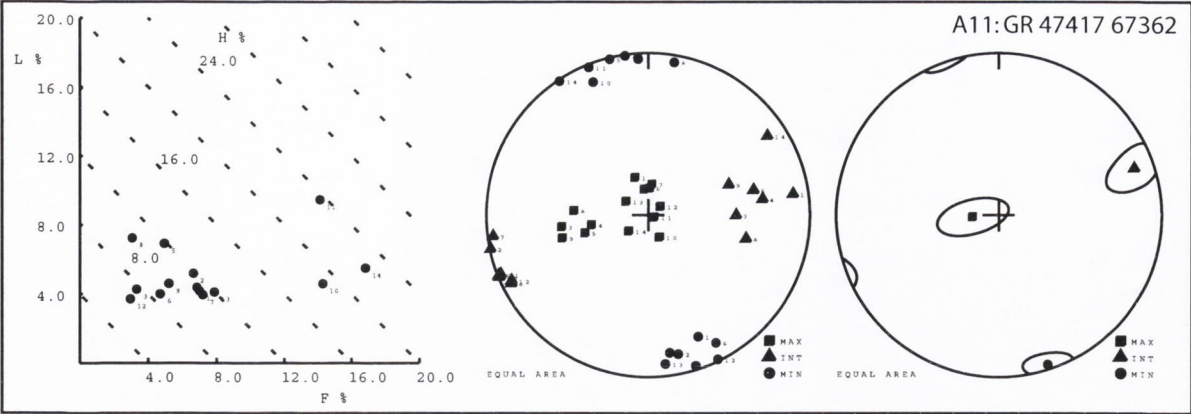


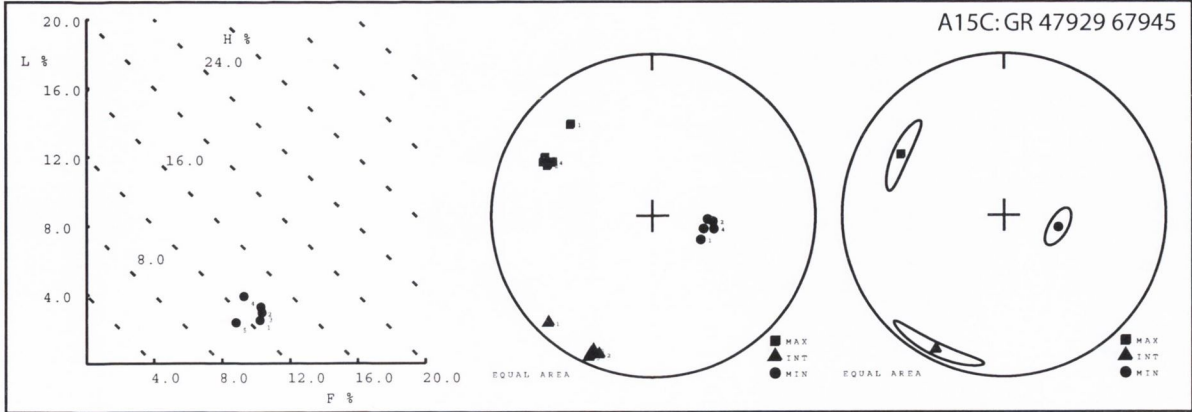
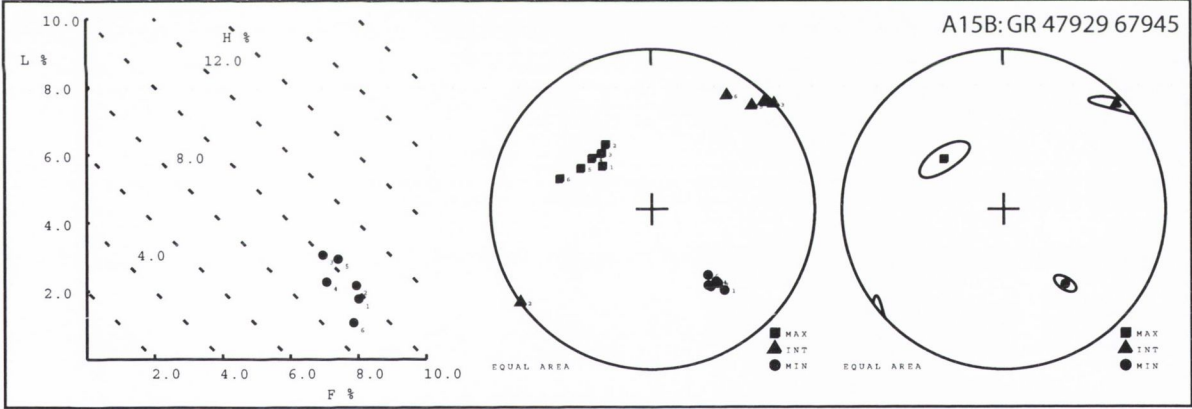
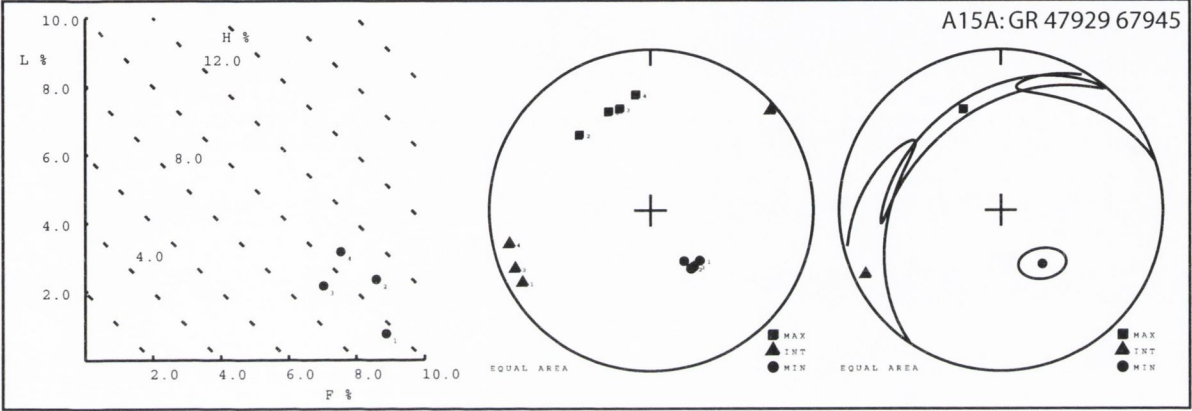
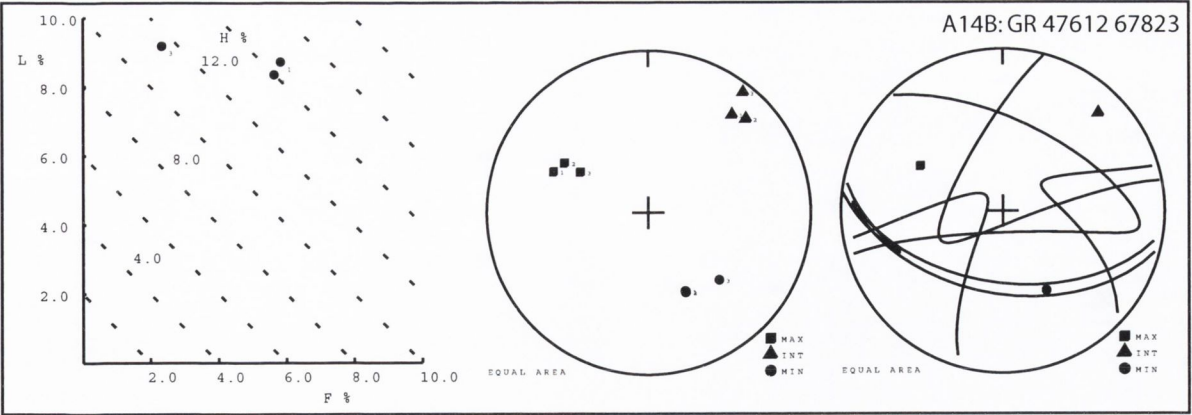
Ardnamurchan Laminated Gabbros

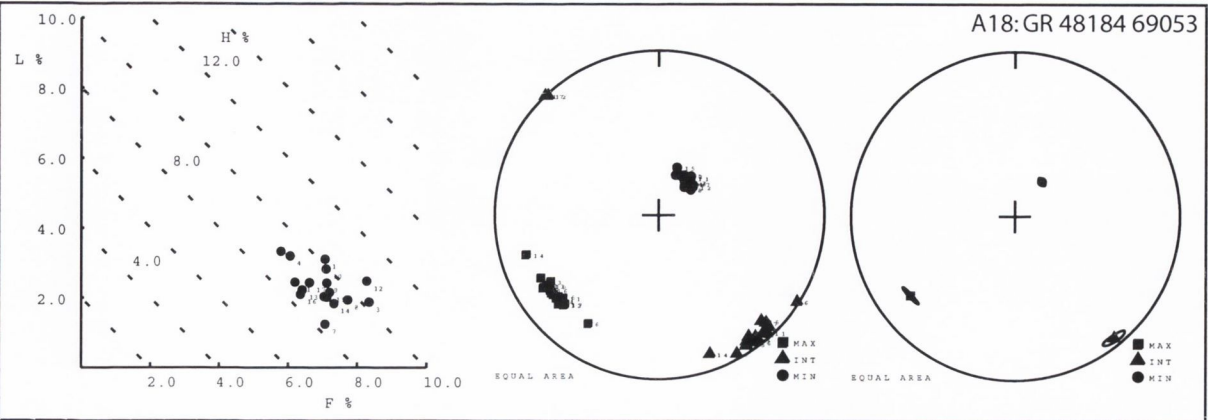
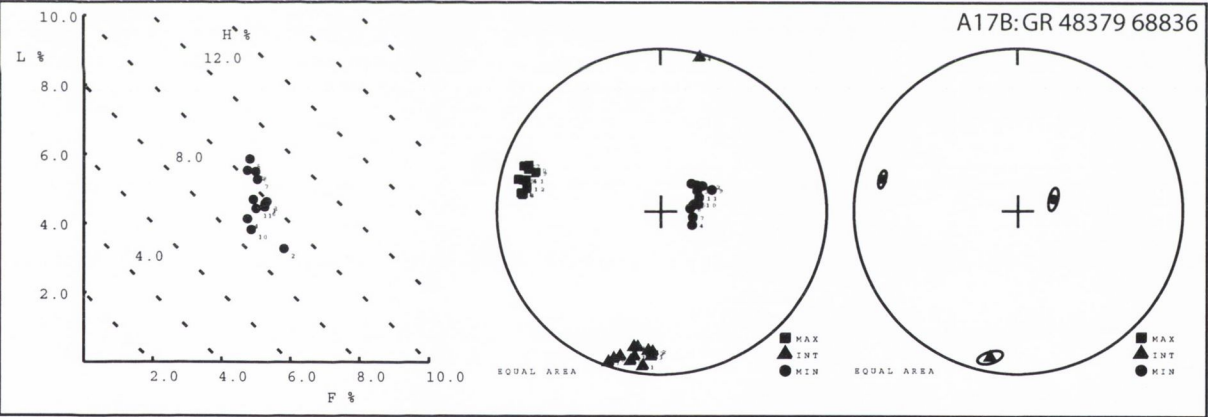
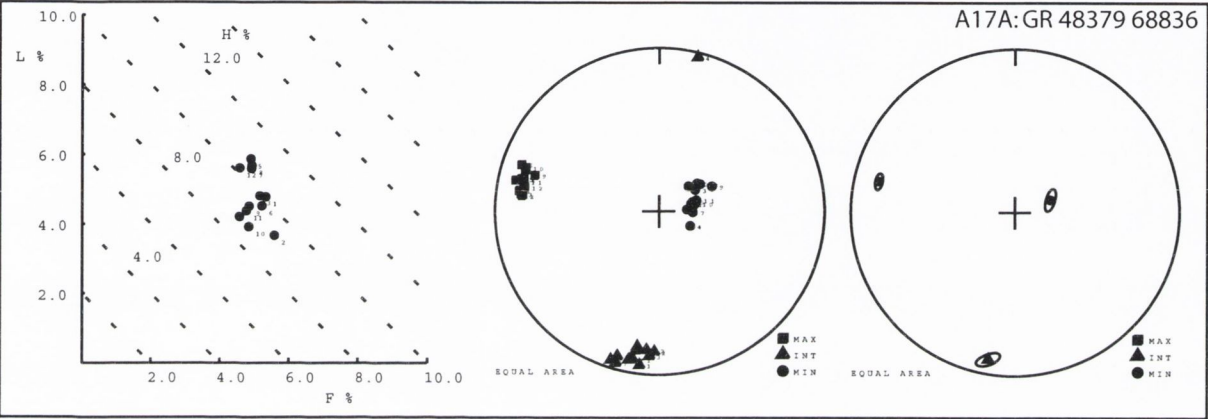
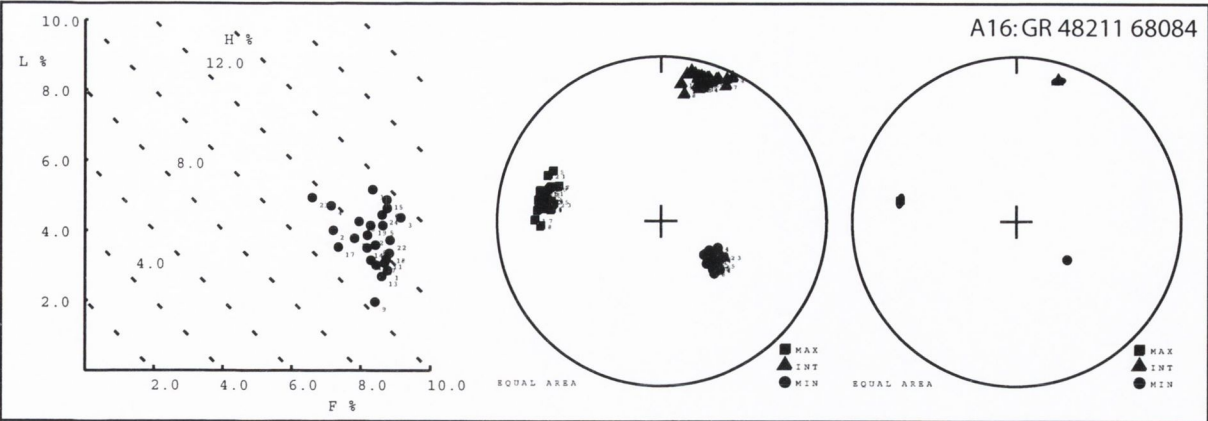


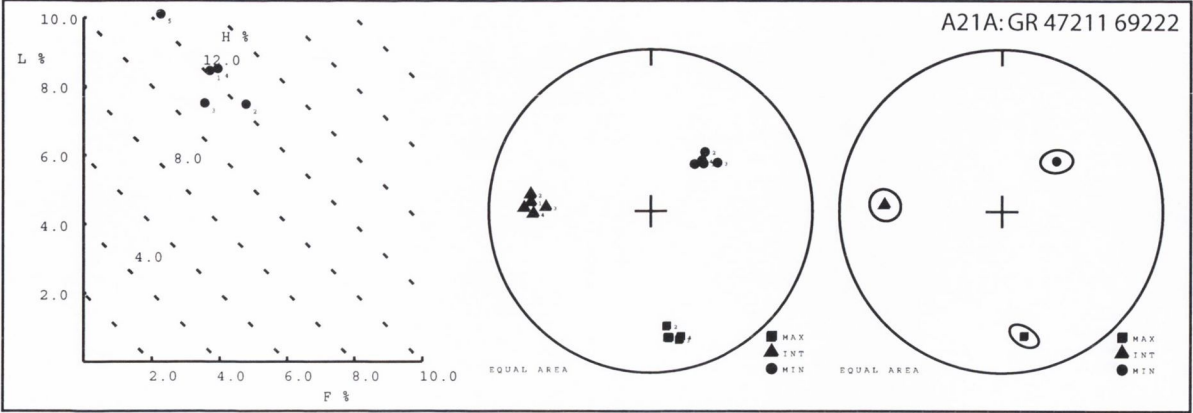
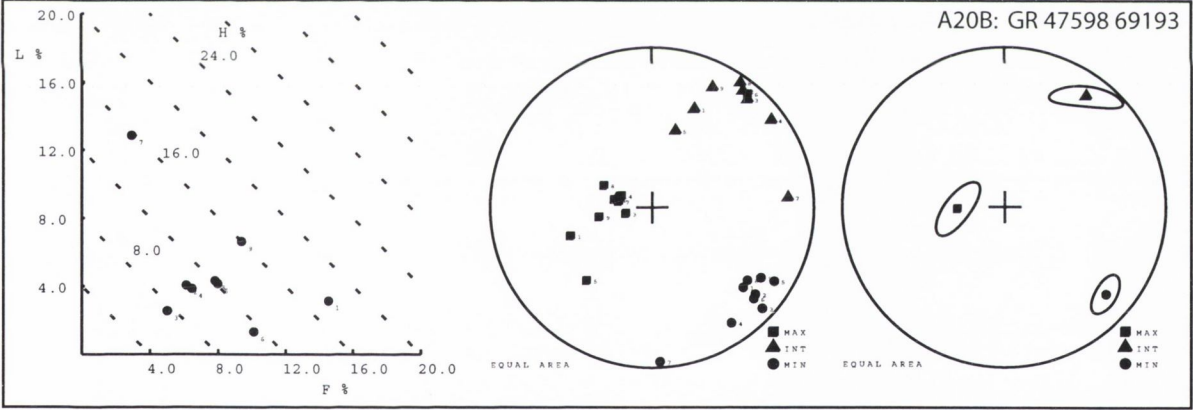
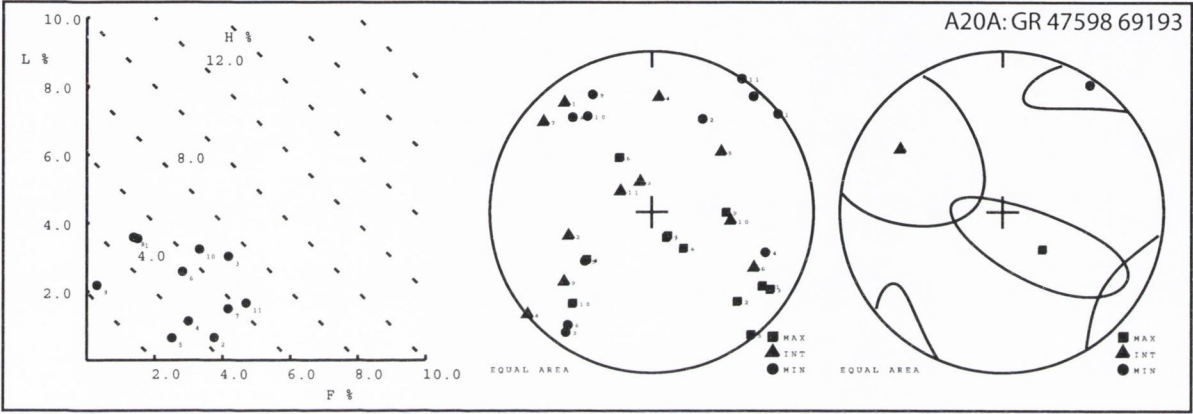
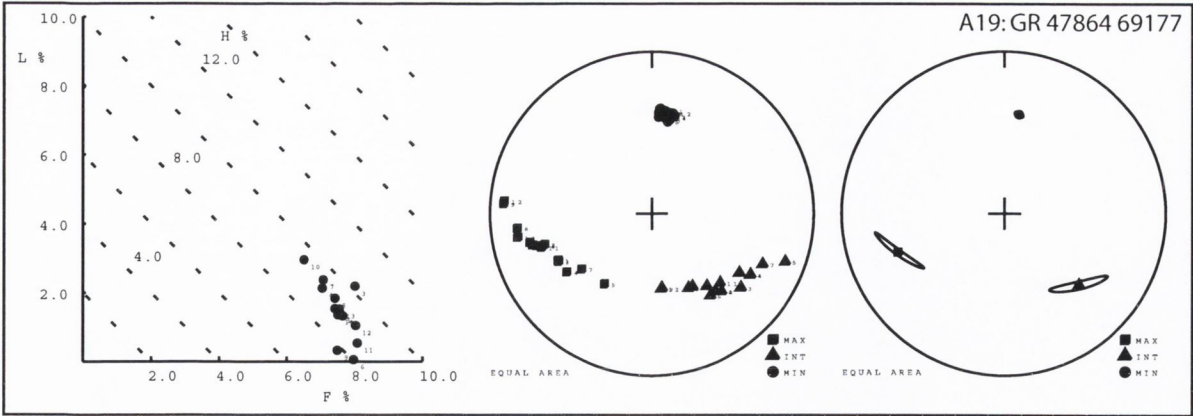


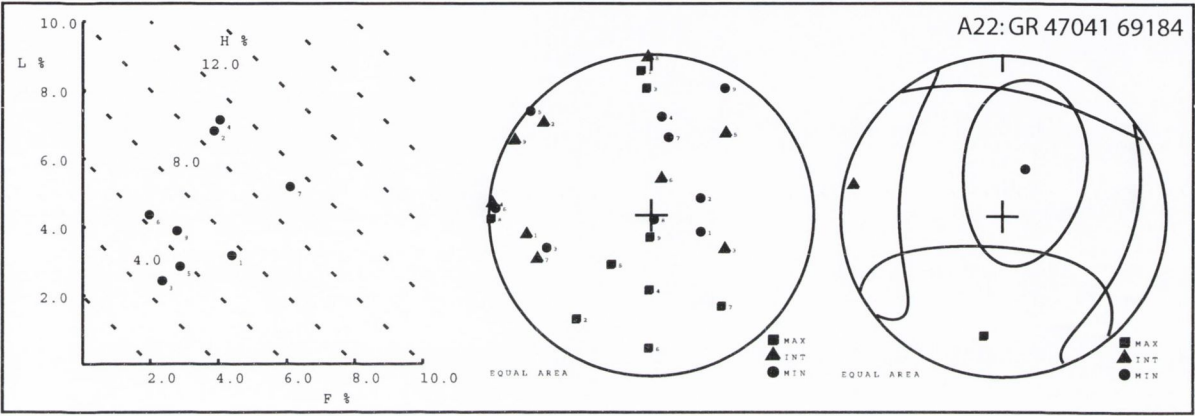
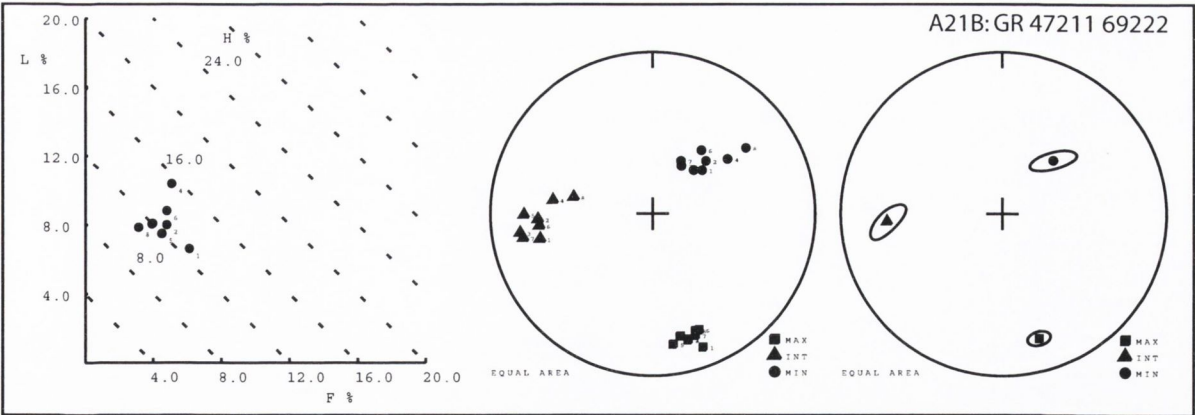




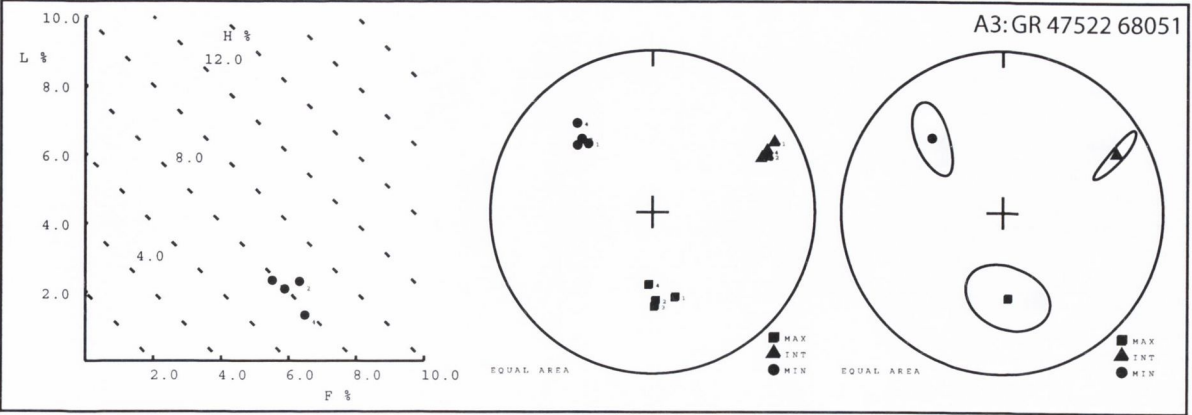
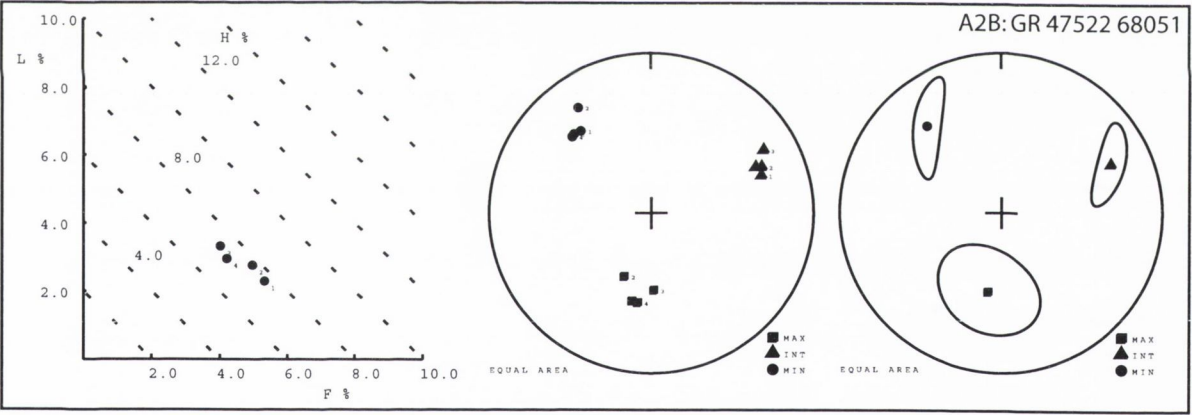
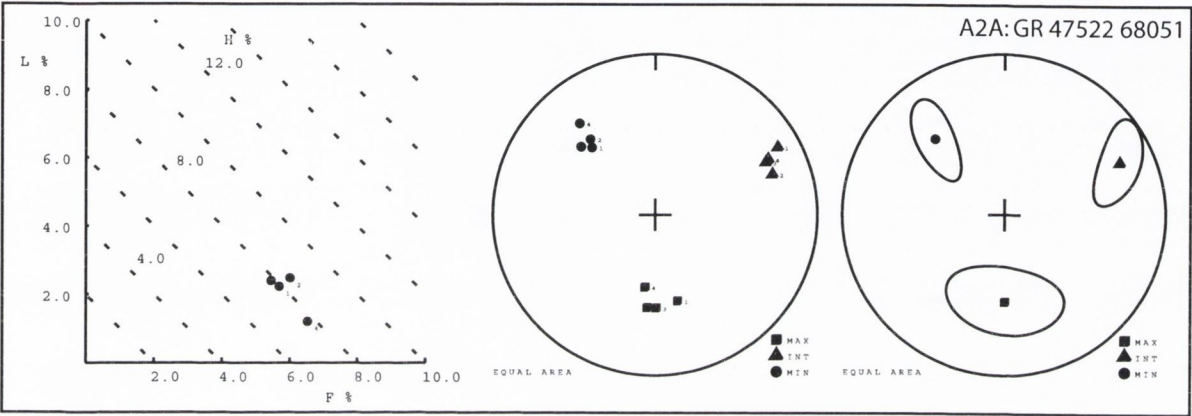
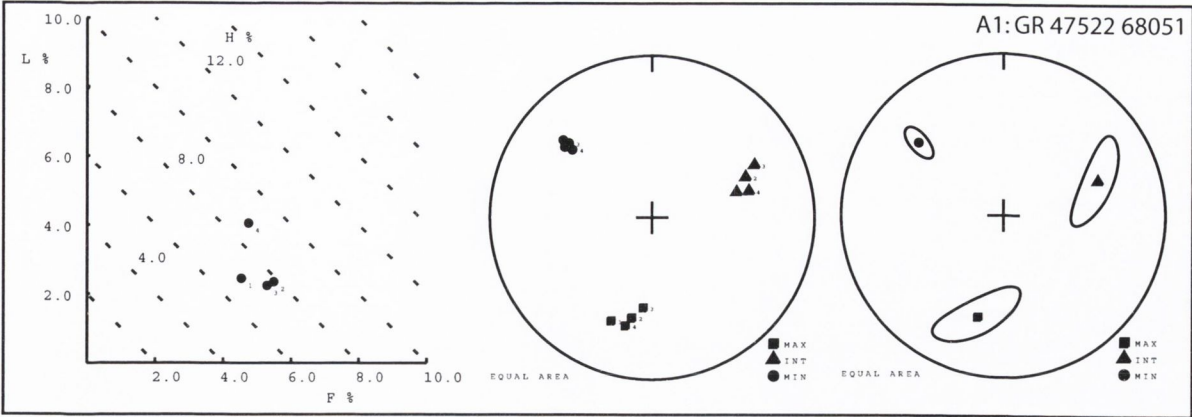




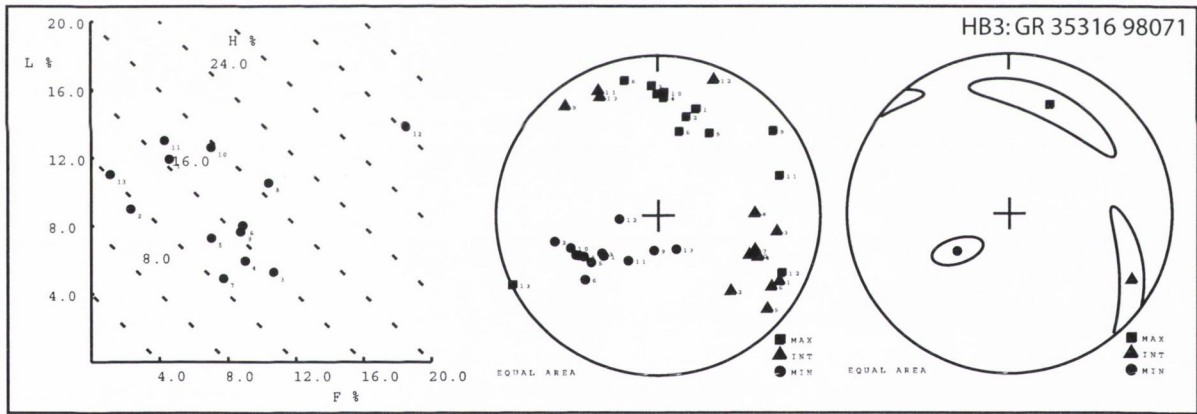
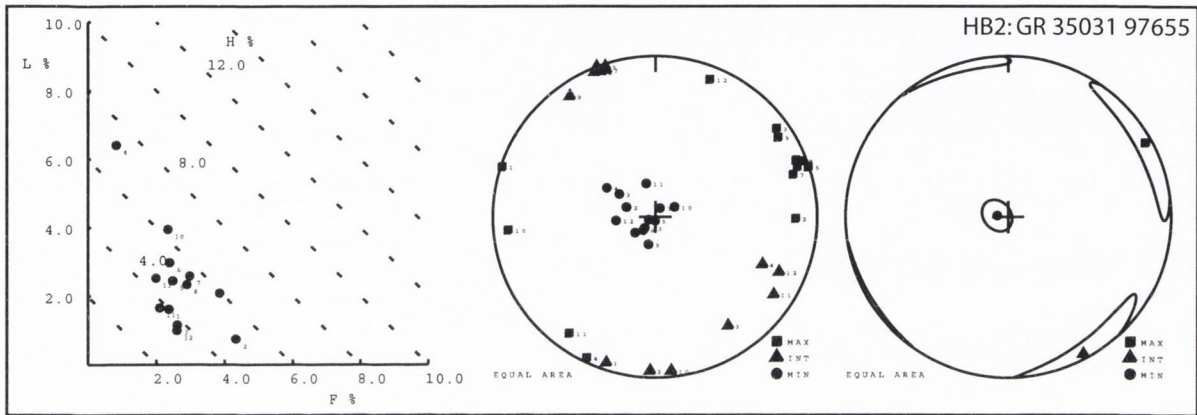
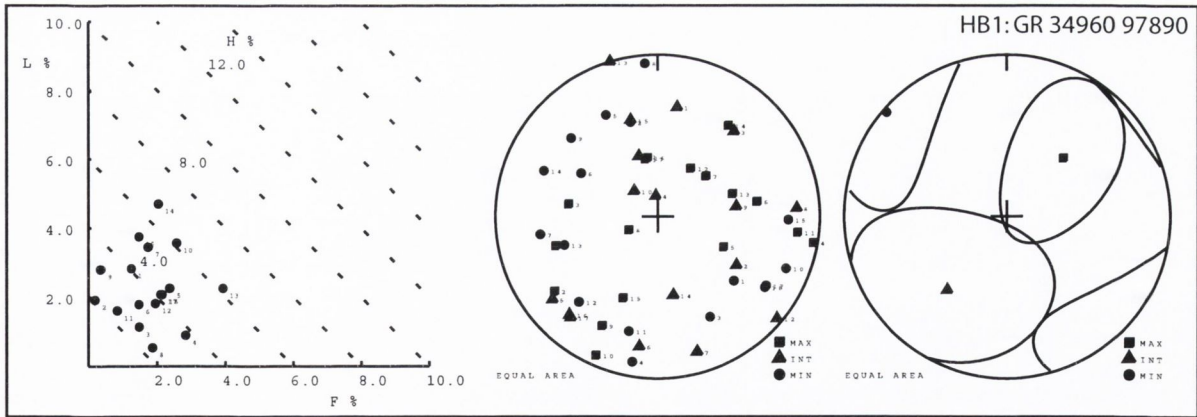




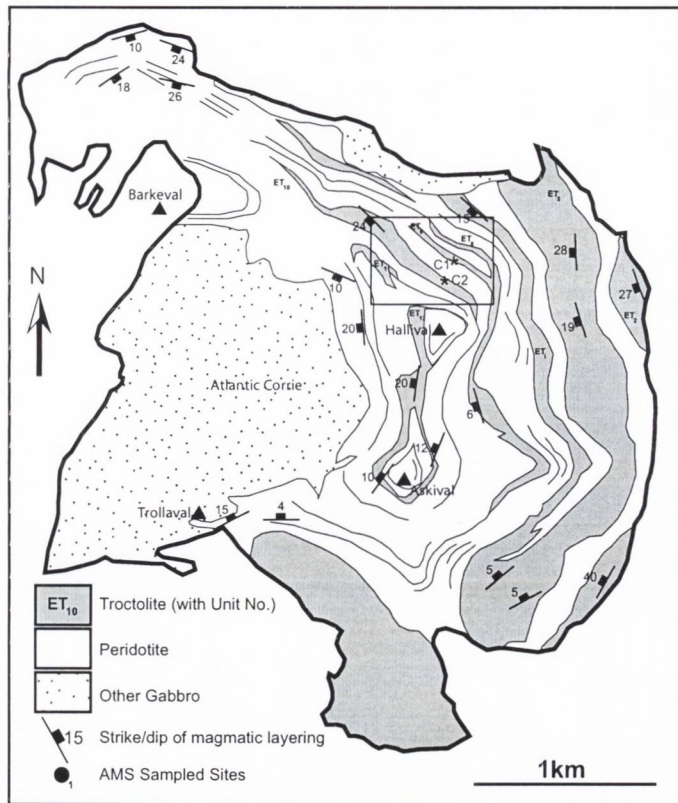
Ardnamurchan Tonalite



RUM AMS DATA

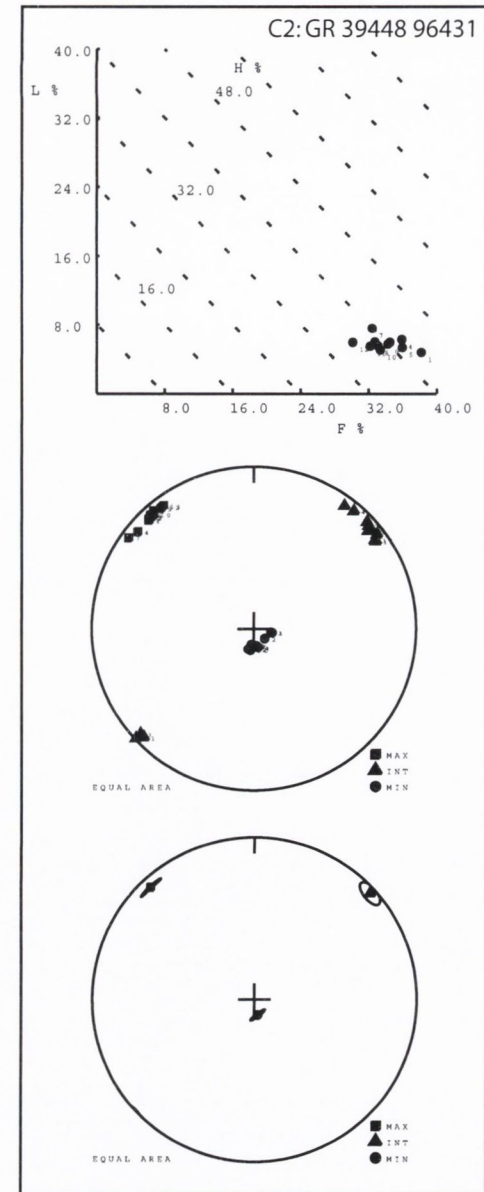
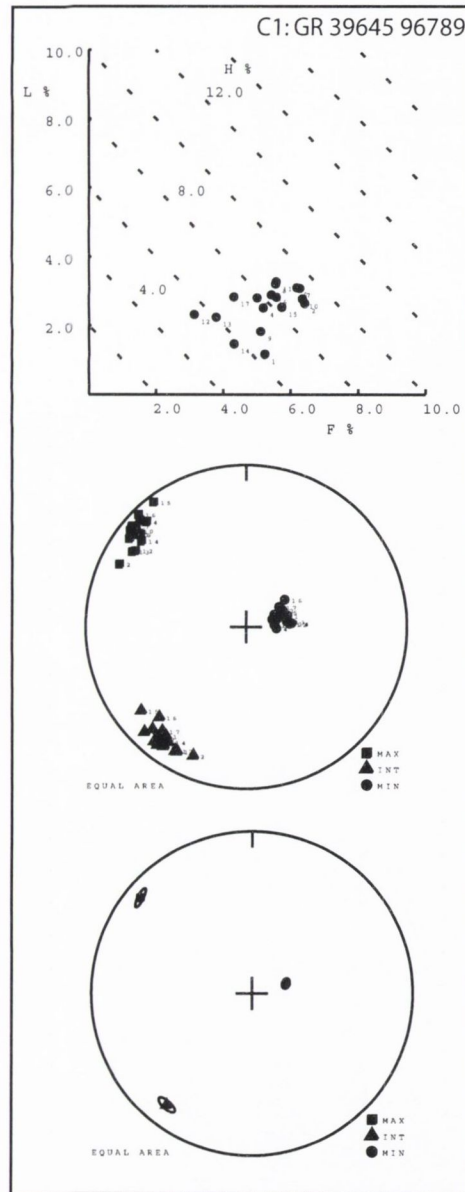


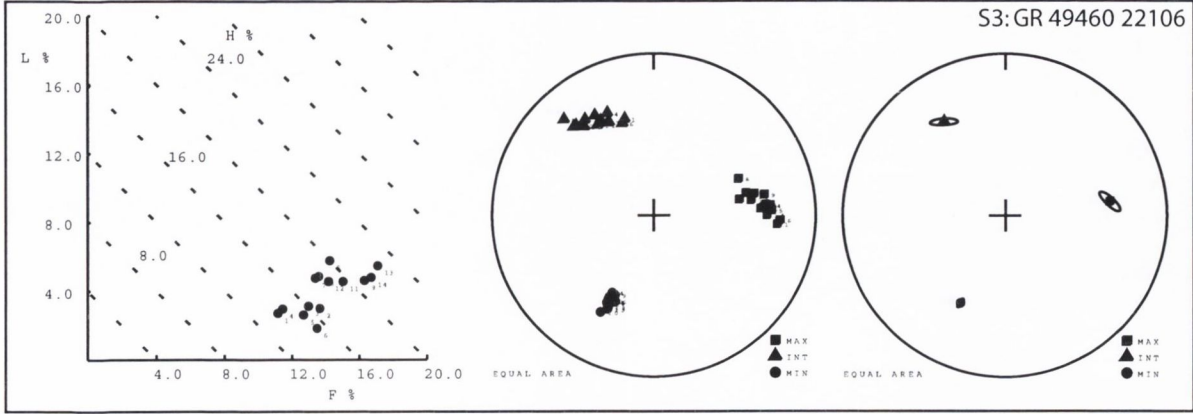
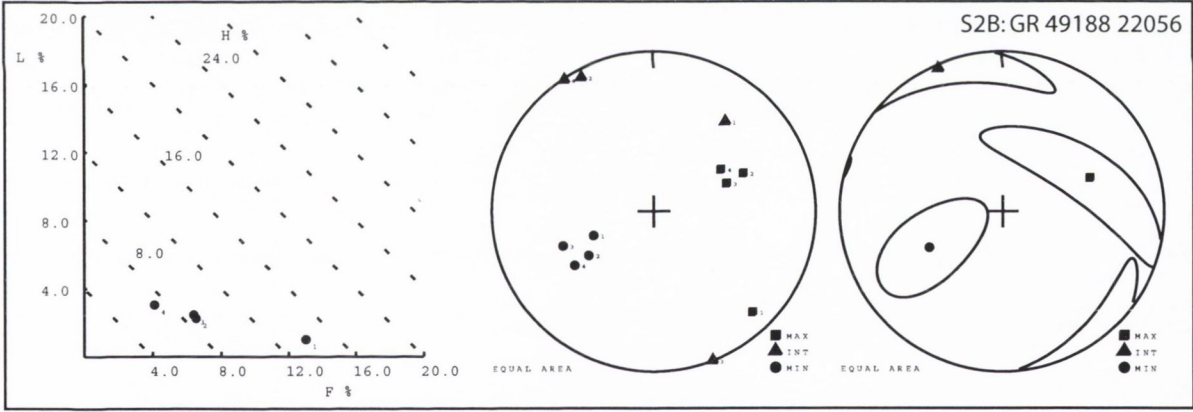
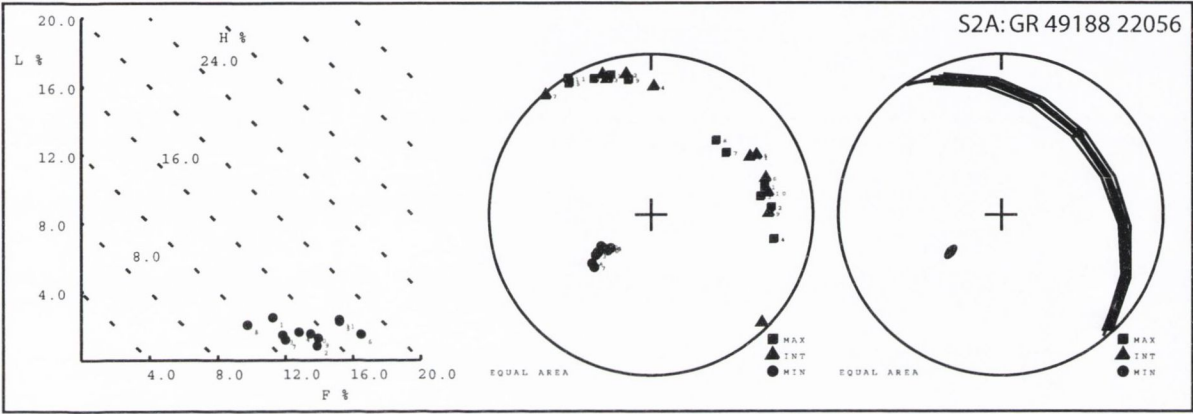
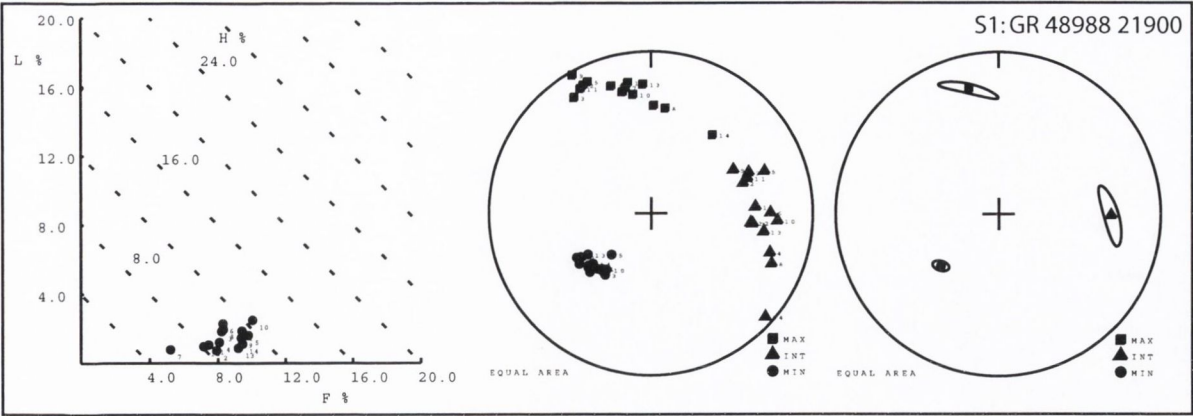
Samples from Ard Mheall for AMS fabric analysis are discussed in text in Chapter 4 (part 3). Note that sample numbers HB1-HB3 bear no relation to samples HB1 and HB2 from Harris Bay, analysed using the CSD technique and discussed in Chapter 4 (part 2).

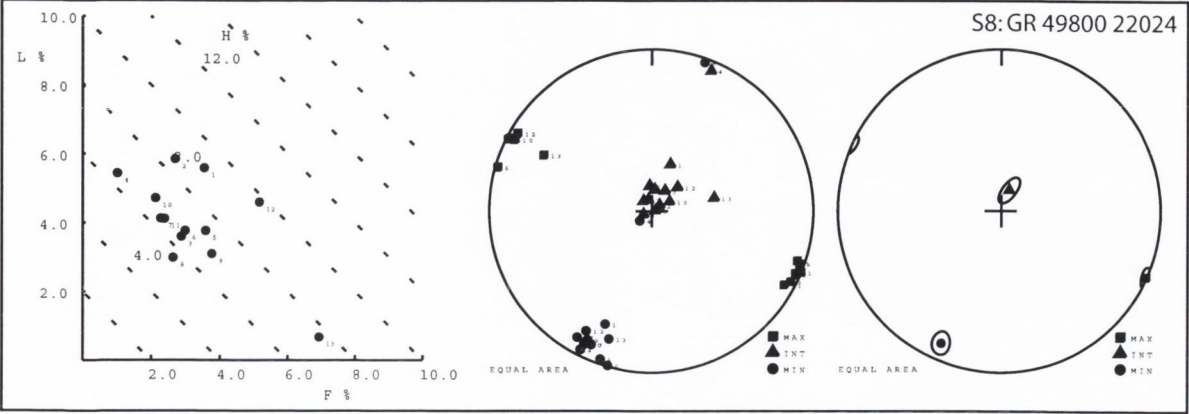
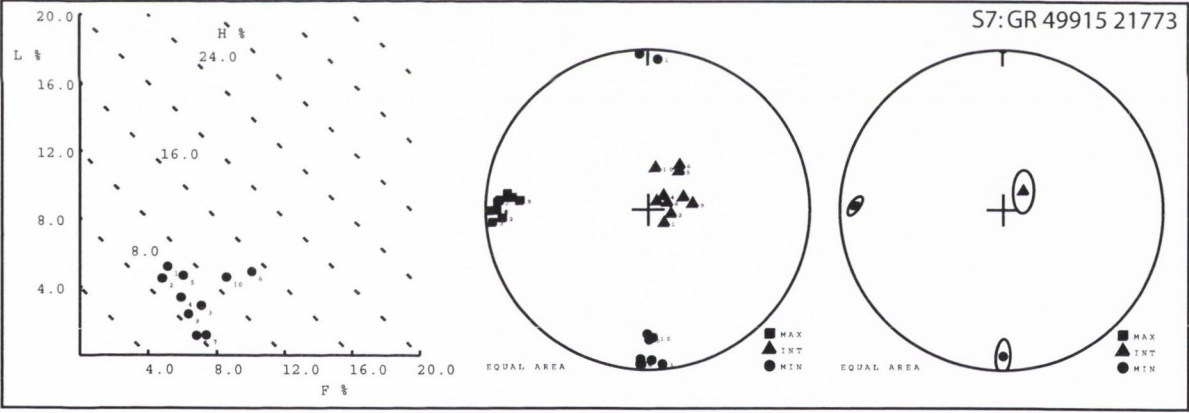
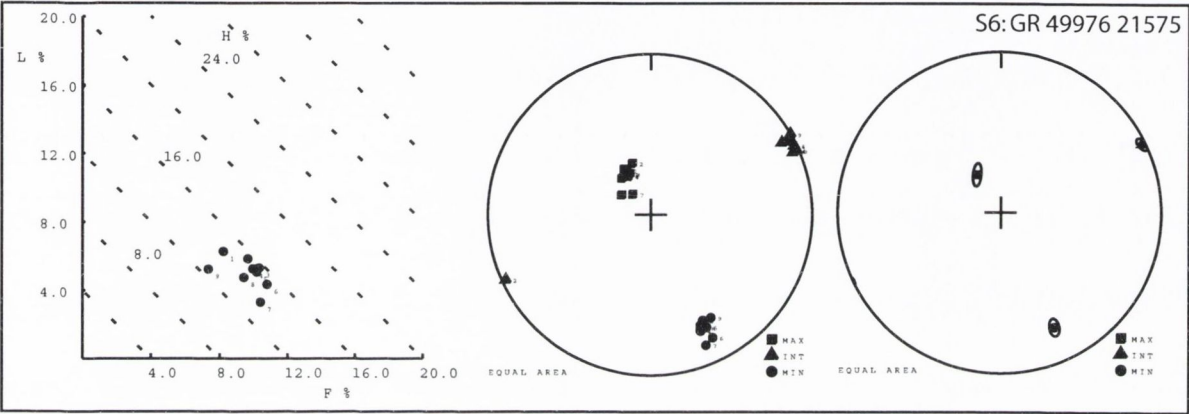
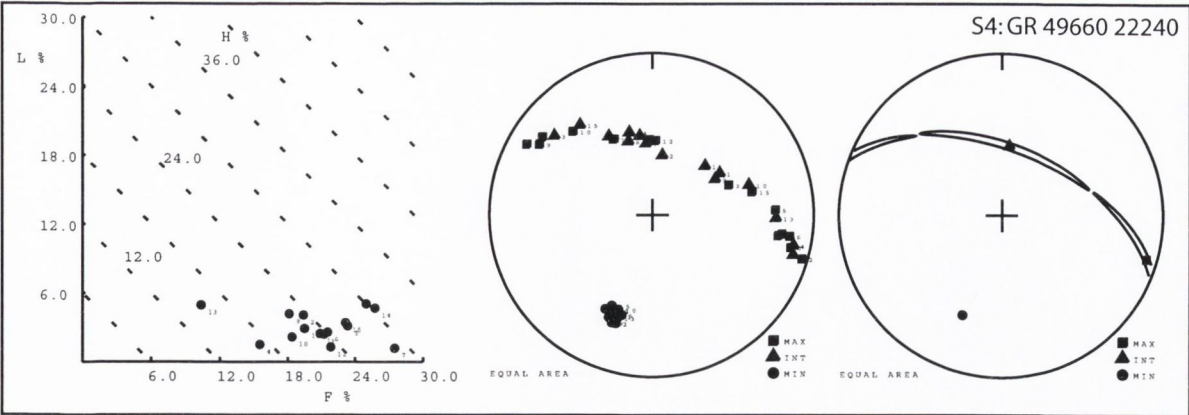


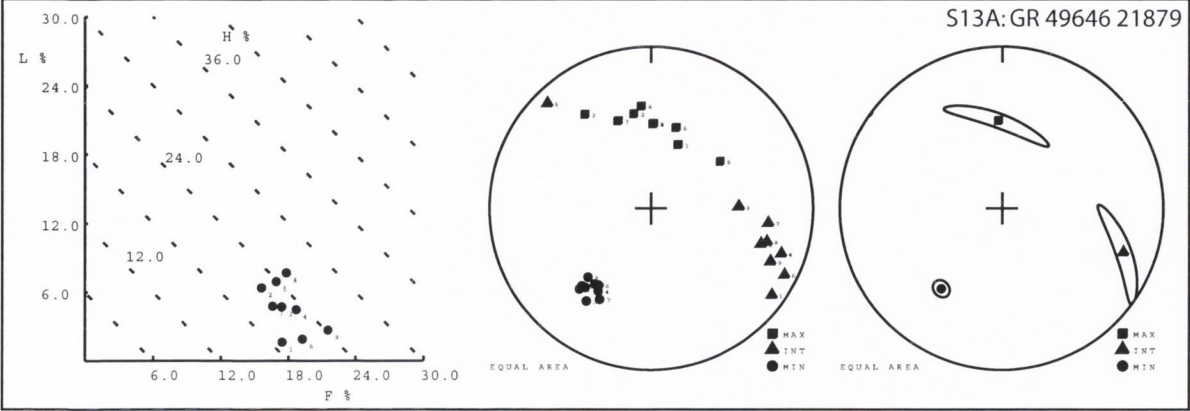
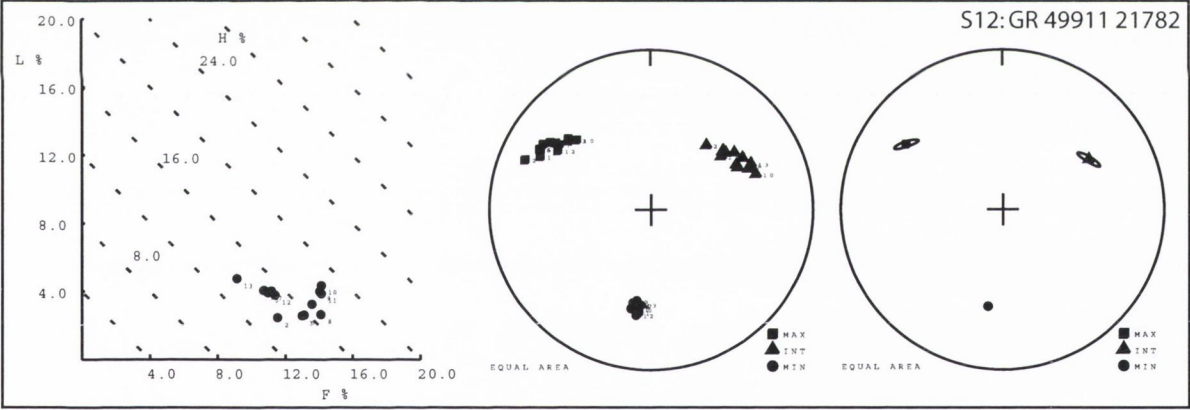
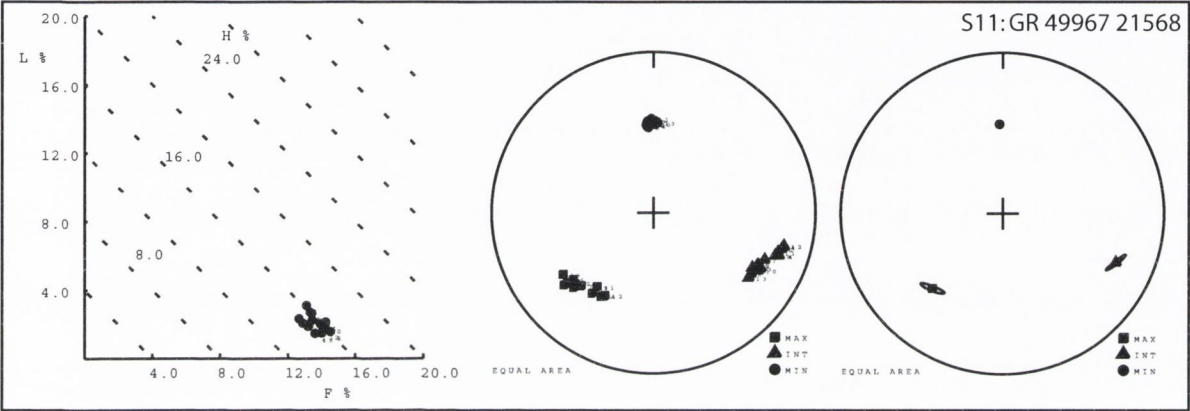
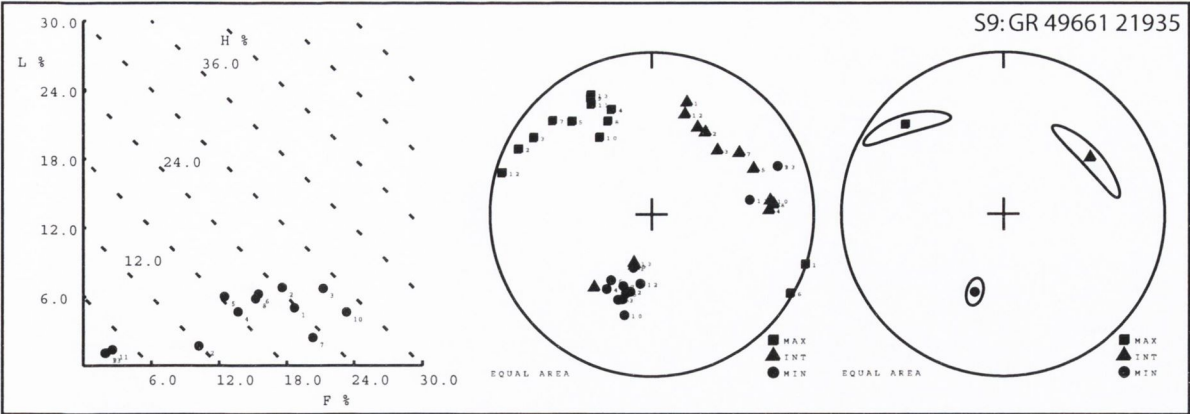
Samples from Unit 9 (C1) and Unit 10 (C2) of the Eastern Layered Intrusion analysed as an independent check on the results presented in Chapter 4 (part 1). Note that the position of each sample is marked on the map and, as with other results, the magnetic foliation approximately parallels the large-scale magmatic layering and the magnetic lineation plunges very gently on this plane. The magnetic fabrics measured for these samples are thus interpreted to substantiate the data presented in Chapter 4 (part 1).

