Caledonian magmatism and major tectonic structures in the SW highlands of Scotland: implications for ascent, siting and emplacement

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Jacques, John Mark (1995) Caledonian magmatism and major tectonic structures in the SW highlands of Scotland: implications for ascent, siting and emplacement. Doctoral thesis, Durham University.

CALEDONIAN MAGMATISM AND MAJOR TECTONIC STRUCTURES IN THE SW HIGHLANDS OF SCOTLAND: IMPLICATIONS FOR ASCENT, SITING AND EMPLACEMENT.

John Mark Jacques

PH.D. Thesis

VOLUME 1

A thesis submitted in partial fulfillment of the degree of Doctor of Philosophy at the Department of Geological Sciences, University of Durham.

1995

Declaration

No part of this thesis has been previously submitted for a degree at this university or any other university. The work described in this thesis is entirely that of the author, except where reference is made to previously published or unpublished work.

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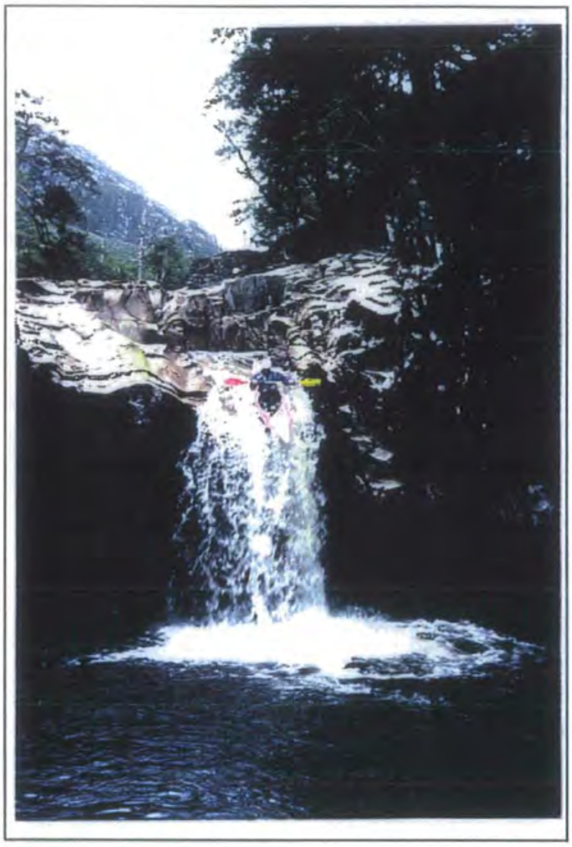

Day off in Glen Etive -- one way to reach those remote outcrops!

Abstract

This thesis describes the emplacement characteristics of four Caledonian plutons, Etive, Glencoe, Rannoch Moor and Strath Ossian, within the SW highlands of Scotland. A brief study of a further two plutons, Ben Nevis and Ballachulish, was carried out to establish whether their emplacement dynamics would provide any additional information on the regional tectonic processes operating at the time of Caledonian plutonism (425-400 ma).

The trans-Caledonoid, linear shaped, Strath Ossian pluton was constructed by a process of multiple sheeting along a major mid-crustal shear zone, within a transtensional segment of a NW-SE-trending lineament. However, the Etive, Glencoe, Rannoch Moor, Ben Nevis and Ballachulish complexes, which have more elliptical forms, have been constructed by a process of *in situ* expansion within an overall sinistral transpressional system; allowing magma to expand predomiantly into the direction of maximum extension imposed by the controlling tectonic structures. A distinct episode of regional sinistral transtension may explain the emplacement of the Etive Dyke Swarm and the high level emplacement phenomenon, the Glencoe Fault Intrusion. Space creation for pluton emplacement at mid-crustal levels has been predominantly achieved by ductile movements along regional shear zones and bulk wall rock shortening by ductile flow. At high crustal levels, brittle translatory mechanisms, such as peripheral ring fault development and subsequent uplift, may provide a major component for space creation.

This study has led to the identification of several major Caledonian NE-SW-trending shear zones and faults, which are distinct from an intersecting set of NW-SE-trending pre-Caledonian crustal lineaments which were reactivated during Caledonian orogenesis. The major intrusive phases of the above plutons, are all sited at shear zone or lineament intersections, where transtensional zones allowed and facilitated their ascent. Based on this new mapping and compilation of existing data, models are presented which may not only show that such lineaments actively controlled the siting of Caledonian magmatism in the NE and Northern Highlands, but also in the development of "gross orogenic flow patterns" and associated structures.

In northern Scotland it may be possible to sub-divide the underlying basement into several 'distinct tectonic domains', characterised by the orientation of geologically-defined lineaments within the cover. A major deep crustal lineament, the "Ossian-Loch Quoich Line", may have controlled the northern limit of NW-directed underthrusting of a tectonically distinct basement unit (characterised by an E-W 'tectonic fabric') beneath the Dalradian and part of the southern Moine cover sequence.

Acknowledgments

First and foremost, I would like to thank my supervisors and friends Dr. Donny Hutton and Dr. R. J. Reavy. My thanks go to Donny for introducing me to the "wonderful world of granites", along with a project title and a "laissez faire" attitude which has given me freedom to follow new pathways, without being restricted by conventional ideas and thoughts. I have benefited greatly from his enthusiasm and experience and numerous discussions are also appreciated. Equal thanks go to John, without whom my initial paper would never have been written, and in particular for his field support. As with Donny, his enthusiasm for the subject has been inspirational.

Words cannot express how grateful I am to Lindsay Campbell, who despite having to work full-time to keep us both financially "afloat", gave up all her spare time for the ominous task of typing up this thesis, and for putting up with more geology on a long-term basis. Helping to present the strain data I would like to thank Pamela Jackson.

On the field work scene, I would like to thank Robyn Hancock for helping with collecting data, and the warm welcome I have always received from Doreen and her family in Blair Atholl, always at short notice during the middle of the winter.

Back in Durham: Wayne, Alun, Adam, Jonny, Jo (and her computer), Simon, Michelle, Roberto, Alwyn, Kate, John, Sarah, Ziad, and the oldies: Thuggy (Ian Alsop), Mike, Gary, Andy, Dunstan, Tim, Chris, Zoe, Sue, Charlotte, Simon, and away from the department, Lucy, Adrian, Danny and Angela; thank you all for making the years fly by.

I would particularly like to thank Dr. H.A. Armstrong, Dr. G. Larwood and, in particular, Dr. Bob Holdsworth for taking an interest. Professor W.S. Pitcher and Dr. S.G. Perkins are also thanked for extremely useful discussions.

Thanks to all the technical staff and secretarial staff, especially Alan Carr, Dave Asbery, Carole Blair, Karen Atkinson, Dave Schofield, Gerry Dresser, Ron Hardy, Julie Southern and Ron Lambert.

Finally, my apologies to anyone who lent a hand in any way, however small, to the completion of this thesis, and whose name I have omitted from the above acknowledgements. A big thankyou to you all. As you may appreciate the list could be as long as the thesis itself!

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CHAPTER 1

INTRODUCTION: GRANITE PETROGENESIS, ASCENT, EMPLACEMENT AND DEFORMATION

1.1 THE ORIGINAL AIMS OF THIS STUDY AND THEIR SUBSEQUENT EVOLUTION

The original purpose of this study was to obtain field data for the Rannoch Moor and Strath Ossian plutons, in the SW Highlands of Scotland, in order to establish the predominant mechanisms that operated during their construction. Both complexes had received little attention structurally, and the petrographical distribution of their intrusive phases was not well constrained. The Strath Ossian pluton is a linear shaped body (approximately 30 km x 6 km), markedly transverse to the regional Caledonian strike, with its long axis trending NW-SE. This is in contrast to the adjacent Rannoch Moor complex, and several other nearby plutons (Etive, Glencoe, Ballachulish and Ben Nevis), which possess more elliptical forms, with the long axes of the Rannoch Moor and Etive complexes orientated NE-SW parallel to the regional Caledonian trend. It was therefore intended that a detailed study of the Strath Ossian and Rannoch Moor complexes, would involve the mapping of: (i) the distribution of their internal intrusive phases; (ii) deformation, fabric type, distribution and intensity; (iii) strain type, magnitude and distribution; (iv) local emplacement phenomena; and (v) synplutonic deformation in the surrounding country rocks. It was hoped that this would provide the information necessary to develop a model of the processes operating during the construction of these plutons, and particularly such an approach, possibly explaining the differences in their overall geometrical form and the orientation of their long axes.

Deformational features within the western part (Kingshouse region) of the Rannoch Moor body, determined from detailed field and microscope analysis, presented a problem as they could not be adequately explained by processes related to the construction of the complex. This raised the possibility that many of these features were caused by the emplacement of the adjacent Glencoe complex which demonstrably had removed part of the Rannoch Moor body. Therefore, the Glencoe plutonic complex, and associated higher level emplacement phenomena such as the Glencoe Fault Intrusion (which takes the form of a partial ring-dyke) were mapped to see if strains related to their emplacement were responsible for the deformation within the Kingshouse region of the Rannoch Moor body. Fabric and strain analysis within the Glencoe plutonic complex suggested that it had also undergone a significant amount of modification, possibly by strains imposed by the adjacent Etive complex, also constructed simultaneously. This, together with the discovery of several major Caledonian NE-SW-trending shear zones that were active during the emplacement of the Strath Ossian, Rannoch Moor and Glencoe complexes, and which appear to be spatially associated with the Etive complex, led to the study of the emplacement features of the Etive intrusion. A significant amount of time was spent mapping the internal deformational characteristics of this body in order to develop an emplacement model, which might also provide additional information on the way the other elliptical plutons (e.g. Glencoe and Rannoch Moor) were constructed within this region. Although this is a large (approximately 300 km^2) and very well exposed pluton, a considerable amount of time was spent mapping its internal deformation features. This was justified because of the information it could provide and ideas about the other plutons in the area whose own data bases were significantly reduced or complicated by the facts that: (i) the western part of the Rannoch Moor complex has been removed by the emplacement of the Glencoe complex, leading to 'primary' emplacement features being overprinted or completely obliterated by this event; and (ii) only part of the Glencoe plutonic phase is exposed through an "erosional window", with the rest presumably occurring directly beneath the Glencoe Cauldron block and associated ring intrusion. Etive in contrast is "whole", extremely well exposed, unaffected by strains related to the emplacement of other plutons, and has benefited from considerable earlier petrological and geochemical investigations.

In this way the thesis developed into the study of a group of related plutons, and ultimately to a comparison of their differing emplacement styles and an assessment of the likely processes responsible. This was augmented at a later stage by the study of the adjacent Ballachulish and Ben Nevis complexes.

1.2 THE CONCEPT OF GRANITE EMPLACEMENT

For two centuries now, since the Scottish geologist James Hutton (1794) first suggested that granite may once have been molten and intruded into the surrounding host rock, the question of how space was created for these bodies has been an infamous problem for geologists. The simple solution to the space problem is one of *in situ* melting and replacement of the country rocks. However, the problem with this is:

(i) the energy input required is vast and the resultant granitic body formed would be out of harmony in time and place with its surrounding metamorphic environment (Walton 1955);

(ii) many granites however, do show some degree of energy disharmony with their surrounding country rocks, indicating that they are likely to have intruded as magmas (transported melts), whatever their origin (Pitcher 1978).

The solutions proposed to overcome the space problem have been traditionally classified into two basic types: "passive" or "permitted", in which it was visualised that magma passively flowed into fractures or voids produced by tectonic stresses, including cauldron subsidence, stoping, cone-sheets, and ring dykes; and "forceful", a concept whereby the granitic body pushes aside its wall rocks, incorporating diapirism, ballooning, doming, translation of blocks along faults, and exploitation of pre-existing anisotropies in the country rocks. This traditional classification of emplacement mechanisms has been questioned by a number of authors. One such author, Hutton (1982), notes that in the Donegal Batholith, NW Ireland, relationships between these two types is obscure and both occur almost simultaneously in time and space. More recently Paterson *et al.* (1991a) have concluded that in general no one single emplacement mechanism can be attributed to the construction of a pluton, as field evidence suggests that a multiple of processes may operate around the same pluton.

It was noted that granite bodies are present within a number of different tectonic environments enabling the categorisation of these intrusives (Eskola 1932; Wegmann 1935). Further elaboration into a scheme known as the 'Granite Series' was suggested by Read in 1949, leading to the classical publications of the 'Granite Controversy' (Read 1957) and 'Granite Emplacement' of Buddington (1959), relating emplacement style to the depth of crystallisation. The essence of these models was that, with increasing depth, granitic plutons and batholiths could be subdivided into epizonal, mesozonal and catazonal categories. The Granite Series theory was however criticised and put into disarray by detailed field observations in the Donegal batholith, Ireland, by Pitcher and Berger (1972). The study showed that all types of emplacement phenomena incorporated within the series could be seen to operate at the same crustal level. Further more, it was made apparent by Pitcher (1978; 1979) that granite type and emplacement style could be generally related to the tectonic regime dominant during its construction. This led to a new tectonic approach in order to establish a link between major structures and emplacement mechanisms. This was explored by Hutton (1982) in the Main Donegal Granite, NW Ireland. He concluded that the emplacement of the pluton was syntectonic, being accommodated within a transtensional environment created by a displacement gradient along a major sinistral shear zone. Recent studies have also followed this approach, emphasising that the process of space creation at the level of pluton construction is a structural problem. Many recent contributions have shown that all the processes leading to the introduction of granite into the continental crust, from magma petrogenesis, its ascent and final pluton construction are fundamentally controlled by the tectonic evolution of that particular part of the crust (Paterson 1989; Hutton & Reavy 1992; D'Lemos *et al.* 1992).

1.3 THE CONCEPT OF GRANITE ASCENT

The process by which granitic magma can ascend and be emplaced within the crust has important implications for the rheological behaviour of the medium through which it travels. Typically, granitic melts ascend 10's of kms from their source region to mid- to upper-crustal levels. At such levels pluton construction may occur, which may or may not influence the Earth's surface 'directly'. The identification of mechanisms that operate to allow the ascent of granitic magma has remained a fundamental problem. One of the main reasons for this is because many granitic complexes throughout the world: (a) only provide information relating to the constructional processes operating during emplacement; and (b) are usually only exposed in their upper to mid-regions. Thus, there is usually little or no information on the way the magma has reached the site of emplacement, i.e. the ascent phase. Exceptions do occur, where the lower portions of plutons are exposed (e.g. Rannoch Moor; see Chapter 5), possibly providing an invaluable insight into the way the magma has intruded and possibly ascended.

There are a limited number of physically viable mechanisms of ascent, which include: (i) zone melting processes; (ii) stoping; (iii) transport via fractures; and (iv) diapirism (for a comprehensive review see Miller *et al.* 1988). By far the most popular ascent process, since the work of Grout (1945), Ramberg (1970; 1981), and others, has been the concept of diapirism; a model based on the density contrasts between the granitic magma and its surrounding country rocks. This allows the buoyant upward ascent of a sizeable plutonic body, which thermally softens and deforms its surrounding wall rocks as it rises. This became the most attractive model by the early 1970's, for several reasons: (i) it appeared to be a physically feasible mechanism, as exemplified by numerical modelling (e.g. Berner *et al.* 1972; Woidt 1978), and laboratory experiments (e.g. Ramberg 1970; 1972; 1981; Whitehead & Luther 1975). These have shown that a granitic mass less viscous than the surrounding walls will become approximately spherical after rising several diameters from its source region. (ii) It was supported by field observations which showed that many granitic plutons are roughly circular or elliptical in plan view. (iii) Marginal wall rock deformation around such plutons has been interpreted as due to the forceful space creation of the diapiric body (e.g. Cruden 1990); and (iv) other low density materials, such as salt and serpentine behave in a similar way to produce analogue structures. However, as noted by Clemens and Mawer (1992), the main reason for accepting diapirism as a major process for magma ascent for so long is probably attributed to two main reasons: (i) until quite recently there has not been a demonstrably viable alternative model, which can be experimentally simulated to produce the results required; and (ii) granitic magma ascending through the crust has so often been portrayed diagramatically as a volumous, inverted tear-drop shaped body, and as a result has received common acceptance, probably because visually it is a geometrically attractive model for the non-specialist.

Many workers (e.g. Ramberg 1970; 1972; Talbot 1974; 1977; Schewerdtner *et al.* 1977; Ramberg 1981; Soula 1982; Cruden 1988; Jackson & Talbot 1989; Cruden 1990; Koyi 1991) have used isothermal centrifuge models to describe flow and fabric development associated with the diapiric rise of magma. Such models have been used to estimate the magnitude and type of strains internally and externally developed during diapiric ascent and emplacement (e.g. Dixon 1975; Schewerdtner & Troeng 1978; Cruden 1988; 1990). Diapiric ascent of a substantial granitic body must result in characteristic deformation of the surrounding country wall rocks (Schmeling *et al.* 1988; Cruden 1990) and therefore should result in the development of such features as: (i) a zone of intense, localised flattening strains pseudoconcentric to the pluton margin; (ii) an intense vertical stretching lineation, together with shear sense indicators which suggest upward movement of the pluton body; (iii) the development of rim synclines; and (iv) an intense 'contact metamorphic zone', as an ascending diapir will lose 3 to 10 times more heat as it thermally softens its surrounding country wall rocks, than that of an equidimensional body which is static (Miller *et al.* 1988). However, such deformational features are extremely rare (e.g. Bateman 1985; Clemens & Mawer 1992), and if present may not be related to diapiric ascent, but to subsequent deformational processes related to construction of the pluton at the emplacement level (see below). By the late 1980's, the concept of diapiric ascent was under question on a number of accounts. The latest and most detailed model of diapirism (Mahon *et al.* 1988) has shown, irrespective of its dimensional characteristics, its temperature, density contrast with its surrounding country rocks and its starting depth, that such granitic plutons will suffer thermal death and crystallise before reaching upper crustal levels because of their heat loss to the country rocks. Thus, many workers (e.g. Brun *et al.* 1990; Marsh 1992) now consider that diapirism must be confined to the ductile lower crust. To overcome this thermal depletion problem, several workers (e.g. Cruden 1988; 1990) have proposed that as the diapir ascends the magma's fluidity allows it to undergo a continual process of internal convection, resulting in the circulation of heat towards the plutons margins, aiding the thermal softening and deformation of the country wall rocks as the diapir upwardly propagates. Modelling by Cruden (1988; 1990) has shown that internal convective overturn will occur several times during the ascent of the diapiric body. Such a process is envisaged by Wickham (1987) to occur at the source region as the magma body is diapirically spawned. As the diapir ascends, this continual internal circulation should result in what has been termed a "fold-and-stretch" chaos pattern (see Mandelbrot 1982; Ottino *et al.* 1988) and should consequently lead to mixing or obliteration of source-inherited isotopic and geochemical characteristics. Such a process has been questioned by several workers (see Miller *et al.* 1988), suggesting that the variabilty in isotopic ratios is likely to be attributable to processes occurring within the source region as granitoids tend to show a much greater diversity in various isotopic ratios than could be explained by analytical uncertainties. As mentioned by Clemens and Mawer (1992) it could be argued that such heterogeneity within a pluton could be due to the build-up of several small, discrete diapiric bodies. However, as they mention, the problem with this model is that these smaller bodies would lose heat too rapidly as they ascend and crystallise before they reach their emplacement level. An alternative view (which will receive further attention below) is that such bodies, when confined to a pre-existing ascent conduit, may form a continuous array of rapidly ascending discrete pulses connected to the source region. In such a model the bodies would be continually thermally enhanced preventing them from "freezing".

Several detailed studies of granitic plutons (e.g. Ardara (Holder 1979); Chindamora (Ramsay 1989); Criffel (Courrioux 1987); Arran (England 1990)) which had previously been regarded as examples of diapiric ascent and emplacement, revealed that their geometries and internal and external structural features were predominantly related to the construction of the pluton by a process of *in situ* expansion (ballooning) at the level of emplacement, often overprinting or completely obliterating structures associated with the ascent process. Many of these studies, however, still adopted a process of diapiric ascent to explain how the magma reached its level of emplacement, with subsequent inflation by a continued input of magma into the body. It is, however, possible that the resultant structural features may be solely due to processes occurring at the emplacement level and thus may have no bearing on the ascent mechanism, similar to a cautionary note first employed by Leake (1978).

Until quite recently there has not been a real alternative for magma ascent. The close spatial and temporal relationship of granitic plutons with regional scale faults and crustal lineaments has led many workers to conclude that such structures may not only control the syntectonic emplacement of granitic magma, but may also control the ascent of the magma through the crust as well (e.g. Pitcher 1979; Cobbing *et al.* 1981; Hutton 82; Castro 1987; Brun *et al.* 1990; Schmidt *et al.* 1990; Hutton & Reavy 1992; D'Lemos *et al.* 1992; Hutton 1992; Petford & Atherton 1992). This has led to a recent alternative model of magma ascent via faults, fractures, or shear zones by a process of sheeting or dyking. Various alternative processes based on this concept have been proposed over the last decade from magma ascent by fracture transport through self-propagating fractures (see Clemens & Mawer 1992; based on earlier work by Cook & Gordon 1964, and Pollard 1977), and dyke-like sheeting via deeply penetrating faults and shear zones (Reavy 1989; McCaffrey 1992; Hutton 1992; Petford *et al.* 1993). A review by Hutton (1992) of granite emplacement within extensional, transcurrent and contractional regimes suggests that, in all three tectonic settings, multiple sheeting parallel to the shear zone walls and deformation fabrics during the construction of a pluton are likely to reflect emplacement along active faults and shear zones. He suggested that this may represent one stage removed from an ascent mechanism of sheeting or dyking along fault zones in the crust.

Work carried out during this study (Ch. 9) suggests that granitic plutons may be intimately associated in terms of siting, ascent and emplacement with syn-tectonic shear zones or lineaments which intersect with one another to form transtensional zones allowing and facilitating their ascent. These recent studies may suggest that the most dominant ascent processes, i.e. transfer of melt from source region to the level where plutons may be constructed (emplacement), within the crust could be a process of dyke-like sheeting principally within shear zones (Reavy 1989; McCaffrey 1992; Hutton 1992; Petford *et al.* 1993) and via extensional conduits where, for example, two shear zones intersect (Jacques & Reavy 1994; Ch. 9). Ascent by these two processes enables continual transfer of material from source to site of pluton construction (emplacement). Within such a regime, the various petrological processes envisaged by Stephens (1992) which could help to account for normally zoned plutons (i.e. restite separation, fractional crystallisation, and rheological segregation of a heterogeneous source) could occur during ascent in such zones. On a finer scale, variations in the rate of magma ascent within a conduit, dependent on such properties as magma buoyancy, viscosity, and supply rate from the source may result in discrete pulses of magma successively arriving at the emplacement site producing several identifiable intrusive events (see Ch. 3). Such an ascent mechanism by the formation of magma pulses has been suggested by Weertman (1971; 1980), Takada (1990), and Clemens and Mawer (1992). Many elliptical plutons are composed of a number of concentrically zoned intrusive phases. Petrological and structural identification of individual magmatic pulses within the larger intrusive components may suggest that the pluton was constructed by a process of rapid sequential uprise of discrete magma batches; accounting for the heterogeneity of most plutons. As mentioned by Clemens and Mawer (1992), the major problem with such a model is that such small diapiric-like bodies would lose too much heat to the surrounding country wall rocks during their ascent and so solidify before they reach the emplacement level. Petford *et al.* (1993) (based on the results of Lister and Kerr (1991)), also question this diapir model and suggest that once the magma has formed a sheet or dyke-like body the conduit developed cannot be completely closed from the bottom upwards as it is impossible to expel viscous magma completely from a narrow gap. However, both arguments rely on the fact that, with such a pulse mechanism, the resultant magma bodies would be essentially isolated, individual units, whereas in all likelihood they could be continuously connected to the source region, forming an array of discrete pulses which do not 'freeze' because of sustained heating of the wall rocks as magma rapidly pulsates up the conduit. A similar concept has been modelled experimentally by Scott (1984; see Scott *et al.* 1986), describing how changes in supply rate can have a profound effect on the form of the ascending buoyant fluid; changing from sheet or dyke-like forms to solitary waves or wavetrains ('magma solitons') in response to changes in supply rate. Numerical modelling by Clemens and Mawer (1992) also favours a pulse type mechanism, with calculations inferring that a fracture 3 m x 1 km in plan could have a maximum vertical extent of 5.8 km, reducing to 4.0 km for a 1 m wide fracture zone. For a more realistic value of the distance from source region to emplacement level, say 20 km depth, only approximately 5 km of that fracture system could be filled with magma at any one time. Concluding, such data implies that the granitic magma must ascend to the emplacement level as a series of pulses rather than as a constant flow. Such a model has been invoked by Speer *et al.* (1994), favouring magma ascent by conduit flow in fault zones with separate magma pulses channelled into and up the same preheated pathways, resulting in composite plutons. Once such a fracture system has been established it will be a likely focus for magma transport throughout its history even if it becomes blocked by crystallised magma at the site of pluton construction. This is because there will be a dramatic increase in tensile stress within the region below the solidified magma, causing a new crack to develop and nucleate upwards, effectively reactivating and opening the old conduit (Weertman 1971). This explains why many plutons show evidence of "reactivation", constructed of a number of intrusive components which have been emplaced during distinct intrusive episodes often spanning quite considerable lengths of time (see Ch.'s 5 & 8).

1.4 GRANITE PETROGENESIS

Our understanding of the origin of granitic magma and the processes operating during the initial stages of granite petrogenesis and its evolution remain relatively poor. A recent review of the models put forward to explain the generation of granite magma derived from crustal sources has been comprehensively summarised by Brown (1994). He outlines two main approaches which have developed in the search for answers on magma generation, its escape from the source region (including segregation, aggregation and ascent) and processes which operate during the ascent of the magma and its final emplacement level which influence the geochemical and petrological characteristics of the granite. One of these approaches is the metamorphic perspective, looking at anatectic processes from the in-depth study of high-grade gneisses and migmatites, gaining an insight into crustal melt mechanisms. The other main approach has been the igneous perspective. Brown (1994) emphasises the complexities which can arise during the generation, ascent, and emplacement of the granite, which can dramatically influence the isotopic composition of the magma. In a so-called 'closed-system' a magma derived from the melting of a source rock does not undergo any interaction with other rocks as it ascends to its emplacement level, hence retaining its inherited isotopic signature derived from its source (parent). However, it is much more likely that, as the magma ascends, it will undergo processes involving fractional crystallisation and assimilation of the country wall rocks, leading to a change in isotopic composition. This may become further complicated if the source region undergoes 'open-system' melting, involving metasomatic melting and/or magma mixing processes. The extent to which deep-level processes (within the source region) ultimately effect the geochemical characteristics of the resultant granitic magma at the emplacement level, compared to the relative importance of shallow-level processes on the final compositional character of a magma remains a greatly debated issue. The two fundamentally different views are: (i) the large, long-lived, shallow level magma chamber model, where it is envisaged that all the major processes which govern the geochemistry and petrology of the granite occur (e.g. "the U.S.G.S. magma chamber model"); and (ii) a model in which deep-level partial melting within the source region is the most important process (e.g. "Australian School of Granites").

Another fundamental problem in the understanding of granitic magma, is the question of how the continental lithosphere is heated to a sufficient temperature to result in large amounts of granitic melt. Again two fundamentally different views have been proposed: (i) the continental lithosphere is thickened within collisional zones (England &

Thompson 1984; 1986; De Yoreo *et al.* 1989), causing the deep burial of rocks which contain radioactive elements, which in turn enhances the thermal productivity of the crust resulting in high temperature metamorphism and anatexis; (ii) the continental crust is underplated, and/or interplated, by mantle-derived basalts (Holland & Lambert 1975; Walls 1981; Bergantz 1989; Bohlen & Mezger 1989; Fountain *et al.* 1989; Clemens 1990; Bohlen 1991), providing a very effective way of transporting thermal energy from the mantle directly into the lower crust. An alternative mechanism which may encompass elements from both these models is the detachment of the lower lithosphere, and its removal by hotter asthenospheric magmas resulting in melting of the lower crust (Bird 1979; Loosveld & Etheridge 1990; Sandiford & Powell 1991; Ellis 1992).

In addition to this approach genetic granite classifications based on geochemistry and structural setting have been proposed. The most commonly used is that of Chappel and White (1974), in which two major types of granite were recognised: S-type granites, which possess properties derived from a sedimentary source rock (White & Chappell 1988), and I-types, which have been produced by the partial melting of older, mataluminous igneous rocks (Chappell & Stephens 1988). S-types are peraluminous, and are characterised by high initial Si^{87}/Si^{86} ratios, whereas I-types are relatively rich in Na_2O and are characterised by low initial Sr^{87}/Sr^{86} ratios. The genetic scheme has been supplemented by White (1979) to encorporate anorogenic (alkali) granites (A-types) and plagiogranites ("trondhjemites"; M-types). Further amendments to the classification have been proposed by Pitcher (1983), sub-dividing I-type granites into I (Cordilleran)-type where tonalitic compositions dominate a range of compositions from diorite to monzogranite, and I(Caledonian)-type where granodiorite to granite compositions are associated with small volumes of gabbro and hornblende diorite.

The comparison between granites from different tectonic settings has remained a difficult problem. Using geochemical patterns (normalised to a hypothetical ocean ridge granite) and trace element -SiO_2 plots, Pearce *et al.* (1984) reveal that granites within different tectonic groups (and sub-groups) exhibit distinctive trace element characteristics. On this basis, granites can be sub-divided into four main groups: (i) ocean-ridge granites (ORG); (ii) volcanic arc granites (VAG); (iii) within plate granites (WPG); and (iv) collision granites (COLG). Granites within each group may be sub-divided further according to precise intrusive settings and petrological character. Using tectonic criteria the ORG group can be sub-divided into subduction-related and subduction-unrelated granites; the VAG group can be sub-divided into intraoceanic and intracontinental granites; the WAG group can be sub-divided into intraoceanic and intracontinental and attenuated continental lithosphere; and the COLG group can be sub-divided according to the type of collision experienced, into continent-continent, arc-continent, and arc-arc granites. These can be further sub-divided depending upon the time of the emplacement relative to these events (syn-collision and post-collision).

It should be noted that in any classification of granite type, using geochemical, petrological and intrusive setting criteria, a particular granite may not fall within a single group, but in reality will be represented by a continuous spectrum of granite types with boundless alternative variations.

THE DEFORMATION OF GRANITE

1.5 THE THEORETICAL TREATMENT OF DEFORMATION AND THE RHEOLOGICAL PROPERTIES OF GRANITE

Rheology is defined as "the science of flow of matter" and is the science of ***deformation*** and ***flow***. The term ***deformation*** in this contribution will be used in a general sense to describe the change in shape, orientation and displacement of rocks between initial and final states. A more restricted term is ***strain***, referring only to the change in shape, or distortion, of the body. The term ***flow*** is used to describe the instantaneous displacement of material particles making up a deforming body. Rheology is the critical study of the properties of elasticity, plasticity (flow), and viscosity exhibited by materials subjected to stress and the relationship between stress, strain, and strain rate.

An explanation of the terms used in this contribution to explain the processes of formation of structures (i.e. deformation) in granitic rocks is given, together with an account of the different behavioural characteristics exhibited by materials in response to stress. Several texts which review the basic theory of deformation and its elementary principles are currently available, e.g. Ramberg (1967); Hobbs *et al.* (1976); Means (1976); Ramsay and Huber (1983, 1987); Park (1989).

1.5.1 Terminology and basic theory of deformation

Stress:

Stress is a pair of equal and opposite forces acting on a unit area, in which its magnitude depends upon the magnitude of the force and the size of the unit area on which it acts. Stress is therefore defined as the amount of force (F) acting per unit area (A). The forces acting on a surface can be separated into normal (Fn) and sliding (Fs) components, generating a ***normal stress*** (σ) acting perpendicular to the surface:

$$\sigma = Fn / A \qquad [\,1.1\,]$$

and a ***shear stress*** (τ) acting parallel to the surface:

$$\tau = Fs / A \qquad [\,1.2\,]$$

Considering the state of stress at a point in three-dimensional space depends upon the component of stress applied. If a unit area is subjected to a component of 'pure' (normal) stress without shear the various forces may be resolved into three mutually perpendicular principal axes of stress ($\sigma_1 \geq \sigma_2 \geq \sigma_3$), which represent the greatest, the intermediate, and the least tensile stress respectively. If the compressive stress is equal in all directions this will tend to reduce the size, but not alter the shape (volume change) of a body. This state of stress is generally referred to as ***hydrostatic stress*** (Fig. 1.1a), corresponding to the stress state in a static fluid; the average or mean stress (σ):

$$\sigma = (\sigma_1 + \sigma_2 + \sigma_3) / 3 \qquad [\,1.3\,]$$

If however, the stresses are unequal (i.e. $\sigma_1 > \sigma_2 \geq \sigma_3$) which is usually the case with tectonic stresses, the ***deviatoric stress*** (σ') or stress difference (Fig. 1.1b) is defined as:

$$\sigma' = \sigma - (\sigma_1 + \sigma_2 + \sigma_3) / 3 \qquad [\,1.4\,]$$

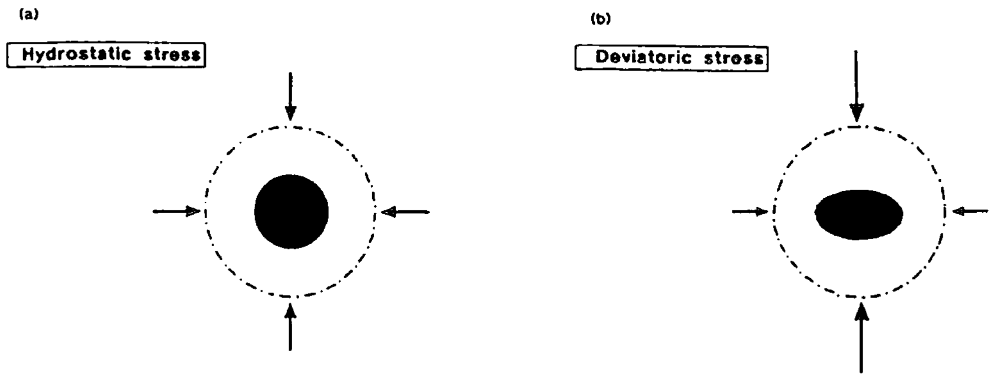


Fig. 1.1. Two dimensional view of the effects of: **(a)** hydrostatic stress (σ) causes a change in volume; **(b)** deviatoric stress (σ_1 - σ & σ_3 - σ) causes a change in shape.

Strain:

The mean and deviatoric stresses measure the departure of the stress system from symmetry and control the extent of distortion or shape change in a body, i.e. strain. In the case of an equal sphere, this will change shape and become an ellipsoid, and ***shear*** will arise as a result. Strain can thus be defined as such a change in size and/or shape of a body resulting from the action of an applied stress field. It is a geometrical expression of the amount of deformation caused by this action and thus, can be expressed as dilation (volume change), or distortion (shape change), or as a combination of these processes.

When the amount of strain is equal throughout the body the strain is referred to as being ***homogeneous***, resulting in uniform deformation. If the strain is unequal in different parts of the body the strain is said to be ***heterogeneous*** (inhomogeneous).

The strain ellipsoid:

One way of describing strain in three-dimensions is similar to that employed for stress. Three mutually perpendicular principal axes x, y, and z, representing the maximum, intermediate, and minimum (or negative) finite extension directions, are selected. These axes are known as the ***principal strain axes***. In this form the strain is generally represented by a ***strain ellipsoid*** (Fig. 1.2), which describes the relative amounts of deformation along the three principal strain axes, of an initial spherical object. The measurement and analysis of strain and its implications in the deformation of granitoids and their wall rocks will be addressed in detail later.

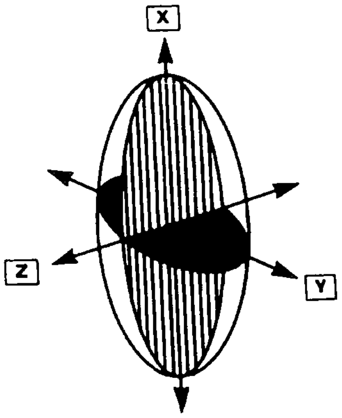


Fig. 1.2. The strain ellipsoid. The principal strain directions are x (long axis), y (intermediate axis), and z (short axis). The principal planes (xy, yz and xz) containing these axis are shown.

Flow:

The instantaneous displacement of material particles making up a deforming body is known as ***flow***. The term ***flow plane*** is used to describe a common plane of zero angular velocity towards which all material lines tend to rotate during homogeneous progressive deformation. This can be described by a ***flow pattern*** or simple velocity field (Fig. 1.3).

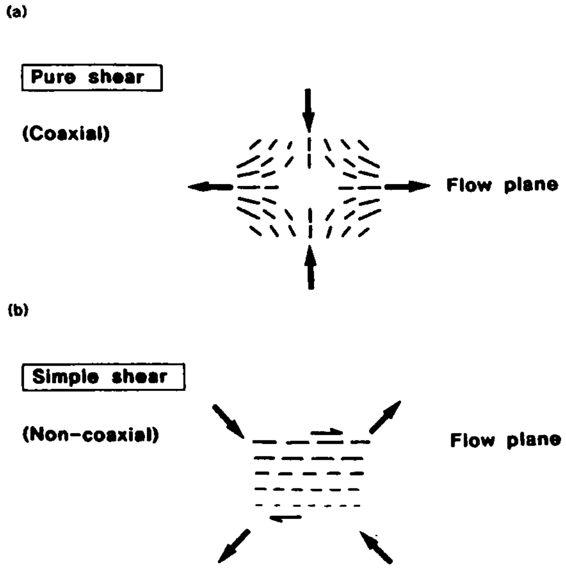


Fig. 1.3. Flow patterns or simple velocity fields, representing two-dimensional displacements of material particles for **(a)** pure shear, and **(b)** simple shear flows. Lengths of markers are proportional to velocities. The instantaneous stretching axes are indicated by arrows. In simple shear the displacement vector is shown. After Hanmer & Passchier (1991).

This pattern however only describes the instantaneous displacement of material particles and so the term ***progressive deformation*** is used to describe the on going process of deformation from the initial state, enabling a sequence of deformational paths to be established (Fig. 1.4). The difference in the distribution of particles between these two states is referred to as ***finite deformation***.

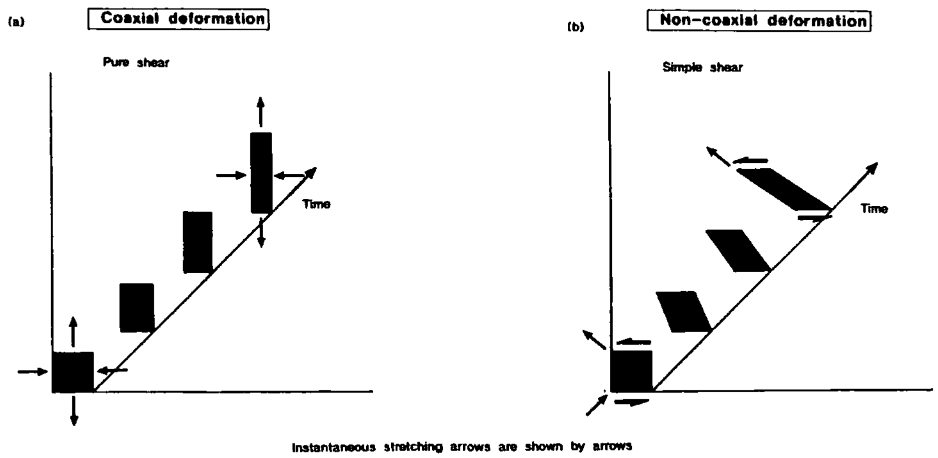


Fig. 1.4. Deformation paths: **(a)** in pure shear the strain accumulates coaxially (see below); **(b)** in simple shear the strain accumulates non-coaxially (see below).

Coaxial and non-coaxial flow:

In geology two types of flow are generally referred to: ***pure shear*** (coaxial) and ***simple shear*** (non-coaxial) (Fig. 1.5a & b). These represent two ideal end-members of a range of more general flow types. The term pure shear is used if during the deformational process the orientations of the principal strain axes x, y, and z do not change. In this case the strain may be described as ***coaxial*** or ***irrotational***. If a change in the orientation of the principal strain axes has occurred, the process is referred to as simple shear and the strain is described as ***non-coaxial*** or ***rotational***. It should be noted that any number of deformational paths, coaxial or non-coaxial, may lead to the same shape of finite strain ellipsoid from an initial circle.

The term ***general non-coaxial flow*** or ***"general shear"*** will be used in this thesis, as adopted by Hanmer & Passchier (1991), to describe a process in which there has been a combination of the two end-member types of flow, i.e. a component of simple shear and a variable component of pure shear (Fig. 1.5c); where the flow remains two-dimensional as there is no instantaneous change in length along the direction of the rotation axis, and the contemporaneous shortening across the ***shear plane*** (i.e. the mean position of the flow plane during progressive deformation) is accommodated by extension along the shear direction. Different methods of expressing the combination of simple and pure shear have been adopted by a number of workers, e.g. Ghosh and Ramberg (1976). This type of flow, i.e. general non-coaxial flow (or "***general shear***"), may also be referred to as "rotational flattening" (e.g. Choukroune & Lagarde 1977), "noncoaxial bulk inhomogeneous flattening" (Bell 1981; 1985), "non-ideal flow" (Hanmer 1990), "general flow" or "shearing flow".

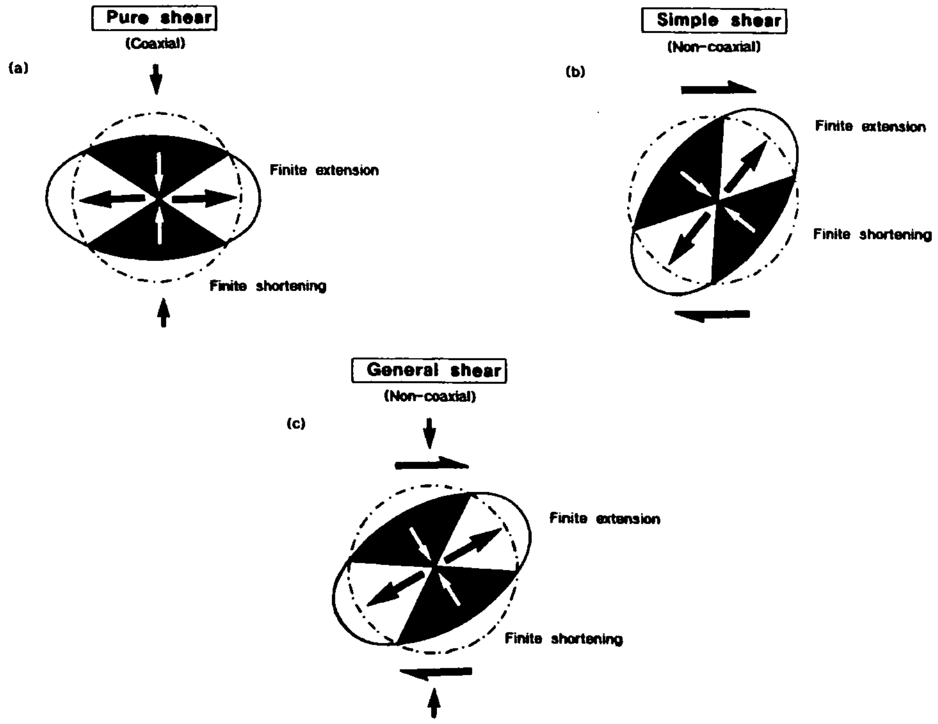


Fig. 1.5. **(a)** Pure shear, which involves coaxial or irrotational strain; **(b)** simple shear, which involves non-coaxial or rotational strain; **(c)** general shear, which describes a process which involves both types of flow, i.e. a component of simple shear and a component of pure shear.

1.5.2 Granite rheology

The rheological properties of a magma or rock is dependent upon a number of internal parameters, including: (i) composition; (ii) crystal content; (iii) amount of crystal interaction; (iv) pressure; (v) temperature; (vi) nature of volatiles, and several external parameters: (i) stress; (ii) strain; (iii) and strain rate.

Material subjected to an external stress field in general show three main types of behaviour.

Elasticity:

Where the applied stress (σ) is proportional to strain (ε) which is recovered when the stress is released:

$$\sigma \propto \varepsilon \qquad [\,1.5\,]$$

This means that once the applied stress subjected to an elastic material is removed the material will return to its original shape (Fig. 1.6). This type of strain is often referred to as ***recoverable*** or ***temporary*** strain. This behaviour can be defined by Hooke's law, where:

$$\varepsilon = \sigma / E \qquad [\,1.6\,]$$

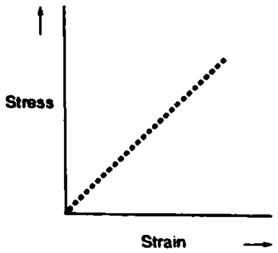


Fig. 1.6. Ideal elastic strain: $\sigma \propto \varepsilon$

The measure of a material's resistance to distortion is defined by Young's modulus:

$$E = \sigma / \varepsilon \qquad [\,1.7\,]$$

Plasticity or yield:

The rheological properties of a material subjected to stress change dramatically beyond a critical value termed the ***Yield stress*** (σ_0), where a sudden amount of plastic deformation (flow) takes place (Fig. 1.7). Before this point the material behaves elastically at low values of stress and the deformation is therefore non-permanent. Continued deformation after the yield point is permanent and behaves in a viscous (see definition below) manner. However, an exception to this can occur if rocks are subjected to slow enough strain rates that deformation by a process of creep occurs below their yield strength (McBirney & Murase 1984).

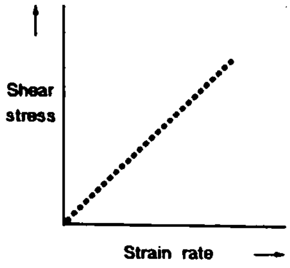


Fig. 1.7. Ideal elastic strain at low values of stress. Continued deformation after the yield point is permanent, where a sudden amount of plastic deformation (flow) takes place.

Viscosity or viscous flow:

In general viscosity (η) can be defined as the coefficient for transfer of momentum (McBirney & Murase 1984). When a fluid is subjected to shear stress (τ) which is proportional to the strain rate (ε^o) it is termed as exhibiting ***Newtonian viscous flow*** (Fig. 1.8 & 1.9):

$$\tau \propto \varepsilon^o \qquad [1.8]$$

or

$$\tau = \eta\, \varepsilon^o \qquad [1.9]$$

After removal of the deforming stress there is no recovery and so all the movement is permanent.

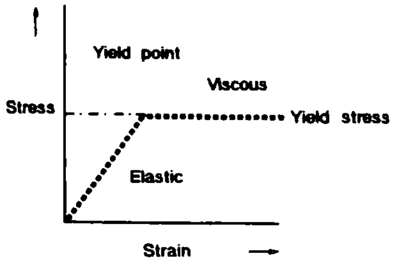


Fig. 1.8. Ideal viscous strain: $\tau \propto \varepsilon^{o}$

Non-ideal rheological behaviour:

Some substances do not comply to the above three types of behaviour when subjected to an external stress. In these cases the relationship between stress and strain rate is non-linear and the materials possess more complex rheological properties. One such behaviour is termed ***Bingham flow*** (Fig. 1.9), in which a substance undergoing shear, elastically deforms showing little or no tendency to flow until a certain shear stress is reached. At this yield point flow rate increases dramatically and permanent ductile deformation occurs.

When Scrope (1872) first suggested the term ‘magma’, he stressed its analogy to such non-Newtonian behaviour. Experimental studies by Van der Molen and Paterson (1979) have generally confirmed this. Their studies have shown that it exhibits elastoplastic behaviour showing a range of rheological properties during crystallisation and cooling. Silica rich melts have been both modelled as Newtonian fluids, dependent upon the fraction of suspended solid particles and consequently the viscosity of the melt (Shaw 1965; Arzi 1978), and as a Bingham fluid, possessing a finite yield strength dependent on the melt fraction (e.g. Shaw *et al.* 1968; Shaw 1969; Murase & McBirney 1973; Sparks *et al.* 1977).

The complexity of the rheological behaviour of granite can also be clearly observed in the field. For example, Pitcher (1987) describes how granite can essentially exhibit brittle type characteristics when intruded rapidly by synplutonic basic magma, but also viscous type behaviour exhibited by the lobate relationships between and along the contacts of the two materials. This behaviour, whether a granite in the course of crystallisation can behave plastically or rigidly, depends upon the prevailing stress conditions at that time

(Wegmann 1963). During rapidly applied stress, fractures can be initiated and sustained, whereas during gradually applied stress, the crystallising magmas can yield plastically. This behaviour will be further addressed in this thesis with regards to the emplacement of the Etive Dyke Swarm (Ch. 8).

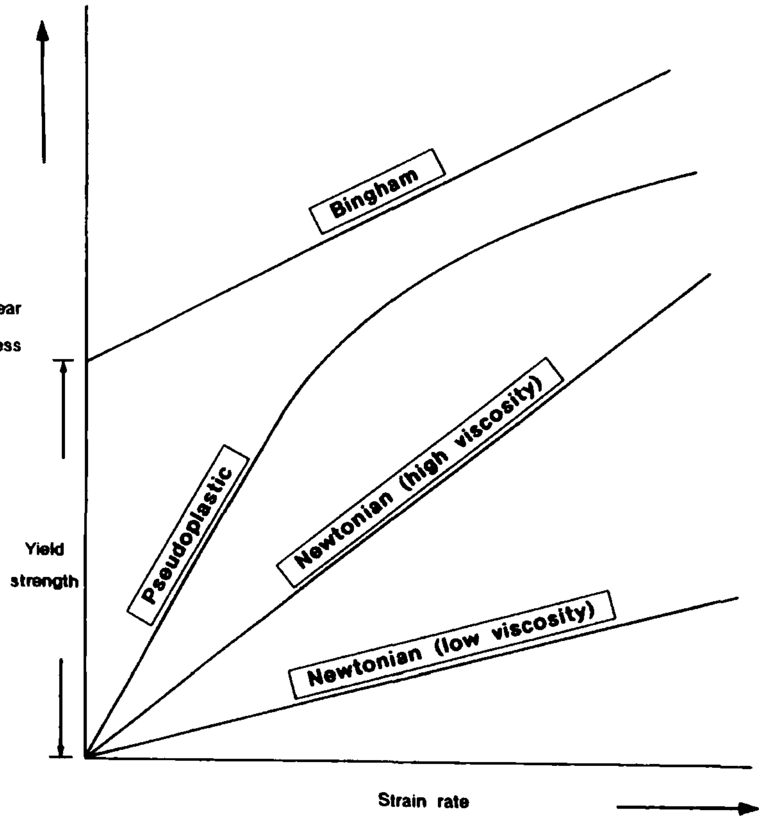


Fig. 1.9. Graph of shear stress (τ) against strain rate (ε°) for various rheologies.

Granitic magma exhibits an ideal Newtonian behaviour when it is in a completely molten state. Its viscosity is governed by strain and strain rate, the amount of volatiles and halogens present, and to a lesser extent by the composition and temperature of the melt (e.g. Bottinga & Weill 1972). At lower crystal contents (< 50 %) the behaviour of a granitic melt generally resembles that of Newtonian viscous flow, dependent on the composition and the distribution, size and shape of crystals within that melt (McBirney & Murase 1984).

During crystallisation, grain to grain interactions become more dominant, until the crystal content of the magma reaches a critical value termed the ***Rheological Critical Melt Percentage*** (RCMP, Arzi 1978; Van der Molen & Paterson 1979; however, see below). At this critical melt fraction (CMF) 'crystal lock-up' occurs, leading to a dramatic increase in viscosity (Fig. 1.10) and the onset of solid-like behaviour. Estimates of the values of the RCMP range from 20 ± 10 % (Arzi 1978) and 30-35 % (Van der Molen & Paterson 1979).

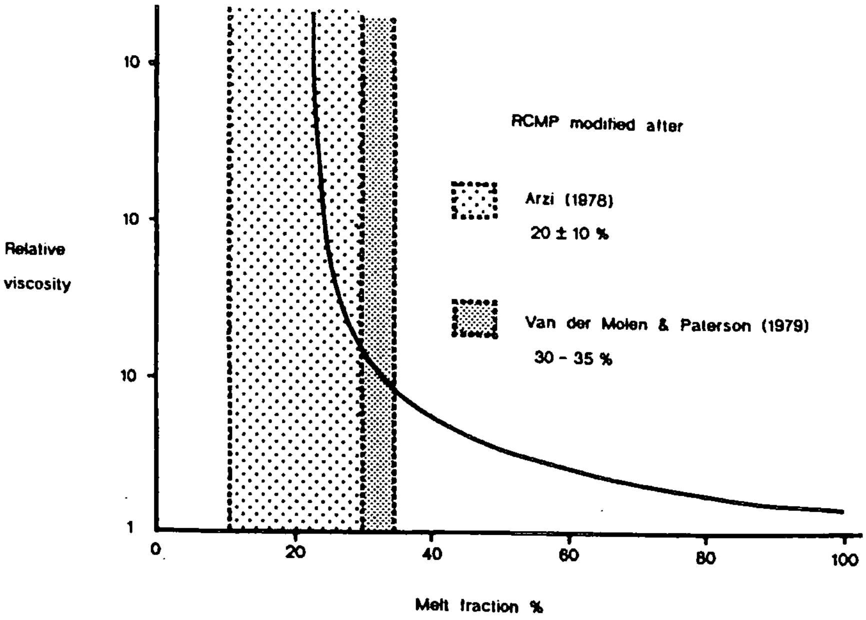


Fig. 1.10. Curve showing relative viscosity versus melt percentage for a Newtonian melt according to Roscoe's formula. The rheologically critical melt percentage (RCMP) estimated by Arzi (1978) and Van der Molen & Paterson (1979) are shown.

These experimental investigations have only been carried out on true granites and not for a diversity of granitic compositions which are typically present in multiphase complexes. This important point was raised by McCaffrey (1989) and subsequent modelling and field studies in order to obtain qualitative information suggests that the more mafic-rich affinities such as granodioritic or tonalitic compositions may have viscosities orders of magnitude less than those of true granites (Hutton 1992; Ingram 1993). Another important point also associated with composition which can have dramatic consequences on the rheological properties of a granitic melt, is governed by the size, shape and distribution of the crystals. This is illustrated by the curve of relative velocity (ηr) versus melt percentage (C) remaining (Fig. 1.10, Arzi 1978), which shows how the changes in viscosity for a Newtonian viscous melt containing rigid spheres, represented by the formula (Roscoe 1952):

$$\eta r = (1.35C - 0.35)^{-2.5} \qquad [1.10]$$

can change considerably if the distribution of spheres are non-uniform in size. For a uniform size particle suspension it indicates a CMF at 26 % melt, which is profoundly changed to lower values if non-equal sizes are distributed (Roscoe 1952; Van der Molen & Paterson 1979). This demonstrates how a number of factors such as compositional variation, size, shape, and distribution of crystals and their order of crystallisation can have fundamental effects on the rheological properties of a granitic melt.

However, recent work by Vigneresse *et al.* (1995) suggests that the transitions from melt to crystals and solid to melt, are not exactly analogous. Four stages have been analysed, which depend on melt fraction and stress (see Fig. 1.11). The results suggest that during magma emplacement, early crystallised particles (20 %) are allowed to rotate independently during deformation, and in wide zones they will align to form fabrics. As crystallisation increases, particles interact to form a "rigid backbone". At approximately 50-60 % crystal content, the cluster of crystals can accumulate stresses, while the melt can still flow (this has been termed as the ***rigid percolation threshold*** (RPT)). At approximately 72-75 % the system is totally locked (***particles locking threshold*** (PLT)). This investigation implies that the estimated rheological critical melt values proposed by Arzi (1978) and Van der Molen and Paterson (1979) may apply to melting, but not crystallisation (see also Rutter (1995)).

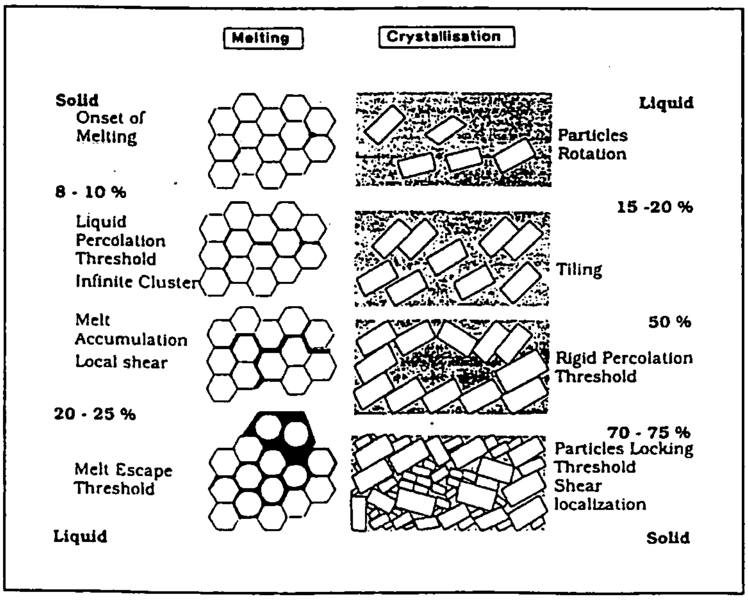


Fig. 1.11. Diagrammatic representation of four identifiable stages during crystallisation and melting. After Vigneresse *et al.* (1995).

1.6 STRUCTURAL DEVELOPMENT IN GRANITIC ROCKS

The first basic analytical approach for the classification of granitic structures was proposed by Hans Cloos (Balk 1937). This involved structures being categorised into two groups: (i) structures formed as a result of "magmatic currents" moving against wall rocks, analogous to water flowing in a stream. This "flow" process leading to the alignment of platy crystals during the crystallisation of the magma. These were termed ***primary structures*** and also included joints, which were thought to have occurred at this time as a result of continued elongation of the magma; (ii) structures formed in the solid state as metamorphic structures, such as cross cutting foliations were termed ***secondary structures***.

Although the same methods of recording the different internal structures of granitic rocks, as proposed by Cloos (e.g. 1936b) and Balk (1937) are essentially the same, the genetically-based classification proposed has been widely criticised by a number of authors (e.g. Berger & Pitcher 1970; Pitcher & Berger 1972; Hutton 1988a). The basis of this criticism is that the rheological behaviour of a silicate melt is clearly not analogous to flowing water. Berger and Pitcher (1970) pointed out that the shapes of microgranitoid enclaves are representative of the shape of the local deformation ellipse, implying that the host material does not possess properties of a true liquid. The shape of an enclave in a magma undergoing flow (retaining liquid properties) is unlikely to change because there would not be high enough deviatoric stresses acting on its surface to deform it (Bateman *et al.* 1983), as hydrostatic stress would be dominant. This has led to the development of a non-genetic system proposed by Hutton (1988a), which regards that the vast majority of structures, such as foliations, are produced as a consequence of deformation as a result of applied stresses. This can happen at any time during or after crystallisation unlike the Cloosian classification (Balk 1937). This development of tectonic structures within granitoids is therefore a result of the imposition of externally derived tectonic-related strains, combined with internal pluton expansion-related strains.

Various authors (see Blumenfeld & Bouchez 1988, Hutton 1988a, and Paterson *et al.* 1989) have discussed and proposed terminology to describe the development of fabrics and associated structures, relative to the time of deformation and crystallisation state. This relationship can be broadly determined from the identification of fabrics and textures, which has led to identification of two basic types, often representing the end-members of a series: ***pre-full crystallisation fabrics*** (PFC) and ***crystal plastic strain fabrics*** (CPS)

(Hutton 1988a). It is this terminology which will be used in the subsequent chapters of this contribution.

1.6.1 Pre-full crystallisation fabrics (or magmatic state fabrics)

This type of deformation occurs before all the phases have crystallised; the development of a fabric in which the amount of melt present is in excess of the CMP (Blumenfeld & Bouchez 1988). In this state, the imposition of strain causes the rigid body rotation of early formed phases, such as feldspar and mafic phenocrysts, into alignment in an uncrystallised matrix (Gay 1968). If the applied stress field is removed and the remaining melt crystallizes, the resultant fabric is one of aligned, internally undeformed, euhedral phenocrysts, set in a matrix of undeformed later interstitial phases (typically quartz) (Fig. 1.12a). Under the nomenclature of Hutton (1988a), this type of fabric is termed a 'pre-full crystallisation state' fabric. Other such terms commonly used to describe such deformation fabrics are 'magmatic state' (Blumenfeld & Bouchez 1988) and 'magmatic flow' (Paterson *et al.* 1989).

As mentioned above, in many cases these fabrics are predominantly produced by the imposition of externally derived tectonic-related strains acting on the magma body, and so the term 'flow' could lead to some confusion as it could be interpreted as implying that internal body-related strains were chiefly responsible for its development.

1.6.2 Crystal plastic strain fabrics (or solid state fabrics)

These fabrics occur at or below the solidus temperature of its constituent minerals when the behaviour of the granite is essentially solid. Deformation will cause an imposition of strain in those minerals, causing crystal alignment to occur, predominantly by plastic deformation mechanisms (Fig. 1.12b). Strain in these crystals is dominantly accommodated by the process of ***creep*** (dislocation creep) and to a lesser extent by diffusion related processes. This internal plastic deformation is exhibited by both early phenocrysts and late interstitial phases. Quartz is more susceptible to this plastic deformation than such minerals as feldspar and mica, often forming ovoid or lenticular shapes as a result of distortion and recrystallisation. It should be noted however, that both ductile and brittle processes occur simultaneously, although ductile deformation appears to dominate. Feldspars in particular can undergo brittle type processes, typically brittle fracturing and sliding. Mica tends to deform by slip on (001) to form kink-band type structures. In this contribution this type of fabric will be termed a 'crystal plastic strain' fabric (Hutton 1988a). Other authors refer to the term 'solid state deformation' (Blumenfeld & Bouchez 1988) to describe such fabrics.

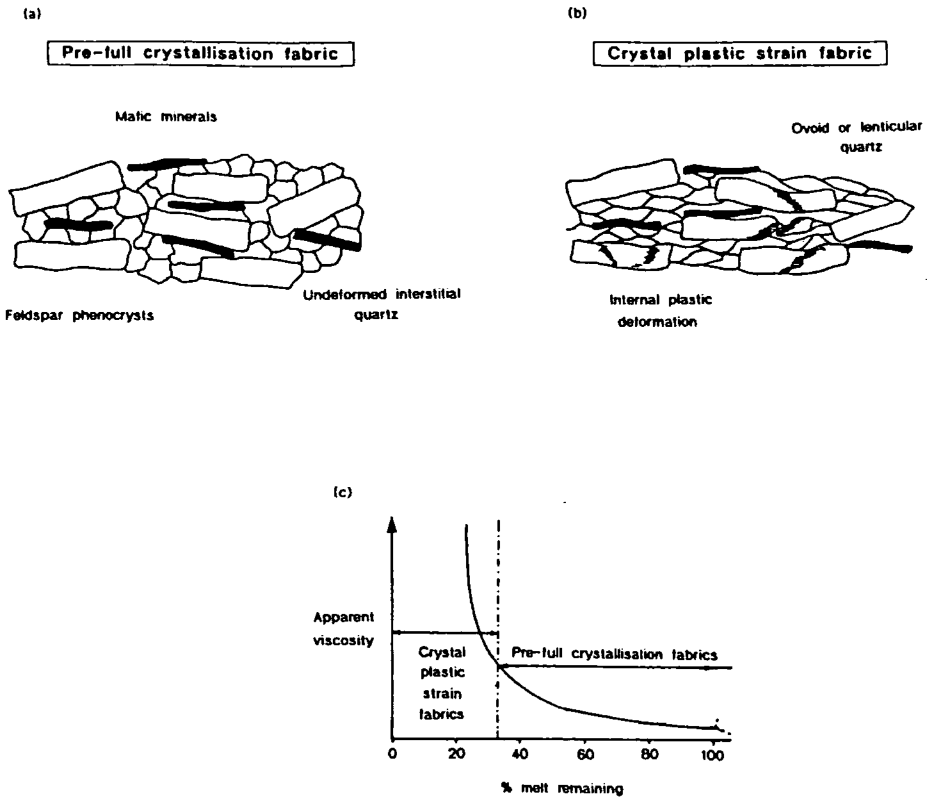


Fig. 1.12. Time of deformation relative to crystallisation state in granitoids: **(a)** pre-full crystallisation fabric (PFC); **(b)** crystal plastic strain fabric (CPS); **(c)** fabric types in relation to Arzi type diagram. Modified after Hutton (1988).

1.6.3 Fabric development across the RCMP (the magma/solid transition)

As mentioned above, a solid state fabric will occur if deformation continues after all the phases of a magma have crystallised. If this deformation is intense and penetrative, the rock essentially becomes a granite gneiss, possessing an entirely metamorphic fabric. However, if the deformational process is less intense or localised and the imposition of strain is removed before the magma has completely crystallised, relict magmatic textures may be preserved locally, in association with the relocation of intercrystalline fluids (see below).

A review of such intense deformation occurring at near-solidus temperatures is given by Hibbard (1987). In general such deformation results in the reshaping of crystals by ductile flow and/or brittle processes and the relocation of fluids. Ductile flow seems to dominate, leading to crystal-plastic deformation. This type of deformation results in a fabric exhibiting a composite of magmatic and metamorphic textures which have evolved essentially simultaneously across the RCMP. This can be referred to as a mylonitic gneiss (Hibbard 1987).

It has been noted by Hutton and Ingram (1992), and during this study, that during deformation at low melt percentages (approximately 30-35 %), before the onset of plastic flow and brittle type processes, strain can become focused into zones where phenocryst phases interact, forming a crystalline framework in which stress is transmitted heterogeneously through the deforming magma. This strain partitioning results in the development of discrete zones of deformation, referred to as 'pre-full crystallisation lock-up' shears (Hutton & Ingram 1992; see Ch. 3, sub-section 3.4.2.1). If deformation continues down-temperature into the solid state regime, overprinting CPS fabrics develop and strain is continuously focussed into the narrow zones of shear, which often results in the development of mylonite along these discrete zones. The processes operating during such down-temperature, brittle deformation, has been addressed by Simpson (1985) (see below).

1.6.4 Redistribution of intercrystalline fluids in relation to deformation

Within an incompletely crystallised magma system, late-stage magmatic fluids or early-stage fluids related to anatectic/solid state processes can be redistributed as a consequence of applied deviatoric stresses (George 1978; Hibbard 1987). In general, during deformation these intercrystalline fluids migrate from zones normal or subnormal to the greatest principal compressive stress direction (σ_1), into zones normal or subnormal to the least principal stress direction (σ_3), corresponding to the direction of maximum extension.

In a deforming granitoid, this process of relocation of late-stage fluids typically results in K-feldspar - myrmekite - microaplite crystallisation (see Hibbard 1987); either (i) within the pressure shadow zones of early magmatic plagioclase and/or K-feldspar crystals; (ii) as isolated lenticular or augen-like units; (iii) or completely around K-feldspar phenocrysts in non-gneissose magmatic granites (Hibbard 1979). The association of myrmekite with K-feldspar in mylonitic gneisses has been addressed by Simpson (1985). In this case myrmekite is not located into the pressure shadow position with respect to the

K-feldspar augen, but in general is located as lobes along the two sides of the porphyroclast, in the zones normal to the finite shortening direction (σ_1) (Fig. 1.13). The formation of the lobes as a consequence of a combination of processes including replacement, exsolution, and strain-enhanced diffusion. This means that this process of myrmekite formation is geometrically related to the stress field imposed on these high grade mylonites. A cautionary note is that, in some cases, the growth of myrmekite is unrelated to stress (Hibbard 1979).

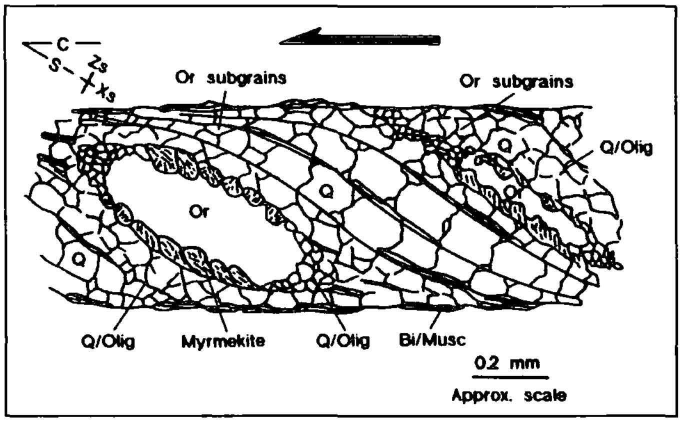


Fig. 1.13. Schematic diagram to illustrate the geometrical relationships amoung C and S planes, orthoclase porphyroblasts (Or), myrmekite zones, and orthoclase sub-grains/recrystallised new grains. Z's and X's represent the finite strain axes for the S foliation only and do not represent the bulk finite strain axes for the rock. After Simpson (1985).

1.6.5 Deformation across the brittle-ductile transition

Deformation of granitic rocks at the brittle-ductile transition involves both ductile and brittle type processes, commonly producing mylonites. In general, quartz and mica deform in a ductile manner, whereas feldspars exhibit brittle deformational features (e.g. Debat *et al.* 1978; Berthé *et al.* 1979; Tullis 1979; White *et al.* 1980; Tullis *et al.* 1982; Simpson 1985).

The types of deformational fabrics produced by granitic rocks across the brittle-ductile transition has been addressed by Simpson (1985). This consisted of a detailed micro-structural analysis of a suite of mylonites that grade into mylonitic gneisses, formed over a range of metamorphic conditions, from lower greenschist to amphibolite facies; the Eastern Peninsular Ranges Mylonite Zone (a major thrust zone), California. This revealed a number of points in relation to fabric development over a range of deformation conditions:

(i) composite planar fabrics in the form of C and S planes (S-C fabrics; see discussion) occur at all metamorphic grades; mylonites at lower greenschist facies (zo-chl-bi-qtz-ol-an) exhibit ductilely deformed quartz and kinked biotite. The quartz crystals have been predominantly deformed by a process of dislocation creep, forming well developed ribbon structures. Feldspar crystals have undergone grain size reduction by microfaulting and microcracking. In tonalitic and dioritic rocks, hornblende underwent a process of grain size reduction by cataclasis and minor replacement by chlorite. All these features being typical of brittle-ductile microstructural development; (ii) at mid- to upper greenschist grade, plagioclase shows evidence of low temperature plasticity, whereas orthoclase exhibits dynamic recrystallisation textures. Biotite ribbons have been progressively rotated to form chevron fold patterns; concluding that the transition from brittle-ductile to completely ductile bulk rock behaviour is exhibited by the onset of ductile deformation of feldspars by low temperature plasticity and dislocation creep processes, occurring within the middle to upper greenschist facies range; (iii) all minerals at epidote-amphibolite grade and above, predominantly show annealing recrystallisation and recovery processes. Well preserved quartz ribbons help to define a gneissosity. These mylonites show no evidence of brittle deformation in any of the constituent minerals.

1.6.6 Strain analysis in granitoids and their wall rocks

The fabrics or foliations produced by deformation in granitic rocks and their wall rocks can be classified and qualitatively related to the shape of the strain ellipsoid as: (i) S (planar) fabrics; (ii) L (linear) fabrics; (iii) LS (a combination of the two) fabrics in the Flinn nomenclature (Fig. 1.14) (Flinn 1965; Pitcher & Berger 1972). The resultant shape of the strain ellipsoid is dependent upon the relative amount of deformation along the intermediate finite extension direction (Y axis) in relation to one of the other two principal strain axes (X or Z). With S fabrics, the Y and X axes are the same length, and are usually produced either by (a) equal extension in the X and Y axes with Z as a constant; or (b) shortening in the Z axis with X and Y constant ($X = Y > Z$), resulting in ***flattening*** or ***uniaxial oblate*** strains. In the case of L fabrics, the Y and Z axes have been shortened by the same amount or the Y and Z axis have remained constant with X elongated ($X > Y = Z$), resulting in a ***constrictional*** or ***uniaxial prolate*** strains. With LS fabrics there has been no relative change in the amount of deformation along the Y axis (i.e. Y remains equal to 1), resulting in a constant volume or no change in length ($X > Y = 1 > Z$), resulting in ***plane strain***.

In granitic rocks, the most common method of determining strain is the measurement of the mean three-dimensional shape of a population of ***microgranitoid enclaves***. These are also commonly referred to as mafic microgranitoid enclaves (M M E'S), mafic xenoliths, autoliths, cognate xenoliths or mafic enclaves. Due to these enclaves being petrologically different from their host, there exists a difference in the rheological behaviour of the two materials. This contrast is important as the more petrologically diverse the enclaves are in relation to their host, the greater is the difference from the apparent values of strain magnitude measured from the actual true values of the strain imposed. Therefore caution must be exercised when comparing strain values from either different intrusive facies within a single pluton or total strain magnitudes from different plutons, even if these granitic complexes occur in the same region.

There is also the problem of whether these enclaves were originally spherical in shape before deformation at the emplacement level and whether they have gone through a number of deformational paths, which can all be related to pluton construction. In reality the actual strain magnitudes determined are probably over- or under-estimates of the amount of strain imposed, but with additional qualitative information such as fabric type, its orientation and intensity, the values obtained provide a basic, fundamental platform in which to describe the strain distribution throughout a granitic complex and the way the strain was imposed during pluton construction.

The determination of strain involves the measurement of the long and short axes of individual enclaves in both the foliation plane (XY) and in the plane orthogonal to the foliation and lineation (YZ). From this, the shape ratio can be calculated for each principal plane. For a population of enclaves (generally between 20-60) the mean shape ratio can be logarithmically calculated for each strain plane. By combining both these mean values the ratio of the third principal plane (XZ) can be calculated, using the equation:

$$R_{XZ} = R_{XY} \cdot R_{YZ} \qquad [\,1.11\,]$$

and also the overall absolute mean shape ***(K-value)*** of the enclave can be determined using the equation:

$$K = (X/Y - 1) / (Y/Z - 1) \qquad [\,1.12\,]$$

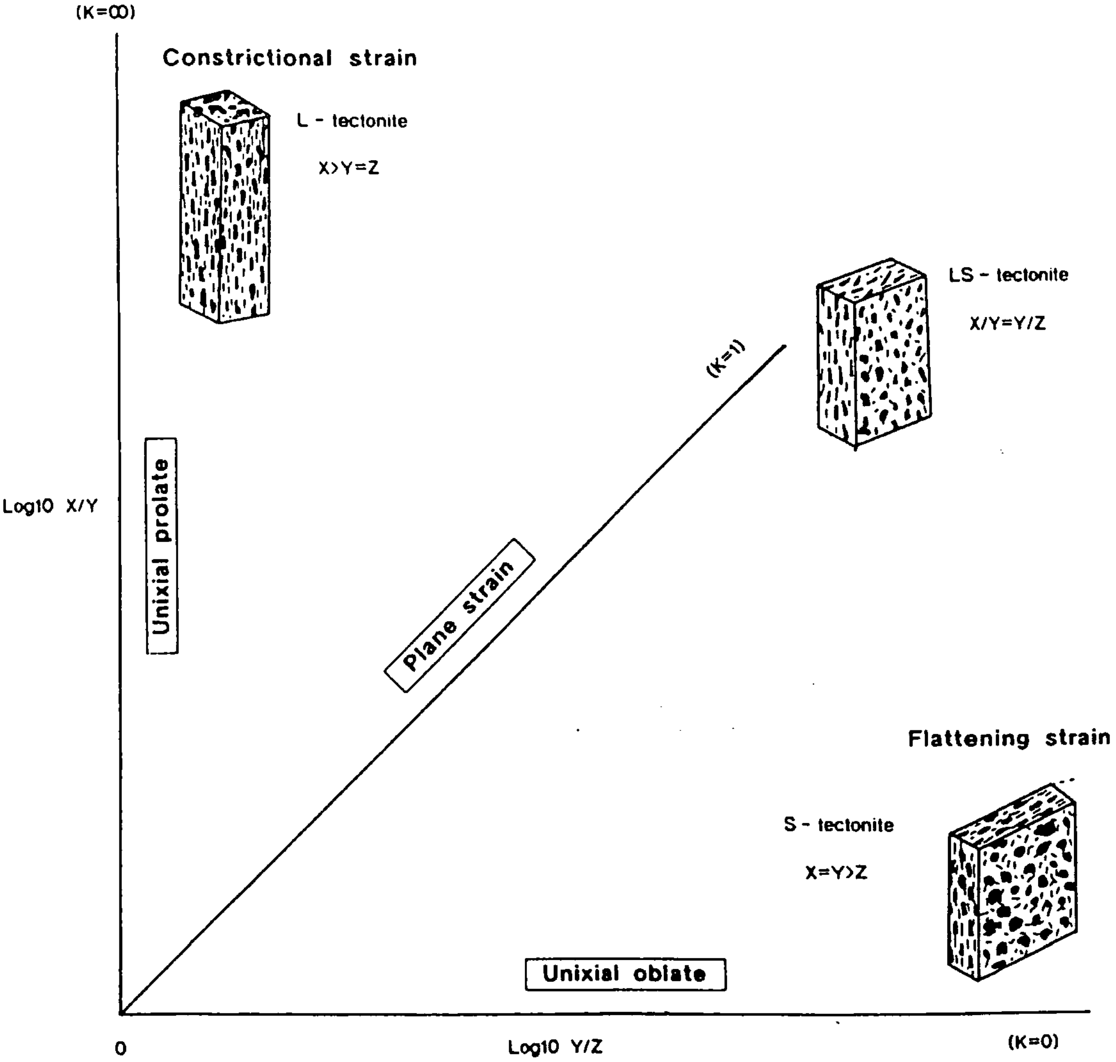


Fig. 1.14. *The Flinn diagram*, which can be used to graphically represent strain data. Basic strain types (end member tectonites) showing qualitative variations in shape change and orientation: plane strain (K = 1), pure flattening strain (K = 0), and prolate, constrictional strain ($1 < K < \infty$).

Another way of determining the K-value is to plot all the values for the mean shape ratios of XY and YZ onto the ***Flinn diagram*** (Fig. 1.14). The best fit line to this data provides the slope from which the K-value can be qualitatively determined assuming simple deformation paths.

Strain magnitude can also be determined by using the ***'nearest neighbour' method of Fry*** (Hanna & Fry 1979; Fry 1979a, b). This is a useful technique, especially if the occurrence of enclaves are localised or sparse throughout the pluton. It involves the measurement of the deformed distribution of phenocrysts. However, for a qualitative value to be close to the true amount of strain imposed, the phenocrysts within the magma have to be essentially uniformly distributed, before the onset of deformation. Another useful technique if the number of enclaves in a particular area is extremely low, is qualitatively estimating the magnitude of strain based on the intensities of PFC and CPS fabrics relative to those in the areas in which enclaves are abundant, allowing quantitative estimates of strain (e.g. Hutton 1988b).

1.7 SHEAR SENSE

As mentioned previously, pure and simple shear represent two members of a range of more general flow types, representing a spectrum from ***irrotational*** (pure shear) to more ***rotational*** (simple shear) flows. The rotational component leads to the development of asymmetries in deformation structures. These asymmetrical structures indicate the ***sense of shear***, (i.e. sense of movement or kinematics) in a progressively non-coaxially deformed material. These structures are termed ***shear sense indicators*** or ***kinematic indicators.*** These are used to describe structures in which information can be obtained about the flow in rocks during progressive deformation. For the determination of the true sense of shear, the indicators must be viewed in a plane that is parallel to the transport direction or stretching lineation and perpendicular to the foliation with which they are associated.

Shear sense can be determined on a variety of scales. Mesoscopically, gross fabric trajectories and the reorientation of regional structures can be used, in conjunction with such information as the amount of strain and the direction of tectonic transport (or the maximum finite extension direction for that particular locality), to deduce the variation of the orientation and magnitude of finite strain across zones of concentrated deformation, i.e. shear zones. Microscopically, a variety of shear sense indicators can be developed within the country rocks surrounding a pluton, and within the granitic rocks themselves, in both PFC and CPS fabrics. The combination of this data from both the deformed pluton and its synchronously deformed aureole are essential in the process of determining how the granite complex was constructed. Two important features are generally recorded (Hutton 1988b): (i) the relative movement between the granite and its wall rocks; (ii) and movements which have been imposed on both the granite and its wall rocks.

1.7.1 Shear zones (non-coaxial regimes)

An important point has been raised by Flinn (1994), that the terms 'shear' and 'shear zone' have so often been used in a wide general sense as synonyms for simple shear, whereas such terms can be equally applied to describe deformation by pure shear. Furthermore, Flinn (1994) notes that simple shear and pure shear are not equal and opposite types of deformation as presented by many authors, as simple shear is two dimensional ($K = 1$) and pure shear is three dimensional ($0 < K < \infty$). This means that the field between these two end-members is infinitely larger than the 'two-dimensional field' generally adopted by most authors.

Recent investigations of orogenic systems suggest that the majority of large crustal scale, transcurrent shear zones are transpressional, consisting of a component of simple shear and a component of pure shear. Along parts of the shear zone system, localised zones of transtension may develop. This transtensional deformation is characterised by a component of simple shear and a component of extension across the zone.

Transpression ('non-coaxial general shear'; see sub-section 1.5.1) is shown by non-coaxial non-plane strains in which K values are typically between 0 and 1. This means that during transcurrent shear the walls bounding the shear zone converge obliquely, which results in the material within the shear zone being shortened horizontally and extended or extruded vertically (Sanderson & Marchini 1984) (Fig. 1.15).

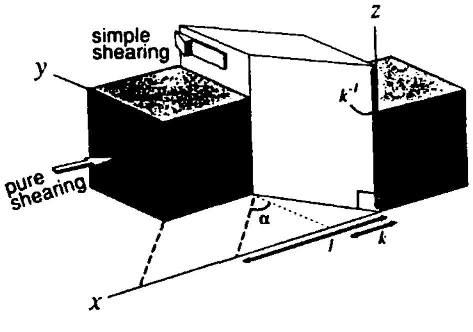


Fig. 1.15. Transpression model (Sanderson & Marchini 1984). Two rigid blocks (dark grey) converge obliquely in a reference system, defining a transpressional zone of deformation (light grey). K and K^{-1} represent the pure shear component of deformation and α denotes the angle of convergence. After Tikoff and Teyssier (1994).

Recent strain modelling by Fossen and Tikoff (1993; see also Tikoff & Fossens 1993, Tikoff & Teyssier 1994, and Teyssier *et al.* 1995) has defined two types of transpression and two types of trantension (Fig. 1.16): wrench-dominated and pure-shear dominated, combined on the basis of the orientation of the strain axis. This modelling shows that, in transpressional settings, the angle of convergence is not parallel to the direction of the compressive instantaneous strain, and the instantaneous and finite strain axes are not coincident. For such reasons, these authors consider that instantaneous strain, rather than stress, is the most relevant quantity to discuss in such tectonic environments.

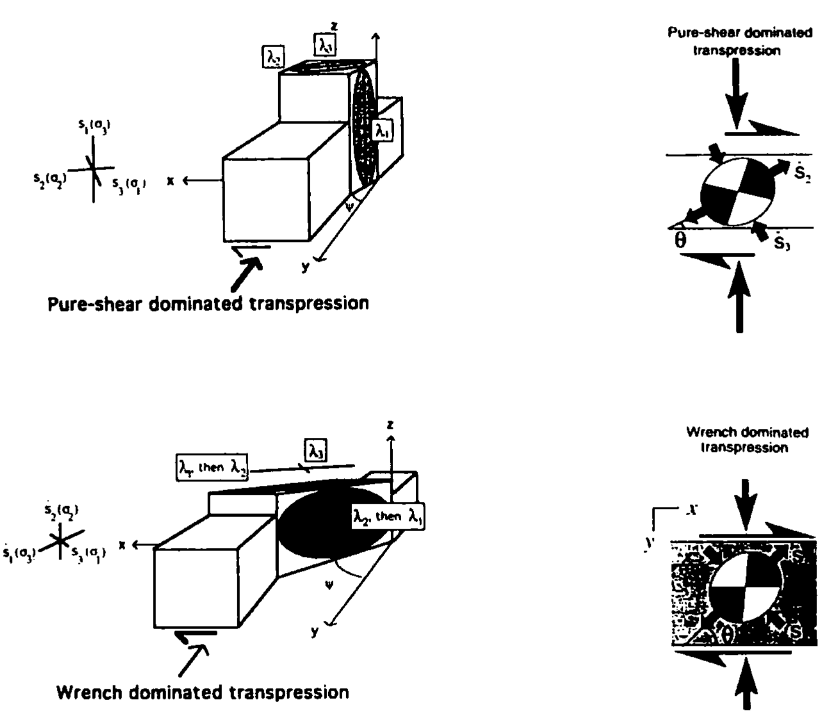


Fig. 1.16. Two types of transpression, distinguished by the orientation of instantaneous strain axes. In pure-shear dominated transpression, the pure shear component dominates both the instantaneous and finite strain. Wrench-dominated transpression results in the mis-orientation of finite and instantaneous strain axes after some deformation, because the instantaneous pure-shear component, although smaller than the simple-shear component, is more efficient at accumulating finite strain. After Tikoff and Teyssier (1994).

1.7.2 The kinematic significance of fabrics (foliations)

1.7.2.1 Simple geometrical relationships

Two types of simple 'shape' fabric can occur in shear zones. Using the nomenclature of Hanmer and Passchier (1991) these are termed as ***strain-sensitive fabrics*** or ***strain insensitive fabrics***.

Strain-sensitive fabrics:

Initially a deformation fabric formed within a continuous, ductile material undergoing progressive simple shear will form at an angle of approximately 45° to the shear zone boundary and to the shear plane (Fig. 1.17). This initial orientation of the foliation is approximately perpendicular to the direction of maximum instantaneous shortening (σ_1). During deformation these fabrics will track the finite strain ellipsoid, being rotated towards the rigid wall rocks bounding the zone of deformation (see Ingles 1986). This model was first proposed by Ramsay and Graham (1970; see also Ramsay 1980a) and accounts for the many observed geometrical relationships of fabrics in natural zones of shear.

Strain-insensitive fabrics:

These fabrics do not closely track the finite strain ellipsoid during non-coaxial progressive deformation. In such rocks as mylonites, which have undergone a high degree of deformation, a fabric often referred to as a ***mylonitic foliation*** (or Sa; Law *et al.* 1984) may develop. In such situations a process of compositional layering and polycrystalline ribbon development (generally quartz) parallel to the shear plane occurs. Commonly developed within monomineralic quartz ribbons in mylonites, the elongated quartz grains lie at an angle of approximately 20-30° to Sa (e.g. Brunel 1980; Lister & Snoke 1984; Law *et al.* 1986; Knipe & Law 1987). The latter relationship was first described theoretically by Means (1981). Such fabrics occur, in general, where, if during the deformational process, distorted grains dynamically recrystallise to form a sub-aggregate of equant grains (Nicolas & Poirier 1976; Poirier & Guillopé 1979) (Fig. 1.18). The geometrical form of the parent grain has therefore gone and the subsequent formation of the sub-aggregate does not contribute to the definition of a shape fabric and so does not closely track the rotating principal directions of finite strain. A process of grain boundary migration occurs, causing coarsening of the sub-aggregate grains (see Kerrich *et al.* 1980; Urai *et al.* 1986) (Fig.

1.18). All these processes occur in the aggregate at any given instant, resulting in the elements of the fabric having an orientation close to the maximum stretching axis of flow.

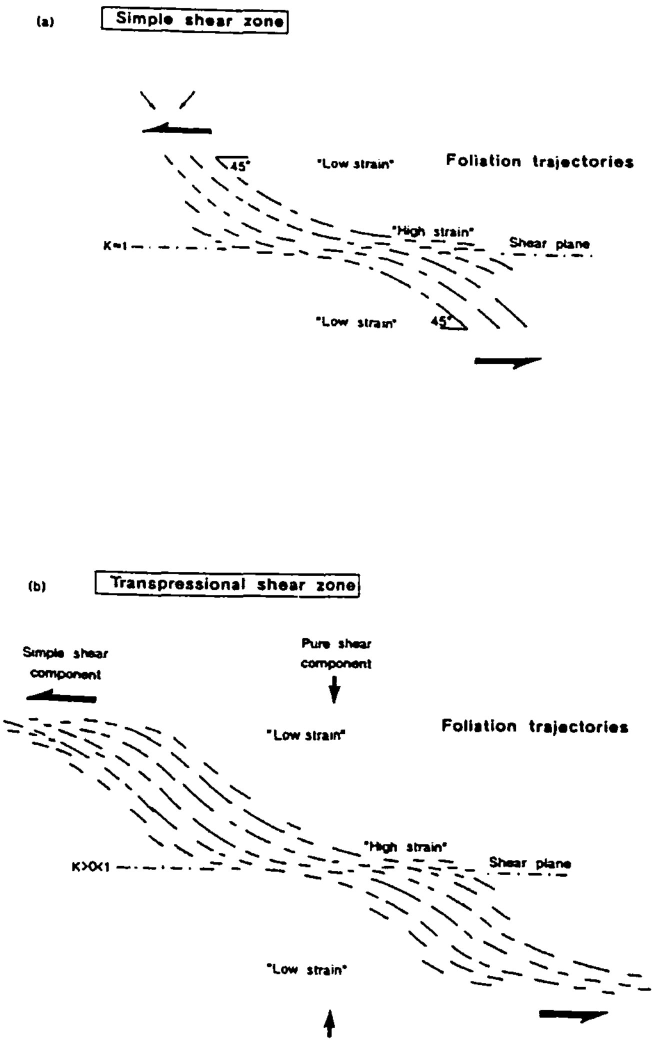


Fig. 1.17. Foliation trajectories for (a) a simple shear zone, and (b) a transpressional shear zone.

Deformation of granitic rocks in the solid state, forming rocks of mylonitic characteristics, could lead to such fabric development. It also appears possible that such geometrical relationships exhibited by strain-insensitive fabrics can develop during the crystallisation of a granitic magma. Within a zone subjected to non-coaxial progressive deformation, early phase phenocrysts such as plagioclase, biotite or hornblende will tend to initially align themselves at approximately 45° to the shear zone boundary. During this progressive deformation these phenocrysts will be rotated towards the rigid wall rocks bounding the zone of deformation, thus forming a sigmoidal foliation trajectory typical of strain-sensitive fabrics. This PFC fabric geometry occurs in granitic magmas with a homogeneous phenocryst distribution. If however the component elements of flow are not uniformly distributed, possibly as a result of mineralogical banding, etc., the material will deform heterogeneously. The deforming media can thus be described as either ***continuous*** or ***discontinuous*** (Berthé *et al.* 1979a; Vialon 1979; Sirieys 1984; Cobbold *et al.* 1984). The development of a strain-sensitive fabric in the magmatic state, will be referred to as a ***continuous non-coaxial PFC fabric*** in this contribution. If some kind of monomineralic banding occurs, a strain-insensitive foliation may develop. In such bands plagioclase phenocrysts, for example, will be more highly concentrated and show a greater tendency for rotation during non-coaxial progressive deformation than the more sparsely distributed phenocrysts outside these zones. This results in the development of essentially monomineralic fabrics which lie sub-parallel to the shear plane. Due to this foliation being a result of non-uniform distribution of flow, it will be termed as a ***discontinuous non-coaxial PFC fabric*** in this thesis (see Ch. 5; sub-section 5.4.2.2). During progressive deformation, both fabrics occur simultaneously.

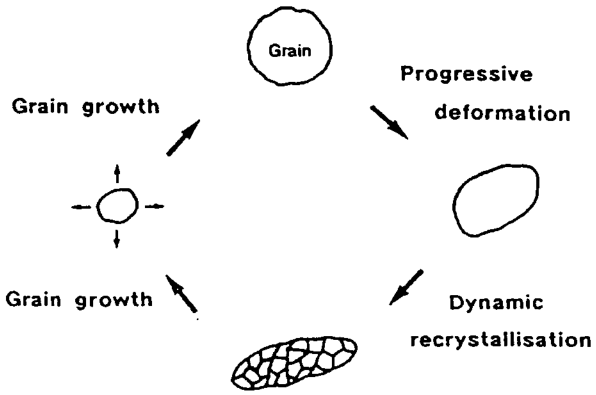


Fig. 1.18. Strain-insensitive simple fabrics. The foliation does not rotate with the finite strain ellipsoid during non-coaxial progressive deformation (see text for explanation). The overall orientation of the fabric-forming elements lies close to the maximum instantaneous stretching axis of the flow. After Hanmer and Passchier (1991).

1.7.2.2 Complex geometrical relationships

The two most kinematically important complex fabrics are ***S-C fabrics*** and ***asymmetrical extensional shear bands***. These fabrics occur in granitic rocks that have been plastically deformed in the solid state and the surrounding metamorphic wall rocks, in which both have been generally subjected to moderately high shear strain.

S-C fabrics:

Berthé *et al.* (1979a; 1979b) first used the concept of asymmetric S-C fabrics in granitic rocks (see also Vernon *et al.* 1983) and this concept has been subsequently used in order to describe shear sense indicators in metamorphic rocks (Lister & Snoke 1984). Shear sense is determined by using the obliquity between two sets of planar foliations (Fig. 1.19): (i) ***S or Schistosité*** (cleavage) planes. This is very much like a strain-sensitive fabric which develops in a continuous shear zone, forming approximately 45° or less to the shear plane and then attempting to track the rotation of the finite strain ellipsoid during non-coaxial progressive deformation (Ramsay & Graham 1970). In granitic rocks this foliation is defined by a shape preferred orientation of lath shaped crystals and deformed lenticular or ovoid crystals or aggregates; (ii) ***C or Cisaillement*** (shear) planes. These lie parallel to the flow plane (using the descriptions of Ponce de Leon and Choukroune (1980)) and essentially represent discrete narrow zones which cross cut and effect an asymmetric shear and extension of the pre-existing schistocity (S planes). Berthé *et al.* (1979a) noted that these shear planes are not simply continuous in nature, but have accommodated differential movements by a combination of mass transfer, crystal-plastic and brittle deformation processes. For this reason, many workers (e.g. Lister & Snoke 1984; Bell & Hammond 1984; Platt 1984; Malavieille & Cobb 1986; Davis *et al.* 1987; Behrmann 1987; Saltzer & Hodges 1988) have used the term shear band to describe such structures, but as pointed out by Hanmer and Passchier (1991) this may lead to confusion as another kinematically important complex fabric, asymmetrical extensional shears (White *et al.* 1980), is often referred to as a 'shear band foliation'.

For shear-sense determination, S-C fabrics are observed in the XZ plane of the finite strain ellipsoid. In moderately deformed granites the spacing between the C planes is often governed by the size of resistant feldspar crystals; the planes are orientated parallel to the bulk shear plane and the shear sense along these planes is synthetic to that of the main S fabric. Along a strain gradient, this spacing decreases with increasing deformation (see Berthé *et al.* 1979a; Cobbold 1977). The S planes are orientated in the extensional quadrants of flow. Later development of secondary planar fabrics may occur; often at high shear strain situations. Both S and C planes are cut by this new generation, which generally form obliquely to both S and the main shear zone (i.e. also oblique to C). These are often referred to as ***extensional crenulation cleavages*** (Platt & Vissers 1980), ***C' planes*** (Ponce de Leon & Choukroune 1980) or ***ecc planes*** (Platt 1984). Multiple sets may occur, with the development of planes which are antithetic with the main shear zone; referred to as ***C' antithetic planes*** or ***ecc2 planes*** (Platt 1984). However, overall these sets are synthetic with the main shear zone.

At high shear strains, the S planes are rotated and may become parallel to both the C planes and to the shear plane of deformation; mylonites result.

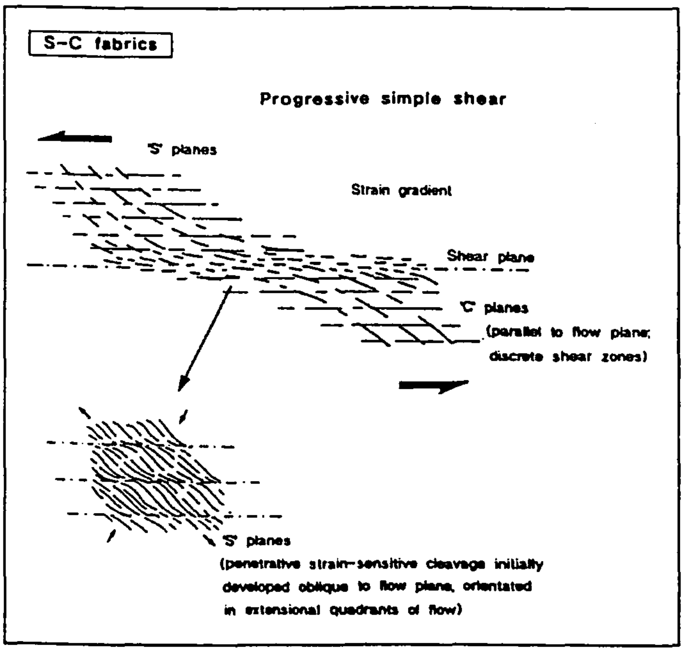


Fig. 1.19. S-C fabrics. C planes are discrete shear zones. The S fabric describes a sigmoidal shape, and in the granite context represents the main penetrative foliation. Modified after Hanmer and Passchier (1991).

Asymmetrical extensional shear bands:

Geometrically asymmetrical extensional shear bands (terminology of Hanmer & Passchier 1991) can appear very similar to S-C fabrics in hand specimen. They are a common shear sense indicator in anisotropic rocks such as mylonites, schists and phyllites, often associated with wall rock deformation around plutons. Several terms, such as ***C' structures*** (Berthé *et al.* 1979b), ***shear band foliation*** (White *et al.* 1980), ***asymmetrical***

extensional crenulation and *cleavage* (Platt & Vissers 1980), have been used to describe such structures.

In general, the geometrical relationships observed are a set of 'shear bands' or discrete shear zones which have developed obliquely to the bulk flow plane; at an angle of approximately 15-25° (Fig. 1.20; e.g. Platt 1984). These shear bands are synthetic to that of the main shear zone and accommodate non-coaxial flow in these bands of finite thickness. Initially two sets of shear bands forming a conjugate arrangement may develop. The main mylonitic foliation is parallel to the bulk flow plane and the shear bands are symmetrically orientated about the instantaneous stretching axes of bulk flow. In general, the set of shear bands closest in orientation to that of the mylonitic foliation (anisotropy) are developed. However, it is not uncommon for both sets of shear bands to develop, forming a conjugate system (see Harris & Cobbold 1985; Behrmann 1987).

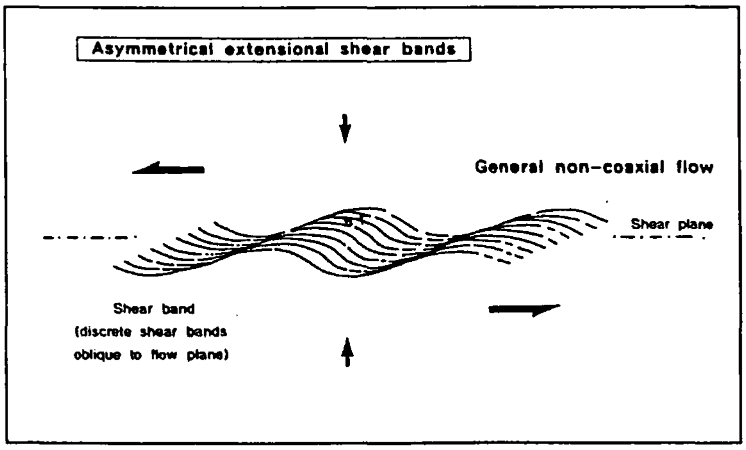


Fig. 1.20. Asymmetrical extensional shear bands. Modified after Hanmer and Passchier (1991)

The bulk shear sense is obtained by viewing such structures in the XZ plane of the finite strain ellipsoid. The oblique relationships of the strongly developed foliation within these rocks and the development of the extensional shear bands gives the asymmetry needed in order to determine the displacement sense.

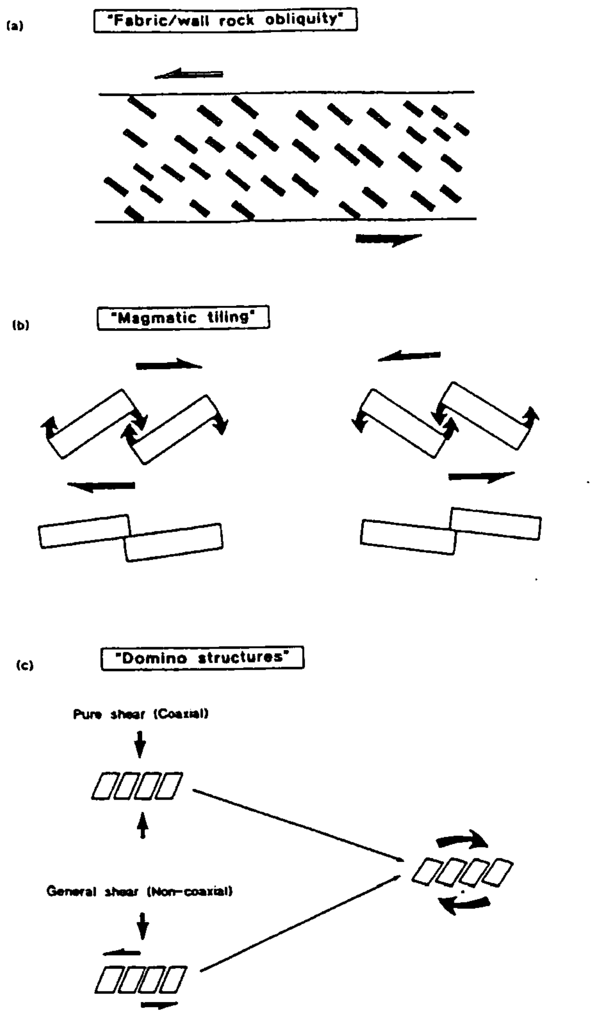


Fig. 1.21. PFC / magmatic state shear sense indicators: **(a)** fabric/wall rock obliquity; **(b)** tiling of early formed phenocrysts, which rotate into contact in response to shear. **(c)** Domino structures.

1.7.3 Shear sense indicators developed in PFC fabrics

Granite magmas which are well in excess of their RCMP (Arzi 1978) can develop a number of fabric-related structures during progressive non-coaxial deformation. These structures are developed during the formation of PFC fabrics by the rotation and alignment of phenocryst phases such as feldspar and mica (Hutton 1988). These lath shaped crystals rotate freely in the remaining melt, as with strain-sensitive fabrics (see Fig. 1.17a), tracking the finite strain ellipsoid. This rotation and alignment leads to the development of oblique fabrics in relation to the undeformed walls bounding the shear zone and the interaction of phenocrysts with each other. These relationships, from which the sense of shear can be deduced, were first described by Blumenfeld and Bouchez (1988). These include: (i) the obliquity between magmatic state fabric (or PFC fabric) and the walls bounding the deforming shear zone (Fig. 1.21a); (ii) the relationship of megacrysts which have collided during rotation, to form tiling or imbrication structures (Fig. 1.21b). In sinistral shear these rotating megacrysts will form left-stepping overlaps; rotating megacrysts in dextral shear will block at right-stepping overlaps (Blumenfeld 1983). These shear sense indicators must be treated with caution, especially with fabric development towards and across the RCMP and in the solid state, as the resultant geometries from such a process can be equally produced by domino type structures (Simpson & Schmid 1983; Brunel 1986) developed during pure shear general non-coaxial flow (with an opposite shear sense) (Fig. 1.21c; Hanmer & Passchier 1991); (iii) and the obliquity between magmatic state sub-fabrics (e.g. Fernandez & Laporte 1991; Ildefonse *et al.* 1992; Ch. 5).

Bimodal fabrics developed during 'magmatic state' deformation

As mentioned above, the obliquity between magmatic state sub-fabrics can be used as a shear sense indicator. This is based on the obliquity of the orientation between particles of different aspect ratios. The importance of bimodal fabrics within igneous rocks has received considerable attention over the last decade, involving experimental modelling (e.g. Fernandez *et al.* 1983; Fernandez 1987; Ildefonse 1987; Ildefonse & Fernandez 1988; Ildefonse *et al.* 1992) and detailed field analysis (e.g. Benn & Allard 1989; Fernandez 1988; McErlean 1992). Before these studies a significant amount of work had been carried out on the problem of rigid particle rotation and orientation in a flowing medium. The first major theoretical study was carried out by Jeffrey (1922), which investigated the motion of ellipsoid particles suspended in a viscous fluid (see Ramsay 1967). Other important investigations included Gay (1968) and Ghosh and Ramberg (1976). Despite the theoretically likely complexities involved (e.g. the three-dimensional behaviour of rotating particles, the interaction and possible deformation of particles as they rotate and collide, and the change in viscosity contrast between particles and matrix during crystallisation), field observations that aimed at determining the sense of shear from sub-fabrics in granites, are comparable with the results of experimental modelling. The concept of bimodal fabric analysis to deduce the sense of shear within granitic rocks has been used with caution during this study (see Ch.'s 4, 5 & 7). The viability of deducing the sense of shear from the analysis of bimodal fabrics within the field during this work, have always been checked with reference to a number of other 'magmatic-state' kinematic indicators such as imbricate tiling, fabric obliquity to wall rocks, and overall gross fabric trajectories.

The development of the preferred dimensional orientation of particles during 'magmatic deformation' is briefly discussed below and is primarily based on the review by Nicolas (1992). As employed by this author, the term 'magmatic deformation', or 'pre-full crystallisation deformation' as used by Hutton (1988; see sub-section 1.6.1) will be used to describe fabric development during the 'magmatic state'. In general, particles (e.g. phenocrysts) are rotated and aligned, and show no internal deformation because the strain is taken up by the liquid matrix. However, in reality these 'deformation markers' or 'active markers' may undergo changes in their form (size and shape) as they grow during the deformation process. Also as crystallisation proceeds and the crystal content rises, the rotating rigid particles will increasingly interact leading to some internal plastic deformation. With increasing down-temperature deformation, into the solid-state regime, 'shape-particles' produced by magmatic deformation give way to 'lattice-fabrics' developed by plastic flow. The following models only consider rigid particles, not particles plastically deformed due to interaction within the melt suspension.

Rigid particle rotation

During pure shear (coaxial deformation) a rigid particle will rotate towards a stable orientation, at which its long axis is parallel to the stretching direction x (Fig. 1.22a). With increasing shape ratio n, the velocity of rotation increases. Once the particles have been rotated into parallelism with the maximum extension direction, their preferred dimensional orientation will remain parallel to this plane even if the pure shear deformation continues.

During simple shear (non-coaxial deformation) a rigid particle will rotate continuously and periodically (Fig. 1.22b). The orientation of a particle with respect to the shear plane ('shear direction') depends on several factors: (i) its shape ratio n; (ii) the magnitude of shear strain γ already imposed; and (iii) the initial orientation of the particle with respect to the shear plane.

The development of shape fabrics during simple shear is controlled by the angle the particle makes with respect to the shear plane, as this governs its velocity, i.e. the angular velocity of the particles varies (Fig. 1.23). The angular velocity is at its maximum when the long axis of the particle is normal to the shear plane, and at a minimum when its long axis is parallel to the shear plane.

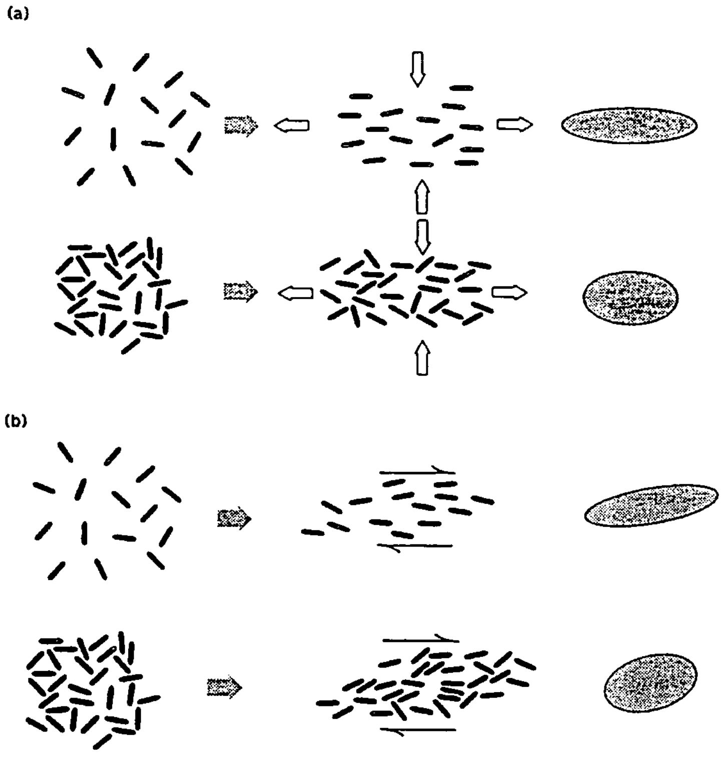


Fig. 1.22. Sketch summarising the Ildefonse and Fernandez (1988) 2-dimensional experiments on rigid particles embedded in a weak matrix. **(a)** Pure shear deformation. **(b)** Simple shear deformation. Upper and lower sketches in (a) and (b) represent non-interacting and interacting particles, respectively. After Nicolas (1992).

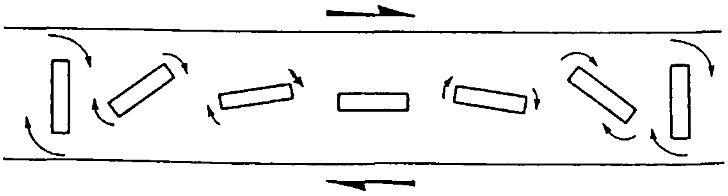


Fig. 1.23. Rotation of a rigid particles during non-coaxial deformation. The length of the arrows is proportional to the angular velocity of the particle. After Nicolas (1987).

As we move more away from these simple cases, and into more realistic conditions where particles as they rotate may collide, complexities will arise during fabric development and provide relationships which can be used to determine shear sense (see below).

How fast particles rotate during deformation is largely governed by their aspect ratio. In general, particles with the smallest aspect ratios rotate faster, than particles with high aspect ratios (Fig. 1.24). However, this is not always the case as it may depend on the shape of the particle (near-spherical particles have limited angular domains) and short particles with aspect ratios of approximately 2.5 may undergo reverse rotation giving the apparent effect that the particles with higher axial ratios have rotated more and faster (see below). These experiments show that in general, a suspension of particles with different aspect ratios subjected to a component of non-coaxial deformation will undergo a 'process of angular sorting', leading to the development of sub-fabrics (Fig. 1.24; see Fernandez *et al.* 1983; Fernandez & Laporte 1991).

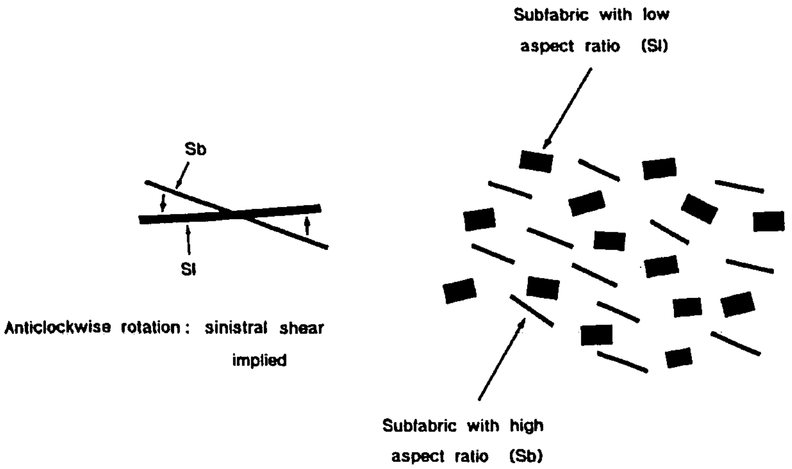


Fig. 1.24. Sub-fabrics resulting from simple shear. The sense of shear is deduced by visually rotating the sub-fabric defined by particles with high aspect ratios towards the sub-fabric defined by particles with low aspect ratios (see text for explanation). Modified after Fernandez and Laporte (1991).

The angular relationship between the sub-fabrics, which correspond to different minerals in a rock (e.g. K-feldspar and biotite), or different families of the same mineral, is used to infer the sense of shear within the XZ plane (Fig. 1.24; Fernandez & Laporte 1991). This is based on the aspect ratio of the particles, as rigid low aspect ratio particles have higher angular velocities (as mentioned above), and so a smaller period of rotation than particles with high aspect ratios. This means that low aspect ratio particles will rotate into parallelism with the shear plane faster than those with higher aspect ratios. The sense of shear is determined by visually rotating the sub-fabric defined by the particles with high aspect ratios towards the sub-fabric defined by particles with low aspect ratios, as this would have been the sense of rotation towards the shear plane if the system had not 'frozen'. This model is based on the assumption that the concentration of particles is low, so preventing interference, and the sub-fabrics are in their first cycle of evolution. However, during magma crystallisation, the crystal content will progressively increase and the crystals ('particles') will interact. This has been modelled two-dimensionally by Ildefonse and Fernandez (1987), and Ildefonse *et al.* (1992), which suggests that in simple shear, the interacting particles tend to pile up to form a tiling or imbrication texture (Den Tex 1969; Blumenfeld 1983). This tiling effect slows down their rotation and thus keeps the particles at an angle to the shear plane for a longer period of time (Fig. 1.25).

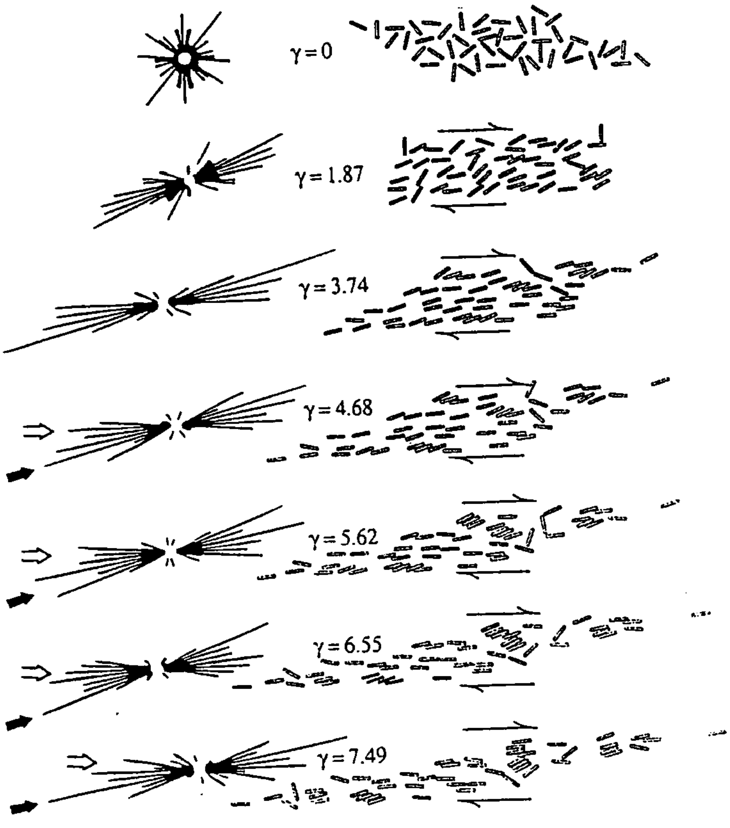


Fig. 1.25. Two-dimensional experiments on orientation during progressive simple shear of identical rigid particles (n = 5) embedded in a weak matrix. Black arrows: sub-fabric of interacting particles; white arrows: sub-fabric of free particles. After Ildefonse and Fernandez (1988) *in* Nicolas (1992).

An interesting point, is that with low aspect ratio particles (n = 2.5), the fabric axis may undergo reverse rotations for large shear strains (Fig. 1.26; Ildefonse & Fernandez 1988) (see Ch. 5, sub-section 5.4.4).