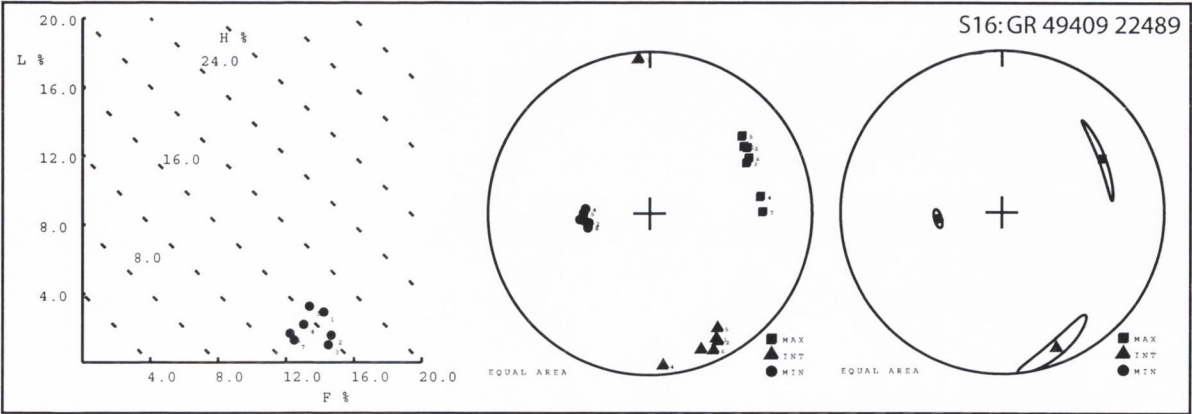
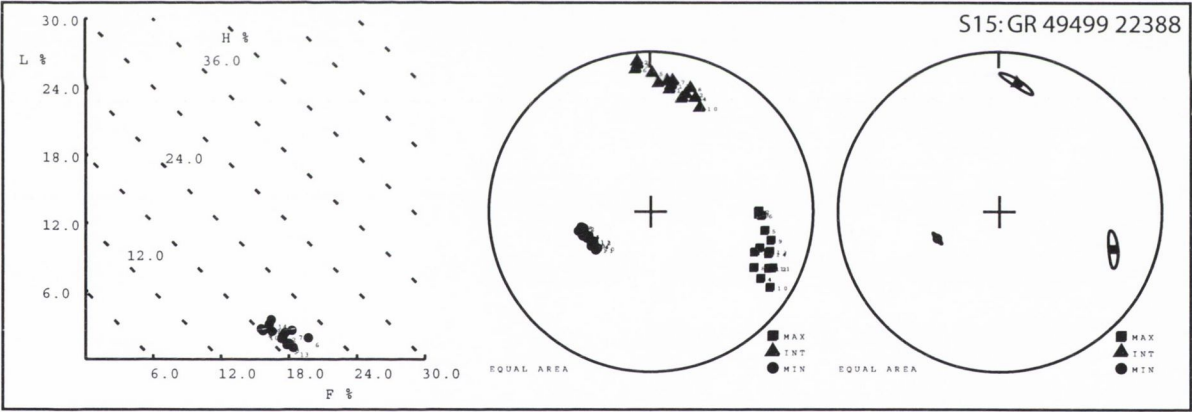
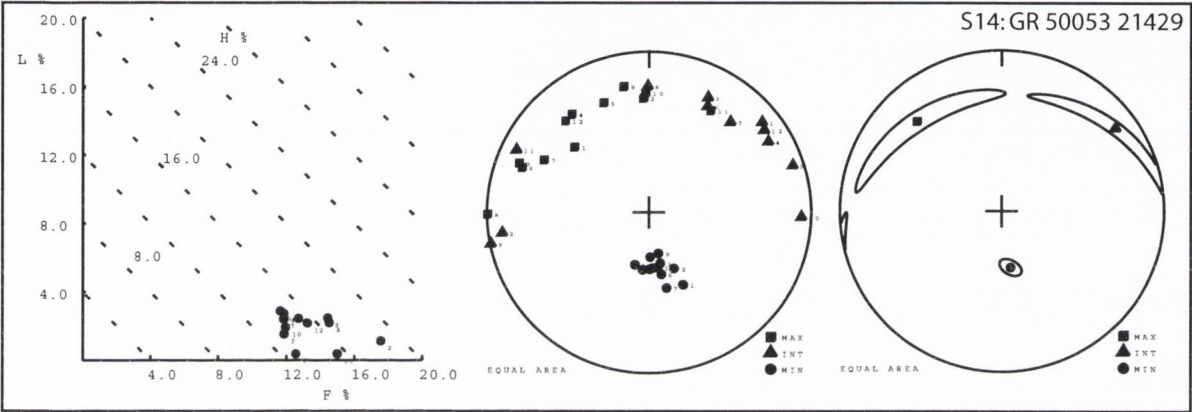
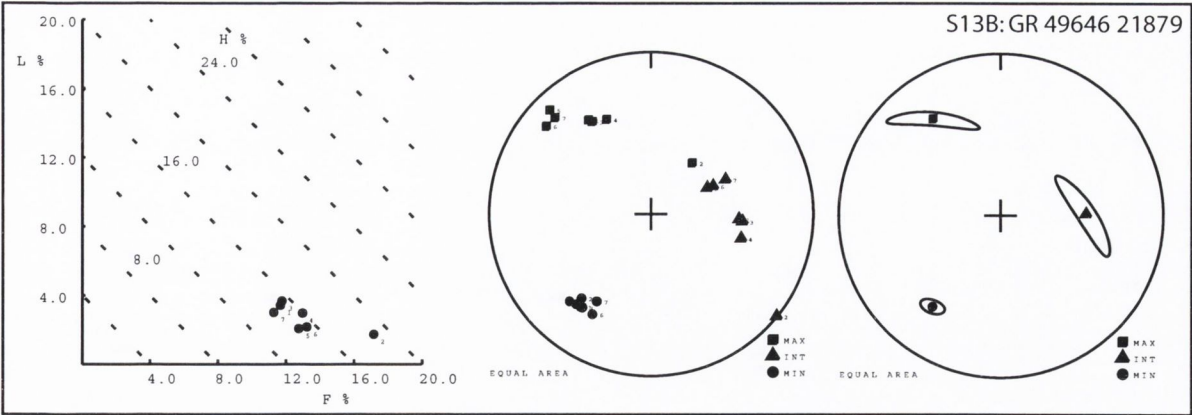
RUM AMS DATA

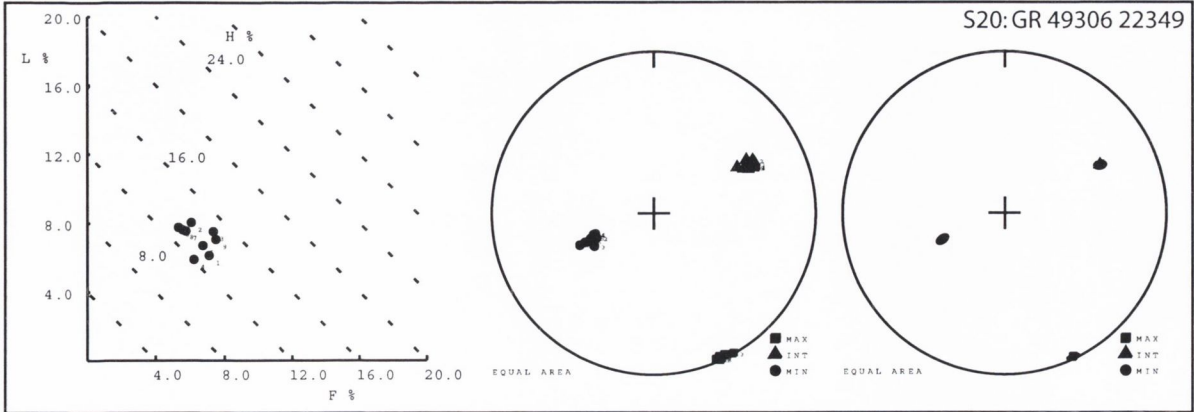
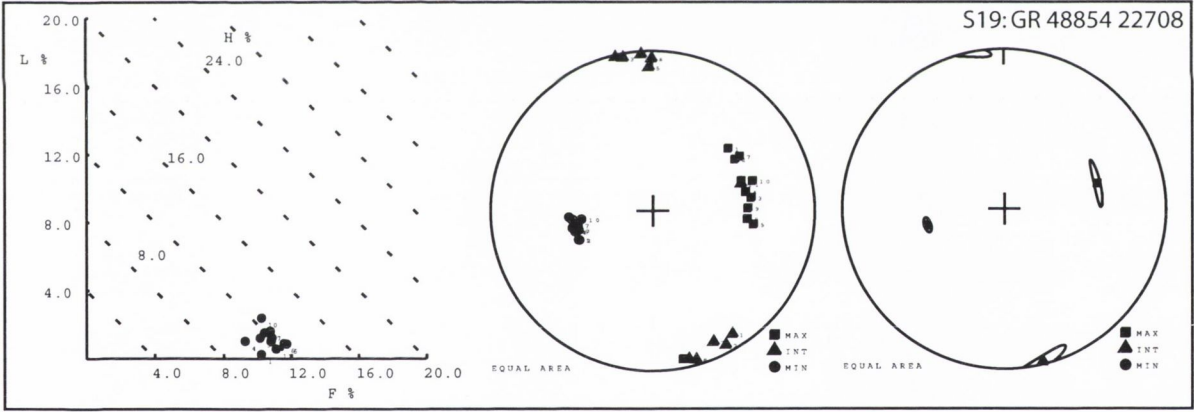
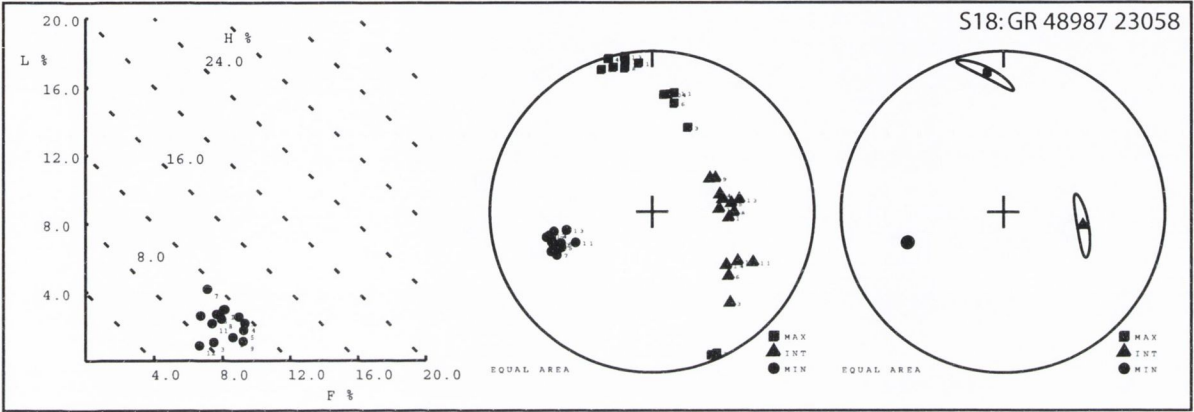
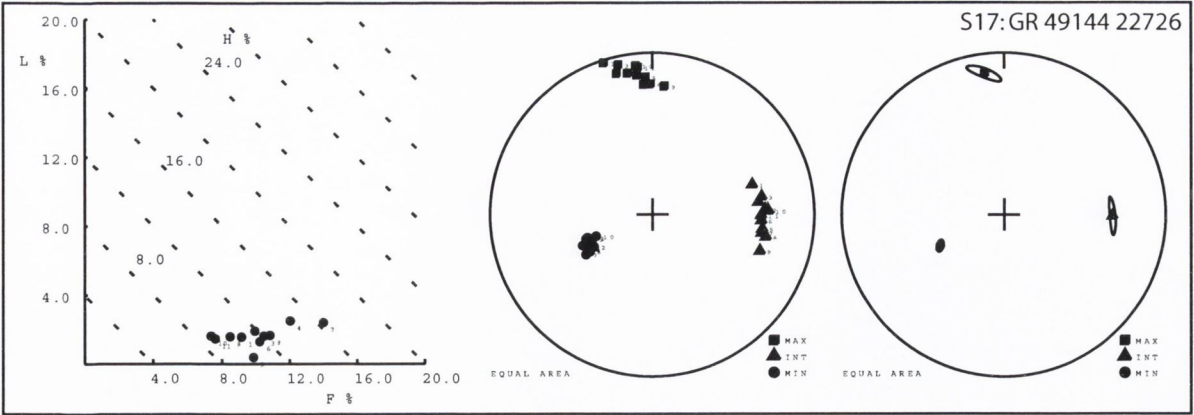


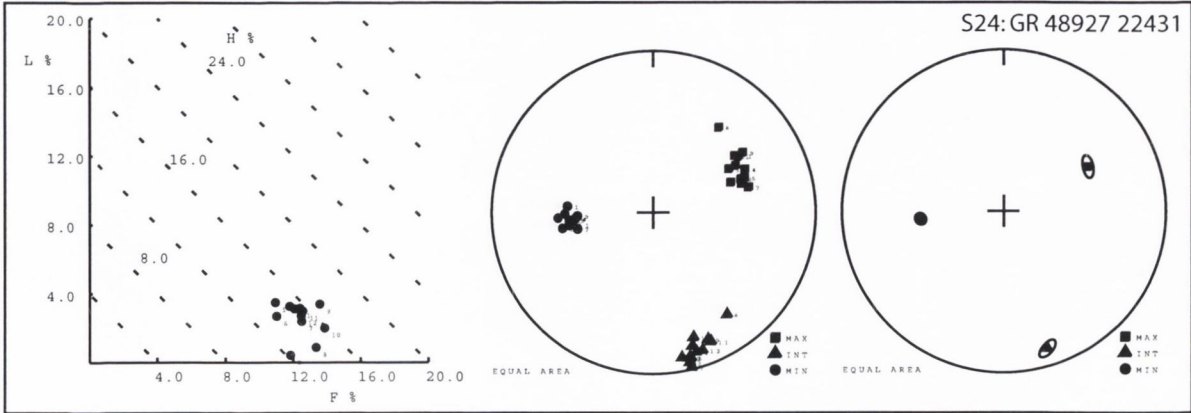
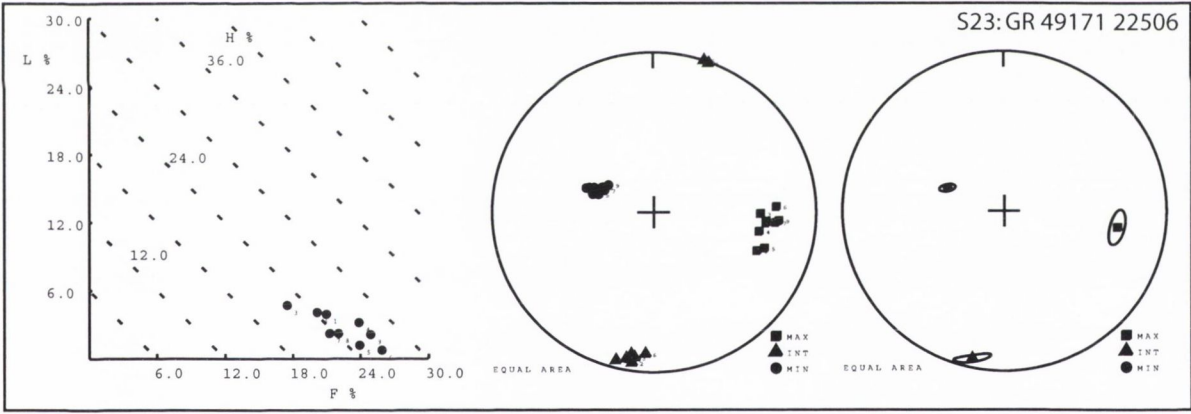
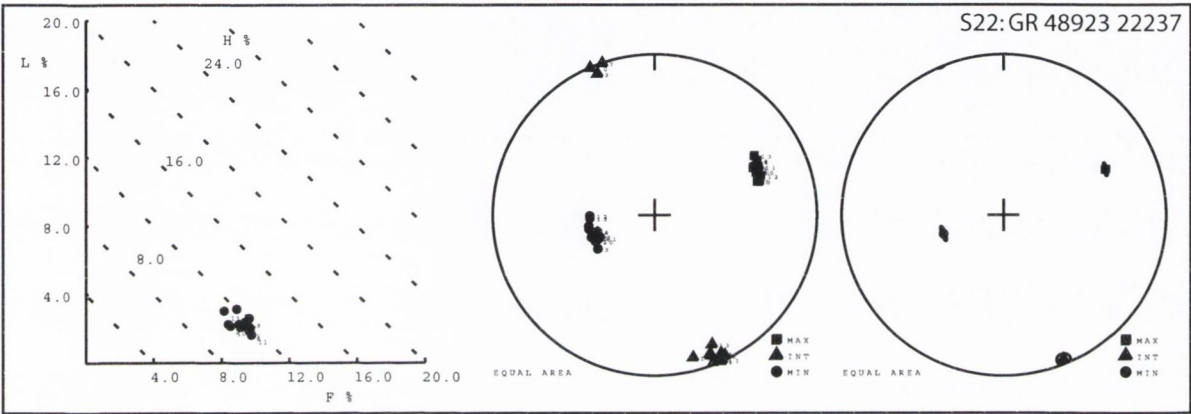
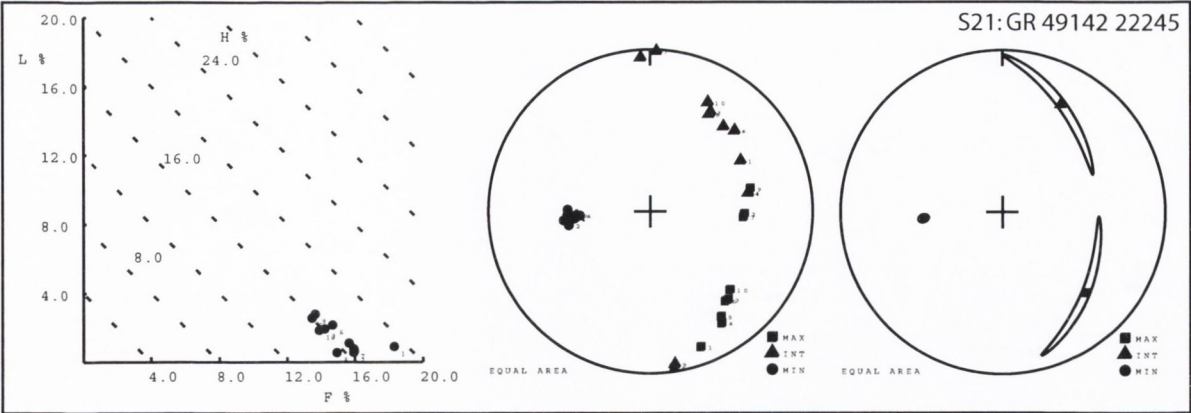


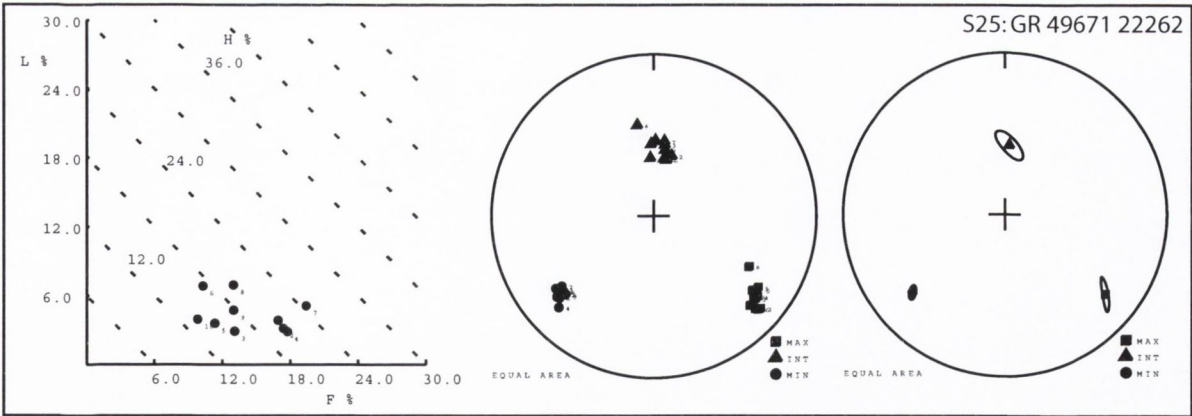




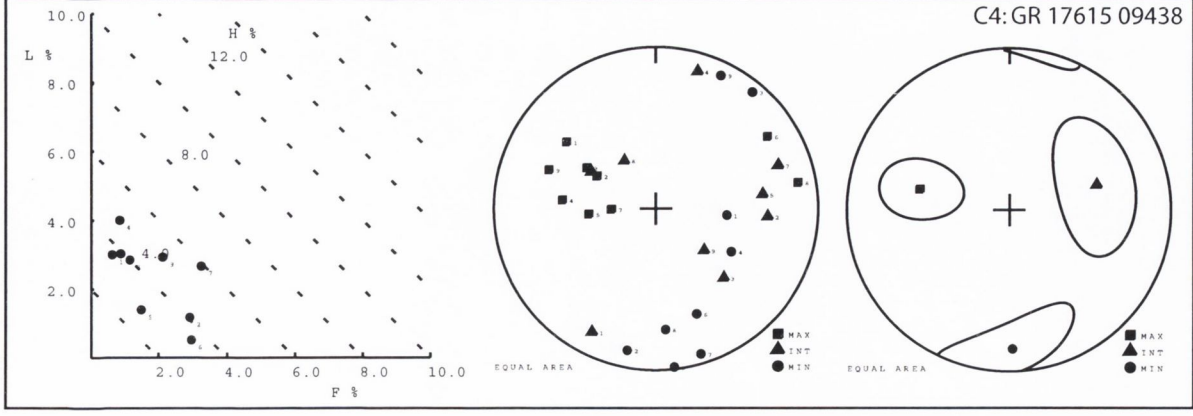
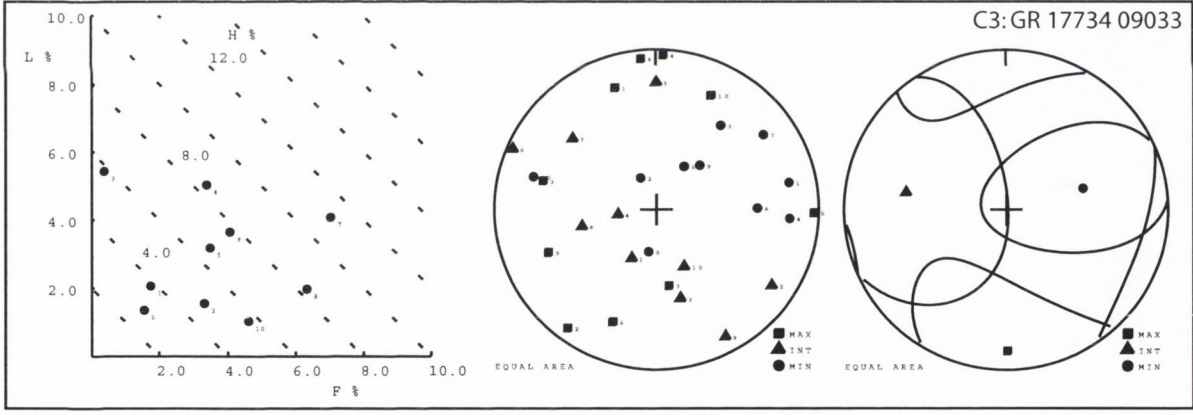
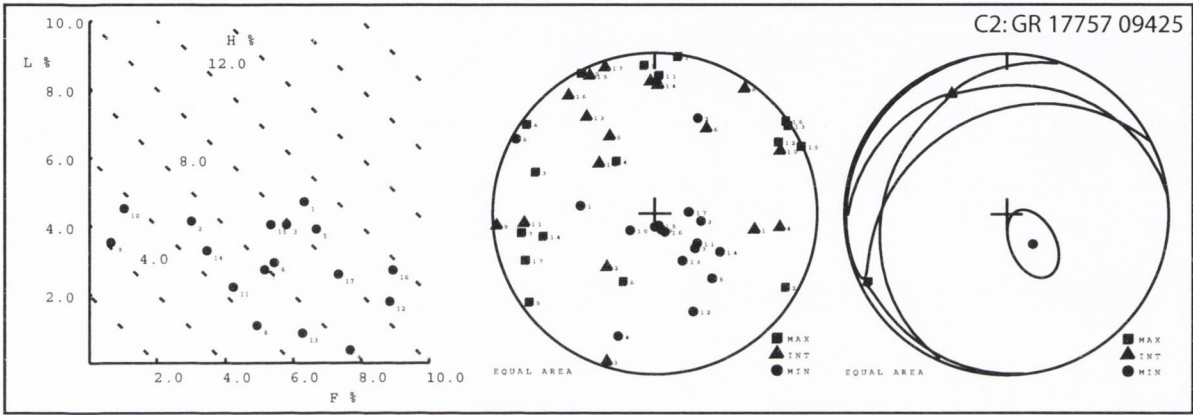
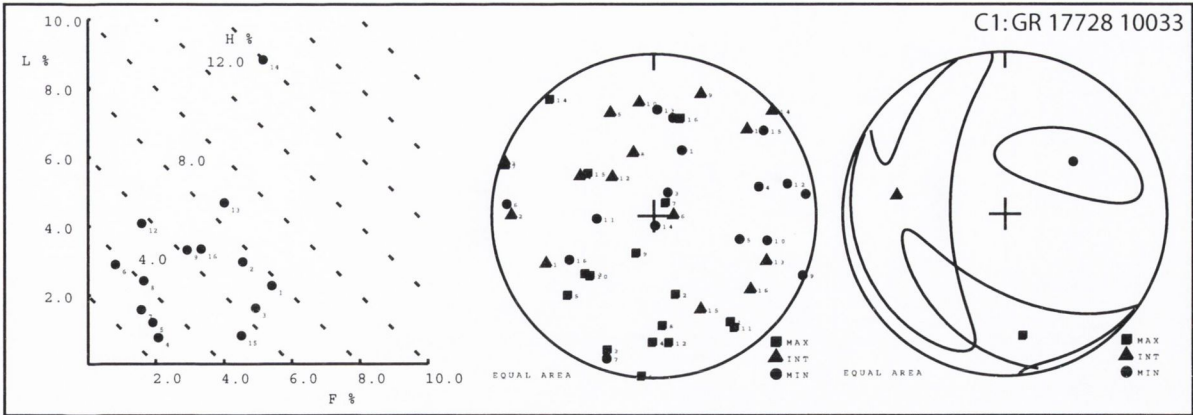


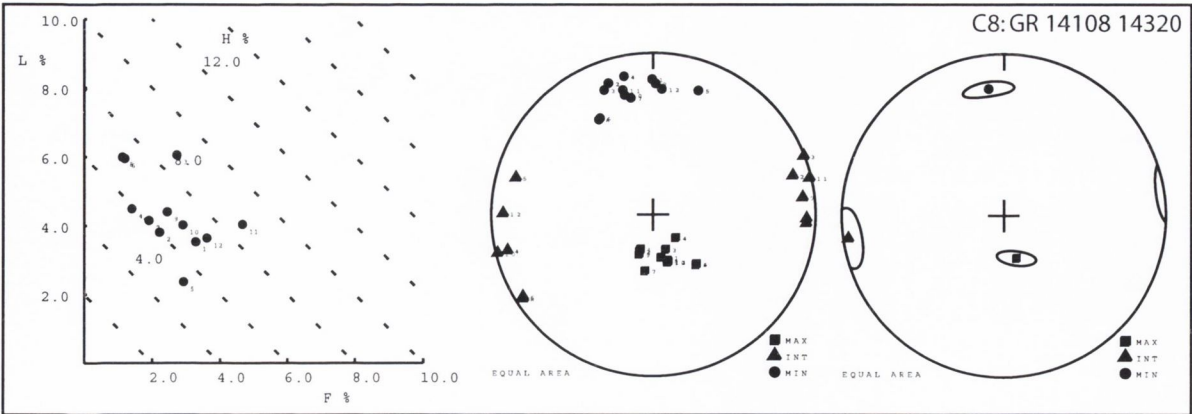
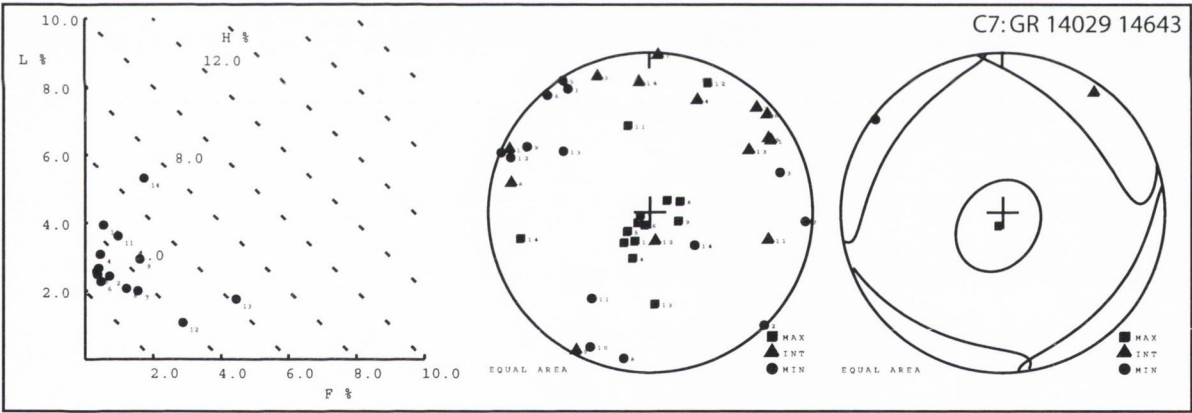
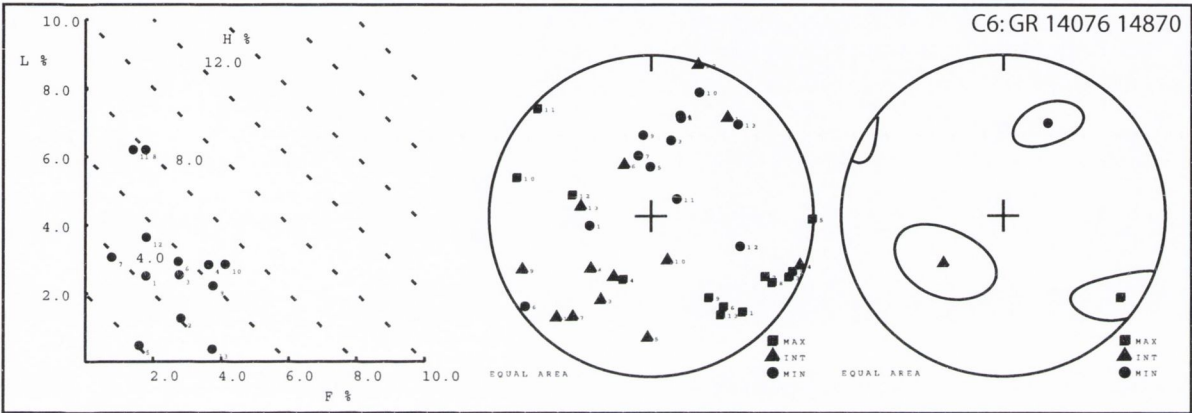
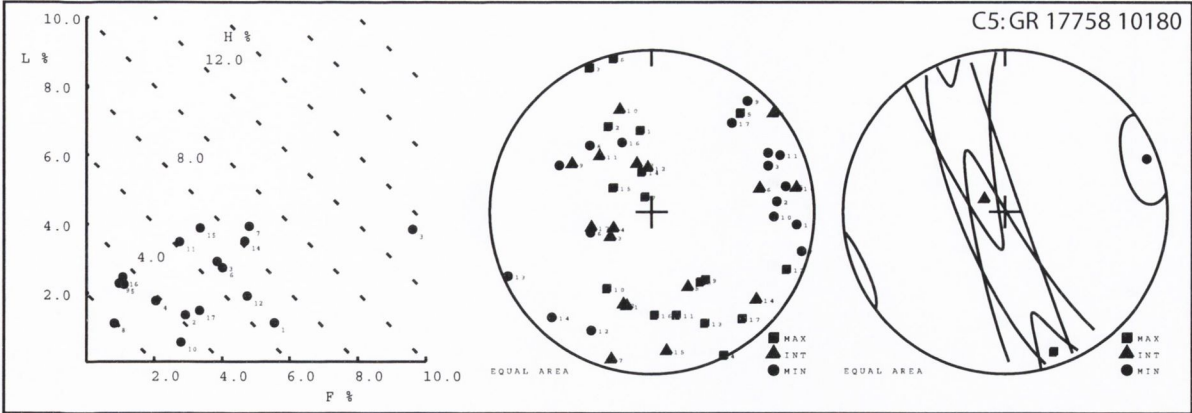


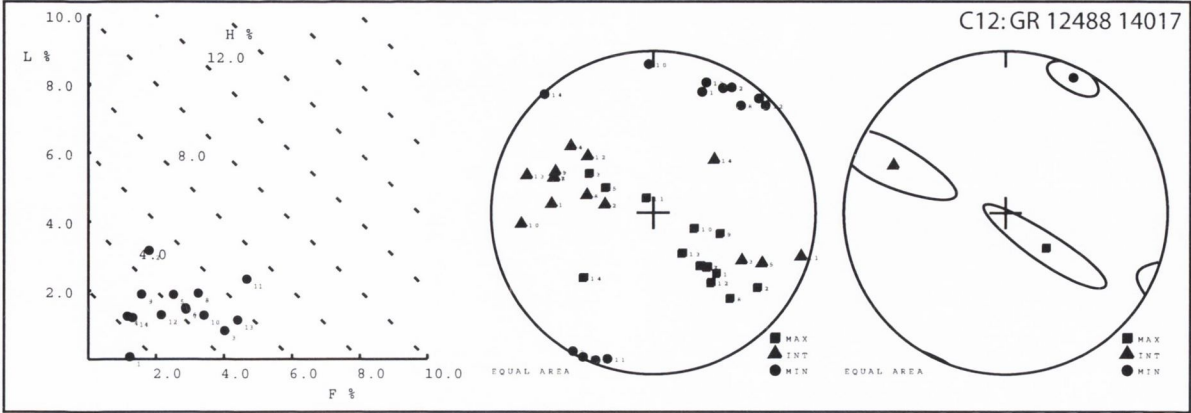
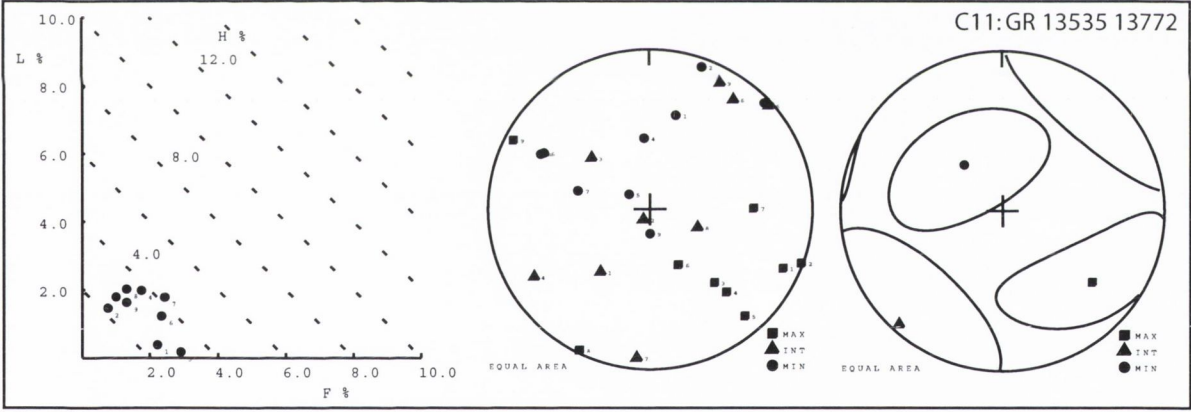
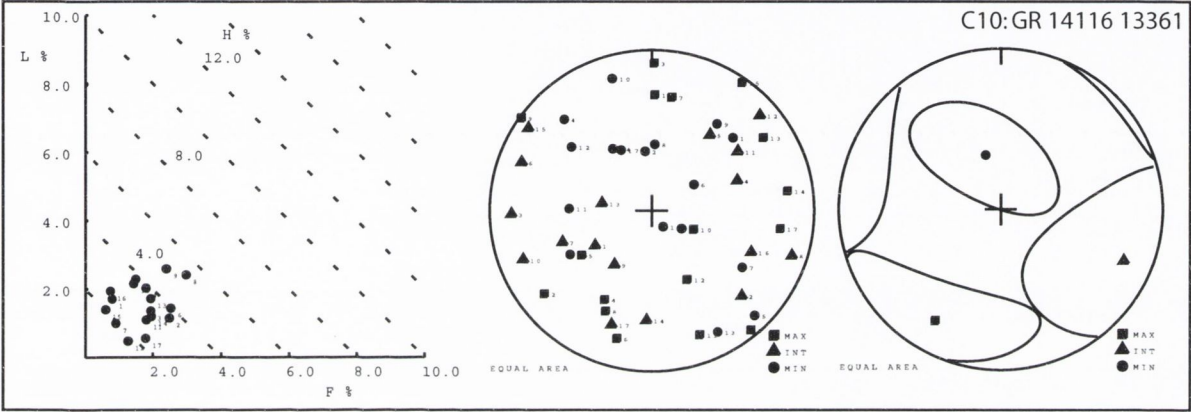
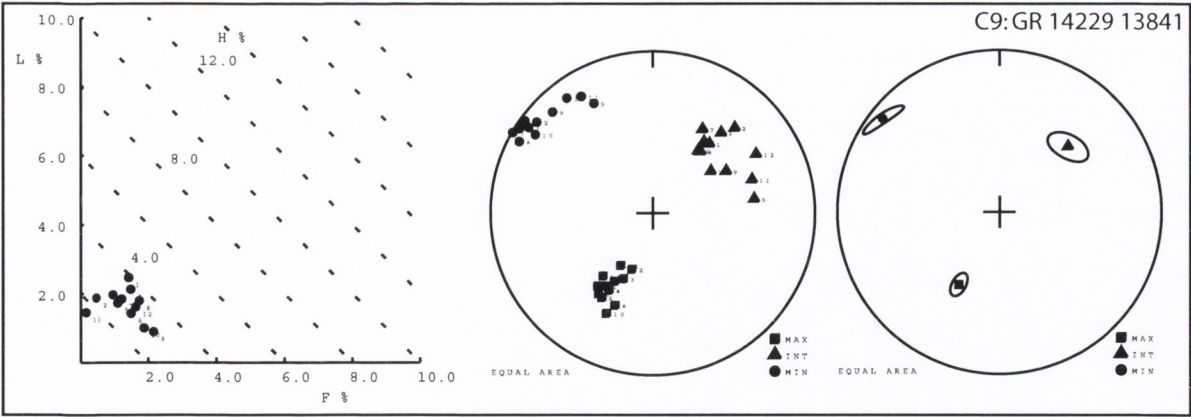


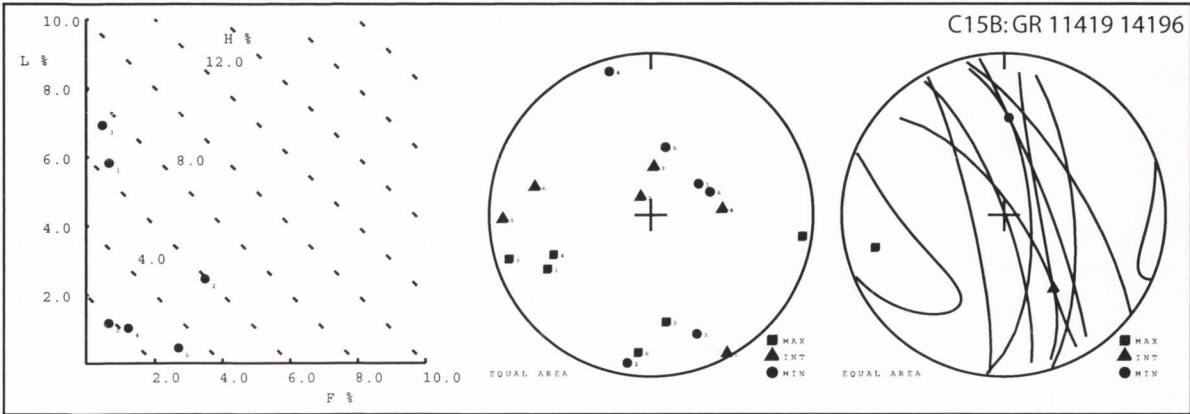
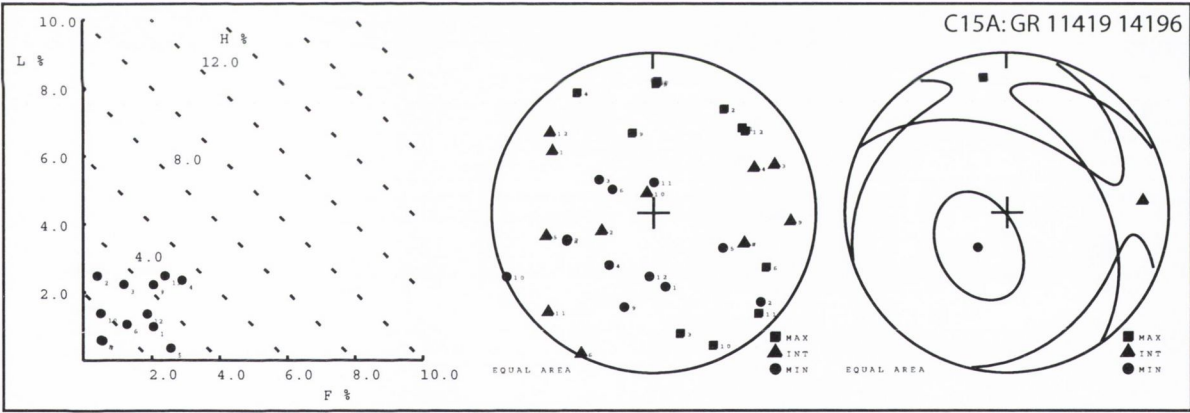
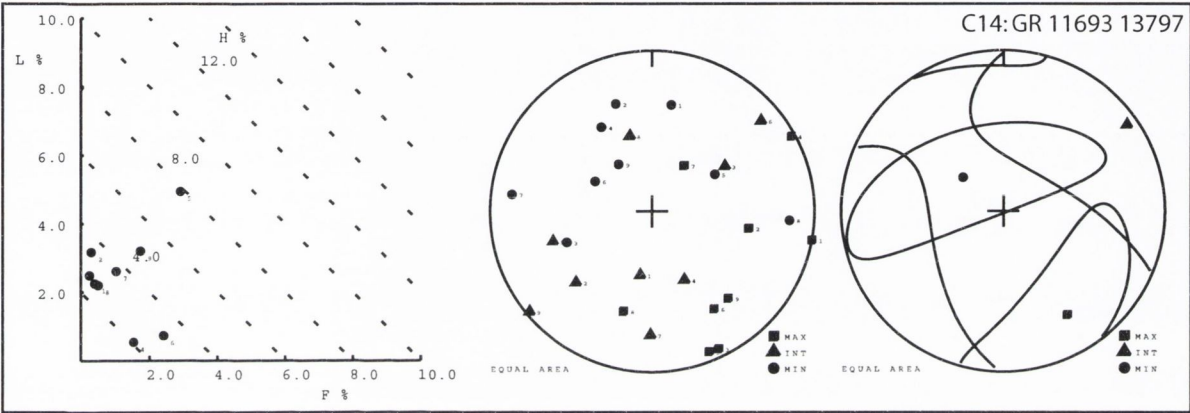
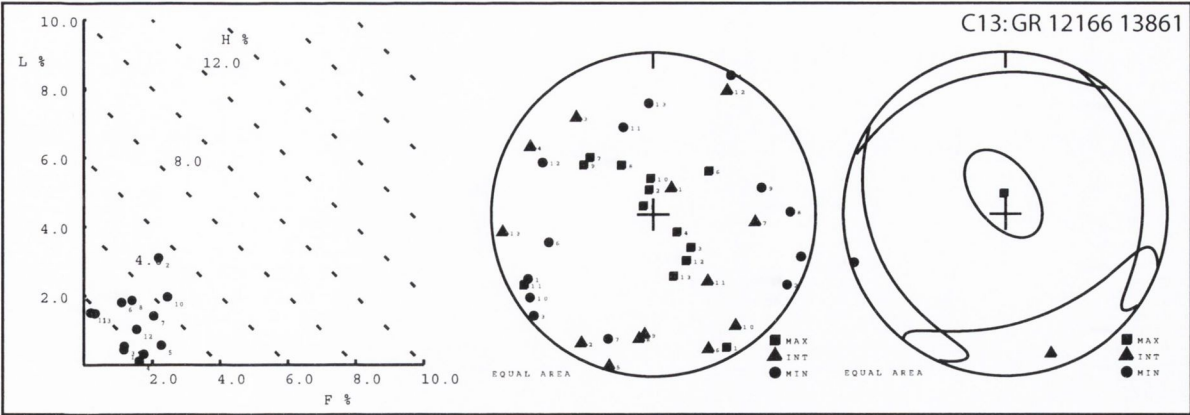


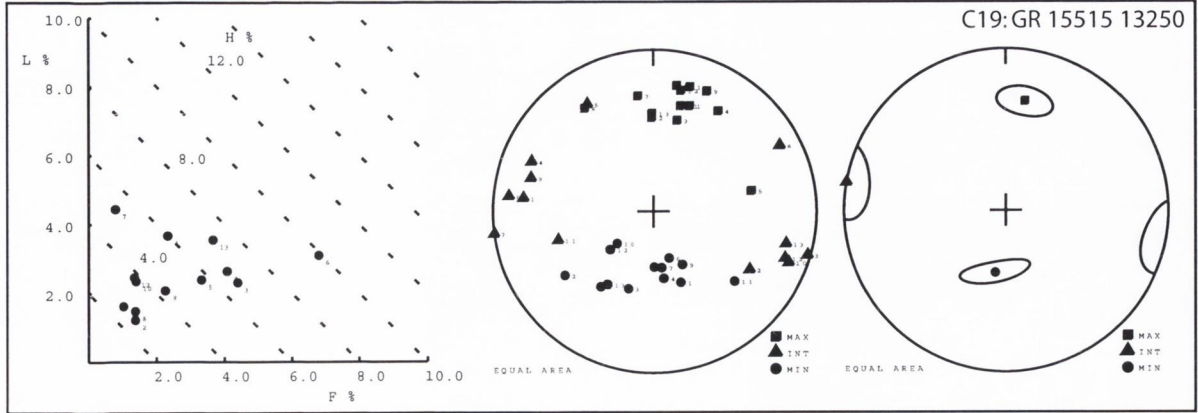
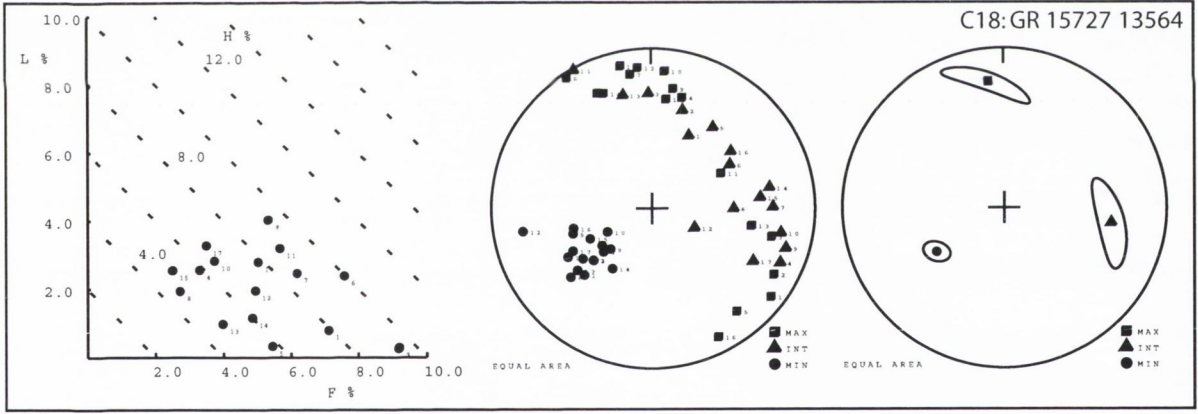
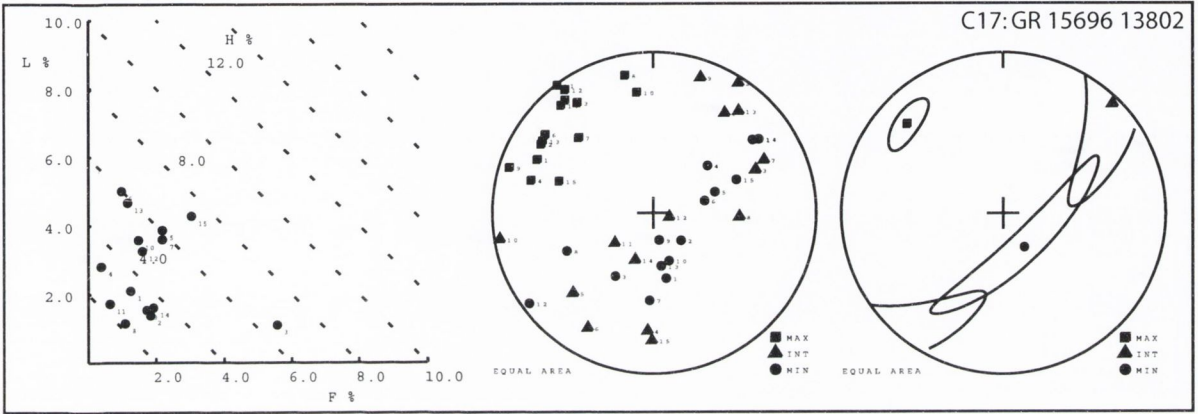
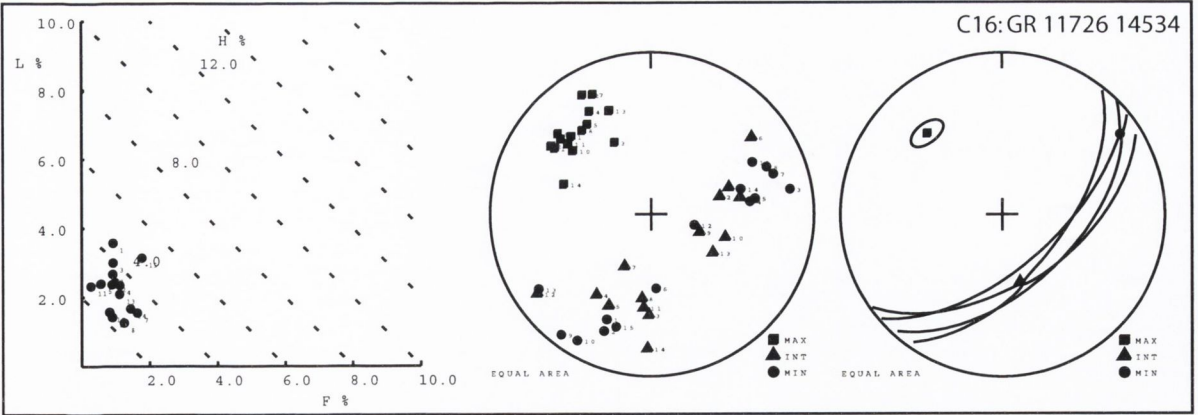
CARLINGFORD AMS DATA