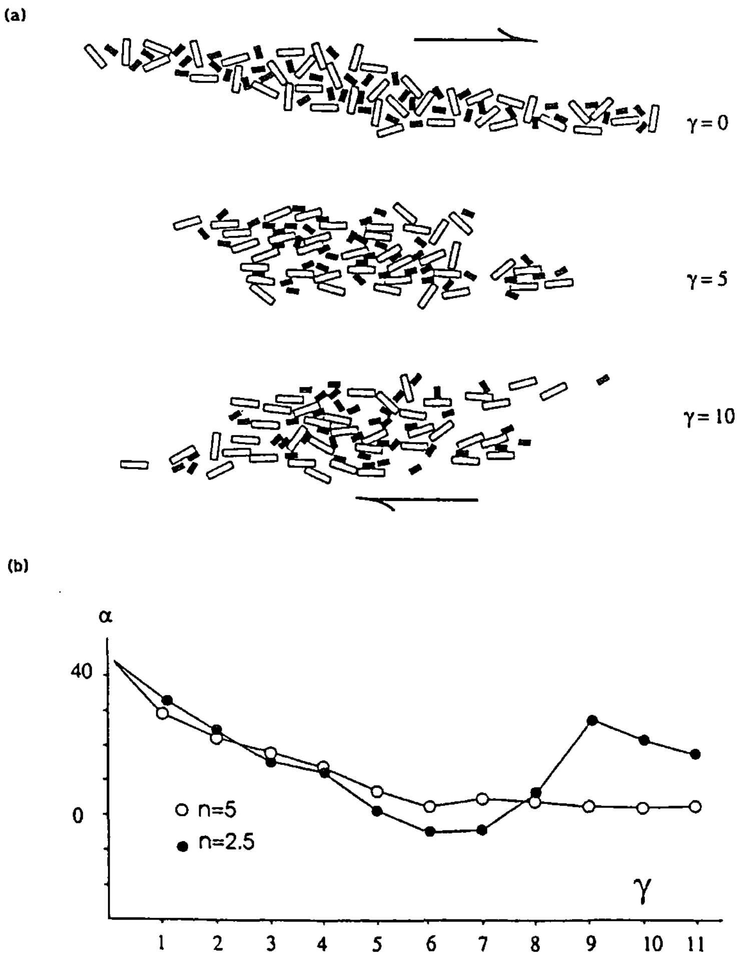


Fig. 1.26. (a) Same as in Fig. 1.25, but with two classes of particles (black: n = 2.5; white: n = 5). **(b)** Related sub-fabric rotations x toward the shear direction (x = 0) as a function of y for the two types of particles. An interesting point is that the short particles' sub-fabric tends to rotate backwards for large shear strains (γ). After Ildefonse and Fernandez (1988) *in* Nicolas (1992).

Another important shear sense indicator is the angular relationship between the long axis of microgranitoid enclaves and the PFC fabric developed within its host. This is because passive markers ('weak inclusions') during non-coaxial deformation will track the finite strain ellipsoid so that its long axis (x) is parallel to the direction of maximum extension, forming an angle to the PFC fabric which progressively rotates towards the shear plane (Fig. 1.27).

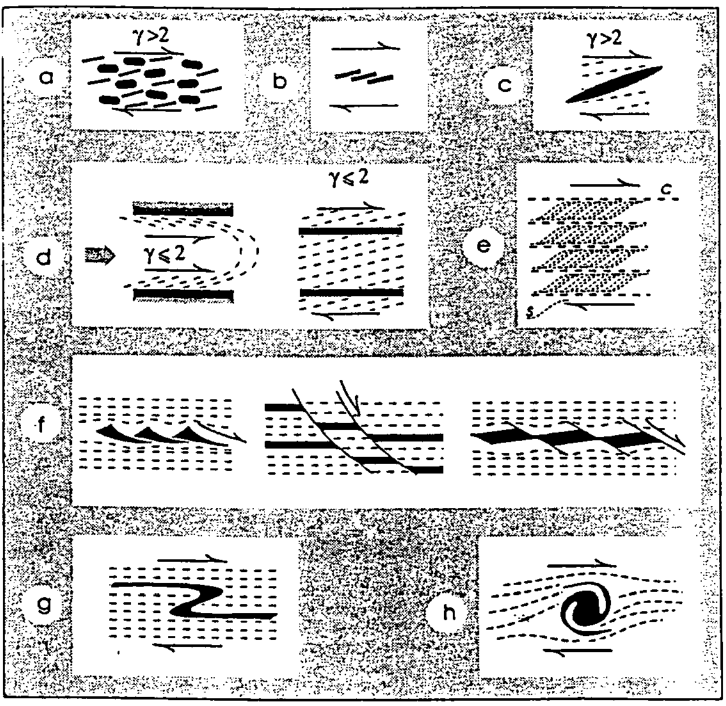


Fig. 1.27. The various shear sense indicators in non-coaxial magmatic flow. **(a)** Obliquity between shorter and longer particles' subfabrics: the shorter particles are closer to the shear direction. **(b)** Tiling of particles in dense suspension. **(c)** Obliquity between weak inclusions or enclaves elongated in the stretching direction and rigid particles' subfabric tending toward the flow plane. **(d)** Obliquity between rigid particles' subfabrics and flow plane; to the left, the flow plane is identified as being parallel to the intrusion wall (pinching effect) and to the right, to strong layers channelling the flow. **(e)** S/C structures (C direction may be that of faint layering). **(f)** Diverse types of normal faults. **(g)** Asymmetrical folds (axis still at some angle to flow lineation). **(h)** Rotation markers, here a snowball inclusion. After Nicolas (1992).

Strain partitioning as a consequence of heterogeneous deformation during pre-full crystallisation may lead to the 'mimicking' of solid state structures, such as S-C fabrics (Fig. 1.28; Bard 1986), and asymmetrical shear band type geometries (see Ch. 3; sub-section 3.4.2.2).

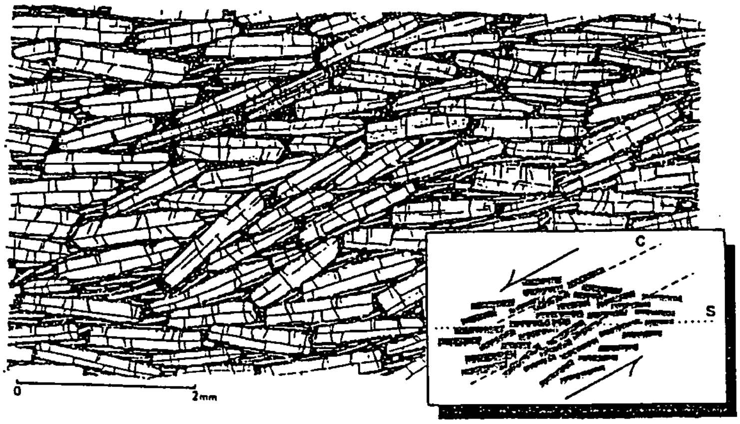


Fig. 1.28. Partitioning of magmatic state deformation into domains where tiling predominates (S orientation) separated by shear bands. 'PFC fabric' essentially mimicking S-C structures. Drawing by Bard (1986), analysed by Nicolas (1992).

1.7.4 Shear sense indicators developed in CPS fabrics and wall rocks

As already mentioned the first application of kinematic indicators in granitic rocks was made by Berthé *et al.* (1979); using the term ***S-C mylonite*** to describe the shear sense indicators in an orthogneiss, developed in the South Armorican Shear Zone, France. S-C fabrics can also develop in the wall rocks of plutons during deformation. Another kinematically important fabric is asymmetrical extensional shear bands (see sub-section 1.6.2.2). As already mentioned, these occur in strongly foliated rocks such as phyllites and mylonites and can be well developed within the aureoles of plutons.

Other shear sense indicators include:

Porphyroblasts:

Crystals which have grown in the solid state (i.e. porphyroblasts) can undergo rotation during or after their growth (e.g. Spry 1969; Rosenfeld 1968; 1970; Wilson 1971; De Wit 1976; Jamieson & Vernon 1987; Mandal & Banerjee 1987). The growth and rotation of these relatively stiff crystals, e.g. garnet, during progressive deformation leads to the development of ***inclusion trails***. Both internal and external trails are developed and are referred to as the ***internal foliation*** (Si) **and** ***external foliation*** (Se) respectively. The difference in orientation between the two foliations is used to determine the relative rotation of the porphyroblast and hence the sense of shear. The term ***snowball structure*** is often used to describe such features produced by porphyroblast growth during shear motion. This process produces an internal foliation with a sigmoidal geometry, which can enable the identification of this ***syntectonic porphyroblast*** (Fig. 1.29a) from ***pretectonic porphyroblasts*** (Fig. 1.29b); essential in determining time relationships between localised deformational episodes and regional metamorphism.

Porphyroclasts or asymmetric augen and asymmetric pressure shadows:

Shear sense indicators, such as ***porphyroclasts* or *asymmetric augens*** and ***asymmetric pressure shadows*** on porphyroclasts, are common structures in both granitic rocks which have undergone deformation in the solid state and their wall rocks. Porphyroclasts develop as a result of rotation and deformation, principally by crystal-plastic state processes, of flow-resistant phenocrysts such as feldspar. This deformational process results in a core- and mantle-microstructure, in which a relatively soft polycrystalline mantle surrounds a stiff relic monocrystalline core (White 1976). During rotation, the soft mantle may be drawn out as either side of the clast along the direction of maximum finite extension, to form ***wings***. Based on the deformation experiments of Passchier and Simpson (1986), porphyroclasts can be classified into ***σ-type porphyroclasts*** (Fig. 1.30a) or ***δ-type porphyroclasts*** (Fig. 1.30b). The geometry of the structures result because as the wings develop they are progressively rotated towards the flow plane. σ-structures are developed when recrystallisation rates are higher than the rotation rates; typically low shear strains. A full mantle is maintained around the clast. δ-structures occur when recrystallisation rates are higher than the rotation rates; typically high shear strains. Other inclusions such as microgranitoid enclaves, which show a competency contrast with its host, may form σ-type geometries reflecting the sense of shear induced.

Pressure shadow development during progressive deformation occurs when the rate of inclusion extension is slower than that of the surrounding matrix. This results in the matrix flowing away from the sides of the inclusion which make a high angle in respect to the direction of maximum extension. Low pressure zones result in the extensional quadrants of flow. Material migrates along the pressure gradient towards these zones of low pressure. This results in the development of the pressure shadows, which are polycrystalline aggregates without an internal shape fabric; a number of modes of formation are possible (see review by Hanmer and Passchier 1991; see also sub-section 1.5.4 'redistribution of intercrystalline fluids'). Caution must be exercised, as in some cases the whole pressure shadow structure can be deformed and rotated, to give an apparent sense of shear that is opposite to that which has been induced (see White and Wilson 1978;

Hanmer 1988a). The above shear sense indicators developed in the solid state are mainly a product of ductile deformation. Other types of shear sense indicator developed in the solid state include: (i) **pressure fringes** (e.g. Fairburn 1950; Zwart & Oele 1966; Choukroune 1971; Durney & Ramsay 1973; Beutner & Diegel 1985; see reviews by Ramsay & Huber 1983; Etchecopar & Malavieille 1987); (ii) ***crystallographic fibres*** (e.g. Lister & Hobbs 1979; Simpson 1986; Low 1990); (iii) ***tension gashes***; en-echelon arrays of sigmoidal veins (Ramsay & Graham 1970); (iv) oblique and curved fibrous **vein-infilling**; synkinematic development (e.g. Choukroune & Seguret 1968; Ramsay & Graham 1970; Beach 1975; Gamond 1983); (v) internal and fabric development in **incompetent veins** (e.g. Berger 1971; Talbot 1982); (vi) deformation of **competent veins**, either by boudinage or ductile necking processes, e.g. forming oblique boudin trains (e.g. Hanmer 1984a); (vii) local observations of **fold asymmetry** (Ramsay *et al.* 1983) and **rotation of planar structures**, i.e. axial planes, fold limbs (Murphy 1987); (viii) geometrical analysis of **fractures** (see Ramsay & Huber 1987); (ix) and **slikenside** and **slikenfibre** development (see Ramsay & Huber 1987).

The presence of antithetic shear in many zones of deformation, means that any one type of kinematic indicator should not be used in isolation. It is therefore important, that in general, a number of different types of structures, on a variety of scales, are used in collaboration with each other when determining the overall shear sense of a locality or region.

Fig. 1.29. **(a)** Syntectonic porphyroblast. **(b)** Pretectonic porphyroblast. After Ramsay and Huber (1987).

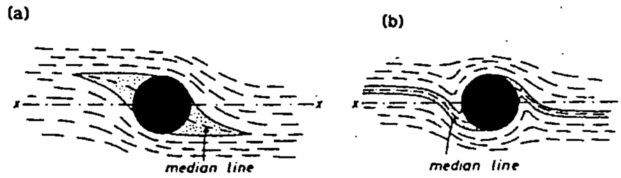


Fig. 1.30. **(a)** σ-type porphyroclast. **(b)** δ-type porphyroclast. After Ramsay and Huber (1987).

CHAPTER 2

THE PLUTONS OF THE ARGYLL SUITE AND THEIR COUNTRY ROCKS

2.1 INTRODUCTION

This Chapter outlines the broad geochemical and isotopic characteristics of the granites and associated intrusives within the Argyll Suite (Stephens & Halliday 1984), briefly presenting the principal models proposed for their genesis. It also provides a summarised account of the deposition and subsequent deformation of the surrounding Dalradian metasedimentary rocks and the structures developed during the evolution of the Caledonian orogenic belt, into which these granites have been intruded.

2.2 PLUTONS WITHIN THE ARGYLL SUITE AND ASSOCIATED INTRUSIVES

The plutons which have been studied in detail within the SW Grampian Highlands are Etive (2), Glencoe (3), Rannoch Moor (7) and Strath Ossian (8) (Fig. 2.1). A brief reconnaissance survey of two more plutons, Ballachulish (1) and Ben Nevis (6) (Fig. 2.1) was also carried out to establish whether their emplacement dynamics would provide any additional information on the regional tectonic processes operating at the time of Caledonian plutonism (425-400 Ma).

These late multiphase Caledonian complexes were emplaced into the late Proterozoic Appin and Argyll Groups of the Dalradian succession (see sub-section 2.4.2). These Siluro-Devonian plutons, known as the "Newer Granites" (Read 1961), based on a variety of petrographic, geochemical, and isotopic criteria (see review by Brown *in* Craig 1991) fall within the 'Argyll Suite' of Stephens and Halliday (1984). Geographically, the Argyll Suite is essentially bounded to the NW by the Great Glen Fault and delimited to the SE by the isotopically-defined 'Mid-Grampian Line' (Fig. 2.1; Halliday & Stephens 1984). Petrographically, a wide range of rock types are present, ranging from ultrabasic and basic compositions, including appinites, pyroxinites, hornblendites, and gabbros, through hornblende +/- biotite diorites, granodiorites and granites.

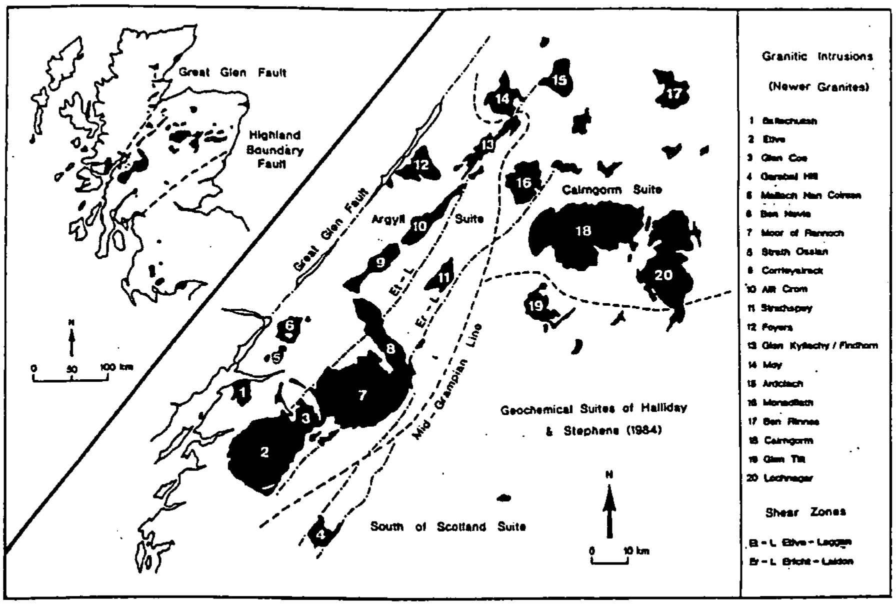


Fig. 2.1. Distribution of granitoids in the Grampian Highlands, showing boundaries of geochemical suites of Halliday and Stephens (1984).

The Appinite Suite

The earliest activity associated with this late Caledonian magmatic event is represented by the appinite suite. Appinites are distinctive coarse-grained, ultramafic to intermediate igneous rocks, generally considered to be related to the lamprophyric group of minor intrusives (Hunter & Rock 1987). They are often interpreted as being cumulates from volatile-rich, K-rich basaltic or intermediate magma (French 1966; Hall 1967; Wright & Bowes 1979), and are therefore generally assumed to be sub-crustal in origin, in which they have been emplaced, often explosively, via, what are often interpreted as deep crustal structures (Bowes & Wright 1967). Their origins are substantiated by geochemical analysis (Wright & Bowes (1979); Hamidulla & Bowes 1987) which reveals that they contain high concentrations of Ni, Cr and MgO, leading to the conclusion that they represent compositions close to primary mantle magmas. Rogers and Dunning (1991) suggested that their high contents of Sr, Ba and LREE also indicate primitive unfractionated compositions, inferring again that magma emplacement must have been rapid via deep seated structures which extend to the base of the crust. Recent studies using U-Pb geochronological techniques (Rogers & Dunning 1991) suggest that the ages of the appinite suite in the Western Highlands lie in a narrow range, and within the Argyll Suite were emplaced at 427 +/- 3 (Rubha Mor intrusion, titanite).

2.3 GENESIS OF CALEDONIAN PLUTONS

The tectonic environment at the time of this late Caledonian plutonism (425-400 Ma) has been related (Soper & Hutton 1984; Hutton 1987) to the final oblique closure of Iapetus. Watson (1984) suggested that the post-collisional tectonic regime dominated by strike-slip movement was the "crucial factor responsible for the onset of magmatism", and that the relationship between tectonics and magmatism was therefore genetic. The termination of the Caledonian orogeny with the closure of the Iapetus Ocean, in the late Precambrian to early Silurian times, was accompanied by the intrusion of a large amount of granitoid material predominantly into the Scottish continental crust. An earlier phase of granite emplacement between approximately 460-430 Ma was subsequently succeeded by a more voluminous event extending from about 430-390 Ma encompassing the plutons under discussion within this study. Read (1961) proposed that these so called 'Late granitoids' could be sub-divided according to their emplacement style, using the term 'Newer granites' for an earlier phase which had been forcefully injected into the country rocks and 'Last granites' for those which had been passively emplaced by processes associated with cauldron subsidence and tensional faulting. Read (1961) suggested that the forceful 'Newer' granites could be separated in time from the passive 'Last' granites by the deposition of the Lower Old Red Sandstone, occurring between the two events. However, such a temporal classification cannot be applied throughout the rest of the British Caledonides, as for instance in the Donegal region, forceful-type emplacement of the Main Donegal pluton (Hutton 1982) post-dates passive-type emplacement of the Rosses complex (Pitcher & Berger 1972). Similar situations occur within the Scottish Southern Uplands and also appears to be the case in the Argyll region (this study; see Chapter 11) again suggesting that such a temporal classification is inapplicable.

One of the most hotly debated questions concerning the distribution of the pluton ages and their compositional characteristics is the genesis of these granitoids and how their production relates to the tectonic setting prevailing at that time. Regional chemical trends amoung the granitoids have led many workers (e.g. Thirlwall 1981; 1982; Soper 1986) to propose the involvement of subduction in their genesis. A north-westward increase in Sr, Ba, La/Y and K in the contemporaneous Old Red Sandstone lavas has led Thirlwall (Fig. 2.2; 1981; 1982; 1989) to suggest that this is related to a WNW-dipping subduction zone. However, there are problems with such a model: (i) the late timing of the granite production relative to the closure of Iapetus; (ii) differences in granite geochemistry (such as lower amounts of Ca) compared to 'true' subduction-related granites, e.g. the Cordilleran granites of Peru; (iii) regional chemical and isotopic trends are not entirely typical of those expected for calc-alkali magmas associated with subduction, with such differences as a decrease in Rb (Stephens & Halliday 1984) moving away from the postulated zone of subduction, opposite to that which would be expected (Gill 1981; Stephens & Halliday 1984). It has been suggested (Clayburn *et al.* 1983; Harman *et al.* 1984) that such isotopic and chemical differences may be due to a change in crustal composition moving from the Southern Uplands to the Highlands of Scotland, thus resulting in a variation in source-inherited components between the two regions. The discrepancies in chemical and isotopic characteristics of these granites from those typical of subduction, led Pitcher (1982) to sub-divide I-type granites (see Ch. 1; sub-section 1.4) into I(Cordilleran)-types and I(Caledonian)-types, suggesting that the latter group had been produced by a different process involving adiabatic decompression melting during rapid post-orogenic uplift (e.g. Simpson *et al.* 1979; Brown *et al.* 1981; Pitcher 1982; Zhou 1985).

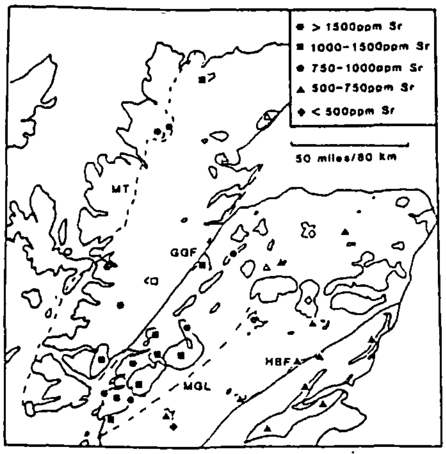


Fig. 2.2. Typical Sr concentrations in magmas with less than 65 % SiO_2 (solid symbols) or with 65-70 % SiO_2 (open symbols) in northern Scotland. MT, Moine Thrust; GGF, Great Glen Fault; MGL, Mid-Grampian Line; HBF, Highland Boundary Fault. Data sources: Stephens & Halliday (1984), Thirlwall (1979, 1982), Thompson & Fowler (1986). Areas of igneous rock with no symbols have no published data for rocks with < 70 % SiO_2. After Thirlwall (1989).

A two-plate model has been suggested by Soper *et al.* (1987) to account for the timing and distribution of the granites, proposing that two separate subduction zones were developed during terrane-accretion; one dipping towards the west generating the granites of the Eastern Highlands, and the other dipping northwards producing the granites of the Western Highlands. This palaeo-tectonic scenario has been questioned on the basis that the closure of Iapetus and associated subduction processes must have been complete by Ordovician or mid-Silurian times (e.g. Phillips *et al.* 1976; Watson 1984) therefore not adequately explaining the genesis and distribution of Siluro-Devonian granites by a subduction-related magmatic arc model (Soper 1986; Thirlwall 1988). To account for such discrepencies a three-plate collision model (Soper 1986, Soper *et al.* 1987) was suggested, in which a series of subduction-related magmatic arcs overlapped in time and space (Fig. 2.3). This geotectonic model attempts to explain the distribution of the 'Late granitoids' north of the Highland Border by northward subduction at the Solway Line during Silurian to early Devonian times, and within the slate belts of the Southern Upland by subduction related to the northward accretion of the Armorican terrane, which resulted in early Devonian collision with Avolonia at the Mid European Caledonide suture (Fig. 2.3). The latter event has been disputed by Thirlwall (1988) on the basis that it does not explain in the Southern Upland a change in ages from 394 Ma in the south to 408 Ma in the north, together with a marked depletion in K, Th, Rb and LREE from south to north.

As mentioned above, the tectonic environment at the time of 'Late granite' emplacement (425-400 Ma) has been related (Soper & Hutton 1984; Hutton 1987) to the final oblique closure of the Iapetus Ocean. Hutton and Reavy (1992) have argued that the Caledonides during this period were therefore subjected to a gross sinistral transpressional deformation, and that NE-SW-trending transpressional faults and shear zones, such as those described by Watson (1984), are the typical expression of this event. This has led Hutton and Reavy (1992) to propose a completely different mechanism for the genesis of the granitoids, in which transcurrent shear zones not only controlled the siting and ascent of magma and the emplacement of plutons, but may have been ultimately responsible for granite petrogenesis due to anatexis of thickened crust at the lower limits of transpressional crustal scale shear zones detatching into the Moho (Fig. 2.4). Although there are many possible causes for differences in petrological and geochemical character between adjacent granitic suites, Jacques & Reavy (1994; Ch. 9) have argued that there is a possibility that differences in tectonic environment during anatexis and magma emplacement within the Grampian Highlands of Scotland, could have been a strong influencing factor in determining petrological characteristics. This is based on observations that the Argyll Suite coincides closely with the region where transpressional strike-slip faults are demonstrably present, whereas such faults are less obviously present in the NE Highlands (Fig. 2.5; see Ch. 9), the area designated as the Cairngorm Suite (Fig. 2.1; Stephens & Halliday 1984).

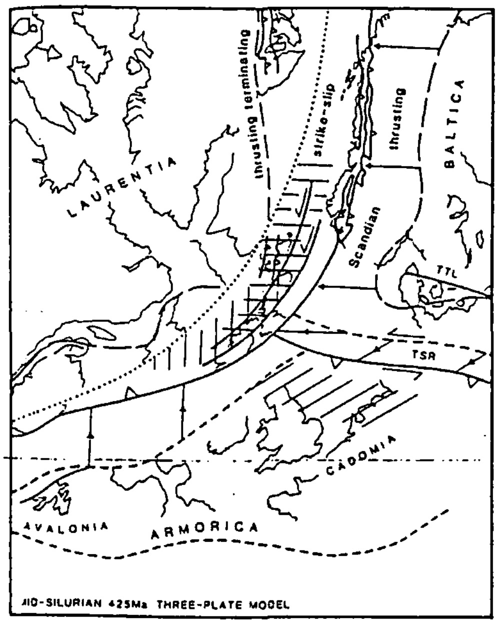


Fig. 2.3. A three-plate model for mid-Silurian time (Soper & Hutton 1984) showing the possible location of magmatic arcs in the British region (shaded). The model does not credibly account for the distribution of Newer Granite magmatism south of the Highland Border, but it could explain the concentration of granites in the Grampians. Pre-Atlantic reconstruction of Le Pichon, Sibuet & Francheteau (1977) used as base. The dotted line represents the possible locus of major sinistral strike-slip in mid-Palaeozoic time. TSR - Tornquist's Sea remnant; TTL - Teisseyre-Tornquist line. After Soper (1986).

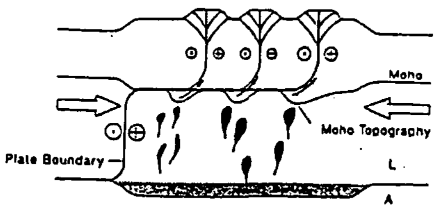


Fig. 2.4. Transpressionally thickened orogen such as the northern part of the British Caledonides. The heavy solid line with the Moho flat (the "plate boundary") (based on Klemperer *et al.* 1991) and upper crustal flower structure is equivalent to the Highland Boundary Fault and separates the foreland/miogeocline on the left from the accreted terranes (not differentiated) on the right. Second order linked transpressional faults within the foreland/miogeocline (thinner lines) are indicated. The lithospheric mantle keel (dotted) is destroyed by convecting asthenosphere and mantle diapirs which rise up to melt off the Moho topography created by transpression at the lower ends of the crustal shear zones. Granitic magmas thus formed rise up the shear zones to emplacement levels higher in the crust. After Hutton & Reavy (1992).

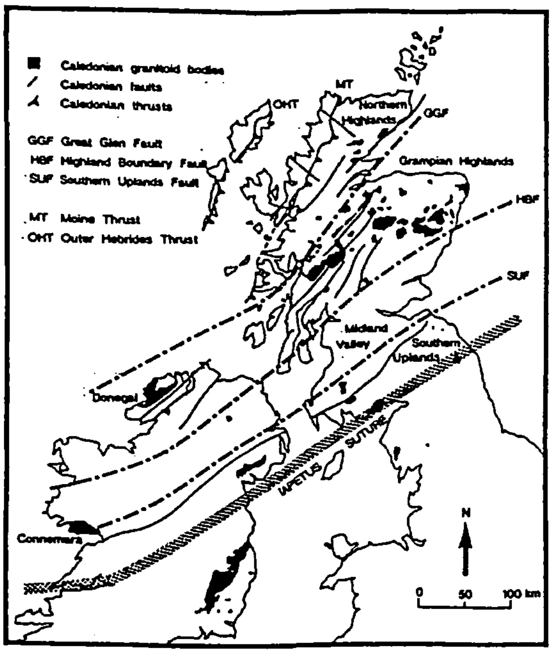


Fig. 2.5. Locality map showing major Caledonian fault systems and associated plutonic bodies.

2.4 THE CALEDONIAN OROGENIC BELT: THE SURROUNDING DALRADIAN ROCKS AND STRUCTURES

2.4.1 Introduction

The Caledonian orogeny is generally regarded as a consequence of the closure of the Iapetus Ocean during the Lower Palaeozoic. The initial development of Iapetus involved an earlier period of continental rifting and separation during the Late Precambrian (Watson 1984). During the development of the Iapetus Ocean, the Dalradian Supergroup of the Scottish Grampian Highlands (Harris *et al.* 1978) was deposited during the Late Proterozoic-Early Cambrian (see sub-section 2.4.1). The closure of the Iapetus Ocean possibly involved two major phases of convergence (Soper & Hutton 1984; Soper *et al.* 1987): (i) an initial stage in the Ordovician to Late Silurian involving the E-W collision of Baltica and Laurentia, resulting in the formation of the 'orthotectonides' of the Grampian Highlands; and (ii) a later deformational period during the Late Silurian-Early Devonian, produced by the northward accretion of the Cadomia terrane (Eastern Avalonia). This latter event was responsible for the development of the slate belts of the 'paratectonides' in northern England and Central Ireland (see Soper *et al.* 1987). It may have also been responsible for the late strike-slip event of the orthotectonides which, as mentioned above, has been related (Soper & Hutton 1984) to the final oblique closure of Iapetus, coinciding with a major phase of Caledonian plutonism (425-400 Ma). The zone of convergence, the 'Iapetus Suture Zone', is thought to be sited along the Solway Firth in northern England, and extends westward across the Irish Sea through the Irish paratectonides (Phillips *et al.* 1976). The eastward continuation of the suture zone is less certain.

This Section summarises the depositional and deformational characteristics of the Dalradian metasediments of the Scottish Grampian Highlands, formed during the development of Iapetus, right through to its destruction and the ending of the Caledonian orogeny in Scotland. The purpose of this review is to emphasise the importance of major tectonic structures which operated during these events, as such structures are referred to in subsequent Chapters regarding their role in siting Caledonian magmatism and their influence during pluton construction.

2.4.2 Dalradian deposition

The Dalradian Supergroup of the Scottish Grampian Highlands (Harris *et al.* 1978) was deposited in the late Proterozoic-early Cambrian times. The Dalradian sequence comprises of a number of local stratigraphic successions, dominated by metasedimentary rocks, some 25 km thick. Harris and Pitcher (1975) have sub-divided these Neoproterozoic metasedimentary rocks into four groups: comprising of the Grampian (oldest), Appin, Argyll and Southern Highland (youngest) Groups.

It is generally accepted that the earliest sediments of the Dalradian succession were deposited during late Proterozoic times onto continental basement which was undergoing stretching and thinning. Variations of thickness and facies changes suggest that the stable shelf environment, on which the oldest Grampian and Appin Groups were being deposited, was progressively subsiding and becoming tectonically unstable. This instability increased towards the southeast and is thought to be the result of an increase in the rate of crustal extension, eventually resulting in the rupture of the Proterozoic Supercontinent (Piper 1982) and the development of the Iapetus Ocean. During this event it is thought that the Argyll and Southern Highland Group sequences were deposited into a series of rapidly subsiding fault-bounded basins (see Anderton 1980; 1982; 1985). During deposition of the Appin and Argyll Groups, a source of mature sediments from the NW is likely (Anderton 1985). Implying an uplifted northern landmass to the NW of the present outcrop, which may be related to a vertical displacement on the Great Glen Fault, as shown on the LISPB profile

(Bamford *et al.* 1979; see Ch. 9), resulting in the Northern Highlands being uplifted approximately 3 km relative to the Grampian Highlands to the SE of this structure.

2.4.3 Dalradian deformation

During the Late Cambrian-Early Ordovician, the Dalradian Supergroup was subjected to polyphase deformation and regional metamorphism. This event was named the Grampian orogeny (Lambert & McKerrow 1976; see review by Johnson *in Craig* 1991). Within the SW Central Highlands (the area under investigation within this study), the metasedimentary rocks underwent ductile folding during this event. The resultant structures have received a great deal of attention by a number of workers, including Bailey (1934), Bailey and McCallien (1937), Anderson (1957), Treagus (1979), Roberts and Treagus (1977), Hickman (1978), Thomas (1979), and Haselock *et al.* (1982).

Within the SW Highlands, the Ben Alder region (within the vicinity of the Strath Ossian complex; Fig. 2.1) is structurally a very critical area to the understanding of the development of the Caledonian orogenic belt. Thomas (1979) proposed that this area was the site of D_1/D_2 collision between two continental blocks, resulting in a zone of steeply inclined folds and associated slides. He suggested that these primary folds emanated from a NE-SW-trending 'root zone' which he termed as the Geal Charn-Ossian Steep Belt (Fig. 2.7, 2.8). On either side of this zone the facing of major primary folds diverge, leading Thomas (1979) to conclude that during deformation along this zone, the resultant nappes formed a 'flower structure' or 'fountain', in which material was essentially spreading laterally away from the steep belt. This 'mush-room' structure had been previously regarded as being formed during the end of the Proterozoic (Late Precambrian). However, recent isotopic ages (590 +/- 2 Ma, Rogers *et al.* 1989; 597 +/- 11 Ma, Pidgeon & Compston 1992) for the Ben Vuirich granite (see Tanner & Leslie 1994) and an age of 595 +/- 5 Ma (Halliday *et al.* 1989) for the Tayvallich Volcanics which occur at the base of the Southern Highland Group, suggest a Palaeozoic age (probably Ordovician) for the main Dalradian deformation (Grampian D1 to D3). Isotope dating (Rb-Sr) of the Rough Craig Granite in Glen Clova (NE Highlands) and relationships between structures and metamorphism described by Robertson (1994) suggest that the deformation can be essentially divided into two main events: (i) The first (D1) occurring at approximately 590 Ma; and (ii) encompassing both regional D2 and D3 deformational phases, which possibly occurred between 520 and 470 Ma. This is in contrast with the Northern Highland Steep Belt in the Moine rocks north of the Great Glen Fault. This has an asymmetric form (see Ch. 9 and Appendix 1) (comprised of steep upright folds and flat belt), and its development post-dated the emplacement of the Late Ordovician Glen Dessary Syenite (456 +/- 5 Ma)

(Roberts *et al.* 1984). However, the change in facing in the Central Highlands across the steep belt has been questioned (Treagus 1987) on the basis that there is a difference in the age of the structures across this zone, due to the SE-facing Tay Nappe being earlier than the NW-facing D2 folds.

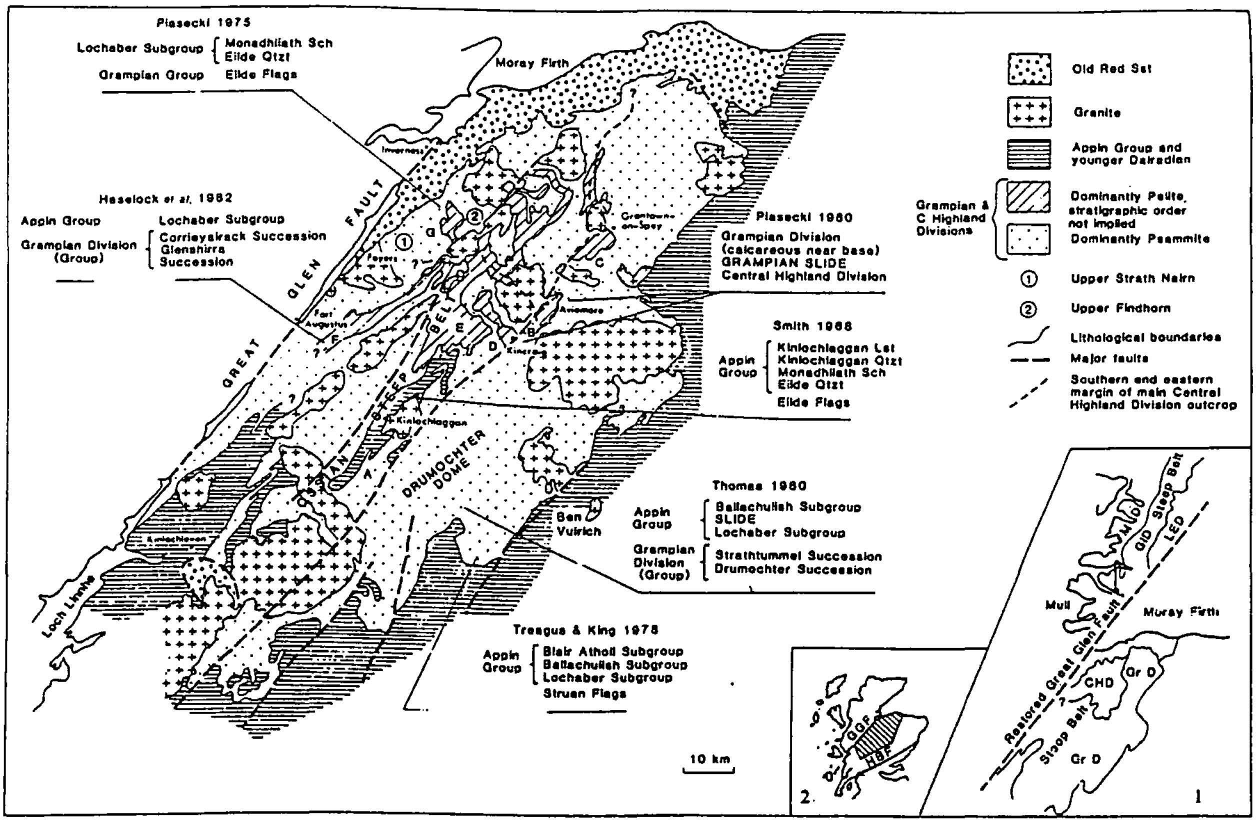


Fig. 2.7. Map to show the Caledonian and pre-Caledonian geology of the Central Highlands (lines mainly after Geological Survey 1: 625,000 Sheet 1). Rocks lying to the north and west of the trace of the Grampian slide form the main outcrop of the Central Highland Division. 1, Upper Strathnairn; 2, Upper Findhorn. References to published work appear in the reference list.

Inset 1 (largely after van Breeman & Piasecki 1983; igneous rocks omitted) to show the disposition of the main Moine divisions following an hypothetical 160 km dextral restoration of the Great Glen Fault (van Breeman & Piasecki 1983). MD, Morar Division; GID, Glenfinnan Division; LED, Loch Eil Division; GrD, Grampian Division. Inset 2 to show the location of the area. After Harris and Johnson *in* Craig (1991).

Van Breeman and Piasecki (1983) have suggested that the Geal Charn-Ossian Steep Belt can be continued towards the NE where it is represented as the 'Grampian Steep Belt'. However, there are problems with such an interpretation as the rocks within the Grampian Steep Belt region (Upper Findhorn) were subsequently assigned by van Breeman and Piasecki (1983) to the Central Highland Division, which show affinities to the Northern Highland Moine. The Grampian Slide (Piasecki 1980; Piasecki & Temperley 1988a) was thought to separate these rocks from the regionally overlying and younger Grampian Group. However, more recent work (Lindsay 1988; Lindsay *et al.* 1989) suggests that the tectonic style, fabrics and structural facing throughout the Central Highland Division and Grampian Group may be continuous, suggesting that they are not separated by an unconformity or tectonic discontinuity. It is therefore suggested that the two units are in stratagraphic continuity, but with local zones of high strain occurring along their boundary. The development of the Geal Charn-Ossian Steep Belt and its significance in the distribution of Caledonian magmatism is discussed in Chapter 9 and Appendix 1.

Late Grampian deformation (D3 and D4) resulted in the development of major NE-SW- and E-W-trending folds. They generally have wavelengths of several kilometres, and possess steep axial planes, e.g. the Ben Lawers Syncline. Numerous, minor late stage structures include: (i) small-scale, open folds such as 'kink-zones' or 'drag-folds' and conjugate fold sets; and (ii) asymmetric folds (e.g. Rast 1963; Harris *et al.* 1976).

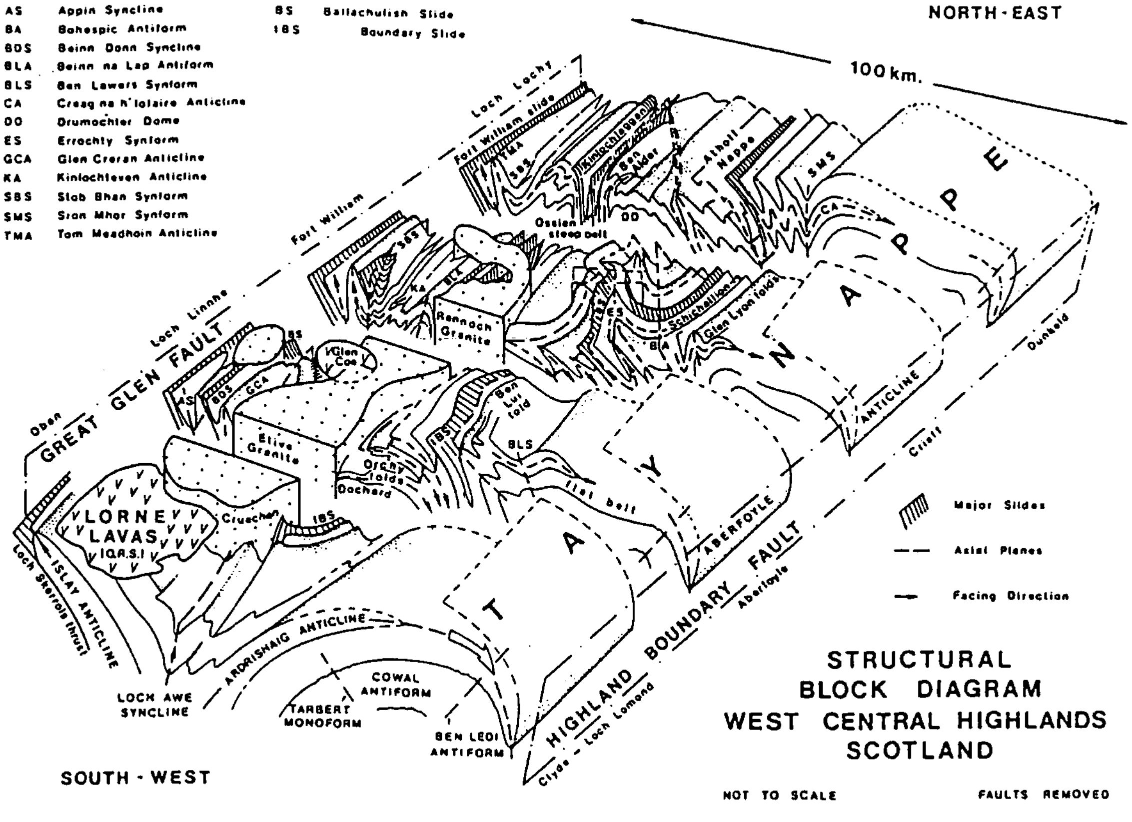


Fig. 2.8. Structural block diagram of major structures in the West Central Highlands. After Thomas (1979).

CHAPTER 3

THE ETIVE COMPLEX

3.1 INTRODUCTION

The Etive complex (MacCulloch 1817; Kynaston & Hill 1908; Bailey & Maufe 1916; Anderson 1937; Bailey 1960) is one of the largest of the Scottish Siluro-Devonian granitoid plutons (approximately 300 Km^2), and was intruded at an emplacement depth of approximately 2-4 Km (Droop & Treloar 1981) into Neoproterozoic Dalradian metasedimentary rocks. It has an elliptical form (approximately 30 km x 15 km), with a long axis trending NE-SW, parallel to the regional Caledonian strike (Fig. 3.1).

If we accept Anderson's (1937) correlation between the Meall Odhar and Stob Gaibhre Granites (his Meall Odhar facies) (however, see below and sub-section 3.2.3), the igneous complex can be sub-divided into six major intrusive components (Fig. 3.2):

G1: The Quarry Intrusion and isolated intrusive bodies (sub-section 3.2.1)
Quartz-diorite and diorites

G2: The Cruachan facies (sub-section 3.2.2)
Felsic monzodiorite

G3: The Meall Odhar facies (sub-section 3.2.3)
Sheets of monzogranite and syenogranite

The Etive Dyke Swarm (sub-section 3.2.4)
Suite of NE-SW-trending porphyrite and microdiorite dykes

G4: The Porphyritic Starav facies (sub-section 3.2.5)
Coarsely porphyritic monzogranite (K-feldspar megacrysts up to 3 cm)

G5: The Central Starav facies (sub-section 3.2.6)
Non-porphyritic monzogranite

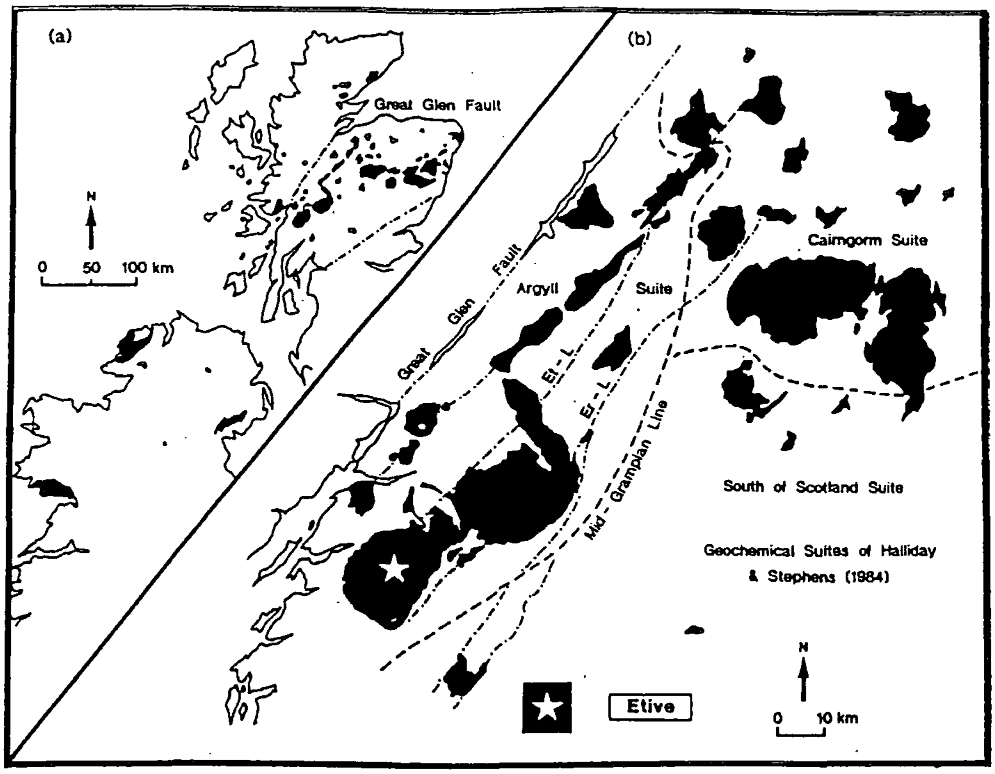


Fig. 3.1. **(a)** Distribution of late Caledonian granites in Scotland and Ireland. **(b)** Distribution of granitoids in the Grampian Highlands, showing the location of the Etive complex.

The petrological characteristics of these intrusive phases are described below. These are based on detailed field and microscope analysis carried out during this current study, combined with information obtained from two principal sources: Anderson (1937) and Batchelor (1987). The latter study (Batchelor 1987) has concentrated on the geochemical characteristics of these major intrusive phases and their bearing on the origin and evolution of the Etive magmas (see also Clayburn *et al.* 1983), together with the petrological variation within the complex. The results of these studies and of several other geochemical investigations (Groome & Hall 1972; Brown 1975; Plant *et al.* 1980; Barritt 1983; Frost & O'Nions 1985; Thirlwall 1986) are summarised in Section 3.3.

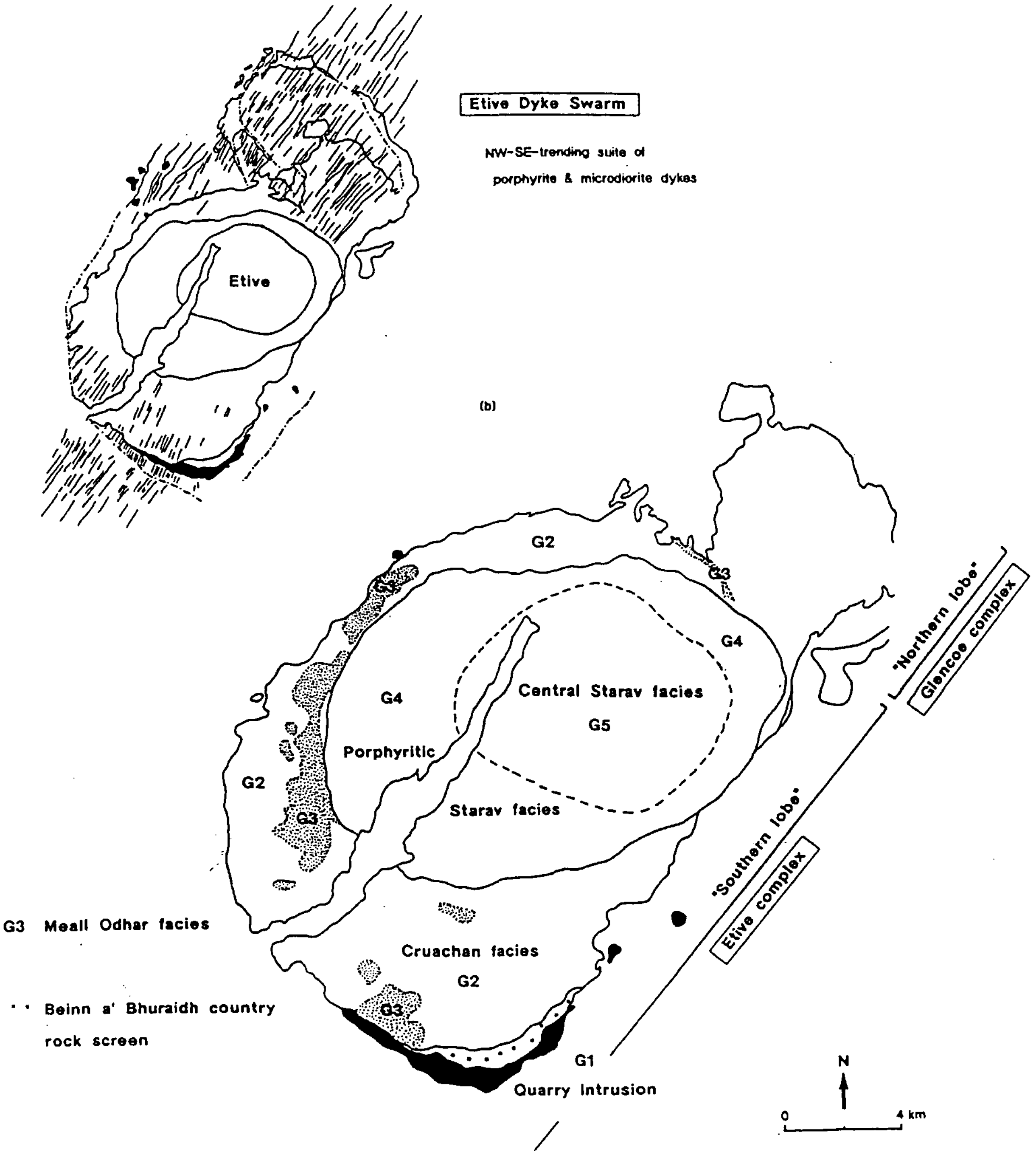


Fig. 3.2. (a) The distribution of the Etive Dyke Swarm. (b) The petrographical distribution of the major intrusive phases within the Etive complex. Modified after Anderson (1937).

The Etive complex has been considered by Anderson (1937) to have been constructed by a series of cauldron subsidence intrusions. Within the south-eastern part of the complex, an arcuate outcrop of mainly andesitic lavas (the Beinn a' Bhuiridh screen) separates the Quarry Intrusion (G1) from the Cruachan facies (G2) (Fig. 3.2).

The screen is interpreted by Anderson (1937) as representing a relict part of a down-faulted country rock block, left behind after two successive episodes of cauldron subsidence. Other evidence used by Anderson (1937) to substantiate such a model was: (i) the arcuate form of the Quarry Intrusion (G1), interpreted as a partial ring dyke intruded along the outer margin of the complex between the Dalradian metasediments and the down-faulted Beinn a' Bhuiridh country rock andesite screen; (ii) the fairly consistent curvature of the boundaries between the major intrusive phases, indicating steep contacts; (iii) the leucogranite Meall Odhar "ring dyke"; and (iv) flat-lying sheets of leucogranite exposed on the highest peaks which rest upon and cross-cut the upper parts of G2. He suggested the leucogranites could be correlated together, with the ring dyke representing the side-walls and the flat-lying sheets forming the top of a cauldron subsidence intrusion. The term "Meall Odhar facies" or "Meall Odhar Granite" (G3) was therefore given to both occurrences.

An alternative model has been proposed by Brown (1975) in which the Cruachan facies (G2) and Porphyritic Starav facies possess a laccolithic form, with the Meall Odhar facies intruding as a series of sub-horizontal sheets from the centre of the complex. The whole complex was then subsequently tilted towards the north-east. Brown (1975) used this model to explain the fact that the "northern lobe" (which is in fact an independent intrusive body, the Glencoe plutonic complex; see Section 3.3 and Ch. 4) is monzogranite, while in the southern part of the Etive complex, the "Cruachan intrusion" is a monzodiorite. This implied that both lobes were a single unit which was compositionally zoned producing a horizontally stratified magma chamber, which when subsequently tilted towards the north-east would result in an increase in the silica content northwards. The concept of tilting was also used by Brown (1975) to explain the north-eastward migration of the centres of successive intrusive phases (i.e. G2, G4 and G5).

There are several problems with both solutions. In the case of Anderson's cauldron subsidence model these include:

(i) the initial problem of creating space within the crust to accommodate such a substantial amount of magma, as it assumes the presence of a pre-existing magma chamber large enough to accommodate a large sunken block (presumably, approximately 300 km^2, i.e. a volume at least 450 km^2 assuming a vertical thickness of say only 1.5 km), in which the intrusion represents the infilling of a "great subterranean cauldron". This vividly illustrates the space problem in granite emplacement;

(ii) the leucogranites of "Meall Odhar" and "Stob Gaibhre" are in fact two distinct types (Batchelor 1987; see sub-section 3.2.3), with the more 'evolved' monzogranites of "Meall Odhar" representing a preceding magma derived from the ascending Starav facies (G4/G5) and the more 'primitive' syenogranites of "Stob Gaibhre" probably produced as a result of the expulsion of interstitial fluids from the Cruachan monzodiorite (G2) by the emplacement of the Starav facies (G4/G5) (Batchelor 1987; see Section 3.3). This therefore disputes the correlation made by Anderson (1937) that these leucogranites represent the top ("Stob Gaibhre" granite) and side-walls ("Meall Odhar" granite) of a cauldron subsidence intrusion;

(iii) the outer margin of the Cruachan facies (G2) has been stated to have "forceful" characteristics (Brown *et al.* 1968);

(iv) Stephenson (1976) suggested that the emplacement of the Central Starav facies (G4/G5) was probably in an "environment of shearing" due to its overall ellipticity and the presence of foliated margins.

(v) it does not explain the distribution of fabrics and an apparent increase in deformation in certain parts of the complex. Two corresponding zones within the north (Allt nan Gaoirean region) and south (Allt Dhoireann/Kingsglass region) of the complex (Fig. 3.3) were noted by Kynaston and Hill (1908), Bailey and Maufe (1916), Anderson (1937) and Bailey (1960) to be different from the rest of the pluton. In the southern part of the Cruachan facies (G2) it "commonly shows a faint foliation in the orientation of its constituent minerals, and of its fairly abundant dark, flat inclusions . This foliation is approximately vertical, and runs roughly parallel with the curving outline of the intrusion" (Bailey 1960; see sub-section 3.4.2). However, within the Allt nan Gaoirean region "the direction varies between ESE and east by south, while in Glen Ure it has turned around to ENE. It would be very difficult to believe that the flat inclusions could have been reorientated after complete consolidation of the magma without seriously modifying the igneous texture of the main product." (Bailey 1960; see sub-section 3.4.2). It was also noted that in Allt nan Gaoirean, at the contact between the Cruachan facies (G2) and the Porphyritic Starav facies (G4), "is the presence of strong shearing along the junction of the two "granites"." (Bailey 1960; see sub-sections 3.4.2 & 3.4.4). It has also been noted that "in many parts of Glen Kingsglass, especially about Acharn, the Cruachan granite assumes a well-marked foliation or gneissic structure close to the margin of the coarse more acid type" (Kynaston & Hill 1908), i.e. the Porphyritic Starav facies (G4). Also the radial disposition of the Etive Dyke Swarm, "keeping at right angles to the curving margin of the Starav granite" (Anderson 1937), is not easily reconciled by a "passive" emplacement model, as such a phenomena is often interpreted as the localisation of expansion-related strains associated with the emplacement of the intrusive body from which the dykes radiate (see Chapter 8). It is also interesting to note, that outside the north-north-easterly and south-south-westerly tangents to the Central Starav facies (G4/G5) dykes are very rare (Anderson 1937). The few dykes which do occur within the Allt nan Gaoirean and Kingsglass regions, have been noted by several workers (e.g. Kynaston & Hill 1908; Bailey & Maufe 1916; Anderson 1937; Bailey 1960) to be conspicuously foliated, especially along their chilled margins. It has noted that "the foliation is irregular, and it may make any angle up to 45° with the alignment of a dyke. The structure has effected the phenocrysts, especially the ferromagnesian minerals, which are drawn out into long lenticles. It is generally traceable right up to the dyke margins, but is only doubtfully recognisable in the massive Cruachan "Granite" outside" (*In* Bailey 1960). These field observations are discussed in this Chapter in relation to their implications for the emplacement of the complex.

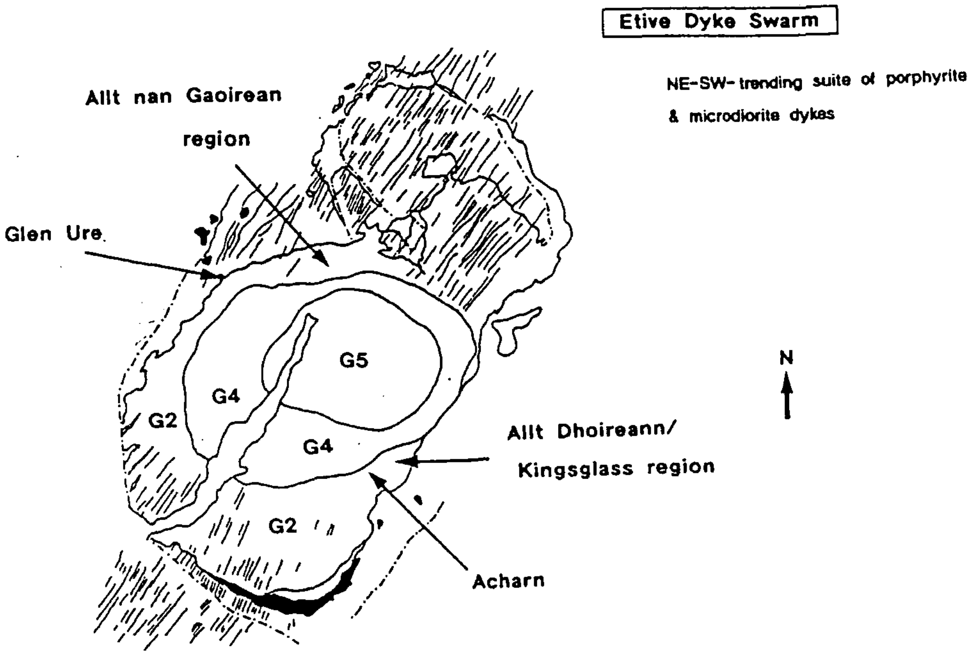


Fig. 3.3. Map of the Etive complex showing the position of the Glen Ure, Acharn, Allt nan Gaoirean & Allt Dhoireann/Kingsglass regions.

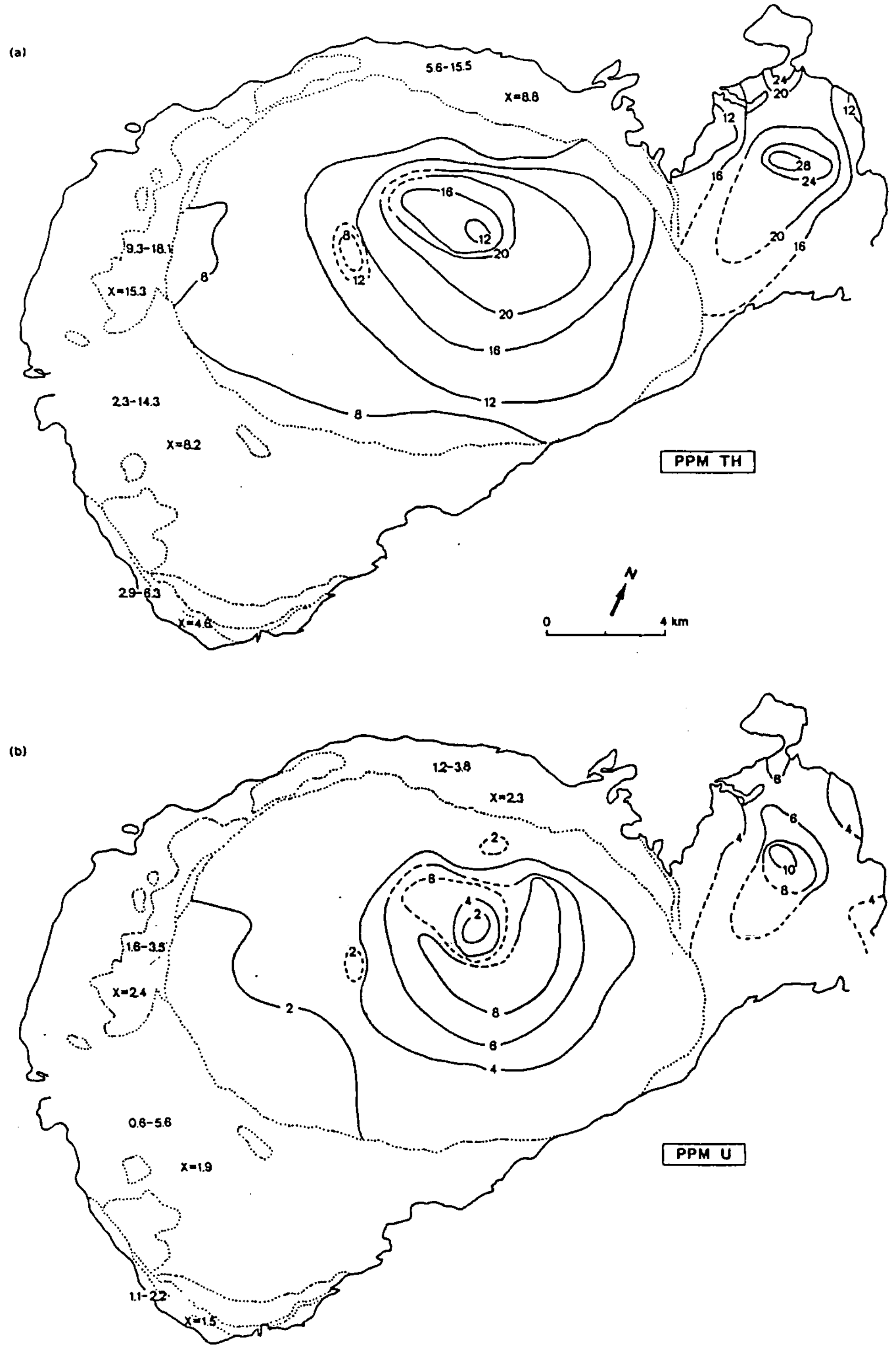


Fig. 3.4. Radioelement maps for the Etive and Glencoe complexes showing the distribution of **(a)** thorium (Th), and **(b)** uranium (U) levels. After Barritt (1983).

A number of problems also arise with Brown's (1975) model. These include:

(i) the assumption that the "northern" and "southern lobes" constitute a single, horizontally stratified magma chamber which has undergone subsequent tilting towards the NE to account for an increase in silica content towards the north. This is however, disputed by Barritt (1983) on radiometric and chemical grounds, concluding that in fact both "lobes" are independent intrusive bodies (Fig. 3.2 & 3.4). Such a model is also ruled out by Perkins (1986) on the basis that the Cruachan facies (G2) within the "southern lobe" is a multi-stage intrusion, with at least seven identifiable intrusive events;

(ii) it does not explain the existence of the Beinn a' Bhuiridh country rock screen, separating the Quarry Intrusion (G1) and Cruachan facies (G2) within the south-eastern part of the complex;

(iii) the location and "partial ring dyke" form of the leucogranite at Meall Odhar is not explained; and

(iv) the low angle contacts between the Cruachan (G2) and Porphyritic Starav facies (G4) indicated by the model are not consistent with the field observations of steep inclinations actually reported by Brown (1975).

For these reasons the purpose of this current investigation was to establish a structural data base, including such information as: (i) fabric type, intensity, distribution and inclination; (ii) the type and distribution of strain; (iii) the identification of local emplacement phenomena; (iv) together with deformational characteristics of the surrounding country rocks; in order to explain the distribution of the internal intrusive phases and associated deformational features, and the predominant mechanisms operating during the construction of the complex.

3.2 MAJOR INTRUSIVE COMPONENTS

3.2.1 G1: The Quarry Intrusion, isolated intrusive bodies and the Beinn a' Bhuiridh screen

The earliest intrusive component, a quartz-diorite/diorite is known as the Quarry Intrusion, and extends as an arcuate outcrop for approximately 10 km, with a maximum width of 1 km. It takes the form of a "partial ring dyke" (Anderson 1937) along the south-eastern margin of the complex between the Dalradian metasediments and the down-faulted Beinn a' Bhuiridh country rock andesite screen (Fig. 3.5a & b). This intrusive phase was first referred to by Kynaston and Hill (1908 p. 84) as a "more basic type" within the Cruachan facies (G2), but was later recognised as a distinct petrological unit by Anderson (1937).

The Quarry Intrusion (G1) can be sub-divided into an outer quartz-dioritic facies and an inner dioritic unit (Anderson 1937; Fig. 3.5a & b). No chilled margins are observed between these two intrusive phases, being described by Anderson (1937 p. 492) as two facies "which everywhere merge into one another"; i.e. a synplutonic relationship.

The predominant mechanisms operating during the construction of the Etive plutonic complex (discussed within this Chapter) are clearly different from those operating during the emplacement of the associated higher level emplacement phenomena, the Etive Quarry Intrusion (G1). For this reason the microstructural features developed within this intrusive phase, and a discussion of the possible mechanisms operating during its emplacement are presented within a separate chapter (Ch. 7: "High level emplacement phenomena: The Glencoe Fault Intrusion and the Etive Quarry Intrusion"). General petrographical descriptions of the outer, quartz-dioritic facies and inner, dioritic facies of the Quarry Intrusion are also given in Ch. 7, together with an account of: (i) the petrological variation within the Quarry Intrusion; (ii) its contact relationships with the country wall rocks, and the Beinn a' Bhuiridh screen; (iii) the petrological variation within the Beinn a' Bhuiridh screen; (iv) a petrological description of an isolated unit of quartz-diorite along the eastern periphery of the complex, known as the Loch Dochard Intrusion (Fig. 3.5c); (v) the distribution of satellite intrusions (Fig. 3.6); and (vi) the petrological characteristics of the Bonawe and Eilean Duirinnis intrusions, which occur as isolated bodies in the SW of the complex (Fig. 3.5b).

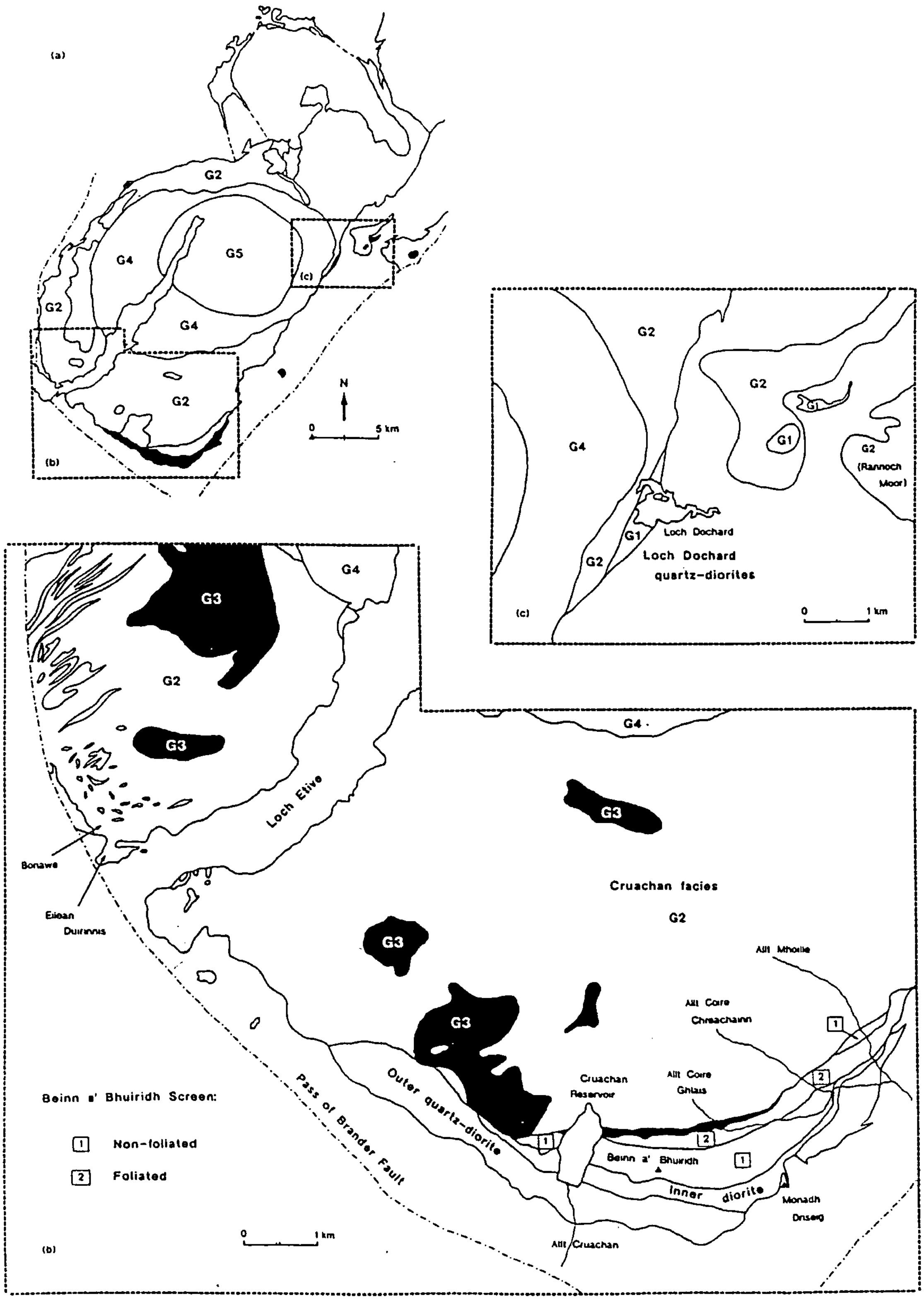


Fig. 3.5. (a) Inset showing the position of **(b)** an enlarged map of the Quarry, Bonawe and Eilean Duirinnis intrusions (G1), and **(c)** an enlarged map of the Loch Dochard quartz-diorites (G1).

3.2.2 G2: The Cruachan facies

G2 constitutes the largest intrusive component of the complex (Fig. 3.2b). Compositionally it is heterogeneous, and is referred to by Anderson (1937) as a fine- to medium-grained, grey quartz-diorite. Detailed mapping has revealed a number of petrologically distinct intrusive units within G2 (Perkins 1986). S. Perkins (pers. comm. 1994) suggests that it can be divided into at least seven intrusive events. Geochemical analysis by Batchelor (1987) has revealed that the Cruachan facies can be sub-divided into five petrographically distinct magmatic pulses; three monzodiorites and two monzogranites (Fig. 3.7).

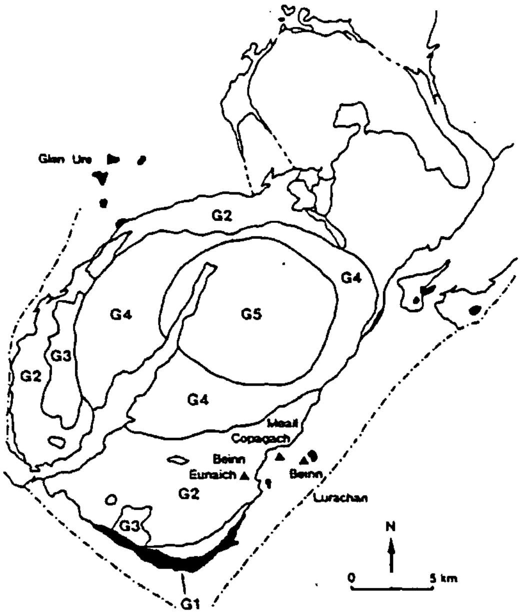


Fig. 3.6. The distribution of quartz-dioritic (G1) satellite intrusions around the Etive complex.

General petrographical description

General description of monzodiorite facies: a fairly equigranular, fine- to medium-grained (2-5 mm) monzodiorite. Plagioclase (An 40-25, zoned with An 60-50 cores) forms subhedral crystals (45-60 %), with variable sericitisation of their cores. Alkali feldspar (15-20 %; microperthite) always occurs as a late stage phase, forming interstitial anhedral to poikilitic grains. Alkali feldspar may poikilitically enclose small crystals of plagioclase and biotite. X-ray diffraction of these alkali feldspars indicates a mixed population of orthoclase and intermediate microcline (Batchelor 1984). Other interstitial minerals include biotite (10-20 %) and quartz (10 %). Accessory minerals include sphene, and minor amounts of zircon and apatite.

This monzodioritic facies has been sub-divided by Batchelor (1987) into three petrographically distinct pulses (Fig. 3.7): (i) an inner, dark monzodiorite; (ii) a normal monzodiorite; and (iii) an outer, felsic monzodiorite.

> *General description of monzogranite facies:* a fairly equigranular, medium-grained (2-5 mm) monzogranite. Plagioclase crystals (30-45 %) are normally zoned (An 50-25). Other essential minerals include alkali feldspar (25-30 %), quartz (15-30 %), biotite (5%) and hornblende (5-8 %). Accessories include opaque minerals, zircon, sphene and apatite.

This monzogranite facies has been sub-divided by Batchelor (1987) into two petrographically distinct pulses (Fig. 3.7): (i) an earlier, outer, more mafic monzogranite; and (ii) an inner, more silicic monzogranite. Barritt (1983) recognised that this monzogranite facies is normally zoned, as the concentric zonation of U and Th distribution increases in value towards the inner pulse (Fig. 3.4).

3.2.3 G3: The Meall Odhar facies

The Meall Odhar facies clearly cross-cuts parts of the Cruachan facies (G2) and surrounding country rocks as a series of sheets and dykes (Fig. 3.2b). Chemical data (Batchelor 1987) supports field evidence for the existence of two distinct types: (i) a pink K-feldspar, fine- to medium-grained monzogranite; and (ii) a leucocratic, fine- to medium-grained syenogranite. The monzogranite forms an arcuate outcrop (approximately 3 km by 100-150 m) between Stob Dubh [NN 166 488] and Meall Odhar [NN 190 465]. At this type locality (Bailey & Maufe 1916; Anderson 1937) the monzogranite forms a partial ring dyke type structure between G2 of the Etive complex and G2 of the Glencoe pluton (Fig. 3.2b). The margins of the monzogranite are never chilled. The syenogranite takes the form of flat-lying sheets resting on and cross-cutting the upper parts of G2, and as cone sheet type structures with moderate inclinations, cross-cutting G2 and parts of the surrounding country rock (e.g. Allt Buidhe [NN 031 439]). Their intrusive relationship to the flat-lying sheets (G3) is complicated, as they clearly post-date an earlier phase and have themselves been subsequently cross-cut by a later intrusive event of sub-horizontal sheets. There is evidence of contact-alteration against the later Porphyritic Starav facies (G4).

General petrographical description

Monzogranite: a pink, fine- to medium-grained (< 3 mm), equigranular monzogranite. Essentially composed of alkali feldspar (30-40 %), plagioclase (20-25 %) and quartz (30-40 %). Biotite is sub-ordinate and has generally been replaced by chlorite. Hornblende is absent. Accessories include iron ores and sphene.

Syenogranite: a leucrocratic, fine- to medium-grained (< 3 mm), equigranular syenogranite, composed of alkali feldspar (50-70 %), of which two generations occur, and small amounts of plagioclase. Accessories include zircon, opaque minerals and chlorite (alteration of biotite).

3.2.4 The Etive Dyke Swarm

This is a suite of NE-SW-trending dykes (Fig. 3.2a) which cross-cut the earlier intrusive phases of the plutonic complex (G1/G2). The majority clearly cross-cut the Meall Odhar facies (G3) and almost all are earlier than the emplacement of the Porphyritic Starav facies (G4). A few dykes are cut by the Meall Odhar granite (G3) (Bailey & Maufe 1916) and may represent a distinct earlier intrusive phase. Petrological analysis of the dyke suite was carried out by Kynaston & Hill (1908) and Bailey & Maufe (1916). The suite can be divided into four groups (after Anderson 1937): (a) felsite and porphry; (b) porphyrite; (c) microdiorite; and (d) lamprophyre dykes. By far the largest portion of the dyke swarm are acid to intermediate porphyrites. They are fine- to medium-grained phaneritic rocks, containing hornblende or biotite and phenocrysts of plagioclase. Quartz and feldspar occur as interstitial crystals. Microdiorites and quartz-porphyries are not uncommon and often occur together in multiple dykes, possibly representing a distinct, slightly later phase (see Ch.'s 4 & 8).

The Etive dykes are concentrated in a zone approximately 15-18 km wide, essentially bounded by the NE-SW-trending Allt Buidhe/Laggan Dam Fault, and the Ericht-Laidon fault to the north and south of the complex, respectively (Fig. 3.2a). Towards the contact of the cross-cutting Porphyritic Starav facies, the concentration of dykes clearly diminishes (Bailey & Maufe 1916). It was also noted by Anderson (1937) that the orientation of the dykes, from the general NE-SW-trend, clearly changed as the G4 contact was approached, forming a radial disposition; generally at right angles to the Porphyritic Starav facies. Their structural features and mechanisms of emplacement are discussed separately in Chapter 8.

3.2.5 G4: The Porphyritic Starav facies

The Starav facies (G4 and G5) forms a simple elliptical mass (approximately 15 km x 11 km) emplaced within G2 (Fig. 3.2b). Batchelor (1987) has sub-divided the Starav facies into 4 geochemically defined, normally zoned, nested pulses (Fig. 3.7). The outer zone of the Starav facies contains large porphyritic, euhedral orthoclase and plagioclase phenocrysts which are generally 1.5 cm long, but can reach up to 3 cm in length. This marginal zone is known as the Porphyritic Starav facies (G4), which is separated from the non-porphyritic Central Starav facies (G5) by a transition zone approximately 350-400 m wide. Across this zone there is generally a decrease in the size of the feldspar crystals and a fall in the amount of alkali feldspar and biotite. Anderson (1937) drew an approximate line, representing a mean position of the transitional zone, between the two intrusive phases (G4/G5) (Fig. 3.2b) and found that the non-porphyritic Central Starav facies (G5) lies well to the NE of the centre of the Porphyritic Starav facies (G4). He also noted a similar asymmetry in the position of the Starav facies (G4/G5) in relation to the Cruachan facies (Fig. 3.2b).

General petrographical description

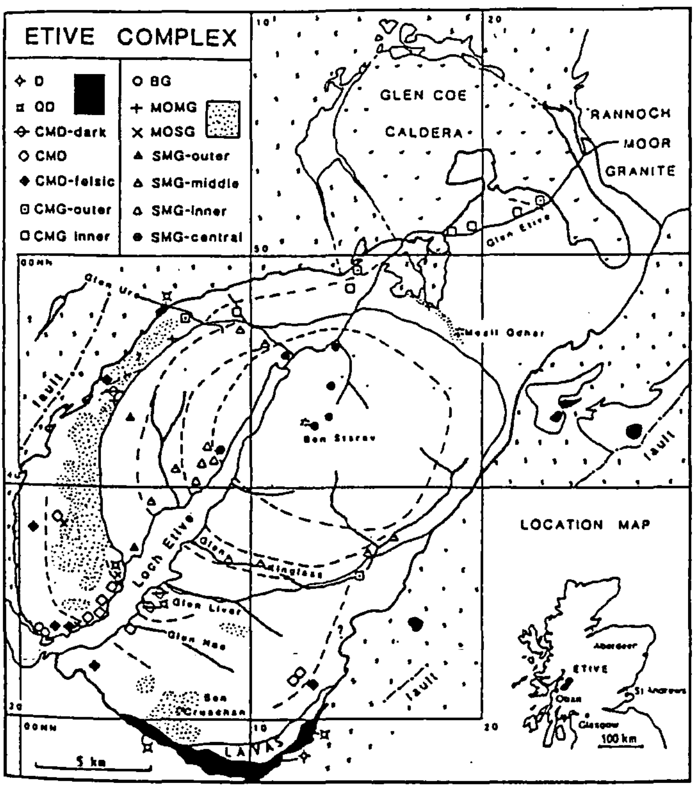
Porphyritic Starav Facies (G4): A coarse-grained porphyritic monzogranite, containing large euhedral phenocrysts (1.5-3.0 cm) of orthoclase (microperthite, 40-50 %) and plagioclase (20-25 %). Quartz (20 %), biotite (2-3 %) and subsidiary hornblende occur within the groundmass. Biotite and hornblende may occur as mafic knots and may show some signs of alteration to epidote and chlorite. Accessory minerals include sphene, opaques and minor amounts of zircon and apatite.

3.2.6 G5: The Central Starav facies

This inner pulse (approximately 10.5 km x 7 km) forms the core of the Starav facies and the complex (Fig. 3.2b). It is a fine- to medium-grained, equigranular monzogranite. The loss of porphyritic character across the 'transitional zone', which separates it from G4, is accompanied by an increase in the percentage of quartz and an increase in the size of the quartz crystals (approximately 0.5 mm). There is also a decrease in the amount of mafic constituents towards the main mass of the Central Starav facies (G5). Throughout this non-porphyritic interior, random local variations in texture occur. Generally the facies can be termed as coarse- to medium-grained with finer varieties generally occurring near to the centre of the complex, which merge into the coarser facies.

General petrographical description

Non-porphyritic Starav Facies (G5): A medium- to coarse-grained, equigranular monzogranite, consisting of quartz (30-40 %), K-feldspar (30-45 %), plagioclase (20 %), and small amounts of biotite (2-3 %). Accessories include small amounts of zircon and opaque minerals.



-◇-	D	Diorite	□	CMG	Cruachan monzogranite— inner
⌘	QD	Quartz diorite	+	MOMG	Meall Odhar monzogranite
-◇-	CMD	Cruachan monzodiorite— dark	×	MOSG	Meall Odhar syenogranite
◇	CMD	— — normal	▲	SMG	Starav monzogranite—outer
◆	CMD	Cruachan monzodiorite— felsic	△	SMG	Starav monzogranite—middle
○	BG	Bonawe granitoid	△	SMG	Starav monzogranite—inner
□	CMG	Cruachan monzogranite—outer	●	SMG	Starav monzogranite—central

Ab	albite	hb	hornblende
amph	amphibole	kspr	alkali feldspar
An	anorthite	mgt	magnetite
and	andesine	opx	orthopyroxene
ap	apatite	or	orthoclase
bi	(Fe)biotite	plag An30	plagioclase feldspar (An30)
bw	bytownite	plag An75	plagioclase feldspar (An75)
ck	charnockite	qz	quartz
cpx	clinopyroxene	sph	sphene

Fig. 3.7. Geological map of the Etive complex, showing sample localities, geological (solid line) and chemical boundaries (dashed line). 's' ornament represents metasediments, 'v' represents the Glencoe volcanic suite. Symbols and abbreviations used in the figure are shown. After Batchelor (1987).

3.3 GEOCHEMICAL ANALYSIS OF THE ETIVE COMPLEX: ORIGIN AND EVOLUTION

The first geochemical analysis of any of the intrusive phases within the Etive complex was carried out by Brown (1975). This study established that the Cruachan facies is enriched in Ba, Sr, Al_2O_3 and TiO_2, and contains high levels of plagioclase and biotite in relation to the Quarry Intrusion and isolated diorites (G1). From the study of the contemporaneous Old Red Sandstone Lorne Lava Suite, Groove & Hall (1972) suggested that the magma source for the Etive complex may have had the same origin. Stream sediment analysis by Plant *et al.* (1980) showed Th, Cu, and Mo anomalies within and around the complex. The heat producing elements U and Th were studied in detail by Barritt (1983) who concluded: (i) that radiometric and chemical data suggests that the "southern" and "northern" lobes referred to by the majority of previous workers (e.g. Anderson 1937) as being part of the same complex, i.e. Etive, are in fact independent bodies, and that the term Etive complex should only refer to the southern body (Fig. 3.2b & 3.4); (ii) the higher concentrations of U and Th within the Starav facies (G4/G5) suggests that it contains a more evolved crustal component compared to that of the Cruachan facies (G2).

Isotopic studies concerned with the origin and evolution of the complex have suggested a number of alternative views:

(i) Clayburn *et al.* (1983) suggests from Sr-, O-, and Pb-isotopic data that an enriched, juvenile, mantle source melt, interacted with older lower crust to produce the granitic rocks of the Etive complex. They envisaged that the resultant very dry, hybrid magma was rapidly intruded into the upper crust via fractures. Each successive magma pulse only suffering minor contamination by local Dalradian metasedimentary upper crust. Enrichments in ^{87}Sr and ^{18}O, together with the progressive depletion of radiogenic Pb in successive intrusive phases indicated that the Meall Odhar facies (G3), Etive Dyke Swarm and Starav facies (G4/G5) possess a larger, lower crustal component than the earlier intrusive phases G1/G2. They also suggested that the reversal in the general fractionation trend after G3 may represent the influx of a new magmatic batch during the development of the later intrusive phases;

(ii) Frost & O'Nions (1985) however, suggest recycled continental lithosphere for the origin of the granitic magmas;

(iii) Thirlwall (1986) envisaged a process of incorporation and interaction of a mantle-derived component into subducted sediment.

Detailed geochemical analysis of the Etive complex by Batchelor (1987) suggests that the origin for both the Cruachan (G2) and Starav (G4/G5) pulses involved either the fractionation of pyroxene and plagioclase from a mafic magma, or by mixing with silicic crust; both pulses being derived from independent parent magmas which can be traced back to dioritic compositions. The geochemical data also substantiates petrographical evidence for multiple magma pulses during the construction of the pluton, leading to the identification of five groups within the Cruachan facies: three monzodiorites, and two monzogranites, and four groups within the Starav facies (Fig. 3.7). This geochemical study (Batchelor 1987) indicated a number of important points for the origin and evolution of the individual intrusive phases:

1. *Dioritic facies (G1)*

   These are the most mafic rocks found within the complex. The Etive source magma for all the intrusive phases may have originated as a high pressure (25-30 kb), partial melt from a garnet- or pyroxene-rich crustal rock, or after fractional crystallisation of a tholeiitic basalt.

2. *Cruachan facies (G2)*

   Variations within each magmatic pulse can be related to the *in situ* crystallisation. The monzodioritic facies was intruded as at least three different magmatic pulses, each of which show evidence of reverse zonation. An interesting point is that these pulses may represent Cruachan monzogranite magma which has undergone movement or "mobilisation", leading to the loss of felsic liquid. The intrusion and expansion of the Starav facies is suggested by Batchelor (1987) as the cause of this process, thermally driven convective either acting as a 'piston' and/or a source of heat for thermal mobilisation. This interpretation, based on geochemical evidence, is upheld on structural grounds in that the Starav facies shows clear evidence of having undergone a process of *in situ* expansion during its emplacement (see Section 3.4).

3. Meall Odhar facies (G3)

As mentioned above, geochemical data supports petrographic evidence for two distinct phases: (i) the monzogranites; an 'evolved' type which includes the classic exposure at Meall Odhar; and (ii) more 'primitive' types which are syenogranites and form both flat-lying sheets and cone-sheet type structures. Batchelor (1987) attributed the 'primitive' syenogranitic phase to be the result of the expulsion of interstitial fluids from the Cruachan monzodiorite (G2) by the emplacement of the Starav facies (G4/G5). However, the monzogranitic phase appears to represent a preceding magma derived from the ascending Starav facies.

4. Starav facies (G4/G5)

The Starav facies cannot be part of a continuous Cruachan facies (G2) fractionation series, as the most mafic Starav monzogranite pulse is more mafic than the most silicic Cruachan monzogranite. The four chemically distinct pulses of the Starav facies exhibit *en echelon* geochemical trends, with each pulse starting off more mafic than the final composition of the previous pulse, suggesting these are independent pulses derived from a fractionating parent magma.

3.4 FABRIC DEVELOPMENT: EVOLUTION OF MICROSTRUCTURES

The purpose of this Section is to present the type of fabrics and microstructures which are common within the intrusive phases of the Etive complex, and to outline the fundamental processes operating during the evolution of fabric types, i.e. from the magmatic state, through the crystallisation transition, and into the solid state regime during progressive deformation. It is not intended as a detailed discussion on the textural development and mechanisms operating during fabric evolution.

The rheology of a magmatic material governs its deformational response to imposed stress. The rheological state of a magma is governed by the ratio of crystals, in relation to the percentage of melt present (see Ch. 1). Other physical factors which control the evolution of fabrics and microstructures during progressive deformation include: (i) the composition of the magma/rock; (ii) the temperature; (iii) shear stress; and (iv) hydrostatic pressure. Two main rheological changes occur, one across the transition from a pre-full crystallisation to a solid state deformation, and the other across the brittle-ductile transition. Both types of transition are exhibited by the rocks of the Etive complex.

3.4.1 G1: The Quarry Intrusion and isolated intrusive bodies

The mechanisms operating during the emplacement of the Etive Quarry Intrusion (G1; Fig. 3.5a) are clearly different from those operating during the construction of the Etive plutonic complex (G2, G3, G4 and G5). The fabrics and microstructures developed within G1 are therefore discussed in Chapter 7, dealing with the emplacement of that body.

3.4.2 G2: The Cruachan facies

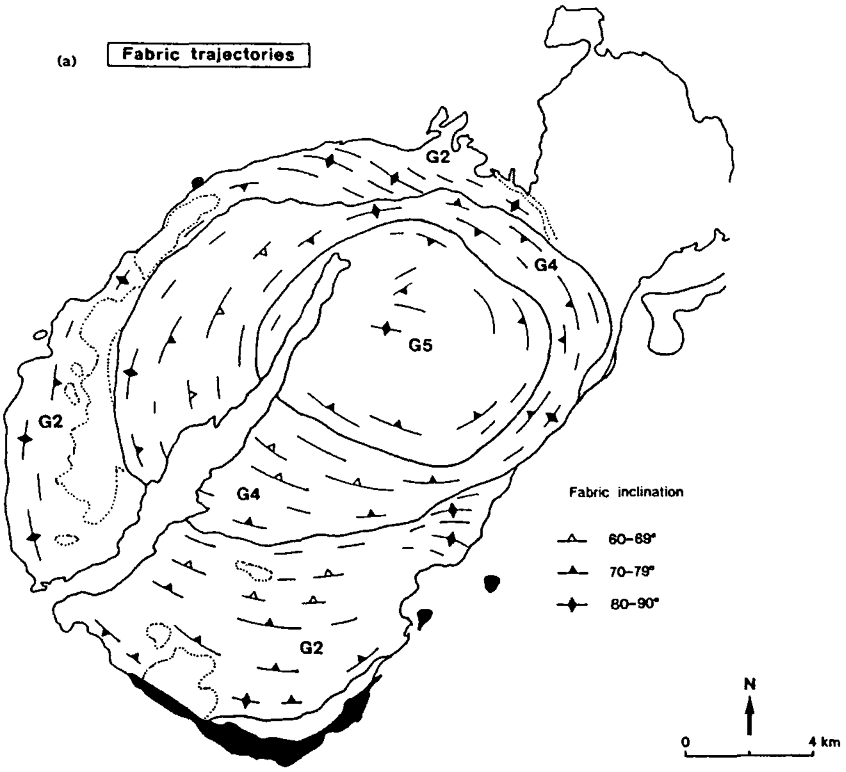
3.4.2.1 Pre-full crystallisation (PFC) fabrics or magmatic state fabrics

The majority of the Cruachan facies (G2) possesses a pseudoconcentric, inward dipping, weak to moderately developed pre-full crystallisation fabric (Fig. 3.8a).

The fabric is characterised by the preferred dimensional orientation of euhedral/subhedral plagioclase phenocrysts, and often by the alignment of euhedral biotite and hornblende crystals. These aligned, internally undeformed euhedral crystals are set in an undeformed matrix of late stage alkali feldspar, and interstitial quartz and biotite.

Developed throughout G2 are small, discrete, conjugate, ductile shears or ‘lock-up’ shears (Hutton & Ingram 1992; Ingram & Hutton 1992) formed during the last stages of pre-full crystallisation deformation (Fig. 3.8b & 3.9). The microstructural characteristics of these discrete, planar PFC lock-up shears have been addressed by Ingram (1992). During crystallisation and PFC fabric development, a point is reached when the melt content drops to the RCMP (Arzi 1978) and there is a sudden increase in the bulk strength of the magma. It is at this point where there is a rapid change from a pervasive homogeneous deformation, and the development of PFC fabrics, to a heterogeneous deformation and the development of discrete zones of shear. The width of these zones of shear tends to be fairly constant, measuring approximately 2.0 to 2.5 cm. Across these zones the phenocryst phases have been deflected and this provides the sense of shear along that zone. These structures generally occur as a conjugate shear set, showing a bulk extensional shear component parallel to the fabric direction (Fig. 3.8a & 3.9b).

Throughout the southern part of the Cruachan facies (G2 monzodiorites) the predominant fabric is a steep, inward dipping, pseudoconcentric PFC fabric (Fig. 3.8a), which tends to intensify towards the pluton margin. However, within the northern part of the complex, where G2 monzogranites dominate (see sub-section 3.2.2), the PFC fabric may show evidence of extensive modification by solid state deformation. For this reason the microstructural features developed within the monzodioritic and monzogranitic facies are discussed separately.



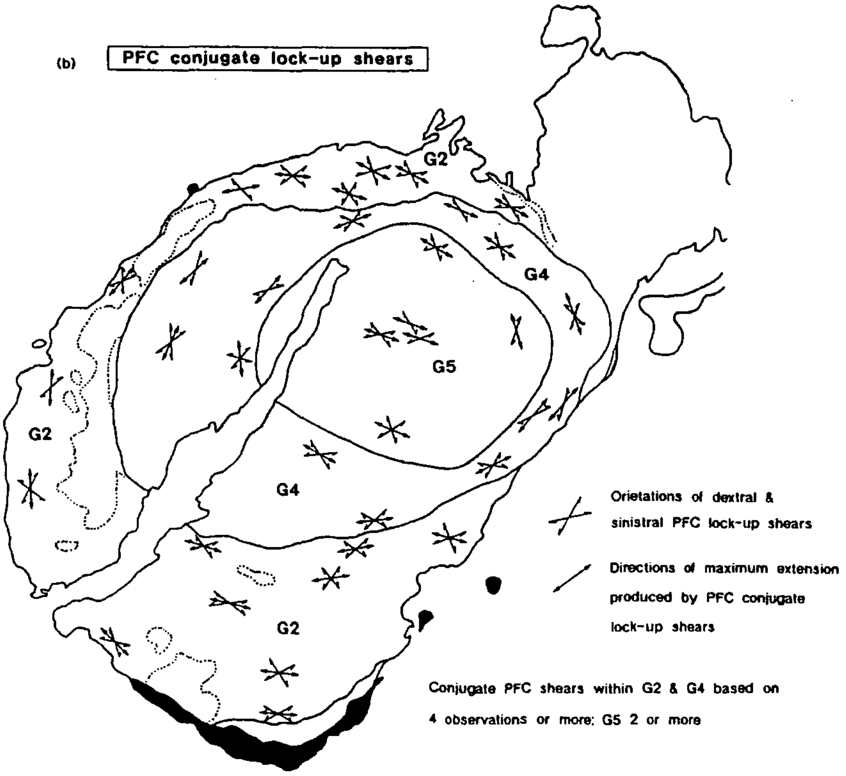


Fig. 3.8. **(a)** Fabric trajectories throughout the major intrusive phases G2, G4 and G5 of the Etive complex. **(b)** The distribution of the PFC conjugate lock-up shears throughout the complex.

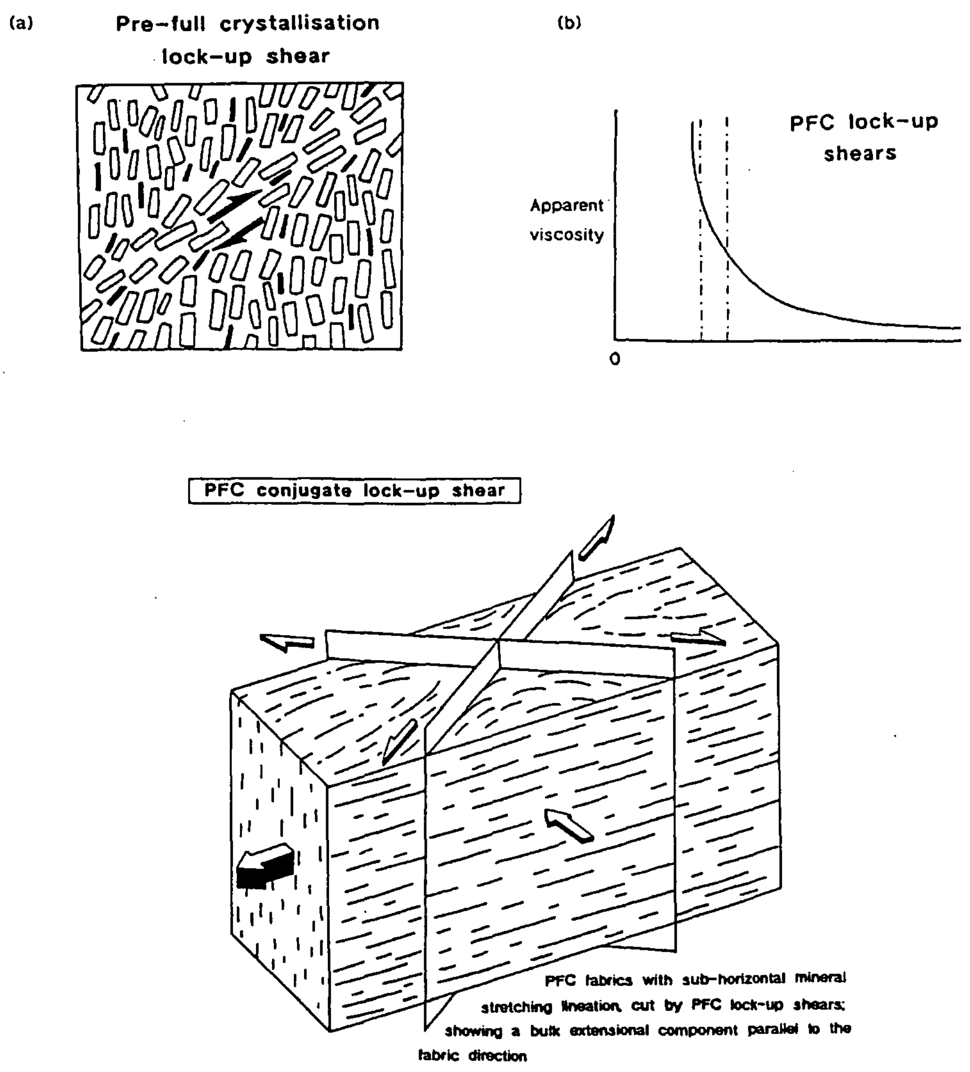


Fig. 3.9. (a) A discrete, conjugate, ductile shear or 'lock-up' shear (Hutton & Ingram 1992; Ingram & Hutton 1992) formed during the last stages of pre-full crystallisation deformation (b). (c) generalised model of a PFC conjugate lock-up shear.

General description of microstructural characteristics

Cruachan monzodioritic facies: Throughout the southern region of the complex, this fine- to medium-grained monzodiorite generally possesses a fairly weak to moderately developed PFC fabric. The fabric is essentially defined by euhedral to sub-euhedral, zoned plagioclase (45-50 %) and biotite laths (10-20 %). These phases are both internally undeformed. Within the matrix, undeformed interstitial crystals include alkali feldspar (15-20 %), biotite, quartz (10 %) and small amounts of sphene. A weak to moderately developed sub-horizontal stretching lineation is generally represented by biotite crystals.

At certain localities, particularly at the contacts between petrographically distinct units (pulses) within G2 (see Fig. 3.7; Batchelor 1987), and at its outer margin, and to a lesser extent at the inner contact with the Porphyritic Starav facies (G4), myrmekitic intergrowths may occur and quartz may exhibit undulose extinction. Alkali feldspar may have also undergone alteration, producing microperthite (an intimate intergrowth of a K-rich feldspar and a Na-rich feldspar) by exsolution. Within these zones, plagioclase crystals may show slight internal deformation in the form of slightly bent compositional planes and the margins of the phenocrysts may be somewhat more irregular. These features indicate, that within these zones the deformation continued for a short period after full crystallisation, resulting in the PFC fabric being slightly modified by crystal plastic strain. The solid state deformational overprint was coplanar leading to the enhancement of the pre-existing (PFC) fabric. In certain isolated areas, within the southern part of the complex, the CPS deformational fabric is non-coaxial with respect to the pre-existing fabric, indicating that the orientation of the imposed strain changed with time.

Throughout the southern part of the Cruachan facies (G2 monzodiorites), X/Z ratios of microdioritic enclaves (from horizontal surfaces) indicate an apparent average value of approximately 2.5. These values increase to approximately 3.0, simultaneously with the increase in PFC fabric intensity towards the pluton margin. The X axis of the microdioritic enclaves are almost always parallel to the pseudoconcentric PFC fabric pervasively developed throughout the monzodiorites. From vertical joint surfaces, perpendicular to the X direction, Y/Z ratios of the microdioritic enclaves were obtained. The Y axis in almost all cases was parallel to the inclination of the inward dipping PFC fabric. Due to the nature of the exposure, vertical surfaces are uncommon, and so the amount of Y/Z ratios measured are limited. However, where obtained they indicate that the enclaves are consistently elongate disc shaped ($0 < K < 1$), and towards the pluton margin oblate shapes ($K \approx 0$) become increasingly more common. Plane strain shapes ($K \approx 1$) on a few occasions within the central parts of G2 have been recorded, whereas prolate shapes ($1 < K < \infty$) have never been observed.

Summary of general microstructural features developed within G2:

① The southern part of the Cruachan facies (G2 monzodiorites) possesses a steep, inward-dipping, pseudoconcentric PFC fabric which intensifies towards the pluton margin.

② Both the monzodiorites and monzogranites (G2) possess a sub-horizontal mineral stretching lineation.

③ Throughout the southern part of G2, X/Z ratios of microdioritic enclaves show an apparent slight increase in strain towards the pluton margin, and K values consistently between 0 and 1 ("flattening strains").

④ PFC conjugate, ductile shears show a bulk horizontal extensional component parallel to the fabric direction.

⑤ At the margins between petrologically distinct units (pulses) within the monzodiorites, and at its inner and outer contacts, the PFC fabric may have been slightly modified by a relatively high temperature solid state deformational overprint.

Model proposed

A simple model to account for all these features could be:

❶ *In situ* expansion of G2, and possibly the subsequent emplacement and expansion of G4/G5. This led to the development of a pervasive pseudoconcentric PFC fabric due to the imposition of predominantly "flattening-type strains", verified by the three-dimensional shapes of microdioritic enclaves which suggest an overall bulk shortening component.

❷ Due to the continued imposition of expansion-related strains during the last stages of pre-full crystallisation deformation, PFC conjugate ductile shears were developed allowing bulk extension to occur parallel to the fabric direction.

❸ As the pluton body continued to 'inflate' and earlier intrusive components crystallised, localised, intense high temperature CPS fabrics were developed at petrological contacts as the imposed deformation proceeded into the solid state regime. This combined with the overall synplutonic rotation of the subsequent intrusive phases G4/G5 (evidence presented in Section 3.5) resulted in the formation of the corresponding zones of high strain within the monzogranites of G2. These two zones, developed within the north (Allt nan Gaoirean region) and south (Kingsglass/Allt Dhoireann region) of the complex, are described in detail in sub-section 3.4.2.2.

❹ A model of *in situ* expansion to account for the construction of the major intrusive phases G2, G4 and G5 (see sub-sections 3.4.4 & 3.4.5 for evidence of *in situ* expansion of G4 and G5, respectively) is proposed. This would account for the overall elliptical form of the pluton and the concentric zonation of the complex, and its induced deformational effects within the adjacent Glencoe plutonic complex as it expanded (see Ch. 4).

Discussion:

A fundamental problem with such a model is how these expansion-related strains are accommodated within the crust, as the surrounding country rocks do not apparently show the types of deformational characteristics which might be expected. This led Read (1961) to suggest that the pluton was an example of "permitted" or "passive" emplacement, with workers such as Anderson (1937) proposing that the complex had been constructed by a series of cauldron subsidence intrusions. As shown by the data in this current study, this clearly is not the case. The mechanisms by which space was accommodated within the crust during the construction of the Etive complex is discussed in Section 3.6 and in more detail in Chapter 11.

Cruachan monzogranitic facies: The majority of fabrics developed within this intrusive phase are high temperature CPS deformational fabrics. Within areas of relatively low strain, the fabric is characterised by zoned plagioclase (30-40 %) and alkali feldspar (25-30 %) which show moderate to good alignment and are dominantly internally undeformed. Interstitial quartz (15-30 %) generally exhibits only slight internal deformation. Biotite (5 %) and hornblende (5-8 %) often occur as mafic clots with many of the biotite crystals showing a slight degree of distortion; bent or kinked crystals. In such regions, these microstructural features suggest that deformation occurred during the crystallisation of the magma, leading to the development of a moderate PFC fabric, and continued for a short period after full crystallisation. This led to a slight modification of the earlier fabric, by crystal plastic strain deformation. Within these regions the overprinting fabric is often coplanar to the pre-existing PFC fabric. However, within the north (Allt nan Gaoirean region) and south (Kingsglass/Allt Dhoireann region) of the complex (Fig. 3.10), two corresponding zones of high strain occur (see sub-section 3.4.2.2), where the solid state fabrics often obliquely overprint the earlier pervasive PFC fabric. In certain parts of these regions, the PFC fabric has been completely obliterated by intense CPS deformation. As already mentioned within Section 3.1, fabrics developed within these two zones were noted by Kynaston and Hill (1908), Bailey and Maufe (1916), Anderson (1937); and Bailey (1960).

As with the monzodioritic facies, a sub-horizontal stretching lineation is commonly developed. Within the monzogranitic facies, this lineation tends to be represented by both biotite and hornblende, and is generally much more intense than is seen in the southern part of the complex.

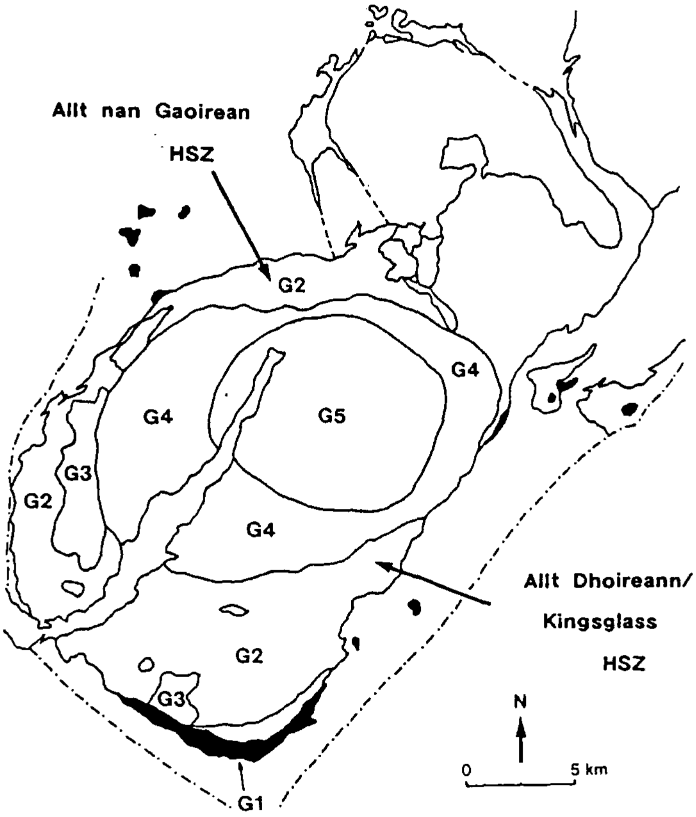


Fig. 3.10. Petrographical distribution map showing position of the Allt nan Gaoirean and Allt Dhoireann/Kingsglass high strain zones (HSZ's) within the Etive complex.

3.4.2.2 Crystal plastic strain (CPS) fabrics or solid state deformation fabrics

These deformation fabrics occur after the magma has reached its RCMP, i.e. at or below the solidus temperature of its consituent minerals, when the behaviour of the granite is essentially solid (Ch. 1). Deformation will cause imposition of strain within those minerals, leading to crystal alignment predominantly by ductile deformation mechanisms. This process may enhance the preferred dimensional orientation of crystals which produce earlier pre-full crystallisation fabrics (PFC) if the deformation is coaxial. Such solid state deformation within G2 is often characterised by the following mineralogical changes:

(i) feldspar tends to have undergone recrystallisation processes, in which well-formed, euhedral phenocrysts have become subhedral by subgraining and recrystallisation of their margins. During this process the crystal structure may become dislocated, forming deformation lamallae. Such strain induced lamellae are commonly developed within the plagioclase phenocrysts of the Cruachan monzodioritic facies, which form high temperature CPS fabrics at the contact with the Porphyritic Starav facies (G4). The larger crystals tend to retain their original oscillatory zoning (An 40-25, zoned with An 60-50 cores), whereas the smaller crystals have no zoning and twinning is sometimes completely obliterated by dissolution. Such subsolidus alteration is common in the alkali feldspars of the Cruachan monzogranitic facies in contact with G4, and in the high strain zones developed within the Allt nan Gaoirean and Allt Dhoireann regions (see below). Alkali feldspars, particularly within the monzodioritic phase, may show evidence of exsolution to microperthite, indicative of subsolidus alteration during periods of increased deformation (Simpson & Wintsch 1989).

During crystal plastic strain deformation, myrmekite can develop (see Ch. 1), as an intimate intergrowth of plagioclase and quartz. In areas where this is well developed, twinning in feldspars is usually erased. With decreasing temperature myrmekitic growth is often concentrated along twin planes and around the periphery of feldspar crystals, and at boundaries between quartz and plagioclase;

(ii) within all the types of crystal plastic strain fabrics developed within both the monzodioritic and monzogranitic facies (see below), biotite is bent, kinked or fractured around feldspar phenocrysts; defining the CPS fabric orientation;

(iii) hornblende tends to remain internally undeformed. However, some hornblendes are subhedral, indicating some degree of subgraining;
(iv) quartz occurs as an interstitial phase, and is the most susceptible essential mineral to crystal plastic strain deformation within the Cruachan facies (G2). It tends to become

elongate and flattened forming polycrystalline lenses which often help to define the orientation of the CPS fabric. Much of the quartz, throughout the range of CPS fabrics developed, possesses strained undulose extinction.

As mentioned above, PFC fabrics developed within both the Cruachan monzodioritic and monzogranitic facies may be overprinted by a weak to moderately developed CPS fabric. Such fabrics generally occur at the major contact with the Porphyritic Starav facies (G4). This type of fabric also commonly occurs within the outer parts of G2, in the southern region of the complex, where the development of the fabric clearly intensifies towards the pluton margin.

Moderate to well developed, high temperature CPS fabrics are very rarely observed within the southern part of the complex (within the monzodioritic facies). These types of fabric are essentially confined to the monzogranitic facies in the NE of the complex, adjacent to the Glencoe plutonic mass, and within the two corresponding zones of high strain (HSZ; Fig. 3.10) developed with the north (Allt nan Gaoirean region) and south (Kingsglass/Allt Dhoireann region) of the complex. Within both these high strain zones, there is a complete transition from moderate PFC fabrics which have been slightly modified and overprinted by a weak CPS fabric, through to relatively high temperature, weak to moderately developed CPS deformation, culminating in the development of an intensely developed, relatively lower temperature CPS fabric which completely obliterates the earlier PFC fabric. Within both these zones, the CPS overprint may be coplanar with the pre-existing PFC fabric, enhancing the preferred dimensional orientation of its constituent minerals, or it may be non-coaxial with respect to the development of the pre-existing (PFC) fabric, implying a component of rotational strain or imposition of strain with a completely different orientation. Within the Allt nan Gaoirean region (northern zone of high strain) there is a progressive zone of transition from moderately developed PFC fabrics which have been slightly overprinted by weak CPS deformation, through to intense CPS development which completely obliterates the earlier pervasive PFC fabric (see Fig. 3.11). In the Allt Dhoireann region (southern zone of high strain) this is somewhat further complicated, due to the presence of a large psammatic country rock raft within G2. The distribution and microstructural characteristics of the fabrics within these two zones are discussed below:

General description of the distribution and microstructural characteristics of the fabrics within the Allt nan Gaoirean high strain zone

Cruachan monzogranitic facies: along a traverse (A-B; Fig. 3.11b) from the inner contact of G2 with G4, through to the outer margin of G2 (pluton contact), fabric development within the monzogranitic facies can be sub-divided into several zones of different fabric type (Fig. 3.11c). The changes in fabric type are progressive, therefore the inferred boundaries separating these zones within Figure 3.11 do not represent abrupt changes.

Zone A

Localised, high temperature, moderate to strongly developed CPS fabric: this localised zone of intense deformation (approximately 10-15 m wide) occurs within the inner margin of G2 (Fig. 3.11c), in contact with the Porphyritic Starav facies (G4). Plagioclase and alkali feldspar phenocrysts have undergone marginal sub-graining, leading to an annealed texture in the areas of particularly high subgrain density. Recrystallisation processes have generally removed magmatic features such as zoning. Many of the feldspar crystals exhibit evidence of internal ductile deformation, most commonly in the form of deformation lamellae and undulose extinction. Some twinning has been removed by dissolution. Biotite and hornblende crystals are parallel to the fabric trend and dimensionally appear to be somewhat more elongate. Biotite laths show clear evidence of internal ductile deformation in the form of kinked and bent crystals, often wrapped around feldspar phenocrysts. The interstitial quartz is highly strained, having undergone internal lattice distortion, forming lenticular crystals which have undergone significant recrystallisation and subgraining. These microstructural features are consistent with CPS deformation occurring at a high temperature. However, the presence of fractured feldspar crystals, suggesting deformation at lower temperatures (< 450°C; Simpson 1985), the high degree of alteration and the development of brittle-ductile structures (Plates 3.1 & 3.2), suggests that this zone was subjected to a later, lower temperature deformational event. This later deformation was probably associated with movements along the Etive-Laggan fault (see Fig. 3.1), which also had a profound effect within the adjacent Porphyritic Starav facies (G4; see sub-section 3.4.4).