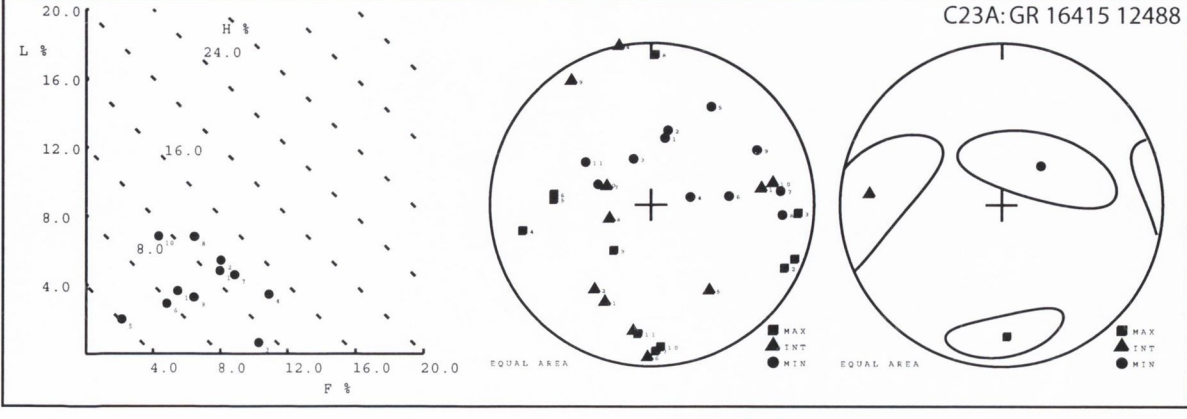
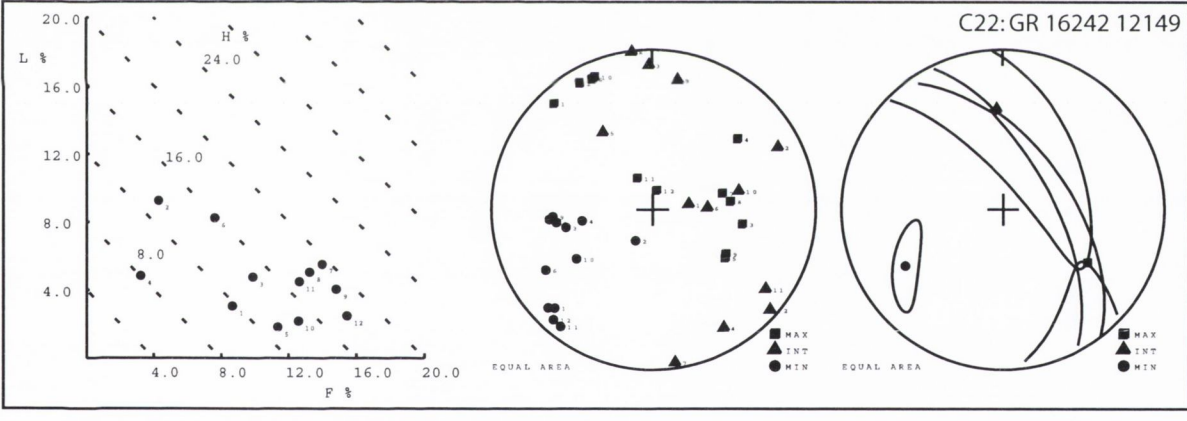
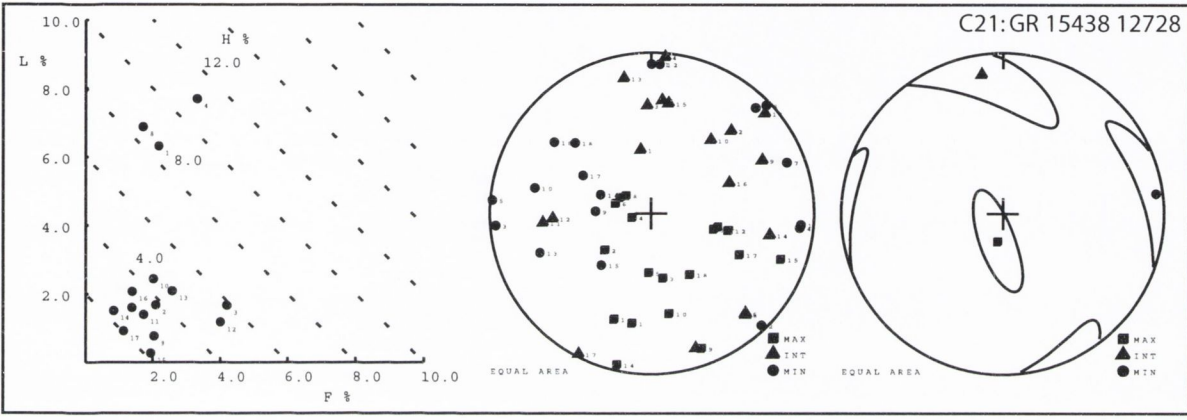
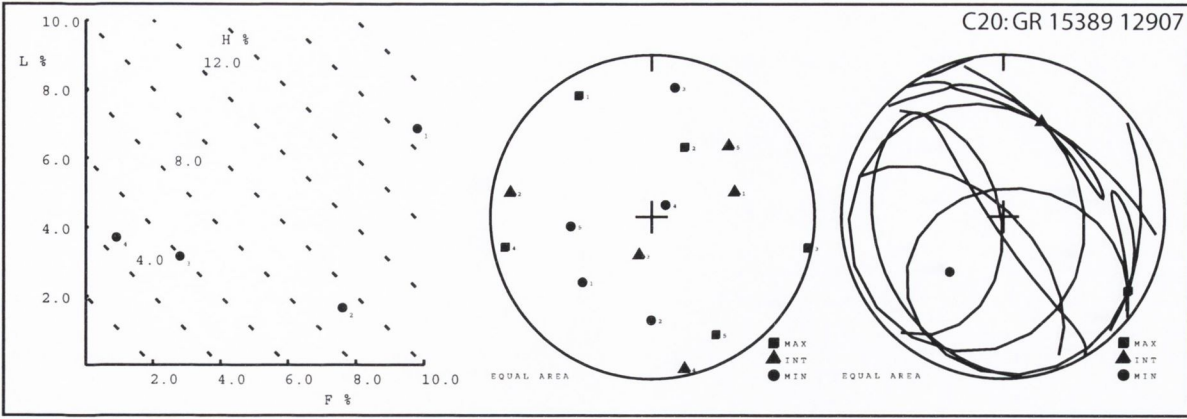


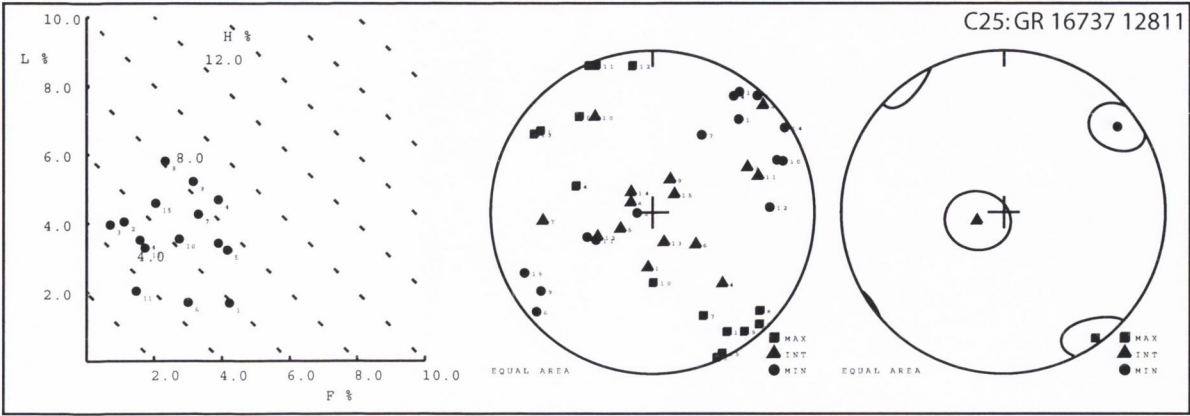
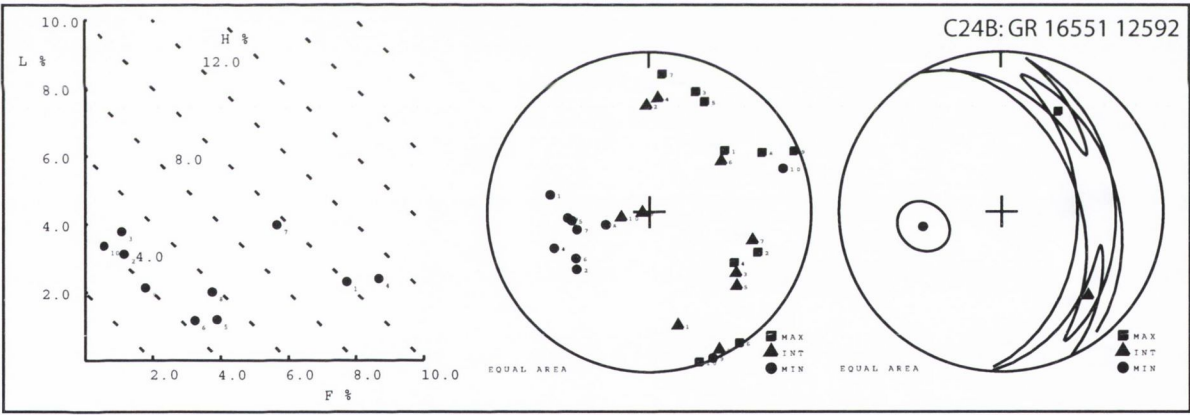
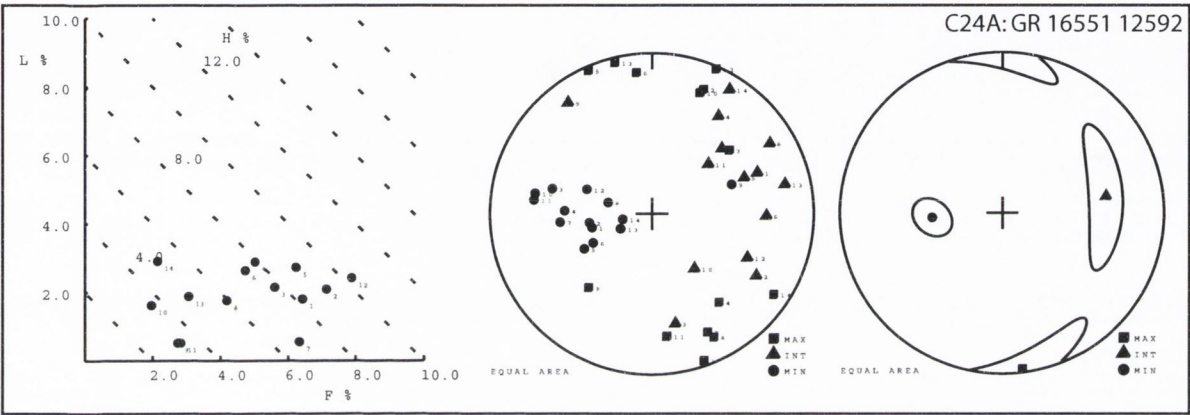
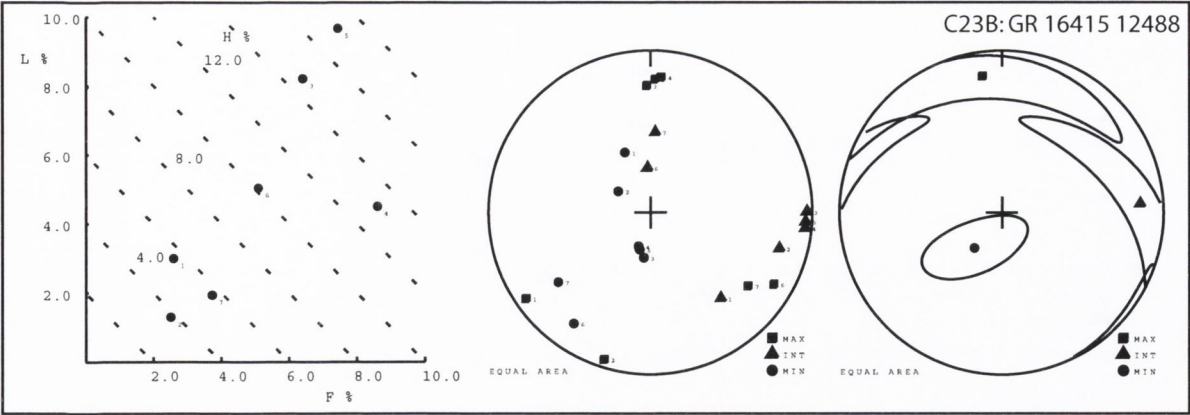


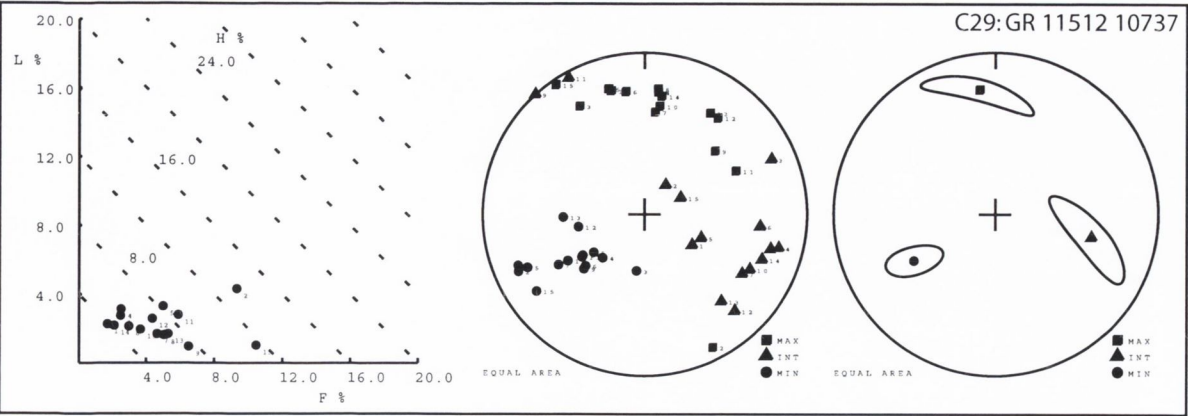
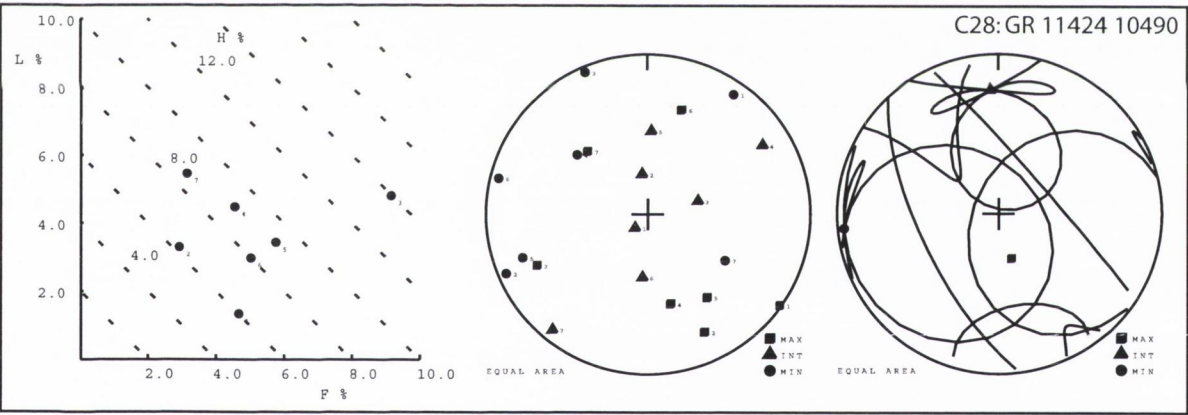
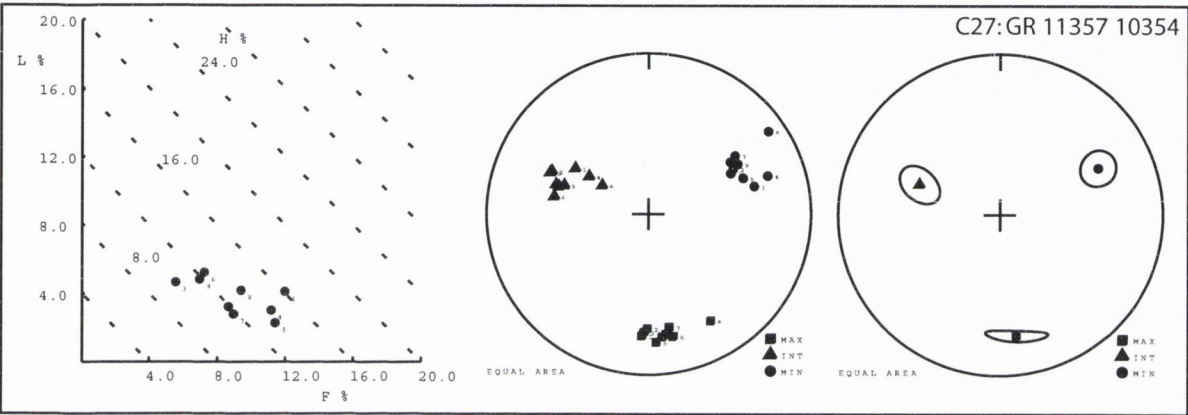
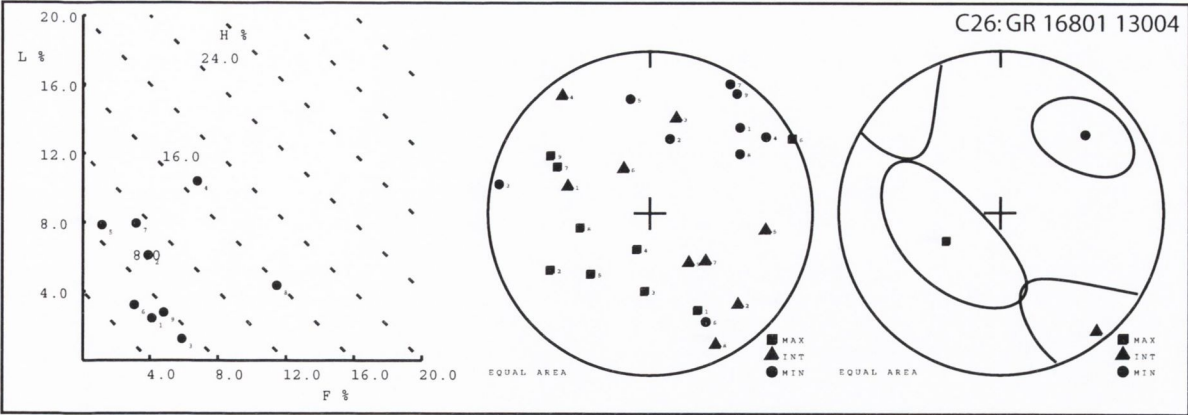


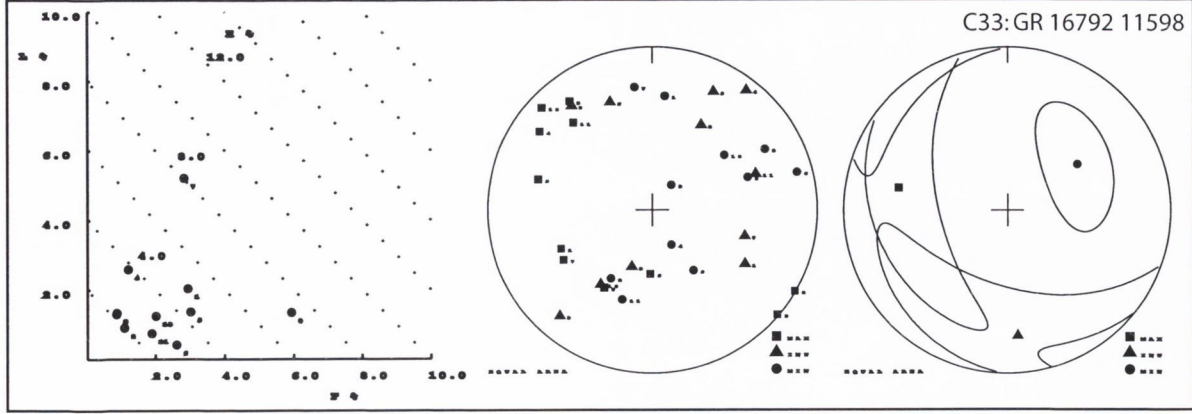
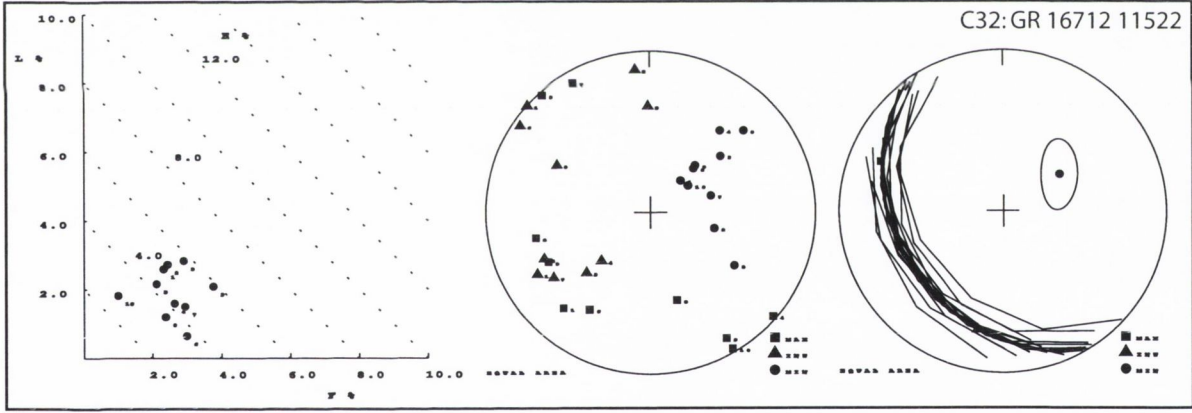
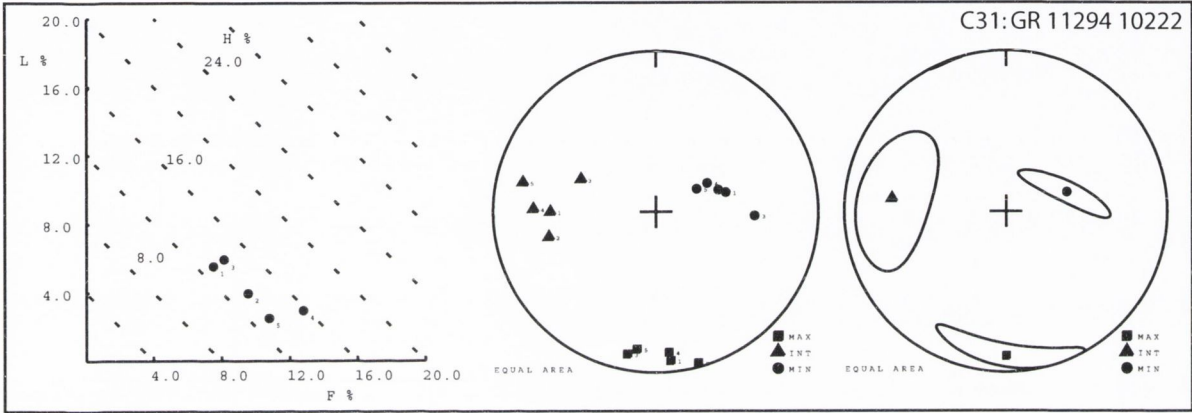
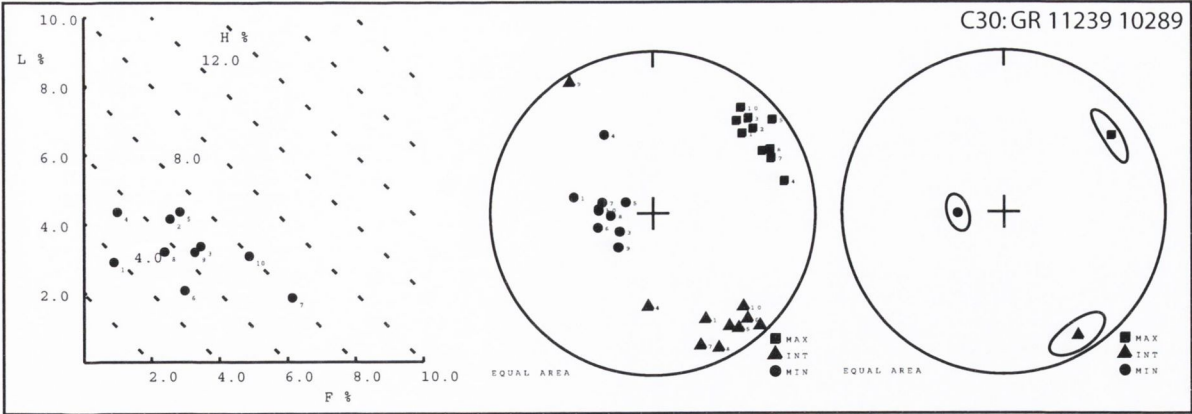


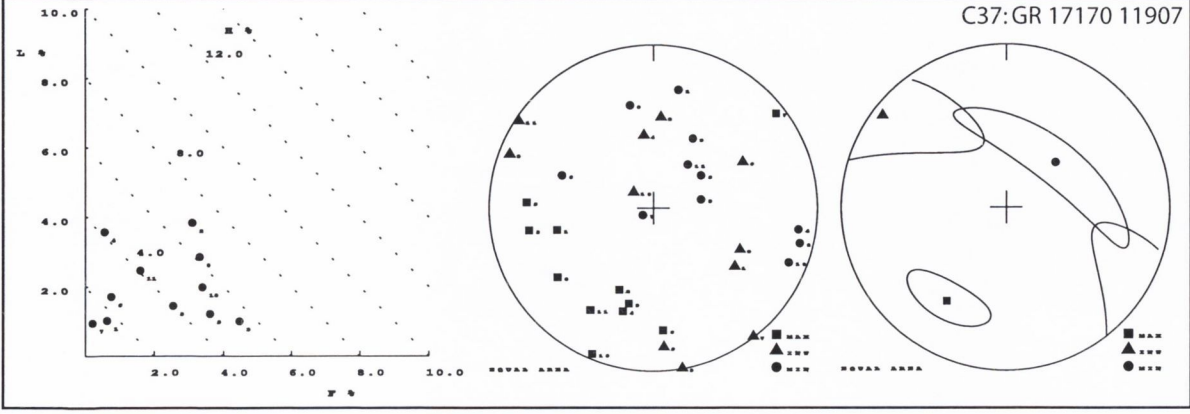
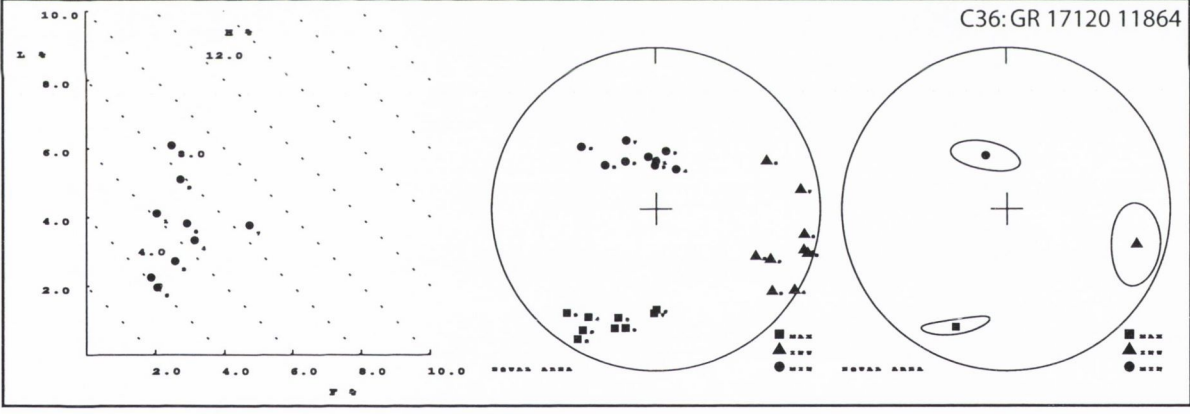
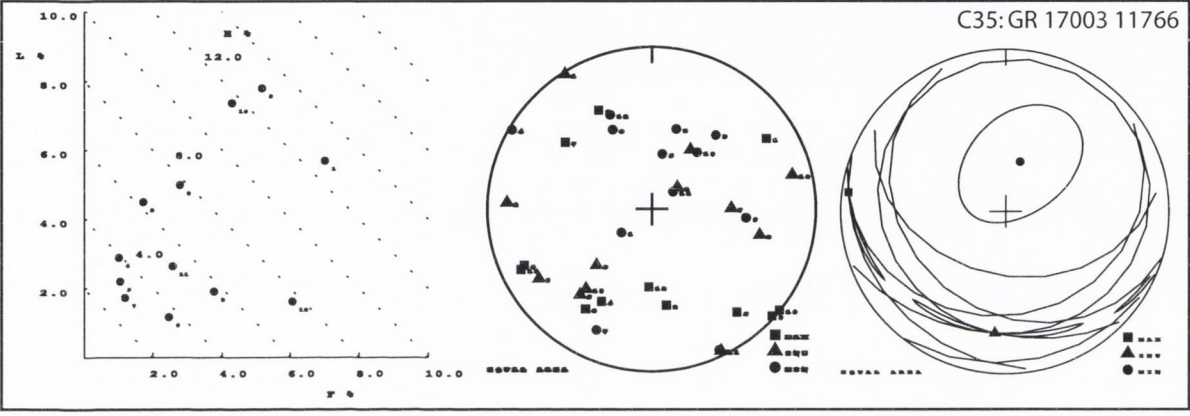
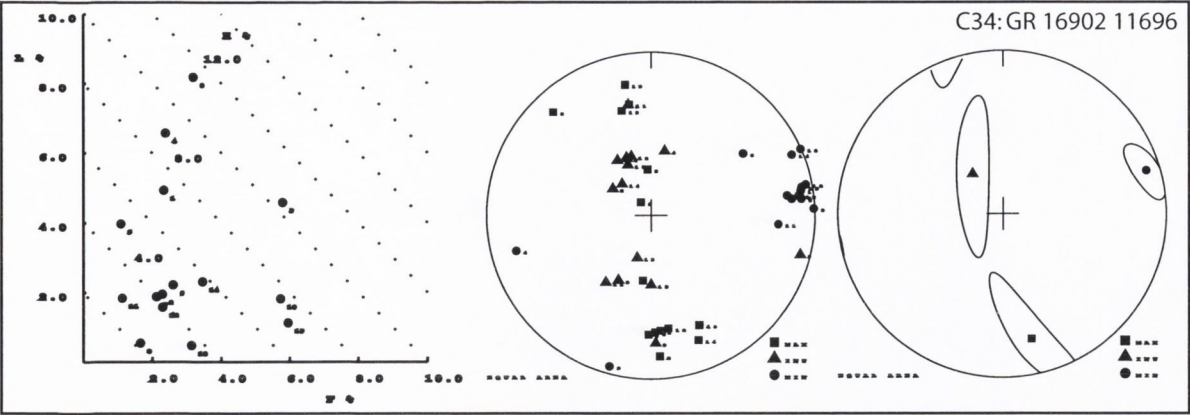


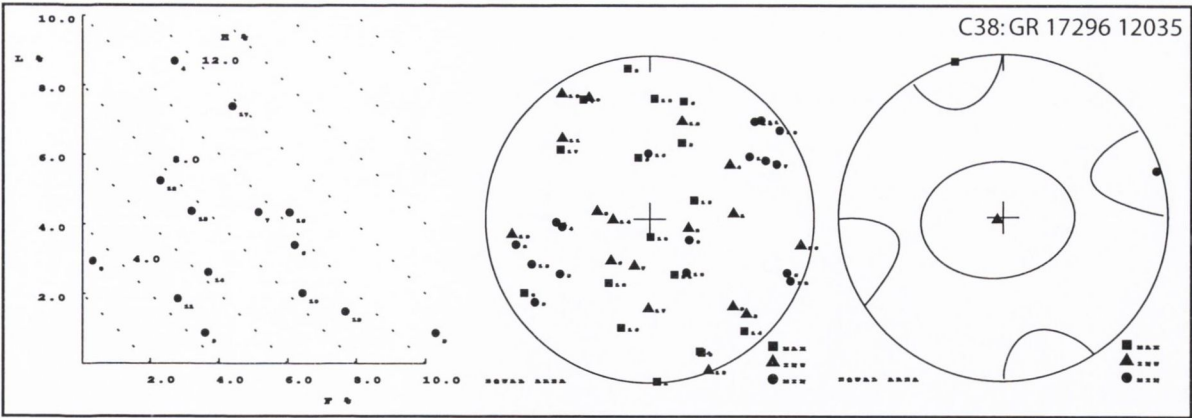












Thermomagnetic Data

Temperature dependence of susceptibility: Great Euclrite (West, A6)

TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC
36.3	771.6	241.8	811.6	473.4	769.5	732.7	130.5	657.9	164.3	460	587.1	292.7	541.8
36.8	771.7	244.3	812.2	476.2	768.6	735.3	127.7	656.3	165.7	459.5	586.8	290.4	541.3
39.1	773.2	246.8	812.7	478.5	767.5	737.6	125.5	654.1	167.8	457.1	585.6	287.9	542.2
42	773.1	249.2	814.6	481.1	767.3	740.3	123.5	651.9	170.3	455.3	586	285.7	541.4
44.8	773.6	252	814.6	483.8	766.6	742.9	121.5	650	172.4	452.9	585.2	283.4	541
47.6	773.4	254.2	815.6	486.5	765.8	745.5	119.8	648.1	174.5	450.6	584.1	281.2	540.5
50.5	773	256.7	816.9	488.8	764	747.8	118	645.9	176.6	447.9	583.5	278.7	539.9
53.1	773.9	258.9	817.8	491.3	763.9	749.8	116.3	644	178.6	445.5	583.1	276.4	539
55.5	774.5	261.4	819.4	493.4	763.3	751.4	114.7	642.1	180.7	443.8	582.7	274.2	538.4
57.8	775.1	263.4	819.5	497.3	762.2	752.4	113.3	640.5	182.5	442.3	582	272	537.5
59.9	775.5	265.6	819.8	500	761	753.4	112.1	639.5	184	440.8	581.6	269.8	536
61.7	776.6	267.8	821.3	502.4	761.8	754.1	111.1	638.6	185.1	439.9	581.5	267.3	535.9
63.8	777	270.3	821.7	505.1	759.7	754.7	109.9	638	186.1	439.1	580.9	264.8	535.2
65.6	777.2	272.5	821.7	507.8	760.5	755.4	108.8	637.6	186.8	438.2	582	262.8	534.9
67.5	777.4	274.8	822.2	510.2	759.1	756	106.2	637	186.9	436.7	580	260.6	534.1
69.3	777.2	277	823.5	512.7	756.9	756.4	107.5	636.7	187.6	435.9	580.4	258.4	533.9
71.1	777.5	279.8	824.1	515.4	756.8	756.4	106.9	636.1	188.3	434.1	581	255.9	533.6
72.7	778	282	824.4	517.8	756.4	756.4	106.1	635.7	188.5	432.3	578.5	253.7	532.9
74.3	777.7	284	825.3	520.5	754.6	756.7	105.7	635.4	189	430.8	580.1	251.2	533.3
75.8	778.2	286.2	826.4	522.9	754.6	756.7	105	635.1	189.4	429.7	578.6	249	532.2
77.7	777.5	288.5	827.3	525.4	752.9	756.7	104.6	634.8	190	428.2	578.4	246.8	531.9
79.2	778.6	290.7	826.8	528.1	751.6	757	103.9	634.2	190.8	427	579	244.8	532.2
80.8	778.7	292.9	827.9	530.5	751.8	757.4	103.2	632.9	192.4	425.8	577.4	242.6	530.7
82.4	778.3	295.5	828.7	533.3	750.6	757.7	102.5	631.6	194	425.3	577.6	240.7	530.7
84.2	779.5	298	829.4	536.3	750.2	758	102.1	630.1	196.2	424.4	577.8	238.5	529.8
85.8	778.9	300.2	830.7	539	749.7	758	101.7	628.2	197	423.8	578.4	236	529.2
87.6	778.7	302.8	830.9	541.5	748.4	758.4	101.1	626	201.8	422.9	576.6	233.8	528.3
89.5	778.3	305	830.9	544.2	747.2	758.4	100.8	623.5	205.4	422	575.4	231.6	528.1
91.3	778.4	307.3	832.2	546.3	746	758.7	100.4	621.6	206.7	420.6	575.7	229.4	527.3
93.2	778.9	309.8	832.5	550	744.8	758.7	99.7	620	212	419.4	575.9	227.5	526.8
95	778.7	312.3	833.1	552.8	742.7	758.7	99.2	618.5	214.3	418	574.8	225.8	526.1
96.8	779.2	314.6	834.4	556.2	739.6	759	98.9	617.2	217	417.1	575.1	223.9	525.7
98.7	779.8	316.8	837	559.2	737.7	759.7	98.7	615.3	220.5	415.7	574.2	222	525.5
100.5	779.4	319.1	834.4	562	724.7	758.4	98.6	613.4	225.2	414.4	573.7	220.1	524.5
102.4	778.7	321.7	834.2	565.1	711.6	758	98.6	611.6	229.7	412.7	572.9	218.2	523.4
104.5	778.8	324.2	834.1	567.8	697.5	757.4	98.7	609.4	234.7	411.5	572.5	216	523.9
106.3	778.2	326.8	834.3	570.3	685.1	756.4	98.8	607.5	239.5	409.8	572.4	213.8	523
108.2	777.5	329.3	835.2	573.1	675.5	755.7	99.1	605.3	244.5	408.6	572.1	211.6	526.3
110	778.3	331.9	834.2	575.2	660.4	755.4	99.1	603.1	248.5	407.2	571.4	209.4	523.2
111.9	777.7	334.4	833.9	578	637.1	755.1	99	600.6	252.4	405.4	571.2	207.2	522.6
113.7	777.7	337	833.2	580.8	599.7	755.1	99	598.5	261.8	403.7	571.1	205.1	522.3
115.6	777.5	339.2	833.3	583.6	548.9	755.1	98.7	596	270.8	401.3	570.2	202.9	522.2
117.7	777.6	341.5	832.5	586	519.8	754.4	98.8	593.8	280.2	399.4	569.2	200.4	521.2
119.6	777.5	343.8	832.2	588.2	464.1	752.8	99.4	591.3	291.2	397	568.6	198.3	520.9
121.4	777.2	346.1	831.1	590.7	431.5	750.4	100.7	588.8	305.2	394.1	568.5	195.8	520.2
123.6	777.2	348.7	830.2	593.8	402.6	747.2	102	586.7	320.5	391.9	568.5	193.9	520.3
125.4	776.7	351.2	828.7	596.6	382.8	744.9	103.3	584.2	338.1	389.5	566.7	191.7	518.3
127.5	776.8	353.5	827.9	599.4	368.2	743.2	104.1	581.7	364	387.7	566.1	189.6	519.1
129.7	777.2	356.1	827.1	601.6	360.1	742.2	104.6	578.9	388.9	385.3	566.4	187.4	517.6
131.8	776.6	358.1	826.3	603.8	350.7	741.6	104.9	576.1	438	384.8	565.6	185	516.8
133.7	777.4	360.7	824.6	605.9	342.8	741.2	104.8	573.4	470.1	383.4	564.8	182.8	516.4
135.8	777.2	363.2	823.7	608.1	333.8	740.9	105.1	570.9	490	381.9	564.8	180.6	516.4
137.9	777.4	365.8	822.6	610.9	322.6	739.9	105.2	568.4	505	380.5	563.8	178.5	516
140.1	777.6	368.1	821.5	613.1	319.5	738.9	105.6	566	514.5	379.1	563.7	176	515.4
141.9	778.5	370.4	821.2	615.3	311.1	737.6	106.1	563.5	521.6	377.6	563.5	173.6	515.1
143.8	778.4	373	819.8	617.8	303.1	735.7	106.8	561.4	527.1	375.8	562.8	171.5	514.7
145.7	779	375.6	818.4	620.3	296.9	733.7	107.8	559.5	531.4	373.6	563	169.3	514.9
147.8	779.9	377.9	816.7	622.8	287.2	732.1	108.6	557.4	534.9	371.6	561.4	167.1	514.5
149.7	780.6	379.9	814.3	625.4	278.9	731.1	109.2	555.2	539.1	369.6	561.2	165.3	514.6
151.6	781.7	381.9	813.2	627.6	273.4	730.1	109.8	553.4	540.7	367.5	562.9	163.4	513.6
153.7	782.3	384.5	812.9	630.1	266.5	729.1	110.4	551.3	544.1	365.8	561	161.5	512.9
155.9	783.1	387.4	810.9	632.6	260.2	728.5	111	549.4	547.5	364.7	559.4	159.3	517.9
158.3	783.5	390	809.6	635.7	253.4	727.5	111.7	547	550.2	363.5	561.3	157.7	513.8
160.4	783.8	392.9	808.5	638.3	247.2	726.2	112.6	544.2	553.2	361.8	561.4	155.9	512.2
162.3	784.4	395.3	806.3	641.1	246.9	724.2	113.9	541.5	559.2	360.4	559.9	153.7	513.7
164.7	785	398.2	805.6	643.3	242.2	722.3	115	538.7	562	358.7	558.8	151.8	511.3
166.9	786.7	400.5	804.3	645.9	237.8	720	116.4	536	564.1	356.4	558.4	149.7	513
169	787.6	403.1	803.5	648.4	233.7	717.7	118	533.3	567.7	354.1	558.5	147.6	514.5
171.2	788	405.4	802.6	650.9	230.2	715.5	119.2	530.8	571.9	351.8	557.4		
173.3	789.7	407.7	800.4	653.6	225.8	713.2	120.4	528.4	574.4	349.8	556.6		
175.8	788.7	410.1	799.6	656.6	221.4	710.9	121.8	526	578.4	348.1	555.7		
178.2	789.4	412.7	797.7	659.5	217.3	709	123	523.5	582	346.7	554.8		
180.6	790.6	414.9	797.1	662.1	213.1	707.3	124	520.8	586.6	345.2	554.3		
183.1	792.3	415.9	796.2	664.6	209	705.7	124.6	518.1	591.7	343.5	554.6		
185.5	792.9	418.2	793.7	667.2	205.2	704.1	125.4	515.7	594.2	342.1	554.3		
187.9	793.8	420.6	792.5	669.7	202.1	702.8	126.4	513.3	596.5	340.7	553.8		
190.1	793.6	422.9	791.6	672.3	199.1	701.2	127	510.9	598.7	339.9	553.3		
192.3	794.9	425	790.9	675.1	196.1	699.6	128	508.7	598.4	338.7	552.8		
194.7	796	427.3	789.7	677.7	192.7	698	129.4	506.3	597.9	337.3	552		
197.2	796.5	429.6	789	680.3	188.8	696	130.4	503.9	599.1	335.5	552		
199.6	797.3	431.7	787.5	683.2	184.5	694.4	131.6	501.5	597.1	334.1	551.4		
201.8	797.8	433.8	786.2	685.7	180.8	692.5	133.3	499.1	597.9	332.4	551.5		
204	799.5	435.8	785	688.5	177.2	690.9	134.5	496.7	595.9	330.7	551.9		
206.4	800	437.9	784.1	690.9	173.9	688.9	136.2	494.3	596.9	328.7	551.3		
208.9	801.6	439.9	783.4	693.4	170.6	687	138.2	491.9	595.4	326.8	550.4		
211.1	802.6	442	781.8	696	167.4	685.1	140.2	489.5	595.4	324.8	550.1		
213.5	803	444.1	781.1	698.3	163.2	683.2	142.1	487.1	594.2	322.6	549.5		
215.4	802.7	446.1	780.8	700.9	161.3	681.2	143.6	484.4	593				

Temperature dependence of susceptibility: Great Eucrite (South, A9)

TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC
33.7	1015.2	238.8	1058.6	473.7	1084.3	729.8	196.7	667.2	245.9	442	924.4	279.2	864.7		
34.2	1017.4	241.5	1058.7	476.1	1083.3	732.1	192.7	665.2	247.3	447.3	924.2	277.3	863.8		
36.5	1018.5	244	1060.2	478.5	1083.6	734.4	189.6	663.3	248.8	437.6	923.5	275.6	863		
39.4	1019.4	246.5	1061.3	480.5	1083.5	736.3	186.7	660.8	248	435.8	922.8	273.9	862.7		
42.5	1019.5	249.2	1062.1	483.2	1083.4	738	183.9	658.2	250.9	433.8	923.6	271.7	862.4		
45.6	1020.3	251.5	1062.3	485.6	1083.3	740.3	181.3	655.7	252.8	432.3	922.2	269.8	862.5		
48.2	1019.9	253.9	1063.2	487.7	1082	742.2	178.5	652.8	254.8	430.8	921.6	267.3	862.2		
50.8	1019.7	256.7	1064.1	490.4	1083.1	744.5	175.6	650.3	257.1	429.7	922.8	264.8	861.1		
53.1	1020	259.2	1065.4	492.8	1082.9	747.2	172.8	647.8	259.8	428.4	919.8	262.3	860.4		
55.2	1020.1	261.4	1066.2	496.1	1081.7	749.8	170.4	645.2	264.1	425.3	920	259.8	859.4		
57.6	1020.8	263.6	1067.5	498.8	1082	751.8	168.6	642.7	268.9	424.4	920.9	257.3	858.7		
59.6	1020.2	265.9	1068.3	501.2	1080.7	753.1	166.8	640.2	272.7	423.8	919.9	255.1	856.5		
61.5	1021	268.1	1068.8	503.3	1079.8	754.4	165.6	637.3	278.4	422.8	919.6	252.6	855.8		
63.5	1021.2	270.6	1070.2	505.7	1080.1	755.4	164.4	634.8	284.2	422.3	919.4	250.3	855.5		
65.4	1021.7	273.1	1071.1	508.4	1079.3	756	163.1	632.6	290.7	421.5	919.2	248.1	854.9		
67.2	1020.9	275.6	1071.5	511.2	1078.4	756.7	162.1	630.4	298.9	420.3	919	246.2	854.1		
69	1022.2	278.1	1072	513.3	1077.6	757	161.4	627.9	310.1	418.8	917.3	244	853.7		
70.6	1022.3	280.3	1073	515.7	1077	757.7	160.6	625.7	322.6	417.4	917.1	241.8	852.8		
72.2	1021.3	282.3	1073.7	518.1	1074.8	758	159.3	623.8	332.4	415.6	917	239.6	852.8		
73.7	1021.8	284.5	1074.3	520.5	1074.8	758.4	159.1	621.6	341.2	414.2	915.4	237.4	851.6		
75.3	1022.1	286.8	1076.3	523.2	1073.9	758.7	158.4	619.7	350.2	412.7	914.5	235.2	851.2		
77.1	1022.3	288.7	1076.1	526	1072.9	759	157.8	617.2	359.5	411.2	914.5	233.5	851		
78.7	1021.7	291	1077.2	528.4	1071.9	759	157.4	614.7	367.5	409.9	914.2	231.6	849.9		
80.5	1021.7	293.2	1078	530.5	1070	759.4	156.8	612.5	373.1	407.7	913.7	230	849.5		
82.4	1023	295.7	1078.9	532.7	1068.4	759.7	156.4	610.3	378.7	405.7	911.1	228	848.4		
84.2	1022.9	298	1079.9	535.9	1064.3	759.7	156	607.8	384.3	404.5	911.8	225.8	847.5		
86.1	1023.4	300.2	1080.1	537.8	1057.8	760	155.8	605.6	390.2	403.4	912.6	223.9	846.9		
87.9	1022.7	302.5	1082.2	540.6	1040.2	760	155.6	603.1	395.2	402.2	911.5	222	846.1		
90	1022.6	304.7	1082.2	543	1016.4	759.7	155.3	600.6	400.6	401.3	910.8	220.1	845.6		
91.8	1023.2	307	1082.1	545.4	991.2	760	155.1	598.5	407	400.2	910.5	218.7	844.8		
93.9	1023.7	309.8	1083	548.2	963.7	760	154.6	596	414.9	398.7	910.1	217.1	844.7		
95.8	1023.6	312.3	1083.4	551.3	932.1	760	154.3	593.8	422.5	397.3	909.9	215.2	844.2		
97.9	1023.4	314.3	1084.2	554.3	901.9	759.7	154.2	591.6	432.7	395.3	908.8	213.5	843.5		
99.7	1023.6	316.8	1084.7	557.1	877.8	759.4	154	589.1	444.8	393.2	908.2	211.6	843		
101.6	1023.6	319.1	1084	559.8	859.7	759	153.9	586.7	461.5	391.2	907.3	209.7	842.2		
103.4	1023.8	321.7	1085.5	562.6	845	759	154.9	584.8	472.5	389.9	907.1	207.5	841.9		
105.3	1023.9	323.9	1086.5	565.4	828.5	758.4	154	583.6	479.4	387.7	905.8	205.6	841.1		
107.4	1025.1	326.2	1085.7	567.8	809.2	757.7	154.2	582.3	491	386	905.1	203.7	840.5		
109.2	1025.7	328.7	1085.9	570	793.5	757	154.4	580.5	507.3	384	905.4	201.5	839.8		
111.1	1026.1	331.3	1086.2	572.8	774.6	757	154.5	578.6	529.1	382.5	904.1	199.3	839.1		
113.2	1026	333.8	1086.8	575.5	742.3	756.7	154.7	576.5	554.4	381.1	903.1	197.2	837.9		
115.1	1026.5	335.8	1087.1	578.3	703.9	755.7	155.2	574.3	578.4	379.9	902.3	195	837.5		
116.9	1026.7	338.1	1086	581	658.6	754.4	155.6	572.1	602	378.8	901.5	193.1	836.7		
119	1026.1	340.1	1086.2	583.9	618.7	752.8	156.3	570	624.1	377.6	902.3	190.9	837		
120.9	1026.8	342.4	1086.9	586.7	583.7	750.8	157.6	567.8	643.8	376.8	901.9	188.8	835.6		
121	1027.1	344.9	1086.8	589.5	555	748.8	157	565.7	658.7	375.9	901.2	186.6	834.5		
124.9	1027.4	347.2	1085.7	592.2	531.3	747.2	159.5	563.5	667.5	375.3	900.7	184.7	833.6		
127	1027.7	349.5	1085.8	594.7	517.1	746.2	160.3	561.4	677.7	374.2	900.7	182.3	833		
128.9	1028.3	351.8	1085.9	597.2	503.7	745.5	160.7	559.6	690.1	373	900.8	180.1	832.9		
131	1028.6	354.1	1086.1	599.7	482.4	745.2	161.1	557.2	699.1	372.1	900.2	177.9	832.4		
132.9	1029.2	356.4	1086	602.5	480.5	744.9	161.3	554	705.7	370.7	899.5	175.8	831.2		
134.7	1029.2	358.7	1085.6	605.3	471.2	744.9	161.4	552.2	712.3	369	898.8	173.6	831		
136.8	1029.3	361.2	1085.5	608.4	459.9	743.9	161.6	550.6	717.9	367.5	898.2	171.5	830.6		
138.7	1029.2	363.8	1086.8	611.3	451	743.2	161.9	548.8	722	366.1	897.8	169	830.3		
140.6	1030	366.1	1086.3	613.4	443.5	741.9	162.4	547	730.1	365	897.8	166.9	829.8		
142.5	1030.6	368.4	1085	616.3	436.5	739.9	163.7	545.4	736.4	363.5	896.8	165	828.7		
144.3	1030.8	371	1085.5	619.1	427.8	738.3	165	543.3	743.7	362.4	895.3	162.8	827.9		
146.5	1031.2	373.3	1086	621.9	420.3	736.7	166.4	541.5	753.1	361.5	894.3	161	827.5		
148.4	1032	375.3	1085.2	624.4	413.2	735	167.9	539	765.6	360.4	895	158.8	826.8		
150.5	1032.3	377	1084.5	626.9	406.5	733.4	169.2	536.6	779.3	358.7	894.7	156.9	826.4		
152.4	1032.8	379.6	1084.8	629.4	399.7	732.1	170.4	534.2	796.4	357.2	894.1	154.8	825.3		
154.5	1033.5	382.2	1085.3	632.6	392.7	730.8	171.8	531.7	814.3	355.5	893.4	152.9	824.9		
156.7	1034.6	385.1	1084.8	635.4	385	729.5	173.3	528.7	835.4	353.2	892	151	824		
158.8	1034.3	387.4	1083.9	638.3	382.2	727.5	174.8	525.7	859.2	351.2	891.2	149.2	823.9		
161	1034.7	389.7	1084.6	641.1	374.6	726.2	176.4	522.6	879.7	348.7	890.6	147	823.1		
163.1	1035.7	392.1	1085.1	644	368.9	724.6	178	520.2	894.8	346.4	889.7	144.9	823.6		
165.3	1036.4	394.7	1084.4	646.5	362	722.9	180	517.8	906.8	344.1	889.4	142.7	823.1		
167.1	1037.3	397	1084.4	649	354.1	721	182	515.1	919.7	341.5	887.6	140.9	822.7		
169.3	1037.5	399.3	1084.7	651.2	341.3	719.4	184.3	512.4	928.7	339.5	886.8	139	822.6		
171.5	1037.9	401.6	1084.3	654.1	327.6	717.7	186.7	509.6	934	338.1	886.7	137.1	821.8		
173.9	1038.4	404.3	1083.9	657.3	313.8	716.1	189.2	506.9	938	336.4	886.1	135.3	822		
176	1038.5	406.9	1084.1	660.5	299.4	714.5	192	504.5	939.1	334.4	885.3	133.4	822.1		
178.2	1039.3	409.2	1084.2	663	290.2	713.2	194.4	502.1	934.4	332.4	884.8	131.8	821.5		
180.9	1040.5	412	1084.1	665.6	284.7	711.9	196.6	499.4	940.4	330.4	883.6				
183.3	1041.4	413.9	1083.5	668.1	282.3	710.9	198.6	496.7	939.1	328.5	882.3				
185.8	1042.3	416.2	1084.7	671	278.5	710.3	200.4	494	940.4	326.8	881.6				
188.2	1042.8	418.5	1084.1	673.9	273.4	708.6	202.9	491.6	938.9	324.5	881.1				
190.1	1041.6	421.2	1083.5	676.4	269.5	706.7	205.3	489.2	939	322.5	882.4				
192.3	1043.1	423.2	1084.8	679.3	267.4	705.4	207.4	486.5	938	321.1	881.8				
194.7	1044.2	425.6	1084.1	681.9	264.5	704.2	209.8	484.1	937.6	319.4	880.4				
196.9	1045.1	427.9	1084.5	684.8	260.9	703.1	210.3	481.4	937.4	317.7	879.6				

Temperature dependence of susceptibility: Great Euclite (Northeast, A23)

[illegible]

Temperature dependence of susceptibility: Great Euclite (North, A28)

TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC
30.8	384.4	242.1	428.9	468.9	455.9	716.4	43.5	681.9	43.5	483.8	302.8	303.3	289.6
31.4	384	244.5	429.4	471.3	455	718.7	41.8	680.6	44.3	480.8	303.1	301.6	290.2
33.4	384.7	247	430.1	473.7	455.5	721	38.9	678	47.2	478.5	303.1	298.7	289.9
36	395.4	249.5	430.9	476.1	456.5	723.3	38.1	677.1	46.1	476.1	304.8	298	289.9
39.1	395.6	252	431.5	478.5	456.6	725.5	36.4	675.1	47.3	473.7	304.7	296.3	288.6
42	394.9	254.5	432.3	480.5	456.3	728.2	34.5	673.9	47.3	470.7	304.7	294.9	288.1
44.6	397.4	257	433.3	482.9	457	730.4	32.6	672.6	48.6	467.7	306.1	293.2	288.4
47.2	395.7	259.2	433.5	485.9	458.2	733.4	30.6	671.6	49	465.1	306.1	287.1	287.7
49.8	396.5	261.7	434.5	488.6	458.7	735.7	28.6	669.6	49.4	462.4	306.8	285.4	287.8
52.1	396.2	263.9	435.1	491.3	458.3	738.3	27	668	50	460	306.7	284	287.3
54.2	396.4	266.4	435.6	493.7	457.5	740.3	25.3	667.5	50.8	457.4	306.7	282	286.7
56.3	396.4	268.9	436.3	496.1	456.7	742.6	23.8	665.2	51.9	455	306.5	280.1	286
58.1	396.7	271.7	436.5	499.1	456.6	744.9	22.2	663.6	53.2	453.2	307.6	277.3	286.3
60.2	396.8	273.9	438.1	501.8	455.6	747.2	20.4	661.4	54.5	452	306.8	275.3	287.1
61.7	396.9	276.4	439.2	504.8	455.2	749.8	18.8	659.5	55.7	450.6	306.8	273.7	285.2
63.5	396.7	279	439.7	507.2	454.6	752.1	17.3	657.6	57	449.1	307.2	272.3	284.8
65.4	397	281.2	439.9	509.3	454.1	753.7	16.2	655.4	58.4	447.6	306.5	270.6	284.8
66.9	396.4	283.4	440.3	511.8	454.4	754.7	15.1	653.5	59.6	445.8	306.8	268.6	284.8
68.8	397	285.7	441.7	514.2	454.1	755.7	14.2	651.9	60.9	444.4	306.3	267	285.1
70.3	397.1	288.2	442.7	516.9	453.7	756.7	13.5	650	62.2	442.9	307	264.8	284.8
72.2	397.4	290.4	443.3	519.3	452.5	757	12.7	648.1	63.5	441.1	305.9	262.8	284.1
73.7	397.1	293.2	443.5	521.4	453	757.7	12.2	646.2	65	439.4	306.7	260.6	283.6
75.6	396.6	295.7	443.2	523.9	452	758	11.6	644	66.9	437	306.2	258.1	283
77.4	397.1	298	444	526.6	451.1	758.4	11.1	642.1	68.6	434.9	305.5	255.9	282.8
79.2	397.6	300.5	445.6	529	450.5	758.4	10.6	639.5	70.5	433.5	305.2	253.9	283.2
81.3	397.9	302.8	445.7	531.4	450.2	758.4	10.2	637.3	72.4	432	305.3	252	283.1
83.2	398.2	305.3	446.3	534.2	447.6	758.4	9.9	634.8	74.2	430.5	305.1	250.6	284.2
85.3	397.5	307.5	447.2	536.6	446	758.7	9.6	632.6	75.5	429.4	305.3	249	283.3
87.1	397.8	309.8	447.3	539	445.5	759	9.3	630.4	77.1	428.2	304.5	247.8	282.4
89.2	397.6	312.1	448.8	541.8	443.3	759.4	8.8	628.2	78.4	426.7	304.6	245.9	281.6
91.3	398.4	314.3	448.9	547.3	440.4	759.7	8.6	626	80.1	425	304.3	244.3	282.3
93.2	398.8	316.6	449.9	550	437	760	8.3	623.8	81.6	423.2	304.4	242.3	281.9
95.3	397.9	318.8	449.9	552.9	433.7	761	7.7	621.9	83.3	420.9	306	240.6	281.3
97.1	397.9	321.4	450.2	555.5	429.8	760.3	7.5	620	85	419.1	304.2	238.2	281.4
99.2	397.7	323.9	450.7	558	425.6	760.7	7.2	617.8	86.8	417.4	304.3	236	282.1
101.1	398.6	326.2	450.4	560.1	420.4	761.3	6.7	615.3	88.2	415	303.5	234.1	282.5
102.9	398.9	328.5	451	562.3	414.3	760.7	6.6	613.1	91.5	412.7	303.7	231.6	283
105	399	330.2	451.3	564.4	408.7	760.7	6.7	611.3	93.3	410.4	303.3	229.4	282.5
106.9	399.2	331.6	451.6	567.2	402.1	760.7	6.3	609	94.6	408.6	302.7	228.9	281.8
108.7	399.8	333	451.8	570	393.4	761	6.1	608.1	96.7	406.9	303	226.9	281.6
110.6	399.4	334.1	451.8	572.4	384.9	761.3	5.9	608.1	96.4	404.8	302.2	222.3	280.7
112.7	399	335.5	451.6	574.9	374.3	760.7	6.2	606.6	98	402.8	302.3	220.1	280.3
114.5	399.2	337.5	451.9	577.7	360.7	760.7	6.2	604.4	100.3	401.3	302.2	217.9	279.6
116.7	399.7	339.5	451.3	580.5	341.3	759.7	6.3	601.6	103.2	399.9	301.1	215.4	279.2
118.8	399.9	341.5	451.4	583.3	321	758.7	6.5	598.5	107.2	398.4	301.8	213.3	279.5
120.6	399.5	343.5	452.1	586	298.8	758.4	6.4	595.4	107.7	395.4	301.7	211.1	278.9
122.8	400.1	345.5	451.7	588.5	277.4	757.4	6.8	592.2	117.8	395	300.7	208.3	278.5
124.6	401.3	347.8	452.1	591	260.7	756.4	7.1	589.5	123.6	392.9	302.4	206.2	278.6
126.7	400.8	349.8	452.3	593.5	247.7	754.4	7.7	586.7	130.3	390.3	300.1	204	278.3
128.6	401.9	351.8	452.2	596.3	224.3	752.6	8.4	584	131.2	388	301.2	201.8	278.2
130.7	401.9	353.8	451.4	599.4	222.1	751.1	8.9	581.1	147.4	385.7	301	199.9	277.4
132.9	401.7	356.1	451.7	601.9	211.8	750.1	9.4	578.6	157.4	384	299.7	197.7	277.4
135	402.7	358.4	451.8	604.4	202.8	749.1	9.8	576.8	165	382.2	299.6	195.5	277.4
137.1	403.6	360.7	451.5	606.6	194.7	747.8	10.4	576.1	167.6	380.2	300.6	193.6	277.5
139	404	363.2	452.1	609.1	187.2	746.8	10.8	575.2	171.8	378.5	298.7	191.7	277.2
141.1	404.2	365.8	452	611.6	179.4	745.5	11.3	573.7	178.8	376.8	299.4	189.8	277.4
143	403.8	367.8	452.5	614.1	172.4	743.9	11.8	571.8	185.7	375.3	299.8	187.7	277.1
144.9	404.6	370.1	452.6	616.3	166.1	742.2	12.6	570	192	373.9	298.5	185.5	277.1
146.7	405.4	372.4	452	618.8	160	739.9	13.5	568.4	197.2	372.7	299.3	183.3	276.6
148.6	406.1	374.7	452	621.3	154.3	738.3	14.4	566.3	203.1	371	299	181.2	276.7
150.8	407.6	377.3	452	623.8	149.1	736.7	15	564.4	208.5	369.8	297.7	179	275.7
152.9	407.7	379.9	451.4	626.3	144.4	735	15.9	562.3	214.1	369	298.4	176.6	275.2
155.1	408.6	382.2	452	628.2	140	733.7	16.7	560.8	218.6	368.1	297.9	174.4	275.6
157.5	409.9	384.5	451.9	630.7	135.8	732.7	17.2	558.6	223.3	366.7	297.8	172.3	275.1
159.3	409.4	387.1	451.9	632.9	131.9	731.7	17.7	556.8	228.2	365.3	298.4	170.1	275.4
161.8	409.7	389.5	452	635.1	128.1	731.1	18.3	555.2	232.1	363.5	297.4	168.2	274.7
163.8	410.4	391.8	451.6	637.6	124.7	729.6	18.8	553.4	235.7	362.1	296.6	166.3	274.6
166.3	410.6	394.1	452.3	639.9	121.5	728.5	19.5	551.9	239.3	360.4	296.8	164.2	274.9
168.5	411.4	396.1	451.4	642.4	118.2	727.2	20	550	242.6	359.2	296.5	162.3	274.2
170.6	411.6	398.4	450.8	644.9	115.2	725.5	20.8	548.5	245.4	357.8	296.5	160.4	274.2
172.8	411.4	401.1	451.4	647.4	112.1	723.6	21.5	546.7	248.9	356.7	296.7	158.5	274.5
175.2	411.4	403.1	450.8	649.7	108.7	721.6	22.6	544.5	252.5	355.5	296.2	156.7	274.3
177.7	412	405.1	451.4	651.9	105.3	719.7	23.7	542.4	254.7	354.4	296.4	154.5	274.7
180.1	413.1	407.5	451.5	654.7	102.2	718.4	24.4	540	257.3	352.9	296.4	152.4	274.6
182.3	413.7	409.8	451.5	657	98.9	717.1	25.4	537.8	259.8	351.8	295.5	150.2	274.3
184.7	414.6	412.1	451	659.8	96.2	716.1	25.9	535.7	263.4	350.4	295.1	148.1	274.8
186	415.3	414.4	451	662.1	93.4	714.5	26.8	533.6	266.4	349.5	294.8	146	274.4
189.15	415.7	416.8	451.2	664.3	90.4	712.2	27.7	532	268.8	348.7	295	144.1	273.8
193.9	416.5	419.1	451.6	666.8	87.6	710.6	28.8	530.8	269.3	347.7	294.8	141.9	272.9
196.1	416.8	421.8	452.3	669.7	84.5	708.6	29.6	528.9	271.7	346.7	294.2	139.8	272.7
198.3	417.3	424.1	452.2	671.9	81.9	707	30.3	528.4	272.5	345.4	294.1	137.9	272.9
200.4	418.1	426.7	452	674.2	79.4	705.1	31.1	526.9	274.7	338.1	293.6	135.8	272.5
202.9	418.9	428.8	452	676.4	77.1	703.8	32.1	524.5	277.8	335.5	293.2	133.7	272.7
205.3	419.5	430.8	452.2	678	75	702.5	33.2	522.3	280.7	333.6	293.8	131.5	272.6
207.5	419.8	433.8	452.7	681.2	73	699.9	33.9	519.9	283.1	331	293.5	129.7	272.9
209.7	420.5	436.1	453	683.8	70.9	697.3	34.8	517.8	283.9	328.7	292.6		
211.9	421.2	438.5	452.9	686	68.5	696	35.5	515.7	285.9	326.5	291.1		
214.3	421.2	440.5	452.8	688.6	66.3	695.4	35.8	513.3	288	324.2	292.8		
216.8	423.3</												

Temperature dependence of susceptibility: Carlingford Later Gabbros (C34)

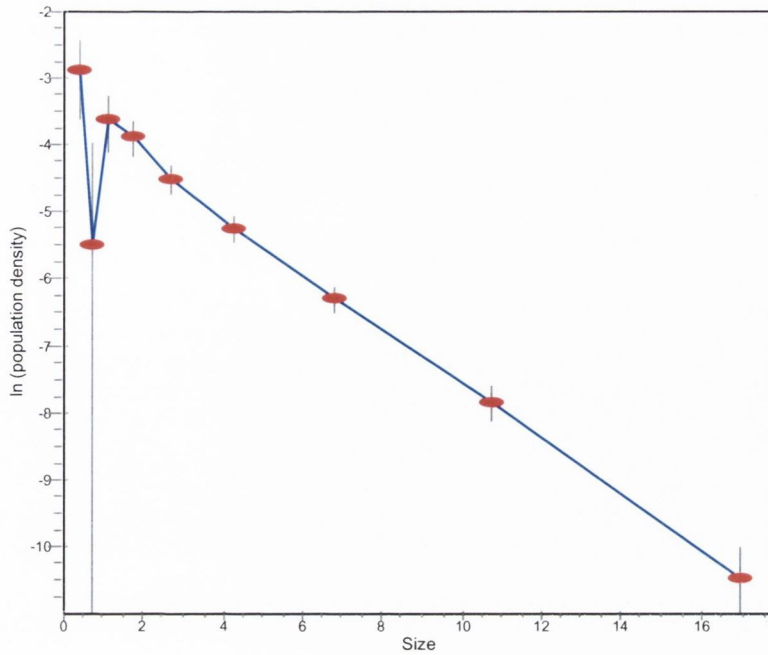
[illegible]

Temperature dependence of susceptibility: Carlingford Later Gabbros (C38)

TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC	TEMP	TSUSC
29.3	175.6	220.6	189	430.8	171.6	670.7	-55.2	703.1	48.5	490.7	134.9	325.6	128	144.1	118.7
30.1	175.5	222.8	189.3	433.2	171.1	672.8	-55.7	701.5	48.4	489.8	134.9	323.9	127.9	141.9	118.7
32.4	175.5	225	189.4	435.5	170.8	675.1	-56	699.6	48.3	488.6	134.9	322.2	127.9	140.1	118.6
35.2	175.5	227.2	189.6	437.9	170.5	677.7	-56.7	698	48.1	487.4	134.9	320.2	127.8	138.5	118.6
38.3	175.4	229.1	189.9	440.2	170.2	680.3	-57.6	696.4	48	486.2	134.9	318.5	127.7	136.3	118.5
41.5	175.8	231.3	190.1	442.6	169.8	682.8	-58.2	694.7	47.7	485	135	316.8	127.6	134.5	118.6
44.3	176	233.8	190.3	445	169.6	685.4	-59.1	693.1	47.6	483.5	134.9	315.2	127.3	132.6	118.6
46.9	176.1	235.7	190.4	447.3	169.2	688	-60.8	691.5	47.3	482.3	135	313.2	127.2	130.7	118.5
49.5	176.2	237.9	190.7	449.7	169	690.5	-61.5	689.8	47.1	480.8	135	311.5	127.1	128.8	118.5
51.8	176.6	240.1	190.8	452	168.7	692.8	-62.1	688	46.9	479.4	135	309.5	127.2	127	118.4
53.9	176.5	242.3	191	454.4	168.5	695.7	-62.7	686	46.5	478.2	135	307.8	126.9	125.4	118.4
56	176.6	244.8	191.1	456.5	168.3	698.6	-63.2	683.8	46.3	476.7	135	305.9	126.8	123.6	118.4
57.8	176.6	247	191.2	458.5	167.9	700.9	-63.6	681.6	45.8	475.2	135.2	303.9	126.7	121.7	118.4
59.6	176.7	249.2	191.5	460.6	167.7	703.1	-64	679.6	44.8	474	135.1	301.9	126.6	119.8	118.4
61.5	176.9	251.5	191.7	462.7	167.5	705.7	-64.3	677.7	44.3	473.1	135.1	299.9	126.5	117.2	118.4
63.3	176.9	253.4	191.8	464.8	167.3	708	-64.7	675.8	43.7	472.5	135.1	298.3	126.4	115.3	118.3
65.1	177.1	255.6	191.9	467.1	167.1	710.3	-65	673.9	43.4	472.2	135	297.1	126.2	113.7	118.3
66.7	177.1	257.8	192.1	469.5	166.8	712.9	-65.4	671.9	42.8	471.6	134.9	296	126.1	111.9	118.4
68.5	177.3	260	192.1	471.9	166.6	715.5	-65.8	669.7	42.4	471	135	294.6	125.9	110.3	118.7
70.1	177.3	262.3	192.2	474	166.5	718.1	-66.4	667.2	42	470.1	134.9	293.2	126	106.9	118.7
71.9	177.4	264.2	192.4	476.1	166.1	720.7	-66.6	664.9	41.8	468.9	135	291.5	125.8	105.3	118.5
73.5	177.5	266.4	192.5	478.2	166	722.9	-66.8	662.4	41.1	467.7	134.9	289.9	125.8		
74.8	177.5	268.6	192.6	480.2	165.7	725.2	-67.2	660.1	40.9	466.6	134.8	287.9	125.6		
76.6	177.6	270.6	192.8	482.6	165.5	727.5	-67.4	658.2	40.6	465.1	134.9	285.9	125.6		
78.2	177.6	272.7	192.8	484.7	165.4	729.5	-67.6	656	40.2	463.3	134.8	284.3	125.5		
79.8	177.8	274.8	193	487.1	165.1	731.7	-68.1	654.4	39.7	461.5	134.7	282	125.5		
81.3	177.8	277	193.2	489.5	165	733.7	-68.3	652.2	39.4	459.7	134.7	279.8	125.4		
83.2	177.9	279	193.4	492.2	164.8	736.3	-68.6	650	38.9	458.2	134.6	277.6	125.4		
84.7	178	281.2	193.5	494.9	164.6	738.6	-68.9	647.8	38.6	456.6	134.6	275.9	125.2		
86.6	178.1	283.1	193.7	497.3	164.4	740.9	-69.3	645.2	37.8	455.6	134.6	274.5	125.1		
88.2	178.2	285.1	193.7	499.7	164.3	743.9	-69.8	642.7	37.3	454.4	134.4	273.1	125		
90	178.2	287.3	193.7	502.7	164.1	746.5	-70.3	640.2	36.9	452.9	134.5	272	125		
91.8	178.2	289.3	193.8	504.2	163.8	748.5	-70.4	638.3	36.4	451.1	134.4	270.6	125		
93.4	178.3	291.5	193.9	506.6	163.8	750.8	-70.7	636.1	35.7	449.7	134.3	269.2	124.8		
95.3	178.4	293.6	194	508.7	163.7	752.4	-71	634.2	35	447.6	134.4	267.5	124.7		
97.1	178.4	295.7	194.2	510.6	163.7	753.7	-71.4	632	34.3	445.5	134.3	265.7	124.7		
98.7	178.5	298	194.3	513	163.5	754.7	-71.6	629.8	33.6	443.5	134.2	264.2	124.6		
100.3	178.6	300.2	194.4	515.1	163.4	755.4	-71.8	627.6	32.9	441.1	134.1	262	124.5		
102.1	178.6	302.5	194.4	517.5	163.3	756.7	-71.8	625.7	32.1	439.1	134	260.3	124.3		
103.7	178.8	304.7	194.6	519.6	163.2	758.7	-71.8	623.2	31.2	437.3	133.9	257.5	124.2		
105.5	179	307	194.6	521.7	163.1	759.4	-72	621	30.3	435.3	133.8	255.6	124.1		
107.4	178.8	309.2	194.6	524.2	163	757.7	-72	618.5	29.5	434.4	133.8	253.7	124		
109.2	178.9	311.5	194.7	526.6	162.8	758.7	-72.3	616.3	28.7	432.9	133.6	252	123.9		
111.1	179.1	313.7	194.8	529	162.5	759	-72.5	614.1	27.8	431.1	133.5	250.1	123.8		
112.9	179.1	315.7	194.7	531.1	162.4	758.4	-72.6	611.9	26.9	429.1	133.5	248.1	123.6		
114.8	179.2	317.7	194.8	533.6	162.1	759.7	-72.7	609.7	26.1	427.3	133.5	246.5	123.6		
116.9	179.3	320	194.8	536	162	760.7	-72.9	607.5	25.3	425	133.4	244.5	123.4		
118.5	179.4	322.5	194.7	538.4	161.9	760.7	-73	605.9	24.3	422.9	133.3	242.6	123.4		
120.4	179.4	324.8	194.8	540.6	161.9	760.7	-73.1	604.1	23.3	420.9	133.3	240.7	123.3		
122.5	179.6	327	194.7	543	161.8	761	-73.2	602.2	22.4	418.5	133.1	238.8	123.3		
124.4	179.6	329.3	194.6	545.8	161.3	761	-73.1	600.3	21.5	416.5	132.9	237.1	123.2		
126.2	179.7	331.6	194.5	548.2	161.1	761	-73.1	598.5	20.6	414.5	132.8	235.7	123		
128.1	179.9	333.5	194.3	551	161	761	-73.1	596.6	19.7	412.9	132.7	234.1	123		
129.9	179.9	335.5	194.1	553.7	160.7	760.7	-73.4	594.1	18.7	412.4	132.6	232.4	122.8		
131.8	180.1	337.5	193.8	556.5	160.4	760.3	-73.3	591.9	17.7	410.9	132.6	230.5	122.7		
133.4	180.2	339.8	193.6	559.2	160.2	760	-73.3	589.8	16.7	409.5	132.5	228.9	122.7		
135.3	180.2	341.8	193.2	561.7	159.8	759.7	-73.3	587.6	15.7	408	132.5	226.9	122.5		
136.9	180.4	344.1	193	564.4	144.8	759.4	-73.3	585.1	14.7	406	132.4	225	122.4		
138.7	180.6	346.1	192.6	566.9	142.7	758.4	-73.4	582.6	13.7	404.3	132.4	223.1	122.3		
140.3	180.6	348.4	192.2	569.7	142.5	756.7	-73.2	580.5	12.7	402.2	132.2	221.2	122.3		
142.2	180.8	350.4	191.8	571.8	142.7	755.1	-73.1	578.3	11.7	399.9	132.2	219.3	122.2		
144.1	181	352.6	191.3	574.3	142.1	753.4	-72.9	575.8	10.7	397.9	132	217.4	122		
145.9	181.2	354.7	190.8	577.1	141.6	752.1	-72.9	573.7	9.7	395.8	131.9	215.7	121.9		
147.8	181.3	356.7	190.2	579.9	141.1	750.4	-72.7	571.5	8.7	394.1	131.8	213.5	121.6		
149.7	181.5	358.9	189.7	582.6	140.6	748.1	-72.6	569.4	7.7	392.4	131.7	211.6	121.6		
151.6	181.6	360.9	189.2	585.4	140.1	746.1	-72.5	567.2	6.7	390.3	131.6	209.7	121.4		
153.7	181.8	363	188.6	588.2	139.6	747.5	-72.6	565.1	5.7	388.3	131.6	207.5	121.4		
155.6	182	365	188	590.7	139.1	746.5	-72.6	562.9	4.7	386.6	131.5	205.6	121.2		
157.5	182.1	367	187.5	592.9	138.6	745.8	-72.5	560.1	3.7	385.1	131.2	204	121.1		
159.3	182.3	369	186.8	595	138.1	744.9	-72.5	558	2.7	383.4	131.3	202.1	121.2		
161.2	182.5	371	186.2	597.2	137.6	743.2	-72.2	555.8	1.7	381.4	131.2	200.4	121		
163.1	182.7	373	185.5	599.4	137.1	741.9	-72.2	553.7	0.7	379.6	131	198.5	120.9		
165	182.6	375.3	184.9	601.9	136.6	740.6	-72.2	551.6	0.2	377.6	130.8	196.6	120.8		
166.9	183.1	377.3	184.3	604.4	136.1	739.9	-71.9	549.7	0.5	376.2	130.8	194.5	120.7		
168.8	183.2	379.6	183.6	606.9	135.6	738.9	-71.8	547.6	0.2	374.7	130.6	192.6	120.6		
170.9	183.4	381.9	182.8	609.4	135.1	738	-71.8	545.1	0.1	373	130.4	190.4	120.4		
173.1	183.7	384	182.2	612.2	134.6	737.3	-71.7	543.3	0.1	371	130.5	188.2	120.3		
175	183.8	386	181.5	614.7	134.1	736.3	-71.6	541.2	0.1	369	130.5	186.3	120.2		
177.1	184.1	387.7	181	617.5	133.6	735	-71.3	539	0.1	367	130.4	184.5	120		
179.3	184.3	390	180.4	620	133.1	733.7	-71.3	536.6	0.1	365	130.3	182.5	120		
181.2	184.6	391.8	179.7	622.8	132.6	732.4	-71.2	534.2	0.1	363	130.2	180.4	119.9		
183.1															

Crystal Size Distribution Data

CSD Corrections 1.37 -- 1.csd



Model - 1.0 : 1.5 : 2.7

Foliated

Roundness = 0.6
Normal orientation



Area = 1607.16

Quality = 0.4

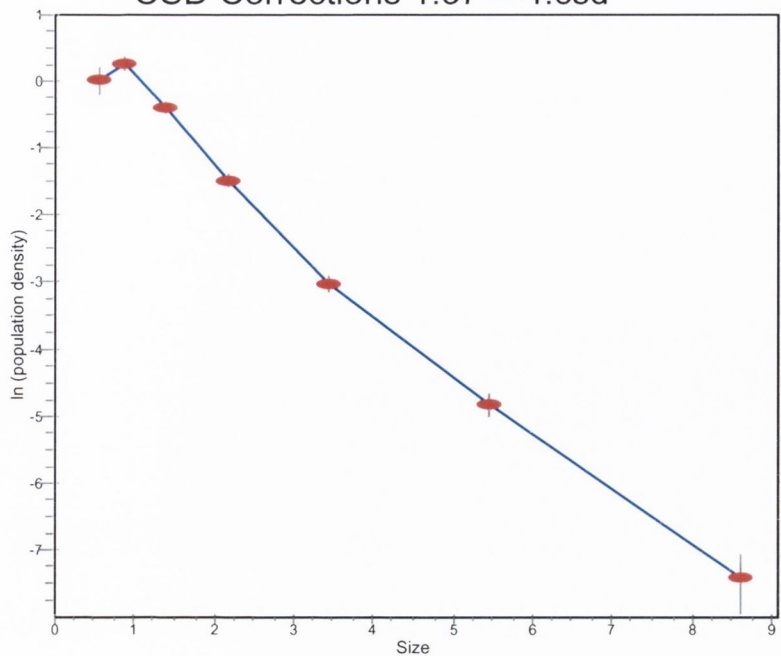
Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	3		0.00	Yes	17.0	-10.47	-11.33	-10.02	0.000123	8.875
10.00	17		0.02	Yes	10.72	-7.84	-8.12	-7.62	0.00108	19.59
6.31	33		0.07	Yes	6.76	-6.30	-6.51	-6.13	0.00318	14.45
3.98	40		0.12	Yes	4.27	-5.24	-5.44	-5.08	0.00576	6.581
2.51	36		0.19	Yes	2.69	-4.51	-4.74	-4.32	0.00758	2.176
1.58	30		0.27	Yes	1.70	-3.88	-4.17	-3.66	0.00897	0.646
1.000	20		0.43	Yes	1.072	-3.62	-4.12	-3.29	0.00736	0.133
0.631	6		0.88	Yes	0.676	-5.49	-Infinity	-3.98	0.000712	0.003
0.398	4		0.05	Yes	0.427	-2.87	-3.62	-2.45	0.00619	0.007
0.251	0			No						

Total 189

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:05:14

CSD Corrections 1.37 -- 4.csd



Model - 1.0 : 1.6 : 3.6

Foliated

Roundness = 0.6
Normal orientation



Area = 717.64

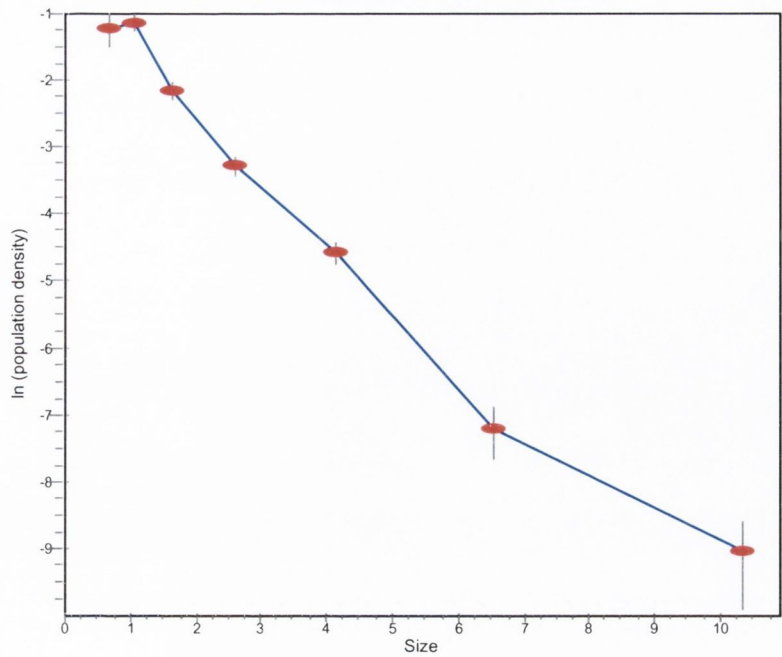
Quality = 0.8

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	6		0.00	Yes	8.62	-7.43	-7.95	-7.09	0.00105	5.905
3.98	33		0.02	Yes	5.44	-4.82	-5.02	-4.66	0.00896	12.69
2.51	81		0.04	Yes	3.43	-3.03	-3.15	-2.92	0.034	12.10
1.58	153		0.06	Yes	2.16	-1.49	-1.58	-1.40	0.1	8.953
1.000	190		0.09	Yes	1.366	-0.39	-0.47	-0.31	0.19	4.260
0.631	156		0.16	Yes	0.862	0.26	0.16	0.35	0.229	1.294
0.398	67		0.38	Yes	0.544	0.03	-0.19	0.21	0.115	0.162
0.251	5		4.39	No	0.343	Over				
0.158	0			No	0.216					
0.100	0			No	0.1366					
0.0631	1		0.00	No	0.0862	Over				
0.0398	0			No						
Total	692									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:10:00

CSD Corrections 1.37 -- 5.csd



Model - 1.0 : 2.3 : 3.6

Foliated

Roundness = 0.6
Normal orientation



Area = 965.24

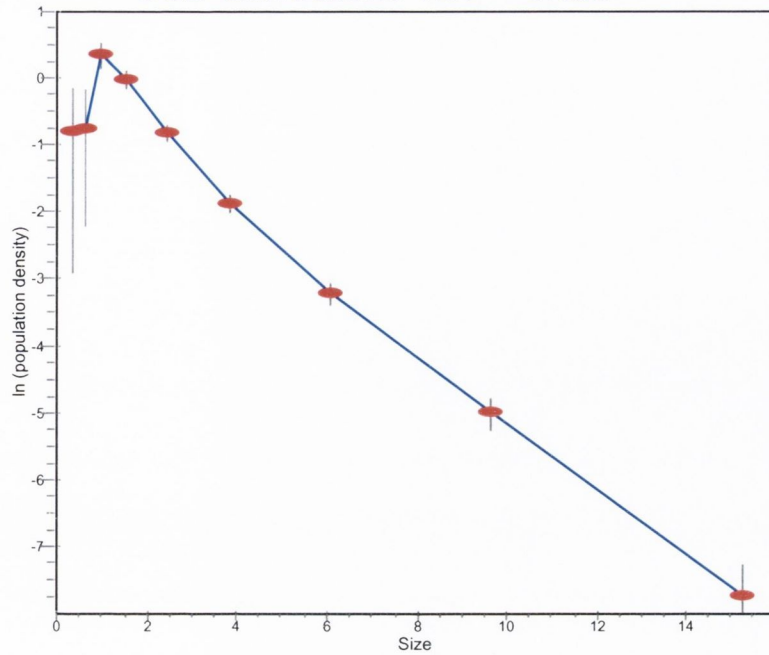
Quality = 0.8

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
10.00	3		0.00	Yes	10.35	-9.05	-9.91	-8.59	0.000358	5.020
6.31	8		0.06	Yes	6.53	-7.20	-7.67	-6.89	0.00143	5.035
3.98	43		0.03	Yes	4.12	-4.57	-4.74	-4.43	0.0125	11.07
2.51	67		0.10	Yes	2.60	-3.28	-3.43	-3.16	0.0287	6.378
1.58	85		0.13	Yes	1.64	-2.16	-2.29	-2.04	0.0556	3.106
1.000	98		0.16	Yes	1.035	-1.14	-1.27	-1.02	0.0977	1.370
0.631	54		0.45	Yes	0.653	-1.22	-1.50	-1.00	0.0566	0.199
0.398	18		1.11	No	0.412	Over				
0.251	3		0.00	No	0.260	Over				
0.158	0			No						
Total	379									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:10:30

CSD Corrections 1.37 -- 6.csd



Model - 1.0 : 2.3 : 9

Foliated

Roundness = 0.6
Normal orientation



Area = 320.3

Quality = 0.3

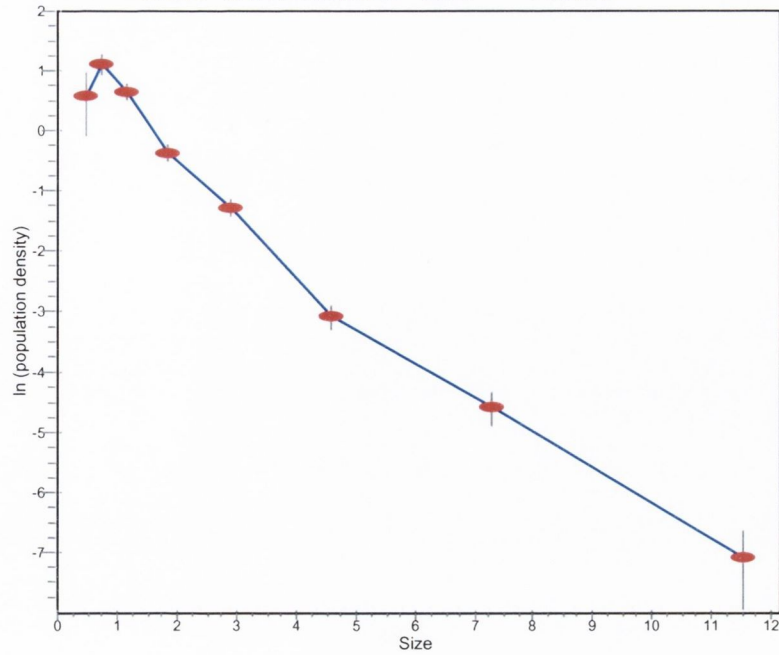
Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	3		0.00	Yes	15.24	-7.75	-8.61	-7.29	0.000776	5.563
3.98	19		0.02	Yes	9.61	-4.99	-5.26	-4.78	0.00767	13.81
2.51	46		0.04	Yes	6.07	-3.21	-3.38	-3.07	0.0287	12.96
1.58	72		0.07	Yes	3.83	-1.87	-2.01	-1.76	0.0691	7.856
1.000	85		0.10	Yes	2.415	-0.82	-0.95	-0.71	0.125	3.571
0.631	80		0.14	Yes	1.524	-0.01	-0.15	0.11	0.177	1.271
0.398	53		0.26	Yes	0.961	0.35	0.15	0.52	0.161	0.289
0.251	16		0.67	Yes	0.607	-0.75	-2.21	-0.18	0.0338	0.015
0.158	3		0.34	Yes	0.383	-0.80	-2.92	-0.17	0.0203	0.002
<i>0.100</i>	<i>0</i>			<i>No</i>						

Total 377

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:11:02

CSD Corrections 1.37 -- 7.csd



Model - 1.0 : 2.7 : 8

Foliated

Roundness = 0.5
Normal orientation

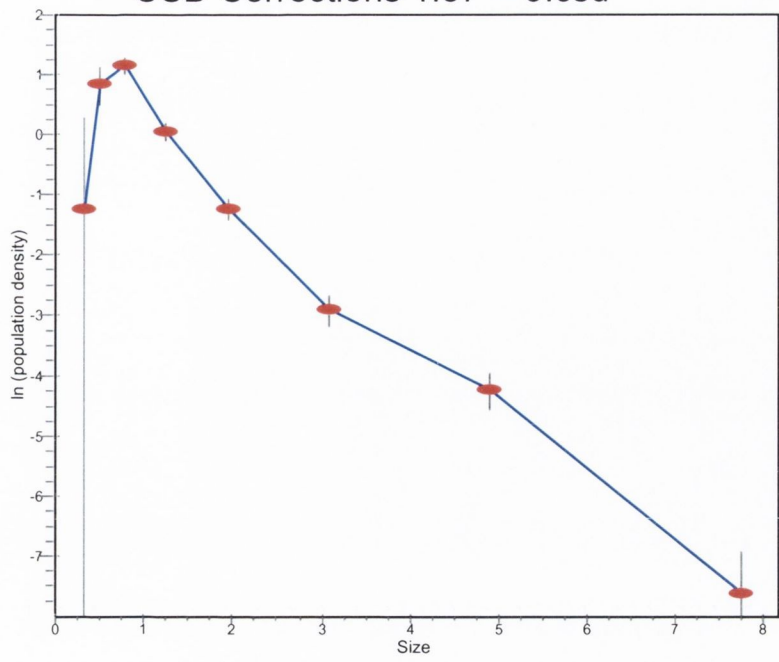
Area = 211.71
Quality = 0.5

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	3		0.00	Yes	11.52	-7.10	-7.96	-6.64	0.00148	7.267
3.98	15		0.02	Yes	7.27	-4.59	-4.89	-4.35	0.0115	14.19
2.51	28		0.05	Yes	4.58	-3.08	-3.30	-2.90	0.0328	10.16
1.58	67		0.05	Yes	2.89	-1.28	-1.42	-1.16	0.125	9.743
1.000	71		0.11	Yes	1.825	-0.37	-0.51	-0.24	0.197	3.846
0.631	80		0.13	Yes	1.152	0.65	0.52	0.77	0.344	1.690
0.398	57		0.23	Yes	0.727	1.11	0.92	1.27	0.344	0.423
0.251	24		0.57	Yes	0.458	0.57	-0.08	0.97	0.127	0.039
<i>0.158</i>	<i>3</i>		<i>3.36</i>	<i>No</i>	<i>0.289</i>	<i>Over</i>				
<i>0.100</i>	<i>0</i>			<i>No</i>	<i>0.1825</i>					
<i>0.0631</i>	<i>2</i>		<i>0.00</i>	<i>No</i>	<i>0.1152</i>	<i>Over</i>				
<i>0.0398</i>	<i>0</i>			<i>No</i>						
Total	350									

Data in italics were not plotted or regressed

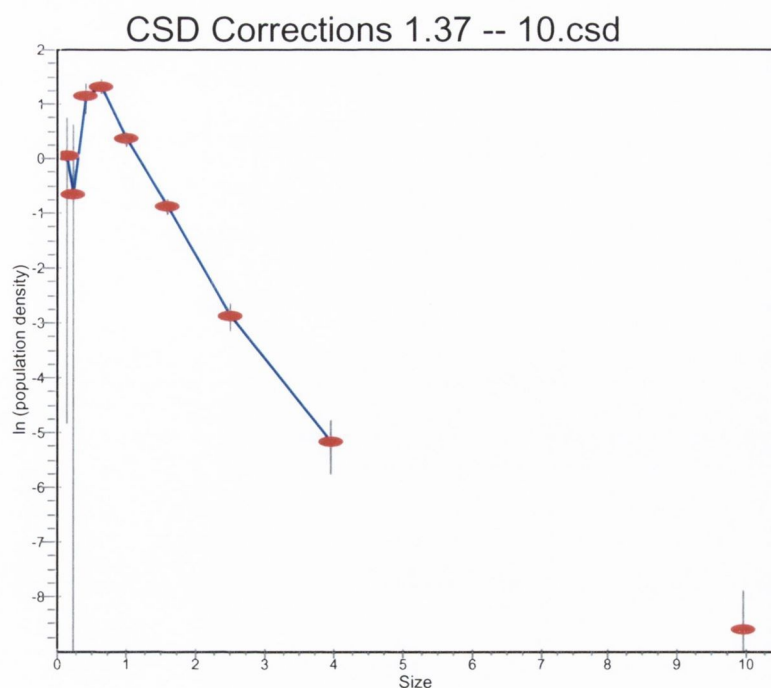
CSDCorrections 1.37: 06/05/2006 14:11:34

CSD Corrections 1.37 -- 9.csd



Model - 1.0 : 1.9 : 3.8				Roundness = 0.6		Area = 169.08				
Foliated				Normal orientation		Quality = 0.6				
Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	1		0.00	Yes	7.74	-7.62	-Infinity	-6.93	0.000875	3.811
3.98	12		0.01	Yes	4.88	-4.22	-4.57	-3.97	0.0165	18.03
2.51	19		0.07	Yes	3.08	-2.91	-3.19	-2.69	0.0388	10.65
1.58	40		0.06	Yes	1.94	-1.23	-1.42	-1.08	0.131	9.020
1.000	59		0.09	Yes	1.226	0.05	-0.11	0.18	0.296	5.127
0.631	73		0.12	Yes	0.774	1.15	1.01	1.28	0.564	2.454
0.398	31		0.39	Yes	0.488	0.85	0.50	1.11	0.262	0.286
0.251	11		0.91	Yes	0.308	-1.23	-Infinity	0.28	0.0207	0.005
<i>0.158</i>	<i>1</i>		<i>8.81</i>	<i>No</i>	<i>0.194</i>	<i>Over</i>				
<i>0.100</i>	<i>0</i>			<i>No</i>	<i>0.1226</i>					
<i>0.0631</i>	<i>1</i>		<i>0.00</i>	<i>No</i>	<i>0.0774</i>	<i>Over</i>				
<i>0.0398</i>	<i>0</i>			<i>No</i>						
Total	248									

Data in italics were not plotted or regressed



Model - 1.0 : 1.7 : 2.8

Foliated

Roundness = 0.6
Normal orientation



Area = 218.19
Quality = 0.6

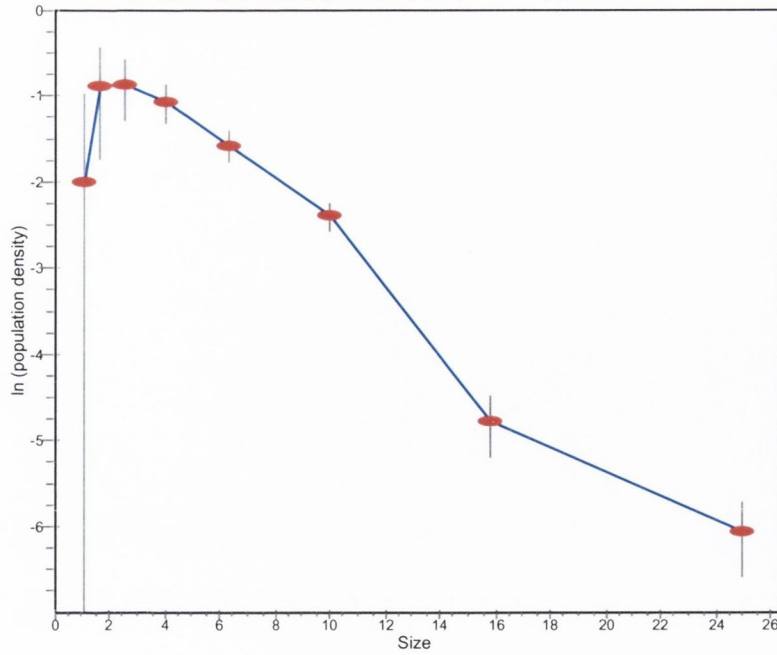
Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
10.00	1		0.00	Yes	9.94	-8.60	-Infinity	-7.91	0.000512	7.799
6.31	0			No	6.27					
3.98	5		0.01	Yes	3.96	-5.16	-5.76	-4.79	0.00636	6.115
2.51	20		0.03	Yes	2.50	-2.87	-3.14	-2.67	0.0394	9.514
1.58	59		0.05	Yes	1.58	-0.88	-1.03	-0.76	0.182	11.02
1.000	86		0.10	Yes	0.994	0.36	0.23	0.47	0.398	6.057
0.631	95		0.15	Yes	0.627	1.32	1.19	1.43	0.657	2.513
0.398	49		0.45	Yes	0.396	1.13	0.83	1.37	0.344	0.330
0.251	21		0.91	Yes	0.250	-0.65	-Infinity	0.62	0.0365	0.008
0.158	2		0.29	Yes	0.158	0.04	-4.83	0.73	0.046	0.002
0.100	0			No						

Total 338

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:06:11

CSD Corrections 1.37 -- 11.csd



Model - 1.0 : 1.15 : 9

Foliated

Roundness = 0.6
Normal orientation



Area = 105.2

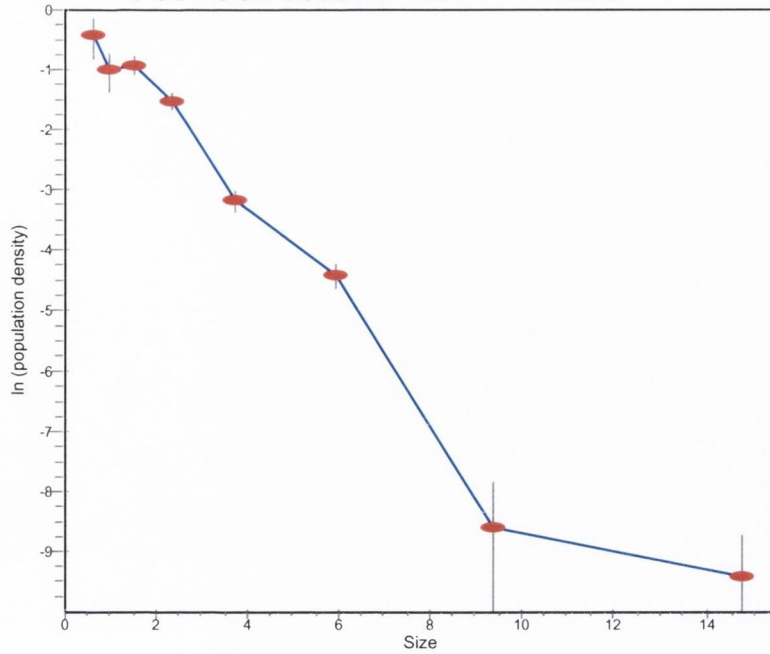
Quality = 0.5

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
3.98	6		0.00	Yes	24.97	-6.07	-6.59	-5.73	0.0034	53.61
2.51	9		0.03	Yes	15.75	-4.78	-5.20	-4.48	0.0078	30.93
1.58	38		0.01	Yes	9.94	-2.40	-2.58	-2.24	0.0533	53.06
1.000	36		0.06	Yes	6.272	-1.58	-1.77	-1.41	0.0763	19.09
0.631	25		0.10	Yes	3.957	-1.07	-1.32	-0.87	0.0801	5.034
0.398	14		0.22	Yes	2.497	-0.86	-1.28	-0.57	0.0619	0.977
0.251	6		0.29	Yes	1.575	-0.89	-1.74	-0.43	0.0382	0.151
0.158	1		0.44	Yes	0.994	-2.00	-Infinity	-0.97	0.00794	0.007
<i>0.100</i>	<i>0</i>			No						
Total	135									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:06:54

CSD Corrections 1.37 -- 13.csd



Model - 1.0 : 1.5 : 4

Foliated

Roundness = 0.6
Normal orientation



Area = 349.87

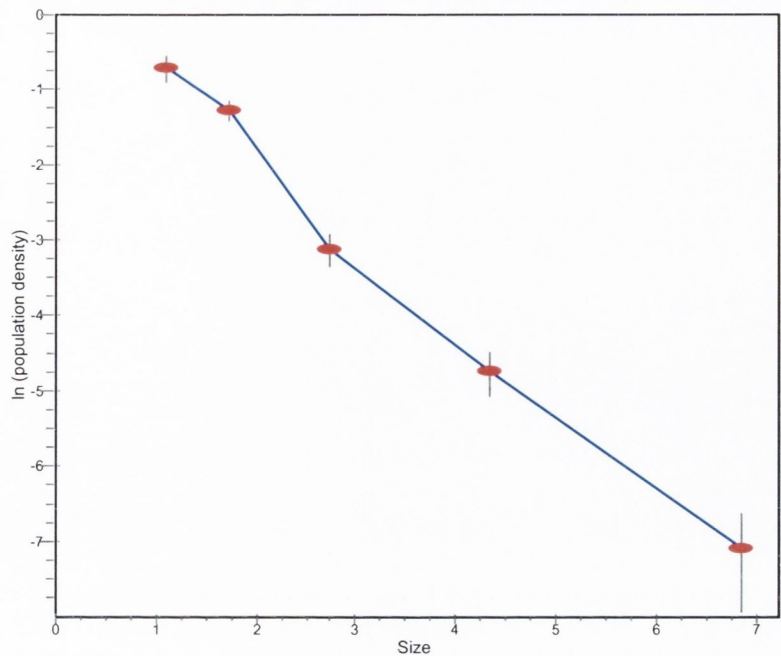
Quality = 0.4

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
10.00	1		0.00	Yes	14.80	-9.43	-Infinity	-8.73	0.000206	4.465
6.31	1		0.09	Yes	9.34	-8.60	-Infinity	-7.86	0.000297	1.619
3.98	24		0.01	Yes	5.89	-4.41	-4.64	-4.23	0.0123	16.90
2.51	35		0.06	Yes	3.72	-3.17	-3.37	-3.01	0.0269	9.241
1.58	72		0.06	Yes	2.35	-1.52	-1.66	-1.41	0.0882	7.627
1.000	59		0.16	Yes	1.480	-0.93	-1.09	-0.78	0.101	2.200
0.631	32		0.43	Yes	0.934	-1.00	-1.37	-0.73	0.0594	0.324
0.398	17		0.24	Yes	0.589	-0.43	-0.81	-0.15	0.0664	0.091
0.251	0			No						
Total	241									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:07:26

CSD Corrections 1.37 -- 15A.csd



Model - 1.0 : 1.6 : 2.9

Foliated

Roundness = 0.6
Normal orientation



Area = 345.51

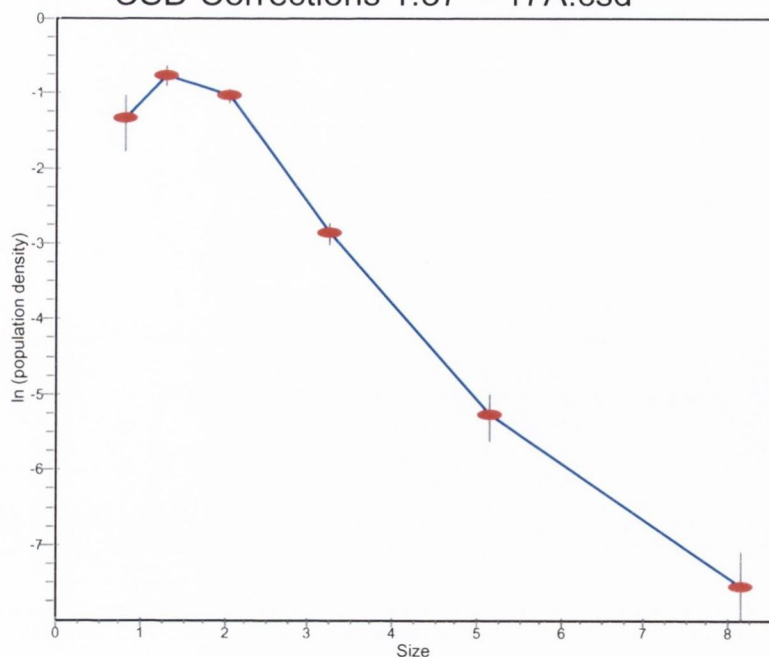
Quality = 0.4

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	3		0.00	Yes	6.86	-7.09	-7.95	-6.64	0.00145	6.352
3.98	13		0.03	Yes	4.33	-4.73	-5.07	-4.48	0.00969	10.66
2.51	27		0.06	Yes	2.73	-3.11	-3.34	-2.93	0.0308	8.505
1.58	67		0.06	Yes	1.72	-1.28	-1.42	-1.16	0.122	8.439
1.000	55		0.19	Yes	1.087	-0.71	-0.90	-0.56	0.135	2.359
0.631	17		1.04	No	0.686	Over				
0.398	5		0.00	No	0.433	Over				
0.251	0			No						
Total	187									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:03:24

CSD Corrections 1.37 -- 17A.csd



Model - 1.0 : 1.3 : 2.9

Foliated

Roundness = 0.6
Normal orientation



Area = 446.44

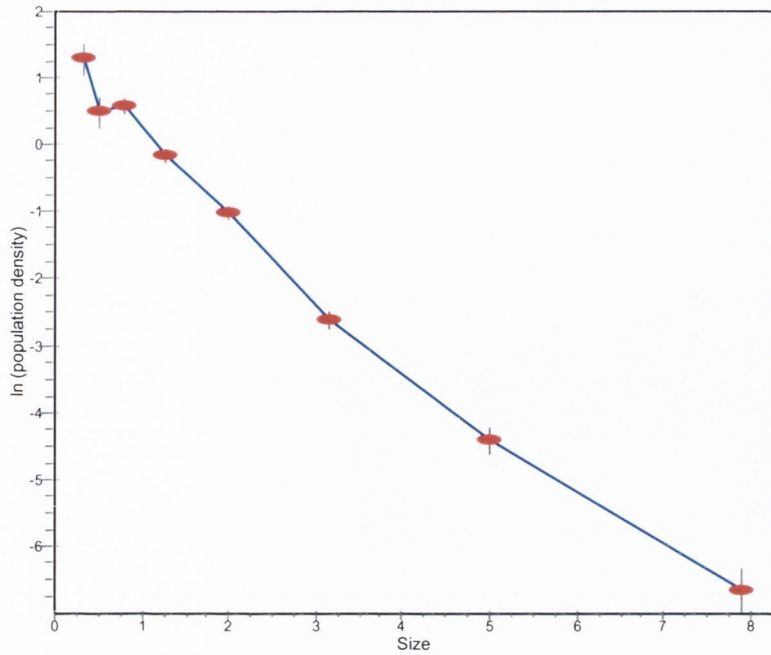
Quality = 0.5

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	3		0.00	Yes	8.15	-7.55	-8.41	-7.10	0.000883	5.281
3.98	12		0.02	Yes	5.14	-5.27	-5.62	-5.01	0.00548	8.232
2.51	53		0.02	Yes	3.25	-2.86	-3.01	-2.73	0.0383	14.47
1.58	133		0.04	Yes	2.05	-1.04	-1.13	-0.95	0.15	14.21
1.000	81		0.17	Yes	1.292	-0.76	-0.90	-0.63	0.125	2.977
0.631	29		0.48	Yes	0.815	-1.33	-1.77	-1.02	0.0446	0.266
<i>0.398</i>	<i>1</i>		<i>11.23</i>	<i>No</i>	<i>0.514</i>	<i>Over</i>				
<i>0.251</i>	<i>0</i>			<i>No</i>	<i>0.325</i>					
<i>0.158</i>	<i>0</i>			<i>No</i>	<i>0.205</i>					
<i>0.100</i>	<i>0</i>			<i>No</i>	<i>0.1292</i>					
<i>0.0631</i>	<i>1</i>		<i>0.00</i>	<i>No</i>	<i>0.0815</i>	<i>Over</i>				
<i>0.0398</i>	<i>0</i>			<i>No</i>						
Total	313									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:07:59

CSD Corrections 1.37 -- 19.csd



Model - 1.0 : 1.6 : 3.6

Foliated

Roundness = 0.5
Normal orientation



Area = 438.08

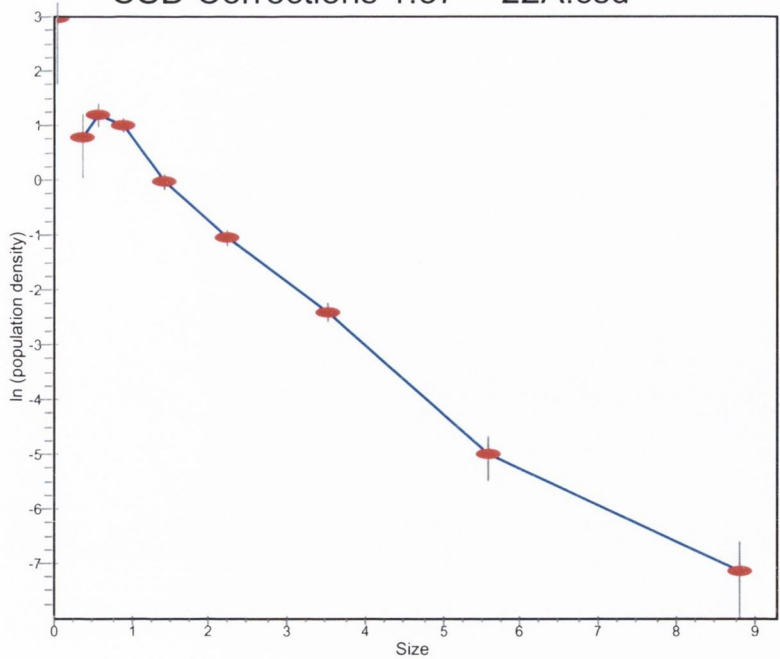
Quality = 0.5

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	7		0.00	Yes	7.91	-6.66	-7.13	-6.33	0.00208	9.681
3.98	27		0.02	Yes	4.99	-4.41	-4.63	-4.23	0.0124	14.52
2.51	66		0.04	Yes	3.15	-2.61	-2.75	-2.49	0.0473	13.86
1.58	132		0.06	Yes	1.99	-1.01	-1.11	-0.92	0.148	10.87
1.000	132		0.12	Yes	1.253	-0.16	-0.27	-0.07	0.218	4.037
0.631	119		0.18	Yes	0.791	0.58	0.46	0.69	0.29	1.347
0.398	65		0.45	Yes	0.499	0.51	0.25	0.71	0.169	0.197
0.251	51		0.38	Yes	0.315	1.30	1.04	1.50	0.235	0.069
0.158	7		1.15	No	0.199	Over				
0.100	0			No						
Total	606									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:08:38

CSD Corrections 1.37 -- 22A.csd



Model - 1.0 : 2 : 4.5

Foliated

Roundness = 0.6
Normal orientation



Area = 191.27

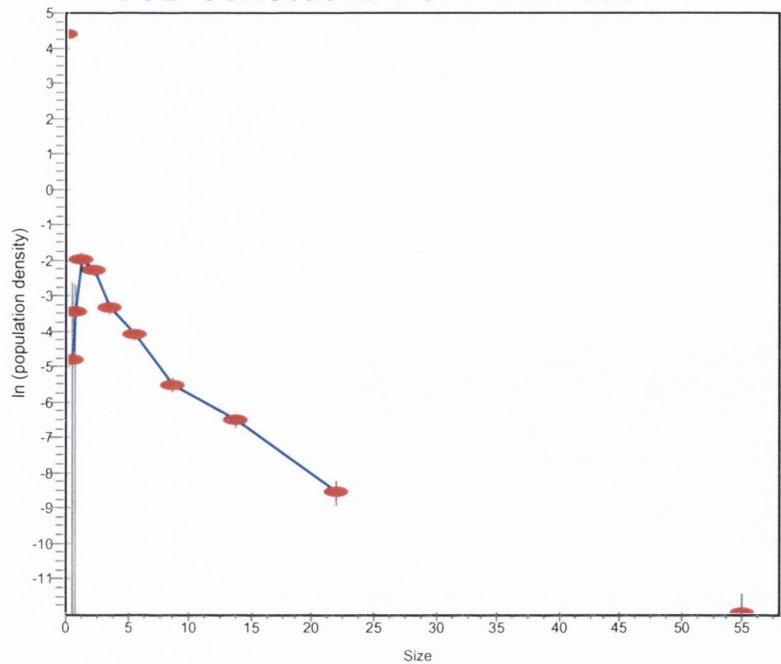
Quality = 0.5

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	2		0.00	Yes	8.82	-7.15	-8.37	-6.61	0.00142	6.892
3.98	7		0.03	Yes	5.57	-5.00	-5.50	-4.67	0.00766	9.314
2.51	37		0.02	Yes	3.51	-2.41	-2.59	-2.25	0.0647	19.77
1.58	60		0.07	Yes	2.22	-1.05	-1.20	-0.92	0.158	12.14
1.000	70		0.11	Yes	1.398	-0.02	-0.16	0.11	0.28	5.401
0.631	80		0.13	Yes	0.882	1.01	0.87	1.13	0.495	2.397
0.398	47		0.28	Yes	0.557	1.20	0.98	1.39	0.38	0.462
0.251	21		0.58	Yes	0.351	0.78	0.04	1.20	0.157	0.047
0.158	0			No	0.222					
0.100	0			No	0.1398					
0.0631	0			No	0.0882					
0.0398	2		0.00	Yes	0.0557	2.99	1.76	3.52	0.226	0.000
0.0251	0			No						
Total	326									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:09:29