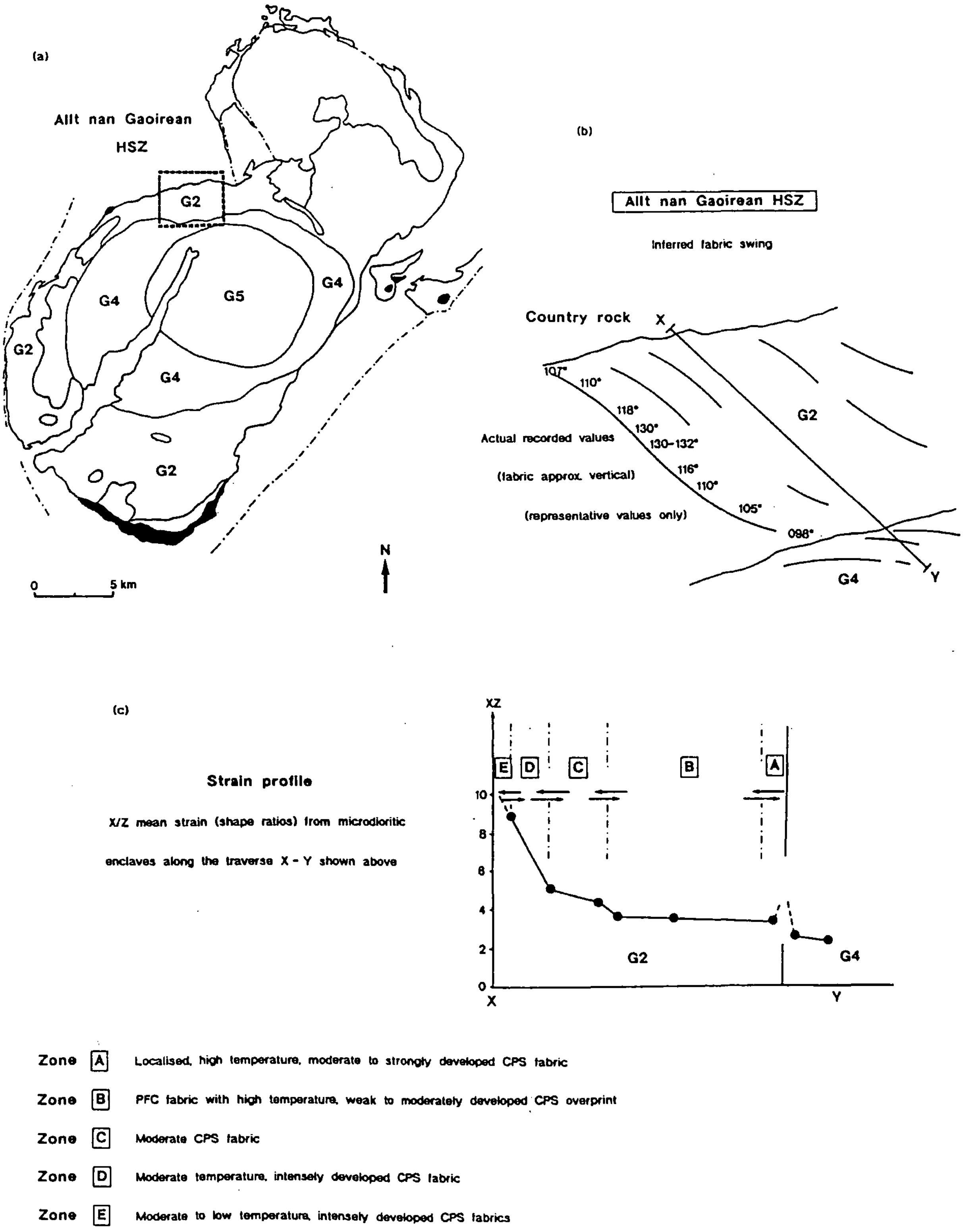


Fig. 3.11. (a) Sketch map showing the position of the Allt nan Gaoirean high strain zone (HSZ) within the Etive complex. (b) Sketch map showing the inferred fabric swing across this region, and (c) associated strain profile and zones of different fabric type.

Plate 3.1. Hand-specimen of G2 (Cruachan facies) from "Zone A" of the Allt nan Gaoirean HSZ. It contains a moderate high temperature solid state overprint. A weakly developed solid state fabric is present, defined mainly by biotite in hand-specimen (as shown by white arrow). This specimen, taken near to the Etive-Laggan Fault zone, has been modified by a low temperature deformational event (see Plate 3.2). (Yellow 'bar' is approximately 2 cm long).

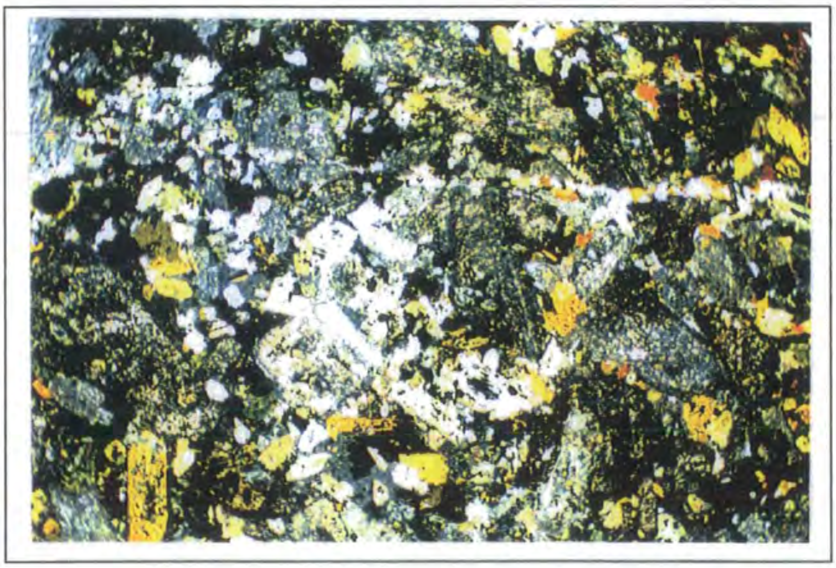


Plate 3.2. Photomicrograph of hand-specimen (G2) in Plate 3.1. Note the highly altered nature of many of the crystals. (Field of view is approximately 18 mm).

The orientation of the CPS foliation is different from the orientation of the earlier PFC fabric which it has overprinted. The pre-existing (PFC) fabric, within this zone, appears to have been developed in an orientation pseudoconcentric to the pluton margin and parallel with what was to become the contact with G4.

This overall deformational history has led to the development of:

① localised, moderate to intensely developed CPS fabrics along both G2 contacts ("Zone A" and "Zone E"), with less intense solid state deformation throughout the central part of the region (from "Zone B" through to "Zone D");

② a sense of obliquity of CPS fabrics in relation to the earlier pre-existing (PFC) fabric. Such a non-coaxial deformation, implies a component of rotational strain or the imposition of strain with a completely different orientation;

③ a general, gradual increase in both the intensity of the earlier pre-existing (PFC) fabric and the overprinting solid state deformational fabric, from "Zone B" through to "Zone D", i.e. towards the pluton margin. This increase in fabric intensity is verified by X/Z ratios of microdioritic enclaves (Fig. 3.11c), which increase fairly progressively.

④ a sigmoidal fabric trace across the region, implying an overall sinistral component of shear (Fig. 3.11b).

These features suggest that during the crystallisation of G2, a strain induced shear component was established across the region, leading to a component of rotational strain during the development of both the earlier PFC fabric and the overprinting CPS fabrics. The whole region being subjected to a component of 'non-coaxial general shear' (i.e. a component of "pure shear" and a component of "simple shear") due to the expansion and synplutonic rotation of G4/G5 and the imposition of tectonic-related strains during movements along the NE-SW-trending shear zones (see below & Section 3.5). This overall deformation has led to the development of a sigmoidal fabric trace across the region, implying that the area was subjected to an overall sinistral component of shear (Fig. 3.11b).

Zone B

PFC fabric with high temperature, weak to moderately developed CPS overprint: as mentioned above, within this zone there is a progressive increase in the amount of CPS deformation towards the pluton margin (Fig. 3.11c). In areas of low to moderate CPS overprint, magmatic features have been preserved, such as oscillatory zoning. Within this zone, an intense PFC fabric is preserved, which has been modified by the superimposition of a coplanar solid state deformation (Plates 3.3 & 3.4). The geometrical orientation of this PFC fabric (Fig. 3.11b) is clearly different from the typical pseudoconcentric PFC fabrics which have developed in the monzodioritic facies within the southern part of the complex (Fig. 3.8a). The continuous sigmoidal PFC fabric trace developed across this zone (Fig. 3.11b), suggests that there must have been enough melt present during the deformational process, to allow the phenocrysts to rotate without significant interference with each other so as to form an intense PFC fabric. The development of an overprinting coplanar, weak to moderately developed CPS fabric, indicates that deformation continued for a short time after full crystallisation. This led to the slight modification of the intense PFC fabric with the development of internal ductile deformation of interstitial quartz (strained undulose extinction and its lenticular form), and the development of bent or kinked biotite laths. Moving through this zone, towards the pluton margin, the amount of CPS overprint increases gradually into "Zone C" (Fig. 3.11c) where a moderate CPS fabric has developed (see below). This intensification in CPS deformation appears to coincide with an apparent progressive increase in the amount of strain inferred from X/Z mean strain (shape ratios) from microdioritic enclaves (Fig. 3.11c). An important feature, is that these microdioritic enclaves are elongated approximately parallel to the sigmoidal fabric trace developed within the monzogranitic facies (Plate 3.5). This suggests that the shear induced rotational strain component which operated within this zone was initially imposed relatively early with respect to the crystallisation of G2, i.e. below its 'critical melt percentage' (Arzi 1978), producing an intense PFC fabric and the deformation and alignment of its microdioritic enclaves. The deformation continued during and after the crystallisation of G2, producing relatively coplanar, high temperature CPS overprinting fabrics. The distribution of strain and these fabric types may be explained by the outer parts of G2 being more crystallised than the inner and this outer part having passed through the 'critical melt percentage' (Arzi 1978), underwent crystal lock-up, and the development of a CPS fabric.

Plate 3.3. Hand-specimen of G2 from "Zone B" of the Allt nan Gaoirean HSZ. It contains a PFC fabric which has been overprinted by a coplanar, high temperature, weakly developed CPS overprint. (Yellow 'bar' is approximately 2 cm long and shows orientation of the PFC fabric).

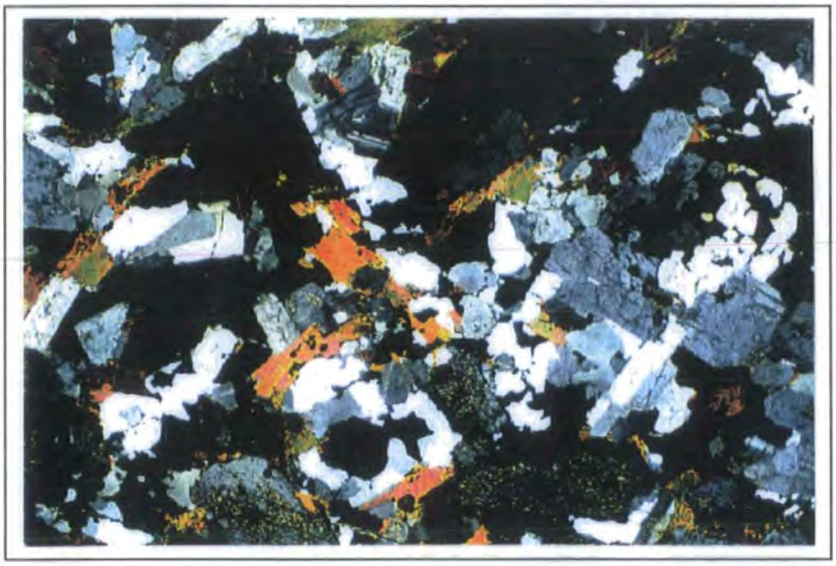


Plate 3.4. Photomicrograph of hand-specimen (G2) in Plate 3.3. Note, magmatic features such as zoning have been preserved. (Field of view approximately 18 mm).

Plate 3.5. A PFC fabric with a coplanar high temperature, weak to moderately developed CPS overprint within "Zone B" of the Allt nan Gaoirean HSZ (see Fig. 3.11). Microdioritic enclaves have been recrystallised and are aligned parallel to the fabric direction.

Also developed throughout this region are small, discrete, conjugate, ductile shears or 'lock-up' shears (Hutton & Ingram 1992; Ingram & Hutton 1992) formed during the last stages of pre-full crystallisation deformation (see Fig. 3.8b). The microstructural characteristics of these discrete, planar PFC lock-up shears have been addressed by Ingram (1992). Within the Allt nan Gaoirean region they are defined by euhedral plagioclase, K-feldspar and biotite laths, which have undergone rotation into parallelism with the shear plane. During crystallisation and PFC fabric development, a point is reached when the melt content drops to the RCMP (Arzi 1978) and there is a sudden increase in the bulk strength of the magma. It is at this point where there is a rapid change from a pervasive homogeneous deformation, and the development of PFC fabrics, to a heterogeneous deformation and the development of discrete zones of shear. The PFC lock-up shears develop as a consequence of the interaction of crystals during their rotation and alignment, transmitting the strain from these areas of crystal lock-up and focusing the deformation into these discrete zones of shear. Within this high strain zone, especially within the outer parts of G2, the deformation continued down temperature into the solid state, resulting in the development of the overprinting CPS fabrics and the imposition of strain into these narrow zones of shear. This continued down temperature deformation generally resulted in the development of a thin veneer of mylonite (< 2 mm wide) showing considerable grain-size reduction.

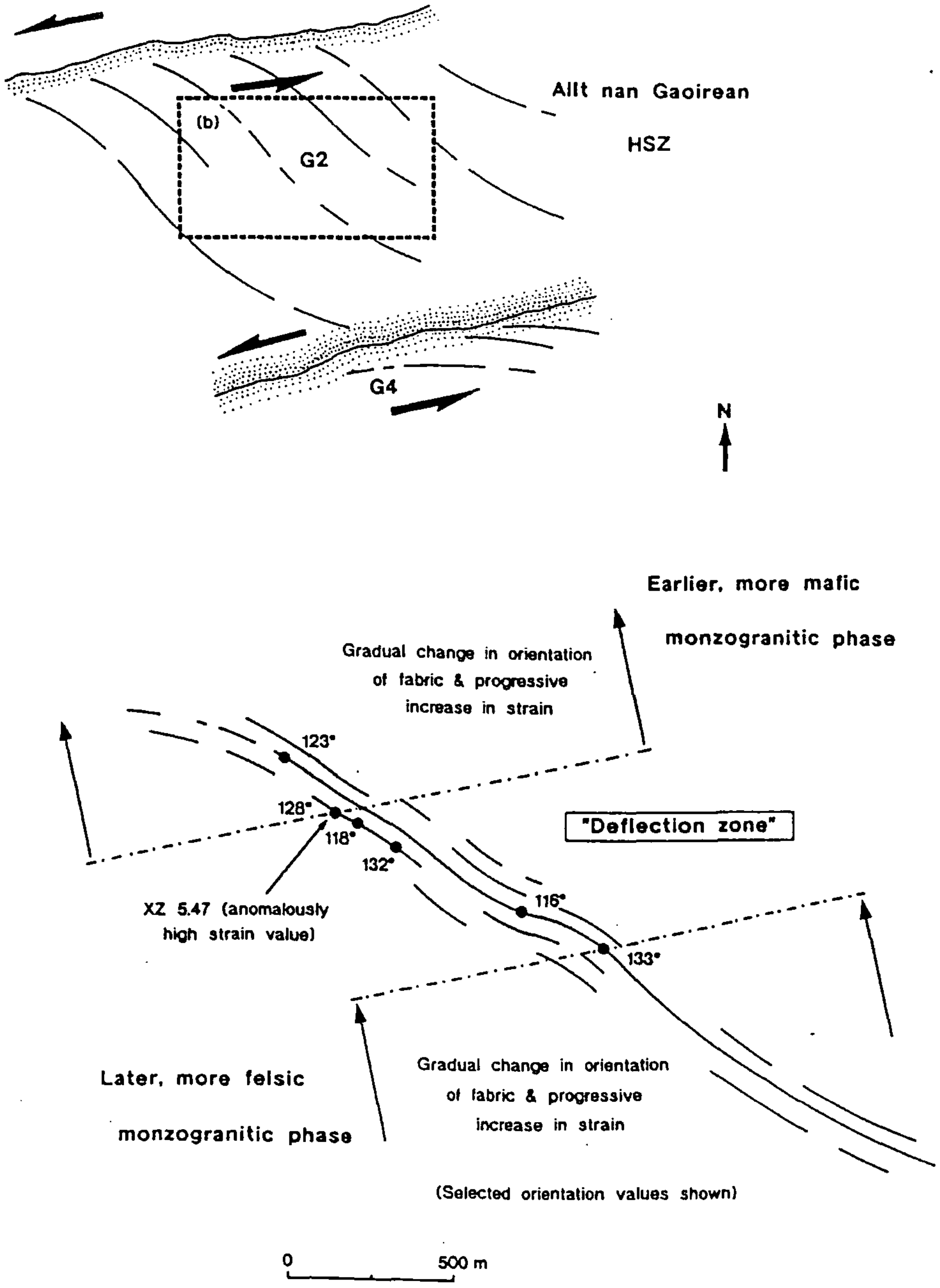


Fig. 3.12. (a) Inset showing where "deflection" in fabric orientation occurs within Allt nan Gaoirean high strain zone (HSZ). (b) Generalised sketch map of the "deflection zone".

Within this zone ("Zone B") the sigmoidal fabric swing has been slightly deflected (Fig. 3.12) over an area of approximately 425-450 m. Although the fabric has been deflected by only a very minor amount, ranging from approximately 128-133° to 116-118°, this is not consistent with the very gradual change in fabric orientation observed on either side of this 'deflection zone', i.e. the 'main' sigmoidal fabric trace across the region (Fig. 3.11b). Outside this 'zone of deflection' strain values (X/Z ratios from microdioritic enclaves) are also extremely constant, whereas within the 'zone' an anomalously high mean X/Z strain value occurs (Fig. 3.12b). The observed features may indicate that this 'zone' was a focus for the imposition of strain and shear during the development of the Allt nan Gaoirean HSZ. The reason why deformation should be locally focused within this area is uncertain, but one explanation could be that within this zone a subtle contact exists between two petrographically distinct units. Geochemical analysis by Batchelor (1984; 1987) suggests that within this region the Cruachan monzogranitic facies (G2) can be sub-divided into two distinct pulses; an early outer, more mafic pulse and a later inner, more silicic pulse. The boundary inferred by Batchelor (1987) to separate these two types, may well occur in the vicinity of this 'deflection zone' (see Fig. 3.7), causing strain and shear to be focussed along the contact of these two slightly, rheologically different intrusive phases, accounting for the change in fabric orientation and the local increase in strain.

Zone C

Moderate CPS fabric: the microstructural development of the monzogranitic facies (G2) in this part of the HSZ is characterised by the formation of a moderately developed CPS fabric which overprints an intense PFC fabric (Fig. 3.11c). The superimposition of the solid state deformation is generally coplanar with respect to the pre-existing fabric. However, through the zone towards the pluton contact, there is a progressive change in the dimensional orientation of both quartz, biotite and hornblende, with respect to the trend of magmatically aligned plagioclase and K-feldspar. The quartz tends to be highly strained, elongate and may form ribbons. Phyllosilicates, particularly biotite, are bent around feldspar phenocrysts, often forming swathes aligned parallel with the CPS fabric. Plagioclase and K-feldspar phenocrysts show distinct rounding due to deformation, resulting in subhedral crystal shapes.

Many of the plagioclase crystals have undergone recrystallisation of their margins and subgraining, and the development of deformation lamallae. However, many of the larger phenocrysts still possess their original oscillatory zoning, indicating either that the CPS deformation never reached too high a magnitude within this zone and/or did not continue for a long enough duration to cause the zoning to be completely destroyed by recrystallisation processes. The formation of myrmekite, as intergrowths with quartz and along the twin planes and crystal edges of feldspar, indicates decreasing temperature during the CPS deformation.

These features suggest that after full crystallisation of the monzogranite, deformation continued into the solid state regime, producing a moderate overprinting CPS fabric. The slight difference in alignment of phyllosilicates and lenticular quartz, compared to the dimensional orientation of feldspar phenocrysts, indicates that the rotational strain component, which resulted in the development of the sigmoidal fabric swing across the region, continued for a short period into the solid state regime.

Zone D

Moderate temperature, moderate to intensely developed CPS fabric: this is a zone of moderate to intense CPS deformation (Plate 3.6) which developed at relatively moderate temperatures (Fig. 3.11c). Oscillatory zoning within plagioclase crystals has been completely removed, and the crystals tend to have undergone dynamic recrystallisation and dissolution. Strong minerals such as feldspar and hornblende tend to be fractured, indicating deformation at temperatures of < 450°C (Simpson 1985), whereas quartz, mica and interstitial feldspar have undergone recrystallisation to finer-grained aggregates. Quartz ribbons define the main CPS fabric trend in thin-section, together with fine-grained, elongate aggregates which form foliations. Biotite tends to form stringers which wrap themselves around the stronger minerals, such as feldspar and quartz. In general there is a progressive grain-size reduction towards the pluton margin.

Zone E

Moderate to low temperature, intensely developed CPS fabrics: this is a localised zone (approximately 50-75 m wide) of intense CPS deformation which developed at relatively moderate to low temperatures (Fig. 3.11c). Many of the microstructural features observed within this zone are very similar to those described in the previous sub-section for "Zone D"; the main differences are: (i) "Zone E" is somewhat finer in grain-size; (ii) plagioclase and hornblende crystals tend to be more fractured; (iii) the imposition of strain was heterogeneous, leading to the formation of an anastomosing "gneissic" CPS fabric, which completely obliterates the earlier PFC fabric. There is also a dramatic increase in strain from "Zone D" to "Zone E", indicated by the X/Z ratios of microdioritic enclaves (see Fig. 3.11c). This suggests that "Zone E" represents a localised zone of high strain at the pluton contact, exhibiting X/Z ratios generally from 8 to 11, compared to the much lower X/Z values observed within "Zone D" (around 4 to 5). Encorporated country rock xenoliths often show extensive modification by this low temperature overprint (Plate 3.7).

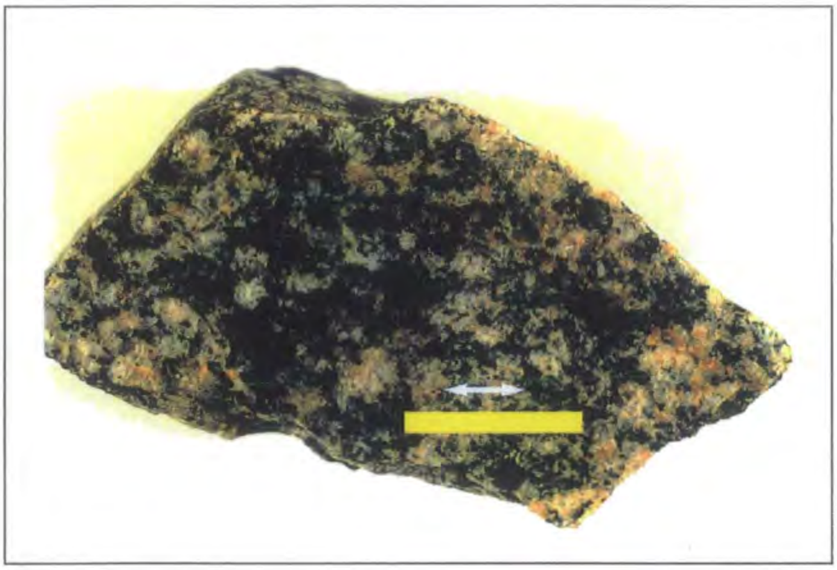


Plate 3.6. Hand-specimen of G2 from "Zone D" of the Allt nan Gaoirean HSZ. It contains a moderately developed, moderate temperature CPS fabric. The approximate trend of the fabric is shown by the white arrow. (Yellow 'bar' approximately 2 cm long).

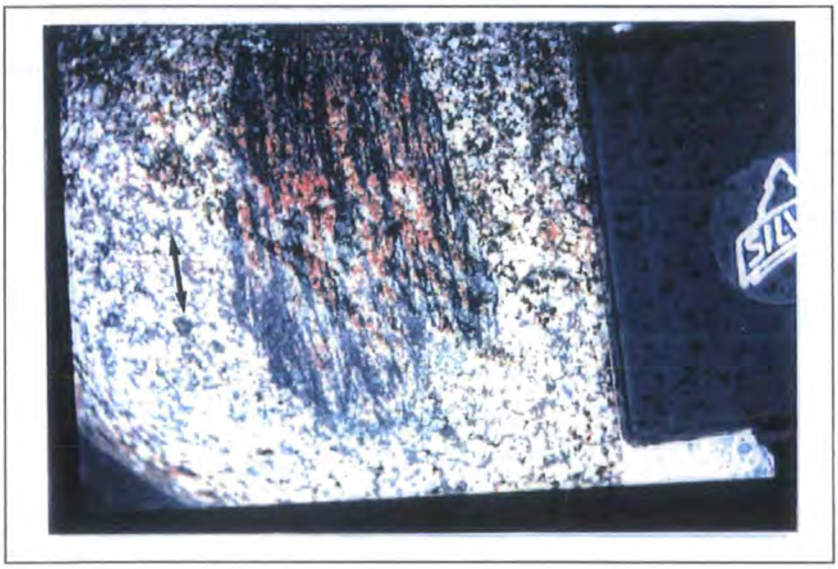


Plate 3.7. Country rock xenolith (presumably Leven Schist) is extensively modified within "Zone E" of the Allt nan Gaoirean HSZ (see Fig. 3.11).

Within the adjacent country wall rock (Leven Schist) are a number of melt-filled brittle-ductile shears (Plate 3.8) which are generally parallel to the contact with G2. Shear bands are also occassionally developed, often showing a sinistral sense of shear. These structures are possibly related to the deformation of G2 during the *in situ* expansion and synplutonic rotation of G4/G5. Within the immediate adjacent wall rock (Leven Schist) there appears to have been a certain degree of grain-size reduction over a highly variable distance of between 5 to 30 m wide (see Plate 3.9).

Plate 3.8. Melt-filled brittle-ductile shears and shear bands developed within the country wall rock adjacent to the Allt nan Gaoirean HSZ (G2). These structures are possibly related to the *in situ* expansion of G4/G5, which led to the extensive 'modification' of G2.

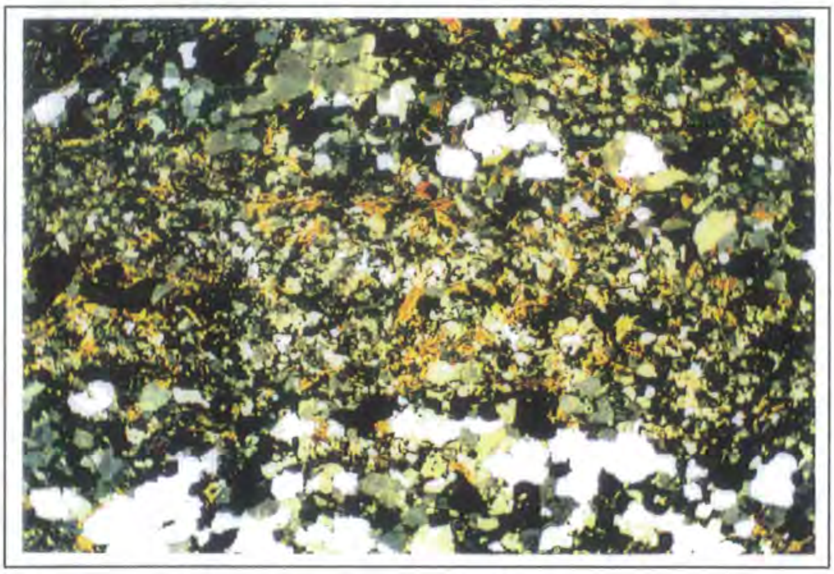


Plate 3.9. Photomicrograph of Leven Schist close to the northern contact of the Allt nan Gaoirean HSZ (G2). Note the grain-size reduction in discrete bands. In the coarser-grained 'bands' the texture is semi-annealed. (Field of view 18 mm).

Summary of microstructural features developed within the Allt nan Gaoirean high strain zone:

During the cystallisation of G2, it is envisaged that the Allt nan Gaoirean high strain zone was further strained by the expansion and synplutonic rotation of G4/G5 and the imposition of tectonic-related strains during movements along the NE-SW-trending shear zones (see below and Section 3.5); thus leading to the development of oblique CPS fabrics. This created a situation where large amounts of this transpressional deformation was locally focussed along both G2 contacts, i.e. at its outer margin with the Dalradian metasediments (see "Zone E"), and at the inner contact with the Porphyritic Starav facies (G4). During crystallisation of G2, a strain induced shear component was established across the region, leading to a component of rotational strain during the development of both the earlier PFC fabric and the overprinting CPS fabrics. This resulted in the development of a sigmoidal fabric trace across the region, which implies that the area was subjected to an overall sinistral component of shear. These features suggest that the whole of the Allt nan Gaoirean region was subjected to a component of 'non-coaxial general shear' during and after the crystallisation of G2, as a consequence of the emplacement, expansion and synplutonic rotation of G4/G5 at the centre of the complex.

General description of the distribution and mirostructural characteristics of the fabrics within the Allt Dhoireann High Strain Zone

Cruachan monzogranitic facies: as with the Allt nan Gaoireann region, this area can be sub-divided into zones of different fabric types (Fig. 3.13). As with the northern HSZ, the boundaries between these represent progressive rather than abrupt changes. As already mentioned, fabric development within the Allt Dhoireann region is somewhat more complicated than within the Allt nan Gaoireann region (as described above). This is attributed to the presence of a large psammitic screen (approximately 175-200 m wide and elongated sub-parallel to the G2 inner contact with the Porphyritic Starav facies (G4)) which appears to have partitioned the strain within the region, which was produced predominantly by the expansion and synplutonic rotation of G4/G5. This resulted in the following distribution of the fabric types (Fig. 3.13):

Zone A

High temperature, intensely developed CPS fabric: this zone of intense deformation (approximately 700-750 m wide) occurs between the psammatic raft and the contact with the Porphyritic Starav facies (G4; Fig. 3.13b & c). Recrystallisation processes have completely removed magmatic features such as zoning. Feldspars commonly show undulose extinction and strain induced lamellae indicative of internal ductile deformation. Twinning has largely been removed by dissolution, and many of the feldspar crystals have undergone dynamic recrystallisation of their margins. Together with sub-graining, this has resulted in; (a) the larger phenocryst phases becoming rounded, forming anhedral to subhedral shapes, and (b) the smaller crystals to become incorporated with quartz and mica to form fine-grained elongate aggregates. An annealed texture has been developed by the subgraining of plagioclase and alkali feldspar. Quartz is highly strained, lenticular, and often forms ribbons which define the CPS fabric. Wrapped around the larger feldspar and quartz crystals are biotite laths which are bent and kinked.

There is a progressive increase in the intensity of the CPS deformation within this zone towards the contact with G4. This is different to the situation observed within the HSZ of the Allt nan Gaoirean region, where in the equivalent corresponding zone, strain intensifies away from the G4 contact towards the outer margin of G2, and the strain accumulation appears to have been of a much lower magnitude resulting in the preservation of the earlier PFC fabric (which is only weakly to moderately overprinted by CPS deformation). The progressive increase in strain and continuation of the sigmoidal fabric across the northern zone (Fig. 3.13b & c) indicates that the strain imposed by the expansion and synplutonic rotation of G4/G5 was distributed throughout the region; the difference in fabric types occurring as a result of the outer parts of G2 cooling more rapidly than the inner and passing through the 'critical melt percentage' (Arzi 1978), combined with strain being focussed at petrological contacts. However, within the Allt Dhoireann HSZ, the presence of a large (approximately 175-200 m wide) metasedimentary screen (see Fig. 3.13b & c) appears to have led to a large amount of the strain, induced by the expansion and synplutonic rotation of G4/G5, to be partitioned, especially during the latter stages of crystallisation. This led to an increase in strain accumulation between the contact of G4 and the psammitic raft, rather than an overall gradual increase in strain towards the pluton margin as seen within the Allt nan Gaoirean HSZ.

Zone B

Moderate to low temperature, extremely intensely developed CPS fabric: this localised zone (approximately 10-15 m wide) of moderate to low temperature, intense solid state deformation development occurred at the outer margin of "Zone A", in contact with the psammitic screen (Fig. 3.13b & c). The monzogranite within this zone is very reddened and has undergone grain-size reduction. Plagioclase and hornblende crystals are fractured indicating deformation at temperatures < 450°C (Simpson 1985). Plagioclase and alkali feldspar phenocrysts have undergone marginal sub-graining, a high degree of recrystallisation, and the formation of undulose extinction. Twinning has often been removed by dissolution within the alkali feldspar crystals. Biotite laths show clear evidence of internal ductile deformation in the form of bent and kinked crystals, and are extremely elongate, as are many of the hornblende crystals. Quartz is highly deformed, exhibiting undulose extinction. Many of the quartz crystals are highly lenticular in form and have also undergone a high degree of recrystallisation. These fabrics are attributed to the localisation of strain at the contact with the psammitic screen during and after complete crystallisation of the monzogranite. Due to the high degree of recrystallisation, reduction in grain-size, elongation of the larger crystals and the finer-grained aggregates, and the fracturing of plagioclase and hornblende, deformation within this zone is inferred to have continued into the solid-state regime and is likely to have persisted through to relatively low temperatures. Whether this was a continuous deformational process related to the development of the fabrics within "Zone A" (discussed above) or a later, separate event which led to the modification of pre-existing fabrics within "Zone B" is unclear. However, the progressive nature of the intensification of the fabrics and more importantly the continuity of the sigmoidal fabric trace right up to the contact of the metasedimentary screen, indicates that the moderate to low temperature CPS fabrics developed within "Zone B" were most likely formed during part of the same deformational period which formed the fabrics seen within "Zone A"; not as a separate episode of overprinting, modifying any earlier fabric developed.

Zone C

PFC fabric with moderately developed CPS overprint: this is a localised zone of deformation along the southern contact of the psammitic screen (Fig. 3.13b & c). The zone is approximately 75-100 m wide and is characterised by a well developed, relatively moderate temperature CPS deformation which overprints the earlier PFC fabric. The solid state deformation is coplanar, which has led to the enhancement of the pre-existing fabric. Within this zone the fabric is essentially sub-parallel to the contact of the metasedimentary screen (see Fig. 3.13b). Moving towards the outer margin of G2 and into "Zone D" the fabric trace is progressively rotated and the relative amount of CPS overprint diminishes (Fig. 3.13b; see below).

Microstructurally the zone is characterised by the following features: (i) plagioclase and alkali feldspar have undergone marginal sub-graining. Many crystals still possess magmatic features such as oscillatory zoning. However, close to the psammite contact recrystallisation processes may have erased such features. Also along this contact, some of the feldspar laths have been broken or fractured, indicating relatively low temperature CPS deformation. Many of the feldspar crystals throughout the rest of the zone do not show this brittle type deformation, but instead the formation of undulose extinction and deformation lamellae indicative of ductile, CPS deformation at relatively high temperatures; (ii) quartz is generally lenticular, sub-grained and is highly strained; (iii) biotite also exhibits evidence of internal ductile deformation in the form of bent and kinked crystals. Many biotite laths are highly elongate, especially close to the metasedimentary screen; (iv) hornblende has been generally undeformed throughout the majority of the zone, an exception being at the contact with the psammitic screen where hornblende laths may be fractured.

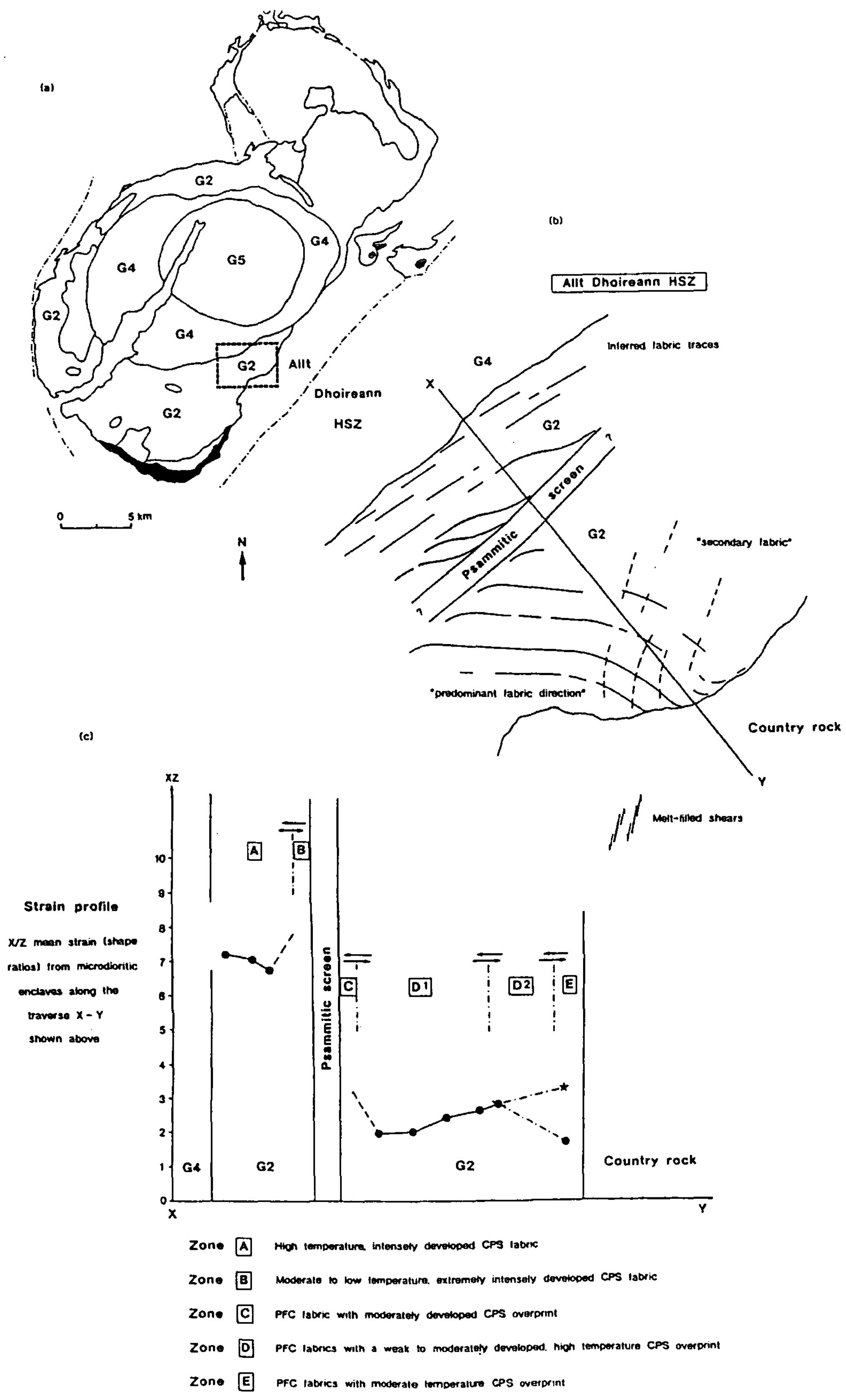


Fig. 3.13. **(a)** Sketch map showing the position of the Allt Dhoireann/Kingsglass high strain zone (HSZ) within the Etive complex. **(b)** Sketch map showing the inferred fabric trajectories across this region, and **(c)** associated strain profile and zones of different fabric type.

Zone D

PFC fabrics with a weak to moderately developed, high temperature CPS overprint: within the majority of this zone (Fig. 3.13c), the predominant fabric trend exhibits very similar characteristics to that of the sigmoidal fabric trace developed across the Allt nan Gaoirean HSZ; where movements along the bounding NE-SW-trending shear zone and the synplutonic rotation and expansion of G4/G5 led to a situation where large amounts of transpressional deformation was focussed into this region (see below & Section 3.5). A similar situation is envisaged for the Allt Dhoireann HSZ, with movements occurring along the bounding Ericht-Laidon shear zone and the overall synplutonic rotation and expansion of G4/G5 at the centre of the complex causing a strain induced shear component to be established across the region. However, within this southern zone of high strain, the situation is somewhat more complex, probably because of: (i) the presence of the large metasedimentary screen within G2 which appears to have partitioned the strain imposed (as mentioned above); and (ii) to the NE of this region, the subsequent pulses G4/G5 have essentially "pinched out" the Cruachan monzogranitic facies (G2); this has occurred because the centre of each subsequent intrusive phase has migrated in an arcuate form towards the NE (see below). This is further demonstrated by the distribution of petrographically distinct pulses within the Starav facies (G4/G5; Batchelor 1987; see Fig. 3.7). The fabrics developed due to these complexities are discussed below.

"Zone D" can be tentatively sub-divided into two zones based on the relative dominance of the different fabric trends developed within the area:

***Zone D^1*:** within this zone (approximately 725-750 m wide) the dominant fabric trend is continuous with the fabric developed within "Zone C", progressively changing in orientation towards the margin of the pluton (Fig. 3.13b & c). This is a moderate PFC fabric which has been overprinted by a coplanar, weak to moderately developed, high temperature CPS fabric. The geometrical form of the fabric trace (Fig. 3.13b) indicates a sinistral shear component across the region during its development; similar to the sigmoidal fabric trace developed across the Allt nan Gaoirean HSZ (see Fig. 11). However, unlike the northern zone of high strain, a secondary fabric is intermittently developed, becoming more pervasive and stronger in intensity towards "Zone D^2" where both fabrics are well developed and no one set dominates (Fig. 3.13b & c; see below).

Microstructurally the secondary fabric within this zone appears to have developed during the latter stages of PFC deformation and through into the solid state regime. This is based on the appearance of many of the plagioclase laths which define this secondary fabric direction. They are internally relatively undeformed, indicating their rotation and alignment occurred in a sufficient melt content, i.e. in excess of its rheological melt percentage (RCMP; Ch. 1), to prevent large amounts of internal ductile deformation. Biotite and hornblende laths may also define this secondary fabric. As with the development of the predominant fabric, deformation continued into the solid state, causing the fabric to be overprinted by a coplanar CPS deformation, enhancing its development. This CPS overprint in both sets of fabrics increases towards "Zone D^2", shown by a progressive increase in the amount of internal ductile deformation of quartz, plagioclase and biotite. Within this zone (D^1) the quartz crystals are somewhat strained and lenticular in form, often elongate parallel to the direction of the secondary fabric. This may indicate that the imposition of strain, causing the CPS deformation within the secondary fabric, continued for a greater period of time after full crystallisation, than the solid state deformation experienced by the predominant fabric, and/or the magnitude of strain causing this CPS deformation was more intense in the direction of the secondary fabric. Such features may indicate that during the crystallisation of G2 (within this zone), the strain fields responsible for the development of the predominant fabric direction, dominated over the strain fields associated with the development of the secondary fabric; leading to the development of a bimodal PFC fabric, and microdioritic enclaves and country rock xenoliths aligned in both directions (with the majority of these enclaves aligned parallel to the direction of the predominant fabric. However, as deformation continued into the solid state regime, there may have been a progressive reversal in the relative dominance of the two respective strain fields, causing a greater amount of CPS deformation in the direction of the "secondary" PFC fabric.

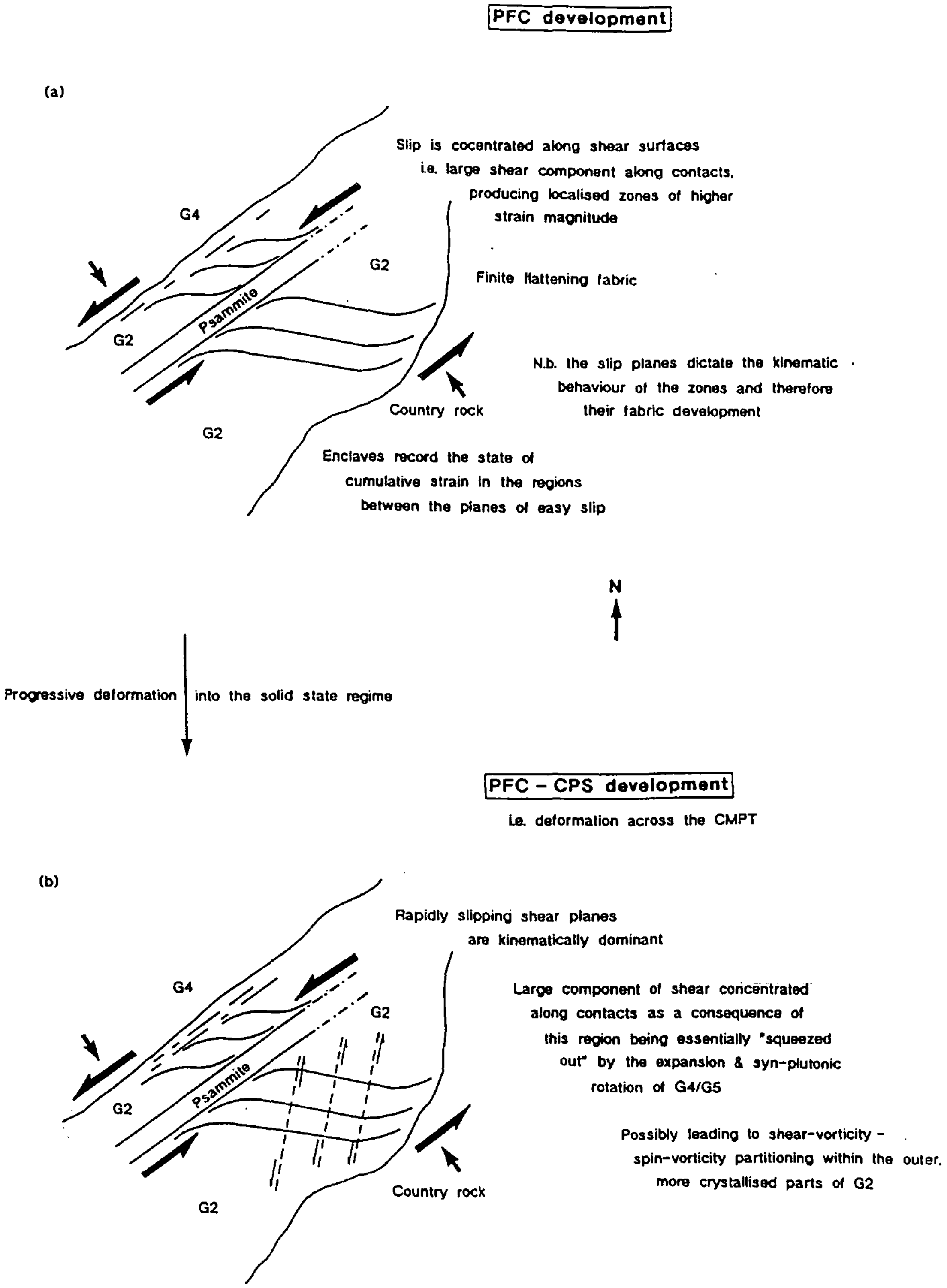
Zone D^2: this is a zone approximately 475-500 m wide and is characterised by both sets of fabrics which occur within "Zone D^1". However, within this zone no one set of PFC fabrics appear to dominate, and large populations of enclaves and country rock xenoliths are aligned in both directions. As mentioned above, the large majority of the microdioritic enclaves within "Zone D^1" are aligned parallel to the dominant fabric trend, with a smaller population aligned sub-parallel to the secondary fabric developed within the zone. X/Z ratios of the largest population suggests a progressive increase in the relative amount of strain magnitude towards "Zone D^2"; ranging from 2.00 to 2.62 (see Fig. 3.13c). However, as "Zone D^2" is reached there is an apparent dramatic decrease in the relative amount of strain, as enclaves parallel to this fabric trace possess an average X/Z ratio of 1.68. Within "Zone D^2" these enclaves no longer form the largest population, as there appears to be just as many enclaves aligned parallel to the "secondary fabric direction". The X/Z ratios of the microdioritic enclaves for both directions are remarkably similar (1.68 and 1.70; see Fig. 3.13c), possibly indicating that no one set of strain fields were obviously dominant during development of the bimodal PFC fabric. An interesting point is that if the apparent progressive strain increase (obtained from the X/Z ratios of microdioritic enclaves aligned parallel to the "predominant fabric direction" within "Zone D^1") is maintained through into "Zone D^2", the inferred value is very close to the value obtained from combining the X/Z ratios of both enclave populations; giving a combined apparent value of 3.38, which is remarkably close to the postulated value of approximately 3.4 to 3.5 (Fig. 3.13c). Whether this is coincidental or not is uncertain, but if not, it could suggest that the "total strain" was 'accommodated' roughly equal by both sets of fabrics during the earlier stages of G2 crystallisation. As mentioned above, it is interesting to note that within this zone the intensity of both sets of PFC fabrics appears to be the same.

As deformation continued into the solid state, it appears that the strain fields which were responsible for the development of the secondary fabric within "Zone D^1", were of much greater dominance, producing internal ductile deformation of quartz, plagioclase and biotite. This resulted in quartz forming elongate grains and aggregates, enhancing the fabric in this direction.

Zone E

PFC fabrics with moderate temperature CPS overprint: this is a localised zone, approximately 300-325 m wide, within the outer margin of G2 (Fig. 3.13b & c). Both PFC fabrics observed within "Zone D" are well developed and both are overprinted by a coplanar, moderate temperature CPS deformation. Crystals such as biotite, plagioclase and particularly quartz show clear evidence of internal ductile deformation. Some degree of fracturing within the plagioclase phenocrysts may indicate that CPS deformation occurred at relatively moderate to low temperatures. At the pluton margin, contact parallel, elongate (mean X/Z ratios of 8.61) country rock xenoliths occur.

The following scenario (shown by Fig. 3.14) may account for the formation and distribution of fabrics and strain across the Allt Dhoireann HSZ:



PFC development

Slip is cocentrated along shear surfaces i.e. large shear component along contacts, producing localised zones of higher strain magnitude

Finite flattening fabric

N.b. the slip planes dictate the kinematic behaviour of the zones and therefore their fabric development

Enclaves record the state of cumulative strain in the regions between the planes of easy slip

Progressive deformation into the solid state regime

PFC – CPS development

i.e. deformation across the CMPT

Rapidly slipping shear planes are kinematically dominant

Large component of shear concentrated along contacts as a consequence of this region being essentially "squeezed out" by the expansion & syn-plutonic rotation of G4/G5

Possibly leading to shear-vorticity - spin-vorticity partitioning within the outer, more crystallised parts of G2

Fig. 3.14. Generalised model for the development of fabrics within the Allt Dhoireann high strain zone (HSZ) during (a) PFC deformation, and (b) deformation into the solid state regime.

❶ As with the Allt nan Gaoirean HSZ, these deformational features are attributed to the whole region being subjected to a component of 'non-coaxial general shear' (i.e. a component of "pure shear" and a component of "simple shear"; see Fig. 3.14a & b) due to the expansion and synplutonic rotation of G4/G5 and the imposition of tectonic-related strains during movements along the NE-SW-trending shear zones (see below). During the crystallisation of G2, an overall strain induced shear component was established across the region. In the Allt nan Gaoirean HSZ this led to a component of rotational strain during the development of both the earlier PFC fabric and the overprinting CPS fabrics, essentially leading to the development of a continuous sigmoidal fabric trace across the region. However, within the Allt Dhoireann region, the presence of a large (approximately 175-200 m wide) psammitic screen has had the effect of partitioning the strain induced within this zone, leading to a somewhat more complicated distribution of fabrics and strain.

It is envisaged that during the initial stages of G2 crystallisation, the strain imposed was partitioned by the metasedimentary screen, leading to the development of a component of rotational strain either side of the psammite unit. This resulted in the development of two sigmoidal fabric traces, with large components of shear being locally focussed along rheologically different, petrological contacts (Fig. 3.14a).

❷ To the NE of this region the subsequent intrusive phases G4 and G5 have essentially "pinched-out" the Cruachan monzogranitic facies (G2) (Fig. 3.15). It is possible that during the expansion and synplutonic rotation of G4/G5, G2 within the Allt Dhoireann region was essentially being "squeezed-out", predominantly towards the SW (see Fig. 3.15a). This "stretching" and "thinning" of G2 being accommodated by the formation of the sigmoidal fabric traces and possibly by the development of a "secondary" PFC fabric (Fig. 3.14 & 15b), developed within the outer parts of G2 ("Zone D"). The exact timing of its development is unclear, however within the outer most parts of G2 (see "Zone D^2") microdioritic enclaves and country rock xenoliths are aligned parallel to both fabric directions indicating that this "secondary fabric" represents a PFC fabric developed before crystal lock-up occurred.

❸ As deformation continued into the solid state regime, both fabrics were progressively overprinted by coplanar, high temperature CPS fabrics. Microstructural features may suggest that as deformation continued into the solid state regime, there may have been a progressive reversal in the relative dominance of the two respective strain fields, causing a greater amount of CPS deformation in the direction of the "secondary" PFC fabric. An interesting point, is that within the adjacent country rocks are a number of melt-filled (granodioritic material) brittle-ductile shears which are generally orientated sub-parallel to this "secondary fabric" direction. A large majority possess a sinistral shear component, from a few centimetres up to 0.5 m (see Plate 3.10). This may indicate that as the deformation within G2 proceeded down-temperature, the strain was predominantly focussed into the "secondary fabric", which may have acted as a kind of "extensional shear fabric" (see Fig. 3.14b & 15b).

Plate 3.10. Shear band and melt-filled brittle-ductile shears developed within the country rock adjacent to the Allt Dhoireann HSZ (G2) (see Fig. 3.15). These structures are believed to be related to the *in situ* expansion of G4/G5, which led to the extensive 'modification' of G2.

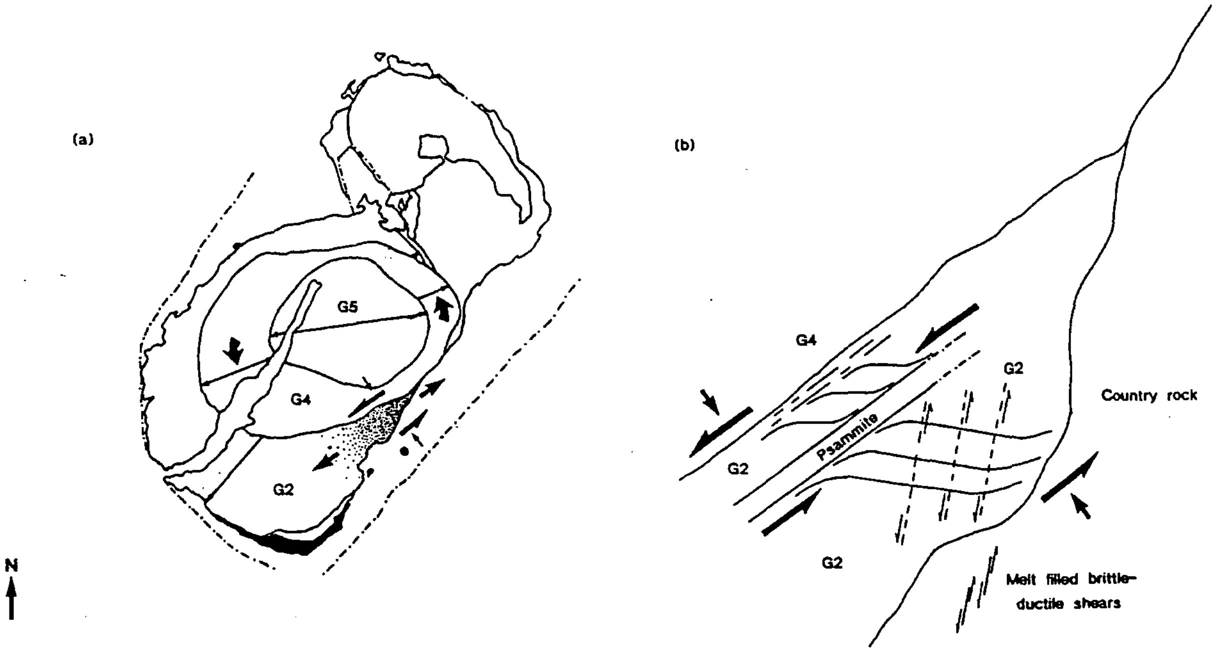


Fig. 3.15. (a) Sketch map of fabrics within the Allt Dhoireann high strain zone (HSZ). **(b)** Generalised model showing how the expansion and synplutonic rotation of G4/G5 was essentially "squeezing-out" G2 within the Allt Dhoireann region.

❹ Once G2 had become fully crystallised, it is envisaged that there was a rapid increase in the amount of solid state deformation experienced by G2 within the zone ("Zone A") between the psammite screen and its inner contact with the Porphyritic Starav facies (G4). With strain accumulating within this zone, due to the presence of the metasedimentary screen the strain was partitioned, preventing it from being more 'uniformly' dispersed throughout the region. This resulted in an accumulation of strain within "Zone A", which consequently led to the development of high temperature, intensely developed solid state fabrics.

Tectonic-related strains

Running through the adjacent wall rocks and in places partially bounding the pluton are the Allt Buidhe fault (Kynaston & Hill 1908; Clough *et al.* 1909), a possible continuation of the Laggan Dam fault (Anderson 1956), in the NW, the Pass of Brander fault (Kynaston & Hill 1968; Clough *et al.* 1909), and the Ericht-Laidon fault (Hinxman *et* *al.* 1923) in the SW (Fig. 3.16). Data presented within this thesis, predominantly based on the recognition of 'pre-full crystallisation' and 'crystal plastic strain' fabrics (Hutton 1988) developed within the adjacent granitic complexes, show that where these structures are spatially associated with plutons, they were acting as shear zones during magmatism. This has led to the recognition that two major structures spatially associated with the Etive complex, may have been acting as major Caledonian NE-SW-trending shear zones during plutonism. These are:

(i) the Etive-Laggan shear zone, an active ductile shear zone controlling the siting of intrusive phases, fabric development and strain distribution during the emplacement of the Strath Ossian (see Ch. 6). Rannoch Moor (see Ch. 5) and Glencoe (see Ch. 4) complexes.

(ii) the Ericht-Laidon shear zone controlling emplacement characteristics of the Strath Ossian and Rannoch Moor complexes.

Fabric trajectories and strain distribution associated with these structures suggest that they were active sinistral shear zones during magmatism. The Ericht-Laidon shear zone essentially bounds the Etive complex to the SE, and the Allt Buidhe-Laggan Dam fault may bound it to the NW (Fig. 3.16). Sinistral ductile deformation along these structures during the construction of the Etive complex may have allowed magma to expand predominantly into the direction of maximum extension imposed by those controlling structures. The maximum expansion direction would have been orientated approximately E-W. The overall ellipticity of the complex, the geographical orientation of the X axis of individual intrusive phases (see Section 3.8) which possesses an elliptical form, and the development of the Allt nan Gaoirean and Allt Dhoireann HSZ's suggests that the complex was subjected to an overall gross transpressional component imposed by the bounding NE-SW-trending structures. Both high strain zones correspond to the direction of maximum compression/construction imposed by these structures. Such high strains developed within these regions are likely to be due to the combined affects of the interaction of these tectonic-related strains, opposing strain fields associated with the expansion and synplutonic rotation of the intrusive phases G2, G4 and G5, which accumulate to give much higher strain magnitudes (see Ch. 10).