CSD Corrections 1.37 -- HB1.csd



Model - 1.0 : 2 : 10

Roundness = 0.4



Area = 997.67

Massive

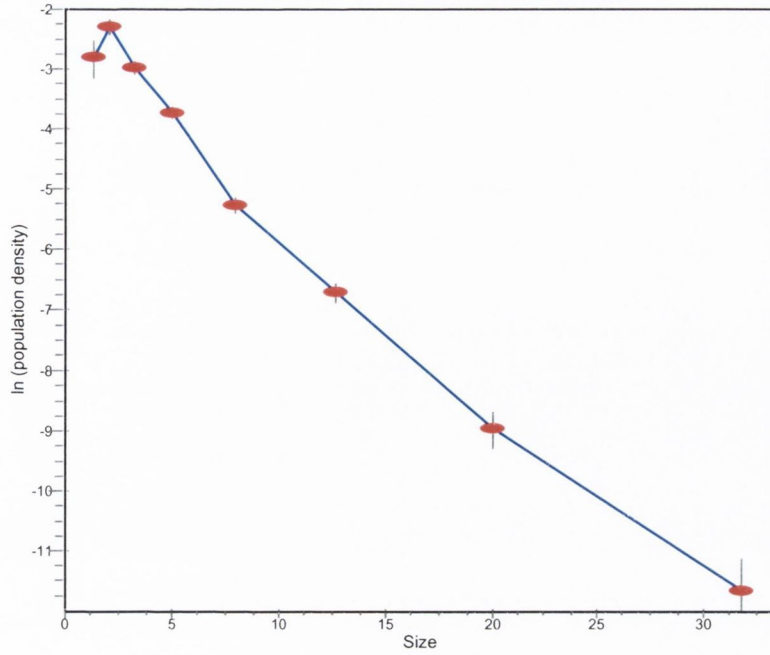
Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
25.1	2		0.00	Yes	54.9	-11.96	-13.19	-11.43	3.23E-5	8.678
15.8	0			No	34.7					
10.00	10		0.01	Yes	21.87	-8.52	-8.90	-8.24	0.000403	6.829
6.31	30		0.02	Yes	13.80	-6.51	-6.72	-6.34	0.00189	8.055
3.98	34		0.06	Yes	8.71	-5.50	-5.70	-5.34	0.00327	3.490
2.51	56		0.05	Yes	5.49	-4.08	-4.23	-3.95	0.00857	2.301
1.58	49		0.10	Yes	3.47	-3.34	-3.51	-3.19	0.0113	0.765
1.000	57		0.09	Yes	2.187	-2.26	-2.42	-2.13	0.021	0.355
0.631	34		0.18	Yes	1.380	-1.96	-2.19	-1.77	0.018	0.076
0.398	8		0.68	Yes	0.871	-3.44	-Infinity	-2.69	0.00258	0.002
0.251	4		0.93	Yes	0.549	-4.78	-Infinity	-2.63	0.000423	0.000
0.158	0			No	0.347					
0.100	0			No	0.2187					
0.0631	0			No	0.1380					
0.0398	0			No	0.0871					
0.0251	25		0.00	Yes	0.0549	4.38	4.16	4.56	0.404	0.000
0.0158	0			No						

Total 309

Data in *italics* were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:56:31

CSD Corrections 1.37 -- HB2.csd



Model - 1.0 : 2.5 : 9

Roundness = 0.5



Area = 2083

Massive

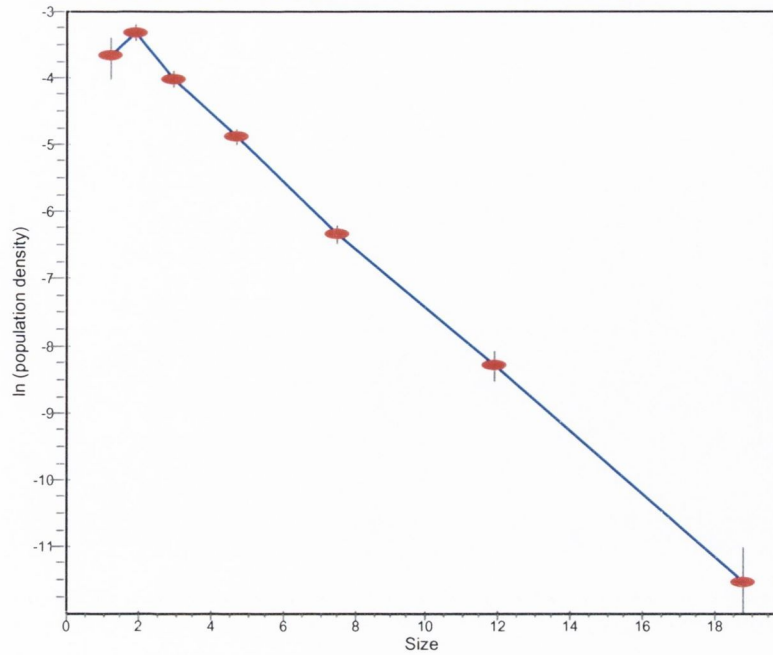
Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	2		0.00	Yes	31.8	-11.66	-12.89	-11.12	3.51E-5	2.642
10.00	12		0.01	Yes	20.04	-8.96	-9.31	-8.70	0.000329	6.227
6.31	46		0.02	Yes	12.64	-6.70	-6.87	-6.56	0.00198	9.417
3.98	80		0.05	Yes	7.98	-5.26	-5.39	-5.15	0.0053	6.325
2.51	148		0.06	Yes	5.03	-3.73	-3.82	-3.64	0.0155	4.638
1.58	134		0.12	Yes	3.18	-2.98	-3.08	-2.88	0.0207	1.558
1.000	114		0.19	Yes	2.004	-2.30	-2.42	-2.19	0.0258	0.488
0.631	44		0.49	Yes	1.264	-2.80	-3.16	-2.54	0.00981	0.046
<i>0.398</i>	<i>4</i>		<i>1.12</i>	<i>No</i>	<i>0.798</i>	<i>Over</i>				
<i>0.251</i>	<i>0</i>			<i>No</i>						

Total 584

Data in *italics* were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:57:00

CSD Corrections 1.37 -- ARH1.csd



Model - 1.0 : 1.4 : 2.8

Roundness = 0.6



Area = 2952.08

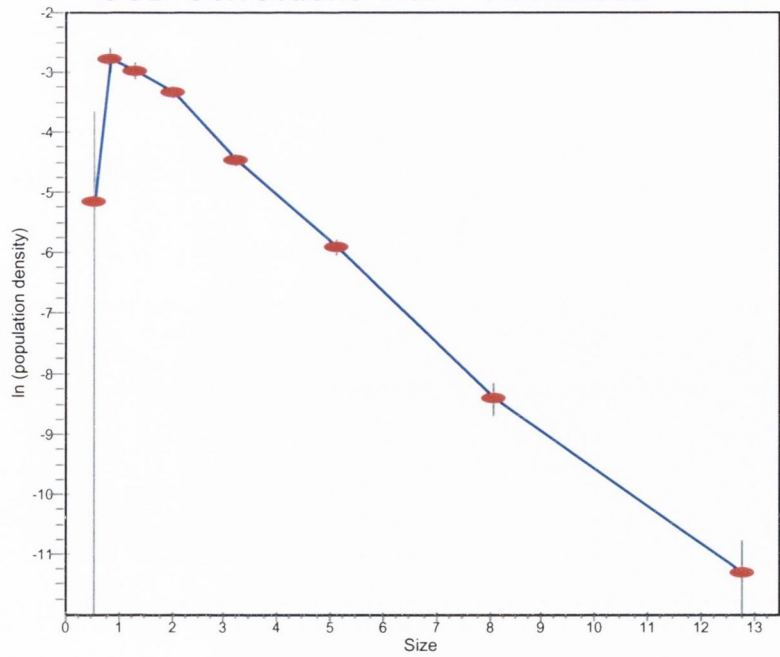
Massive

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	2		0.00	Yes	18.8	-11.55	-12.78	-11.01	4.18E-5	3.552
10.00	21		0.01	Yes	11.87	-8.28	-8.53	-8.09	0.00069	14.72
6.31	60		0.03	Yes	7.49	-6.34	-6.48	-6.21	0.00305	16.33
3.98	106		0.06	Yes	4.73	-4.88	-4.99	-4.78	0.00829	11.16
2.51	107		0.12	Yes	2.98	-4.01	-4.13	-3.91	0.0124	4.202
1.58	92		0.18	Yes	1.88	-3.31	-3.45	-3.19	0.0158	1.340
1.000	39		0.46	Yes	1.187	-3.66	-4.02	-3.41	0.007	0.149
<i>0.631</i>	<i>14</i>		<i>1.11</i>	<i>No</i>	<i>0.749</i>	<i>Over</i>				
<i>0.398</i>	<i>2</i>		<i>0.00</i>	<i>No</i>	<i>0.473</i>	<i>Over</i>				
<i>0.251</i>	<i>0</i>			<i>No</i>	<i>0.298</i>					
<i>0.158</i>	<i>0</i>			<i>No</i>	<i>0.188</i>					
<i>0.100</i>	<i>7</i>		<i>0.00</i>	<i>No</i>	<i>0.1187</i>	<i>Over</i>				
<i>0.0631</i>	<i>0</i>			<i>No</i>						
Total	450									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:53:54

CSD Corrections 1.37 -- ARH2.csd



Model - 1.0 : 1.5 : 1.9

Roundness = 0.6



Area = 3104.98

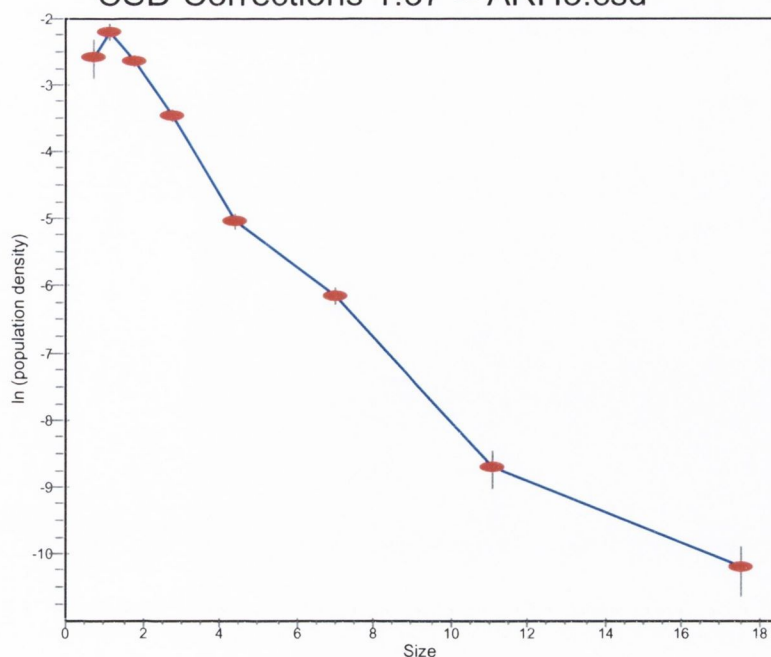
Massive

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	2		0.00	Yes	12.8	-11.32	-12.54	-10.78	5.66E-5	3.521
10.00	15		0.02	Yes	8.07	-8.40	-8.70	-8.16	0.000662	10.33
6.31	73		0.03	Yes	5.09	-5.90	-6.03	-5.79	0.00505	19.81
3.98	130		0.08	Yes	3.21	-4.46	-4.56	-4.37	0.0135	13.34
2.51	169		0.12	Yes	2.03	-3.32	-3.41	-3.24	0.0266	6.583
1.58	115		0.26	Yes	1.28	-2.97	-3.10	-2.85	0.024	1.490
1.000	70		0.42	Yes	0.807	-2.78	-3.00	-2.59	0.0183	0.285
0.631	27		0.94	Yes	0.509	-5.16	-Infinity	-3.66	0.00106	0.004
0.398	7		3.06	No	0.321	Over				
0.251	1		0.00	No	0.203	Over				
0.158	0			No	0.128					
0.100	0			No	0.0807					
0.0631	21		0.00	No	0.0509	Over				
0.0398	0			No						
Total	630									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:54:40

CSD Corrections 1.37 -- ARH3.csd



Model - 1.0 : 1.3 : 2.4

Massive

Roundness = 0.6



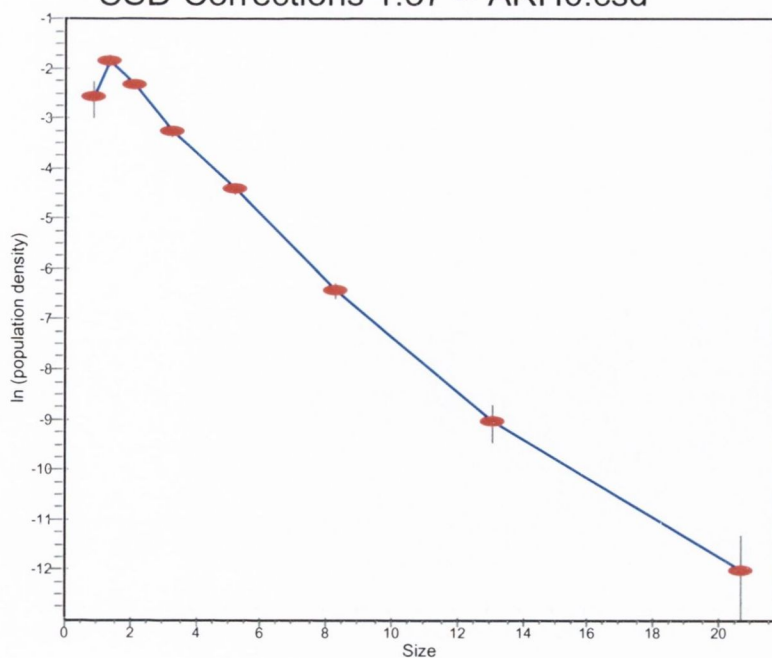
Area = 3214

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	8		0.00	Yes	17.6	-10.21	-10.65	-9.91	0.000161	14.04
10.00	15		0.04	Yes	11.07	-8.70	-9.02	-8.47	0.000458	10.02
6.31	75		0.02	Yes	6.99	-6.15	-6.28	-6.04	0.00371	20.41
3.98	97		0.07	Yes	4.41	-5.03	-5.14	-4.92	0.0072	9.945
2.51	186		0.07	Yes	2.78	-3.45	-3.53	-3.37	0.0221	7.652
1.58	179		0.13	Yes	1.76	-2.63	-2.72	-2.55	0.0314	2.737
1.000	126		0.23	Yes	1.107	-2.19	-2.31	-2.08	0.0309	0.676
0.631	55		0.52	Yes	0.699	-2.57	-2.90	-2.32	0.0133	0.073
<i>0.398</i>	<i>8</i>		<i>2.97</i>	<i>No</i>	<i>0.441</i>	<i>Over</i>				
<i>0.251</i>	<i>0</i>			<i>No</i>	<i>0.278</i>					
<i>0.158</i>	<i>0</i>			<i>No</i>	<i>0.176</i>					
<i>0.100</i>	<i>0</i>			<i>No</i>	<i>0.1107</i>					
<i>0.0631</i>	<i>19</i>		<i>0.00</i>	<i>No</i>	<i>0.0699</i>	<i>Over</i>				
<i>0.0398</i>	<i>0</i>			<i>No</i>						
Total	768									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:55:10

CSD Corrections 1.37 -- ARH6.csd



Model - 1.0 : 1.5 : 3.6

Roundness = 0.5



Area = 2138.45

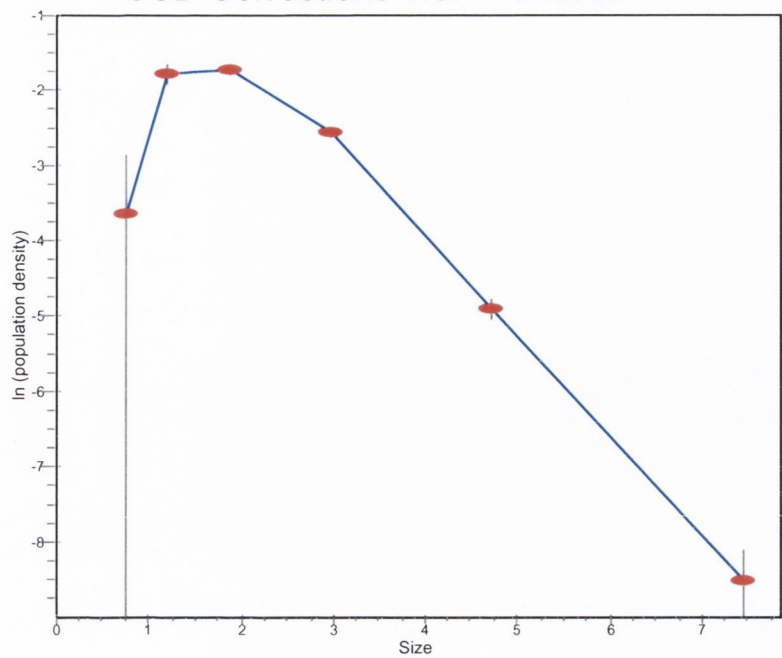
Massive

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	1		0.00	Yes	20.7	-12.02	-Infinity	-11.33	2.39E-5	1.867
10.00	8		0.01	Yes	13.05	-9.03	-9.47	-8.72	0.0003	5.888
6.31	43		0.02	Yes	8.24	-6.43	-6.60	-6.29	0.00254	12.52
3.98	131		0.03	Yes	5.20	-4.41	-4.50	-4.32	0.0121	14.98
2.51	171		0.07	Yes	3.28	-3.27	-3.36	-3.19	0.0239	7.426
1.58	183		0.12	Yes	2.07	-2.33	-2.42	-2.25	0.0387	3.019
1.000	131		0.21	Yes	1.305	-1.85	-1.97	-1.75	0.0393	0.771
0.631	48		0.58	Yes	0.824	-2.56	-2.98	-2.27	0.0122	0.059
0.398	13		1.76	No	0.520	Over				
0.251	1		0.00	No	0.328	Over				
0.158	0			No	0.207					
0.100	14		0.00	No	0.1305	Over				
0.0631	0			No						
Total	744									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:55:39

CSD Corrections 1.37 -- P1.csd



Model - 1.0 : 1.4 : 2.8

Roundness = 0.6



Area = 1812

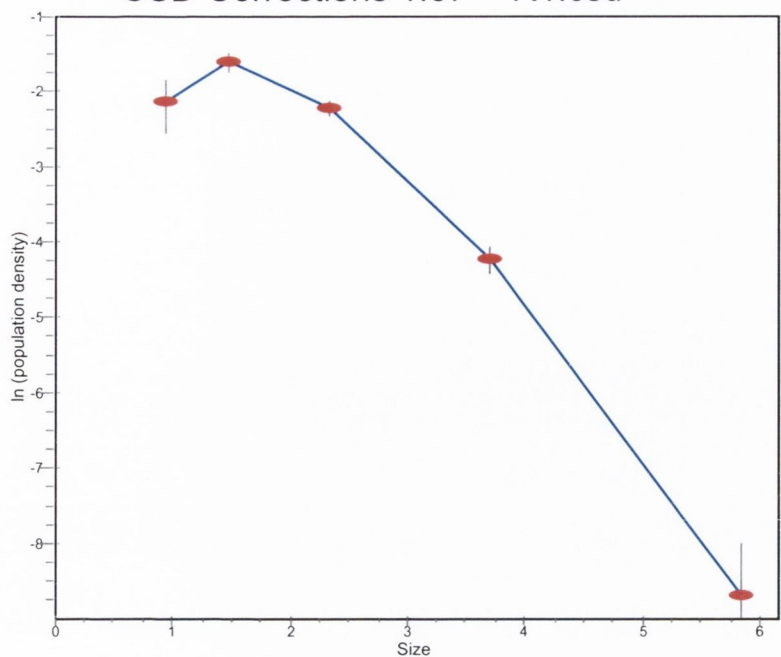
Massive

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	4		0.00	Yes	7.45	-8.51	-9.21	-8.11	0.000344	1.814
3.98	59		0.01	Yes	4.70	-4.91	-5.05	-4.79	0.00799	10.58
2.51	249		0.02	Yes	2.97	-2.56	-2.63	-2.50	0.0526	17.50
1.58	251		0.10	Yes	1.87	-1.72	-1.79	-1.65	0.0772	6.455
1.000	121		0.30	Yes	1.181	-1.78	-1.92	-1.66	0.0458	0.960
0.631	38		0.86	Yes	0.745	-3.64	-Infinity	-2.86	0.00452	0.023
0.398	12		2.74	No	0.470	Over				
0.251	0			No	0.297					
0.158	0			No	0.187					
0.100	4		0.00	No	0.1181	Over				
0.0631	0			No						
Total	738									

Data in *italics* were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:57:26

CSD Corrections 1.37 -- R1.csd



Model - 1.0 : 1.2 : 1.7

Roundness = 0.7



Area = 648.92

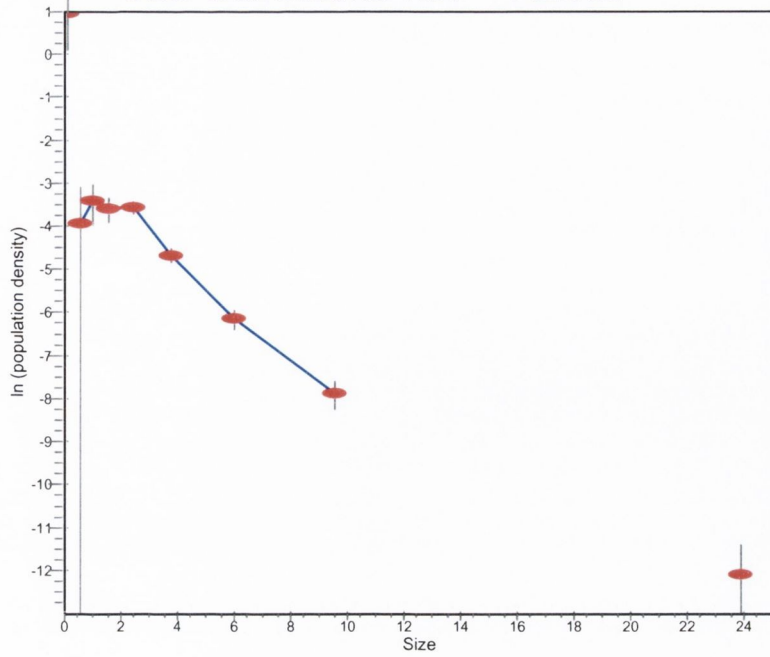
Massive

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	1		0.00	Yes	5.84	-8.70	-Infinity	-8.01	0.000315	1.736
3.98	35		0.00	Yes	3.68	-4.23	-4.42	-4.07	0.0174	24.10
2.51	107		0.04	Yes	2.32	-2.23	-2.34	-2.13	0.0813	28.25
1.58	90		0.16	Yes	1.47	-1.61	-1.74	-1.49	0.0952	8.309
1.000	37		0.52	Yes	0.925	-2.14	-2.55	-1.84	0.0355	0.778
0.631	9		1.92	No	0.584	Over				
0.398	1		0.00	No	0.368	Over				
0.251	0			No						
Total	280									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:57:51

CSD Corrections 1.37 -- R2.csd



Model - 1.0 : 1.25 : 1.9

Roundness = 0.7



Area = 1218.67

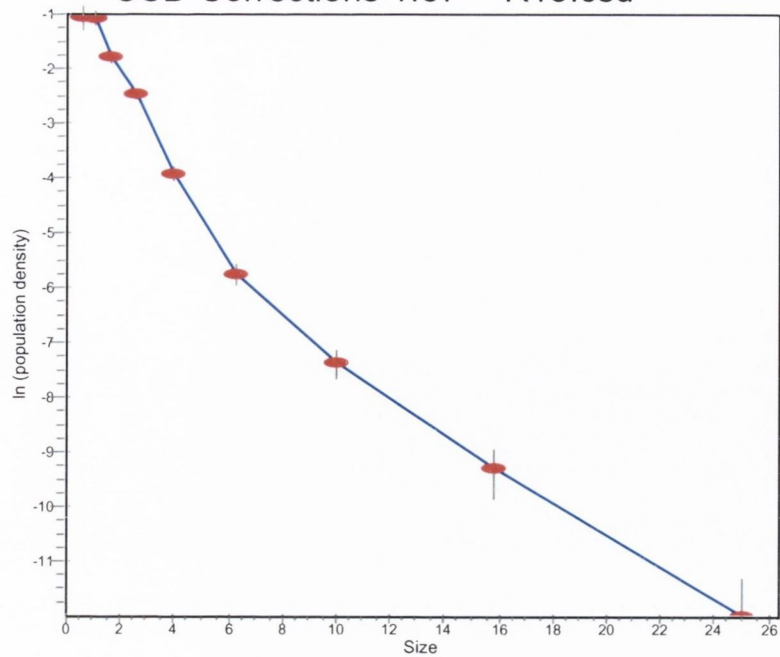
Massive

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
25.1	1		0.00	Yes	23.9	-12.11	-Infinity	-11.42	3.96E-5	12.41
<i>15.8</i>	<i>0</i>			No	<i>15.1</i>					
10.00	11		0.00	Yes	9.50	-7.88	-8.24	-7.61	0.00109	21.57
6.31	26		0.05	Yes	5.99	-6.14	-6.37	-5.96	0.0039	19.37
3.98	46		0.07	Yes	3.78	-4.67	-4.85	-4.53	0.0107	13.35
2.51	58		0.11	Yes	2.39	-3.56	-3.72	-3.43	0.0205	6.430
1.58	29		0.31	Yes	1.51	-3.59	-3.90	-3.35	0.0126	0.992
1.000	17		0.43	Yes	0.950	-3.40	-3.95	-3.04	0.00962	0.190
0.631	9		0.75	Yes	0.599	-3.93	-Infinity	-3.08	0.00358	0.017
<i>0.398</i>	<i>0</i>			No	<i>0.378</i>					
<i>0.251</i>	<i>0</i>			No	<i>0.239</i>					
<i>0.158</i>	<i>0</i>			No	<i>0.151</i>					
<i>0.100</i>	<i>0</i>			No	<i>0.0950</i>					
0.0631	3		0.00	Yes	0.0599	0.96	0.10	1.41	0.0473	0.000
<i>0.0398</i>	<i>0</i>			No						
Total	200									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 15:00:17

CSD Corrections 1.37 -- R15.csd



Model - 1.0 : 2.5 : 5

Foliated

Roundness = 0.5
Parallel orientation



Area = 1357.52

Quality = 0.6

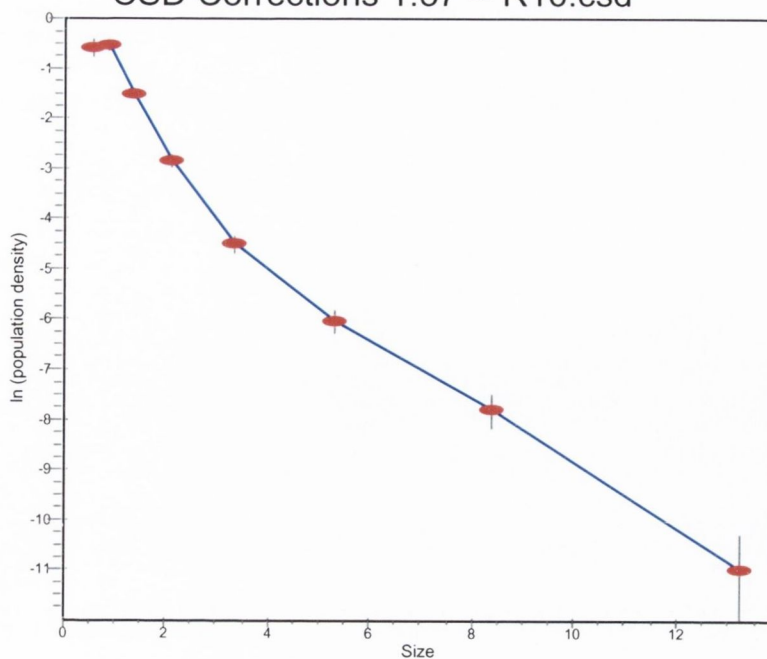
Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
25.1	1		0.00	Yes	25.0	-12.00	-Infinity	-11.31	3.54E-5	4.225
15.8	6		0.02	Yes	15.8	-9.30	-9.84	-8.96	0.000331	9.912
10.00	17		0.04	Yes	9.96	-7.37	-7.66	-7.14	0.00145	10.91
6.31	35		0.06	Yes	6.28	-5.75	-5.94	-5.58	0.00463	8.748
3.98	86		0.06	Yes	3.97	-3.92	-4.04	-3.81	0.0181	8.606
2.51	149		0.08	Yes	2.50	-2.47	-2.57	-2.39	0.0486	5.794
1.58	131		0.17	Yes	1.58	-1.78	-1.90	-1.68	0.0611	1.829
1.000	115		0.23	Yes	0.996	-1.06	-1.19	-0.95	0.0792	0.596
0.631	63		0.43	Yes	0.628	-1.05	-1.30	-0.85	0.0508	0.096
0.398	16		1.45	No	0.397	Over				
0.251	2		0.00	No	0.250	Over				
0.158	0			No	0.158					
0.100	0			No	0.0996					
0.0631	2		0.00	No	0.0628	Over				
0.0398	0			No						

Total 623

Data in *italics* were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:58:23

CSD Corrections 1.37 -- R16.csd



Model - 1.0 : 1.25 : 1.8

Massive

Roundness = 0.7



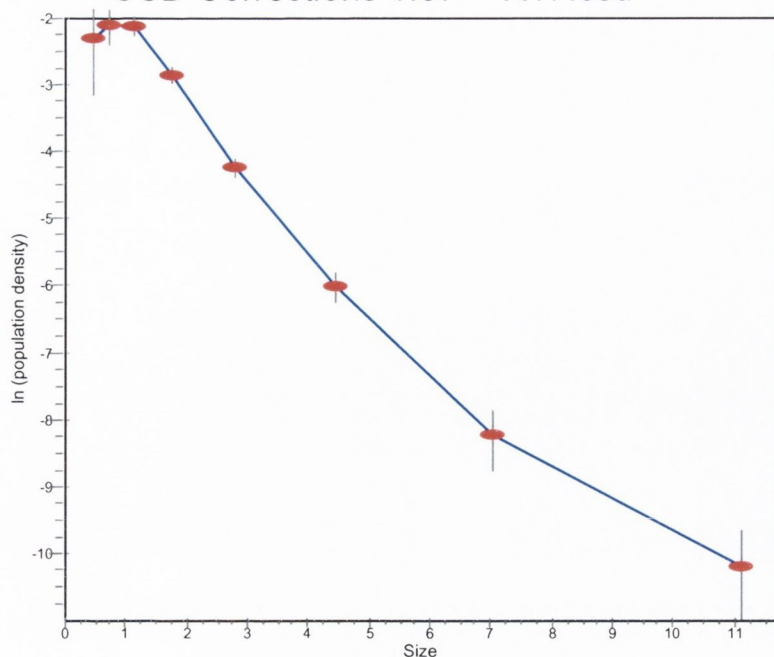
Area = 1126.58

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	1		0.00	Yes	13.3	-11.00	-Infinity	-10.31	7.08E-5	4.239
10.00	10		0.01	Yes	8.36	-7.79	-8.17	-7.51	0.00111	16.68
6.31	24		0.05	Yes	5.28	-6.03	-6.27	-5.84	0.00406	15.32
3.98	45		0.07	Yes	3.33	-4.50	-4.68	-4.35	0.0118	11.21
2.51	93		0.07	Yes	2.10	-2.85	-2.97	-2.75	0.0388	9.238
1.58	146		0.09	Yes	1.33	-1.51	-1.60	-1.42	0.0941	5.633
1.000	161		0.13	Yes	0.836	-0.54	-0.63	-0.45	0.156	2.350
0.631	80		0.34	Yes	0.528	-0.59	-0.78	-0.44	0.0933	0.352
<i>0.398</i>	<i>22</i>		<i>1.04</i>	<i>No</i>	<i>0.333</i>	<i>Over</i>				
<i>0.251</i>	<i>2</i>		<i>0.00</i>	<i>No</i>	<i>0.210</i>	<i>Over</i>				
<i>0.158</i>	<i>1</i>		<i>0.00</i>	<i>No</i>	<i>0.133</i>	<i>Over</i>				
<i>0.100</i>	<i>0</i>			<i>No</i>	<i>0.0836</i>					
<i>0.0631</i>	<i>2</i>		<i>0.00</i>	<i>No</i>	<i>0.0528</i>	<i>Over</i>				
<i>0.0398</i>	<i>0</i>			<i>No</i>						
Total	587									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:58:57

CSD Corrections 1.37 -- R17.csd



Model - 1.0 : 1.4 : 1.7

Foliated

Roundness = 0.5
Parallel orientation



Area = 1105.52

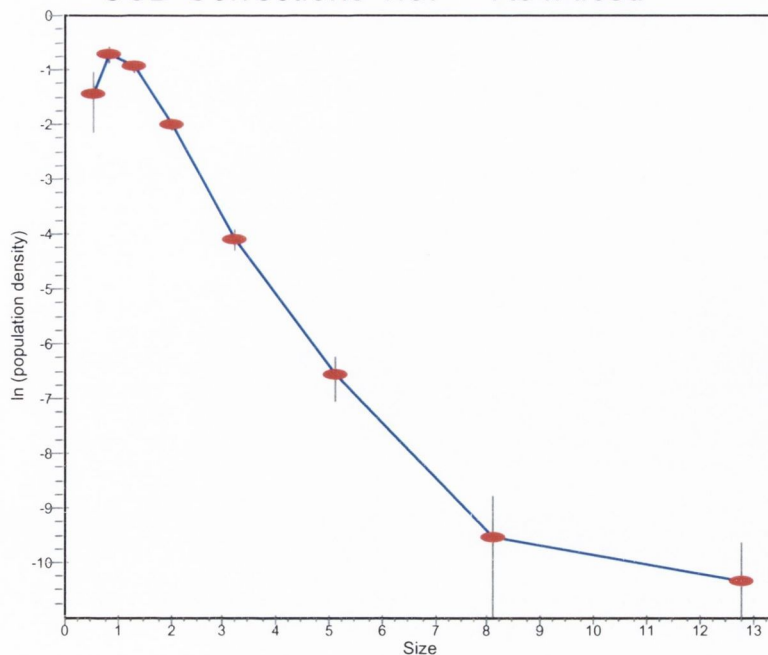
Quality = 0.1

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	2		0.00	Yes	11.1	-10.21	-11.43	-9.67	0.000156	7.933
10.00	6		0.04	Yes	7.02	-8.22	-8.77	-7.87	0.000715	9.127
6.31	22		0.04	Yes	4.43	-6.00	-6.25	-5.80	0.00415	13.31
3.98	52		0.06	Yes	2.80	-4.24	-4.40	-4.11	0.0152	12.27
2.51	86		0.09	Yes	1.76	-2.85	-2.98	-2.74	0.0386	7.804
1.58	80		0.18	Yes	1.11	-2.11	-2.26	-1.98	0.0512	2.601
1.000	44		0.40	Yes	0.702	-2.11	-2.40	-1.88	0.0324	0.413
0.631	24		0.64	Yes	0.443	-2.30	-3.15	-1.85	0.0168	0.053
<i>0.398</i>	<i>10</i>		<i>1.25</i>	<i>No</i>	<i>0.280</i>	<i>Over</i>				
<i>0.251</i>	<i>1</i>		<i>0.00</i>	<i>No</i>	<i>0.176</i>	<i>Over</i>				
<i>0.158</i>	<i>0</i>			<i>No</i>	<i>0.111</i>					
<i>0.100</i>	<i>0</i>			<i>No</i>	<i>0.0702</i>					
<i>0.0631</i>	<i>1</i>		<i>0.00</i>	<i>No</i>	<i>0.0443</i>	<i>Over</i>				
<i>0.0398</i>	<i>0</i>			<i>No</i>						
Total	328									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:59:30

CSD Corrections 1.37 -- R31A.csd



Model - 1.0 : 1.7 : 2.3

Foliated

Roundness = 0.6
Parallel orientation



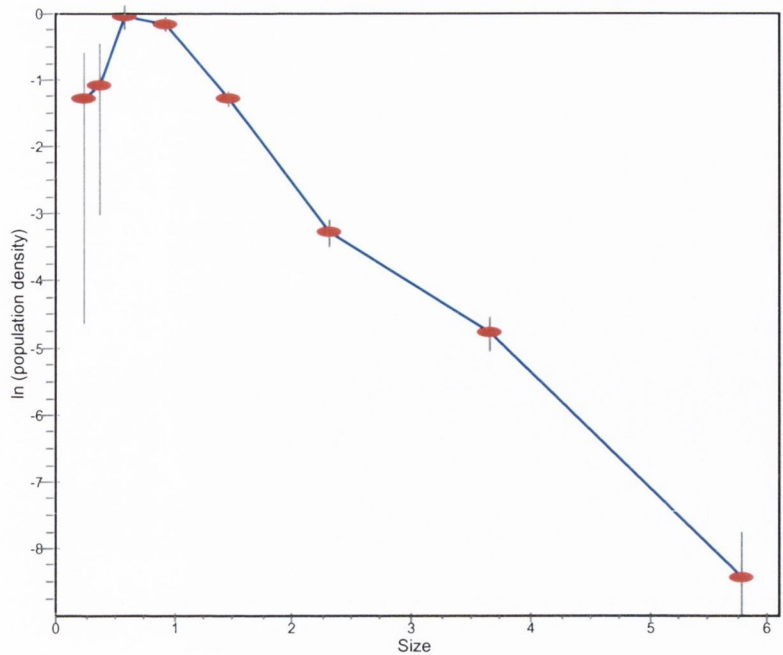
Area = 641.48
Quality = 0.4

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	1		0.00	Yes	12.8	-10.33	-Infinity	-9.64	0.000142	6.853
10.00	1		0.12	Yes	8.08	-9.54	-Infinity	-8.78	0.000198	2.393
6.31	7		0.02	Yes	5.10	-6.56	-7.05	-6.24	0.00244	7.428
3.98	33		0.03	Yes	3.22	-4.10	-4.30	-3.93	0.0182	13.85
2.51	109		0.04	Yes	2.03	-2.00	-2.10	-1.90	0.0939	18.00
1.58	135		0.11	Yes	1.28	-0.94	-1.04	-0.84	0.171	8.222
1.000	82		0.27	Yes	0.808	-0.72	-0.88	-0.58	0.134	1.622
0.631	33		0.65	Yes	0.510	-1.45	-2.15	-1.04	0.0408	0.124
0.398	11		1.67	No	0.322	Over				
0.251	2		0.00	No	0.203	Over				
0.158	0			No	0.128					
0.100	0			No	0.0808					
0.0631	1		0.00	No	0.0510	Over				
0.0398	0			No						
Total	415									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 15:00:48

CSD Corrections 1.37 -- R31B.csd



Model - 1.0 : 1.25 : 1.8

Roundness = 0.7



Area = 508.51

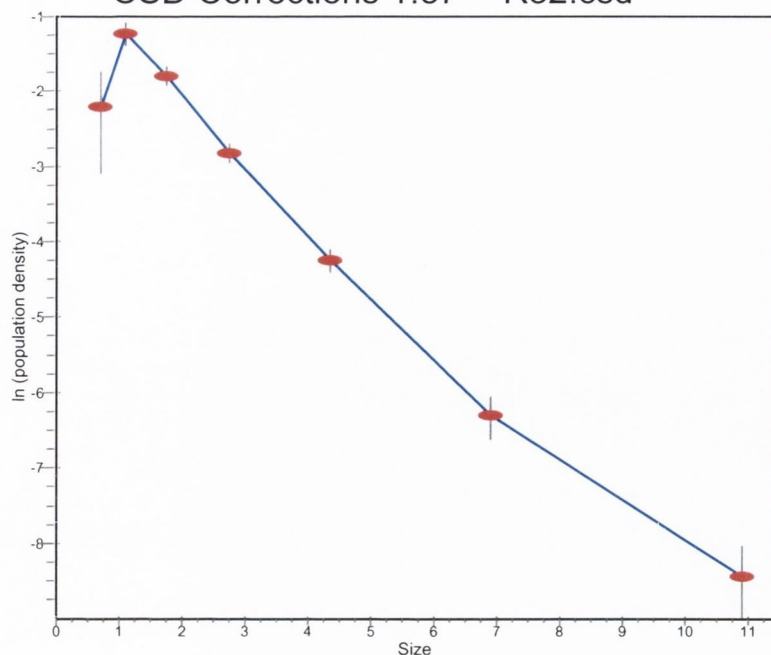
Massive

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	1		0.00	Yes	5.78	-8.45	-Infinity	-7.76	0.000395	1.963
3.98	16		0.01	Yes	3.65	-4.76	-5.05	-4.54	0.00995	12.41
2.51	30		0.07	Yes	2.30	-3.28	-3.49	-3.10	0.0278	8.722
1.58	86		0.05	Yes	1.45	-1.28	-1.40	-1.17	0.129	10.15
1.000	113		0.11	Yes	0.916	-0.15	-0.26	-0.05	0.252	4.988
0.631	64		0.30	Yes	0.578	-0.05	-0.25	0.12	0.176	0.874
0.398	30		0.79	Yes	0.365	-1.07	-3.02	-0.45	0.04	0.049
0.251	4		0.48	Yes	0.230	-1.27	-4.63	-0.60	0.0206	0.006
0.158	0			No						
Total	344									

Data in *italics* were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 15:01:28

CSD Corrections 1.37 -- R32.csd



Model - 1.0 : 1.6 : 3.2

Foliated

Roundness = 0.5
Parallel orientation



Area = 744.58

Quality = 0.2

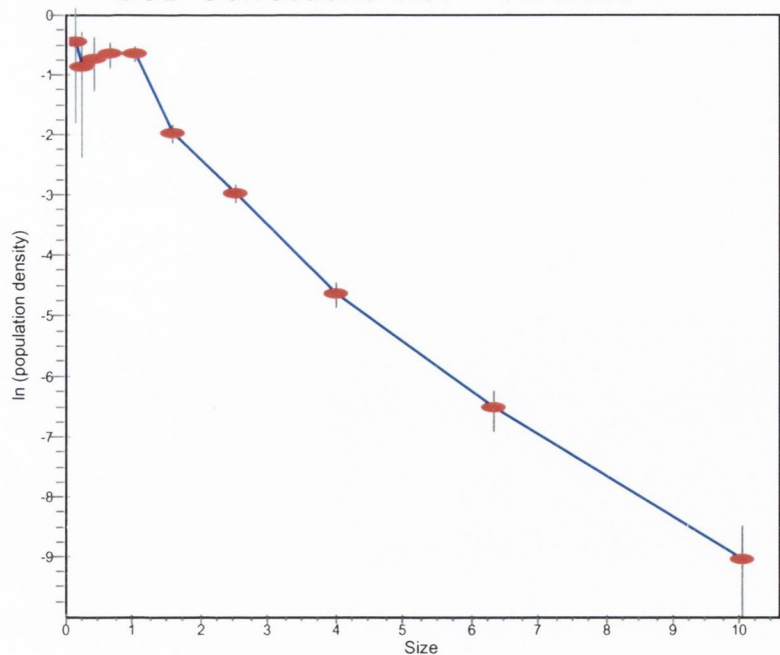
Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
10.00	4		0.00	Yes	10.91	-8.45	-9.14	-8.04	0.000537	8.301
6.31	14		0.03	Yes	6.88	-6.30	-6.62	-6.06	0.00291	11.27
3.98	44		0.03	Yes	4.34	-4.24	-4.41	-4.10	0.0144	13.99
2.51	75		0.06	Yes	2.74	-2.82	-2.95	-2.71	0.0375	9.190
1.58	88		0.11	Yes	1.73	-1.79	-1.92	-1.68	0.0664	4.084
1.000	69		0.20	Yes	1.091	-1.22	-1.39	-1.08	0.074	1.143
0.631	23		0.65	Yes	0.688	-2.21	-3.10	-1.75	0.0174	0.067
0.398	9		1.33	No	0.434	Over				
0.251	2		0.00	No	0.274	Over				
0.158	0			No	0.173					
0.100	0			No	0.1091					
0.0631	3		0.00	No	0.0688	Over				
0.0398	0			No						

Total 331

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 15:01:54

CSD Corrections 1.37 -- R33.csd



Model - 1.0 : 1.25 : 2

Roundness = 0.7



Area = 687.45

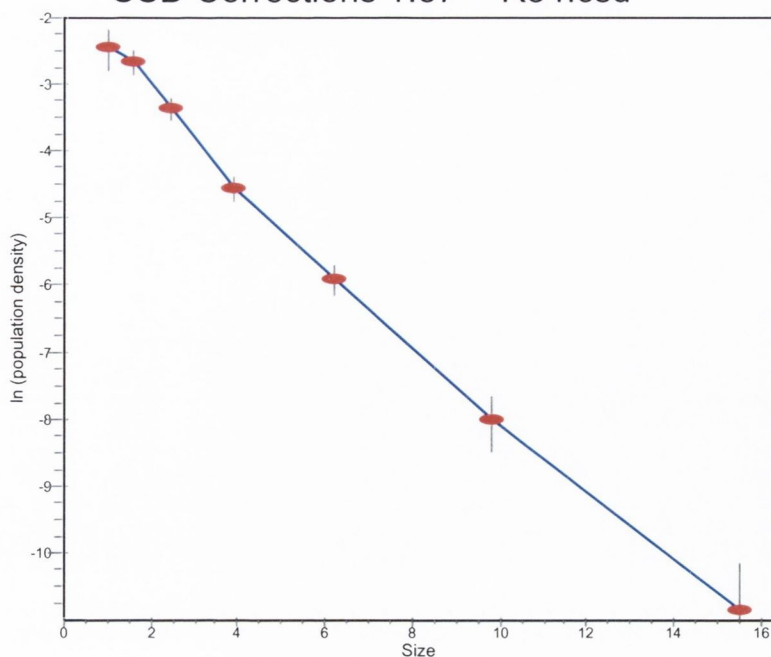
Massive

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
10.00	2		0.00	Yes	10.04	-9.04	-10.26	-8.50	0.000344	7.252
6.31	10		0.02	Yes	6.33	-6.53	-6.92	-6.25	0.00266	14.09
3.98	27		0.04	Yes	4.00	-4.64	-4.86	-4.45	0.0111	14.82
2.51	58		0.06	Yes	2.52	-2.97	-3.12	-2.84	0.0374	12.48
1.58	66		0.12	Yes	1.59	-1.98	-2.13	-1.85	0.0632	5.302
1.000	98		0.11	Yes	1.004	-0.65	-0.77	-0.54	0.151	3.178
0.631	52		0.33	Yes	0.633	-0.65	-0.89	-0.46	0.0949	0.502
0.398	28		0.54	Yes	0.400	-0.73	-1.27	-0.39	0.0553	0.073
0.251	12		0.63	Yes	0.252	-0.87	-2.37	-0.29	0.0305	0.010
0.158	4		0.32	Yes	0.159	-0.44	-1.79	0.11	0.0294	0.002
0.100	0			No						
Total	357									

Data in *italics* were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 15:02:22

CSD Corrections 1.37 -- R34.csd



Model - 1.0 : 1.2 : 1.9

Roundness = 0.7



Area = 847.14

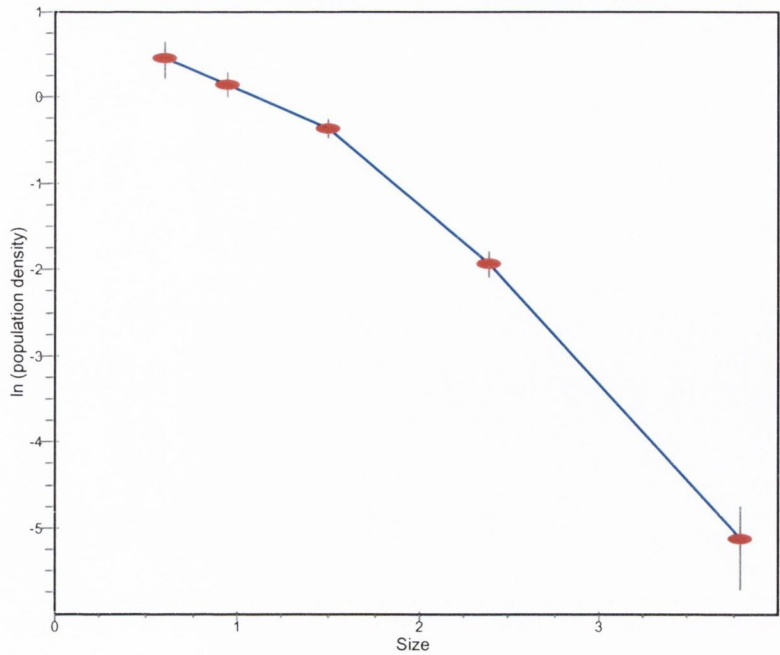
Massive

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	1		0.00	Yes	15.5	-10.85	-Infinity	-10.16	8.76E-5	7.285
10.00	7		0.02	Yes	9.81	-8.00	-8.48	-7.68	0.000957	19.98
6.31	23		0.03	Yes	6.19	-5.91	-6.15	-5.71	0.00489	25.63
3.98	37		0.07	Yes	3.90	-4.55	-4.75	-4.39	0.0119	15.73
2.51	50		0.10	Yes	2.46	-3.36	-3.53	-3.21	0.0249	8.237
1.58	44		0.18	Yes	1.55	-2.66	-2.86	-2.49	0.0316	2.627
1.000	28		0.36	Yes	0.981	-2.45	-2.80	-2.19	0.0247	0.516
<i>0.631</i>	<i>6</i>		<i>1.35</i>	<i>No</i>	<i>0.619</i>	<i>Over</i>				
<i>0.398</i>	<i>2</i>		<i>0.00</i>	<i>No</i>	<i>0.390</i>	<i>Over</i>				
<i>0.251</i>	<i>0</i>			<i>No</i>						
Total	198									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 15:02:52

CSD Corrections 1.37 -- R36A.csd



Model - 1.0 : 1.2 : 1.8

Roundness = 0.7



Area = 220.49

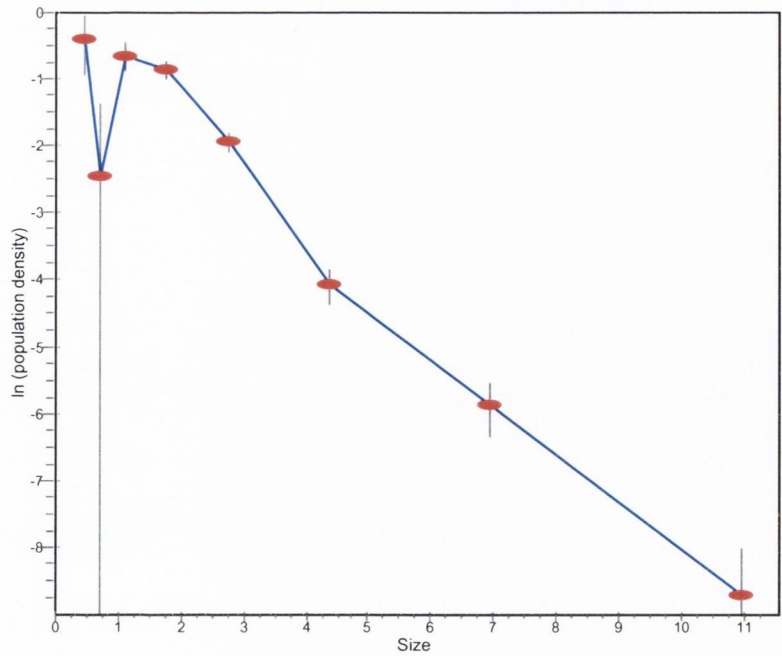
Massive

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
3.98	5		0.00	Yes	3.77	-5.12	-5.72	-4.75	0.0069	9.161
2.51	49		0.01	Yes	2.38	-1.93	-2.09	-1.80	0.106	35.32
1.58	98		0.06	Yes	1.50	-0.37	-0.48	-0.26	0.32	26.81
1.000	74		0.17	Yes	0.948	0.15	0.00	0.28	0.339	7.136
0.631	46		0.28	Yes	0.598	0.45	0.22	0.64	0.289	1.527
<i>0.398</i>	<i>8</i>		<i>2.30</i>	<i>No</i>	<i>0.377</i>	<i>Over</i>				
<i>0.251</i>	<i>0</i>			<i>No</i>	<i>0.238</i>					
<i>0.158</i>	<i>1</i>		<i>0.00</i>	<i>No</i>	<i>0.150</i>	<i>Over</i>				
<i>0.100</i>	<i>0</i>			<i>No</i>						
Total	281									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 15:03:52

CSD Corrections 1.37 -- R36B.csd



Model - 1.0 : 1.6 : 3.2

Foliated

Roundness = 0.6
Parallel orientation



Area = 290.05

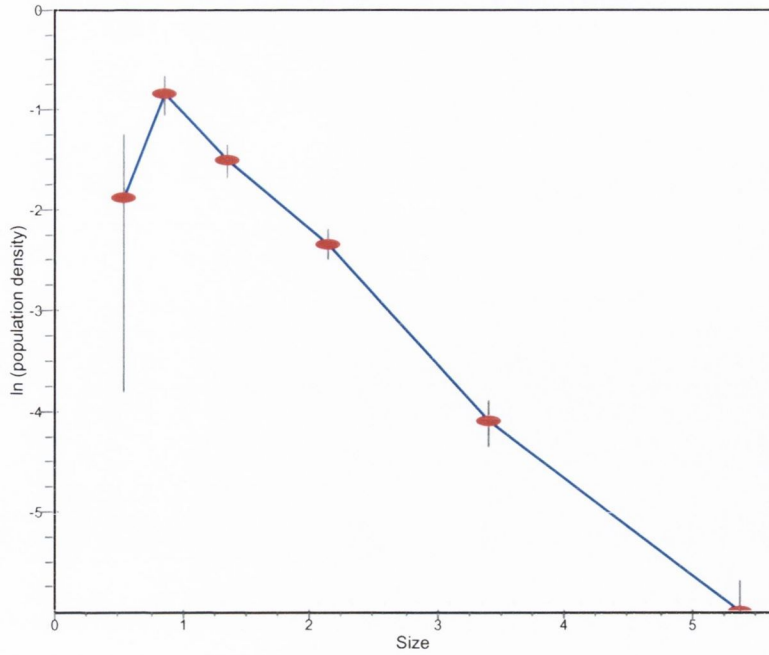
Quality = 0.7

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
10.00	1		0.00	Yes	10.96	-8.72	-Infinity	-8.03	0.000412	6.055
6.31	7		0.01	Yes	6.92	-5.86	-6.35	-5.54	0.00452	16.68
3.98	17		0.03	Yes	4.36	-4.08	-4.37	-3.86	0.017	15.74
2.51	57		0.03	Yes	2.75	-1.94	-2.09	-1.82	0.0907	21.13
1.58	71		0.08	Yes	1.74	-0.86	-0.99	-0.73	0.17	9.953
1.000	42		0.24	Yes	1.096	-0.65	-0.88	-0.47	0.131	1.931
0.631	16		0.87	Yes	0.692	-2.45	-Infinity	-1.39	0.0137	0.050
0.398	7		0.08	Yes	0.436	-0.41	-0.93	-0.06	0.067	0.062
0.251	0			No						
Total	218									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 15:04:24

CSD Corrections 1.37 -- R37.csd



Model - 1.0 : 1.25 : 1.7

Massive

Roundness = 0.6



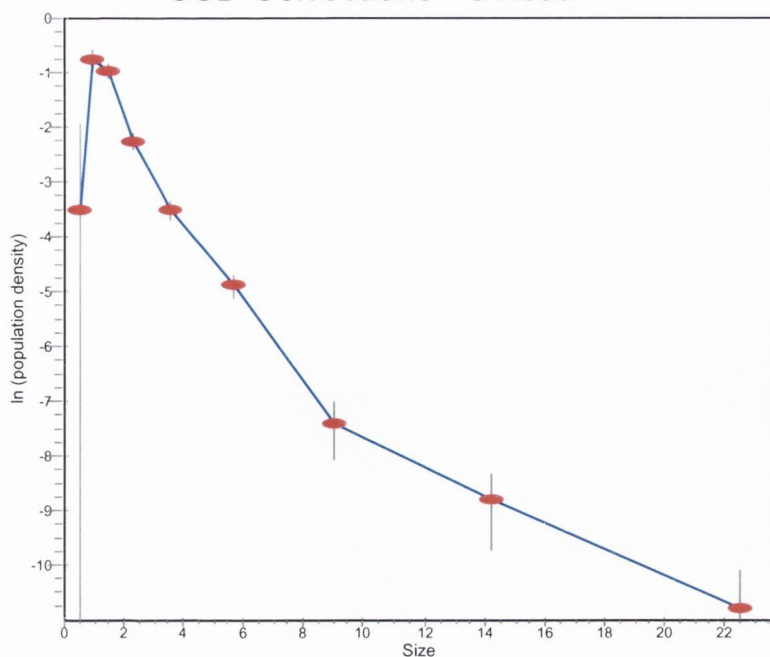
Area = 351.63

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	8		0.00	Yes	5.37	-6.00	-6.43	-5.70	0.00452	21.62
3.98	22		0.04	Yes	3.39	-4.10	-4.35	-3.90	0.019	22.82
2.51	52		0.05	Yes	2.14	-2.34	-2.49	-2.20	0.0701	21.17
1.58	52		0.13	Yes	1.35	-1.50	-1.67	-1.35	0.102	7.751
1.000	44		0.21	Yes	0.851	-0.84	-1.06	-0.67	0.124	2.362
0.631	18		0.72	Yes	0.537	-1.87	-3.81	-1.25	0.028	0.134
0.398	2		3.71	No	0.339	Over				
0.251	2		0.00	No	0.214	Over				
0.158	0			No						
Total	200									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 15:05:00