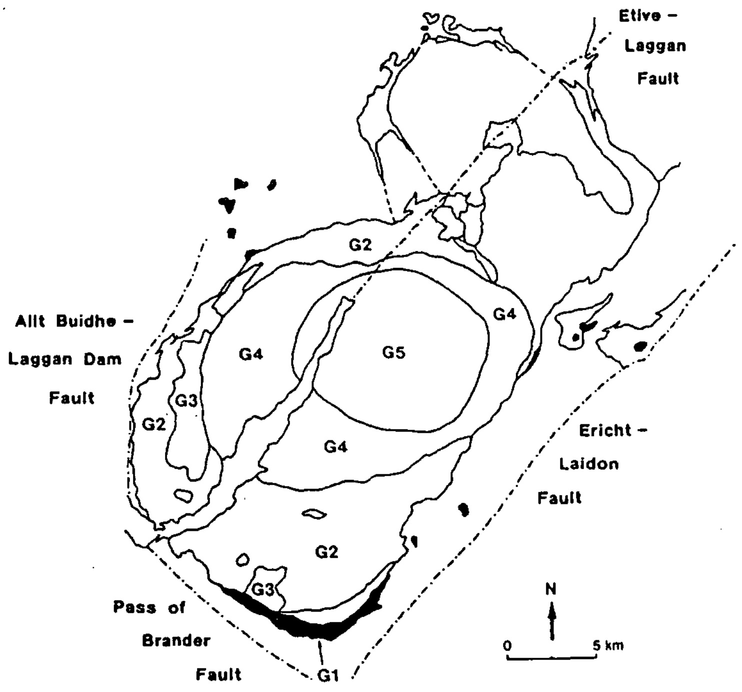


Fig. 3.16. Structural controls on the emplacement of the Etive complex.

3.4.3 G3: The Meall Odhar facies

The majority of the syenogranitic sheets within the southern part of the complex, have no apparent fabrics, as observed either in hand-specimen or thin-section. However, within the NW of the complex, particularly from Allt Buidhe [NN 040 440] north-eastwards through Beinn Sgulaird [NN 054 461] towards Glen Ure (Fig. 3.17), the syenogranitic intrusions possess fairly moderately developed CPS fabrics, generally trending sub-parallel to the contact with G4 and not the pluton margin. This is essentially a moderate temperature solid state fabric (Plates 3.11 & 3.12), which also occurs as a pervasive overprint throughout the Cruachan facies (G2) within this region. The fabric, both within G2 and G3, locally, slightly intensifies towards the G4 contact and regionally increases north-eastwards towards Glen Ure, and into the "Allt nan Gaoirean high strain zone". It seems conceivable that this fabric has been produced as a consequence of the imposition of strain by the expansion and synplutonic rotation of the subsequent intrusive phases G4/G5.

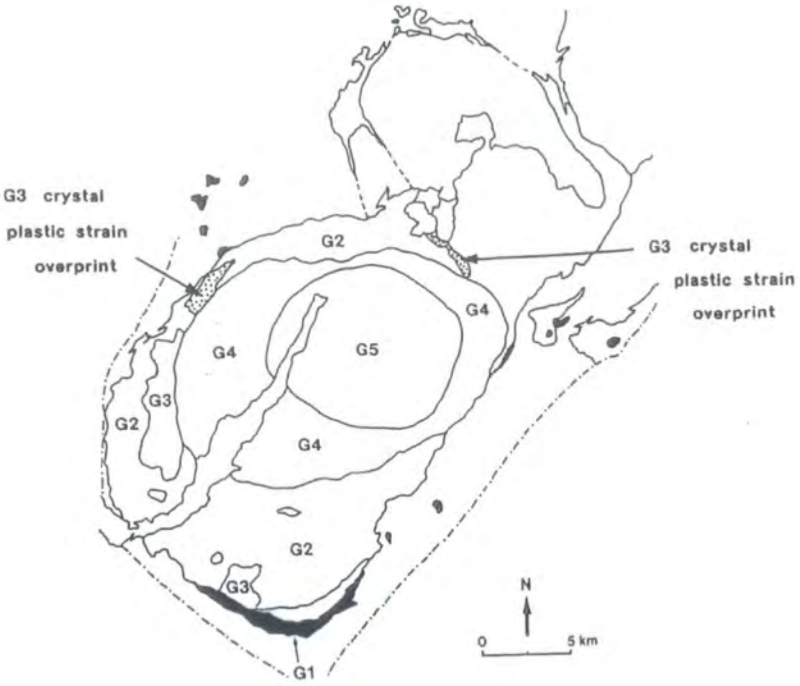


Fig. 3.17. Sketch map showing distribution of CPS fabrics within G3 of the Etive complex.

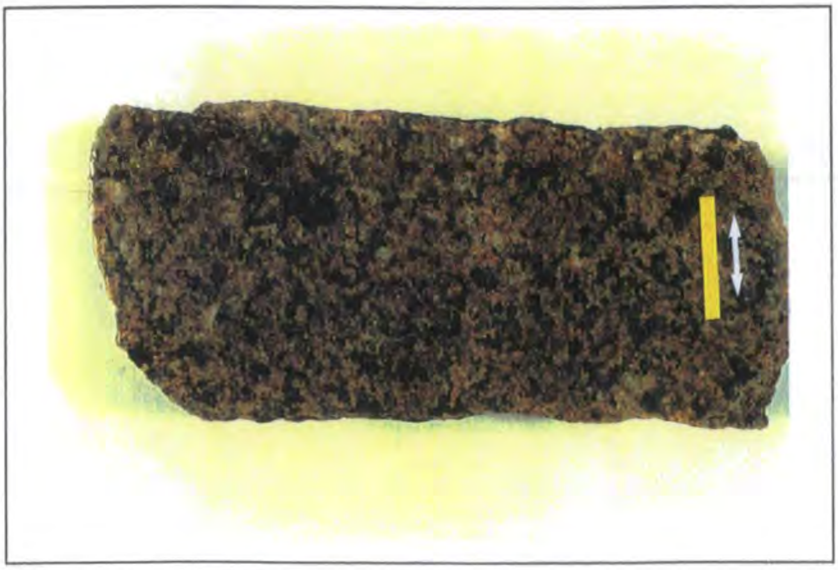


Plate 3.11. Hand-specimen of G3 (Meall Odhar facies) from the Allt Buidhe area [NN 040 440]. It possesses a moderate temperature solid state fabric, defined by elongate quartz and biotite laths. White arrow shows fabric trend. (Yellow 'bar' is approximately 18 mm).

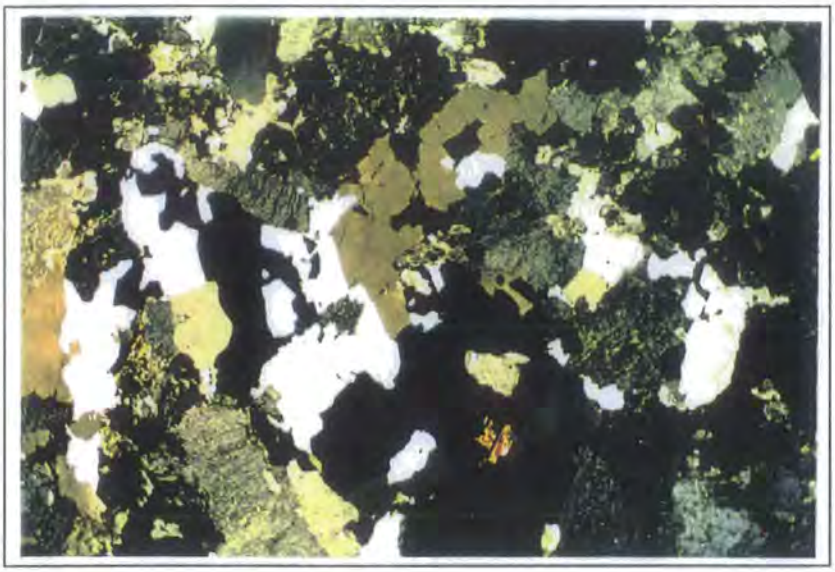


Plate 3.12. Photomicrograph of the hand-specimen (G3) shown in Plate 3.11. Note the elongate nature of the quartz crystals. (Field of view approximately 18 mm).

Such high to moderate temperature solid state fabrics are also observed within the partial "ring dyke body" of monzogranite (the "Meall Odhar ring dyke" of Anderson (1937)) within the NE, between G2 (Cruachan facies) of the Etive complex and G2 (Clach Leathad facies) of the Glencoe pluton. This CPS overprint may also be due to the emplacement of G4/G5 and possibly the *in situ* expansion of the adjacent Glencoe pluton. It has been noted that within this body there are thin seams "in which the rock occurs in a finely sheared, granulitic condition. These seams are individually about half an inch wide, and have been traced for short distances parallel to the general run of the intrusion" (Clough 1910; *in* Bailey 1960). These are mylonitic shears, probably produced during the later stages of the solid state deformation of G3, as strain was focused into these discrete zones as the deformation continued down temperature.

The moderate temperature CPS fabrics within G3 are characterised by the following microstructural features: (i) the quartz is strained, possessing undulose extinction, and forms fairly elongate crystals; (ii) plagioclase has often developed deformation lamellae; (iii) plagioclase and alkali feldspar may be subhedral as a result of "rounding" by recrystallisation of their margins and sub-graining; and (iv) within the monzogranitic body, at the type locality (Anderson's "Meall Odhar ring dyke"), biotite laths are often kinked or bent.

3.4.4 G4: The Porphyritic Starav facies

Throughout the Porphyritic Starav facies a pervasive, slightly inward-dipping, PFC fabric is weak to moderately developed, and is generally pseudoconcentric to its outer margin (Fig. 3.8a). The fabric is characterised by the preferred dimensional orientation of plagioclase, alkali feldspar, biotite and hornblende crystals. The much larger euhedral phenocrysts (1.5-3.0 cm long) of plagioclase and orthoclase are generally less well aligned.

Locally developed, weak to moderately developed, high temperature CPS fabrics may occur along the outer contact with G2 (Plate 3.13). This is generally a coplanar solid state overprint, enhancing the pre-existing (PFC) fabric. Much more intense CPS fabrics occur in association with the two corresponding zones of high strain (HSZ) developed within the Cruachan facies (G2), i.e. within the north, the Allt nan Gaoirean HSZ, and in the south, the Allt Dhoireann HSZ (see sub-section 3.4.2.2). In both these regions, the width of G4 is remarkably less than throughout the rest of the complex (see Fig. 3.10) and the development of these high temperature CPS fabrics may be due to the expansion and synplutonic rotation of the next intrusive phase, G5, and/or strain imposed by the bounding NE-SW-trending shear zones. The fabrics are characterised by lenticular quartz and phyllosilicates, particularly biotite, which are often bent around feldspar crystals. Overall, there has been a progressive grain-size reduction by recrystallisation processes. Many of the plagioclase crystals possess deformation lamellae.

Both G2 and, particularly G4, have been affected by a later deformational event associated with the reactivation of the NE-SW-trending Etive-Laggan structure. It occurred after both G2 and G4 had fully crystallised, producing a localised zone of low temperature CPS deformation along the fault. This is best exposed along the River Etive section, particularly at the confluence with the Allt nan Gaoirean [NN 144 474], where G4 in particular, is highly brecciated, quartz veined, and chloritised (Plates 3.14, 3.15, 3.16 & 3.17). Large, lenticular quartz "pods" up to 1.5 m in length are common. The quartz veins and "pods" are associated with brittle shears which trend, in general, approximately 050-065° (ENE-WSW) sub-parallel to the high temperature CPS fabric developed within G4. The quartz veins may be either pre-, syn-, or post-tectonic, with respect to movements along the brittle shears. Another possible set of shears trend approximately 162-170° (NNW-SSE), often cross-cutting the quartz veins and structures which trend sub-parallel to the CPS fabric developed within G4. A large number of these shears possess a sinistral shear component and their high angle with respect to the orientation of the CPS fabric developed within G4 and the other set of brittle shears suggests that these are R_2 Reidal shears, locally developed as a response to brittle deformation along the Etive-Laggan fault. This implies that there was a late sinistral displacement along the Ericht-Laidon fault after G4 had fully crystallised. The amount of movement and timing of this event in unclear, however, Perkins (1986), using inferred offsets of the boundaries of the major intrusive phases (G4, and within G2) across Loch Etive, suggests sinistral displacements of 0.6-0.8 km across this fault zone.

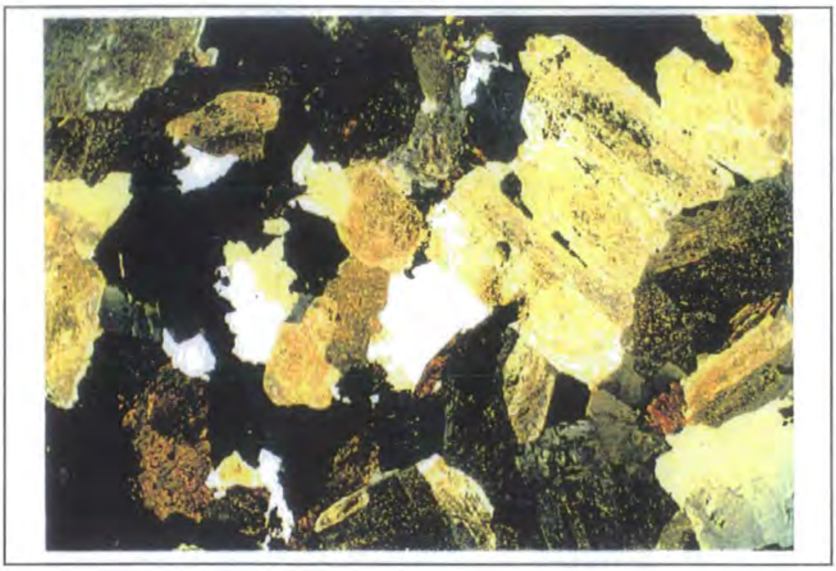


Plate 3.13. Photomicrograph of G4 showing a weak to moderately developed, high temperature solid state overprint. Hand-specimen taken from Glen Liver [NN 070 355], close to the contact with G2. (Field of view approximately 18 mm).

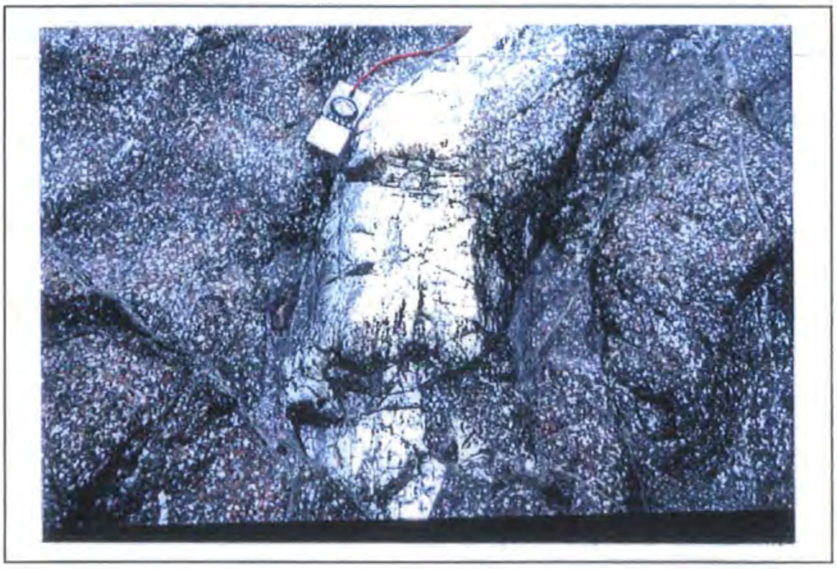


Plate 3.14. Large Quartz "pods" and associated brittle shears cross-cut G4 in the vicinity of the Etive-Laggan fault. River Etive section, at the confluence with the Allt nan Gaoirean [NN 144 474].

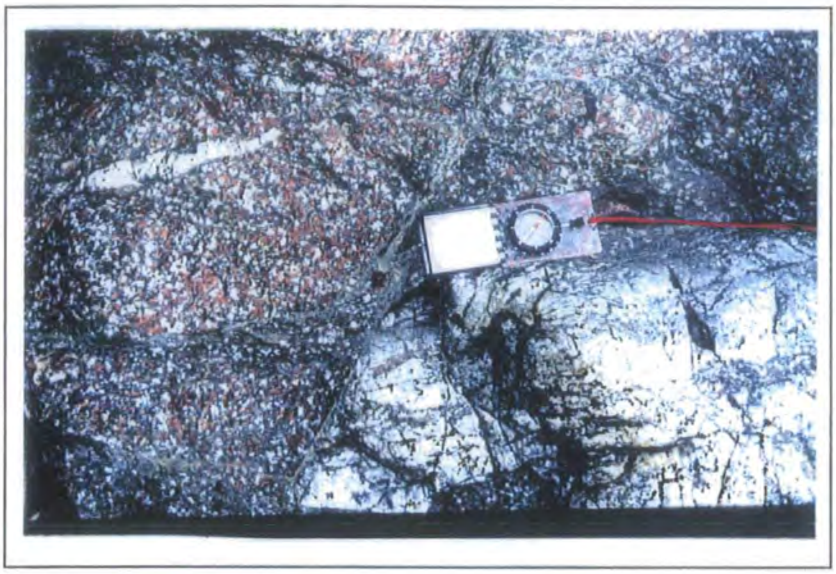


Plate 3.15. Closer view of part of Plate 3.14. Note the highly red nature of G4 and the chloritised brittle shears.

Plate 3.16. Hand-specimen of G4 taken from the area shown in Plates 3.14 and 3.15. G4 has experienced a solid state deformational overprint, and is highly brecciated, quartz veined and chloritised. (Yellow 'bar' is approximately 2 cm long).

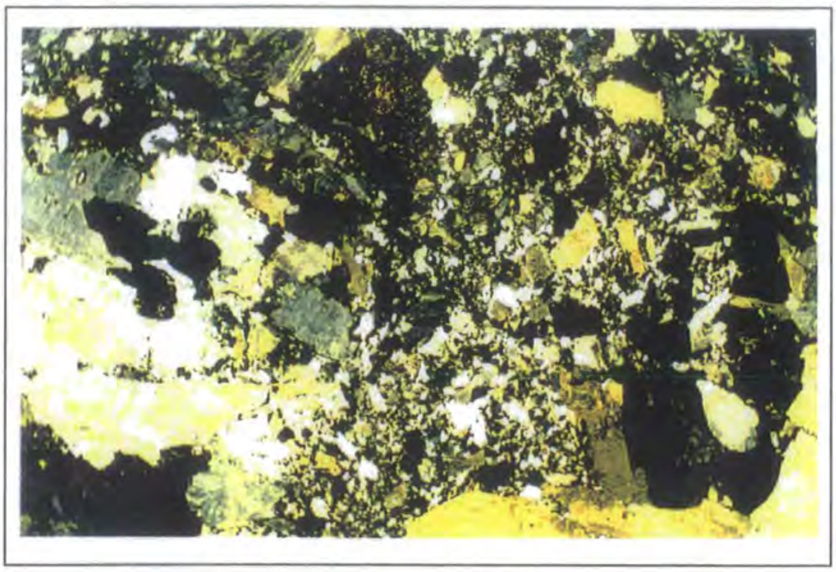


Plate 3.17. Photomicrograph of G4 taken from hand-specimen shown in Plate 3.16. Most crystals are broken and heavily altered indicating a low temperature, brittle deformational event. Quartz veins and brittle shears truncate host crystals. (Field of view approximately 18 mm).

At one locality [NN 145 476], the Etive-Laggan fault runs directly along the contact between G2 and G4 (Plate 3.18). The fault zone is represented by 0.5-1.0 m of blue-grey, ultra fine-grained cataclastic material (Plates 3.19, 3.20 & 3.21). Both intrusive phases have an extremely red appearance (3.14 & 3.15), possibly suggesting late stage fluid activity along the fault zone, leading to Fe oxidation.

Plate 3.18. River Etive exposure [NN 145 476] looking south-eastwards along the line of the NE-SW-trending Etive-Laggan fault. The fault within this particular area runs directly along the contact between G2 and G4, as shown.

Plate 3.19. Closer view of the Etive-Laggan fault zone, which is represented by a 0.5-1.0 m wide zone of blue-grey, ultra fine-grained cataclasite material.

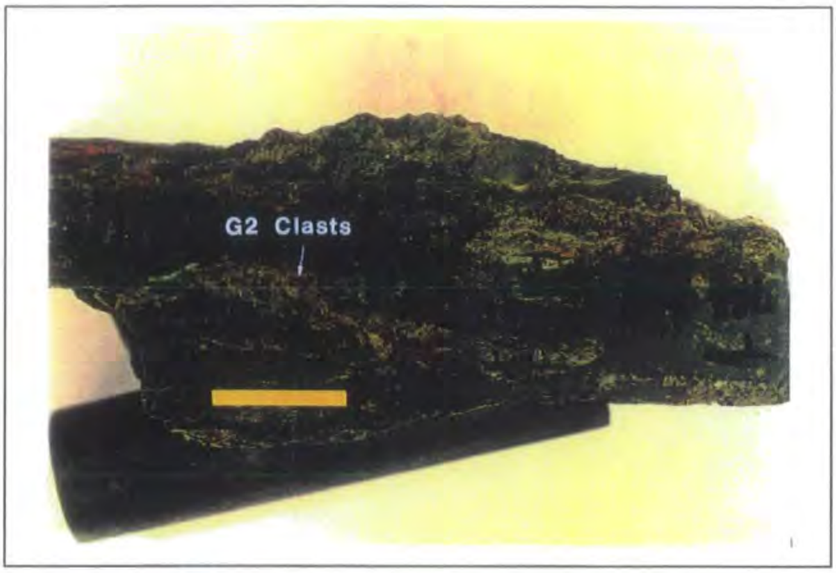


Plate 3.20. Hand-specimen illustrating the ultra-fine grain-size of the material within the Etive-Laggan fault zone. Note the brecciated G2 clasts. (Yellow 'bar' is approximately 2 cm long).

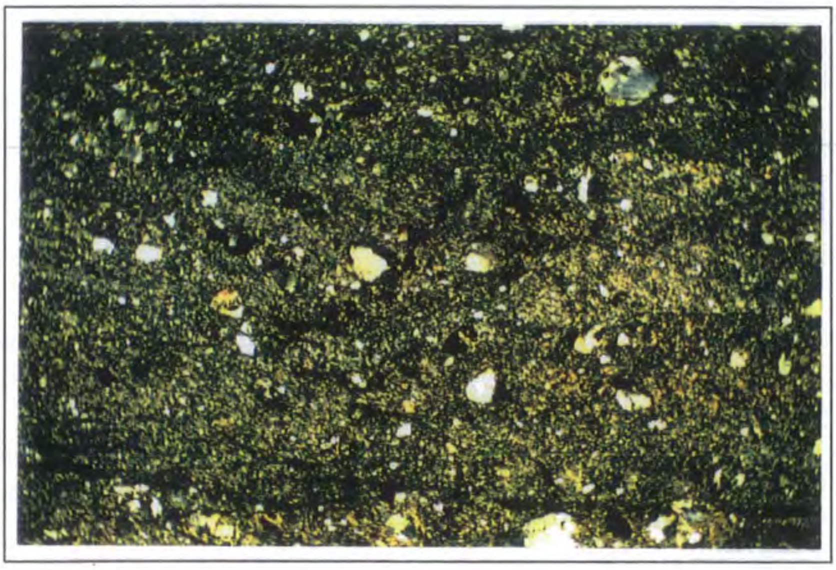


Plate 3.21. Photomicrograph of hand-specimen ('cataclasite') shown in Plate 3.20. The fault-rock may contain clasts of both G2 and G4. (Field of view approximately 18 mm).

3.4.5 G5: The Central Starav facies

PFC fabrics are weak to moderately developed throughout this facies. They are predominantly developed within the outer parts of G5 where they are pseudoconcentric with respect to the general geometrical form of this intrusive phase. As mentioned in sub-section 3.2.6, no actual contact is observed between G4 and G5; instead a 'transitional zone' occurs, approximately 350-400 m wide. Across this zone no overprinting CPS fabrics occur within either G4 or G5, which suggests that the emplacement of the two phases occurred as a fairly continuous intrusive event, with no great lapses in time between successive pulses which would have resulted in the formation of "well defined" petrological contacts. This implies that the deformation imposed by the *in situ* expansion and synplutonic rotation of the subsequent G5 pulse, occurred as G4 was still essentially behaving rheologically as a magma, i.e. below its 'critical melt percentage' (Arzi 1978). This resulted in: (i) the development of pseudoconcentric, weak to moderate PFC fabrics within the outer parts of G5; and (ii) no strain localisation at the "contact" between G4 and G5 because it represents a "transitional zone", preventing the development of high temperature CPS fabrics, which are commonly developed at the pluton margin and between G2 and G4.

3.5 EVIDENCE FOR SYNPLUTONIC ROTATION DURING THE *IN SITU* EXPANSION OF THE MAJOR INTRUSIVE PULSES G2, G4 AND G5

This is based on observations from a variety of scales. At the largest scale ("macro-scale"), these features include the geographical orientation of the X axis of individual intrusive phases relative to each other, and the synplutonic rotation of regional country rock foliations. "Meso-scale" features include gross fabric trajectories and strain patterns developed within certain areas (see Allt nan Gaoirean and Allt Dhoireann HSZ; see sub-section 3.4.2.2). On a much smaller scale ("micro-scale") contact relationships between major intrusive phases, suggest expansion and synplutonic rotation processes during the emplacement and construction of subsequent intrusive phases. This evidence is presented below as a series of points, commencing with "macro-scale" features, through to "micro-scale" phenomena:

① Based on the apparent X/Z ratios for the intrusive phases and the geometrical orientation of their X axis relative to each other (Fig. 3.18), a sinistral shear component imposed by the bounding NE-SW-trending shear zones is implied. With magma initially expanding predominantly E-W into the direction of maximum extension imposed by these structures. As the gross 'non-coaxial' deformation applied to the whole complex continued, the pulses were progressively deformed and rotated, tracking the finite strain ellipsoid (Fig. 3.18a). If the X/Z ratios for the intrusive phases G2, G4 and G5 are plotted against geographical orientation of the X axis (Fig. 3.18b), the resulting straight line implies that the transpressional deformation imposed remained fairly constant during the expansion process.

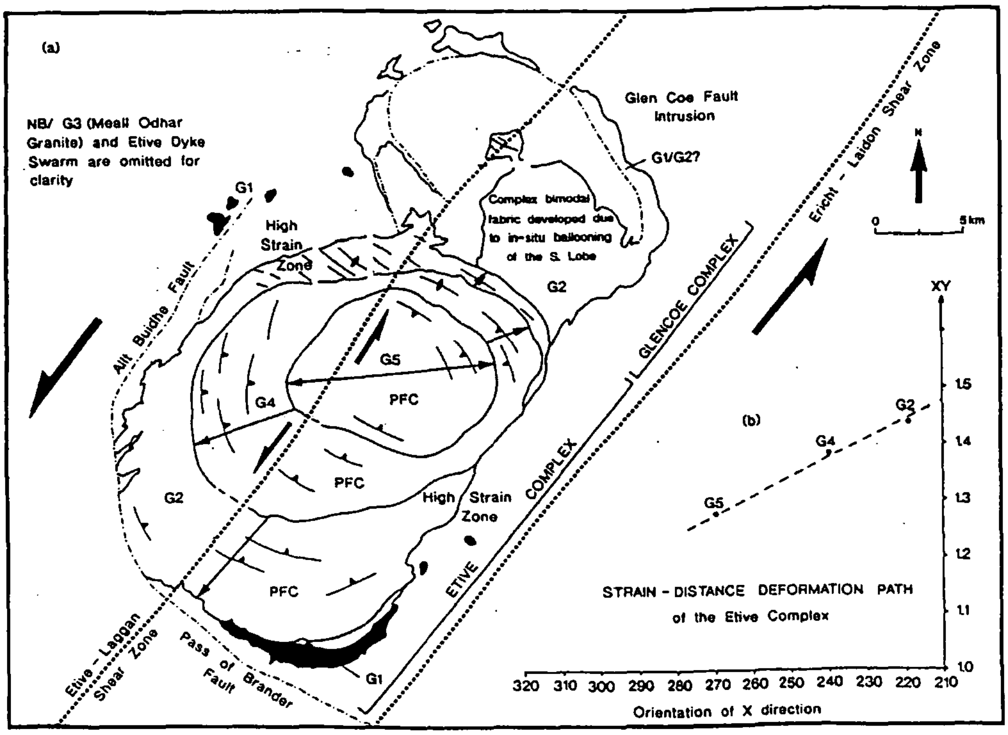


Fig. 3.18. (a) Generalised model for the emplacement of the intrusive phases of the Etive complex and its associated deformation within the Glencoe plutonic complex. (b) A plot which shows the X/Z ratios for the intrusive phases G2, G4 and G5 against the orientation of the X direction.

② Fabric development and strain distribution both within the northern and southern zones of high strain developed within G2 (Allt nan Gaoirean and Allt Dhoireann regions, respectively) show that both regions were subjected to transpressive deformation. By definition this type of deformation comprises of a component of "pure shear" and a component of "simple shear". The "simple shear" component being derived from the synplutonic rotation of G4/G5 at the centre of the complex, along the inner contact of G2, and a sinistral shear component imposed by the bounding NE-SW-trending structures along the outer margin of G2.

③ Along Allt Ceitlein [NN 148 477], the northern part of the complex, the contact between G2 (Cruachan facies) and G4 (Porphyritic Starav facies) is curvilinear, and moderately dips at approximately 65-72° towards the pluton centre (Fig. 3.19a). Cuspate and lobate geometries at the contact between these two phases, suggest that G4 was emplaced before G2 had fully crystallised, i.e. before it had passed through its 'critical melt percentage' (Arzi 1978) and undergone crystal lock-up. In places, the contact between the two phases is defined by a 'line' of K-feldspar megacrysts (1-3 cm in length) (Fig. 3.19b). The 'line' is occasionally broken by the concentration of euhedral/subhedral hornblende megacrysts (approximately 1.0 x 0.3 cm, up to 2.0 cm long), which form sigmoidal 'swathes', irregular clusters or alignments within G4 (Plate 3.22). Between these hornblende rich zones and the contact-parallel K-feldspar megacrysts, a much finer-grained granitic material is generally present. Along certain parts of the contact, where the hornblende bands have disrupted the 'line' of K-feldspars, the G2/G4 contact may be breached and hornblende crystals may be seen incorporated within G2. These tend to form irregular clusters, which are much more dispersed than in the case of G4. Due to the G2 pulse being earlier, its relative temperature compared to G4 must have been somewhat lower. This may have resulted in the K-feldspar megacrysts, which have aligned themselves along the contact within G4, undergoing 'crystal lock-up' essentially forming a discrete zone of 'chilling'. However due to deformation being focused along this petrological contact by the expansion and synplutonic rotation of G4, the discrete zone of 'crystal lock-up' may have been transtensionally pulled apart along certain sections of the contact. During this process it is envisaged that the hornblende crystals were drawn into these low pressure regions, producing "tension-gash" type structures or melt-filled shears (Fig. 3.19c; Plate 3.22). The sinuous form of some of these hornblende 'swathes' may suggest a sinistral deformational component across the contact. This is verified by the development of a sigmoidal PFC fabric swing in G2, which has been overprinted by a coplanar, high temperature CPS deformation (Fig. 3.19c). These features suggest that a localised, sinistral shear component was established across the G2/G4 contact as the pulses underwent gross sinistral transpressive deformation (as mentioned above), causing them to synplutonically rotate during their expansion.

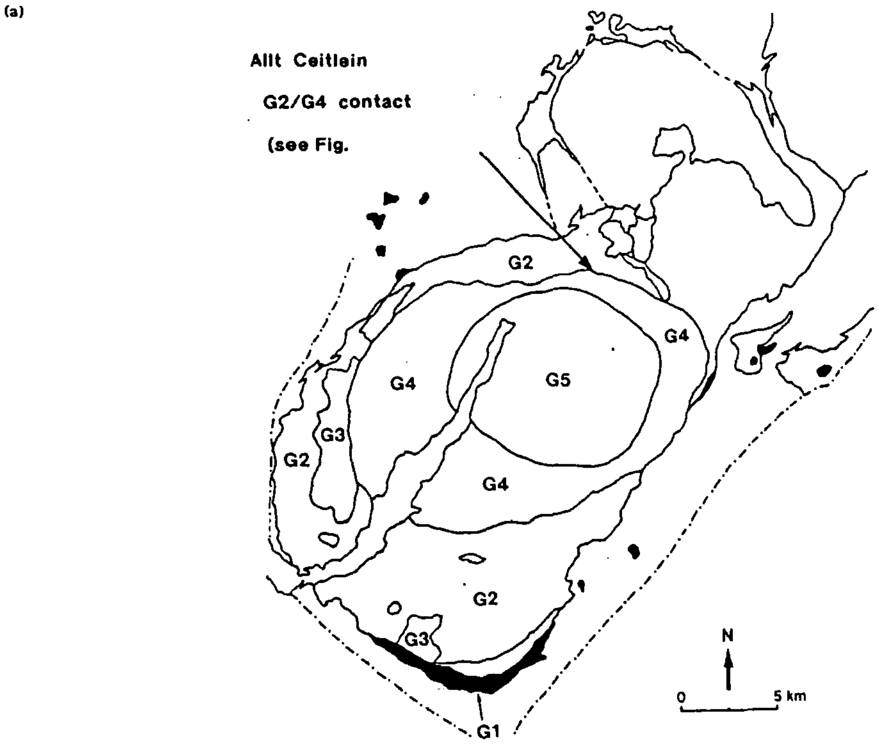


Fig. 3.19. (a) Inset showing location of the G2/G4 contact at Allt Ceitlein within the Etive complex.

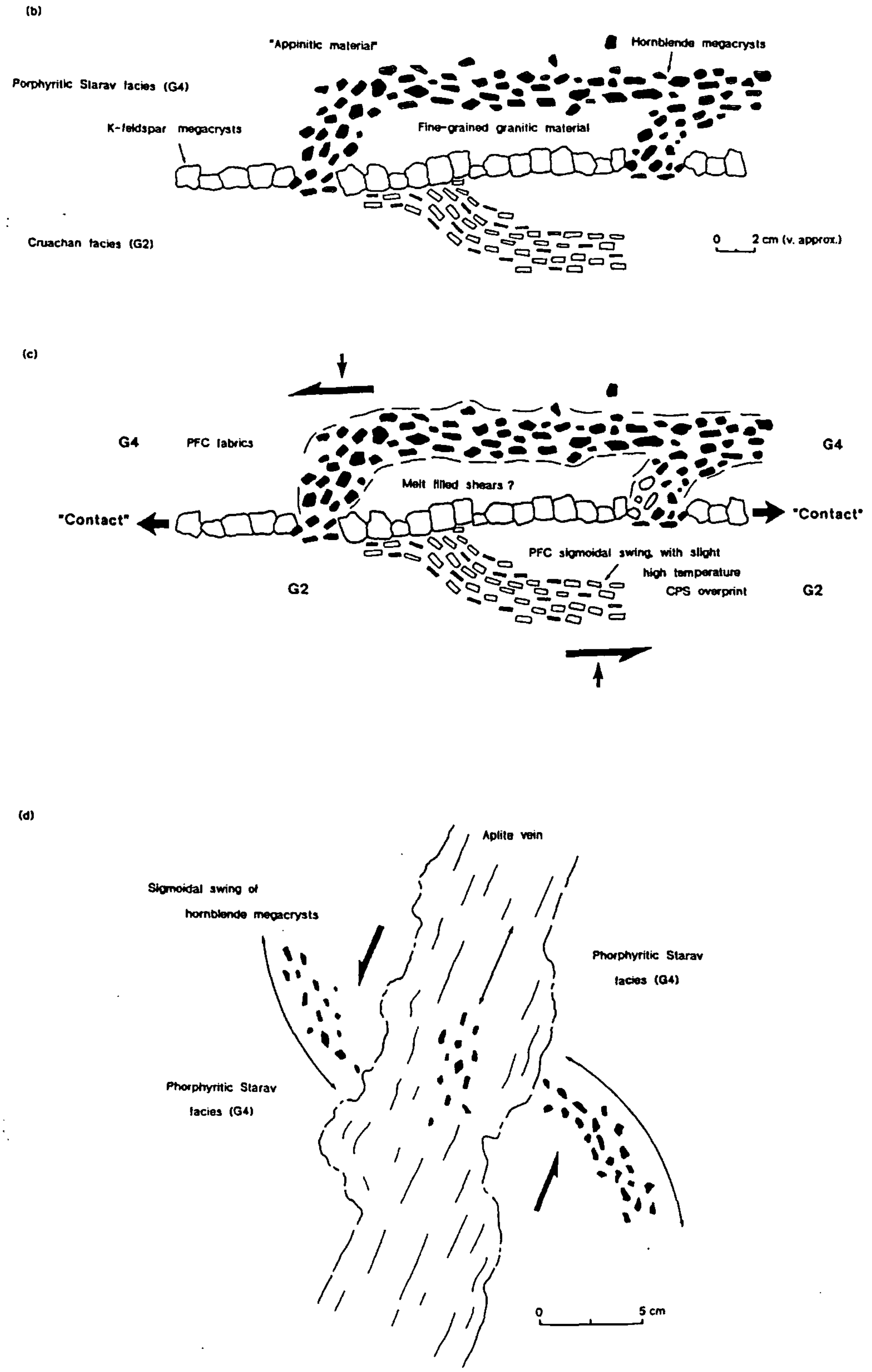


Fig. 3.19. (b) Contact relationships between G2 and G4. (c) Generalised model, possibly explaining the features observed at the G2/G4 contact (see text for explanation). (d) Aplite veins showing synplutonic relationships with G4.

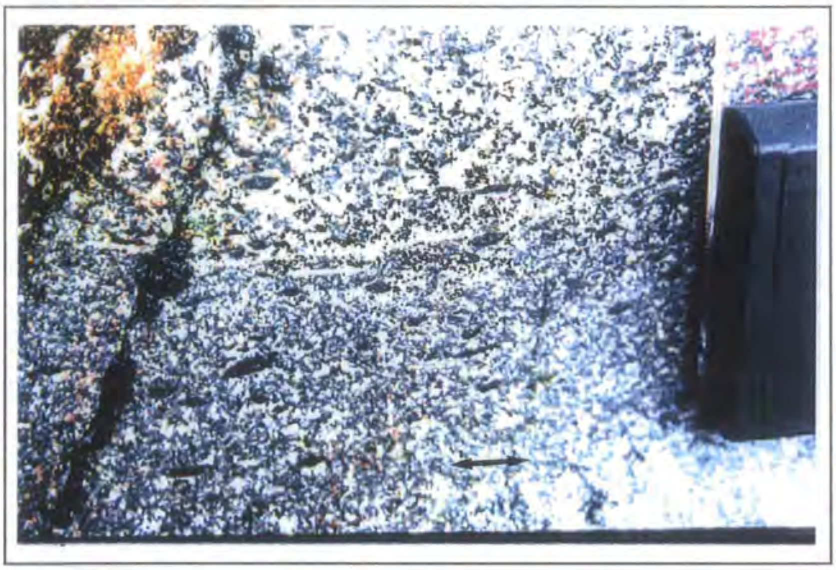


Plate 3.22. Example of alignment of hornblende megacrysts within G4 (Porphyritic Starav facies), near the contact with G2 (Cruachan facies) in the Allt Ceitlein area [NN 148 477].

Also present within this area are: (i) aplite veins (approximately 5-10 cm wide) which trend approximately 025°; and (ii) quartz-rich "pods" which contain large K-feldspar megacrysts (some up to 5 cm long and 3 cm wide) (Plate 3.24). The aplite veins possess synplutonic relationships with G4 (Fig. 3.19d), and may ductiley, sinistrally displace bands containing hornblende megacrysts which are set in a dark, mafic-rich phase of the Porphyritic Starav facies (G4).

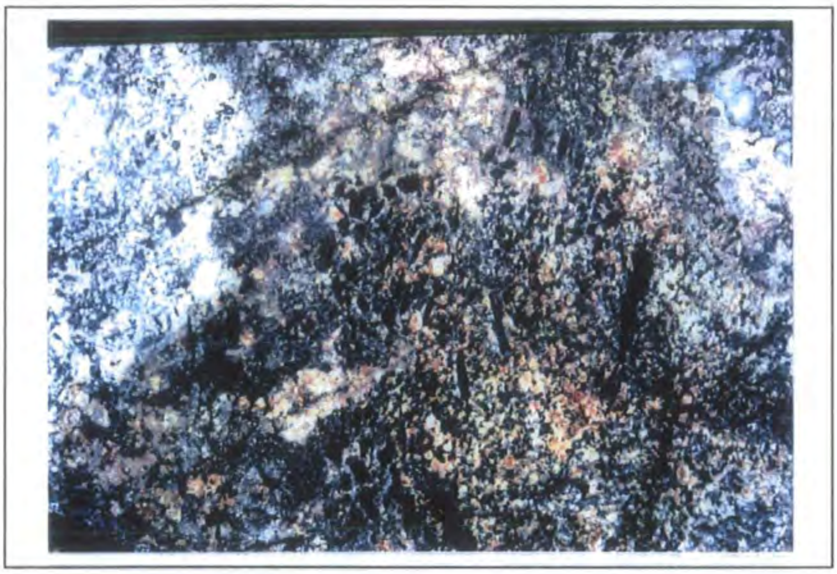


Plate 3.23. Example of hornblende megacrysts concentrated in a 'melt-filled shear' within G4. The sinuous form of some of these 'swathes' indicate a sinistral shear component along the contact of G4/G2 during their development; Allt Ceitlein area [NN 148 477].

Plate 3.24. Within the Allt Ceitlein area [NN 149 478] a number of quartz "pods" containing large K-feldspar megacrysts cross-cut the fabric developed within G2 (Cruachan facies). The "pods" appear to be associated with the intrusion of G4 (Porphyritic Starav facies), which itself contains large K-feldspar megacrysts (generally 1.5 cm long).

3.6 CONTACT RELATIONSHIPS AND COUNTRY ROCK DEFORMATION

The outer contact of the pluton is extremely variable. It can be (a) extremely complex forming an intricate intrusive relationship with the surrounding country rocks, (b) simple and well defined, and (c) fault controlled.

Within the western part of the complex, the Allt Buidhe fault (Kynaston & Hill 1908) roughly follows the curvature of the pluton margin. Within this area G2 contains a large amount of country rock xenoliths (Fig. 3.20), which range from metres to hundreds of metres in length. The majority are extremely lenticular in form, and are generally sub-parallel to one another, trending approximately NE-SW, oblique to the bounding Allt Buidhe fault. Some of these highly elongate xenolith 'rafts' show a slight deflection in continuity moving towards the Allt Buidhe fault (Fig. 3.20). This tends to occur within a zone approximately 75-100 m wide, and the sense of deflection may suggest that the Allt Buidhe fault (sometimes known as the "Cruachan Boundary fault"), possessed a sinistral shear component. It is also interesting to note that within this region the country rocks show conspicuous stratigraphic re-orientation (Fig. 3.21; see Litherland (1980)) close to the pluton contact, within an area essentially bounded by the Allt Buidhe fault (Cruachan Boundary fault) and Pass of Brander fault. Both faults trend approximately NE-SW, until they reach the southern part of the Etive complex where they progressively change in orientation, eventually trending NW-SE (Fig. 3.21).

Another interesting feature within this area is the way there is remarkable change in the nature of the regional crenulation cleavage, S2 (or 'slaty' cleavage in meta-pelites) (Fig. 3.22; see Litherland 1982). This change occurs across the Benderloch Slide, from a steeply dipping, NE-SW-trending, composite 'slaty' cleavage NW of the Slide, to a shallow dipping (30-40°) crenulation cleavage inclined to the west or SW, cutting S1 at high angles (Litherland 1982) This change coincides exactly with the possible south-westward continuation of the Ballachulish-Corrieyairach shear zone, which was an important structure during the siting and construction of the nearby Ballachulish complex (see Ch. 9). Moving south, from the Benderloch Slide, S2 has a sigmoidal form which progressively changes to a NW-SE-trend towards the pluton margin (Fig. 3.22).

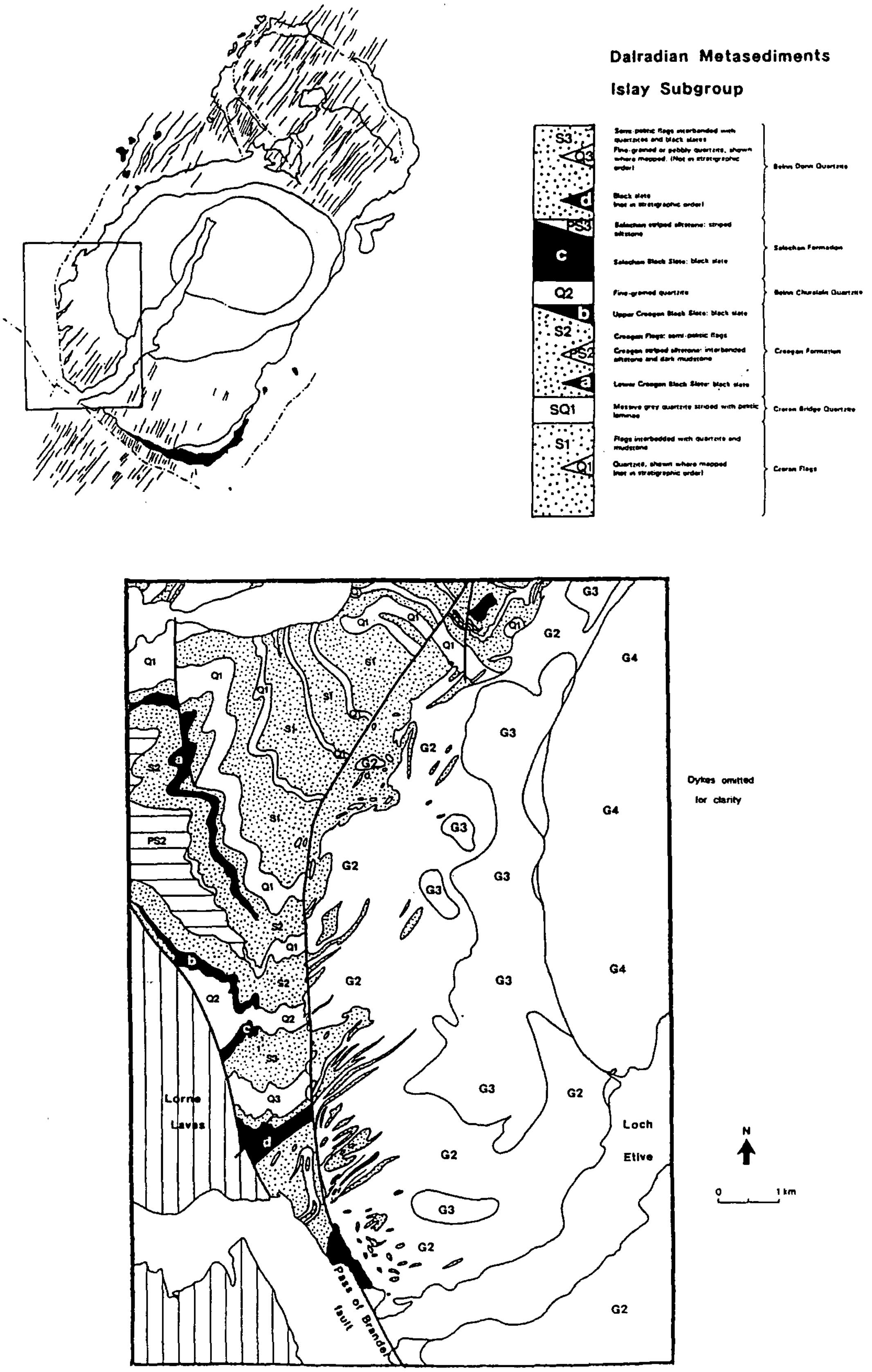


Fig. 3.20. Sketch map of the south-western part of the Etive complex showing the distribution and form of country rock xenoliths within G2. Modified after Sheet 45W (1:50 000 Series) (BGS).

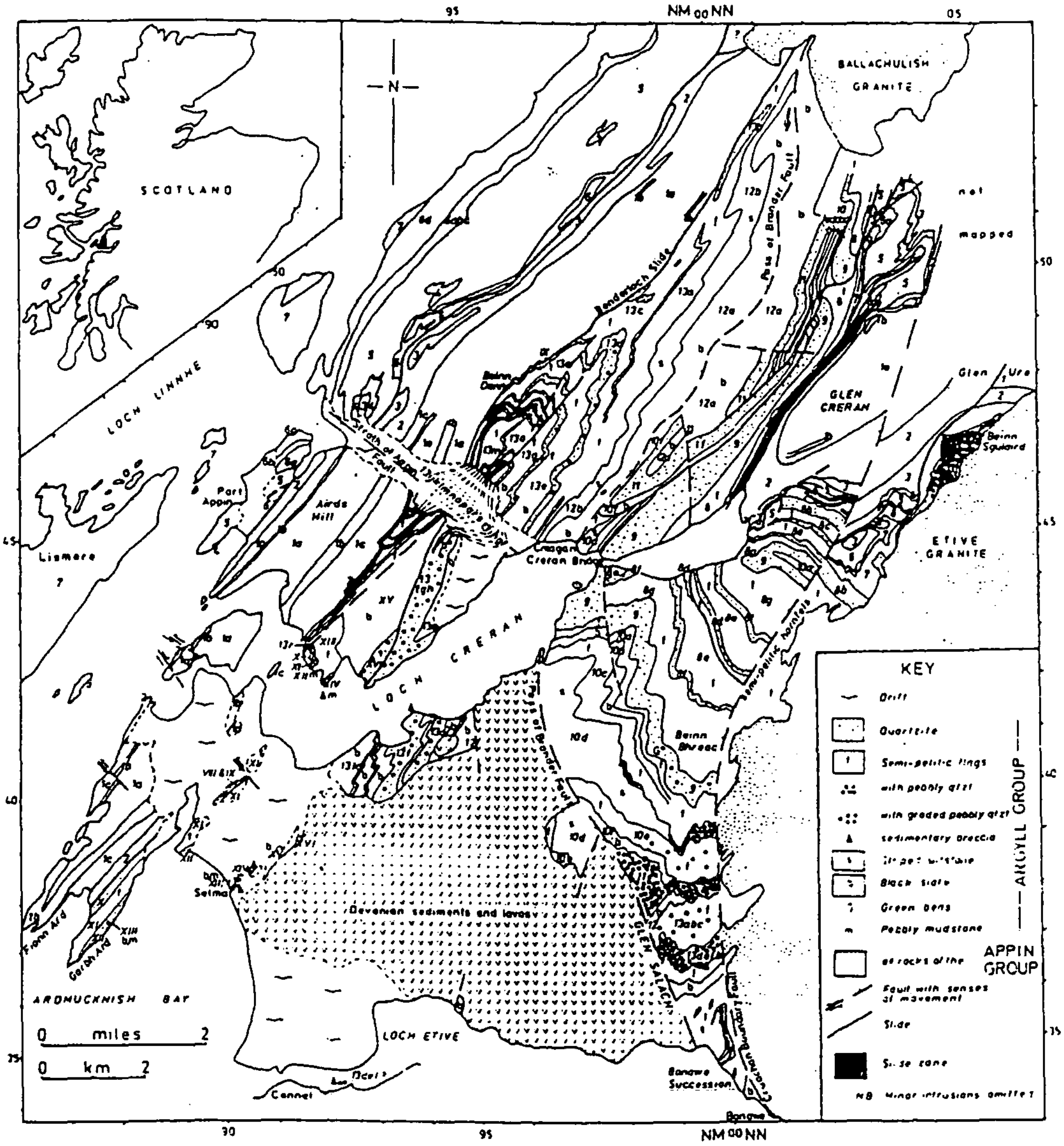


Fig. 3.21. Geological map of the Loch Creran area based on Litherland's 1:10 560 mapping. For stratigraphic notation see Litherland (1980; Tables 1 & 2). Some lines N of the Strath of Appin and W of the major Benderloch Slide are taken from Sheet 53 (Geol. Surv. Scotland). Minor intrusions omitted. After Litherland (1980).

Whether such relationships are associated with the emplacement of the Etive complex is extremely unclear. It is possible that these features have been controlled by a NW-SE-trending deep-seated basement structure, which not only played an important role during Caledonian magmatism (see Ch. 9), but may have been influential during the structural development of these cover rocks. This basement structure will be referred to as the Pass of Brander lineament. This is to prevent confusion with the name "Cruachan line or lineament" which has been used by many workers (e.g. Graham 1986; Fettes *et al.* 1986) to describe a feature recognised on Bouger gravity anomaly (Hipkin & Hussain 1983) and magnetic anomaly (Westbrook & Bonodaile 1978) maps, and seismic reflection profiles (Hall *et al.* 1984; Hall 1985), which may represent a NW-SE-trending structure which separates two different types of basement. The confusion arises because some workers have used the same term, i.e. Cruachan line or lineament, to define a NW-SE alignment of appinitic bodies from the Ardsheal Hill/Cuil Bay region in the NW (within the vicinity of the Ballachulish complex) to the Garabal Hill pluton in the SE (e.g. Watson 1984; see review in Ch. 9); this lineament lies considerably further NE (approximately 10-15 km) than the change in basement type defined by geophysical surveys. Watson (1984) suggested that this lineament may represent a basement structure which actively controlled the siting and ascent of these appinites. Due to these problems the term "Pass of Brander lineament" will be used to describe the NW-SE feature which appears to separate two different basement types, as this change closely coincides with the topographically defined, NW-SE-trending part of the Pass of Brander fault. The term "Cruachan lineament" will be used in this thesis for the NW-SE-trending basement structure which controlled the distribution of appinitic bodies further to the NE.

In the N, SE and E of the complex, the outer contact of G2 with the country rock tends to be steep and generally clean cut. However, in the vicinity of Beinn Fhionnlaidh [NN 095 497] in the NE of the complex (Fig. 3.23), the contact has been described as an "intimate mixture of altered schist and granite, in some parts presenting a profusion of small elongated fragments of schist embedded in a "granite" matrix" (Kynaston, *in* Bailey 1960). The country rock xenoliths are angular and tend to be lenticular. G2 (Cruachan facies) clearly exploits the pre-existing foliation within the country rocks, forming sheets of varying width. A very weak, contact parallel PFC fabric may have developed. In certain areas the monzogranite has clearly intruded in a "forceful" ductile fashion, causing the country rock schistosity to be deflected. These relationships are seen moving east right along the outer periphery of G2, from Beinn Fhionnlaidh to Creag na Caillich [NN 145 494] (Fig. 3.23), and are exposed along the 'road section' within the latter area [NN 147 490] (Plate 3.25).

The overall relative amount of synplutonic deformation within the country rocks around the pluton is remarkably low, considering that the plutonic complex was predominantly constructed by a process of *in situ* expansion. Around most of the periphery of the complex, the country rocks are not deflected into parallelism and do not generally show any substantial increase in strain intensity towards the pluton. The mechanisms by which space was created during its emplacement has been addressed in

Chapter 11. Where significant amounts of synplutonic deformation has occurred, this appears to have been confined to two main regions: (i) in the north, within the country rocks adjacent to the Allt nan Gaoirean HSZ; and (ii) in the south, in the wall rocks adjacent to the Allt Dhoireann HSZ (see sub-section 3.4.2.2). In the north, strain associated with the expansion and synplutonic rotation of subsequent intrusive phases appears to have been accommodated to some extent by ductile flow type processes within the adjacent wall rocks, re-orientating regional fabrics to form a localised partially concordant contact aureole. It should be noted that the relative magnitude of bulk wall rock shortening within these wall rocks does not appear to be as high as those observed within the aureoles of the sub-elliptical Rannoch Moor (Ch. 5) and Ballachulish (Ch. 9) complexes. The reason why this should be the case is discussed in Chapter 11. In the south, there may have also been a degree of bulk wall rock shortening, leading to the re-orientation of regional fabrics, but this is less certain. Both regions possess melt-filled brittle-ductile shears within the adjacent country rocks. These structures may have accommodated strain during the deformation of G2 within this region (see sub-section 3.4.2.2).

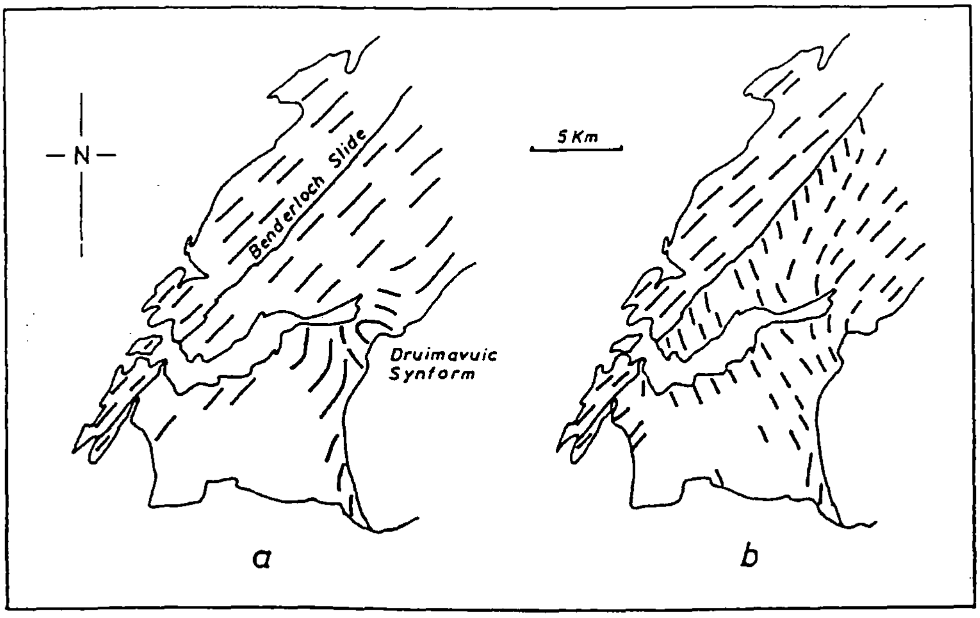


Fig. 3.22. Primary inflexions of **(a)** S1; and **(b)** S2 over the Loch Creran area. After Litherland (1982).

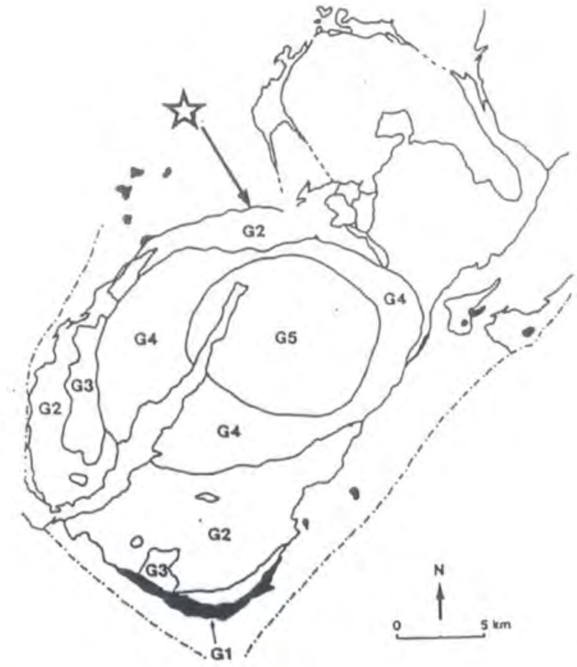


Fig. 3.23. Inset showing location of "intricate intrusion complex" within the vicinity of Beinn Fhionnlaidh.

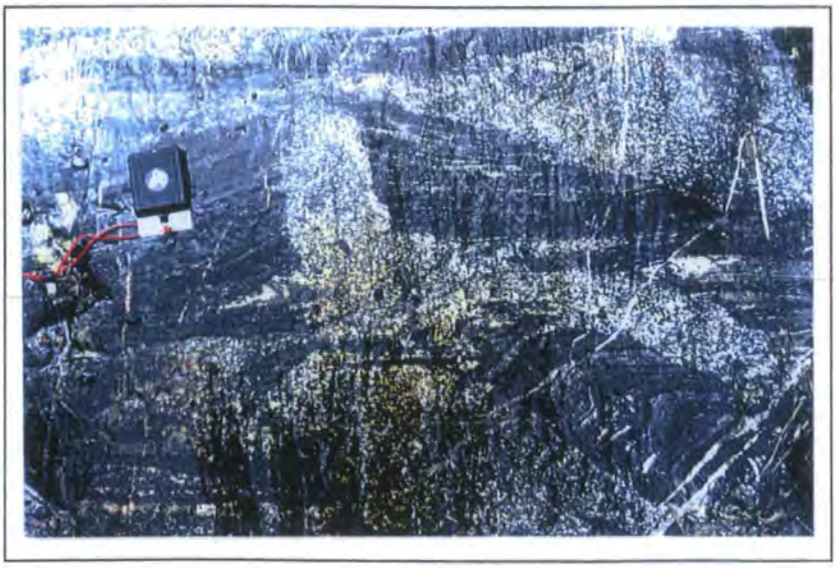


Plate 3.25. The "sheeting and stoping" complex in the Creag na Caillich area [NN 147 490]. It appears that G2 has intruded in a "forceful" ductile manner by the way it has deflected the schistocity within country rock xenoliths.

3.7 EVIDENCE FOR SEQUENTIAL, RAPID UPRISE OF MAGMA PULSES

Anderson (1937) considered the Etive complex as an example of "passive" or "permitted" emplacement, constructed by a series of cauldron subsidence intrusions. This concept has been employed by Perkins (1986), suggesting that within the southern part of the complex, G2 (Cruachan facies) represents a multi-stage intrusion, composed of at least seven identifiable intrusive events. These may be sometimes separated by a finer-grained facies, indicating a time lapse between successive events. Geochemical analysis by Batchelor (1987) has also revealed that G2 is composed of several distinct petrological units, sub-dividing the Cruachan facies into five magmatic pulses: three monzodiorites and two monzogranites (see sub-section 3.2.2; Fig. 3.7). Perkins (1936) has attributed this petrological variation to the successive input of magma during the downward descent of the cauldron block, leading to the formation of ring dykes which terminate upwards into approximately planar horizontal sheet-form tops ("bell-jar units"). Due to density contrasts between successive units, Perkins (1986) has proposed that earlier phases may have been cross-cut by later events, resulting in complex intersecting relationships. Field and microscope analysis of the monzodiorites (G2) within the southern part of the complex during this study, also suggests that G2 is somewhat variable in terms of subtle variations in mineralogy and also texturally, sometimes forming slightly finer-grained varieties against petrographically different, possibly somewhat earlier phases.

The data already presented within this Chapter demonstrates that the main phases of the pluton, G2, G4 and G5, were constructed by a process of *in situ* expansion whilst undergoing sinistral transpression. The subtle petrological features observed within G2 by the detailed mapping of Perkins (1986) and during this current study reveal steeply inclined sheets and sub-horizontal sill-like bodies, which suggest contrasts in a cauldron subsidence type process. To account for such relationships, it is envisaged that successive magma pulses were fed into the enlarging pluton, producing steeply inclined sheets parallel to its margins and flattish sheets across the top (Fig. 3.24). Magma emerged from an ascent conduit at the centre of the complex (see Ch. 9), as small, discrete, rapidly ascending pulses ("magmatic micro-pulses" or "magma solitons"; see Ch. 1) which continuously fed the expanding pluton during construction of one of its major intrusive phases (G2, G4 or G5). The complex intersecting relationships described by Perkins (1936) may be due to the fact that each pulse itself may be concentrically zoned, and so as it intrudes into the centre of the complex it will cross-cut earlier phases and push them aside as it expands (Fig. 3.24a). Along the roof zone the earlier phases, which are still in an incompletely crystallised state, may be essentially "squeezed out" from this region as a new 'magmatic micro-pulse' enters the system (Fig. 3.24). A slight delay in the arrival of a new 'magmatic micro-pulse' may result in the development of chilled margins or at least a grain-size difference at their contacts producing finer-grained varieties (Fig. 3.24 b).

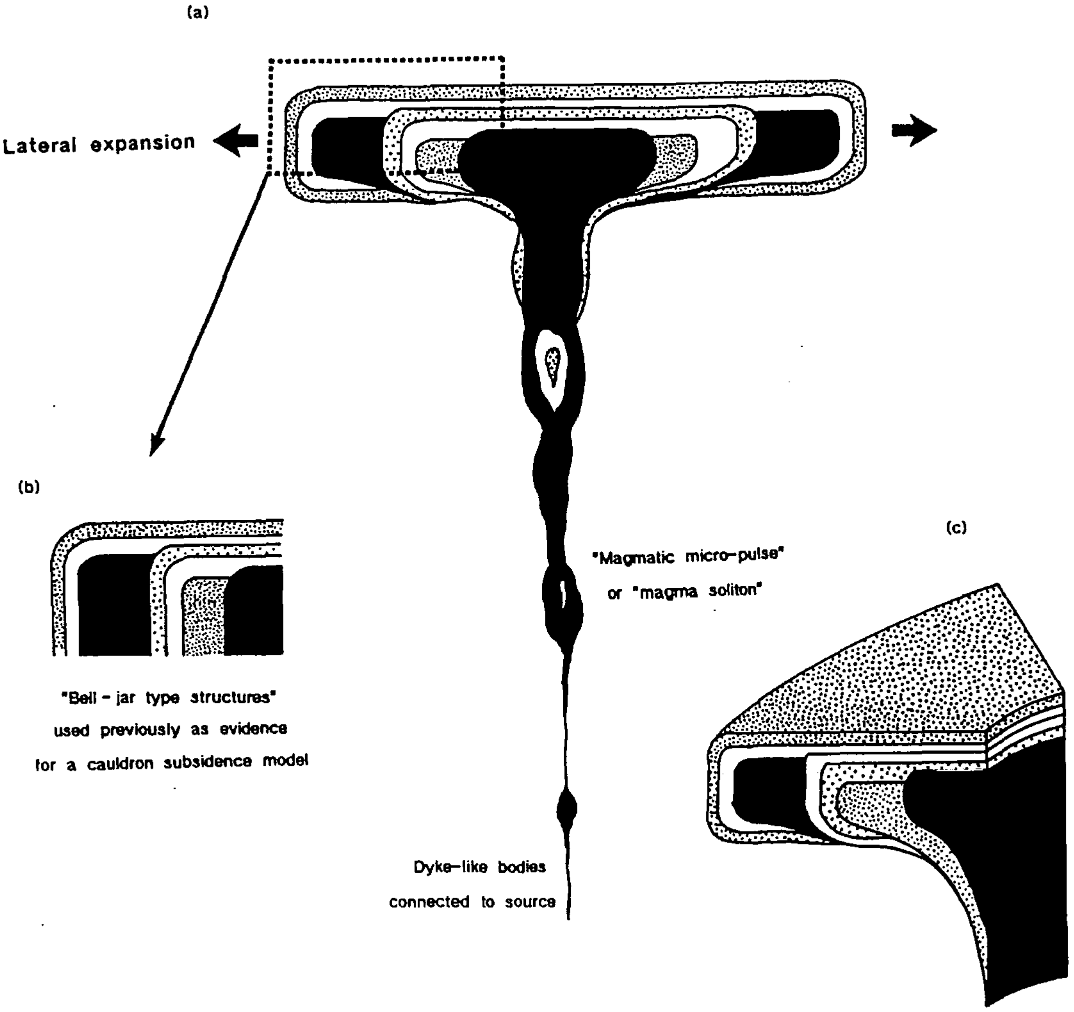


Fig. 3.24. (a) Speculative model showing how the main phases of the Etive complex could have been constructed by a series of "magmatic micro-pulses" or "magma solitons", producing complex intersecting relationships and finer-grained ("chilled") facies. This may have resulted in (b) steeply inclined sheets and sub-horizontal sill-like bodies ("bell-jar type units"). (c) Three-dimensional segment of (a).

The reason why such features only appear to be preserved in the monzodiorites (G2) within the southern part of the complex may be due to the fact that this region was only subjected to a relatively low amount of strain, compared to the monzogranites within the north (see sub-section 3.4.2); thus preserving features related to the constructional process. The reason why such features have not been observed within G4 and G5 might be because they were constructed much more quickly, not allowing any significant cooling of earlier pulses as magma was sequentially placed into the system. This rapid input is actually demonstrated by the contact relationship between G4 and G5, which are separated by a 'transition zone' approximately 350-400 m wide (see sub-sections 3.2.5 & 3.2.6).

Ascent by this process enables continual transfer of material from source to site of pluton construction (emplacement). Within such a regime, the various petrological processes envisaged by Stephens (1992) which could help to account for normally zoned plutons (i.e. restite separation, fractional crystallisation and rheological segregation of a heterogeneous source) could occur during ascent in such zones. On a finer scale, variations in the rate of magma ascent within a conduit, dependent on such properties as magma buoyancy, viscosity and supply rate from the source may result in discrete pulses of magma successively arriving at the emplacement site producing several identifiable intrusive events within one major unit.

3.8 CONSTRUCTION OF THE ETIVE COMPLEX: AN EMPLACEMENT MODEL

This Section summarises the most important features regarding the geometry of the pluton, the distribution of its internal intrusive phases, and its internal and external deformational characteristics in relation to major tectonic structures. An account of the predominant mechanisms operating during the construction of these individual intrusive phases are proposed, based on the data presented within this chapter.

Controls on the Etive Complex

➊ This is an elliptical shaped pluton (approximately 30 km x 15 km), with its long axis trending NE-SW, parallel to the regional Caledonian strike.

❷ Running through the adjacent wall rocks and in places partially bounding the pluton are the Allt Buidhe fault (a possible continuation of the Laggan Dam fault) in the NW, the Pass of Brander fault in the SW and the Ericht-Laidon shear zone to the SE. The Etive-Laggan shear zone runs through the centre of the complex.

❸ The E, SE and SW margins of the pluton in places show evidence of ring faulting indicating that cauldron subsidence has occurred at relatively high crustal levels similar to that seen in nearby Glencoe. The major occurrence of G1 (known as the "Quarry Intrusion") takes the form of a partial ring dyke, intruded along the ring fault which downfaults metavolcanics against Dalradian country rock. The emplacement of this earliest intrusive activity is discussed separately in Chapter 7. The Etive complex was emplaced at a relatively high crustal level (3-6 km, Droop & Treloar 1981). Ring-faulting and the intrusive form of G1 suggests that the pluton interacted with the free surface, at least during the initial stages of emplacement (see Ch.'s 7 & 11 for discussion on mechanisms of space creation during the construction of the complex).

❹ G2 (Cruachan facies) was constructed by a process of *in situ* expansion. This led to the development of a pervasive (steep, inward-dipping), pseudoconcentric, PFC fabric, which intensifies towards the pluton margin, and possesses a sub-horizontal mineral stretching lineation. Due to the continued imposition of expansion-related strains during the last stages of pre-full crystallisation deformation, PFC conjugate ductile shears were developed allowing bulk extension to occur parallel to the fabric direction.

❺ The next intrusive event was the emplacement of the Meall Odhar facies (G3). Two distinct types occur: (i) a monzogranite which forms an arcuate outcrop (approximately 3 km by 100-150 m) between Stob Dubh [NN 166 488] and Meall Odhar [NN 190 465]; and (ii) a leucocratic, fine- to medium-grained syenogranite. The syenogranite takes the form of flat-lying sheets resting on and cross-cutting the upper parts of G2, and as cone-sheet type structures with moderate inclinations, cross-cutting G2 and parts of the surrounding country rock.

The present distribution of part of the syenogranite phase takes the form of flat-lying sheets exposed on the highest peaks, which rest on and cross-cut the upper parts of G2. The G3 conduit, presumably at the centre of the complex, has now been obliterated by the emplacement of G4 and G5. Such relationships would be impossible if a large sunken block, produced by cauldron subsidence, existed.

However, the concentric gentle dip of some of the upper G2 sheets suggests some central downwarping during G3 emplacement. It is envisaged that this initiated the intrusion of a partial ring dyke of monzogranite in the NE, between the Etive and Glencoe complexes. A large number of syenogranite sheets, of moderate to steep, inwardly dipping attitudes, cross-cut G2 and parts of the surrounding country rock. These may have been intruded during periods of high magmatic pressure, producing cone sheet type structures. Their intrusive relationship to the flat-lying sheets is complex, as they clearly post-date an earlier phase and have themselves been subsequently cross-cut by a later intrusive event of sub-horizontal sheets. The "cone-sheets" have varying attitudes and cross-cut one another. Such relationships may indicate that during the period of G3 emplacement, there were a number of significant fluctuations between positive and negative "expansion-related forces" which affected the overlying country rocks as well as the pluton itself (see Ch. 11).

❻ This was followed by the emplacement of the NE-SW-trending Etive Dyke Swarm. The majority of these dykes clearly cross-cut the Meall Odhar facies (G3) and almost all are earlier than the emplacement of the Porphyritic Starav facies (G4). Their structural features and mechanisms of emplacement are discussed separately in Chapter 7. However, it should be noted that their intrusive form may be related to forces imposed primarily by 'magma buoyancy', induced by the ascent of G4 and possibly G5. This probably had the effect of updoming the upper country rock cap and creating an overall transtensional environment, both within the igneous complex as a whole and within the adjacent country rocks. This increase in expansion-related strains would account for the radial disposition of the Etive Dyke Swarm, "keeping at right angles to the curving margin of the Starav granite" (Anderson 1937). Another interesting observation made by Anderson (1937) was that outside the north-north-easterly and south-south-westerly tangents to the Central Starav facies (G4/G5) dykes are very rare. Anderson (1937) further commented that the few dykes which do occur within the Allt nan Gaoirean and Kingsglass regions are conspicuously foliated, especially along their chilled margins (see also Kynaston & Hill 1908; Bailey & Maufe 1916; Bailey 1960). These regions correspond to the Allt nan Gaoirean and Allt Dhoireann/Kingsglass high strain zones (HSZ's) developed within G2 (see sub-Section 3.4.2.2). It is envisaged that both HSZ's were subjected to an overall gross transpressional component imposed by the bounding NE-SW-trending Ericht-Laidon shear zone in the SE, and the Allt Buidhe-Laggan Dam fault in the NW. This 'component' was further enhanced by the expansion and synplutonic rotation of G4/G5 at the centre of the complex (see below). It is therefore possible that the transtensional environment created during the emplacement of the Etive Dyke Swarm, was locally removed within the Allt nan Gaoirean and Allt Dhoireann regions because these areas were being subjected to a major component of non-coaxial general shear (sub-section 3.4.2.2).

❼ As with G2, the Central Starav facies (G4/G5) was constructed by a process of *in situ* expansion. This also led to the development of a pervasive, slightly inward-dipping, pseudoconcentric PFC fabric both within G4 and G5. PFC conjugate ductile shears are developed which show a bulk extensional component parallel to the fabric direction. The geographical orientation of the X axis and the X/Z ratios of the individual intrusive phases (G2, G4 and G5), suggests that the complex was subjected to an overall gross transpressional component imposed by the bounding NE-SW-trending structures (Fig. 3.7a; Jacques & Reavy 1994). Sinistral ductile deformation along these structures during the construction of the Etive complex allowed magma to expand predominantly into the direction of maximum extension imposed by these controlling structures. This would suggest a maximum expansion direction orientated approximately E-W. At the centre of G5, a few PFC conjugate lock-up shears imply an extensional component orientated in this direction (see sub-Section 3.4.5). It is likely that such structures were developed during the initial stages of the *in situ* expansion process. Such features have been better preserved within the Glencoe complex (Ch. 4). If the X/Z ratios for the G2, G4 and G5 pulses are plotted against geographical orientation of the X axis (Fig. 3.18b), the resulting straight line implies that the strain imposed remained fairly constant during the expansion process.

As the pluton body expanded and earlier intrusive components crystallised, localised, intense high temperature CPS fabrics were developed at petrological contacts as the imposed deformation proceeded into the solid state regime. This combined with the overall synplutonic rotation of the subsequent intrusive phases G4/G5 resulted in the formation of two corresponding zones of high strain within the monzogranites of G2: the Allt nan Gaoirean in the north, and the Kingsglass/Allt Dhoireann region in the south. These zones also correspond to the direction of the maximum shortening ('compression') imposed by the bounding Allt Buidhe-Laggan Dam fault and the Ericht-Laidon shear zone (Fig. 3.16). These combined effects resulted in both regions being subjected to a large component of transpressional deformation. Within both zones, PFC fabrics within G2 have been modified or even completely obliterated by overprinting solid state fabrics as deformation continued into the solid state regime.

Model proposed for the main construction of the pluton

The major intrusive components G2, G4 and G5 were constructed by a process of *in situ* expansion whilst undergoing sinistral transpression. Magma predominantly expanded approximately E-W into the direction of maximum extension imposed by the controlling NE-SW-trending major faults and shear zones.

CHAPTER 4

THE GLENCOE COMPLEX

4.1 INTRODUCTION

The Glencoe complex (Fig. 4.1) is one of the smallest of the Scottish Siluro-Devonian plutons (approximately 80 km^2). Most previous workers, such as Kynaston and Hill (1908), Bailey and Maufe (1916), Anderson (1937), Bailey (1960), and Brown (1975) have regarded the "plutonic phase" of this complex to be part of the Etive complex (see Ch. 3), generally referred to as the "northern lobe" (Fig. 4.2). They considered that the Cruachan (G2) monzodiorites and monzogranites of the "southern lobe" and the monzogranites of the "northern lobe" represent variations within one single intrusive body (see Ch. 3). However, subsequent work by Barritt (1983) has revealed that the lobes are radiometrically and chemically distinct units, i.e. independent intrusive bodies. Structural data presented within this Chapter (see also Ch. 3) also substantiate this, concluding that the term Etive complex should only refer to the southern body. The term Glencoe complex will be used to encorporate the plutonic intrusive phases of the "northern lobe", and the higher level emplacement phenomena, the Glencoe Fault Intrusion (Fig. 4.2). The latter intrusive phase takes the form of a "partial ring-dyke", encircling the Glencoe Caldera (Clough *et al.* 1909; Bailey & Maufe 1916; Bailey 1960).

Data presented within this Chapter suggests that only part of the Glencoe plutonic complex is exposed. This occurs in two areas (Fig. 4.2): (i) at the centre of the complex (Lairig Gartain); and (ii) within the Glen Etive region. Both provide an "erosional window", exposing the upper most parts of the plutonic body; whereas in the NW of the complex, where the Glencoe Cauldron and associated Fault Intrusion have been preserved, it is likely that the Glencoe plutonic body occurs directly beneath.

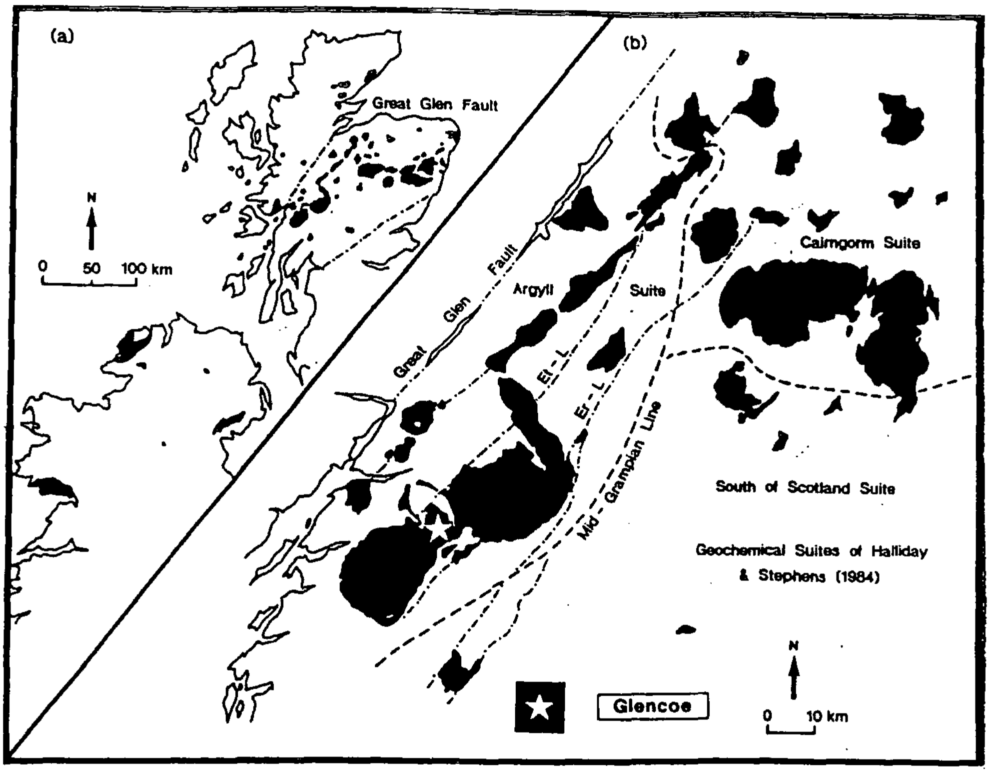


Fig. 4.1. **(a)** Distribution of late Caledonian granites in Scotland and Ireland. **(b)** Distribution of granitoids in the Grampian Highlands, showing the location of the Glencoe complex.

The complex can be sub-divided into three intrusive components (Fig. 4.2):

G1: The Early and Main Fault Intrusions (sub-section 4.2.1; see Ch. 7)
"Early" phase: diorite to porphyrite compositions
"Main" phase: granitoid to porphyroid varieties

G2: The Clach Leathad facies (sub-section 4.2.2)
Medium- to coarse-grained monzogranite

G3: The Aonach Mór facies (sub-section 4.2.3)
Pink, fine- to medium-grained, equigranular monzogranite

The petrological characteristics of these intrusive phases are described below. These descriptions are based on detailed field and microscope analysis carried out during this current study, combined with information obtained from four principal sources: Bailey and Maufe (1916), Anderson (1937), Bailey (1960), and Batchelor (1987). The geochemical characteristics of these intrusive phases are discussed in Section 4.5.

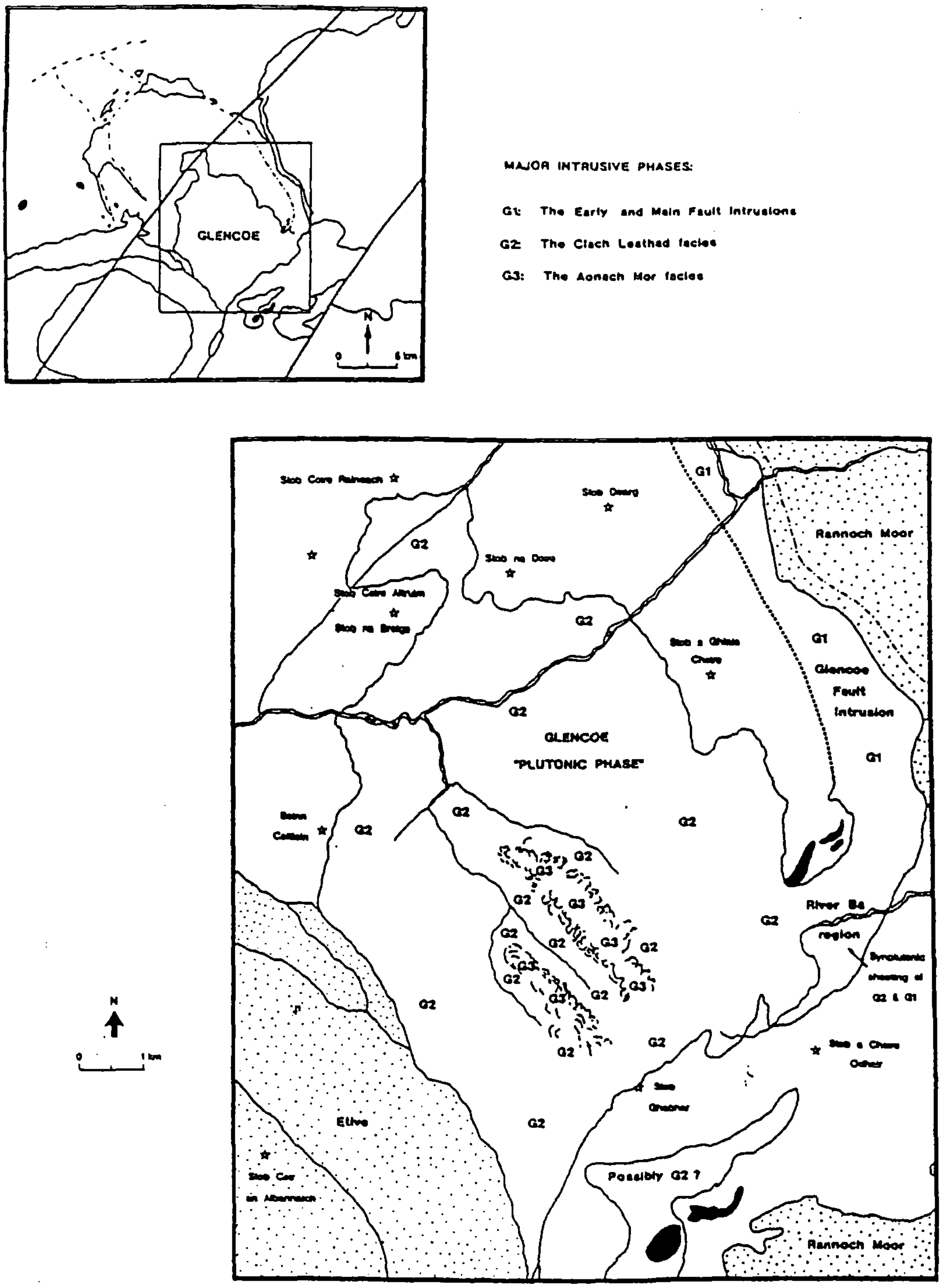


Fig. 4.2. The petrographical distribution of the major intrusive phases within the Glencoe complex.

4.2 MAJOR INTRUSIVE COMPONENTS

4.2.1 G1: The Glencoe Fault Intrusion

The Glencoe Fault Intrusion takes the form of a "partial ring-dyke", encircling a down-faulted block (13 km x 10 km) of metasedimentary rocks, which are overlain unconformably by Lower Devonian volcanics. The NW-SE elongation of the cauldron block is probably due to the subsequent emplacement of the NE-SW-trending Etive Dyke Swarm (Fig. 4.3); removal of the dykes gives an original circular form to the down-faulted mass.

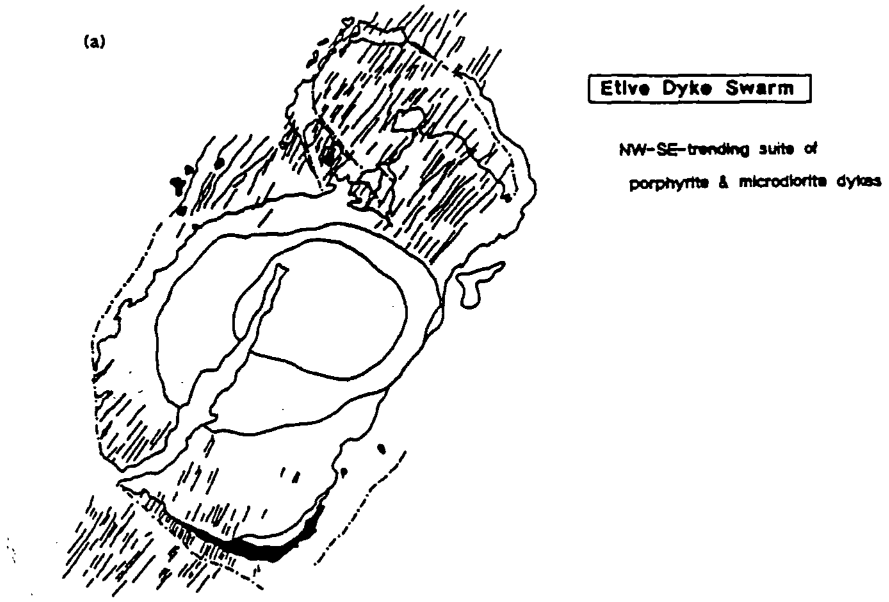


Fig. 4.3. The Glencoe complex, showing distribution of the NE-SW-trending Etive Dyke Swarm.

Early studies (see Clough *et al.* 1909; Bailey & Maufe 1916; Bailey 1960) recognised that the Fault Intrusion could be essentially sub-divided into two distinct facies: (i) an earlier intrusive phase, ranging from diorite to porphyrite compositions, known as the Early Glencoe Fault Intrusion. Within this compositionally diverse facies are hornblendic varieties which "are extremely similar to the basic phase of the Beinn a' Bhuiridh Diorite at the south-east corner of the Etive complex" (*in* Bailey 1960) (see Ch. 3, sub-section 3.2.1 & Ch. 7, sub-section 7.5.1); and (ii) a later phase, known as the Main Glencoe Fault Intrusion, which compositionally varies from granitoid to porphyroid varieties, and which may be pink or grey. The Early and Main Glencoe Fault Intrusions are therefore thought to represent two major distinct intrusive episodes, emplaced during cauldron subsidence along the Early and Main Ring Fault systems respectively.

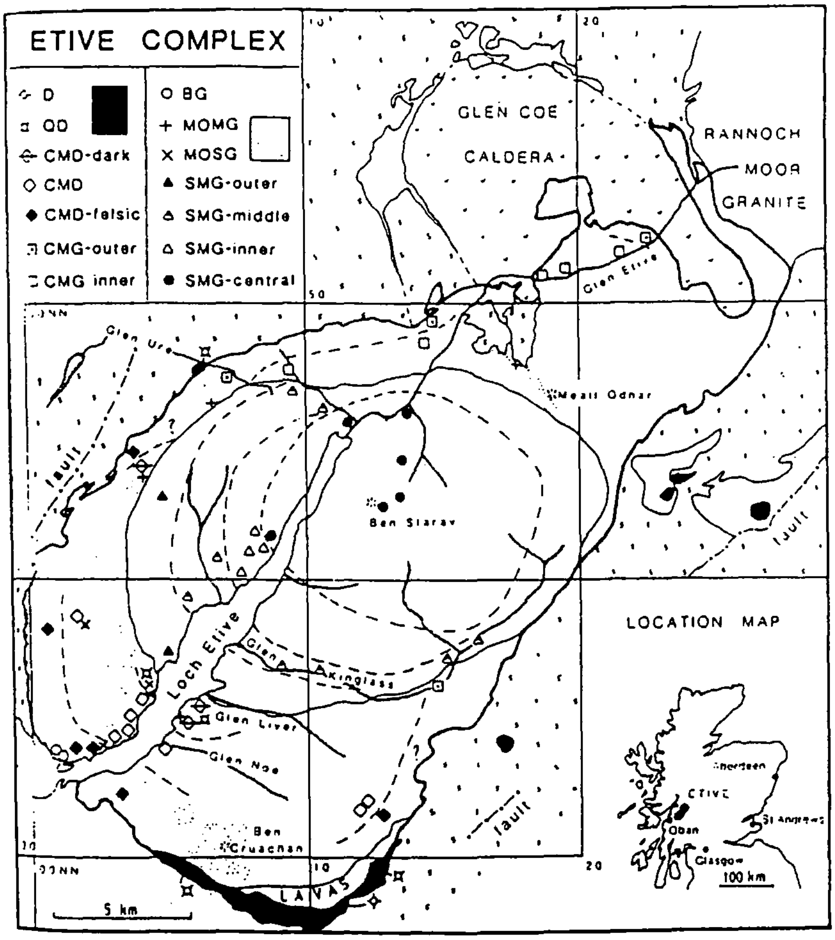
The predominant mechanisms operating during the construction of the Glencoe plutonic complex (discussed within this Chapter) are clearly different from those operating during the emplacement of the associated higher level emplacement phenomena, the Glencoe Fault Intrusion (G1). For this reason the microstructural features developed within this intrusive phase, and a discussion of the possible mechanisms operating during its emplacement are presented within a separate chapter (Ch. 7: "High level emplacement phenomena: the Glencoe Fault Intrusion and the Etive Quarry Intrusion"). General petrographical descriptions of the Early and Main Glencoe Fault Intrusions are also given in Chapter 7, together with an account of: (i) the petrological variation of the Early and Main Glencoe Fault Intrusions; and (ii) the types, distribution and formation of fault-rocks developed along the ring fault surfaces of the down-faulted cauldron block.

4.2.2 G2: The Clach Leathad facies

This constitutes the largest component of the Glencoe plutonic complex (Fig. 4.2). These rocks have been generally regarded as belonging to the Cruachan facies (G2) of the Etive complex, with workers such as Kynaston and Hill (1908), Bailey and Maufe (1916) Anderson (1937), Bailey (1960), and Brown (1975) considering that the Cruachan (G2) monzodiorites and monzogranites of the "southern lobe" (Etive complex) and "northern lobe" (Glencoe complex) represent variations within one single intrusive body. This led Brown (1975) to suggest that the compositionally zoned pluton had undergone subsequent tilting, resulting in the exposure of monzodiorites in the southern part of the complex and more silicic rocks (monzogranites) in the north. The compositional variation being attributed to the relative depth of emplacement, with the southern part of the Cruachan facies representing a deeper crustal level than to north (Brown 1975; Droop and Treloar 1981). Subsequent work by Barritt (1983) has revealed that the "southern" and "northern" lobes are radiometrically and chemically distinct units, i.e. independent intrusive bodies. Structural data (see Jacques and Reavy 1994; Ch. 8) within this thesis also substantiates this, concluding that the term Etive complex should only refer to the southern body. It therefore seems necessary to clarify the terminology used to describe the intrusive phases of the two complexes, introducing here the term "Clach Leathad facies" to refer to the monzogranitic phase of the Glencoe complex, and retaining the term "Cruachan facies" solely for the monzodioritic and monzogranitic rocks within the Etive complex.

The Clach Leathad facies is a pink monzogranite (Plate 4.1). Geochemical analysis by Batchelor (1987) has revealed that the facies can be sub-divided into two distinct magmatic phases (Fig. 4.4); a more silicic phase which occurs in Glen Etive within the centre of the plutonic mass, and an earlier more mafic phase which occurs at the outer part of the body. Concentric zonation of U and Th and their increase into the inner, later pulse, indicates that zoning is normal (Barritt 1983). Barritt's data also shows that the intrusive mass at the centre of the complex (Lairig Gartain) may represent a geochemically distinct unit (see Fig. 4.5).

Plate 4.1. Hand-specimen of G2 (Clach Leathad facies). A fairly equigranular, medium-grained monzogranite. (Yellow 'bar' is approximately 2 cm long).



⌖	D	Diorite
⌑	QD	Quartz diorite
◈	CMD	Cruachan monzodiorite— dark
◇	CMD	—— —— normal
◆	CMD	Cruachan monzodiorite— felsic
○	BG	Bonawe granitoid
▢	CMG	Cruachan monzogranite—outer
▢	CMG	Cruachan monzogranite— inner
+	MOMG	Meall Odhar monzogranite
×	MOSG	Meall Odhar syenogranite
▲	SMG	Starav monzogranite—outer
△	SMG	Starav monzogranite—middle
△	SMG	Starav monzogranite—inner
●	SMG	Starav monzogranite—central

Ab	albite
amph	amphibole
An	anorthite
and	andesine
ap	apatite
bi	(Fe)biotite
bw	bytownite
ck	charnockite
cpx	clinopyroxene
hb	hornblende
kspr	alkali feldspar
mgt	magnetite
opx	orthopyroxene
or	orthoclase
plag An30	plagioclase feldspar (An30)
plag An75	plagioclase feldspar (An75)
qz	quartz
sph	sphene

Fig. 4.4. Geological map of the Glencoe and Etive complexes, showing sample localities, geological (solid line) and chemical boundaries (dashed line). 's' ornament represents metasediments, 'v' represents the Glencoe volcaic suite. After Batchelor (1987).

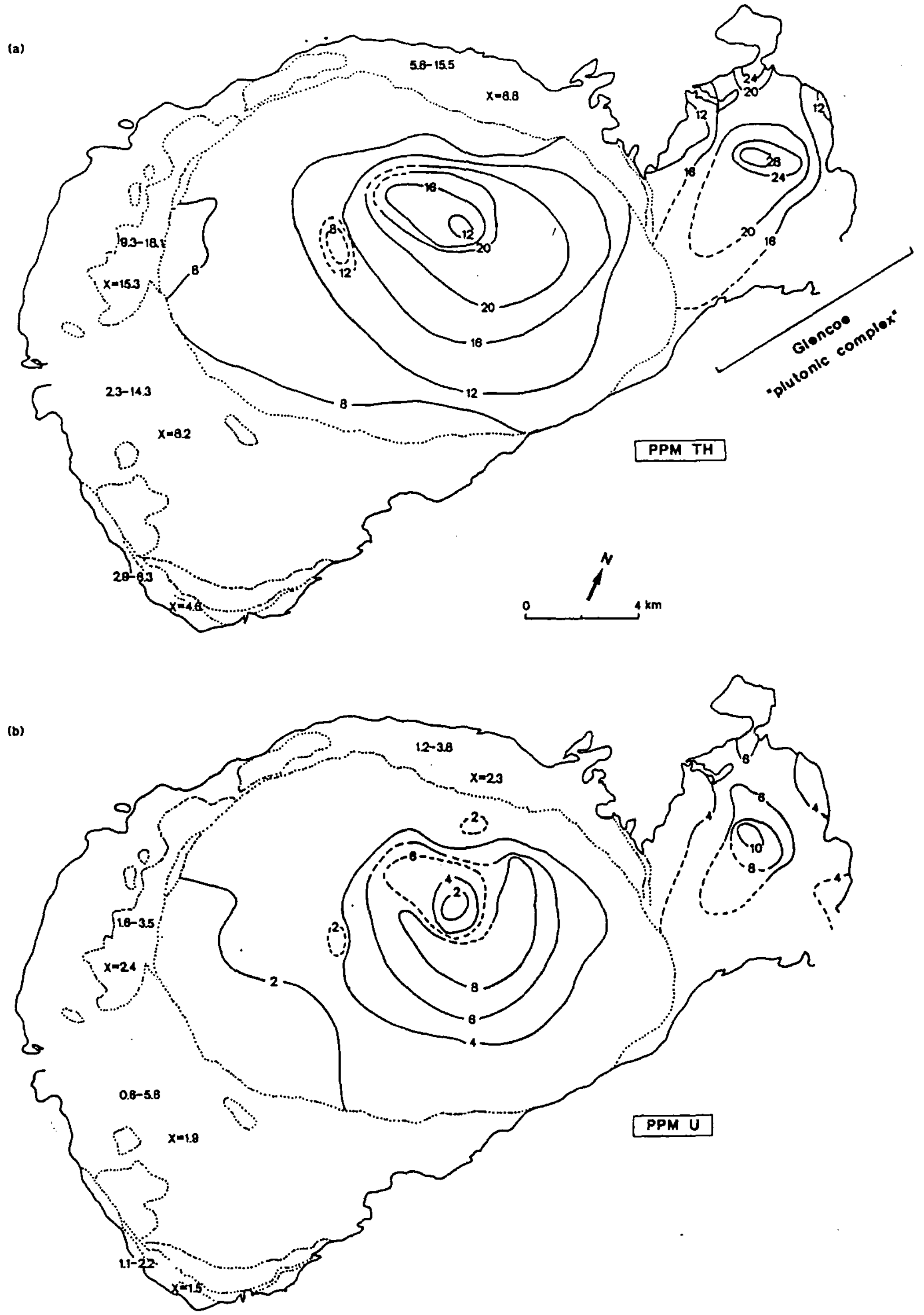


Fig. 4.5. Radioelement maps for the Etive and Glencoe complexes showing the distribution of **(a)** thorium (Th), and **(b)** uranium (U) levels. After Barritt (1983).

Within the SE of the complex (Fig. 4.2), along the River Bà, synplutonic sheeting of the Clach Leathad facies and tonalitic material of the major phase of the Main Fault Intrusion is clearly visible (Plate 4.2), with no chilled contacts observed between the two facies. This suggests that the two are penecontemporaneous and that above G2, cauldron subsidence occurred which allowed the emplacement of the Fault Intrusion along outer ring faults (as mentioned in sub-section 5.4.1).

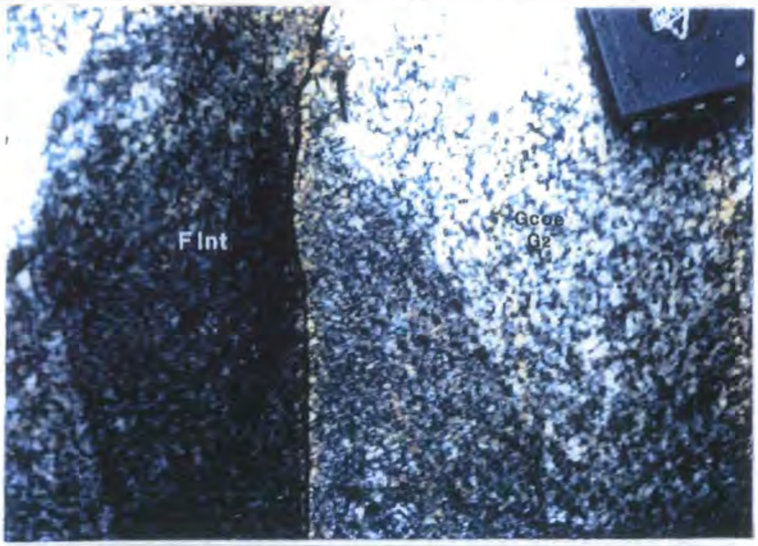


Plate 4.2. Along the River Bà section [NN 258 478] showing synplutonic sheeting of the Clach Leathad facies and the major intrusive phase of the Main Fault Intrusion. Note, no chilled contacts are observed between the two facies, suggesting a penecontemporaneous emplacement.

General Petrographical description:

General description of monzogranitic facies: a pink/red, fairly equigranular, medium-grained (2-5 mm) monzogranite. This is generally composed of plagioclase (30-45 %), alkali feldspar (25-35 %) and quartz (15-30 %). The plagioclase is usually normally zoned (An 50-25), and deformational lamellae are not uncommon. Biotite (up to 5 %) and hornblende (5-8 %) are minor phases and may occur as mafic clusters. Biotite is often bent or kinked. Accessory minerals include opaques, sphere, zircon and apatite.

Interestingly, the high percentage of drusy cavities within this phase led Kynaston and Hill (1908) to suggest it may have contained a large proportion of occluded gas in the original magma, possibly collecting as a "eutectic residue" within the upper portion of the plutonic body. This is in contrast to the Etive complex, which contains a very low percentage of drusy cavities. Combined with structural data (this study; see sub-section 4.4.2) obtained from the Clach Leathad facies (G2) and its relationship to the higher level Glencoe Fault Intrusion, it seems likely that the Glen Etive region provides an "erosional window", exposing the upper part of the plutonic body; whereas in the NW of the complex the Glencoe Cauldron and associated ring-intrusion have been preserved, with presumably the Clach Leathad facies (G2) occurring directly beneath. The geometrical form of both the Fault Intrusion and the plutonic body below, i.e. the complex as a whole, would have an almost perfect circular form (after removal of the cross-cutting NE-SW-trending Etive Dyke Swarm).

4.2.3 G3: The Aonach Mór facies

Mineralogically and texturally these rocks are very similar to the Meall Odhar facies (G3) of the Etive complex which forms an arcuate outcrop between Stob Dubh [NN 166 488] and Meall Odhar [NN 190 465] (see Ch. 3, sub-section 3.2.3). The Aonach Mór facies is generally a pink, fine- to medium-grained (< 3 mm), equigranular monzogranite (Plate 4.3). Two NW-SE-trending ridges, the Aonach Mór [NN 219 479] and Sròn a' Ghearrain ridges [NN 214 469] (Fig. 4.2) are composed of this rock type (Anderson 1937) . However, their intrusive contacts with G2 are not observed. As with the intrusive body at Meall Odhar (within the Etive complex), their apparent form suggests that they may represent partial ring-dyke structures and it is interesting to note that the continuation of the "Sròn a' Ghearrain intrusive body" towards the NW would approximately coincide with the Main Ring Fault of the Fault Intrusion at Gleann Fhaolain.

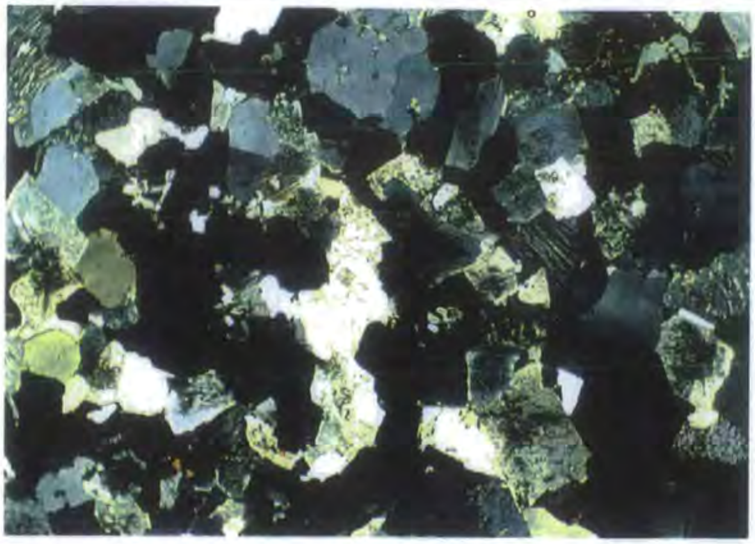


Plate 4.3. Photomicrograph of G3 (Aonach Mór facies). A medium-grained, equigranular monzogranite. (Field of view was approximately 18 mm).

General Petrographical description

The Aonach Mór facies: a pink, fine- to medium- grained (< 3 mm), equigranular monzogranite. Composed of alkali feldspar (30-45 %), quartz (30-40 %), plagioclase (20-25 %) and minor amounts of biotite (< 4 %). Accessories include opaques and sphenes.

4.2.4 The Etive Dyke Swarm

This suite of NE-SW-trending porphyrite and microdioritic dykes have originated from the Etive complex (see Ch. 8). An extremely large number of dykes of variable composition and relative time of emplacement with respect to the crystallisation of G2 (the Clach Leathad facies) cross-cut the Glencoe complex (Fig. 3). In general, field studies and microscopic analysis suggest that the dyke swarm can be sub-divided into: (i) an earlier phase of pink and grey porphyrite dykes, which have intruded into an incompletely crystallised magma (G2; Clach Leathad facies); and (ii) a later, somewhat more minor phase of microdioritic dykes which often intrude into the earlier phase forming a composite arrangement. This latter phase essentially intruded G2 when the host was near to full crystallisation. Both intrusive phases have locally deformed G2. The earlier phase has locally induced ductile strains up to 2-3 m from the dyke margin, expressed as changes in the PFC fabric orientation within G2. The later phase has deformed G2 by brittle-ductile processes. These deformational features within G2 will be discussed in Chapter 8.

4.3 GEOCHEMICAL ANALYSIS OF THE GLENCOE COMPLEX

As mentioned above, the Glencoe plutonic complex has been regarded as being part of the Etive complex, forming a "northern lobe" to that intrusive body, and as such has been geochemically analysed as part of the Cruachan facies (G2) of the Etive complex (see Clayburn *et al.* 1983; Batchelor 1987). On a broad geochemical basis the rocks of the Clach Leathad facies (G2) of the Glencoe complex, are essentially equivalent to the monzogranitic rocks of the Etive complex, and therefore their origin and evolution can be regarded as being very similar (see Ch. 3, Section 3.3).

4.4 FABRIC DEVELOPMENT: EVOLUTION OF MICROSTRUCTURES

The purpose of this Section is to present the type of fabrics and microstructures which are common within the Clach Leathad (G2) and Aonach Mór (G3) facies which constitute the major intrusive components of the Glencoe plutonic phase. A general outline of the fundamental processes operating during the evolution of fabric types, from pre-full crystallisation deformation, through the crystallisation transition, and into crystal plastic strain deformation within the solid state regime will be given. It is not intended as a detailed discussion on the textural development and mechanisms operating during fabric evolution.

4.4.1 G1: The Fault Intrusion

The mechanisms operating during the emplacement of the Glencoe Fault Intrusion (G1; Fig. 4.2) are clearly different from those operating during the construction of the Glencoe plutonic complex (G2 and G3). The fabrics and microstructures developed within G1 are therefore discussed in Chapter 7, dealing with the emplacement of that body.

4.4.2 G2: The Clach Leathad facies

This constitutes by far the largest component of the Glencoe plutonic complex (Fig. 4.2). Radiometric evidence shown by the distribution of U and Th (Barritt 1983; Fig. 4.5), and microstructural data obtained during this study (see below), suggests that the intrusive mass at the centre of the complex (Lairig Gartain) represents a geochemically distinct unit from the monzogranites exposed to the south, within the Glen Etive region. Microstructural evidence (see below) suggests that G2 could be composed of two 'pulses': the centre of the earliest phase sited within the vicinity of Allt a' Chaorainn which will be referred to as the "Chaorainn pulse", and a later pulse sited at the centre of the complex, which will be named the "Lairig Gartain pulse". The centre of each pulse is geographically defined by the concentric zonation of U and Th (Fig. 4.6; Barritt 1983). The "Chaorainn pulse" is characterised by a complex arrangement of bimodal PFC fabrics, which have been progressively modified and subsequently overprinted by weak to moderately developed solid state deformation associated with externally derived strains. The distribution of fabrics within the "Lairig Gartain pulse" is somewhat different, and does not show such extensive modification, possibly resulting in the preservation of "primary emplacement features". For these reasons the microstructural features developed within the 'Lairig Gartain and Chaorainn pulses' are discussed separately.

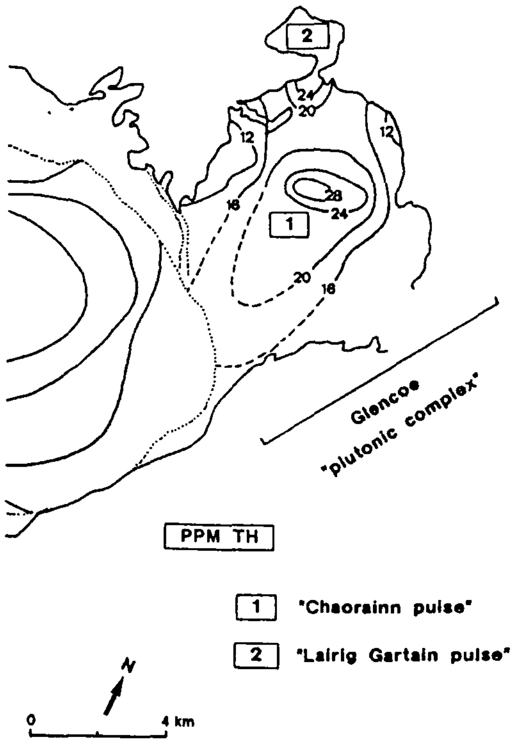


Fig. 4.6. Map showing the position of the "Lairig Gartain and Chaorainn pulses". The centre of each pulse may be defined by the concentric zonation of U and Th (Barritt 1983) (see Fig. 4.5).

As discussed in sub-section 4.2.2, geochemical analysis (Batchelor 1987) may suggest that this monzogranitic facies can be sub-divided into two distinct magmatic pulses; a more silicic phase which occurs in Glen Etive within the centre of the plutonic mass, and an earlier mafic phase which occurs at the outer part of the body (see Fig. 4.4). This relationship may suggest that the 'Chaorainn pulse' is concentrically zoned. Detailed field and microscope analysis during this study may verify this distribution, both mineralogically and structurally. The outer, mafic phase occurs particularly in the west (E and S of Stob na Bròige [NN 191 526]) and east (S and SE of Stob na Doine [NN 207 533]), possibly suggesting a roughly concentric arrangement (Fig. 4.4). This is also suggested by the concentric zonation of U and Th (Fig. 4.5 & 4.6), which show an increase in their concentration into the inner, later pulse, indicating that zoning is normal (Barritt 1983). The boundary between these two petrologically distinct units, appears to be transitional, varying from approximately 5-10 m wide, up to 20 m across in several places. Within the wider zones, the material may be somewhat variable in composition, whereas within the more common narrow zones the transition is much more regular, generally characterised by an increase in the percentage of mafic minerals, and a slight decrease in the amount of quartz. Microstructurally no localised increase in solid state deformation occurs along the 'transition zone' within either the outer, more mafic monzogranite or the inner, more felsic unit, suggesting that the emplacement of the two phases may have occurred as a fairly continuous intrusive event, with no great lapses in time between successive pulses which would have resulted in the formation of "well defined" petrological contacts, and the localisation of strain.

4.4.2.1 The 'Chaorainn pulse'

This pink/red, medium-grained (2-5 mm) monzogranite is fairly well exposed along the Glen Etive river section and its associated tributaries, particularly towards the south of this body along the Allt Fionn Ghlinne, Allt a' Chaorainn, Allt Coire Ghiubhasan and Allt Coire a' Chaorlainn river/stream sections. Detailed fabric analysis and strain determinations from microdioritic enclaves were carried out along these sections, combined with data, generally of fabric type and orientation only, obtained throughout the rest of the complex.

The monzogranite is fairly equigranular, unlike the geochemically similar Cruachan monzogranite of the adjacent Etive complex which is somewhat porphyritic (see Ch. 3; sub-section 3.2.2). This equigranular texture, composed of essential quartz (15-30 %), plagioclase (30-45 %), and alkali feldspar (25-35 %) makes the determination of weak to moderately developed fabrics more difficult within the field, unlike the petrographically similar intrusive phases of the Etive (Cruachan facies; Ch. 3), Rannoch Moor (Blackwater facies, G2; Ch. 5), and Strath Ossian (Sgòr Choinnich facies, G2; Ch. 6) complexes which are generally much more porphyritic. Fabric determination within the Clach Leathad facies of the 'Chaorainn pulse' is also complicated by the fact that many of the fabrics developed during pre-full crystallisation deformation form bimodal arrangements in which one fabric may dominate over another in one particular area, whereas this relationship may be opposite in another (see below). The complexity increases with the imposition of solid state deformation, which may be coplanar with either sub-fabric, or may appear to overprint both fabrics obliquely.

Pre-full crystallisation (PFC) fabrics or magmatic state fabrics

Throughout the Clach Leathad facies of the 'Chaorainn pulse', the monzogranite generally possesses a fairly weak to moderately developed bimodal PFC fabric (Plate 4.4; Fig. 4.7). The sub-fabrics appear to have been produced by a 'process of angular sorting' (see Ch. 1; sub-section 1.7.3, and references within), with generally plagioclase crystals forming one set of fabrics, and biotite laths forming the other. The two sub-fabrics presumably forming due to the smallest aspect ratio crystals (i.e. plagioclase) rotating faster during non-coaxial deformation, than crystals with higher aspect ratios (i.e. biotite) (Fernandez *et al.* 1983; Fernandez & Laporte 1991). The angular relationship between these two sub-fabrics can be used to infer the sense of shear within the X/Z plane (Fernandez & Laporte 1991). However, the angular relationship, orientation of both sub-fabrics, and the spatial distribution of these changes relative to each other is extremely variable across the whole of this region. One sub-fabric may be clearly dominant in an area, changing, what appears to be instantaneously, to form the weaker sub-fabric, or removed completely in an adjacent area. The X axis of microdioritic enclaves are often aligned sub-parallel to one of these sub-fabric directions. It is not uncommon for the enclaves to form two populations, with the largest population trending sub-parallel to the apparently weaker sub-fabric direction. X/Z ratios (horizontal surfaces) from the analysis of these enclave populations, do not always infer that the more deformed enclaves form the population sub-parallel to the dominant, most intensely developed sub-fabric (Fig. 4.7). A possible solution is that one of these sub-fabrics represents a 'tiling' or 'imbricate' texture (Den Tex 1969; Blumenfeld 1983) formed due to the interaction of crystals slowing down their rotation and causing them to pile up (see Ch. 1, sub-section 1.7.3). This will effectively keep these crystals at an angle to the shear plane for a longer period of time, than those crystals outside these zones which are allowed to rotate more freely. This may explain why the weaker of the two sub-fabrics is often characterised by the preferred dimensional orientation of biotite. It may appear more weakly developed because it is interspersed with feldspar crystals which have also become incorporated and essentially 'locked-up' to form a tiling-type fabric'. Whereas, outside these zones, plagioclase and biotite crystals are allowed to move more freely, allowing the plagioclase crystals to rotate faster towards the shear plane, due to them having smaller aspect ratios, resulting in their alignment and the apparent effect that they form the most intense alignment of the two sub-fabrics.