CSD Corrections - S4.csd



Model - 1.0 : 2.4 : 6

Foliated

Roundness = 0.5
Normal orientation



Area = 561.67

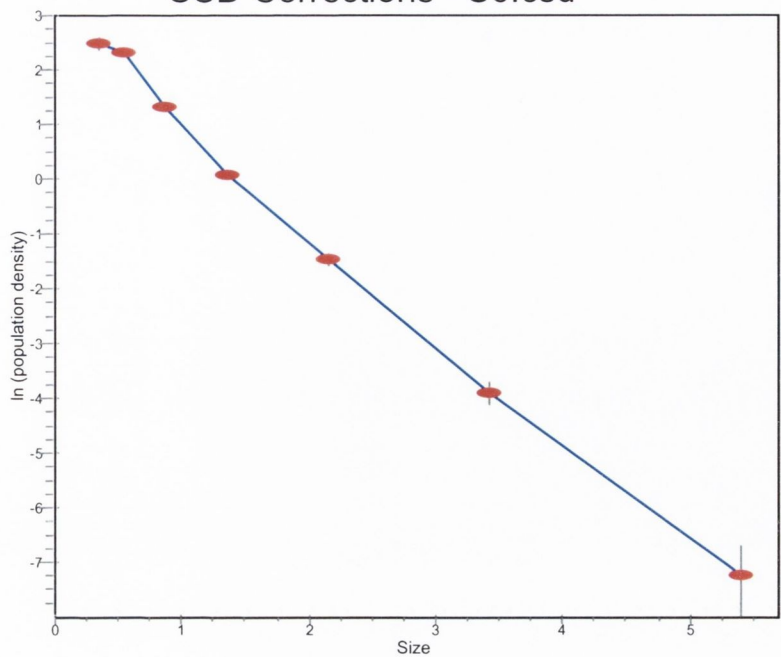
Quality = 0.7

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	1		0.00	Yes	22.5	-10.80	-Infinity	-10.11	8.47E-5	4.927
10.00	3		0.03	Yes	14.22	-8.81	-9.72	-8.35	0.00039	5.699
6.31	5		0.07	Yes	8.97	-7.42	-8.07	-7.03	0.000994	3.650
3.98	24		0.03	Yes	5.66	-4.89	-5.12	-4.70	0.00788	7.266
2.51	39		0.07	Yes	3.57	-3.52	-3.71	-3.36	0.0195	4.507
1.58	56		0.09	Yes	2.25	-2.26	-2.42	-2.12	0.0433	2.518
1.000	82		0.09	Yes	1.422	-0.97	-1.10	-0.85	0.0997	1.457
0.631	48		0.24	Yes	0.897	-0.76	-0.97	-0.59	0.0772	0.283
0.398	12		0.92	Yes	0.566	-3.51	-Infinity	-1.95	0.00313	0.002
0.251	5		1.66	No	0.357	Over				
0.158	0			No	0.225					
0.100	0			No	0.1422					
0.0631	3		0.00	No	0.0897	Over				
0.0398	0			No						
Total	278									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:29:53

CSD Corrections - S6.csd



Model - 1.0 : 1.6 : 3.6

Foliated

Roundness = 0.6
Normal orientation

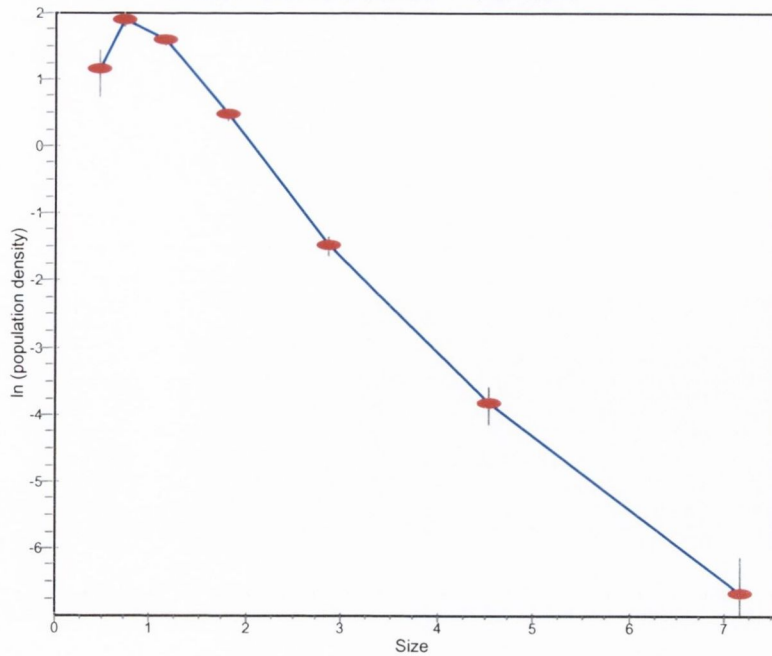
Area = 516.78
Quality = 0.7

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
3.98	2		0.00	Yes	5.41	-7.25	-8.48	-6.72	0.000786	1.097
2.51	23		0.01	Yes	3.41	-3.90	-4.13	-3.70	0.0142	4.983
1.58	105		0.02	Yes	2.15	-1.47	-1.57	-1.37	0.101	8.938
1.000	204		0.05	Yes	1.359	0.08	0.01	0.16	0.303	6.696
0.631	288		0.08	Yes	0.858	1.32	1.25	1.38	0.658	3.656
0.398	322		0.11	Yes	0.541	2.32	2.25	2.38	1.12	1.567
0.251	184		0.27	Yes	0.341	2.48	2.37	2.57	0.832	0.291
<i>0.158</i>	<i>44</i>		<i>1.14</i>	<i>No</i>	<i>0.215</i>	<i>Over</i>				
<i>0.100</i>	<i>3</i>		<i>0.00</i>	<i>No</i>	<i>0.1359</i>	<i>Over</i>				
<i>0.0631</i>	<i>16</i>		<i>0.00</i>	<i>No</i>	<i>0.0858</i>	<i>Over</i>				
<i>0.0398</i>	<i>0</i>			<i>No</i>						
Total	1191									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:30:32

CSD Corrections - S8.csd



Model - 1.0 : 1.4 : 4.5

Foliated

Roundness = 0.6
Parallel orientation



Area = 257.06

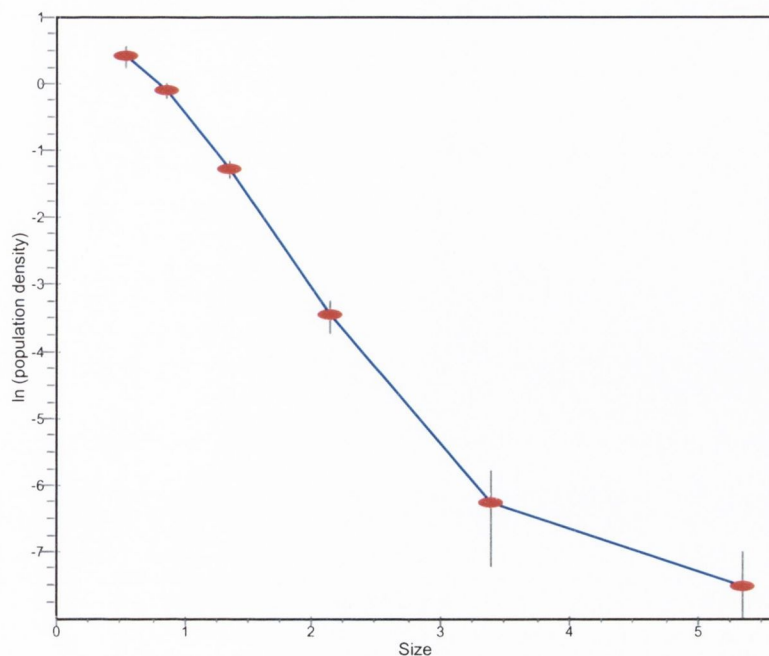
Quality = 0.1

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
3.98	2		0.00	Yes	7.16	-6.69	-7.91	-6.15	0.00128	2.322
2.51	14		0.01	Yes	4.52	-3.83	-4.15	-3.59	0.014	6.399
1.58	59		0.02	Yes	2.85	-1.48	-1.62	-1.36	0.093	10.64
1.000	168		0.03	Yes	1.799	0.48	0.39	0.55	0.415	11.92
0.631	214		0.07	Yes	1.135	1.59	1.52	1.66	0.8	5.779
0.398	133		0.19	Yes	0.716	1.91	1.79	2.01	0.69	1.251
0.251	46		0.56	Yes	0.452	1.16	0.75	1.44	0.206	0.093
<i>0.158</i>	<i>1</i>		<i>23.00</i>	<i>No</i>	<i>0.285</i>	<i>Over</i>				
<i>0.100</i>	<i>1</i>		<i>0.00</i>	<i>No</i>	<i>0.1799</i>	<i>Over</i>				
<i>0.0631</i>	<i>4</i>		<i>0.00</i>	<i>No</i>	<i>0.1135</i>	<i>Over</i>				
<i>0.0398</i>	<i>0</i>			<i>No</i>						
Total	642									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:31:17

CSD Corrections - S15.csd



Model - 1.0 : 1.15 : 1.6

Foliated

Roundness = 0.6
Parallel orientation



Area = 400.6

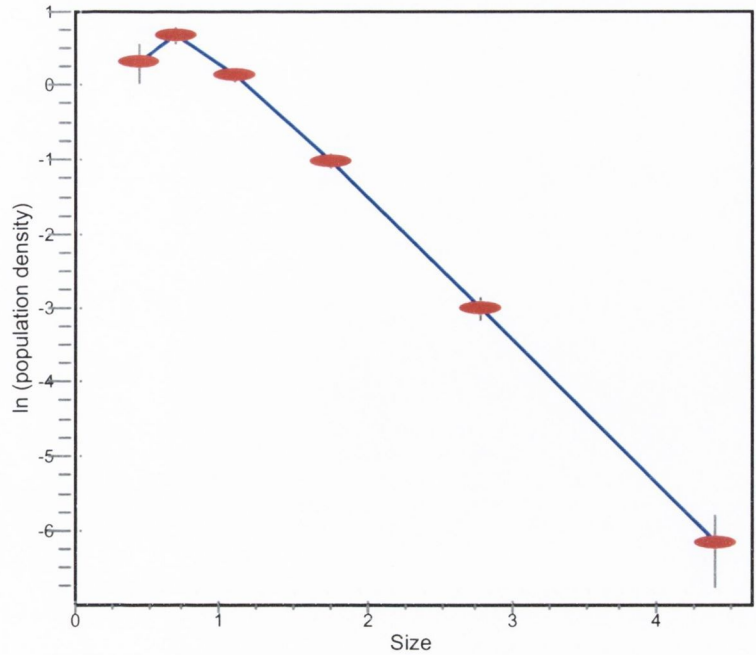
Quality = 0.1

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	2		0.00	Yes	5.36	-7.53	-8.76	-6.99	0.000954	4.699
3.98	3		0.06	Yes	3.38	-6.26	-7.21	-5.78	0.00213	2.640
2.51	19		0.02	Yes	2.13	-3.45	-3.72	-3.24	0.0223	6.937
1.58	67		0.03	Yes	1.35	-1.28	-1.42	-1.16	0.124	9.647
1.000	92		0.08	Yes	0.849	-0.10	-0.22	0.01	0.255	5.005
0.631	70		0.20	Yes	0.536	0.41	0.25	0.55	0.268	1.319
<i>0.398</i>	13		<i>1.62</i>	<i>No</i>	<i>0.338</i>	<i>Over</i>				
<i>0.251</i>	4		<i>0.00</i>	<i>No</i>	<i>0.213</i>	<i>Over</i>				
<i>0.158</i>	0			<i>No</i>						
Total	270									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:24:45

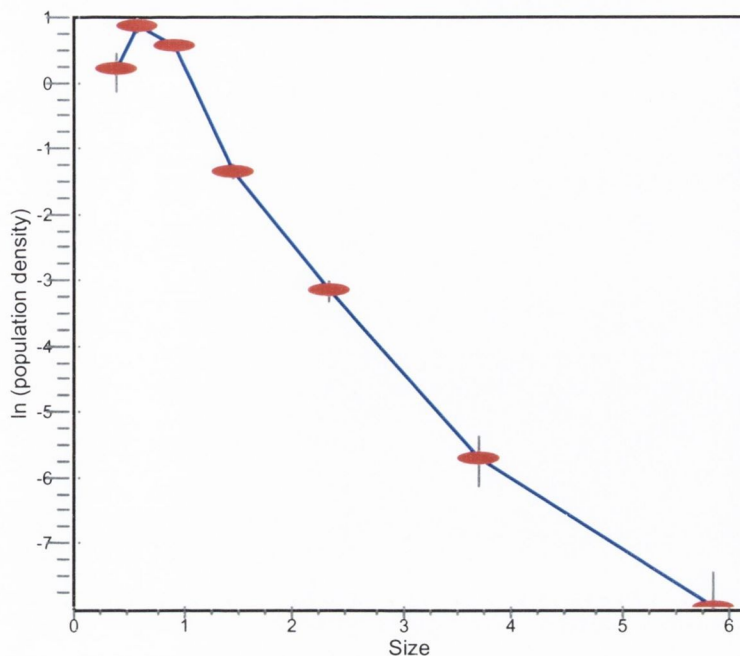
CSD Corrections 1.37 -- S18AP.csd



Model - 1.0 : 3.2 : 5.5				Roundness = 0.5	Area = 604.89					
Foliated				Parallel orientation	Quality = 0.1					
Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
3.98	5		0.00	Yes	4.40	-6.17	-6.76	-5.80	0.00246	1.682
2.51	48		0.01	Yes	2.77	-3.00	-3.16	-2.86	0.037	6.352
1.58	142		0.04	Yes	1.75	-1.02	-1.12	-0.94	0.168	7.270
1.000	193		0.09	Yes	1.104	0.15	0.06	0.22	0.342	3.710
0.631	149		0.20	Yes	0.697	0.68	0.58	0.78	0.37	1.008
0.398	65		0.49	Yes	0.440	0.32	0.04	0.54	0.162	0.111
<i>0.251</i>	<i>17</i>		<i>1.93</i>	<i>No</i>	<i>0.277</i>	<i>Over</i>				
<i>0.158</i>	<i>1</i>		<i>0.00</i>	<i>No</i>	<i>0.175</i>	<i>Over</i>				
<i>0.100</i>	<i>0</i>			<i>No</i>	<i>0.1104</i>					
<i>0.0631</i>	<i>8</i>		<i>0.00</i>	<i>No</i>	<i>0.0697</i>	<i>Over</i>				
<i>0.0398</i>	<i>0</i>			<i>No</i>						
Total	628									

Data in italics were not plotted or regressed

CSD Corrections 1.37 -- S18APY.csd



Model - 1.0 : 1.3 : 2.1

Foliated

Roundness = 0.6
Parallel orientation



Area = 638.66
Quality = 0.1

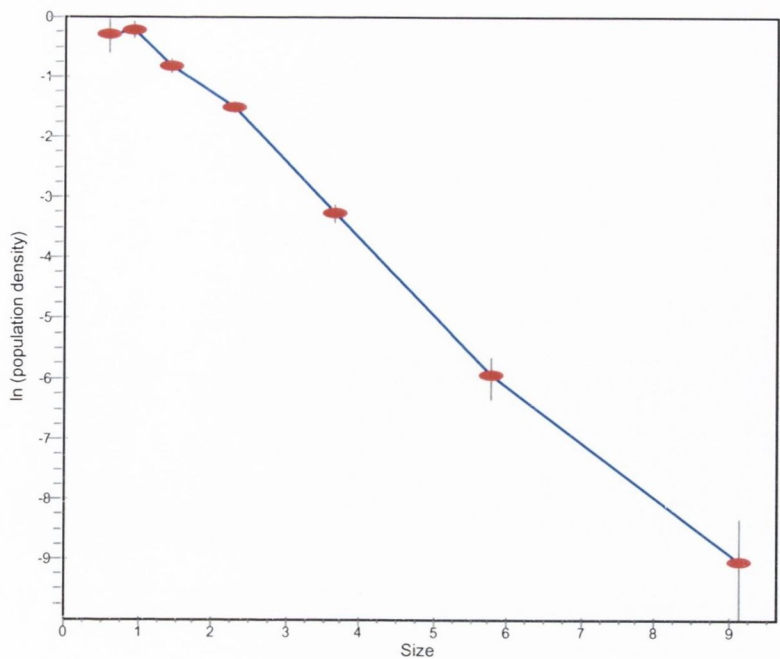
Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	2		0.00	Yes	5.84	-7.97	-9.20	-7.44	0.000574	2.401
3.98	8		0.02	Yes	3.68	-5.69	-6.14	-5.38	0.00355	3.731
2.51	40		0.02	Yes	2.32	-3.16	-3.33	-3.01	0.0282	7.443
1.58	100		0.04	Yes	1.47	-1.34	-1.45	-1.24	0.109	7.243
1.000	267		0.05	Yes	0.925	0.56	0.49	0.62	0.461	7.683
0.631	172		0.19	Yes	0.584	0.87	0.77	0.96	0.399	1.668
0.398	65		0.56	Yes	0.368	0.21	-0.13	0.46	0.129	0.135
0.251	17		1.93	No	0.232	Over				
0.158	1		0.00	No	0.147	Over				
0.100	0			No	0.0925					
0.0631	16		0.00	No	0.0584	Over				
0.0398	0			No						

Total 688

Data in italics were not plotted or regressed

CSDCorrections 1.37: 26/06/2006 13:25:02

CSD Corrections - S18BP.csd



Model - 1.0 : 3.2 : 7

Foliated

Roundness = 0.5
Normal orientation

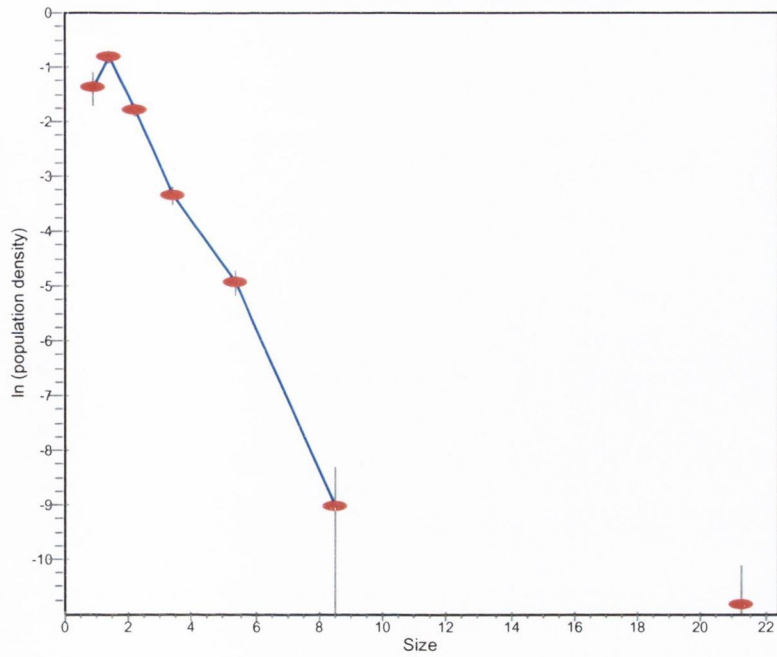
Area = 590.47
Quality = 0.7

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
6.31	1		0.00	Yes	9.14	-9.04	-Infinity	-8.35	0.000228	0.864
3.98	9		0.01	Yes	5.76	-5.94	-6.35	-5.64	0.00321	3.059
2.51	52		0.02	Yes	3.64	-3.27	-3.42	-3.14	0.0292	6.983
1.58	125		0.05	Yes	2.29	-1.50	-1.60	-1.41	0.108	6.488
1.000	110		0.14	Yes	1.448	-0.81	-0.93	-0.71	0.136	2.047
0.631	86		0.21	Yes	0.914	-0.22	-0.37	-0.09	0.155	0.586
0.398	44		0.43	Yes	0.576	-0.29	-0.59	-0.05	0.0912	0.086
0.251	11		1.74	No	0.364	Over				
0.158	4		0.00	No	0.229	Over				
0.100	0			No	0.1448					
0.0631	9		0.00	No	0.0914	Over				
0.0398	0			No						
Total	451									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:27:16

CSD Corrections - S18BPY.csd



Model - 1.0 : 1.8 : 4.5

Foliated

Roundness = 0.5
Normal orientation



Area = 590.47

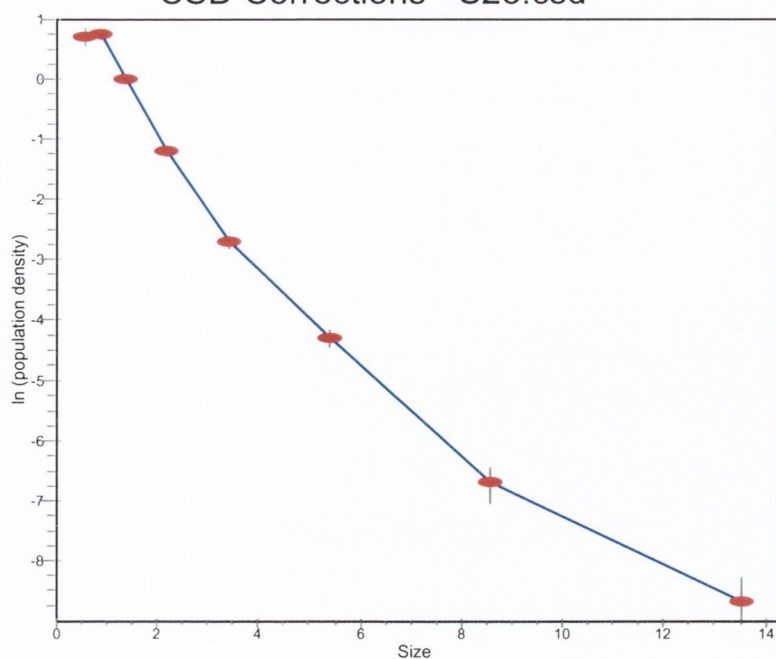
Quality = 0.7

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
15.8	1		0.00	Yes	21.3	-10.82	-Infinity	-10.13	7.83E-5	5.110
<i>10.00</i>	<i>0</i>			No	<i>13.43</i>					
6.31	1		0.05	Yes	8.47	-9.03	-Infinity	-8.31	0.000187	0.768
3.98	23		0.01	Yes	5.35	-4.93	-5.16	-4.74	0.00713	7.377
2.51	47		0.05	Yes	3.37	-3.33	-3.50	-3.19	0.0221	5.749
1.58	90		0.06	Yes	2.13	-1.78	-1.90	-1.67	0.0663	4.323
1.000	100		0.11	Yes	1.343	-0.81	-0.92	-0.70	0.111	1.811
0.631	35		0.42	Yes	0.847	-1.36	-1.70	-1.10	0.0401	0.165
<i>0.398</i>	<i>6</i>		<i>1.85</i>	No	<i>0.535</i>	<i>Over</i>				
<i>0.251</i>	<i>1</i>		<i>0.00</i>	No	<i>0.337</i>	<i>Over</i>				
<i>0.158</i>	<i>0</i>			No	<i>0.213</i>					
<i>0.100</i>	<i>0</i>			No	<i>0.1343</i>					
<i>0.0631</i>	<i>1</i>		<i>0.00</i>	No	<i>0.0847</i>	<i>Over</i>				
<i>0.0398</i>	<i>0</i>			No						
Total	305									

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:28:39

CSD Corrections - S23.csd



Model - 1.0 : 2.1 : 5

Foliated

Roundness = 0.5
Normal orientation

Area = 684.62
Quality = 0.8

Maximum length	Data Set 1	Data Set 2	Corr Fact		Mid Interval	Pop Den	Min PD	Max PD	Crystal number	Vol %
10.00	4		0.00	Yes	13.53	-8.69	-9.38	-8.29	0.00044	6.961
6.31	12		0.03	Yes	8.53	-6.70	-7.06	-6.44	0.00203	8.056
3.98	52		0.02	Yes	5.38	-4.31	-4.46	-4.18	0.014	13.99
2.51	105		0.05	Yes	3.40	-2.71	-2.82	-2.62	0.0436	10.93
1.58	192		0.06	Yes	2.14	-1.20	-1.28	-1.13	0.125	7.861
1.000	262		0.09	Yes	1.353	0.00	-0.07	0.07	0.262	4.149
0.631	236		0.15	Yes	0.853	0.75	0.67	0.82	0.349	1.387
0.398	117		0.35	Yes	0.538	0.70	0.55	0.84	0.21	0.210
0.251	34		1.08	No	0.340	Over				
0.158	5		0.00	No	0.214	Over				
0.100	1		0.00	No	0.1353	Over				
0.0631	8		0.00	No	0.0853	Over				
0.0398	0			No						

Total 1028

Data in italics were not plotted or regressed

CSDCorrections 1.37: 06/05/2006 14:29:16

Electron Microprobe Data

Electron microprobe data: Traverse 1-Ardnamurchan Laminated Gabbros

Point	Mg	Ca	Na	Ba	Sr	Total Fe	K	Distance (m ^{-d})	Total Fe	K
1	0.05	1.94	0.00	0.00	0.00	99.572	0.373	0.262	99.572	0.373
2	0.032	13.082	3.722	79.522611	0.037	99.572	0.373	0.262	99.572	0.373
3	0.035	13.068	3.722	79.520968	0.035	99.572	0.373	0.262	99.572	0.373
4	0.035	13.068	3.722	79.520968	0.035	99.572	0.373	0.262	99.572	0.373
5	0.035	13.068	3.722	79.520968	0.035	99.572	0.373	0.262	99.572	0.373
6	0.036	12.464	4.104	77.0460788	0.03	99.536	0.422	0.319	99.536	0.422
7	0.033	12.787	4.146	77.3172405	0.04	99.536	0.422	0.319	99.536	0.422
8	0.033	12.787	4.146	77.3172405	0.04	99.536	0.422	0.319	99.536	0.422
9	0.061	12.794	3.829	78.555596	0.023	99.467	0.386	0.299	99.467	0.386
10	0.044	12.468	3.902	78.206127	0.027	99.076	0.358	0.301	99.076	0.358
11	0.044	12.468	3.902	78.206127	0.027	99.076	0.358	0.301	99.076	0.358
12	0.053	12.672	3.881	78.1789255	0.056	99.151	0.416	0.335	99.151	0.416
13	0.039	12.409	3.959	77.122402	0.034	99.05	0.347	0.337	99.05	0.347
14	0.039	12.409	3.959	77.122402	0.034	99.05	0.347	0.337	99.05	0.347
15	0.032	12.719	4.121	76.8384367	0.001	99.865	0.427	0.321	99.865	0.427
16	0.032	12.719	4.121	76.8384367	0.001	99.865	0.427	0.321	99.865	0.427
17	0.072	12.116	4.164	76.279838	0.041	98.965	0.367	0.361	98.965	0.367
18	0.072	12.116	4.164	76.279838	0.041	98.965	0.367	0.361	98.965	0.367
19	0.081	12.514	3.968	77.060597	0.036	99.388	0.387	0.339	99.388	0.387
20	0.081	12.514	3.968	77.060597	0.036	99.388	0.387	0.339	99.388	0.387
21	0.082	12.56	3.864	78.252405	0.004	98.327	0.395	0.347	98.327	0.395
22	0.082	12.56	3.864	78.252405	0.004	98.327	0.395	0.347	98.327	0.395
23	0.069	12.036	3.789	77.172874	0.026	98.932	0.4	0.358	98.932	0.4
24	0.069	12.036	3.789	77.172874	0.026	98.932	0.4	0.358	98.932	0.4
25	0.052	12.605	4.006	77.6664412	0.043	98.867	0.412	0.336	98.867	0.412
26	0.052	12.605	4.006	77.6664412	0.043	98.867	0.412	0.336	98.867	0.412
27	0.05	12.694	3.841	78.506472	0.047	98.523	0.356	0.347	98.523	0.356
28	0.05	12.694	3.841	78.506472	0.047	98.523	0.356	0.347	98.523	0.356
29	0.033	12.719	3.903	78.848265	0.021	99.415	0.373	0.357	99.415	0.373
30	0.033	12.719	3.903	78.848265	0.021	99.415	0.373	0.357	99.415	0.373
31	0.051	12.719	3.85	78.500791	0.029	98.831	0.44	0.381	98.831	0.44
32	0.051	12.719	3.85	78.500791	0.029	98.831	0.44	0.381	98.831	0.44
33	0.046	13.073	3.689	79.660767	0.02	98.703	0.394	0.353	98.703	0.394
34	0.046	13.073	3.689	79.660767	0.02	98.703	0.394	0.353	98.703	0.394
35	0.039	13.068	3.722	79.520968	0.03	98.505	0.398	0.302	98.505	0.398
36	0.039	13.068	3.722	79.520968	0.03	98.505	0.398	0.302	98.505	0.398
37	0.044	14.209	3.271	78.764223	0.037	98.802	0.417	0.269	98.802	0.417
38	0.044	14.209	3.271	78.764223	0.037	98.802	0.417	0.269	98.802	0.417
39	0.048	13.361	3.567	80.539923	0.001	99.077	0.416	0.282	99.077	0.416
40	0.048	13.361	3.567	80.539923	0.001	99.077	0.416	0.282	99.077	0.416
41	0.052	12.209	3.807	79.337171	0.022	99.388	0.482	0.284	99.388	0.482
42	0.052	12.209	3.807	79.337171	0.022	99.388	0.482	0.284	99.388	0.482
43	0.056	13.304	3.71	79.8510273	0.033	99.467	0.42	0.32	99.467	0.42
44	0.056	13.304	3.71	79.8510273	0.033	99.467	0.42	0.32	99.467	0.42
45	0.061	13.143	3.715	79.831107	0.008	98.999	0.441	0.348	98.999	0.441
46	0.061	13.143	3.715	79.831107	0.008	98.999	0.441	0.348	98.999	0.441
47	0.048	13.237	3.665	79.9697914	0.028	98.861	0.411	0.361	98.861	0.411
48	0.048	13.237	3.665	79.9697914	0.028	98.861	0.411	0.361	98.861	0.411
49	0.048	13.237	3.665	79.9697914	0.028	98.861	0.411	0.361	98.861	0.411
50	0.044	13.915	3.302	82.324225	0.01	98.884	0.459	0.317	98.884	0.459
51	0.044	13.915	3.302	82.324225	0.01	98.884	0.459	0.317	98.884	0.459
52	0.051	13.681	3.379	81.244784	0.019	99.072	0.446	0.308	99.072	0.446
53	0.051	13.681	3.379	81.244784	0.019	99.072	0.446	0.308	99.072	0.446
54	0.033	14.528	3.641	84.076404	0.004	99.151	0.557	0.246	99.151	0.557
55	0.033	14.528	3.641	84.076404	0.004	99.151	0.557	0.246	99.151	0.557
56	0.066	13.716	3.328	81.9981775	0.035	98.175	0.428	0.291	98.175	0.428
57	0.066	13.716	3.328	81.9981775	0.035	98.175	0.428	0.291	98.175	0.428
58	0.058	13.641	3.43	81.8503881	0.004	98.948	0.41	0.289	98.948	0.41
59	0.017	14.038	3.434	81.87757	0.037	98.391	0.551	0.296	98.391	0.551
60	0.017	14.038	3.434	81.87757	0.037	98.391	0.551	0.296	98.391	0.551
61	0.066	13.716	3.328	81.9981775	0.035	98.175	0.428	0.291	98.175	0.428
62	0.065	14.924	2.855	85.244971	0.041	100.558	0.451	0.224	100.558	0.451
63	0.024	15	2.896	85.1286882	0.014	167.72	0.896	0.502	167.72	0.896
64	0.024	15	2.896	85.1286882	0.014	167.72	0.896	0.502	167.72	0.896
65	0.041	13.41	3.669	80.566255	0.032	99.258	0.452	0.338	99.258	0.452
66	0.065	13.53	3.55	80.8143873	0.024	99.237	0.495	0.315	99.237	0.495
67	0.065	13.53	3.55	80.8143873	0.024	99.237	0.495	0.315	99.237	0.495
68	0.066	13.534	3.457	81.1251782	0.016	98.351	0.44	0.301	98.351	0.44
69	0.066	13.534	3.457	81.1251782	0.016	98.351	0.44	0.301	98.351	0.44
70	0.052	13.741	3.572	80.981532	0.052	99.237	0.495	0.315	99.237	0.495
71	0.052	13.741	3.572	80.981532	0.052	99.237	0.495	0.315	99.237	0.495
72	0.14	13.457	3.513	80.892303	0.004	99.065	0.445	0.312	99.065	0.445
73	0.14	13.457	3.513	80.892303	0.004	99.065	0.445	0.312	99.065	0.445
74	0.057	13.462	3.529	80.828257	0.012	99.137	0.505	0.245	99.137	0.505
75	0.057	13.462	3.529	80.828257	0.012	99.137	0.505	0.245	99.137	0.505
76	0.047	13.548	3.537	80.8917635	0.016	98.667	0.426	0.307	98.667	0.426
77	0.037	13.526	3.521	80.864827	0.0	100.558	0.451	0.224	100.558	0.451
78	0.048	13.421	3.609	80.430518	0.016	99.326	0.477	0.301	99.326	0.477
79	0.04	13.302	3.697	79.955285	0.003	99.437	0.468	0.278	99.437	0.468
80	0.04	13.302	3.697	79.955285	0.003	99.437	0.468	0.278	99.437	0.468
81	0.052	13.734	3.747	79.702825	0.016	99.131	0.443	0.272	99.131	0.443
82	0.052	13.734	3.747	79.702825	0.016	99.131	0.443	0.272	99.131	0.443
83	0.048	13.463	3.756	79.8446113	0.021	98.3	0.416	0.29	98.3	0.416
84	0.048	13.463	3.756	79.8446113	0.021	98.3	0.416	0.29	98.3	0.416
85	0.066	13.172	3.667	79.7962489	0.016	99.904	0.457	0.371	99.904	0.457
86	0.037	13.527	3.711	79.6682116	0.005	98.604	0.52	0.287	98.604	0.52
87	0.037	13.527	3.711	79.6682116	0.005	98.604	0.52	0.287	98.604	0.52
88	0.044	13.212	3.789	79.797524	0.013	99.408	0.513	0.296	99.408	0.513
89	0.044	13.212	3.789	79.797524	0.013	99.408	0.513	0.296	99.408	0.513
90	0.044	13.212	3.789	79.797524	0.013	99.408	0.513	0.296	99.408	0.513
91	0.045	13.225	3.785	79.7954765	0.01	98.877	0.517	0.28	98.877	0.517
92	0.04	13.144	3.748	79.7519786	0.015	98.955	0.474	0.232	98.955	0.474
93	0.04	13.144	3.748	79.7519786	0.015	98.955	0.474	0.232	98.955	0.474
94	0.052	13.387	3.887	79.578122	0.005	98.673	0.493	0.31	98.673	0.493
95	0.049	13.194	3.742	79.578051	0.026	98.01	0.479	0.369	98.01	0.479
96	0.037	13.1	3.683	79.7205139	0.017	98.66	0.488	0.371	98.66	0.488
97	0.037	13.1	3.683	79.7205139	0.017	98.66	0.488	0.371	98.66	0.488
98	0.041	13.21	3.675	79.8021215	0.044	98.531	0.448	0.384	98.531	0.448
99	0.034	12.865	3.788	78.9631359	0.044	98.551	0.444	0.345	98.551	0.444

Electron microprobe data: Traverse 2-Ardnamurchan Laminated Gabbros

Point	Na	Al	Mg	Si	K	Ar	Ar ₂	Distance (m ²)	K	Ar	Ar ₂	Na	Ca	Fe	Distance (m ²)	Fe						
1	4.358	11.617	0.064	0.41	0.163	55.818	64.5866	30.76	0.472	0.41	95	4.395	11.669	0.057	0.035	1719	99.598	74.58312	3229.5	0.382	0.404	
2	4.399	11.411	0.051	0.029	0.17	99.712	74.1951	61.52	0.438	0.277	98	3.889	12.882	0.055	0.025	0.174	100.1	75.5446	3260.56	0.342	0.36	
3	4.419	13.566	0.091	0.031	0.163	99.649	81.41255	122.04	0.413	0.277	98	3.759	13.989	0.051	0.024	0.172	100.26	79.36984	3282.84	0.381	0.333	
4	3.5	3.725	13.24	0.031	0.019	99.95	81.80651	153.8	0.445	0.288	99	3.748	13.004	0.048	0.025	0.167	99.742	79.20277	3388.6	0.453	0.317	
5	3.729	13.24	0.052	0.031	0.063	99.071	79.48489	184.56	0.399	0.287	100	3.75	13.004	0.049	0.032	0.161	100.182	79.2674	3414.36	0.479	0.337	
6	3.729	13.24	0.052	0.031	0.063	99.071	79.48489	184.56	0.399	0.287	100	3.75	13.004	0.049	0.032	0.161	100.182	79.2674	3414.36	0.479	0.337	
7	3.729	13.24	0.052	0.031	0.063	99.071	79.48489	184.56	0.399	0.287	100	3.75	13.004	0.049	0.032	0.161	100.182	79.2674	3414.36	0.479	0.337	
8	3.949	12.668	0.073	0.02	0.171	100.968	76.04027	248.68	0.429	0.36	102	3.818	13.077	0.098	0.033	0.176	99.861	79.02714	3471.86	0.436	0.41	
9	3.733	12.667	0.056	0.04	0.194	100.302	79.4605	278.84	0.391	0.332	102	3.747	12.501	0.072	0.024	0.168	99.602	78.65661	3506.64	0.387	0.429	
10	3.739	13.333	0.035	0.023	0.173	99.553	79.24479	307.8	0.446	0.251	104	4.359	11.625	0.048	0.009	0.189	98.371	74.67233	3531.4	0.461	0.371	
11	3.739	13.333	0.035	0.023	0.173	99.553	79.24479	307.8	0.446	0.251	104	4.359	11.625	0.048	0.009	0.189	98.371	74.67233	3531.4	0.461	0.371	
12	5.559	11.294	0.081	0.066	0.176	99.697	69.82719	389.12	0.364	0.373	108	3.49	13.28	0.045	0.038	0.171	99.74	80.7895	3588.92	0.387	0.349	
13	4.105	12.25	0.076	0.019	0.178	100.302	76.14222	399.88	0.349	0.365	108	3.574	13.353	0.148	0.035	0.172	100.051	80.5085	3629.68	0.397	0.378	
14	4.077	12.43	0.06	0.028	0.165	99.885	77.17127	401.4	0.408	0.388	109	2.718	16.385	0.041	0.016	0.195	99.974	80.7895	3721.96	0.387	0.349	
15	4.077	12.43	0.06	0.028	0.165	99.885	77.17127	401.4	0.408	0.388	109	2.718	16.385	0.041	0.016	0.195	99.974	80.7895	3721.96	0.387	0.349	
16	3.873	12.97	0.036	0.028	0.167	101.555	78.11346	492.16	0.438	0.421	111	2.043	16.5	0.045	0.017	0.153	99.996	80.99068	3752.48	0.466	0.122	
17	4.026	12.97	0.038	0.017	0.177	99.833	77.2852	522.92	0.338	0.381	111	1.976	16.325	0.033	0.015	0.155	100.051	80.99068	3752.48	0.466	0.122	
18	3.811	12.79	0.034	0.026	0.157	99.699	76.09797	584.4	0.438	0.364	114	1.976	16.325	0.033	0.015	0.155	100.051	80.99068	3752.48	0.466	0.122	
19	3.516	13.319	0.034	0.026	0.157	99.699	76.09797	584.4	0.438	0.364	114	1.976	16.325	0.033	0.015	0.155	100.051	80.99068	3752.48	0.466	0.122	
20	3.644	13.61	0.056	0.027	0.175	100.448	78.29303	649.96	0.338	0.37	115	1.994	16.505	0.063	0.025	0.154	100.231	80.19314	3865.52	0.381	0.148	
21	3.644	13.61	0.056	0.027	0.175	100.448	78.29303	649.96	0.338	0.37	115	1.994	16.505	0.063	0.025	0.154	100.231	80.19314	3865.52	0.381	0.148	
22	3.538	13.07	0.057	0.044	0.187	99.865	80.37566	701.48	0.401	0.307	115	2.08	16.68	0.022	0.025	0.164	100.023	89.861	3968.04	0.533	0.133	
23	3.448	13.666	0.06	0.028	0.162	99.818	80.07728	738.24	0.415	0.344	118	2.06	16.467	0.097	0.024	0.155	99.74	89.8139	3998.8	0.463	0.183	
24	3.48	12.656	0.06	0.028	0.162	99.818	80.07728	738.24	0.415	0.344	118	2.06	16.467	0.097	0.024	0.155	99.74	89.8139	3998.8	0.463	0.183	
25	3.48	12.656	0.06	0.028	0.162	99.818	80.07728	738.24	0.415	0.344	118	2.06	16.467	0.097	0.024	0.155	99.74	89.8139	3998.8	0.463	0.183	
26	3.48	12.656	0.06	0.028	0.162	99.818	80.07728	738.24	0.415	0.344	118	2.06	16.467	0.097	0.024	0.155	99.74	89.8139	3998.8	0.463	0.183	
27	3.43	12.947	0.025	0.153	0.195	99.879	76.54858	799.76	0.429	0.347	128	3.586	13.167	0.048	0.012	0.168	99.718	80.2537	4304	0.464	0.318	
28	3.43	12.947	0.025	0.153	0.195	99.879	76.54858	799.76	0.429	0.347	128	3.586	13.167	0.048	0.012	0.168	99.718	80.2537	4304	0.464	0.318	
29	3.35	3.506	13.368	0.043	0.033	0.169	99.875	80.93625	1076.6	0.486	0.348	139	3.906	13.207	0.06	0.036	0.169	99.875	80.1895	4339.16	0.476	0.375
30	3.35	3.506	13.368	0.043	0.033	0.169	99.875	80.93625	1076.6	0.486	0.348	139	3.906	13.207	0.06	0.036	0.169	99.875	80.1895	4339.16	0.476	0.375
31	3.35	3.506	13.368	0.043	0.033	0.169	99.875	80.93625	1076.6	0.486	0.348	139	3.906	13.207	0.06	0.036	0.169	99.875	80.1895	4339.16	0.476	0.375
32	3.35	3.506	13.368	0.043	0.033	0.169	99.875	80.93625	1076.6	0.486	0.348	139	3.906	13.207	0.06	0.036	0.169	99.875	80.1895	4339.16	0.476	0.375
33	3.279	13.22	0.032	0.178	0.197	99.872	78.67515	1107.96	0.442	0.38	139	3.84	13.606	0.04	0.008	0.173	99.884	80.7346	4396.92	0.474	0.375	
34	3.279	13.22	0.032	0.178	0.197	99.872	78.67515	1107.96	0.442	0.38	139	3.84	13.606	0.04	0.008	0.173	99.884	80.7346	4396.92	0.474	0.375	
35	3.279	13.22	0.032	0.178	0.197	99.872	78.67515	1107.96	0.442	0.38	139	3.84	13.606	0.04	0.008	0.173	99.884	80.7346	4396.92	0.474	0.375	
36	3.279	13.22	0.032	0.178	0.197	99.872	78.67515	1107.96	0.442	0.38	139	3.84	13.606	0.04	0.008	0.173	99.884	80.7346	4396.92	0.474	0.375	
37	3.279	13.22	0.032	0.178	0.197	99.872	78.67515	1107.96	0.442	0.38	139	3.84	13.606	0.04	0.008	0.173	99.884	80.7346	4396.92	0.474	0.375	
38	3.279	13.22	0.032	0.178	0.197	99.872	78.67515	1107.96	0.442	0.38	139	3.84	13.606	0.04	0.008	0.173	99.884	80.7346	4396.92	0.474	0.375	
39	3.279	13.22	0.032	0.178	0.197	99.872	78.67515	1107.96	0.442	0.38	139	3.84	13.606	0.04	0.008	0.173	99.884	80.7346	4396.92	0.474	0.375	
40	3.279	13.22	0.032	0.178	0.197	99.872	78.67515	1107.96	0.442	0.38	139	3.84	13.606	0.04	0.008	0.173	99.884	80.7346	4396.92	0.474	0.375	
41	3.279	13.22	0.032	0.178	0.197	99.872	78.67515	1107.96	0.442	0.38	139	3.84	13.606	0.04	0.008	0.173	99.884	80.7346	4396.92	0.474	0.375	
42	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
43	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
44	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
45	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
46	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
47	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
48	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
49	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
50	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
51	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
52	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
53	3.706	13.367	0.072	0.194	0.161	99.836	79.5837	1291.16	0.487	0.41	138	3.585	13.177	0.093	0.028	0.164	99.871	80.2461	4552.48	0.534	0.404	
54	3.706	13.367	0.072	0.194	0.161	99.836	79.5837</															

Lithium microprobe data: Traverse 3-Ardnamurchan Laminated Gabbros

Point	Na	Ca	Mg	Ba	Sr	Total	Distance (m ⁻⁶)	An%	Fe	K	Point	Na	Ca	Mg	Ba	Sr	Total	Distance (m ⁻⁶)	An%	Fe	K
1	4.278	12.018	0.072	0.026	0.176	99.686	23.38	75.63833	0.445	0.437	91	3.583	13.491	0.032	0.021	0.176	99.206	2454.9	80.62546	0.426	0.282
2	3.997	12.131	0.046	0.035	0.181	101.868	46.76	77.03436	0.413	0.391	92	3.578	13.306	0.062	0.001	0.176	98.422	2478.28	80.43305	0.422	0.313
3	4.155	11.93	0.049	0.034	0.178	99.434	70.14	76.03822	0.438	0.377	93	3.57	13.178	0.071	0.013	0.166	99.111	2525.04	80.31366	0.435	0.351
4	3.956	11.328	0.069	0.036	0.176	99.718	93.52	75.989	0.468	0.368	94	3.569	13.985	0.062	0.026	0.172	98.805	2548.42	80.56332	0.361	0.354
5	4.226	12.229	0.058	0.024	0.162	98.206	116.9	76.18024	0.454	0.358	95	3.548	13.325	0.046	0.036	0.167	98.836	2571.8	80.58537	0.412	0.317
6	4.003	12.467	0.058	0.026	0.172	99.307	140.28	77.48798	0.394	0.302	96	3.515	13.378	0.047	0.016	0.179	98.859	2595.18	80.79283	0.4	0.331
7	4.243	12.197	0.071	0.049	0.175	97.985	163.66	76.05964	0.389	0.305	97	3.572	13.569	0.066	0.026	0.17	98.742	2618.56	80.76317	0.391	0.357
8	4.417	11.747	0.044	0.034	0.173	99.391	187.04	74.61475	0.481	0.424	98	3.623	13.362	0.082	0.011	0.159	98.951	2641.94	80.22681	0.406	0.339
9	4.638	11.207	0.032	0.015	0.18	98.612	210.42	72.75619	0.496	0.369	99	3.594	13.383	0.042	0.009	0.178	98.983	2665.32	80.45144	0.533	0.317
10	4.175	13.141	0.033	0.008	0.159	95.308	280.56	77.67203	0.459	0.35	100	3.613	13.195	0.069	0.042	0.175	97.924	2688.7	80.14421	0.405	0.368
11	3.749	13.365	0.047	0.035	0.159	96.478	303.94	79.75712	0.401	0.34	101	3.644	13.245	0.037	0.035	0.167	98.508	2712.08	80.06833	0.411	0.346
12	3.523	13.435	0.039	0.029	0.162	99.27	327.32	80.82351	0.379	0.307	102	3.715	13.23	0.043	0.026	0.174	99.263	2735.46	79.74029	0.527	0.368
13	3.453	12.79	0.237	0.044	0.167	98.177	350.7	80.36796	0.554	0.66	103	3.687	13.231	0.054	0.029	0.172	99.303	2758.84	79.86345	0.475	0.352
14	3.558	13.451	0.033	0.037	0.171	99.543	374.08	80.68838	0.396	0.308	104	3.708	13.155	0.043	0.004	0.175	98.922	2805.6	79.67885	0.451	0.351
15	3.441	13.52	0.053	0.018	0.17	99.576	397.46	81.06155	0.453	0.316	105	3.624	13.184	0.061	0.029	0.164	98.551	2828.98	80.08249	0.536	0.356
16	3.555	13.454	0.041	0.178	99.219	420.84	80.70499	0.433	0.33	106	3.662	13.139	0.058	0.027	0.173	98.906	2852.36	79.86066	0.474	0.35	
17	3.549	13.345	0.053	0.028	0.165	99.334	444.22	80.60442	0.506	0.339	107	3.639	13.066	0.032	0.017	0.161	98.689	2899.12	79.87238	0.461	0.341
18	3.605	13.362	0.026	0.044	0.174	99.114	467.6	80.37858	0.461	0.32	108	3.624	13.18	0.032	0.007	0.18	98.914	2922.5	80.07765	0.35	0.341
19	3.557	13.309	0.029	0.02	0.163	100.074	490.98	80.52687	0.504	0.317	109	3.581	13.329	0.034	0.017	0.16	100.452	2945.88	80.44494	0.441	0.43
20	3.603	13.429	0.056	0.003	0.174	99.432	514.36	80.46606	0.464	0.34	110	3.672	12.702	0.052	0.002	0.172	100.201	2969.26	79.26335	0.565	0.409
21	3.54	13.373	0.065	0.026	0.18	99.751	561.12	80.67678	0.436	0.392	111	3.446	12.975	0.135	0.018	0.164	101.752	2992.64	80.62527	0.462	0.406
22	3.027	12.996	0.058	0.02	0.17	99.57	584.5	82.95371	0.52	0.377	112	3.606	12.851	0.046	0.003	0.181	99.605	3016.02	79.75183	0.444	0.409
23	3.54	13.444	0.038	0.015	0.174	99.64	607.88	80.7592	0.467	0.36	113	3.738	12.856	0.061	0.035	0.179	97.735	3039.4	79.17147	0.436	0.401
24	3.586	13.344	0.089	0.048	0.18	99.57	641.26	80.44058	0.451	0.412	114	3.689	12.84	0.052	0.011	0.181	99.451	3062.78	79.79009	0.445	0.393
25	3.265	12.978	0.047	0.046	0.168	99.05	701.4	81.45769	0.531	0.476	115	3.75	13.312	0.042	0.01	0.168	98.831	3086.16	79.68857	0.458	0.374
26	3.456	13.476	0.221	0.022	0.145	98.767	771.54	81.16597	0.565	0.385	116	4.25	12.354	0.052	0.028	0.151	88.555	3109.54	76.26192	0.557	0.48
27	3.385	13.654	0.052	0.016	0.169	99.804	794.92	81.67843	0.518	0.286	117	3.8	13.156	0.056	0.031	0.173	98.133	3132.92	79.28038	0.432	0.357
28	3.118	13.803	0.083	0.028	0.17	99.803	813.67	82.13407	0.468	0.281	118	3.743	13.248	0.052	0.028	0.173	98.2612	3156.3	79.26912	0.401	0.325
29	3.322	13.776	0.049	0.019	0.16	99.374	841.68	82.08307	0.475	0.284	119	3.662	13.178	0.041	0.01	0.166	98.677	3179.68	79.90828	0.513	0.36
30	3.375	13.955	0.051	0.013	0.164	99.921	865.06	82.04612	0.483	0.297	120	3.671	13.265	0.051	0.032	0.181	98.787	3203.06	79.97444	0.431	0.362
31	3.402	13.99	0.091	0.046	0.157	98.931	958.58	81.96555	0.506	0.216	121	3.726	13.034	0.045	0.034	0.171	98.755	3226.44	79.44896	0.446	0.361
32	3.12	14.185	0.025	0.166	99.678	982.58	82.55865	0.468	0.201	122	3.801	12.705	0.042	0.021	0.161	97.909	3249.62	78.03711	0.453	0.28	
33	2.997	14.527	0.041	0.018	0.169	99.761	1028.72	84.26965	0.511	0.211	123	3.691	12.896	0.041	0.013	0.188	98.341	3273.2	79.43016	0.379	0.379
34	3.198	14.212	0.044	0.019	0.148	99.582	1052.1	83.08402	0.414	0.246	124	3.944	12.724	0.043	0.031	0.151	96.726	3296.58	78.09698	0.414	0.493
35	3.298	13.957	0.031	0.037	0.165	99.337	1075.48	82.89565	0.446	0.254	125	3.72	13.072	0.04	0.037	0.178	98.623	3319.96	79.52361	0.427	0.364
36	3.324	13.867	0.068	0.036	0.17	99.567	1098.86	83.17489	0.462	0.26	126	3.655	13.348	0.034	0.021	0.165	99.555	3340.8	80.14375	0.468	0.397
37	3.413	13.884	0.051	0.015	0.167	99.567	1122.24	81.83048	0.422	0.265	127	3.698	13.045	0.05	0.006	0.171	97.372	3366.72	79.58646	0.477	0.349
38	3.344	13.975	0.037	0.004	0.18	99.537	1145.62	82.2026	0.454	0.258	128	3.645	13.091	0.101	0.023	0.172	99.461	3390.1	79.87662	0.42	0.414
39	4.181	12.694	0.047	0.023	0.181	99.633	1169	77.04071	0.406	0.252	129	3.686	13.092	0.185	0.028	0.164	97.786	3413.48	79.69746	0.497	0.444
40	3.689	13.593	0.046	0.003	0.166	99.381	1192.38	80.28548	0.321	0.298	130	3.751	13.366	0.047	0.055	0.166	96.249	3436.86	79.74971	0.414	0.391
41	3.312	13.818	0.028	0.032	0.173	101.13	1215.78	82.17798	0.436	0.251	131	3.808	13.261	0.052	0.033	0.181	97.98	3460.24	79.74971	0.497	0.371
42	3.637	13.425	0.055	0.026	0.168	99.182	1239.14	80.3133	0.384	0.271	132	3.813	14.219	0.033	0.013	0.168	99.312	3483.62	83.15689	0.428	0.298
43	4.59	11.52	0.055	0.03	0.177	99.387	1262.52	73.50188	0.418	0.36	133	3.037	14.504	0.059	0.05	0.145	98.536	3507	84.07189	0.464	0.287
44	4.367	11.529	0.057	0.172	98.748	1285.9	74.47532	0.474	0.36	134	3.257	13.949	0.022	0.027	0.156	99.146	3530.38	82.5582	0.462	0.314	
45	3.526	13.442	0.042	0.02	0.171	99.16	1309.26	80.81954	0.422	0.267	135	3.293	13.932	0.042	0.044	0.17	98.435	3553.76	82.39486	0.449	0.324
46	3.322	13.823	0.066	0.029	0.17	98.895	1332.66	82.13909	0.32	0.267	136	3.411	13.851	0.06	0.008	0.169	99.102	3577.14	81.77809	0.476	0.308
47	3.371	13.88	0.046	0.018	0.162	99.655	1379.42	81.98412	0.421	0.22	137	3.474	13.878	0.051	0.05	0.177	98.003	3600.52	81.53312	0.48	0.344
48	3.877	12.542	0.04	0.029	0.176	99.024	1426.18	78.14359	0.323	0.264	138	3.342	13.778	0.035	0.023	0.166	99.085	3623.9	82.00279	0.469	0.331
49	3.519	13.452	0.058	0.028	0.177	99.567	1446.56	80.97505	0.453	0.251	139	3.346	13.756	0.076	0.033	0.172	98.2	3647.28	81.96151	0.45	0.355
50	3.753	13.068	0.042	0.025	0.167	99.454	1472.94	79.37441	0.451	0.264	140	3.41	13.695	0.063	0.03	0.169	99.171	3670.86	81.6131	0.489	0.342
51	3.59	13.324	0.049	0.039	0.168	99.041	1496.32	80.39941	0.431	0.273	141	3.336	13.764	0.034	0.015	0.159	98.021	3694.04	82.0143	0.512	0.307
52	3.561	13.633	0.042	0.026	0.173	99.784	1519.7	80.88391	0.376	0.239	142	3.372	13.799	0.052	0.011	0.168	99.199	3717.42	81.80311	0.643	0.303
53	3.755	13.063	0.049	0.017	0.17	99.394	1543.98	79.35942	0.441	0.314	143	3.334	13.937	0.05	0.037	0.167					

Electron microprobe data: Traverse 4-Ardnamurchan Laminated Gabbros

Point	Na	Ca	Mg	Ba	Sr	Total	Distance (m ⁻⁶)	An%	Fe	K	Point	Na	Ca	Mg	Ba	Sr	Total	Distance (m ⁻⁶)	An%	Fe	K
1	5.142	10.497	0.106	0.027	0.196	99.952	33.02	69.28931	0.69	0.219	91	3.908	12.917	0.057	0.015	0.162	99.828	3665.22	78.508528	0.571	0.347
2	4.575	11.575	0.03	0.038	0.162	99.868	66.04	73.6581	0.573	0.302	92	3.903	12.909	0.06	0.004	0.183	99.484	3698.24	78.519674	0.503	0.341
3	4.443	11.809	0.038	0.013	0.159	99.763	99.06	74.65876	0.464	0.27	93	3.909	12.878	0.016	0.022	0.156	99.443	3731.26	78.453139	0.512	0.359
4	4.476	11.735	0.035	0.015	0.178	99.926	165.21	74.34031	0.458	0.281	94	3.92	12.864	0.022	0.025	0.164	99.12	3764.281	78.392484	0.497	0.351
5	4.54	11.653	0.032	0.041	0.156	100.084	198.12	73.93647	0.464	0.292	95	3.873	12.832	0.026	0.043	0.176	99.956	3797.3	78.548895	0.44	0.316
6	4.836	11.036	0.056	0.047	0.189	99.883	264.16	71.60816	0.435	0.312	96	3.898	12.97	0.03	0.013	0.175	98.927	3830.32	78.620634	0.503	0.334
7	4.509	11.508	0.022	0.043	0.186	100.169	297.18	73.82707	0.559	0.323	97	3.845	12.887	0.047	0.024	0.169	98.994	3863.34	78.742579	0.598	0.345
8	4.446	11.474	0.047	0.015	0.154	99.569	330.2	73.82586	0.542	0.388	98	3.824	12.895	0.039	0.026	0.155	98.954	3896.36	78.805562	0.482	0.318
9	4.451	11.628	0.062	0.026	0.178	99.963	363.22	74.27516	0.457	0.431	99	3.89	12.963	0.045	0.015	0.165	98.401	3929.38	78.646081	0.508	0.341
10	4	12.747	0.038	0.019	0.162	99.964	396.24	77.88598	0.527	0.334	100	3.701	13.097	0.033	0.01	0.172	98.917	3962.4	79.637865	0.544	0.338
11	3.543	13.663	0.072	0.031	0.164	100.199	429.26	80.996	0.542	0.313	101	3.687	13.188	0.038	0.006	0.158	98.473	3995.42	79.611053	0.53	0.33
12	3.606	13.591	0.053	0.052	0.17	100.141	462.28	80.64087	0.535	0.291	102	3.745	13.17	0.037	0.016	0.17	99.346	4028.44	79.594161	0.585	0.338
13	3.503	13.706	0.049	0.027	0.172	99.707	528.32	81.21813	0.42	0.304	103	3.594	12.983	0.034	0.047	0.176	99.413	4061.46	79.969794	0.521	0.472
14	3.33	13.923	0.054	0.032	0.17	100.031	561.34	82.20944	0.534	0.26	104	3.732	13.271	0.06	0.019	0.169	99.41	4094.48	79.716509	0.544	0.313
15	3.358	13.931	0.037	0.032	0.165	99.796	594.36	82.09509	0.492	0.247	105	3.692	13.186	0.058	0.042	0.166	99.866	4127.5	79.786762	0.518	0.345
16	3.347	13.972	0.055	0.032	0.172	99.887	627.38	82.18634	0.509	0.273	106	3.743	13.24	0.034	0.042	0.166	99.714	4160.52	79.630972	0.536	0.354
17	3.298	14.131	0.041	0.013	0.169	99.585	660.4	82.56473	0.57	0.292	107	3.624	13.359	0.07	0.015	0.158	99.28	4193.54	80.291986	0.525	0.354
18	3.194	14.334	0.039	0.022	0.173	99.907	693.42	83.2213	0.538	0.24	108	3.686	13.12	0.094	0.017	0.165	98.537	4226.56	79.732011	0.626	0.412
19	3.418	13.881	0.091	0.024	0.174	100.124	726.44	81.77978	0.538	0.266	109	3.723	13.154	0.09	0.008	0.171	99.296	4250.58	79.612167	0.616	0.364
20	3.207	14.417	0.06	0.026	0.159	100.131	759.46	83.24519	0.501	0.253	110	3.84	12.91	0.058	0.028	0.187	98.904	4292.6	78.794161	0.648	0.377
21	3.14	14.538	0.039	0.048	0.171	99.858	792.48	83.65222	0.535	0.244	111	3.878	12.715	0.06	0.034	0.172	98.795	4325.62	78.372295	0.593	0.366
22	3.219	14.249	0.031	0.024	0.177	100.222	825.5	83.0285	0.496	0.248	112	3.805	13.167	0.039	0.008	0.183	99.058	4358.64	79.272504	0.555	0.349
23	3.657	13.018	0.025	0.008	0.163	99.186	891.54	79.73353	0.495	0.333	113	4.015	12.377	0.055	0.044	0.173	98.334	4391.66	77.308878	0.544	0.381
24	3.829	13.036	0.033	0.021	0.173	99.637	924.56	79.00362	0.474	0.369	114	3.727	12.994	0.059	0.029	0.161	99.022	4457.7	79.395245	0.653	0.358
25	3.969	12.508	0.049	0.011	0.164	98.788	957.58	77.95626	0.524	0.392	115	3.748	13.171	0.057	0.056	0.164	98.747	4480.72	79.520297	0.603	0.394
26	3.934	12.583	0.041	0.027	0.167	99.799	990.6	77.94944	0.487	0.403	116	3.681	13.147	0.038	0.007	0.175	99.303	4523.74	79.787113	0.633	0.355
27	3.888	12.752	0.048	0.01	0.173	100.031	1023.62	78.37789	0.481	0.383	117	3.696	13.171	0.052	0.011	0.199	99.217	4556.76	79.750918	0.643	0.338
28	4.001	12.587	0.031	0.039	0.169	100.163	1089.66	77.66332	0.528	0.333	118	3.681	13.029	0.035	0.023	0.164	99.023	4589.78	79.64132	0.602	0.33
29	3.999	12.799	0.03	0.027	0.178	99.931	1122.88	78.39236	0.477	0.352	119	3.745	13.027	0.04	0.022	0.175	99.173	4622.6	79.324688	0.648	0.343
30	3.977	12.894	0.051	0.036	0.158	100.4	1155.7	78.18136	0.501	0.333	120	3.723	13.045	0.05	0.014	0.162	98.876	4655.82	79.476774	0.627	0.356
31	3.9	12.839	0.044	0.041	0.174	100.454	1188.72	78.44083	0.498	0.32	121	3.657	13.195	0.08	0.016	0.166	98.266	4688.84	79.950883	0.588	0.343
32	3.839	12.982	0.031	0.039	0.178	100.202	1221.74	78.91828	0.446	0.318	122	3.609	13.264	0.062	0.005	0.163	99.125	4721.86	80.244644	0.687	0.34
33	3.777	13.893	0.062	0.021	0.164	100.211	1260.2	81.96104	0.524	0.312	123	3.609	13.173	0.05	0.045	0.165	98.973	4754.86	80.519204	0.561	0.359
34	3.207	11.485	0.053	0.014	0.141	86.716	1287.78	79.83057	0.461	0.314	124	3.643	13.138	0.05	0.013	0.199	99.597	4787.9	79.94297	0.682	0.335
35	3.329	12.78	0.072	0.061	0.182	103.634	1320.8	80.92651	0.439	0.397	125	3.646	13.19	0.054	0.006	0.156	99.051	4820.92	79.930602	0.516	0.289
36	3.01	14.112	0.051	0.054	0.159	97.076	1353.82	83.82301	0.451	0.333	126	3.634	13.334	0.098	0.011	0.166	99.249	4853.94	80.218638	0.591	0.355
37	3.128	14.465	0.049	0.027	0.178	100.493	1400.45	83.63573	0.561	0.217	127	3.595	13.187	0.057	0.045	0.163	98.872	4888.82	80.440027	0.622	0.322
38	3.076	14.524	0.056	0.033	0.166	99.989	1419.86	83.91888	0.431	0.252	128	3.53	13.287	0.23	0.023	0.148	99.314	4919.98	80.620244	0.754	0.323
39	3.108	14.422	0.045	0.051	0.166	99.954	1452.88	83.68272	0.488	0.23	129	3.618	13.535	0.041	0.035	0.159	99.285	4986.02	80.524278	0.578	0.296
40	3.001	14.788	0.063	0.025	0.173	100.119	1485.9	84.49679	0.567	0.273	130	3.918	12.982	0.026	0.025	0.172	99.209	5019.04	78.550072	0.548	0.35
41	2.966	14.715	0.072	0.036	0.162	99.932	1518.96	84.87073	0.589	0.31	131	3.918	13.058	0.01	0.068	0.168	99.245	5052.06	80.224765	0.593	0.31
42	3.021	14.822	0.051	0.006	0.163	100.258	1552.08	84.42974	0.562	0.236	132	3.522	13.527	0.052	0.043	0.171	99.108	5085.08	80.933442	0.583	0.332
43	2.986	14.846	0.038	0.022	0.169	99.844	1584.96	84.60341	0.52	0.239	133	3.792	12.219	0.059	0.022	0.16	97.721	5118.1	78.076518	0.465	0.335
44	2.967	14.783	0.043	0.019	0.17	99.75	1617.98	84.63114	0.594	0.223	134	3.579	13.568	0.047	0.042	0.172	99.007	5151.12	80.731593	0.548	0.303
45	2.984	14.863	0.057	0.015	0.154	100.328	1649.54	84.62703	0.571	0.234	135	3.461	13.263	0.048	0.016	0.159	99.003	5184.14	80.296829	0.493	0.304
46	3.035	14.712	0.05	0.006	0.174	100.151	1684.02	84.27038	0.533	0.249	136	3.478	13.641	0.035	0.013	0.173	98.878	5217.16	81.254944	0.544	0.324
47	3.027	14.47	0.057	0.014	0.152	99.691	1717.04	84.08462	0.486	0.227	137	3.427	13.836	0.039	0.015	0.155	99.467	5250.18	81.692048	0.54	0.298
48	2.941	14.712	0.049	0.028	0.167	99.877	1750.06	84.68293	0.506	0.251	138	3.538	13.161	0.051	0.014	0.168	98.039	5283.2	80.435341	0.479	0.293
49	3.279	13.913	0.041	0.018	0.157	99.572	1783.08	82.42364	0.55	0.278	139	3.462	13.681	0.043	0.035	0.174	99.046	5316.22	81.369403	0.508	0.303
50	3.379	13.792	0.029	0.044	0.152	99.792	1816.1	81.81163	0.539	0.279	140	3.52	13.698	0.046	0.016	0.166	98.977	5362.26	81.135234	0.571	0.296
51	3.531	13.616	0.064	0.01	0.165	99.774	1849.12	80.99518	0.506	0.315	141	3.393	13.691	0.141	0.013	0.168	99.013	5415.28	81.683604	0.702	0.359
52	3.575	13.624	0.038	0.015	0.172	99.43	1882.14	80.81293	0.422	0.297	142	3.373	13.896	0.062	0.041	0.161	99.218	5448.3	81.992375	0.587	0.228
53	3.426	13.612	0.055	0.036	0.161																

Electron microprobe data: Traverse 1-Druim Hain Gabbros

	Na	Ca	K	Mg	Fe	An	Distance (m^-6)	Total	Point	Na	Ca	K	Mg	Fe	An	Distance (m^-6)	Total
1	4.096	10.047	0.209	0.033	0.387	73.052655	53.46	91.1896	44	4.168	12.553	0.215	0.066	0.465	76.8979149	2886.84	99.9234
2	4.58	9.674	0.198	0.051	0.309	70.0100271	106.92	93.1802	45	4.101	12.368	0.212	0.055	0.455	76.9220358	2940.3	100.269
3	4.657	9.957	0.362	0.025	0.28	70.2647464	374.22	94.8283	46	4.344	12.569	0.231	0.035	0.532	76.1781308	3047.22	100.8645
4	4.857	11.013	0.297	0.039	0.379	71.4774689	427.68	100.6042	47	3.322	12.512	0.216	0.055	0.444	80.6301307	3100.68	99.6436
5	4.356	11.491	0.262	0.067	0.392	74.4604984	481.14	97.9349	48	4.209	12.646	0.232	0.03	0.455	76.8551178	3154.14	100.347
6	3.323	10.051	0.356	0.107	0.411	76.9738753	534.6	90.8597	49	4.226	12.414	0.217	0.065	0.387	76.4516266	3207.6	100.0181
7	4.458	11.843	0.249	0.055	0.391	74.5938966	588.06	99.4831	50	4.178	12.537	0.218	0.029	0.494	76.8326215	3314.52	99.6623
8	3.761	11.504	0.306	0.045	0.412	77.171887	641.52	94.6135	51	4.202	12.59	0.229	0.05	0.504	76.8057438	3367.98	100.5893
9	4.121	11.318	0.299	0.034	0.368	75.2190822	694.98	95.4928	52	4.146	12.896	0.195	0.042	0.459	77.4658574	3421.44	100.5557
10	4.998	10.97	0.274	0.057	0.351	70.8096879	908.82	100.7214	53	4.204	12.671	0.195	0.06	0.462	76.9113441	3474.9	100.8039
11	4.913	11.102	0.283	0.05	0.391	71.4077974	962.28	101.084	54	4.181	12.515	0.204	0.051	0.488	76.7885524	3528.36	100.5501
12	4.693	11.638	0.233	0.064	0.404	73.2674805	1015.74	100.7204	55	4.245	12.474	0.216	0.045	0.463	76.4576698	3581.82	100.4483
13	4.184	12.506	0.205	0.021	0.425	76.7629357	1069.2	100.4097	56	4.247	12.356	0.208	0.059	0.398	76.2776338	3635.28	100.1982
14	4.16	12.631	0.207	0.054	0.494	77.041775	1176.12	100.3589	57	4.206	12.38	0.21	0.074	0.368	76.4876361	3688.74	100.3884
15	4.271	12.271	0.2	0.041	0.437	76.0500105	1229.58	100.5213	58	4.095	12.016	0.273	0.056	0.434	76.4318791	3742.2	98.9506
16	4.244	12.384	0.214	0.048	0.389	76.3313367	1283.04	100.7098	59	4.189	12.221	0.209	0.067	0.365	76.3276264	3795.66	100.2549
17	4.524	11.772	0.227	0.062	0.417	74.1994281	1336.5	100.6341	60	4.518	11.59	0.211	0.035	0.55	73.9256107	3902.58	99.9329
18	4.22	11.746	0.284	0.089	0.557	75.467626	1389.96	96.4122	61	4.517	11.789	0.252	0.06	0.494	74.2566567	3956.04	99.7326
19	3.233	11.131	0.243	0.098	0.556	79.1890051	1443.42	101.7161	62	4.476	11.889	0.23	0.025	0.441	74.5909982	4009.5	99.998
20	4.464	11.892	0.243	0.074	0.503	74.64662	1496.88	100.5413	63	4.508	12.023	0.226	0.043	0.43	74.6683252	4062.96	100.001
21	4.292	12.209	0.242	0.06	0.356	75.8679422	1550.34	99.8913	64	4.446	11.993	0.221	0.044	0.455	74.8824142	4116.42	99.9875
22	4.189	12.452	0.202	0.049	0.461	76.664299	1603.8	100.7912	65	4.296	12.226	0.213	0.046	0.452	75.8763615	4169.88	100.0791
23	4.273	12.208	0.263	0.062	0.473	75.9475814	1657.26	99.3423	66	4.474	11.918	0.24	0.045	0.38	74.645604	4223.34	100.1683
24	4.133	12.549	0.246	0.086	0.423	77.0417468	1710.72	100.7137	67	4.869	11.276	0.277	0.054	0.576	71.9063399	4276.8	100.2794
25	4.593	12.011	0.218	0.096	0.426	74.29431	1764.18	100.8493	68	4.817	11.062	0.271	0.066	0.457	71.7358619	4330.26	100.269
26	4.683	11.533	0.222	0.047	0.469	73.131529	1871.1	100.2556	69	4.886	11.195	0.267	0.048	0.509	71.6897893	4383.72	100.2858
27	4.599	11.335	0.261	0.075	0.446	73.1469084	1924.56	103.3481	70	4.769	11.603	0.268	0.07	0.449	72.8921887	4437.18	100.3394
28	4.729	11.282	0.229	0.064	0.482	72.5025265	1978.02	100.0727	71	4.629	11.588	0.252	0.071	0.502	73.4516882	4490.64	100.0211
29	4.282	12.573	0.217	0.058	0.585	76.4437496	2031.48	100.6318	72	4.531	11.752	0.255	0.046	0.451	74.1372287	4544.1	100.2604
30	4.138	12.777	0.207	0.059	0.445	77.3374864	2084.94	100.4979	73	4.592	11.844	0.332	0.096	0.439	74.0301898	4597.56	99.5014
31	4.106	12.486	0.209	0.069	0.503	77.0686428	2138.4	100.0912	74	4.33	12.219	0.205	0.042	0.395	75.7212451	4651.02	99.534
32	4.114	12.654	0.212	0.054	0.473	77.2698234	2191.86	100.5217	75	4.274	12.293	0.196	0.025	0.487	76.0698413	4704.48	100.5966
33	4.273	12.567	0.204	0.068	0.441	76.4730296	2245.32	100.2705	76	5.265	10.632	0.28	0.045	0.533	69.0577316	4757.94	95.8958
34	4.57	12.157	0.225	0.035	0.454	74.6195708	2352.24	100.5081	77	4.847	11.093	0.266	0.052	0.46	71.6666679	4811.4	100.2011
35	4.363	12.078	0.255	0.046	0.546	75.3665493	2405.7	101.2232	78	4.984	10.937	0.274	0.038	0.415	70.805395	4864.86	99.8711
36	4.427	11.809	0.251	0.054	0.491	74.6715768	2459.16	100.2291	79	4.957	10.884	0.278	0.043	0.36	70.8172661	4918.32	99.1506
37	4.271	12.219	0.227	0.076	0.53	75.9725769	2512.62	100.5731	80	5.002	11.043	0.286	0.044	0.33	70.9300961	4971.78	100.3818
38	4.09	12.647	0.217	0.042	0.472	77.3627317	2566.08	100.1229	81	5.039	10.91	0.28	0.053	0.4	70.5266598	5025.24	100.1261
39	4.123	12.483	0.201	0.05	0.533	76.991285	2619.54	100.4616	82	4.972	10.787	0.322	0.067	0.43	70.5692	5078.7	99.802
40	4.159	12.665	0.199	0.059	0.517	77.0935331	2673	100.3883	83	4.963	11.038	0.311	0.036	0.389	71.0819193	5132.16	100.2864
41	4.06	12.653	0.213	0.047	0.479	77.499673	2726.46	99.8625	84	4.827	11.027	0.276	0.043	0.401	71.6294398	5185.62	100.1374
42	4.124	12.636	0.17	0.063	0.442	77.2021105	2779.92	100.65	85	5.156	10.352	0.447	0.113	0.447	68.9343343	5239.08	95.7633
43	4.119	12.637	0.189	0.038	0.498	77.2248473	2833.38	100.5517									

Electron microprobe data: Traverse 2-Druim Hain Gabbros

Point	Na	Ca	K	Mg	Fe	An	Distance (m^-6)	Total	Point	Na	Ca	K	Mg	Fe	An	Distance (m^-6)	Total
1	3.322	8.401	0.189	0.047	0.255	73.649231	42.98	77.6307	43	4.87	11.265	0.232	0.034	0.314	71.88246894	2363.9	100.3477
2	2.878	7.21	0.34	0.052	0.303	73.466196	85.96	69.2305	44	4.698	11.468	0.264	0.02	0.373	72.95727891	2406.88	100.2724
3	3.401	10.24	0.379	0.319	0.662	76.89274	128.94	91.4668	45	4.764	11.37	0.28	0.038	0.391	72.51041829	2449.86	100.7337
4	4.963	10.731	0.253	0.062	0.476	70.498678	171.92	100.2563	46	4.565	11.816	0.258	0.032	0.426	74.09800356	2492.84	99.4523
5	4.981	10.147	0.462	0.045	0.444	69.244608	257.88	98.8641	47	4.279	12.173	0.208	0.066	0.507	75.86941575	2535.82	99.6764
6	4.374	10.616	0.396	0.067	0.556	72.843896	300.86	97.7855	48	4.208	12.395	0.205	0.057	0.451	76.50086075	2578.8	99.5847
7	4.738	10.767	0.274	0.071	0.438	71.522612	343.84	98.9032	49	4.166	12.533	0.188	0.071	0.442	76.87810893	2621.78	99.8355
8	4.316	10.193	0.253	0.058	0.348	72.300259	386.82	92.9588	50	4.216	12.185	0.2	0.039	0.434	76.15781819	2664.76	99.4299
9	4.526	11.482	0.235	0.061	0.508	73.710479	472.78	100.0268	51	4.177	12.03	0.218	0.036	0.471	76.09405111	2707.74	99.1197
10	5.051	11.145	0.244	0.064	0.695	70.918668	515.76	90.5734	52	3.821	11.825	0.243	0.094	0.534	77.3772413	2750.72	94.8611
11	4.348	12.222	0.205	0.053	0.491	75.649421	601.72	100.6967	53	4.298	12.131	0.207	0.052	0.445	75.72473398	2793.7	99.4842
12	4.079	12.278	0.191	0.073	0.485	76.887855	644.7	100.7407	54	4.552	11.778	0.193	0.04	0.526	74.09091417	2836.68	100.2868
13	3.248	11.576	0.197	0.114	0.629	79.75299	687.68	102.3207	55	4.174	12.562	0.209	0.062	0.438	76.88508963	2879.66	99.4984
14	4.22	12.508	0.221	0.074	0.519	76.61263	730.66	100.3228	56	4.177	12.437	0.222	0.04	0.456	76.69404441	2922.64	99.5303
15	3.787	12.27	0.24	0.089	0.521	78.170253	816.62	103.4575	57	4.428	12.235	0.243	0.045	0.448	75.33175912	2965.62	99.9466
16	3.969	10.98	0.209	0.132	0.596	75.354211	859.6	96.5398	58	4.859	11.424	0.31	0.051	0.501	72.2102802	3094.56	94.0341
17	4.324	12.018	0.254	0.05	0.51	75.440715	902.58	99.2296	59	4.993	11.652	0.267	0.048	0.436	72.06067781	3137.54	99.2278
18	4.243	12.167	0.196	0.044	0.485	76.014768	945.56	100.5801	60	4.182	12.654	0.24	0.054	0.402	76.98060312	3180.52	99.9322
19	4.408	11.972	0.222	0.075	0.4	75.010681	988.54	100.0703	61	4.396	11.587	0.343	0.067	0.368	74.44487915	3223.5	99.1794
20	4.449	11.826	0.231	0.056	0.503	74.60497	1031.52	100.7044	62	4.701	11.548	0.252	0.019	0.411	73.08165827	3266.48	99.9313
21	4.351	12.001	0.25	0.044	0.497	75.298882	1074.5	100.4958	63	4.776	11.872	0.538	0.117	0.482	73.31398663	3309.46	99.2679
22	4.294	12.2	0.232	0.038	0.442	75.845905	1117.48	100.4005	64	4.242	12.311	0.331	0.062	0.44	76.23289943	3352.44	100.9878
23	4.389	11.855	0.275	0.071	0.391	74.907421	1160.46	97.263	65	3.968	12.415	0.353	0.075	0.525	77.56816145	3395.42	98.5204
24	3.488	9.447	0.458	0.171	0.605	74.95852	1203.44	98.5716	66	5.011	11.111	0.158	0.04	0.436	71.01952727	3438.4	99.9547
25	4.602	11.971	0.216	0.051	0.43	74.193087	1289.4	99.9183	67	4.868	11.345	0.255	0.049	0.441	72.03355096	3481.38	100.249
26	4.459	11.971	0.247	0.042	0.308	74.792858	1332.38	100.6397	68	4.973	10.946	0.276	0.03	0.473	70.86803215	3524.36	99.6903
27	4.888	11.891	0.293	0.038	0.492	72.88965	1375.36	93.9178	69	5.081	10.759	0.249	0.036	0.465	70.06231552	3567.34	100.0412
28	5.316	10.492	0.353	0.102	0.416	68.566383	1418.34	95.8452	70	3.235	8.363	0.916	0.272	0.533	74.07404856	3739.26	71.5779
29	5.297	10.559	0.477	0.072	0.421	68.780352	1461.32	100.5546	71	5.007	11.284	0.251	0.08	0.416	71.35281002	3782.24	100.4851
30	4.369	12.174	0.235	0.042	0.468	75.487815	1590.26	102.4546	72	4.348	12.254	0.214	0.047	0.389	75.69755603	3825.22	100.4852
31	4.553	11.569	0.291	0.054	0.476	73.741486	1676.22	99.0593	73	4.451	12.168	0.245	0.038	0.446	75.13290698	3868.2	100.7803
32	4.606	11.96	0.249	0.02	0.479	74.158835	1762.18	99.8351	74	5.017	10.797	0.329	0.049	0.431	70.40103733	3911.18	99.5674
33	4.686	11.828	0.223	0.057	0.524	73.612468	1805.16	97.584	75	3.309	7.795	0.299	0.05	0.663	72.24944857	3954.16	78.3898
34	4.615	12.128	0.235	0.058	0.474	74.388073	1848.14	98.9996	76	4.432	9.667	0.358	0.065	0.479	70.68014119	4126.08	91.2507
35	4.397	12.124	0.208	0.048	0.45	75.292933	1934.1	100.9031	77	4.401	10.035	0.372	0.063	0.34	71.59133218	4169.06	92.0264
36	4.647	11.993	0.24	0.013	0.469	74.041638	1977.08	99.7918	78	3.991	10.355	0.273	0.074	0.351	74.14387946	4212.04	90.9267
37	3.892	11.511	0.281	0.063	0.51	76.574025	2063.04	101.5266	79	3.855	11.312	0.25	0.043	0.362	76.43225246	4298	92.6036
38	4.536	11.735	0.277	0.046	0.406	74.088295	2106.02	100.5259									
39	4.583	11.82	0.25	0.04	0.374	74.02891	2149	100.5219									
40	4.36	11.687	0.225	0.042	0.493	74.763484	2191.98	99.0852									
41	4.715	11.422	0.234	0.058	0.365	72.806453	2277.94	100.7435									
42	4.85	11.484	0.275	0.052	0.362	72.352377	2320.92	100.7089									

Electron microprobe data: Traverse 3-Druim Hain Gabbros

Point	Na	Ca	K	Mg	Fe	An	Distance (m^-6)	Total	Point	Na	Ca	K	Mg	Fe	An	Distance (m^-6)	Total
1	4.629	11.915	0.24	0.041	0.439	73.9907869	48.89	101.1182	44	4.293	12.263	0.217	0.085	0.487	75.9443935	2688.95	99.4002
2	4.696	11.626	0.266	0.067	0.463	73.2347454	97.78	100.5369	45	4.929	11.099	0.262	0.055	0.485	71.3358419	2737.84	99.8367
3	4.798	11.585	0.216	0.061	0.457	72.7414572	146.67	100.532	46	4.973	11.141	0.238	0.057	0.426	71.2312362	2786.73	99.7035
4	4.493	12.017	0.212	0.067	0.662	74.7218883	342.23	87.8563	47	4.944	11.158	0.261	0.049	0.417	71.3820955	2835.62	99.5866
5	4.262	12.503	0.19	0.067	0.392	76.4275142	391.12	100.1264	48	4.994	11.165	0.24	0.044	0.492	71.188962	2884.51	100.1003
6	4.174	12.651	0.198	0.047	0.457	77.010319	440.01	100.5752	49	4.708	11.537	0.221	0.048	0.477	73.0336122	2933.4	99.1169
7	4.357	12.464	0.198	0.064	0.551	75.9710547	488.9	100.524	50	4.736	11.432	0.196	0.059	0.564	72.7357374	3031.18	99.5166
8	4.172	12.63	0.192	0.041	0.537	76.9893847	635.57	100.7046	51	4.779	11.543	0.238	0.054	0.505	72.7481166	3080.07	99.9022
9	4.684	11.783	0.258	0.031	0.533	73.5466653	880.02	100.4023	52	4.522	12.089	0.204	0.069	0.609	74.7131966	3128.96	99.6096
10	4.402	11.979	0.221	0.066	0.487	75.047152	928.91	99.7788	53	4.644	11.657	0.222	0.067	0.501	73.5043361	3177.85	99.8155
11	4.118	12.712	0.249	0.062	0.422	77.3330119	977.8	100.6097	54	4.47	12.133	0.208	0.051	0.523	74.9992655	3226.74	99.9736
12	4.127	12.632	0.257	0.087	0.483	77.1837341	1026.69	99.5005	55	4.211	12.608	0.215	0.037	0.523	76.7930777	3275.63	99.8859
13	4.058	12.912	0.217	0.06	0.492	77.859534	1075.58	100.3568	56	4.053	12.942	0.19	0.053	0.546	77.9207322	3324.52	99.6735
14	4.314	12.305	0.226	0.07	0.513	75.9176985	1124.47	100.5128	57	4.369	12.186	0.248	0.068	0.542	75.5060403	3373.41	99.709
15	4.331	12.122	0.218	0.061	0.474	75.5701576	1173.36	99.9621	58	4.998	11.207	0.3	0.052	0.558	71.2495126	3422.3	99.261
16	4.47	12.237	0.226	0.048	0.559	75.1589607	1222.25	100.2612	59	4.969	11.167	0.301	0.059	0.449	71.2954507	3471.19	99.7378
17	4.436	12.332	0.203	0.068	0.597	75.4447876	1271.14	100.8134	60	5.016	11.034	0.294	0.056	0.482	70.855598	3520.08	98.7892
18	3.922	11.775	0.432	0.11	0.778	76.8419706	1320.03	99.1665	61	4.998	12.093	0.281	0.045	0.486	70.8529601	3568.97	100.0037
19	4.183	12.857	0.202	0.047	0.469	77.2572127	1368.92	100.1524	62	5.548	9.986	0.376	0.041	0.489	66.5472699	3617.86	99.0663
20	4.145	12.78	0.2	0.04	0.497	77.3119673	1417.81	100.3074	63	5.286	10.271	0.309	0.041	0.474	68.2285516	3666.75	99.2874
21	4.15	12.926	0.2	0.029	0.49	77.4895765	1515.59	100.7683	64	5.035	10.945	0.305	0.034	0.456	70.6096766	3715.64	98.9109
22	4.276	12.487	0.199	0.045	0.383	76.3452634	1564.48	100.1365	65	4.818	10.663	0.371	0.049	0.367	70.9808344	3764.53	96.1112
23	4.594	11.934	0.217	0.042	0.295	74.1671209	1613.37	100.674	66	4.721	11.668	0.282	0.041	0.423	72.8608163	3813.42	99.7097
24	4.378	12.259	0.189	0.033	0.486	75.5783692	1662.26	100.1484	67	4.74	11.404	0.284	0.032	0.329	73.0142414	3862.31	99.7602
25	4.692	11.686	0.219	0.063	0.481	73.3521848	1711.15	100.0966	68	4.713	11.609	0.273	0.051	0.416	73.1351139	3911.2	99.8311
26	4.695	11.584	0.21	0.033	0.515	73.1679268	1760.04	99.6711	69	4.663	11.528	0.269	0.025	0.418	73.2070385	4106.76	99.5262
27	4.727	11.629	0.243	0.054	0.483	73.1106497	1808.93	100.4792	70	4.186	12.701	0.218	0.06	0.446	77.0293219	4155.65	99.282
28	4.661	11.734	0.234	0.068	0.433	73.5613559	1857.82	99.7436	71	4.32	12.412	0.255	0.042	0.443	76.0503307	4204.54	99.8451
29	4.404	12.429	0.225	0.058	0.54	75.7229852	1906.71	100.8666	72	4.401	12.41	0.252	0.018	0.515	75.7073851	4253.43	99.9901
30	4.324	12.476	0.199	0.079		76.127064	1955.6	99.5211	73	4.549	12.013	0.268	0.034	0.477	74.4808801	4400.1	99.5855
31	4.468	12.326	0.215	0.03	0.549	75.3023358	2004.49	100.2092	74	3.466	11.238	0.247	0.028	0.516	78.1824791	4448.99	91.8331
32	4.439	12.186	0.246	0.057	0.471	75.2108815	2053.38	99.8868	75	5.687	10.75	0.318	0.026	0.392	71.7104813	4546.77	96.4631
33	4.702	11.785	0.243	0.035	0.51	73.4752839	2102.27	100.1787	76	4.987	10.685	0.319	0.021	0.299	70.3086457	4595.66	98.5638
34	4.282	12.575	0.201	0.061	0.616	76.4466137	2151.16	100.0571	77	4.351	10.607	0.263	0.052	0.542	72.9313226	4644.55	101.6874
35	4.08	12.872	0.165	0.05	0.43	77.7124964	2200.05	99.8374	78	4.601	8.495	0.281	0.088	0.562	67.1115934	4693.44	66.9045
36	4.087	12.835	0.207	0.053	0.516	76.6328469	2248.94	99.9547	79	5.002	9.829	0.339	0.029	0.373	68.4716333	4742.33	95.0468
37	4.16	12.83	0.174	0.041	0.456	77.3170966	2297.83	100.1109	80	4.405	10.072	0.278	0.042	0.273	71.6476726	4840.11	91.3521
38	3.579	12.534	0.209	0.077	0.627	79.4683957	2395.61	103.9501	81	4.193	9.819	0.262	0.042	0.285	72.1303241	4889	89.9295
39	4.3	12.677	0.185	0.08	0.586	76.5164723	2444.5	100.0916									
40	4.306	12.621	0.191	0.061	0.555	76.4117037	2493.39	100.4634									
41	4.583	12.022	0.242	0.028	0.537	74.3533736	2542.28	99.8218									
42	4.247	12.381	0.257	0.082	0.549	76.3141888	2591.17	100.0807									
43	4.236	12.595	0.214	0.049	0.53	76.6689729	2640.06	99.8627									

Electron microprobe data: Traverse 4-Druim Hain Gabbros

Point	Na	Ca	K	Mg	Fe	An	Distance (m^-6)	Total	Point	Na	Ca	K	Mg	Fe	An	Distance (m^-6)	Total
1	4.254	12.498	0.148	0.072	0.593	76.4541463	48.37	100.0783	46	4.729	11.572	0.205	0.029	0.42	73.0056083	2757.09	100.0225
2	4.22	12.644	0.15	0.071	0.534	76.8058404	96.74	99.8053	47	4.782	11.565	0.243	0.052	0.602	72.7734172	2805.46	100.1858
3	4.267	12.618	0.157	0.039	0.66	76.5710364	145.11	100.3741	48	4.811	11.725	0.2	0.04	0.484	72.9255951	2853.83	100.2764
4	4.24	12.811	0.162	0.059	0.571	76.955025	193.48	99.7827	49	4.676	11.709	0.183	0.048	0.508	73.4572554	2902.2	100.3376
5	4.213	12.735	0.173	0.05	0.579	76.9627955	241.85	99.9422	50	4.68	11.652	0.229	0.045	0.508	73.3452865	2950.57	100.1911
6	4.182	12.714	0.168	0.047	0.584	77.0643206	290.22	100.1409	51	4.641	11.794	0.2	0.055	0.519	73.7437769	2998.94	100.0265
7	4.143	12.958	0.141	0.045	0.603	77.5620703	386.96	100.3358	52	4.567	12.111	0.24	0.049	0.602	74.5601645	3047.31	100.6814
8	4.204	12.773	0.166	0.056	0.541	77.0534126	435.33	99.5359	53	4.595	12.015	0.19	0.051	0.477	74.2923548	3095.68	100.6007
9	4.135	12.83	0.147	0.076	0.582	77.4226356	483.7	99.9476	54	4.534	11.945	0.183	0.058	0.567	74.4357365	3144.05	100.3001
10	4.131	12.863	0.174	0.06	0.478	77.4843957	532.07	100.1575	55	4.298	12.52	0.17	0.051	0.666	76.3002204	3192.42	100.4278
11	4.358	12.658	0.179	0.06	0.468	76.2477148	580.44	100.4026	56	4.177	12.906	0.18	0.014	0.55	77.3491383	3240.79	100.6965
12	4.713	12.499	0.191	0.067	0.517	74.5614239	628.81	99.8979	57	4.55	12.056	0.192	0.067	0.495	74.5445627	3289.16	100.2313
13	4.406	12.324	0.162	0.072	0.611	75.5582998	725.55	100.0021	58	4.685	12.059	0.201	0.073	0.564	73.990558	3337.53	100.5694
14	4.177	11.88	0.207	0.121	0.508	75.8650579	773.92	97.6752	59	4.545	11.953	0.205	0.061	0.66	74.4023519	3385.9	100.7985
15	4.343	12.39	0.167	0.072	0.593	75.9210661	822.29	99.6319	60	4.718	11.887	0.187	0.074	0.512	73.5769079	3434.27	100.3555
16	4.345	12.588	0.136	0.068	0.608	76.2013574	870.66	100.1914	61	4.453	11.972	0.149	0.056	0.625	74.8198092	3482.64	100.1159
17	4.486	11.407	1.214	0.103	0.688	73.7554835	919.03	100.2091	62	4.381	12.3	0.194	0.072	0.601	75.62732	3531.01	100.4105
18	4.312	12.492	0.151	0.049	0.534	76.2007841	967.4	99.4115	63	4.638	11.882	0.176	0.06	0.499	73.8999307	3579.38	99.7648
19	4.289	12.764	0.149	0.045	0.648	76.6849718	1015.77	99.9495	64	4.485	12.334	0.149	0.066	0.565	75.2437282	3627.75	100.5177
20	4.176	12.953	0.162	0.069	0.572	77.4169492	1064.14	99.9552	65	4.322	12.304	0.151	0.066	0.483	75.8823223	3724.49	99.9439
21	4.073	13.02	0.136	0.067	0.571	77.939416	1112.51	100.4604	66	4.137	12.798	0.155	0.056	0.473	77.3704882	3772.86	99.8814
22	4.775	11.454	0.193	0.067	0.555	72.6110516	1160.88	99.7514	67	4.153	12.895	0.141	0.042	0.421	77.4350409	3821.23	100.1016
23	4.853	11.39	0.174	0.054	0.565	72.1752488	1209.25	100.8603	68	4.233	12.786	0.158	0.044	0.456	76.9496857	3869.6	100.3618
24	4.857	11.469	0.178	0.057	0.633	72.2973478	1257.62	99.6235	69	4.203	12.908	0.138	0.06	0.441	77.2429599	3917.97	100.8317
25	4.802	11.57	0.219	0.055	0.431	72.6992234	1305.99	99.8496	70	4.332	12.679	0.149	0.048	0.487	76.3858302	3966.34	100.7084
26	4.729	11.621	0.252	0.046	0.416	73.0887994	1354.36	99.655	71	4.65	11.859	0.205	0.044	0.443	73.812625	4063.08	100.3816
27	5.019	10.938	0.23	0.024	0.494	70.6624234	1596.21	100.1347	72	5.046	11.247	0.174	0.032	0.417	71.1265477	4159.82	100.5347
28	4.109	12.853	0.152	0.059	0.505	77.5638865	1644.58	100.1552	73	4.891	11.485	0.183	0.151	0.716	72.1854164	4208.19	100.8344
29	4.196	12.757	0.154	0.046	0.546	77.0649269	1692.95	100.3469	74	4.228	12.839	0.167	0.047	0.524	77.0438852	4256.56	100.4532
30	4.282	12.571	0.138	0.076	0.63	76.4408848	1741.32	99.6892	75	4.137	12.75	0.148	0.061	0.668	77.3046297	4304.93	100.328
31	4.169	12.63	0.149	0.055	0.568	77.0021259	1789.69	100.1547	76	4.149	12.896	0.141	0.021	0.536	77.4532283	4353.3	100.4825
32	4.142	12.541	0.143	0.11	0.706	76.9919554	1838.06	100.2038	77	4.171	12.979	0.157	0.05	0.518	77.4729034	4401.67	100.1107
33	3.264	10.63	0.613	0.097	0.718	78.2578992	1886.43	87.8907	78	4.191	12.695	0.123	0.049	0.513	76.9998256	4498.41	100.5479
34	4.111	12.812	0.166	0.046	0.612	77.4997525	1983.17	100.3298	79	4.672	11.823	0.182	0.054	0.472	73.6623444	4546.78	100.4969
35	4.081	12.844	0.16	0.062	0.525	77.6705067	2079.91	100.2083	80	4.973	11.738	0.131	0.04	0.457	72.2889628	4595.15	101.0887
36	4.142	12.89	0.199	0.098	0.656	77.4745823	2176.65	100.1528	81	4.531	12.185	0.189	0.056	0.419	74.8249042	4643.52	100.4465
37	4.116	12.787	0.161	0.038	0.63	77.4444495	2273.39	100.3267	82	4.545	12	0.161	0.044	0.429	74.4770206	4691.89	100.1004
38	4.215	12.561	0.181	0.073	0.527	76.7094944	2321.76	100.2928	83	5.077	11.58	0.171	0.059	0.529	71.597672	4740.26	100.6642
39	4.166	12.698	0.21	0.335	0.781	77.1097852	2370.13	100.1308	84	4.538	11.985	0.161	0.055	0.515	74.4825434	4788.63	100.4018
40	4.12	12.853	0.166	0.048	0.45	77.5173275	2466.87	100.2784	85	4.314	12.24	0.165	0.047	0.439	75.8207328	4837	99.9303
41	4.218	12.764	0.202	0.049	0.554	76.9820891	2515.24	100.4698									
42	4.081	12.931	0.182	0.059	0.495	77.7873691	2563.61	100.1916									
43	4.107	12.668	0.181	0.054	0.513	77.3191167	2611.98	99.6849									
44	4.117	12.769	0.18	0.046	0.496	77.4155863	2660.35	100.3231									
45	4.491	12.039	0.189	0.031	0.645	74.7648218	2708.72	100.2171									

Appendix B

The Great Eucrite intrusion of Ardnamurchan, Scotland: Reevaluating the ring-dike concept

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ABSTRACT

Ring-dikes are cylindrical sheet intrusions that develop at a subvolcanic level due to ascent of magma along steep outward-dipping ring fractures. Magma ascent is triggered by central block subsidence, and fully formed ring-dikes are composed of a flat-lying sill-like roof as well as steeply outward-dipping walls on all sides. The Great Eucrite of the Ardnamurchan Paleocene igneous complex, NW Scotland, is a spectacular gabbro intrusion that has been cited as one of the classic examples of a ring-dike for the past 70 yr. We combine field observations, detailed structural measurements of primary magmatic features, and anisotropy of magnetic susceptibility data in a reinvestigation of this intrusive body. Magmatic layering and macroscopic planar crystal arrangements dip inward, and magnetic lineations plunge consistently toward the center of the intrusion, in contrast to what would be expected for a ring-dike. We propose that the Great Eucrite ring-dike is in fact a lopolitic intrusion with an overall funnel-shape geometry. This conclusion brings into question the presence of three individual foci of activity in Ardnamurchan, purported to have shifted throughout the development of the complex. It also has significant implications for the status and structural evolution of other igneous complexes of the British Paleocene igneous province, which contain layered mafic intrusions currently regarded as ring-dikes.

Keywords: Great Eucrite, Ardnamurchan, lopolith, ring-dike.

INTRODUCTION

Caldera ring-fault development and associated subsidence of a central block are the dominant structural processes that allow the intrusion of ring-dikes (Roche et al., 2000). Ring faults are widely envisaged as steeply outward-dipping (reverse) structures, because models for ring-dike development require that subsidence of the central block is accommodated during collapse (Roche et al., 2000; Walter and Troll, 2001). Ring-dikes are therefore traditionally envisaged as having a bell-jar-like geometry, forming broadly cylindrical intrusions at shallow, subvolcanic levels (Fig. 1).

The igneous complexes of the British Paleocene igneous province represent the deeply dissected roots of major volcanoes in a region that was the site of intense igneous activity between ca. 60.5 and 58.7 Ma (Chambers et al., 2005). The British Paleocene igneous province is also where many of the original models for ring-dike emplacement were first developed (Richey and Thomas, 1930; Anderson, 1936). The Ardnamurchan igneous complex hosts the Great Eucrite, frequently referred to as the classic example of a wholly complete mafic ring-dike (Wager and Brown, 1968; Woodcock and Strachan, 2000; Bell and Williamson, 2002). This interpretation has never been seriously questioned since it was first proposed by Richey and Thomas (1930). Our study of magnetic fabrics of the Great Eucrite, combined with structural measurements on macroscopic, primary magmatic features, suggests that magma emplacement was not parallel to outward-dipping ring-fractures (Fig. 1), a key criterion in the identification of ring-dikes (Anderson, 1936; Roche et al., 2000).

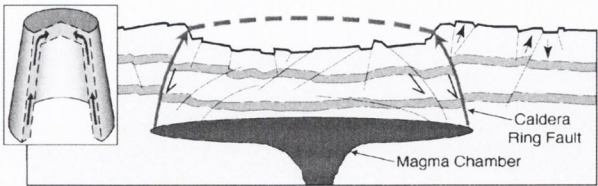


Figure 1. Schematic diagram showing subvolcanic level and ring-fault system along which ring-dikes are emplaced (after Walter and Troll, 2001). Inset: Bell-jar geometry of typical ring-dike intrusion and expected magma flow directions during emplacement.

Three distinct foci of activity have been recognized in the Ardnamurchan complex (centers 1, 2, and 3; Fig. 2). Each of these is dominated by intrusive mafic rocks that were emplaced either as concentric, inward-dipping sets of cone sheets related to doming and extension, or as larger annular intrusions historically interpreted as outward-dipping ring-dikes associated with central subsidence (Richey and Thomas, 1930). The areal extent of center 3 is dominated by the Great Eucrite (~70%), corresponding to the area (~10 km²) occupied by gabbros 1–4 of this study (Fig. 2). The Great Eucrite wholly encompasses a suite of smaller, arcuate gabbro bodies, which have been interpreted as partial ring-dikes, and a central tonalite body, which is considered to be a late-stage intrusion into these arcuate gabbros (Richey and Thomas, 1930).

LITHOLOGICAL RELATIONSHIPS AND PRIMARY MAGMATIC FEATURES

The term eucrite is given to gabbroic rocks containing plagioclase that is bytownitic to anorthitic in composition (An₇₀–An₁₀₀). Detailed

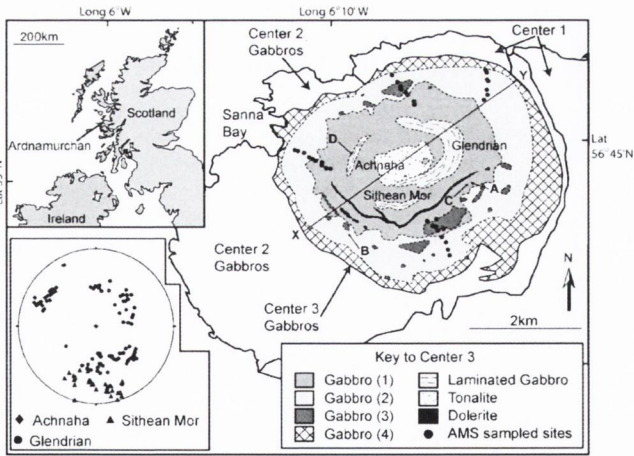


Figure 2. Location map for centers 1, 2 (unornamented), and 3 of Ardnamurchan intrusive complex, together with position of anisotropy of magnetic susceptibility (AMS) sampling traverses. A–D are localities of photographs in Figure 3. Inset bottom left: Equal-area projections illustrating poles to lamination planes for Achnaha, Glendrian, and Sithean Mor areas.

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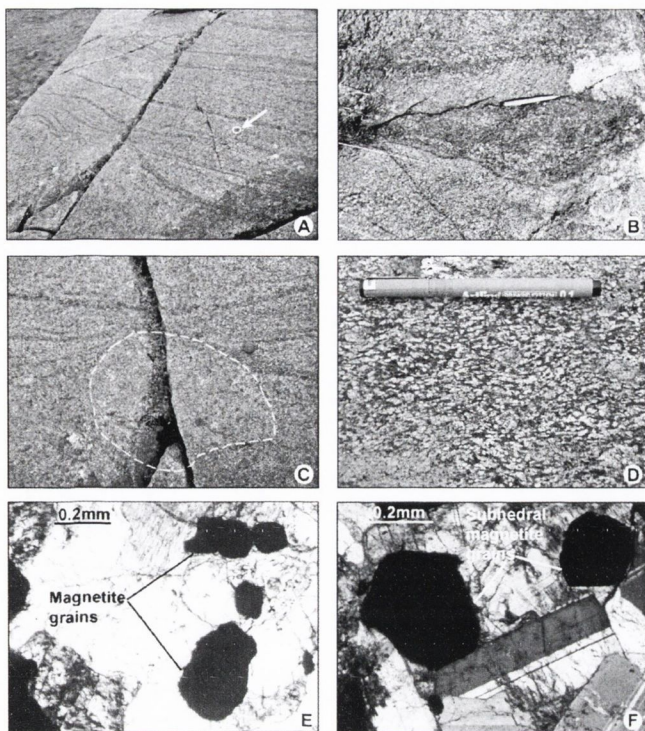


Figure 3. A: Well-developed magmatic layering in gabbro 1 (lens cap for scale is highlighted). B: Slump structure in layered gabbro 2. C: Magmatic layers draping block (highlighted) in gabbro 1 (lens cap for scale above highlighted block). D: Strong lamination of tabular plagioclase feldspars in Achnaha laminated gabbro. E and F: Large subhedral magnetite grains in Great Euclite gabbro.

remapping of the Great Euclite of Ardnamurchan suggests it includes four further, distinct petrological facies of gabbro, distinguished on textural and mineralogical grounds, and traceable around the full circumference of the intrusion (Fig. 2). The two most common lithologies are a dark-gray, partially layered olivine gabbro (1) that is surrounded by an extremely heterogeneous, brownish light-gray, partially layered olivine gabbro (2). Both of these rocks contain variably sized xenoliths and rafts (from <1 m up to 1 km in length) of an olivine-glomerocrystic, unlayered gabbro (3). A highly altered, unlayered, olivine-deficient gabbro (4) is found around the outer margin of the intrusion.

Magmatic layering is common in gabbros 1 and 2, composed of thin sequences of plagioclase-rich layers alternating with olivine-rich layers, and less commonly pyroxene-rich layers (Fig. 3A). Individual layer thicknesses rarely exceed 25 cm, and the maximum thicknesses of sequences of layers is typically ~10 m. Layer planes consistently strike parallel to the outer margins of the Great Euclite, can be traced for up to 20 m laterally, and generally dip inward toward the center of the intrusion at 40–60°. Magmatic sedimentary structures are present and are associated with the layering. These include slump structures, fallen-blocks that affect layering (Figs. 3B and 3C), and graded bedding.

Three arcuate areas of a fifth olivine-deficient, plagioclase-rich gabbro are observed at the center of the pluton, at Achnaha, Sithean Mor, and around Glendrian (Fig. 2). This gabbro is characterized by a very common, sometimes intensely developed, igneous lamination defined by the planar arrangement of tabular plagioclase crystals (Fig. 3D). Earlier work (Richey and Thomas, 1930) referred to these rocks as fluxion gabbros, in particular the Sithean Mor and Glendrian laminated zones, and interpreted them as distinct fluxion gabbro ring-dikes.

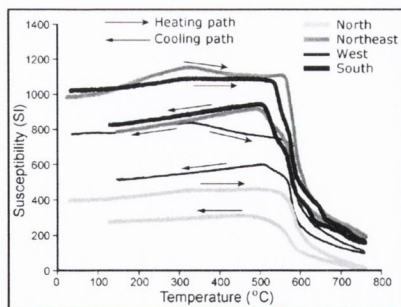


Figure 4. Susceptibility vs. temperature plots showing heating and cooling paths for selected Great Euclite samples (one from each traverse).

However, no chilled margins or intrusive contacts have been observed between these bodies and gabbro 1, and their lamination always strikes parallel to their outer margins and consistently dips toward the center of the pluton (Fig. 2).

Poor exposure makes contact data from around the outer margin of the Great Euclite extremely rare, but one boundary with Jurassic sediments in the north of the peninsula is traced laterally for ~15 m and is observed to dip inward at ~50°. Two late bodies intrude the center 3 gabbros (Fig. 2). The first of these is a thin, fine-grained, sheet-like dolerite intrusion extensively net-veined with a younger microgranite. Contact measurements for this intrusion show that it also dips inward at 50–70° around its circumference. The second is the central tonalite that displays a steeply outward-dipping intrusive contact and a chilled margin toward the laminated gabbro.

MAGNETIC FABRIC ANALYSIS

The anisotropy of magnetic susceptibility (AMS) of a rock sample is described by a second rank tensor (K) and can be visualized as a susceptibility ellipsoid (Tarling and Hrouda, 1993; Dunlop and Özdemir, 1997). K is specified by six parameters that define the magnitude and orientation of the three principal susceptibilities ($K_1 \geq K_2 \geq K_3$) of the ellipsoid. These principal susceptibilities are used to derive alternative combinations of magnitude parameters, such as the bulk susceptibility [$K_{\text{mean}} = (K_1 + K_2 + K_3)/3$], the magnetic lineation [$L = (K_1 - K_3)/K_{\text{mean}}$], and magnetic foliation [$F = (K_2 - K_3)/K_{\text{mean}}$]. The total anisotropy ($H = L + F$) is a measure of the strength of the magnetic fabric (Owens, 1974). The relative strength of L to F is used to classify the shape of the ellipsoid as prolate, triaxial, or oblate.

AMS measurements were carried out on drilled cores from a set of 42 field-orientated gabbro block specimens using an AGICO KLY3 Kappabridge, which measures specimen susceptibility axes to within $\pm 2^\circ$ (95% confidence limits). Block sampling was carried out at 80–100 m intervals along four radial traverses (8–10 sampled stations each), which were approximately perpendicular to the outer margin of the Great Euclite (Fig. 2). Ten to fourteen subsamples were then drilled from each block, and site mean tensor data were calculated from the measurements (Owens, 2000).

The data revealed bulk susceptibilities of 7.9×10^{-3} to 3.3×10^{-2} SI in the Great Euclite. These values suggest that the susceptibility (and therefore the AMS) in these samples is overwhelmingly due to magnetite, in volume concentrations of up to ~1% (Balsley and Buddington, 1958). This has been corroborated by measurement of the temperature dependence of susceptibility using an AGICO CS-3 furnace, which also shows the dominance of magnetite with Curie temperatures of 575–580 °C (Fig. 4). Reflected and transmitted light microscopy indicates that magnetite occurs as large (generally >150 μm) subhedral grains throughout the rock (Figs. 3E and 3F).

In magnetite-bearing rocks, susceptibility anisotropy normally arises from the shape-preferred orientation of inequant grains (with the maximum susceptibility in the direction of maximum long-axis concentration). The anisotropic distribution of grains may also influence

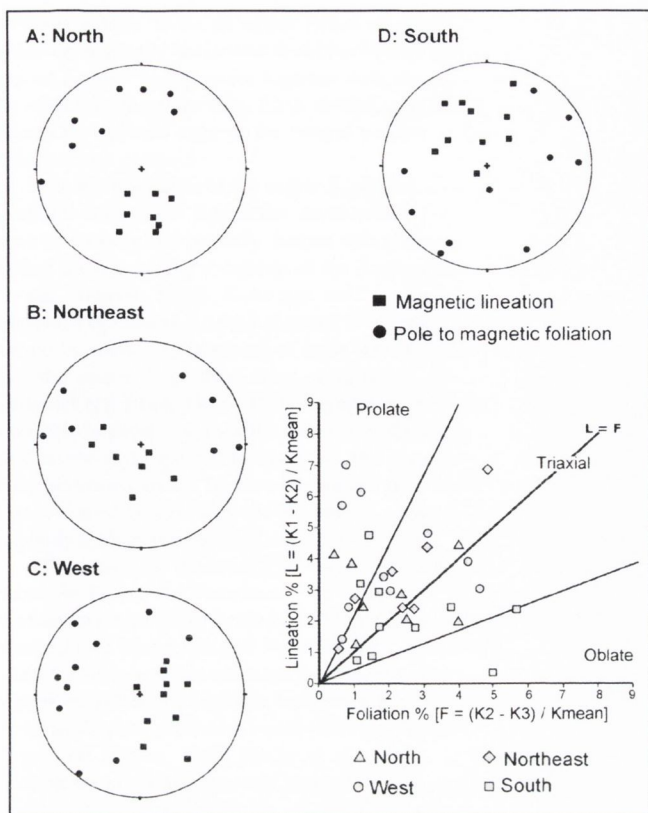


Figure 5. A–D: Equal-area projections illustrating magnetic fabric data for each of four traverses. E: Subdivision of anisotropy of magnetic susceptibility (AMS) data from Great Eucrite into prolate, triaxial, and oblate fabrics on basis of an L - F plot.

the AMS if the magnetite concentration is sufficiently high and the distribution of magnetite sufficiently nonuniform (Hargraves et al., 1991; Bouchez, 1997; Launeau and Cruden, 1998). However, the volume concentration of magnetite in rocks of the Great Eucrite, for which H is typically 5% (range 2%–9%), is sufficiently low for it to be unlikely that distribution anisotropy is a significant contributor to the fabric.

The AMS results are summarized in Figure 5. For all but one of the blocks sampled, the susceptibility ellipsoids are triaxial to prolate in shape (Fig. 5E), indicating that the magnetic lineation (K_1) is the most clearly defined component of the magnetic fabric overall. The directions of this axis are remarkably consistent, generally plunging toward the center of the intrusion at 40–70° (Fig. 5A–D). The K_1 axis also exhibits a weak steepening-inward trend on both the southern and northern traverses (see the GSA Data Repository¹). The magnetic foliation also dips inward without exception, though the strikes are not as consistent, trending either parallel or slightly obliquely to the outer margins of the intrusion at different stations (Fig. 5A–D).

DISCUSSION

The presence of an inward-dipping intrusive contact along the northern margin of the Great Eucrite strongly suggests that the intrusion does not have the classic bell-jar geometry of a ring-dike. The well-developed magmatic layering in gabbros 1 and 2 exhibits sedi-

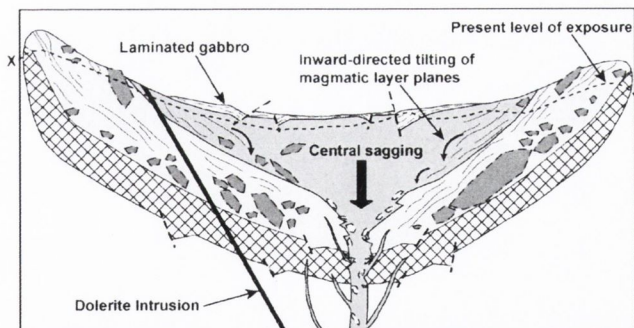


Figure 6. Schematic diagram along the line X-Y (see Fig. 2) showing proposed (pre-tonalite) form of center 3 gabbro intrusion and its magma flow planes as suggested by structural data and magnetic fabric results.

mentary structures that suggest that layering developed from magmatic flow and associated fluid-dynamic processes. Such localized, gravity-controlled layering is generally considered to form due to the action of crystal-laden density currents on horizontal to gently sloping magma-mush interfaces that are often parallel or subparallel to the outer walls of the intrusion (Wager and Brown, 1968). The fact that layering typically dips comparatively steeply toward a central focal point in the intrusion suggests a significant degree of syn- to postdepositional tilting of basal surfaces toward the center of the pluton.

Magnetic fabrics in the Great Eucrite are dominantly triaxial to prolate, with a clearly defined K_1 axis in the direction of flow described above. These fabrics are unusual as flow fabrics in that they are not oblate (Rochette et al., 1999) and the magnetic foliation is not always coincident with layering. This inconsistency may result from abnormal or complex fabrics, in the sense of Rochette et al. (1999), because of the strongly prolate nature of some of the susceptibility ellipsoids. However, the consistent inward plunge of the magnetic lineation at 40–70° (approximately down-dip on layering) in the Great Eucrite suggests that it may be validly used as a structural element. We suggest, therefore, that the magnetic lineation may also have developed due to the sedimentation processes described here, and tilted inward simultaneously with layering.

Evidence from contact relations, magmatic layering, and magnetic fabrics suggests that the center 3 gabbros comprise a lopolithic, composite pluton, of which the Great Eucrite forms a component part (Fig. 6). This is in agreement with one of the principal findings of Wager and Brown (1968) that layered mafic and ultramafic intrusions are predominantly funnel-shaped lopoliths. Rotation of originally subhorizontal, magnetic lineations has been described by Cowan (1999) in the Sudbury igneous complex, where it may have been related to a cantilever-type, syn- to postemplacement, inward-tilting of the intrusion floor (Cruden, 1998). Indeed, such centrally directed sagging and inward-dipping magmatic layering is well documented for layered mafic-ultramafic lopoliths worldwide, e.g., the Bushveld complex (Carr et al., 1994), the Rum Layered Suite (Emeleus et al., 1996), and the Skaergaard intrusion (McBirney and Nicolas, 1997). In addition, the weakly developed steepening-inward trends observed in the northern and southern traverses bear similarities to documented examples of inward-steepening structures attributed to central sagging in a number of mafic-felsic complexes (Wiebe and Collins, 1998).

An important line of evidence used by Richey and Thomas (1930) for their ring-dike model was the reported outward-dipping nature of the late dolerite sheet. The contact data measured for the dolerite sheet in this study indicate that it has the form of a large inward-dipping cone sheet, removing another argument in favor of the ring-dike model for center 3 gabbros. We consider the three arcuate zones of laminated

¹GSA Data Repository item 2006036, plot of K_1 axes vs. distance towards the center of the Great Eucrite, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA

(fluxion) gabbro to be an upper facies of gabbro in the lopolith, in which an originally horizontal to subhorizontal igneous lamination was rotated progressively inward together with the magmatic layering and the magnetic lineations (Fig. 6). A chilled margin and intrusive contact toward the gabbros suggest the central tonalite body represents a late intrusion into center 3.

The interpretation of the center 3 gabbros as an intrusion fed from a central source has significant implications for the presence of the three temporally and spatially distinct foci of activity purported to have shifted throughout the evolution of the Ardnamurchan complex (Richey and Thomas, 1930). K-Ar age studies carried out on the gabbro intrusions of centers 2 and 3 showed that very little time (≤ 0.2 m.y.) passed between emplacement of both sets of intrusions, and suggest that the center 2 gabbros may actually be the younger intrusions (Mitchell and Reen, 1973). If the layered gabbros of center 2 are also lopolithic in geometry, then the concept of migrating centers of activity may be seriously flawed. In that case, the geometry of the Ardnamurchan intrusions would be best envisaged as a vertical stack of offset funnel-shaped bodies, with the gabbros of center 2 comprising a younger body underlying those of center 3.

The historical importance of the British Paleocene igneous complexes in laying the foundation for understanding the emplacement mechanisms of shallow crustal-level intrusions elsewhere is well documented (see Woodcock and Strachan, 2000, and Bell and Williamson, 2002, for reviews). In particular, the concept of ring-dike intrusion and central subsidence of caldera volcanoes has been applied to subvolcanic geological problems worldwide for decades (Anderson, 1936; Wager and Brown, 1968; Roche et al., 2000), as it provides critical information regarding the way magma system emplacement and evolution occurs, in particular the physical and chemical interaction between the subsiding central block and the underlying magma chamber. However, even though ring-dikes are emplaced at shallow (2–3 km) crustal levels (Saunders, 2004), good examples are rarely well exposed, because they tend to be obscured by sedimentary volcanic caldera infill and other intrusive bodies with different emplacement mechanisms and three-dimensional geometries, e.g., cone sheets, laccoliths, and lopoliths.

We have carried out the first magnetic fabric and structural study of one of the classic British Paleocene igneous province ring-dikes, and propose instead that it has the geometry of a lopolith or funnel-shape intrusion. This raises the prospect that the layered, mafic-ultramafic “ring-dikes” of the other Paleocene igneous complexes, such as Carlingford (NE Ireland) and the Isles of Mull and Skye (Scotland), are lopoliths as well. The implication for British Paleocene igneous complexes is that a reappraisal of the mechanisms of emplacement and structural architecture of their intrusive elements, employing modern methods of igneous fabric analysis together with other advanced geophysical techniques e.g., three-dimensional seismic modeling (cf. Møller-Sørensen et al., 2004), is now required. To be identified as ring-dikes, in the British Paleocene igneous province and elsewhere, intrusions must be shown to have intruded along a vertical to outward-dipping concentric ring-fracture and to have been accompanied by block subsidence related to caldera collapse.

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REFERENCES CITED

Anderson, E.M., 1936, The dynamics of the formation of cone-sheets, ring-dikes, and cauldron-subsidence: *Proceedings of the Royal Society of Edinburgh*, v. 56, p. 128–156.

- Balsley, J.R., and Buddington, A.F., 1958, Iron-titanium oxide minerals, rocks and aeromagnetic anomalies of the Adirondack area, New York: *Economic Geology and the Society of Economic Geologists Bulletin*, v. 53, p. 777–805.
- Bell, B.R., and Williamson, I.T., 2002, Tertiary igneous activity, in Trewin, N.H., ed., *The geology of Scotland* (4th edition): London, Geological Society of London, p. 371–408.
- Bouchez, J.L., 1997, Granite is never isotropic: An introduction to AMS studies of granitic rocks, in Bouchez, J.L., Hutton, D.H.W., and Stephens, W.E., eds., *Granite: From segregation of melt to emplacement fabrics*: Dordrecht, Kluwer Academic Publishers, p. 95–112.
- Carr, H.W., Groves, D.I., and Cawthorn, R.G., 1994, The importance of syn-magmatic deformation in the formation of Merensky Reef potholes in the Bushveld complex: *Economic Geology and the Society of Economic Geologists Bulletin*, v. 89, p. 1398–1410.
- Chambers, L.M., Pringle, M.S., and Parrish, R.R., 2005, Rapid formation of the Small Isles Tertiary centre constrained by precise $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb ages: *Lithos*, v. 79, p. 367–384.
- Cowan, E.J., 1999, Magnetic fabric constraints on the initial geometry of the Sudbury igneous complex: A folded sheet or basin shaped igneous body?: *Tectonophysics*, v. 307, p. 135–162.
- Cruden, A.R., 1998, On the emplacement of tabular granites: *Geological Society of London Journal*, v. 155, p. 853–862.
- Dunlop, D.J., and Özdemir, O., 1997, *Rock magnetism, fundamentals and frontiers*: Cambridge, Cambridge University Press, 573 p.
- Emeleus, C.H., Cheadle, M.J., Hunter, R.H., Upton, B.G.J., and Wadsworth, W.J., 1996, The Rum Layered Suite, in Cawthorn, R.G., ed., *Layered igneous rocks*: Amsterdam, Elsevier, p. 403–440.
- Hargraves, R.B., Johnson, D., and Chan, C.Y., 1991, Distribution anisotropy: The cause of AMS in igneous rocks?: *Geophysical Research Letters*, v. 18, p. 2193–2196.
- Launeau, P., and Cruden, A.R., 1998, Magmatic fabric acquisition mechanisms in a syenite: Results of a combined anisotropy of magnetic susceptibility and image analysis study: *Journal of Geophysical Research*, v. 103, p. 5067–5089.
- Møller-Sørensen, A., Planke, S., Svensen, H., and Jamveit, B., 2004, Formation of saucer-shaped sills, in Breiterkreuz, C., and Petford, N., eds., *Physical geology of high-level magmatic systems*: Geological Society [London] Special Publication 234, p. 215–227.
- McBirney, A.R., and Nicolas, A., 1997, The Skaergaard layered series: Part III. Dynamic layering: *Journal of Petrology*, v. 38, p. 569–580.
- Mitchell, J.G., and Reen, K.P., 1973, Potassium-argon ages from the Tertiary ring complexes of the Ardnamurchan Peninsula, western Scotland: *Geological Magazine*, v. 110, no. 4, p. 331–340.
- Owens, W.H., 1974, Mathematical model studies on factors affecting magnetic anisotropy of deformed rocks: *Tectonophysics*, v. 24, p. 115–131.
- Owens, W.H., 2000, Statistical applications to second-rank tensors in magnetic fabric analysis: *Geophysical Journal International*, v. 142, p. 115–131.
- Richey, J.E., and Thomas, H.H., 1930, *The geology of Ardnamurchan, north-west Mull and Coll: Memoir of the Geological Survey [Scotland]*, HMSO, 393 p.
- Roche, O., Druitt, T.H., and Merle, O., 2000, Experimental study of caldera formation: *Journal of Geophysical Research*, v. 105, p. 395–416.
- Rochette, P., Aubourg, C., and Perrin, M., 1999, Is this magnetic fabric normal? A review and case studies in volcanic formations: *Tectonophysics*, v. 307, p. 219–234.
- Saunders, S.J., 2004, The possible contribution of circumferential fault intrusion to caldera resurgence: *Bulletin of Volcanology*, v. 67, p. 57–71.
- Tarling, D.H., and Hrouda, F., 1993, *The magnetic anisotropy of rocks*: London, Chapman and Hall, 217 p.
- Wager, L.R., and Brown, G.M., 1968, *Layered igneous rocks*: Edinburgh, Oliver and Boyd, 588 p.
- Walter, T.R., and Troll, V.R., 2001, Formation of caldera periphery faults: An experimental study: *Bulletin of Volcanology*, v. 63, p. 191–203.
- Wiebe, R.A., and Collins, W.J., 1998, Depositional features and stratigraphic sections in granite plutons: Implications for the emplacement and crystallization of granite magma: *Journal of Structural Geology*, v. 20, p. 1273–1289.
- Woodcock, N., and Strachan, R., 2000, *Geological history of Britain and Ireland*: Cambridge, Blackwell Science, 423 p.

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Magmatic lineations inferred from anisotropy of magnetic susceptibility fabrics in Units 8, 9, and 10 of the Rum Eastern Layered Series, Scotland

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Abstract

The Eastern Layered Series of the Rum Layered Suite, NW Scotland, comprises a sequence of sixteen (30-150m thick) cyclic units, each comprising a peridotite base and a troctolite top. The upper troctolite parts of each of these units exhibit small-scale magmatic layering, as well as a pervasive, layer-parallel igneous lamination. Magmatic layering and igneous lamination in troctolite are frequently associated with 'sedimentary' structures, and a sporadic, macroscopic, magmatic lineation, that is occasionally measurable on igneous lamination planes. Three of these units, (8, 9, and 10) were studied for Anisotropy of Magnetic Susceptibility (AMS) fabrics in the north of the Eastern Layered Series, on the basis of comparatively good exposure and Unit 10 being the type unit of the Eastern Layered Series. Magnetic fabrics measured for the troctolites of each Unit generally yield consistent layer-parallel, NW-SE striking, SW-dipping magnetic foliations and NW-SE trending, shallowly plunging, bimodal magnetic lineations. Magnetic fabrics measured for two detailed traverses through Unit 10 on the northern side of Hallival yield one dominant trend, similar to that described above for other magnetic foliations and lineations measured throughout the Eastern Layered Series. A second minor trend is observed toward the centre of Unit 10 in each traverse, in which the magnetic lineation trends approximately downdip (SW) on magmatic layer planes. The implications of these results are discussed with reference to previous textural and rock fabric observations on Rum, and a model in which cumulus olivine and plagioclase crystals are oriented transverse to current flow during central sagging of the Rum mafic intrusion is proposed.

An Origin for Harrisitic and Granular Olivine in the Rum Layered Suite, NW Scotland: A Crystal Size Distribution Study

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Dendritic crystal morphologies occur in a number of igneous rocks and are thought to originate from the rapid growth of crystals, yet many examples of dendritic morphologies are found in plutonic igneous rocks where cooling rates should be low. Results from crystal size distribution (CSD) measurements on harrisitic olivines from Rum, Scotland, combined with estimated olivine growth rates, suggest that the characteristic skeletal hopper and branching olivines of harrisitic cumulates that are up to centimetres long, may have exceptionally short crystal growth times (several hours to several hundreds of days). This, together with very low calculated nucleation densities for harrisitic olivine, supports the interpretation of harrisite being a disequilibrium texture, developed in response to supersaturation of the magma in olivine. We propose that this supersaturation arose through undercooling of thin picrite sheets emplaced along the Rum magma chamber floor, beneath cooler resident magma. It is envisaged that the picrite sheets were largely free of suspended olivine crystals. Coupled with the olivine-enriched composition of the melt and the increasing cooling rate, this allowed homogenous nucleation of olivine to set in at deeper undercooling and greater olivine supersaturation than if there had been plentiful suspended olivines to act as heterogeneous nuclei. The enhanced supersaturation caused rapid growth of olivine once nucleation began, with skeletal and dendritic shapes. It is suggested that the observed, interlayered sequences of harrisite and cumulus peridotite found throughout the Rum Layered Suite are a result of multiple episodes of harrisite crystallisation resulting from picrite emplacement that alternated with periods of crystal growth and accumulation in the main body of magma at lesser degrees of undercooling.

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MAGMATIC LAYERING AND MAGNETIC FABRICS IN THE PALAEOGENE CARLINGFORD LATER GABBROS, CO. LOUTH, IRELAND

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Abstract

A detailed magnetic fabric study of the annular partially-layered Palaeogene Carlingford 'Later Gabbros', Co. Louth, is combined with field observations to constrain existing emplacement models for the intrusion. The Anisotropy of Magnetic Susceptibility (AMS) fabrics are generally quite inconsistently oriented. Only in three of seven traverses of the intrusion is consistency in orientation observed, suggesting that little can be drawn from the data by way of interpretation. However, the traverse in the north of the intrusion, at Ballintreskin, corresponds to an area of considerable syn-magmatic deformation of layering. Magnetic fabrics in this area exhibit consistently oriented inward dipping and inward plunging magnetic foliations and lineations respectively. Comparison of this data with a recent AMS study of the Great Eucrite of Ardnamurchan, NW Scotland, suggests that though central subsidence may have occurred in the Later Gabbros too, it was neither as important nor as extensive as in Ardnamurchan. This is supported to some degree by the presence of a shallowly-dipping ($\sim 20^\circ$) intrusive contact between the Later Gabbros and an extensive granophyre intrusion, which also suggests that the latter is the older intrusion. This conclusion is inconsistent with previous interpretations of the granophyre as the youngest intrusion in the Carlingford igneous centre.

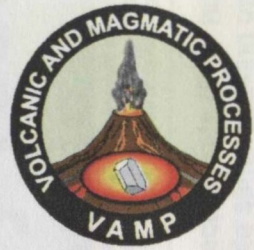
The Great Eucrite intrusion of Ardnamurchan, NW Scotland: re-evaluation of the ring-dyke concept

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1. Ring-dykes

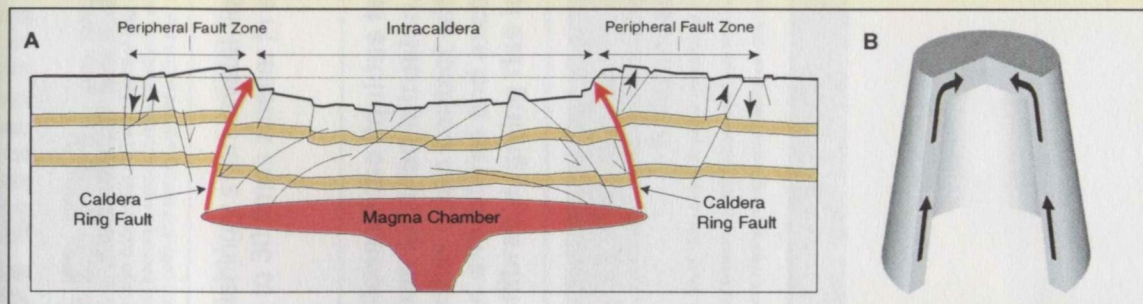


Figure 1. A. Schematic diagram illustrating caldera ring-fault development and associated subsidence of a central block causing ring-dyke intrusion. (modified from Holohan et al. 2004), and B. The typical bell-jar like geometry of a ring-dyke forming a broadly cylindrical intrusion with steeply outward-dipping walls on all sides and a flat sill-like roof.

2. Ardnamurchan: Geological Setting

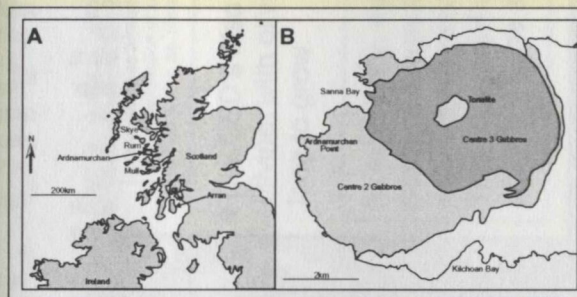


Figure 2. A. Location of the Ardnamurchan central intrusive complex. B. NW Ardnamurchan: the Gabbros of Centres 2 & 3.

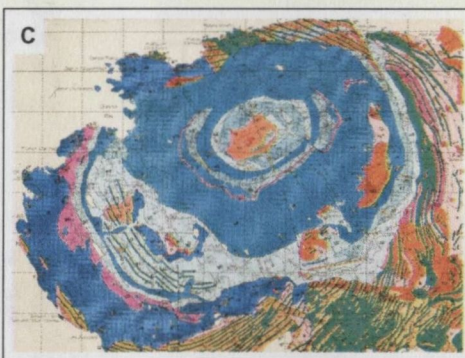


Figure 2. C. Map of Ardnamurchan peninsula and the Great Eucrite (blue-coloured central mass (UE), after Richey et al. 1930). D. Aerial photograph illustrating the annular topographic expression of the Great Eucrite.

- The central intrusive complexes of the **British Palaeogene Igneous Province (BPIP)** (Fig. 2A) represent the deeply-dissected roots of major volcanoes in a region that was the site of intense igneous activity during the Palaeocene and early Eocene (c.a. 63-52Ma, Bell & Williamson 2002).
- The intrusive complex of Ardnamurchan consists of three distinct volcanic centres (Fig. 2B), each of which mainly comprise mafic rocks. They consist predominantly of suites of rocks emplaced mainly as cone-sheets, but also larger intrusive bodies that have traditionally been interpreted as **ring-dykes** (Richey et al. 1930).
- The third and youngest of these centres is dominated by a major, concentric gabbro intrusion called the **Great Eucrite** (Fig. 2C), frequently referred to as the **classic example of a wholly complete basic ring-dyke**.



3. Lithological Relationships



Figure 3. A. Block/xenolith of Olivine Glomerocrystic Gabbro in Inner Gabbro (see Fig. 8). Pen in the middle of photo gives scale. B. Arcuate raised ridge area in the middle of Centre 3 defines the concentric area of outcrop of the Glendrian Laminated Gabbro.

- Detailed re-mapping of Centre 3 suggests that the Great Eucrite comprises **4 distinct generations of gabbro**, all of which are traceable around most of the circumference of the intrusion (Fig. 3A & Fig. 7C).
- A fifth, plagioclase-rich, well-laminated gabbro crops out in **3 arcuate zones towards the middle of Centre 3**; at Achnaha, Sithean Mor, and around Glendrian (Fig. 3B & Fig. 7C).
- Contact data from the outer margin of the intrusion is rare, but one boundary with Jurassic sediments in the north of the peninsula is observed **dipping moderately inward at ~50°** (Fig. 7C).
- Two late bodies intrude the Centre 3 Gabbros. One of these is an intermediate tonalite body that displays a steeply outward dipping contact and chilled margin towards the gabbros. The other is an **inward-dipping sheet-like dolerite** intrusion frequently net-veined with granophyre (Fig. 7C).

4. Magmatic Layering



- Magmatic layering in the gabbros of the Great Eucrite typically exhibits structures that indicate it developed due to **magmatic sedimentation** (Fig. 4A & 4B).
- Layering in both the Inner Gabbro and the Outer Layered Gabbro typically **strikes parallel to the outer margins of the Great Eucrite, and dips inwards** (Fig. 8).
- Strong igneous laminations developed in the plagioclase-rich rocks towards the middle of Centre 3 are oriented similarly, and **dip inward without exception** (Fig. 4C, 7A & 7B).

Figure 4. A. Well-developed magmatic layering in the Inner Gabbro. B. Magmatic sediments deposited onto a block of earlier crystallized gabbro. C. Strong lamination of tabular plagioclase feldspars in the Achnaha laminated Gabbro. D. Small-scale layering developed in the Inner Gabbro at the outer margin of the Achnaha Laminated Gabbro.

5. Anisotropy of Magnetic Susceptibility (AMS) analysis

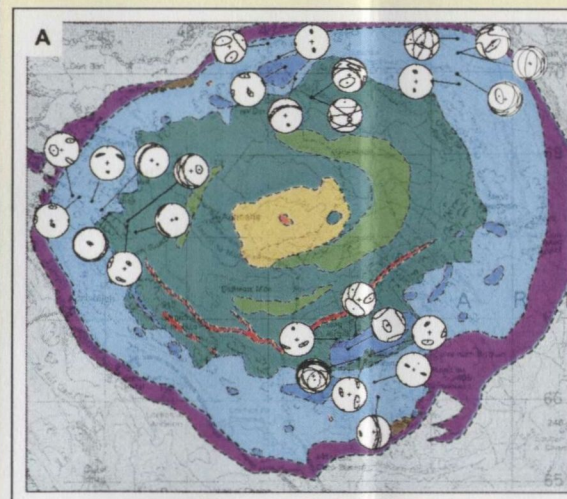
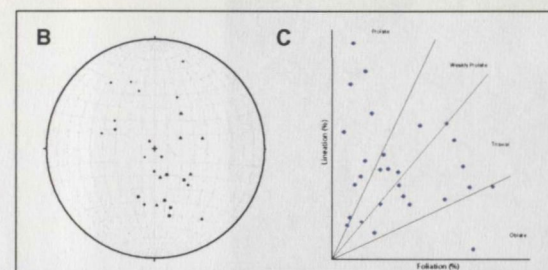
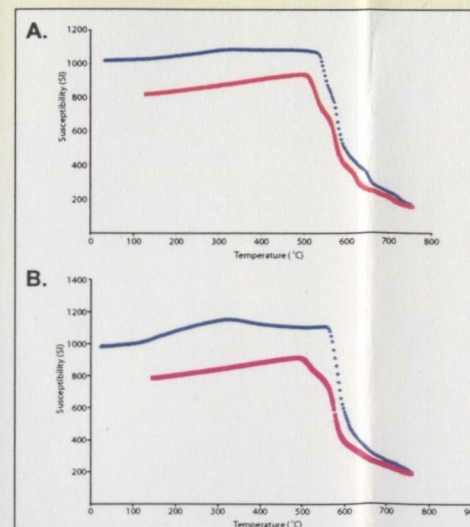


Figure 5. A. AMS fabric data plotted on equal area stereonet. Squares represent the AMS ellipsoid major axis (magnetic lineation), triangles the intermediate axis, and circles the minor axis (or poles to the magnetic foliation plane). B. Equal-area stereonet highlighting magnetic lineations plunging toward the middle of Centre 3. Small circles, triangles, squares and diamonds represent the southern, western, northern, and north-eastern traverses respectively. C. L-F illustrating the largely prolate-triaxial nature of AMS fabrics of the Great Eucrite.

- Anisotropy of Magnetic Susceptibility (AMS) analysis allows the three-dimensional anisotropic distribution of magnetic minerals in a rock to be established, and may be used as reliable **magma flow indicators** to a high degree of accuracy.
- Mafic magma will generally acquire a magnetic fabric (anisotropy) with the maximum axis (lineation) oriented **parallel to the direction of magma flow**.
- AMS data for the gabbros of the Great Eucrite are remarkably consistent. Anisotropies are generally of **moderate strength**, and **magnetic lineations typically plunge toward the centre of the intrusion** (Fig. 5A, 5B, & 5C).

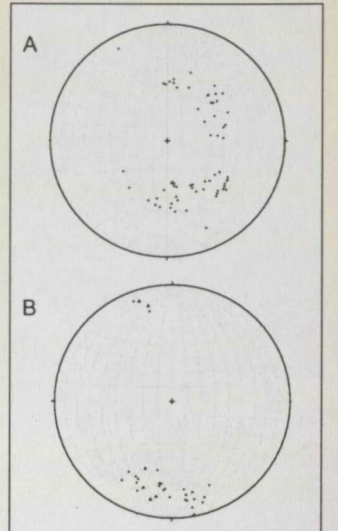
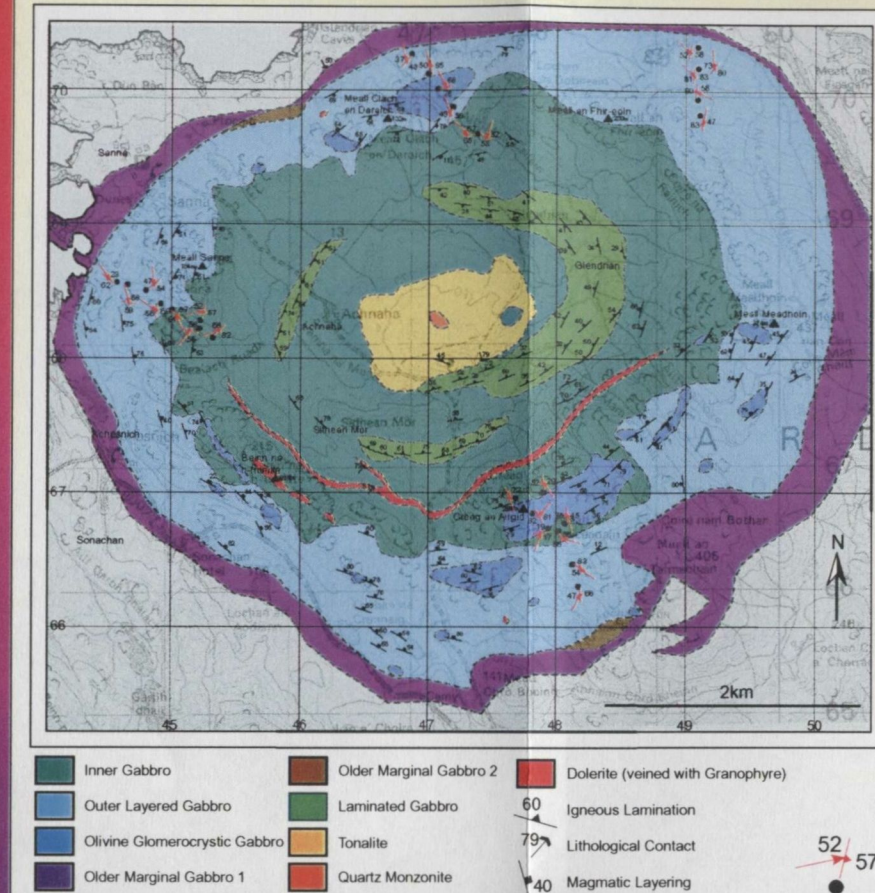


6. Thermomagnetic analysis



- The AMS of any rock is carried by minerals that may vary in the strength of their susceptibilities. **Thermomagnetic analysis** was carried out on samples of the Great Eucrite in order to quantitatively establish which **magnetic minerals** define the prolate-triaxial anisotropy observed.
- Sufficient thermal energy eventually overcomes the magnetization of any magnet, which will tend to zero at a particular temperature called the **Curie temperature (T_c)**.
- The Curie temperature is thus an intrinsic property of any given mineral, and may be used as a diagnostic parameter for identification purposes.
- The gabbros of the Great Eucrite exhibit very strong susceptibilities, as illustrated by two examples (Fig. 6A & B) on the left, and as would be expected for mafic rocks. In each case, **T_c is ~575-580°C**, indicating that **magnetite, whose Curie temperature falls in this range, is responsible for the AMS in these rocks**.

7. Structure of the Great Eucrite



Above: Figure 7. Equal-area stereonet projections for poles to macroscopic lamination planes in: A. The Glendrian and B. The Sithean Mor Laminated Gabbros. Left: Figure 7. C. Geological map of the Ardnamurchan Centre 3 gabbros showing AMS sampled sites, AMS and macroscopic data, lithological divisions, and contact data (see key below).

8. Discussion & Conclusions

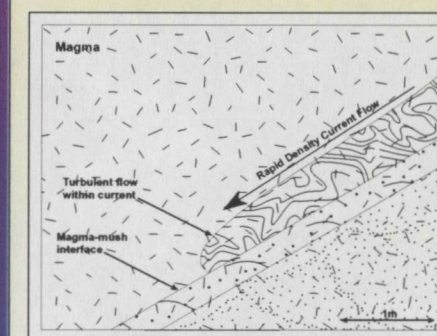
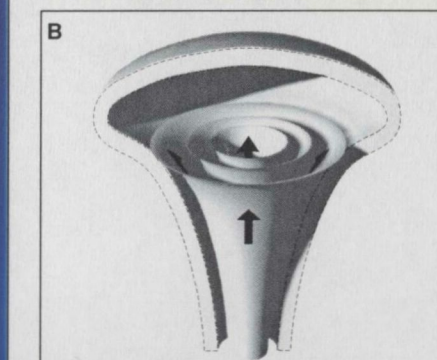


Figure 8. A. Schematic diagram showing the development of magmatic layering due to density current action.

- It is hardly conceivable that an intrusion with the steeply outward-dipping contacts of a ring-dyke (Fig. 1B) could produce anything but magma flow indicators that plunged outward and away from the intrusion centre. Linear magnetic fabrics thus indicate that initial emplacement of magma occurred as illustrated in Fig. 8B, and that subsequent gravity driven sedimentary processes (Fig. 8A) resulted in the inward dipping layering observed throughout Centre 3.



We propose that there are no outward dipping intrusions (ring-dykes) in Centre 3, Ardnamurchan, and that the gabbros of the Great Eucrite comprise part of a composite lopolithic intrusion with an overall 'funnel-like' geometry (Fig. 8B). These conclusions bring into question the status of other layered, mafic 'ring-dykes' elsewhere in the BPIP, and further afield.

Figure 8. B. Simplified hypothetical model for the overall form of the Great Eucrite. Emplacement of magma occurred in the direction of the arrows, with the outer sheet intruded first, followed successively by each of the progressively smaller inner sheets. Magmatic layering is envisaged to have developed after magma emplacement.

References

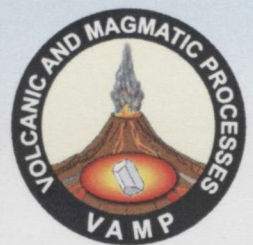
- Bell, B.R. & Williamson, I.T. (2002). Tertiary Igneous Activity. In: Trewhin, N.H. (ed.), *The Geology of Scotland*. Geological Society, London, Chptr. 14. 371-408.
- Holohan E.P., Troll V.R., Walker T.R., Munn S., McDonnell S. and Shipton Z. (2004). Influence of regional tectonics on collapse calderas: an experimental approach. *Journal of Volcanology and Geothermal Research*. Invited paper towards 'Tectonics and Physics of Volcanoes' Special Issue, Eds. A. Gudmundsson and V. Accorcia. (in press).
- Richey, J.E. & Thomas, H.H. (1930). *The Geology of Ardnamurchan, North-west Mull, and Coll. Memoir Geol. Surv. Scotland*, HMSO.

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A textural study of harrisitic olivine: preliminary results from Crystal Size Distribution (CSD) analysis

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1. The Rum Harrisite

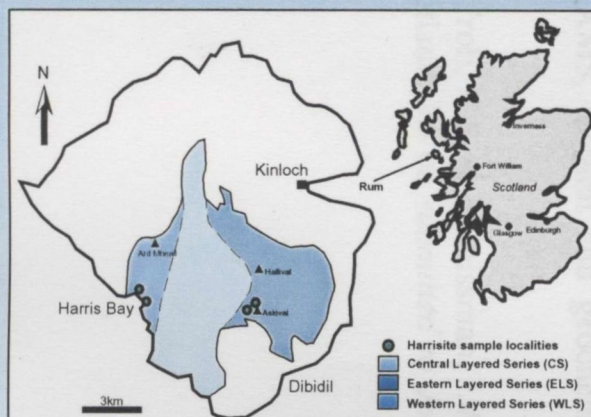


Fig. 1a. Map of the Rum Layered Intrusion illustrating the harrisite sampling localities at Harris Bay and Askival. The former is the type locality for harrisite.



Fig. 1b. Olivine 'dendrites' and 'spinifex' texture in harrisite, Harris Bay.

- Harrisite is an ultrabasic, plutonic rock that occurs interlayered with feldspathic peridotite in the **Rum Layered Intrusion**, NW Scotland (Fig. 1a).
- It typically contains **>25% olivine crystals**, many of which are characterised by **skeletal** (e.g. poikilitic, dendritic, spinifex) crystal forms (Fig. 1b).
- Harrisitic olivines typically grow at **steep angles** to planes of magmatic layering, and may grow **up to 2m in length** (Fig. 1c).
- Harrisitic olivines are therefore generally **larger** than olivine crystals in contiguous peridotite layers.



Fig. 1c. Cross-cutting skeletal olivine crystals at Harris Bay (crystal major axes highlighted).

2. Field Observations



Fig. 2a. Small-scale alternating peridotite/harrisite layers.



Fig. 2b. Imbrication (highlighted) of fragmented harrisitic olivine crystals in feldspathic peridotite.

- Peridotite layers are often associated with **small-scale structures** (slumping, graded bedding, and scour structures) that suggest deposition of the peridotite as a **magmatic sediment**.
- However some of the thicker peridotite layers contain larger, **fragmented xenocrysts of harrisitic olivine**. These are often **imbricated**, and may occur as **linear trains of crystals** (Figs. 2b & 2c).
- Harrisite layers do **not** contain any such evidence for an active magmatic flow regime, and thus harrisitic olivine probably **crystallised in-situ** in the magma chamber, rather than being deposited.

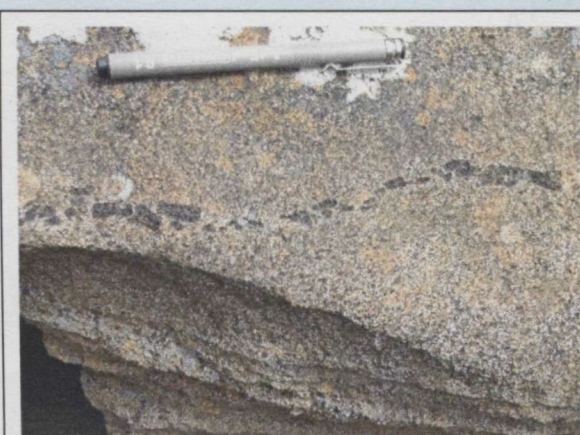


Fig. 2c. Linear train of fragmented olivine crystals in feldspathic peridotite.

3. Textural Analysis: Methodology

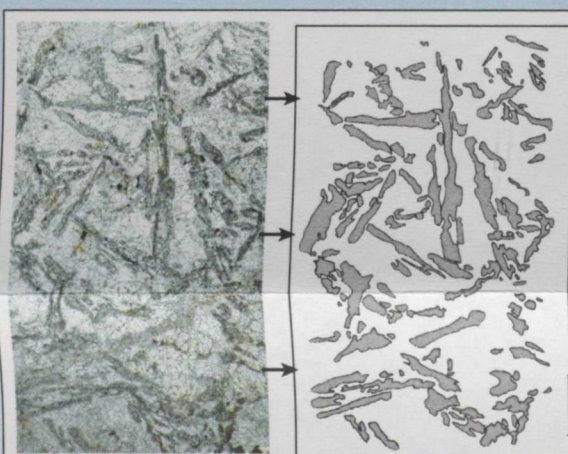
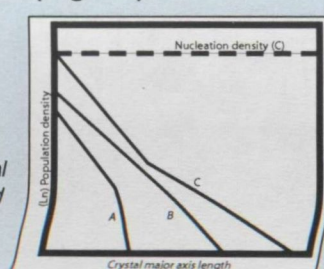


Fig. 3a. High quality scans of harrisite photomicrographs are digitised and the crystal populations analysed using commercially available NIH Image software.

- CSD analysis is a means of **quantitatively** studying the textures of igneous rocks by measuring the **distribution of different crystal populations** in the rock (Fig. 3a).
- CSD curves plot **crystal size (length)** against the **natural logarithm of the population density**. **Log linear** CSD curves suggest a non-fractionating equilibrated system, whilst **curved (kinked)** CSD's suggest fractionation or accumulation of crystals (Fig. 3b).

Fig. 3b. Hypothetical CSD curves illustrating: A. Crystal fractionation, B. Equilibrated system, C. Crystal accumulation.



Morphology	GR (cms ⁻¹)	Relative GR
Equant	1.2 x 10 ⁻⁶	1
Rounded	3.1 x 10 ⁻⁶	2.5
Irregular	3.1 x 10 ⁻⁶	2.5
Tabular	4.8 x 10 ⁻⁶	4
Harrisitic	6.4 x 10 ⁻⁶	5.3

Fig. 3c. Growth rates (GR) have been calculated for olivine crystals of a range of different morphologies using uranium diffusion (after Henderson & Williams 1979).

- The **slope** of a CSD plot may also be used to estimate magma chamber residence (**crystal-liquid contact**) times, using the equation $T_r = G/m$, where T_r is the residence time, G is the growth rate, (Fig. 3c) and m is the slope of the CSD curve.
- Samples for texture analysis were taken from the type locality for harrisite growth, (**Harris Bay, WLS**), and also **Askival, (ELS)** (Fig. 1a).

4. CSD Results

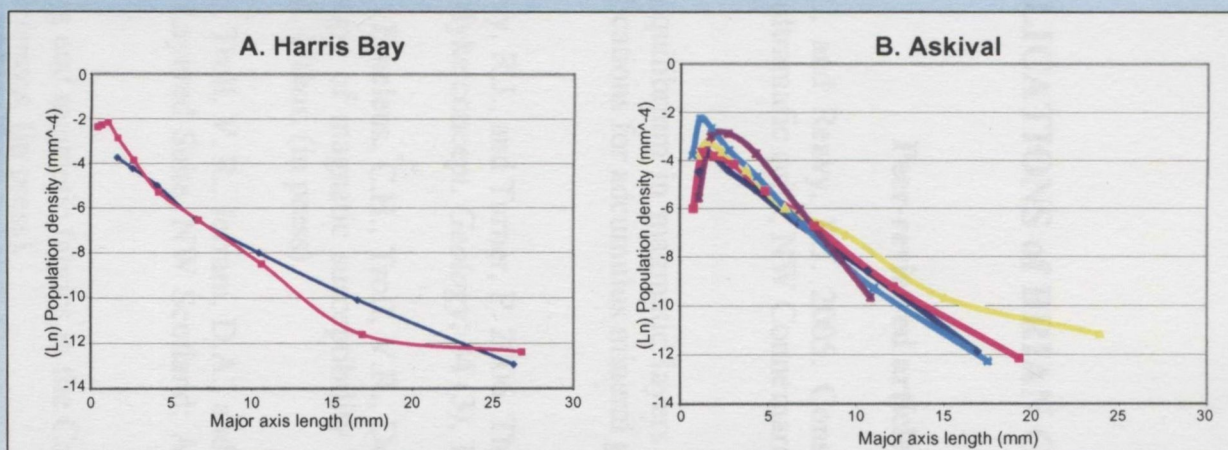


Fig. 4. CSD curves for A. Harris Bay samples, and B. Askival samples.

Olivine residence times (hours)

Harris Bay Sample 1	9.59
Harris Bay Sample 2	11.62
Askival Sample 1	17.79
Askival Sample 2	15.14
Askival Sample 3	15.94
Askival Sample 4	13.27
Askival Peridotite Sample	39.9

- **Log linear to mildly concave-up** curves are observed in both Harris Bay and Askival samples. Most of the curves also exhibit a **'humped'** profile at smaller crystal sizes (Fig. 4).
- The CSD plots yield **magma chamber residence times** as follows: harrisitic olivine crystals **3-4cm in length** have grown in **9-11 hours**, whilst smaller crystals from the ELS (Askival) have only marginally longer residence times (**13-17 hours**). Olivine crystals in a regular 'control' peridotite sample from Askival have grown in **~40 hours**.

5. Discussion and Conclusions

- The development of harrisite has previously been attributed to the **breakdown of convection cells** and subsequent **massive supersaturation** in olivine of melt in the Rum magma chamber (Donaldson 1975).
- The presence of imbricated fragments of harrisitic olivine in magmatic sediment (peridotite) confirms that harrisite **could not have developed in an active flow regime** (i.e. a convecting magma chamber).
- Harrisitic olivines exhibit **slightly concave upward to log linear CSD's curves**, indicating an environment in which **neither crystal fractionation nor accumulation** was occurring, i.e. an **open system in dynamic or 'steady-state' equilibrium**. The 'humped' profiles at small crystal sizes suggest **Ostwald ripening** and/or **annealing** may have been important processes during olivine crystallisation.
- The repeated occurrence of interlayered sequences of peridotite and harrisite, and the fact that the Rum reservoir is a well-documented example of an **open magmatic system characterised by frequent replenishments of mafic magma** (Troll *et al.* 2004), support the idea of a system in equilibrium, and help explain the geometries of the CSD's illustrated above.

Fig. 5. Development of harrisite in the Rum Intrusion

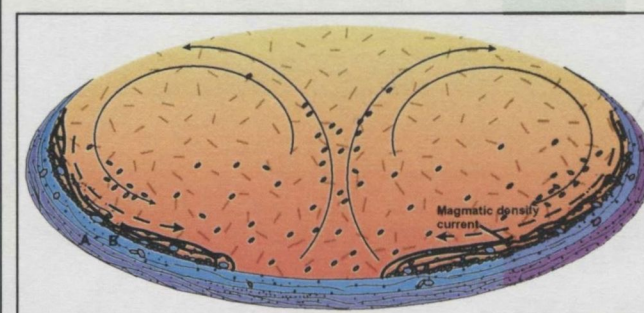


Fig. 5a. Nucleation and subsequent deposition of olivine crystals occurs through density current action on the walls and floor of a convecting magma chamber. This leads to the build-up of peridotite layers A & B through magmatic sedimentation.

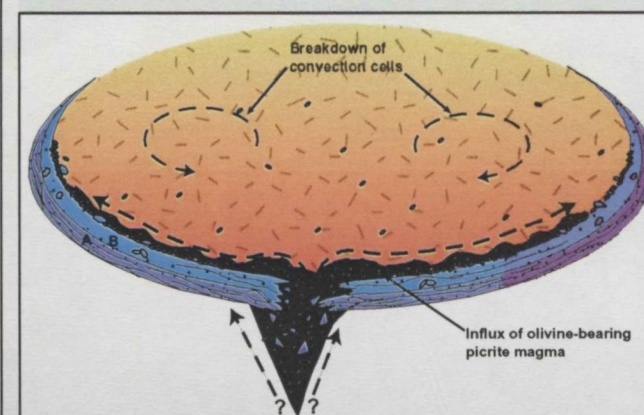


Fig. 5b. Breakdown of convection cells and replenishment of the reservoir by hot dense picritic magma. This spreads across the chamber floor onto newly deposited cumulus olivine crystal piles.



Fig. 5c. Cooling of hot picrite against the colder magma above induces the former to degas and devolatilise, causing its liquidus temperature to increase. As convection has broken down, cooling occurs through conduction into the chamber floor. 5d. The increased liquidus temperature causes undercooling, and inhibits nucleation of new olivine grains. The melt becomes supersaturated in olivine, and rapidly precipitates olivine onto already existing (deposited) cumulus olivine grains. 5e. Re-establishment of convection cells and density current action then causes erosion and fragmentation of harrisitic olivine crystals.

- The CSD's also indicate astonishingly short crystal-liquid contact periods (9-17 hours) for harrisitic olivine, with olivine crystals up to 30 times smaller in a peridotite sample taking up to 4 times as long to grow.

In summary, cyclic perturbations of the liquidus temperature of a replenishing picrite melt occurred repeatedly in the Rum Layered Intrusion. It is proposed here that this was caused by exsolution of volatiles upon contact with the cooler magma already in place. This triggered oscillatory, but short-lived and exceptionally fast, bursts of olivine crystal growth as the system re-equilibrated, giving rise to harrisitic texture.

References

1. Donaldson, C.H. (1975) A petrogenetic study of harrisite in the Isle of Rhum pluton, Scotland. Unpublished Ph.D thesis, University St. Andrews.
2. Henderson, P. & Williams, C.T. (1979). Variation in trace element partition (crystal/magma) as a function of crystal growth. In: *Origin & Distribution of the Elements*, ed. L.H. Ahrens. Pergamon, 191-196.
3. Troll V.R., Donaldson C.H. and Emmeus C.H. (2004). Pre-eruptive magma mixing in intra-caldera ash-flow deposits of the Rum Igneous Centre, Scotland. *Contributions to Mineralogy and Petrology* 147: 722-739.

PUBLICATIONS of BRIAN O'DRISCOLL

Peer-reviewed articles

O'Driscoll, B., Powell, D.G.R., and Reavy, R.J. 2005. Constraints on the development of magmatic layering in a syntectonic mafic-ultramafic suite, NW Connemara, Ireland. *Scottish Journal of Geology*, **41** (2), 119-128.

O'Driscoll, B. 2005. Textural equilibrium in magmatic layers of the syn-tectonic Lough Fee ultramafic intrusion, NW Connemara: implications for adcumulus mineral growth. *Irish Journal of Earth Sciences*, **23**, 39-45.

O'Driscoll, B., Troll, V.R., Reavy, R.J., and Turner, P. 2006. The Great Eucrite intrusion of Ardnamurchan, Scotland: re-evaluating the ring-dyke concept. *Geology*, **34** (3), 189-192.

O'Driscoll, B., Hargraves, R.B., Emeleus, C.H., Troll, V.R., Donaldson, C.H., and Reavy, R.J. Magmatic lineations inferred from anisotropy of magnetic susceptibility fabrics in Units 8, 9, and 10 of the Rum Eastern Layered Series, Scotland. *Lithos*, (in press).

O'Driscoll, B., Donaldson, C.H., Troll, V. R., Jerram, D.A., and Emeleus, C.H. An origin for harrisitic and granular olivine from the Rum Layered Suite, NW Scotland: A crystal size distribution study. *Journal of Petrology*, (in press).

O'Driscoll, B. Magmatic layering and magnetic fabrics in the Carlingford 'Later Gabbros', Co. Louth, Ireland, *Irish Journal of Earth Sciences*, (in press).

In review

* *Manuscript is available upon request*

*Stevenson, C.T.E., **O'Driscoll, B.**, Holohan, E.P., Couchman, R., and Reavy, R.J. The structure, fabrics and AMS of the Slieve Gullion ring-complex, N. Ireland: testing the ring-dyke emplacement model, *Journal of the Geological Society Special Publication*, (in review).

***O'Driscoll, B.** Country-rock blocks, peridotite xenoliths and deformed magmatic layering in the Centre 3 gabbro intrusion, Ardnamurchan, NW Scotland, *Geological Magazine*, (in review).

In preparation

O'Driscoll, B., and Chew, D.M. Petrogenesis and emplacement of the Connemara serpentinites. *To be submitted to Journal of the Geological Society in August 2006.*

O'Driscoll, B., Stevenson, C.T.E., and Troll, V.R. Mechanisms of fabric acquisition in some Tertiary layered gabbros: a combined AMS, textural and geochemical study. *To be submitted to Journal of Petrology in July 2006.*

Petronis, M.S., **O'Driscoll, B.**, Troll, V.R. and Geissman, J.W. Structure and emplacement of the Western Granite, Isle Of Rum, NW Scotland. *To be submitted to Journal of the Geological Society, London in August 2006.*

Selected abstracts and published reports

O'Driscoll, B., Powell, D.G.R., and Reavy, R.J. (2004). Magmatic Sedimentation and Fabric Development in the Dawros-Currywongaun-Doughruagh Complex, NW Connemara, Ireland. *Volcanic and Magmatic Study Group Meeting 2004 Bath, UK*. Abstract Volume.

O'Driscoll, B., and Troll, V.R. (2004). Flow Related Crystal Arrangements: Preliminary Results From Analogue Modelling. *Irish Journal of Earth Sciences*, 22.

O'Driscoll, B., Powell, D.G.R., and Reavy, R.J. (2004). Syn-tectonic intrusion of the Grampian Dawros-Currywongaun-Doughruagh Complex, NW Connemara. *Irish Journal of Earth Sciences*, 22.

Meade, F, O'Halloran, A, Troll, V.R. **O'Driscoll, B.** and Meighan, I. (2004). Flow dynamics in cone-sheet intrusions of the Carlingford Igneous Centre. *Irish Journal of Earth Sciences*, 22.

O'Driscoll, B., Troll, V.R., Reavy, R.J., Turner, P., and Owens, W.H. (2004). Tertiary rocks of the Centre 3 igneous complex, Ardnamurchan, Scotland. *Irish Research Council for Science Engineering and Technology (IRCSET) Annual Symposium*. Abstract Volume.

O'Driscoll, B. (2005). Report on a field visit to the Ardnamurchan Tertiary Igneous Centre. Mineralogical Society Bulletin: <http://www.minersoc.org/pages/announce/bursary/.html>.

O'Driscoll, B., O'Dowd, K., McCourt, E., Troll, V.R., Donaldson, C.H., Jerram, D.A., and Emeleus, C.H. (2005). Crystal Size Distribution measurements on harrisitic olivine, Isle of Rum, Scotland. *Volcanic and Magmatic Study Group Meeting 2005 Milton Keynes, UK*. Abstract Volume.

O'Driscoll, B., Troll, V.R., Reavy, R.J., and Turner, P. (2005). Emplacement of the Great Euclite intrusion of Ardnamurchan, NW Scotland. *Volcanic and Magmatic Study Group Meeting 2005 Milton Keynes, UK*. Abstract Volume.

O'Driscoll, B., Troll, V.R., Donaldson, C.H., Jerram, D.A., and Emeleus, C.H. (2005). Olivine crystal morphologies in layered rocks of Rum, Scotland. *Irish Journal of Earth Sciences*, 23.

O'Driscoll, B., Troll, V.R., Reavy, R.J., and Turner, P. (2005). The Great Euclite intrusion of Ardnamurchan, NW Scotland: re-evaluation of the ring-dyke concept. *European Geosciences Union (EGU) annual meeting*. Abstract Volume.

O'Driscoll, B. Report on a VMSG sponsored trip to EGU (Vienna) to present results of fieldwork carried out in Ardnamurchan in 2004 (<http://www.dur.ac.uk/d.a.jerram/VMSG/reports2005.html>).

Stevenson, C., Couchman, R., **O'Driscoll, B.**, and Thomson, K. (2006). Anisotropy of Magnetic Susceptibility of the Slieve Gullion Ring-Dyke, Co. Down: Preliminary results. *Volcanic and Magmatic Study Group Meeting Leeds, UK*. Abstract Volume.

Leacy, L., **O'Driscoll, B.**, Troll V., and Sumner, J. (2006). Rheomorphic flow in welded ignimbrites: analogue experiments and field observations from Gran Canaria. *Volcanic and Magmatic Study Group Meeting Leeds, UK*. Abstract Volume.

O'Driscoll, B., Reavy, R.J., Stevenson, C.T.E., and Troll, V.R. (2006). Magnetic fabrics and igneous laminations in Tertiary layered gabbros, NW Scotland. *Irish Geological Research Meeting Cork, Ireland*.

Couchman, R., Stevenson, C.T.E., Holohan, E.P., and **O'Driscoll, B.** (2006). Emplacement of the quartz feldspar porphyry (felsite) in the Slieve Gullion complex, Co. Armagh. *Irish Geological Research Meeting Cork, Ireland*.

Stevenson, C.T.E., Couchman, R., **O'Driscoll, B.** and Holohan, E.P. (2006). Emplacement and evolution of the Slieve Gullion ring-dyke, Co. Armagh: new insights from AMS. *Irish Geological Research Meeting Cork, Ireland.*

Leacy, L., **O'Driscoll, B.**, Troll V., and Sumner, J. (2006). Structural and experimental analysis of rheomorphic flow in the highly-welded Ignimbrite B, Gran Canaria. *Irish Geological Research Meeting Cork, Ireland.*

O'Driscoll, B., Reavy, R.J., Stevenson, C.T.E., and Troll, V.R. (2006). Mechanisms of fabric acquisition in layered gabbros: insights from anisotropy of magnetic susceptibility analysis. LASI II (Physical Geology of Sub-volcanic Systems) meeting on the Isle of Skye, Scotland. *Visual Geosciences (in press).*

Stevenson, C.T.E., Couchman, R., **O'Driscoll, B.** (2006). Anisotropy of Magnetic Susceptibility of the Slieve Gullion ring-dyke, Co. Armagh. LASI II (Physical Geology of Sub-volcanic Systems) meeting on the Isle of Skye, Scotland. *Visual Geosciences (in press).*

Petronis, M.S., **O'Driscoll, B.**, Troll, V.R. and Geissman, J.W. (2006). Anisotropy of magnetic susceptibility and paleomagnetic data bearing on magma ascent and emplacement of the Western Granite, Isle Of Rum, NW Scotland. *European Geosciences Union (EGU) annual meeting. Abstract Volume.*

Appendix C

CURRICULUM VITAE of BRIAN O'DRISCOLL

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1999-2003: University College Cork, Ireland

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1992-1999: Clifden Community School, Clifden, Co. Galway, Ireland.

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