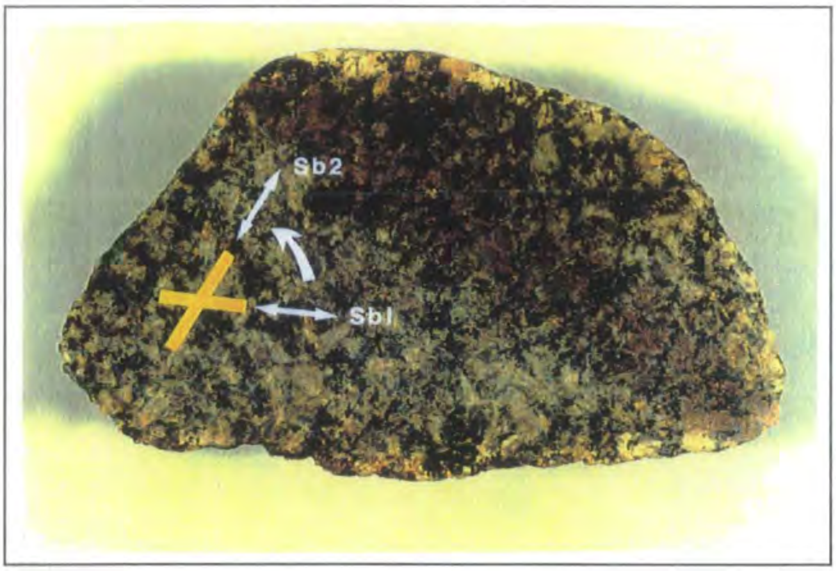


Plate 4.4. Hand-specimen of G2 from the 'Chaorainn pulse'. It shows a bimodal PFC fabric which is defined by the preferred dimensional orientation of plagioclase phenocrysts. A 'process of angular sorting' during non-coaxial deformation has produced two sub-fabrics (Sb1 & Sb2). Sb1 is defined by a relatively high percentage of biotite laths, whereas Sb2 is defined by predominantly smaller plagioclase crystals which rotated faster during the non-coaxial deformational event (see text for explanation). The angular relationship between these sub-fabrics can be used to deduce the sense of shear during their development, which in this case is sinistral. (Yellow 'bars' are approximately 2 cm long).

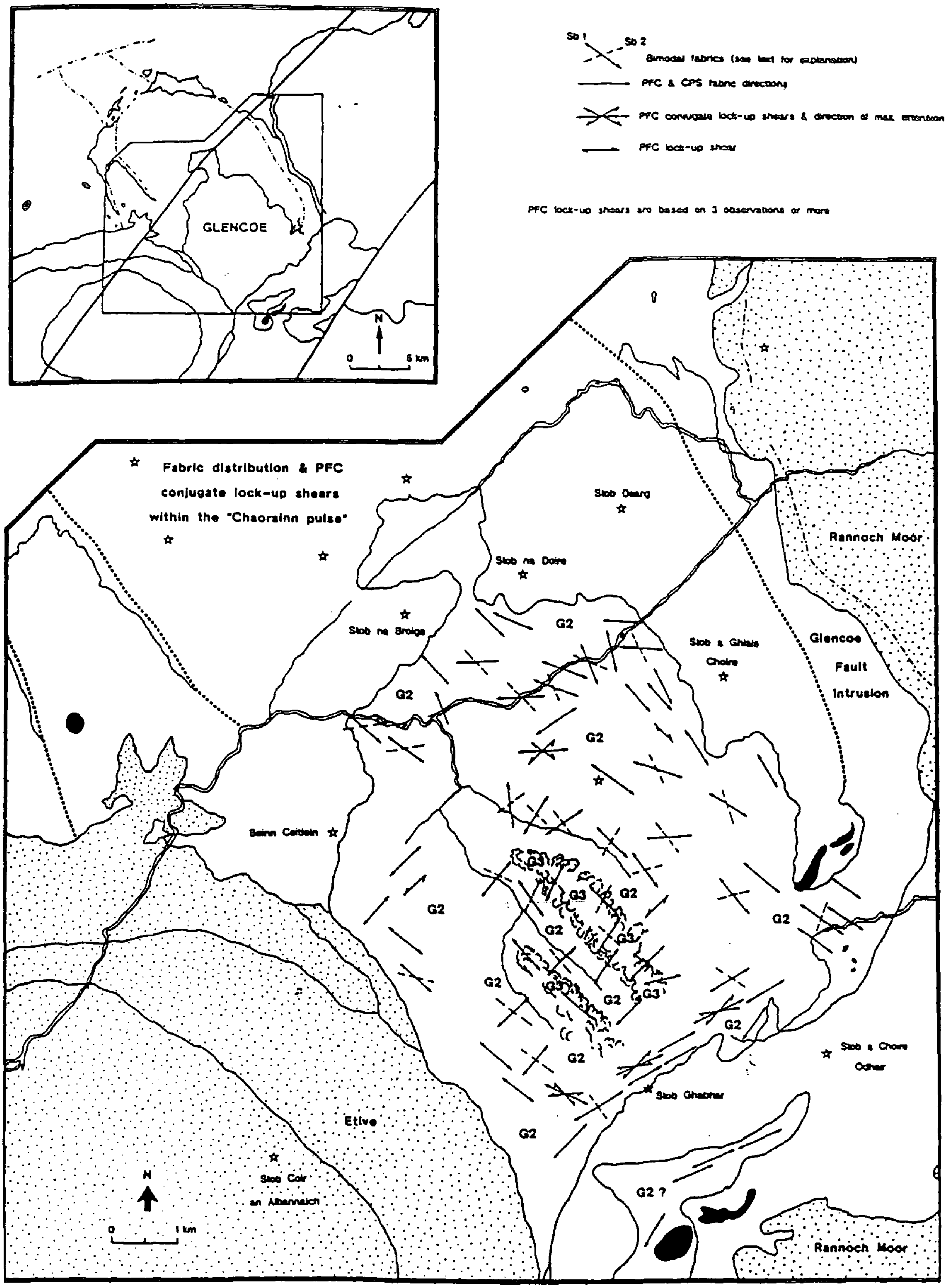


Fig. 4.7. Fabric orientation and the distribution of PFC 'lock-up shears' throughout the 'Chaorainn pulse'.

Within the south of the complex, the predominant PFC fabric is steep, and contact-parallel to the pluton margin. Towards the country rock contact there appears to be a progressive increase in the intensity of the PFC fabric, combined with an increase in the intensity of a high temperature coplanar CPS overprint.

As mentioned above, the orientation of the X axis of microdioritic enclaves may define two populations (e.g. Allt Fionn Ghlinne [NN 227 522]; Plates 4.5 & 4.6). Each population is generally aligned roughly sub-parallel to one of the sub-fabrics which form a bimodal PFC arrangement. X/Z ratios may vary from approximately 1.59 to 2.50 within the central parts of the 'Chaorainn pulse', with X/Z values generally slightly higher for enclaves orientated NW-SE (130-170°), than those trending roughly NE-SW (025-040°) (Fig. 4.8). Y/Z ratios, measured from vertical joint surfaces perpendicular to the X-direction, were obtained from several localities within the central part of the 'pulse'. K values range from 0.56 to 0.96 (Fig. 4.8), with enclaves possessing elongate disc shapes ($0 < K < 1$) to plane strain shapes ($K \approx 1$). Prolate shapes ($1 < K < \infty$) on a few occasions have been observed. In the south, X/Z values increase to approximately 3.2, simultaneously with an increase in both PFC and CPS (see below) fabric intensity towards the pluton margin.

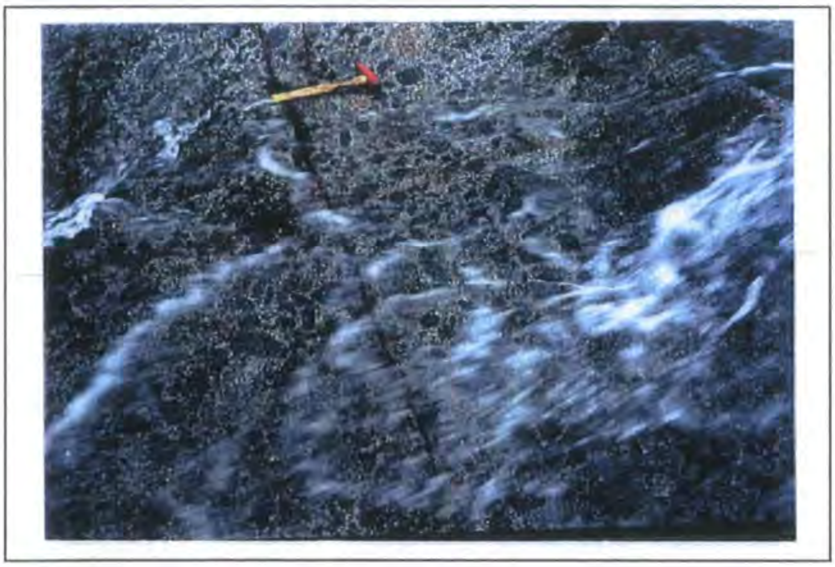


Plate 4.5. Within the Allt Fionn Ghlinne [NN 227 522] region, large, localised concentrations of microdioritic/appinitic enclaves occur ("appinitic/microdioritic pipes").

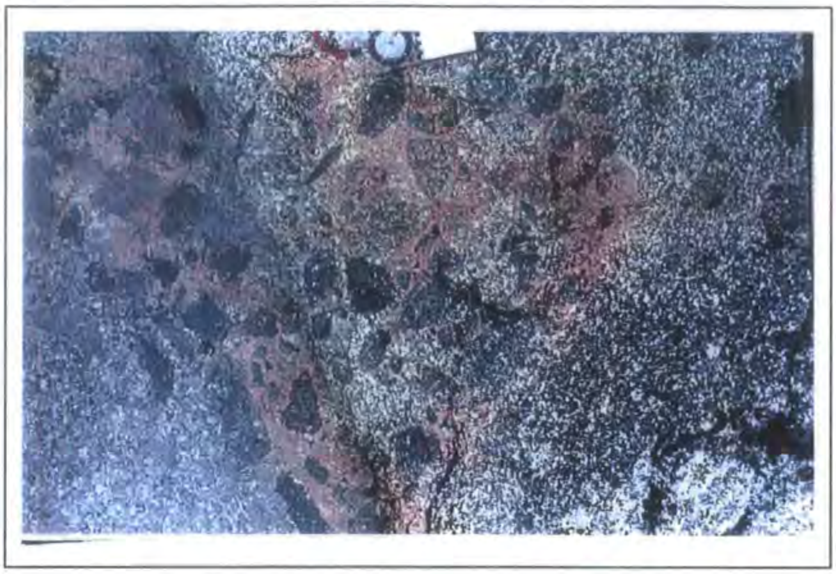


Plate 4.6. This shows 'a close-up view' of the distribution and alignment of a few of the microdioritic enclaves shown in Plate 4.5. The orientation of the x axis of these enclaves define in many cases two populations. Each population is generally aligned roughly sub-parallel to one of the bimodal fabrics developed within the host G2.

Throughout the 'Chaorainn pulse' are discrete ductile shears or 'lock-up' shears (Fig. 4.7; Hutton & Ingram 1992; Ingram & Hutton 1992) formed during the last stages of pre-full crystallisation deformation. The development of these structures has been described in Chapter 3, sub-section 3.4.2.1. The majority of these PFC lock-up shears are approximately 2.0 to 2.5 cm wide. They may form conjugate shear sets, in which the shears may trend sub-parallel to the PFC sub-fabrics developed throughout most of the monzogranites (Plate 4.7). Two possible populations occur, one trending 025-040° often showing a sinistral sense of shear by the way phenocryst phases have been deflected across the zone, and another less common set which trend approximately 120-170°. The sense of shear along the 'NW-SE-trending set' is generally much more variable and, difficult to determine. Both sets of lock-up shears, in particular the NE-SW-trending set, show evidence that the deformation along these zones continued into the solid state, resulting in the development of overprinting CPS fabrics. As deformation continued still further down-temperature, a band of mylonite generally < 2 mm wide was developed along the lock-up shear. In the south, close to the pluton margin, these structures may form conjugate shear sets which show a bulk extensional component parallel to the pervasive 'contact-parallel' PFC fabric developed throughout this part of the 'Chaorainn pulse' (Fig. 4.7).

Plate 4.7. Conjugate PFC 'lock-up' shears developed within G2 of the 'Chaorainn pulse'. Down-temperature deformation along these shears has resulted in the development of a thin band of mylonite generally < 2 mm wide.

It should be noted that locally, fabrics have been deflected and modified by the emplacement of the NE-SW-trending Etive Dyke Swarm (see Ch. 8). Synplutonic relationships such as cuspate/lobate margins between G2 and Etive dykes of mainly porphyrite compositions, and local deflections in the PFC fabric trend within the host (i.e. G2), suggest that this phase of dyke emplacement occurred before G2 had fully crystallised. However, see later phase of dyke emplacement below.

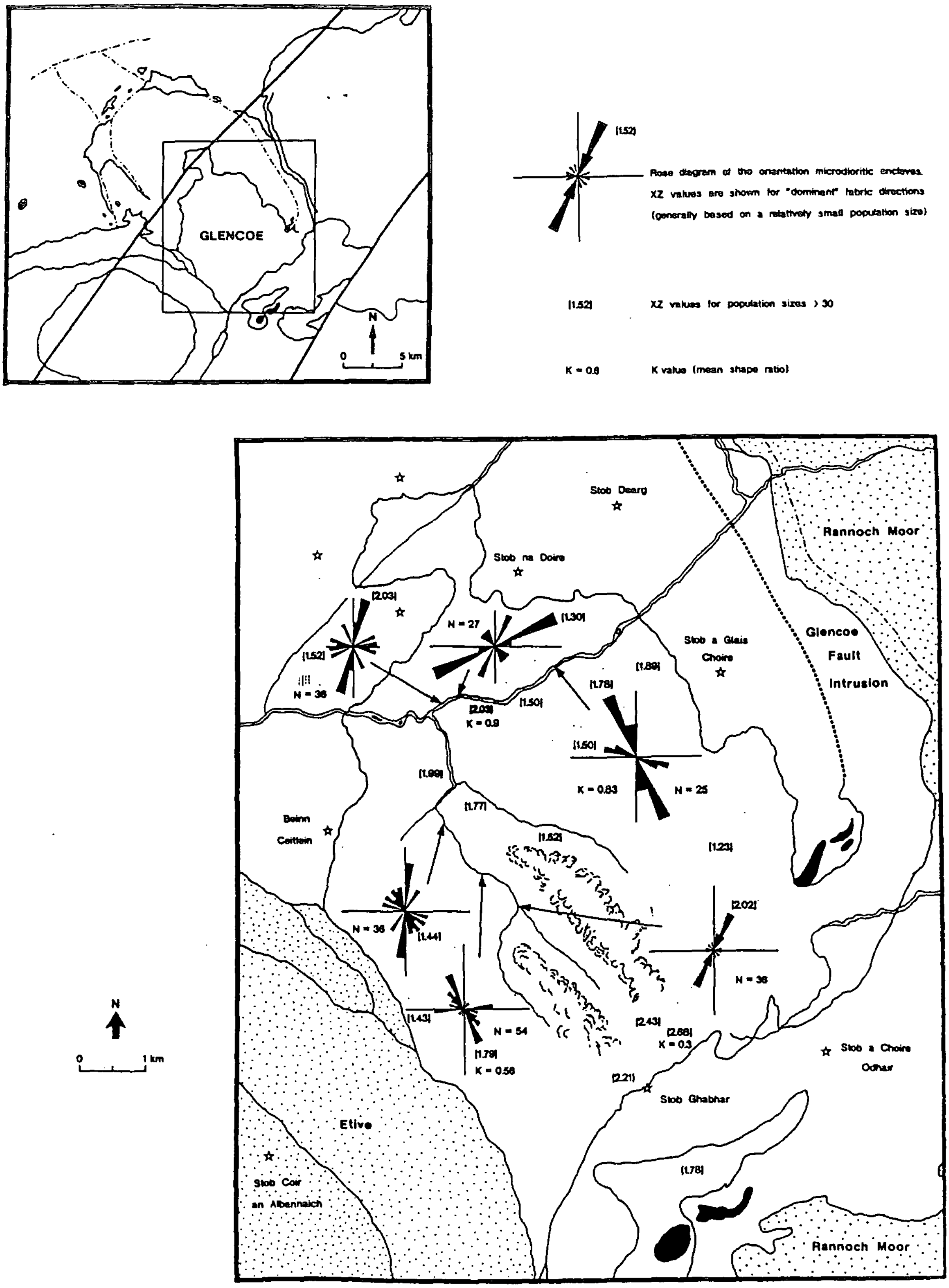


Fig. 4.8. Rose diagrams showing orientation of microdioritic enclaves and strain distribution throughout the 'Chaorainn pulse'.

Crystal plastic strain (CPS) fabrics or solid state fabrics

Fabric development becomes more complicated due to the imposition of solid state deformation. This is a high temperature CPS deformational overprint, which can occur coplanar to either set of sub-fabrics, or can be seen obliquely overprinting both (Plates 4.8, 4.9 & 4.10). It is generally an extremely weakly developed CPS fabric, characterised by the internal ductile deformation of quartz (strained undulose extinction and its lenticular form), and the development of bent or kinked biotite laths. Within these areas of relatively low solid state deformation, magmatic features such as oscillatory zoning have generally been preserved. Moving south, towards the G2/country rock contact, the intensity of the high temperature CPS deformation increases to a relatively moderately developed overprint, particularly within the Stob Ghabhar region (Fig. 4.7 & 4.8). The resultant solid state fabric is coplanar to the pre-existing contact-parallel PFC fabric. To the south of the 'main plutonic mass' is an irregular shaped body (approximately 3 km^2) of what appears to be Glencoe G2 (Clach Leathad facies) (Fig. 4.7 & 4.8). The fabrics developed within this body are high temperature CPS fabrics which trend approximately 070°, sub-parallel to the "contact-parallel" fabrics developed within the main mass.

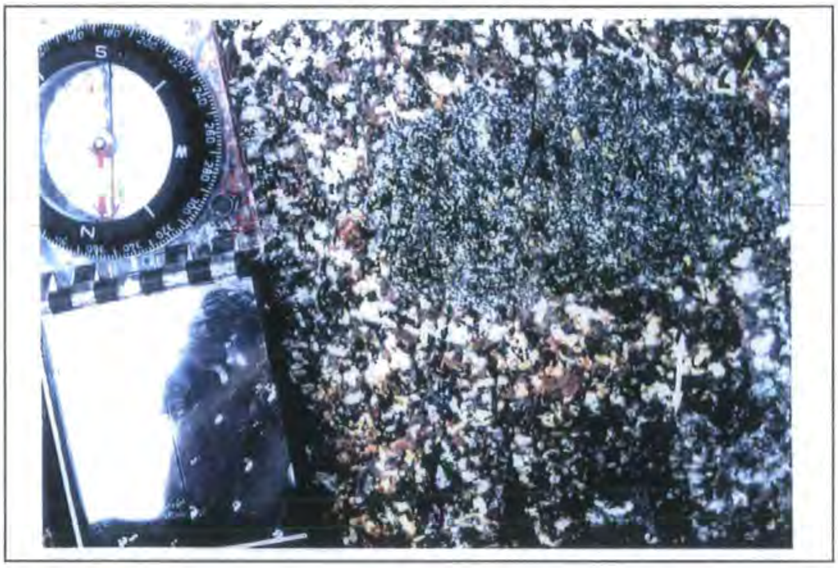


Plate 4.8. A high temperature CPS fabric developed within G2 of the 'Chaorainn pulse'. The microdioritic enclave is aligned parallel to the pre-existing PFC fabric, and has been clearly obliquely overprinted by a solid state deformational overprint, causing recrystallisation. The white arrow shows the orientation of the CPS fabric.

Plate 4.9. Hand-specimen of G2 from the 'Chaorainn pulse'. The white arrow shows the orientation of a weakly developed, high temperature CPS fabric. (Yellow 'bar' is approximately 2 cm long).

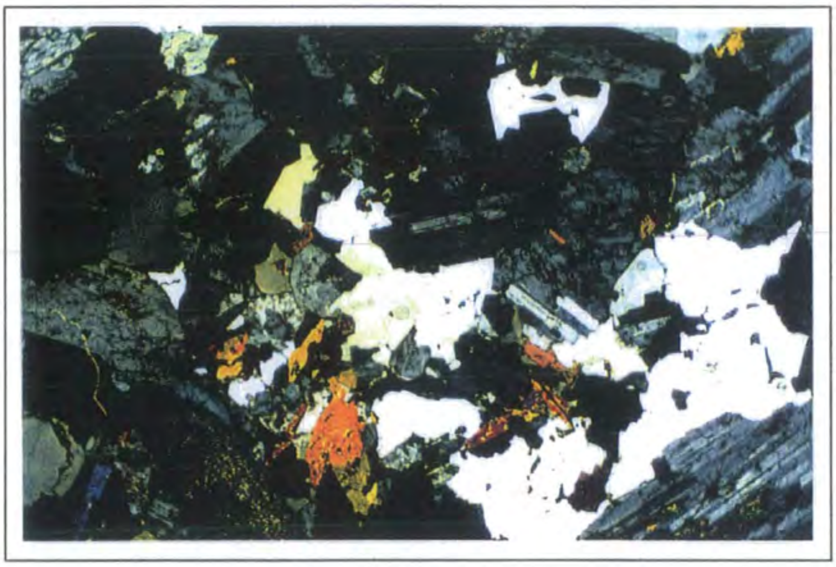


Plate 4.10. Photomicrograph of hand-specimen shown in Plate 4.9. A weak solid state deformational overprint, generally only affecting quartz which may show a slight lenticular form. (Field of view approximately 18 mm).

Localised, crystal plastic strain (CPS) deformation

As mentioned above, the Clach Leathad facies (G2) has been cross-cut by the NE-SW-trending Etive Dyke Swarm. Many of these microdioritic dykes have sharp, planar contacts, in contrast with many of the porphyrite dykes described above. These microdioritic dykes are also generally associated with the development of localised, high temperature CPS fabrics along their contacts within G2. Their emplacement has also led to the development of many NE-SW-trending 'PFC/CPS lock-up shears' and other types of brittle-ductile structure (see Ch. 8, sub-section 8.3.2.2). These features suggest that these microdioritic dykes may represent a distinct, slightly later phase, which were emplaced shortly after G2 had fully crystallised.

A major, NE-SW-trending fault zone, named here as the Starav-Chaorainn fault, can be traced through the 'Chaorainn pulse' (Fig. 4.9). In the NE, within the Glencoe cauldron, the fault appears to run directly along the River Etive. South-eastwards the fault diverges from the river as it continues into the Clach Leathad facies (G2), where it can be traced in the numerable cross-cutting, NW-SE-trending stream sections which pass down the slopes of Beinn Mhic Chasgaig (Fig. 4.9). It passes through the confluence of the Allt Coire Ghuibhasan and Allt a' Chaorainn, and is topographically expressed from here for approximately 1.5 km by the latter river section. This part of the fault zone is shown on the British Geological Survey Sheet 53, as a "shatter belt" (Fig. 4.9). The fault appears to continue SE into the Etive complex, passing directly through Coire Glas [NN 163 455], as marked on the British Geological Sheet 45. This structure can be identified approximately 1-2 km SE of Coire Glas within the Allt Mheuran stream sections, and again along strike within the Allt nam Meirleach (Fig. 4.9). From this point the south-westward continuation of the fault is uncertain due to the topography and exposure.

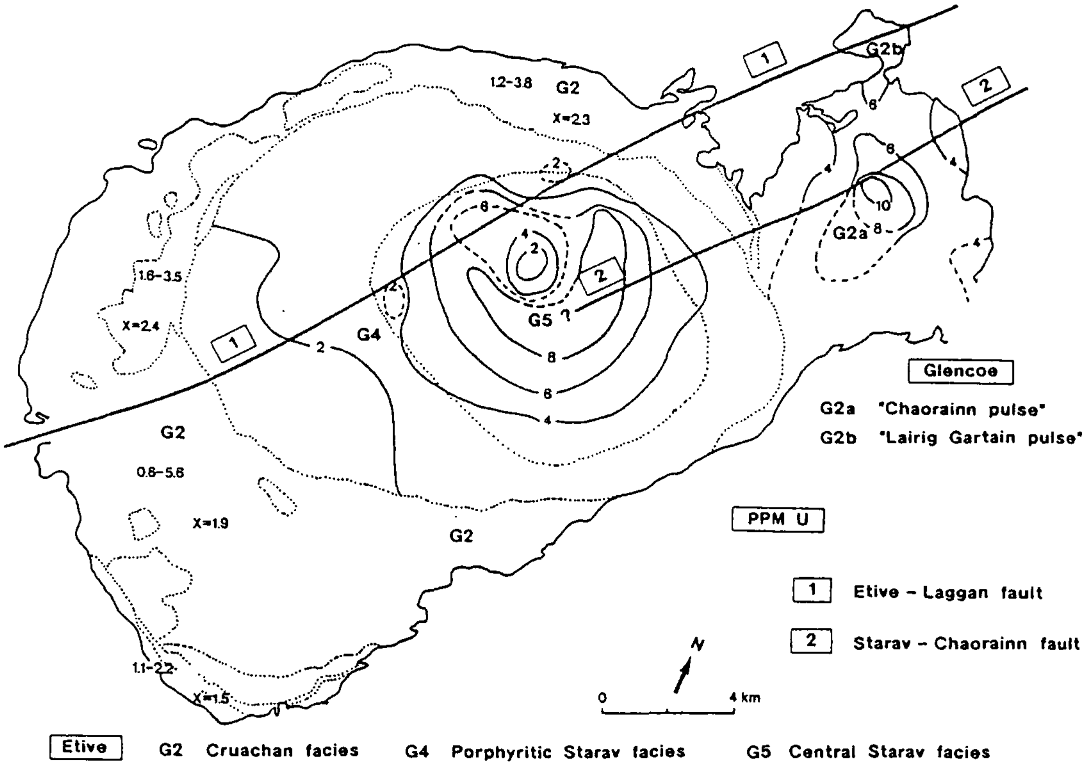


Fig. 4.9. Locality map showing trace of the NE-SW-trending Starav-Chaorainn and Etive-Laggan faults, and their spatial association with the centres of the 'Chaorainn and Lairig Gartain pulses', respectively. The concentric zonation of U by Barritt (1983) is shown to illustrate the position of the two pulses.

The most striking feature about this structure is that geographically it coincides exactly with the centre of the Etive Starav facies (G5; see Ch. 3) and appears to be spatially associated with the centre of the Glencoe 'Chaorainn pulse' if we accept the concentric zonation of U and Th by Barritt (1983). The possibility that the Starav-Chaorainn fault has influenced the siting of these two intrusive components is discussed in Chapter 9. It is also interesting to note that this structure may have also been exploited by felsite/quartz-porphyry dykes belonging to the Etive Dyke Swarm. Petrographically similar dykes are also concentrated along the Ciaran-Ossian fault zone, which can be traced south-eastwards from the Kingshouse region of the Rannoch Moor complex (see Ch. 5), and into the northern exposure of the 'Chaorainn pulse' (Fig. 4.9). Although detailed mapping of microstructures along and in the vicinity of this structure did not reveal PFC or CPS fabric geometries which could be directly related to deformation along this zone during pluton construction or shortly after crystallisation, it does not exclude its existence or influence on the siting and on earlier emplacement processes. As it is quite foreseeable that any earlier movements along this structure were subsequently overprinted/modified or completely obliterated by expansion-related strains associated with the construction of the Etive complex (Ch. 3) and Glencoe plutonic phase (see below).

Within Glencoe G2 (Clach Leathad facies), intensely developed solid state deformation is localised along the Starav-Chaorainn fault. The width of this zone appears to be extremely variable, from a few meters up to 10 meters across. In areas where the pervasive, relatively weakly developed, high temperature CPS deformation (see above) is trending around 140° (Fig. 4.7), it clearly increases in intensity across the structure. Microgranitoid enclaves which are aligned oblique to this fabric direction are clearly overprinted by this solid state deformation. A large number of NE-SW-trending sinistral, brittle-ductile shears were noted along this zone, possibly developed during this high temperature solid state deformational event. This structure has been subsequently affected by at least one phase of reactivation, producing low temperature fabrics and associated brittle structures. The fault zone, which is marked on the British Geological Survey Sheet 53 as a "shatter belt", is represented by brecciated and cataclastic material. Glencoe G2 within this zone generally has an extremely red appearance, possibly suggesting late stage fluid activity along the fault, leading to Fe oxidation.

Summary of general microstructural features developed within the 'Chaorainn pulse' (G2):

① The majority of G2 possesses a complex arrangement of weak to moderately developed bimodal PFC fabrics. These sub-fabrics appear to have been produced by a 'process of angular sorting' leading to one set forming a 'tiling-type fabric' and the other set forming discrete PFC 'lock-up shears'. This implies that during this deformation, strain was partitioned during PFC fabric development, leading to the formation of two sets of PFC fabric which possess geometrical relationships very similar to solid state 'S-C fabrics'. Shear sense inferred from the angular relationship of these sub-fabrics suggests that the orientation and distribution of strain throughout the region was extremely heterogeneous during pre-full crystallisation. This heterogeneity continued into the solid state regime, leading to the development of high temperature CPS fabrics which may be coplanar with either PFC sub-fabric, or may obliquely overprint both sets.

② Microdioritic enclaves may be aligned sub-parallel to both PFC sub-fabric directions. K values range from 0.56 to 0.96, with enclaves possessing elongate disc shapes ($0 < K < 1$) to plane strain shapes ($K \approx 1$).

③ In the south, the predominant PFC fabric is steep, and contact-parallel to the pluton margin. PFC conjugate, ductile shears often show a bulk extensional component parallel to this fabric direction. There is a progressive increase in intensity of this PFC fabric towards the contact, combined with an apparent increase in the intensity of a high temperature, coplanar CPS overprint. A similar situation may occur, but to a lesser extent in the eastern part of the complex.

④ The emplacement of the cross-cutting NE-SW-trending Etive Dyke Swarm may have occurred as two distinct intrusive events relative to the crystallisation of G2. Many porphyrite dykes possess synplutonic relationships with their host (G2), and have clearly, locally modified PFC fabrics developed within G2 during their emplacement (see Ch. 8); thus, suggesting G2 was not fully crystallised during this phase of dyke intrusion. However, a suite of microdioritic dykes may be somewhat later, resulting in the development of: (i) localised, high temperature solid state fabrics within G2, along their contacts; (ii) a large number of NE-SW-trending 'PFC/CPS lock-up shears'; and (iii) brittle-ductile structures, such as en-echelon tension gash arrays.

Model proposed

The following features may suggest that the initial development of the 'Chaorainn pulse' was by a process of *in situ* expansion: (i) there is a progressive intensification of steep contact-parallel PFC fabrics towards the southern, and possibly western margins of this intrusive phase; (ii) the development of PFC conjugate ductile shears which often show a bulk extensional component parallel to this fabric direction; and (iii) within these outer zones, the PFC fabric has been generally overprinted by a high temperature, coplanar CPS fabric. The concentric zonation of U and Th (Barritt 1983), and the petrographical distribution of two distinct units (Batchelor 1987) may suggest that G2 within this region is composed of at least two 'magmatic pulses'.

However, such a process is generally characterised by the following deformational features, which are generally pervasively developed throughout large parts of the pluton, particularly within its outer periphery (see Etive and Rannoch Moor complexes (Ch's. 3 & 5 respectively)):

(i) Moderately developed, generally inward-dipping, pseudoconcentric

PFC fabrics which intensify and steepen towards the pluton margin.

(ii) Sub-horizontal mineral stretching lineations.

(iii) PFC conjugate, ductile shears which show a bulk extensional component parallel to the fabric direction.

(iv) X/Z ratios of microdioritic enclaves generally show an apparent increase in strain towards the pluton margin. The overall absolute mean shape values of these enclaves generally suggest an overall bulk shortening component, with K values consistently between 0 and 1 ("flattening strains"), which progressively become more oblate (K ≈ 0) towards the pluton margin.

The possible reasons why some of these features, indicative of *in situ* expansion, were modified or completely removed, either during (a) the *in situ* expansion stage, (leading to the development of such a complex arrangement of bimodal PFC fabrics), or (b) shortly after the complete crystallisation of G2 (high temperature CPS fabric development), could be:

➊ During the emplacement of the 'Chaorainn pulse', strains related to its expansion may have been extensively modified by the imposition of expansion-related strains associated with the simultaneous construction of the adjacent, much larger Etive complex. The subsequent emplacement of the Central Starav facies (G4/G5) within the adjacent Etive complex may have also influenced fabric development within this region. The same may be true of the *in situ* expansion of the slightly later 'Lairig Gartain pulse' (see sub-section 4.4.2.2) sited at the centre of the Glencoe complex.

➋ The 'Chaorainn pulse' and 'Lairig Gartain pulse' are sited along the Starav-Chaorainn and Etive-Laggan faults, respectively. Their spatial association, together with information obtained from the 'Lairig Gartain pulse', which is unaffected by this deformation and may represent the preservation of the initial stages of *in situ* expansion (see sub-section 4.4.2.2), suggest that these structures not only sited these 'pulses', but may have ultimately controlled their initial development. It is therefore possible that these structures may have been active shear zones during magmatism, influencing the distribution and types of fabric developed throughout the region.

❸ The importance the emplacement of the Etive Dyke Swarm may have had, during the development of PFC fabrics within G2, should not be underestimated. In the Glen Etive river section alone, 16 dykes were recorded over a distance of approximately 515 m (measured at right angles to their strike), constituting approximately 26.4 % of that section. This is comparable with the result obtained by Anderson (1937a, p. 509) of 29 % for this part of the River Etive section. *This implies that in some sections the emplacement of the Etive dykes produces at least 25 % dilation of the crust.* The earlier, synplutonic porphyrite dyke phase clearly influences PFC fabric development, causing re-orientation and intensification of the fabrics (see Ch. 8). Particularly within the northern most parts of the 'Chaorainn pulse' , where the concentration of porphyrite dykes is high, the angular relationship of bimodal fabrics within the intervening belt of G2, i.e. between two dykes, suggest a dextral rotational component during their development (see Fig. 4.10). This generally results in: (i) An E-W-trending (approximately 090-095°) high aspect ratio sub-fabric composed of biotite, hornblende, and plagioclase laths. This essentially forms a "tiling-type fabric" (S; Fig. 4.10c). (ii) A NNW-SSE-trending (approximately 140-170°) low aspect ratio sub-fabric composed of tabular plagioclase crystals, which represent 'PFC lock-up shears' (C; Fig. 4.10c). During down-temperature deformation, strain is focussed into these narrow zones of shear, often culminating in the development of a high temperature, 'pervasive' NNW-SSE-trending CPS overprint. A highly idealised solution to account for such bimodal fabric development is shown by Fig. 4.10a and b. This model assumes that each dyke essentially represents a narrow shear zone. During the initial stages of dyke emplacement, sinistral transcurrent deformation along these zones causes a strain induced shear component to be established between two developing dykes. This results in a sigmoidal fabric swing to be developed within the host (G2), between the two dykes. Such fabric trajectories are not uncommon (see Ch. 8). Within the central part of G2 (between the two dykes), the resultant fabric will be orientated approximately E-W. As the dykes widen, the transtensional shear component, causes the intervening belt of G2 to be subjected to non-coaxial general shear. This causes a gross clockwise rotation within G2, causing the E-W fabric to be progressively modified by a 'process of angular sorting', resulting in the angular relationship of the two sub-fabrics now observed.

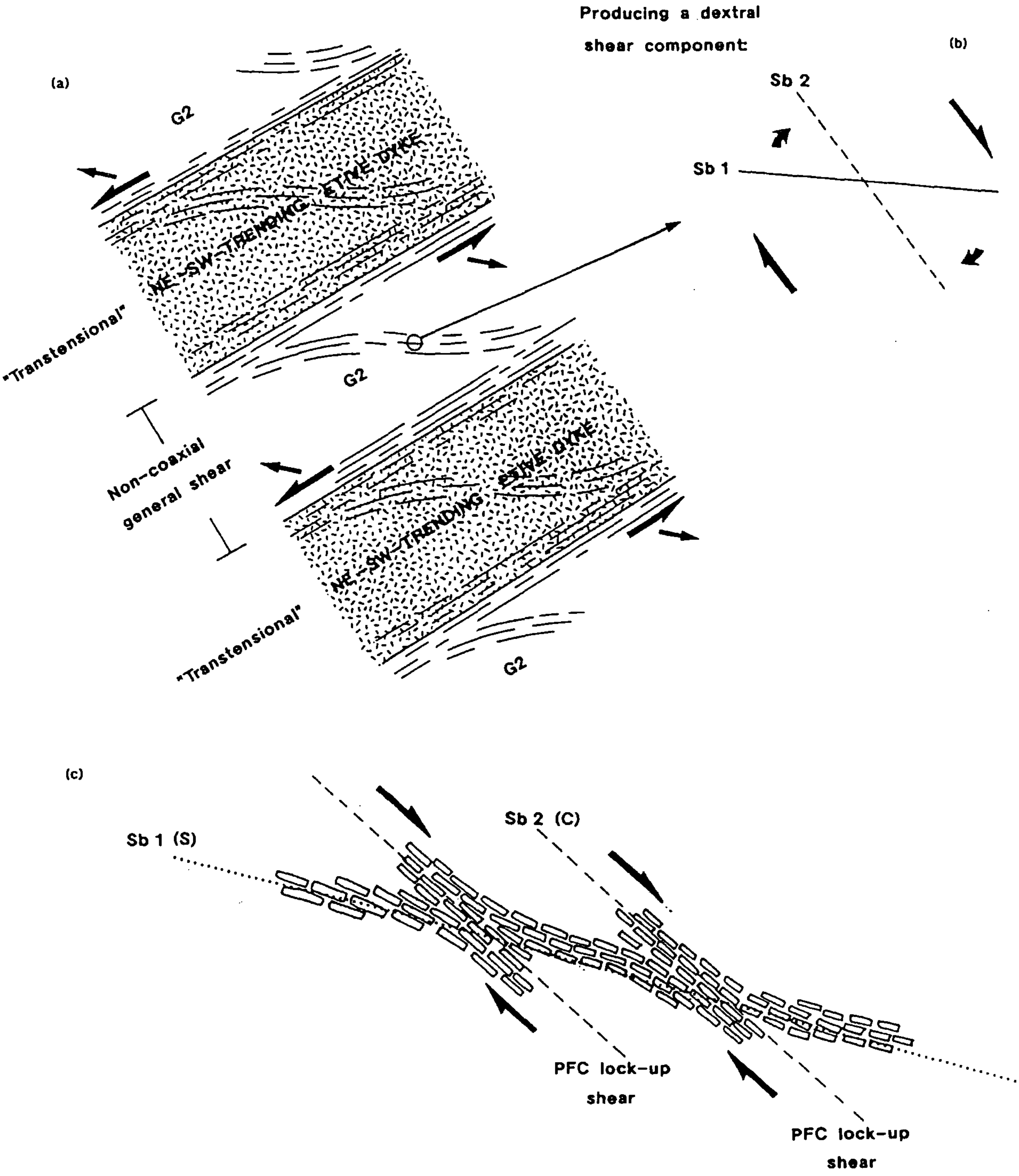


Fig. 4.10. A generalised model possibly explaining bimodal PFC arrangements within G2 as a consequence of the emplacement of the Etive Dyke Swarm. A highly idealised model is presented showing (a) the initial development of a PFC fabric swing within G2, between two dykes undergoing 'construction', and (b) the gross clockwise rotation within G2, induced by the sinistral transcurrent motion along the dykes margins as they widen, resulting in G2 undergoing 'angular sorting', producing a bimodal PFC arrangement. (c) The angular relationship of the two sub-fabrics developed within G2.

➍ Within the south of the complex, in the Allt Coire an Easain-River Bà region, G2 (Clach Leathad facies) appears to synplutonically 'merge' with the higher level emplacement phenomena, the Main Glencoe Fault Intrusion (see sub-section 4.22, & Ch. 7, sub-section 7.3.1). The Main Fault Intrusion takes the form of a "partial ring-dyke", emplaced during an episode of cauldron subsidence along the Main Ring Fault system (see sub-section 4.2.1, and references within. See emplacement model proposed in Ch. 7, Section 7.4). These may suggest that at least part of this cauldron subsidence event occurred during or shortly after the construction of this plutonic phase G2, allowing the block to descend into the "magma chamber" below, and leading to the development of the Fault Intrusion. This displacement of the central block into the 'plutonic body' below, could have presumably modified or completely obliterated deformational features related to the emplacement of the 'Chaorainn pulse'.

The major problem with the microstructural analysis of the Glencoe plutonic phase G2, in order to obtain information regarding its emplacement, is that only part of it is exposed through an "erosional window", with the rest presumably occurring directly beneath the Glencoe Cauldron block and associated ring-intrusion.

4.4.2.2 The 'Lairig Gartain pulse'

Fabrics within this area appear to have been largely unaffected by the deformation experienced by the 'Chaorainn pulse'. The pre-full crystallisation fabric preserved here shows a sigmoidal swing into the NE-SW-trending Etive-Laggan fault zone (Fig. 4.11), suggesting it was an active sinistral shear zone during G2 emplacement. Conjugate ductile shears imply extension towards 120°, the direction of the dominant fabric. A secondary, weaker PFC fabric trending 040°, parallel to the Etive-Laggan shear zone is occasionally preserved, but in general is overprinted by a weak to moderately developed, high temperature, coplanar solid state overprint (Plates 4.11 & 4.12). This NE-SW-trending CPS fabric forms a localised zone, up to approximately 200 m wide, along the Etive-Laggan shear zone, suggesting that deformation continued along this structure for a short period after G2 had fully crystallised. This solid state deformation is microstructurally characterised by highly strained, lenticular quartz, and bent crystals of biotite. Some plagioclase and alkali feldspar laths show evidence of internal ductile deformation, most commonly in the form of undulose extinction and deformation lamellae. Moving towards the fault zone, the intensity of this solid state overprint increases, with the feldspar crystals often having undergone marginal sub-graining and recrystallisation processes. The presence of fractured feldspar and occasionally hornblende crystals, may suggest this zone was subjected to a later, lower temperature (< 450°C; Simpson 1985) deformational event (Plates 4.13 & 4.14). This is verified by an intense zone of brecciated and cataclastic material along this structure. A later period of low temperature deformation associated with movements along the Etive-Laggan fault zone was also observed within the adjacent Etive complex (see Ch. 3, sub-section 3.4.4).

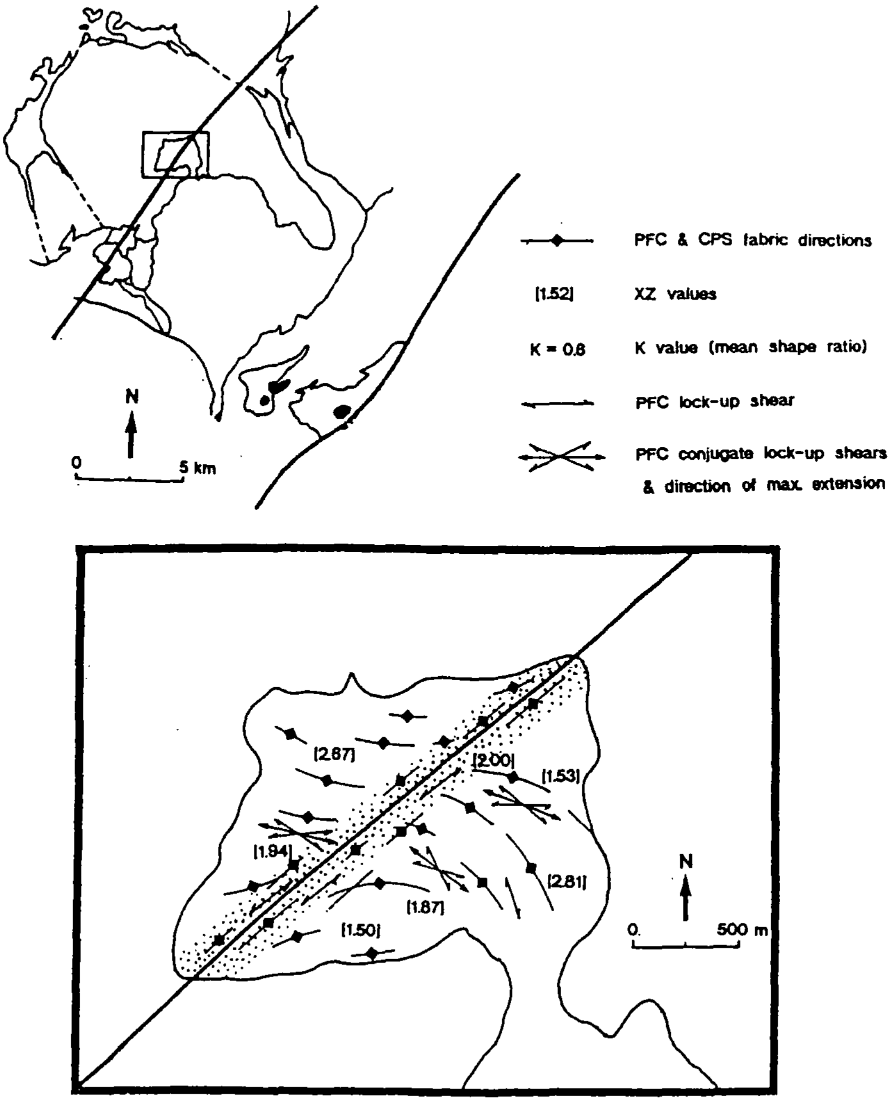


Fig. 4.11. Sketch map of orientation of fabrics, PFC 'lock-up shears', and strain distribution within the 'Lairig Gartain pulse'.

Plate 4.11. A typical hand-specimen of G2 from the 'Lairig Gartain pulse'. Possesses a moderately developed, high to moderate temperature CPS fabric which is defined by biotite crystals. White arrow shows fabric direction. It has experienced a later, lower temperature deformational overprint. (Yellow 'bar' is approximately 2 cm long).

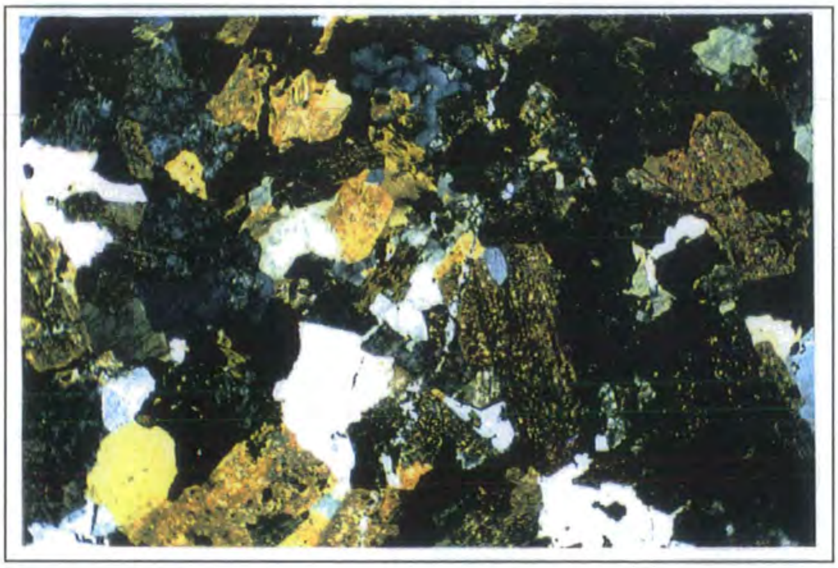


Plate 4.12. Photomicrograph of specimen shown in Plate 4.11. Note that a large amount of twinning has been removed. (Field of view is approximately 18 mm).

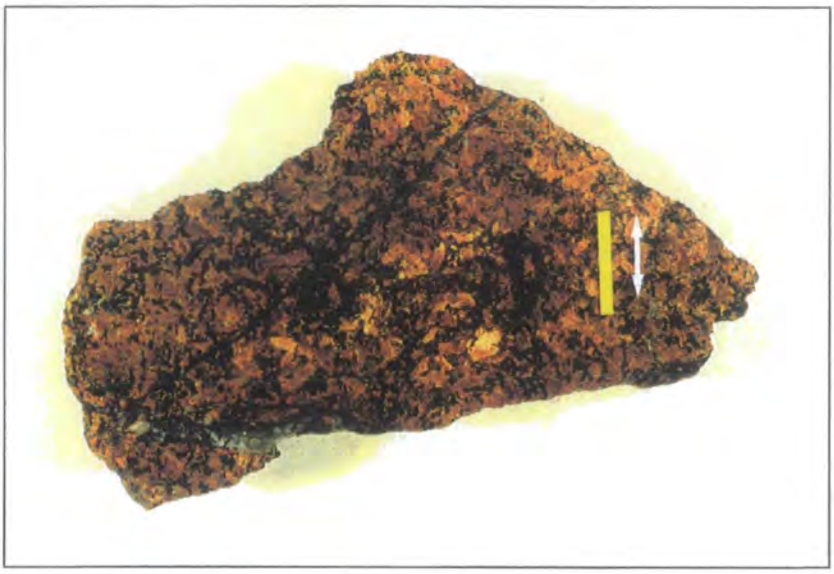


Plate 4.13. Hand-specimen of G2 from the 'Lairig Gartain pulse'. This specimen was collected approximately 20 m from the fault zone. It has been subjected to a low temperature deformational overprint. (Yellow 'bar' is approximately 2 cm long).

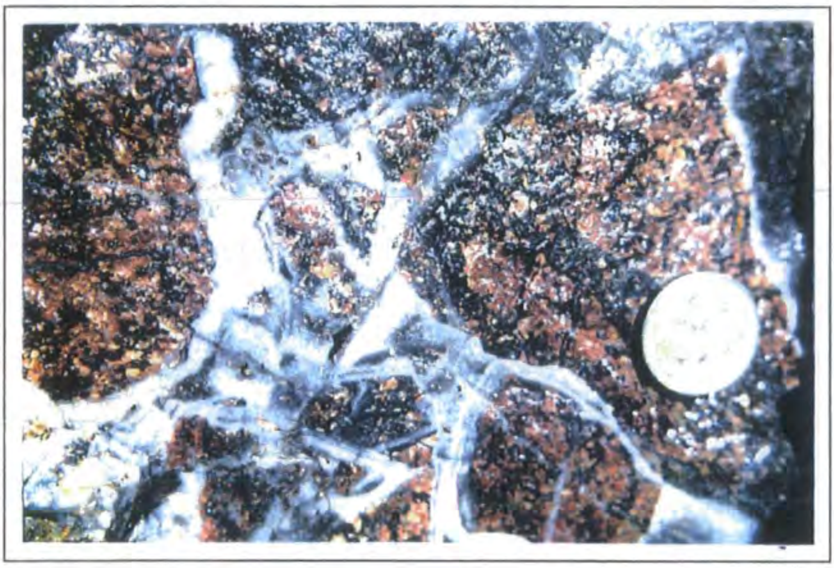


Plate 4.14. This shows a typical outcrop of the hand-specimen shown in Plate 4.13. Note its extremely red colour, and the network of brittle shears and quartz veins which cross it.

As mentioned above, many of the conjugate ductile shears show a bulk extensional component parallel to the dominant fabric direction (approximately 120_). This possibly suggests that magma was allowed to expand predominantly into the direction of maximum extension imposed by the sinistral, transcurrent movements along the Etive-Laggan shear zone. Microdioritic enclaves within this "zone of maximum expansion" (see Fig. 4.11), are aligned parallel to the dominant fabric direction (approximately 120_) and possess X/Z values (from horizontal surfaces) ranging from around 1.6 to 2.8, with a general increase towards the outer parts of the body (Fig. 4.11). However, outside this zone ratios from horizontal surfaces range from 1.5 to 2.0, and the three-dimensional analysis of these enclaves suggests that the X axis is sub-vertical, with X/Z values (from vertical surfaces) ranging from 2.7 to 3.0. Within these two corresponding zones where the X axis of enclaves is sub-vertical (Fig. 4.11), the absolute mean shapes of the enclaves are consistently elongate disc shaped ($0 < K < 1$), similar to the shapes observed within the "zone of maximum expansion". It should be noted that these strain determinations are based on limited population sizes. Although the data base is small, the features observed are fairly consistent, and may suggest the following scenario:

① This zone may represent the preservation of a situation where magma is emerging from an ascent conduit and being fed outwards into an incipient balloon.

② Sinistral transcurrent deformation along the Etive-Laggan shear zone during this event, caused magma to expand predominantly into the direction of maximum extension imposed. The X axis of microdioritic enclaves are sub-horizontal, and aligned parallel to this "stretching" (extensional) direction.

③ Outside this "zone of maximum expansion", the X axis of microdioritic enclaves are generally sub-vertical in orientation. This could speculatively suggest, that these zones still preserve a vertical "stretching" component related to the vertical intrusion of magma into the system via the ascent conduit, presumably at the centre of the body (see Ch. 9).

4.4.3 G3: The Aonach Mór facies

This monzogranitic phase occurs within the "Chaorainn pulse" along two NW-SE-trending ridges, the Aonach Mór and Sròn a' Ghearrain ridges (Fig. 4.2; see sub-section

4.2.3). Both bodies have microstructural features very similar to those developed within the surrounding, coarser-grained monzogranites of the Clach Leathad facies (G2); generally possessing a fairly weak to moderately developed bimodal PFC fabric (Fig. 4.7). As with G2, these sub-fabrics appear to have been produced by a 'process of angular sorting' leading to one set forming a 'tiling-type fabric' and the other set forming discrete PFC 'lock-up microshears' (see Fig. 4.7; see sub-section_4.4.2.1). A slight solid state overprint may be coplanar with either PFC sub-fabric, or may obliquely overprint both sets.

The contacts between this intrusive phase and G2 are not exposed, making their age relationship with the Clach Leathad facies (G2) and form uncertain. The similarity of the fabrics developed within this phase to those formed within G2 of the 'Chaorainn pulse' suggests that it also underwent a significant amount of modification during both pre-full crystallisation and solid state deformation, possibly by the imposition of externally derived strains.

4.5 CONSTRUCTION OF THE GLENCOE COMPLEX: AN EMPLACEMENT MODEL

Model proposed for the main construction of the pluton

The model proposed is based on the structural analysis of only part of the Glencoe plutonic complex. Two areas have been investigated which provide an "erosional window", exposing the upper most parts of the plutonic body: (i) at the centre of the complex (Lairig Gartain); and (ii) within the Glen Etive region. The rest of the Glencoe plutonic body presumably lies directly beneath the Glencoe Cauldron and Fault Intrusion in the NW of the complex. Detailed microstructural evidence (this study), combined with the distribution of radioelements (Barritt 1983) suggest that the plutonic complex is composed of at least two "magmatic pulses": (i) an earlier phase, the "Chaorainn pulse" which may have been sited along the Starav-Chaorainn fault; and (ii) the "Lairig Gartain pulse" sited at the centre of the complex along the Etive-Laggan shear zone. It is envisaged that both have been constructed by a process of *in situ* expansion, with only the slightly later, "Lairig Gartain pulse" preserving features characteristic of such a process (Fig. 4.12).

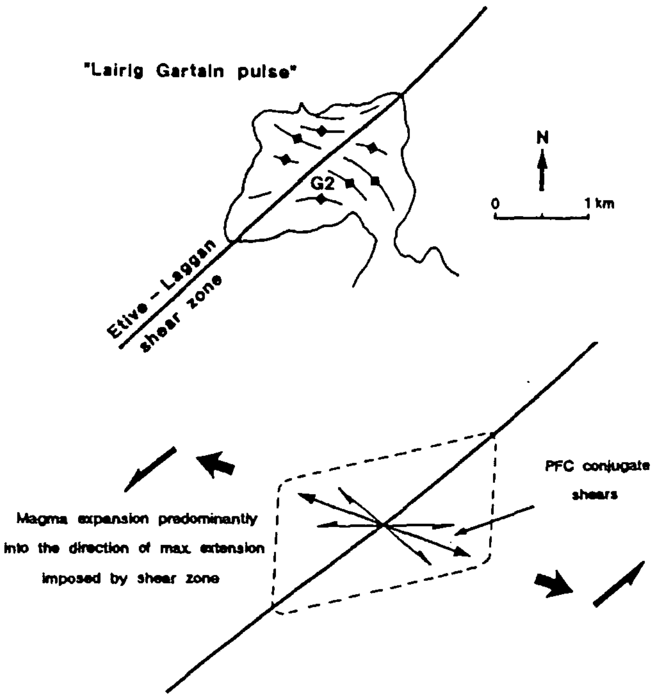


Fig. 4.12. Sketch map of the centre of the Glencoe complex ("Lairig Gartain pulse') showing orientation of fabric and associated structures during initial stages of *in situ* expansion.

Fabrics within the latter 'pulse' have not been extensively modified, possibly resulting in the preservation of a situation where magma is emerging from an ascent conduit and being fed outwards into an expanding pluton. This is in contrast to the "Chaorainn pulse" which is characterised by a complex arrangement of bimodal PFC fabrics, which have been progressively modified and subsequently overprinted by weak to moderately developed solid state deformation associated with externally derived strains. The 'original' structures associated with *in situ* expansion may have been affected by deformation related to:

❶ the *in situ* expansion of the adjacent Etive complex.

❷ the emplacement of the NE-SW-trending Etive Dyke Swarm.

❸ movements along the NE-SW-trending Etive-Laggan and Starav-Chaorainn faults.

❹ the subsidence of the Glencoe Cauldron into the Glencoe "plutonic body", leading to the emplacement of the Fault Intrusion.

CHAPTER 5

THE RANNOCH MOOR COMPLEX

5.1 INTRODUCTION

The Rannoch Moor igneous complex is one of the largest of the late Caledonian plutons of the British Caledonides (approximately 350 km^2) (Fig. 5.1). The pluton is bisected by the NE-SW-trending Ericht-Laidon fault, and a late sinistral offset along this structure displaces the pluton margins by some 7-8 km (Fig. 5.2a; Hinxman *et al.* 1923). Restoration of this displacement shows that the complex has a somewhat elliptical form (approximately 28 km x 18 km), with a long axis orientated NE-SW parallel to the regional Caledonian trend (Fig. 5.2b).

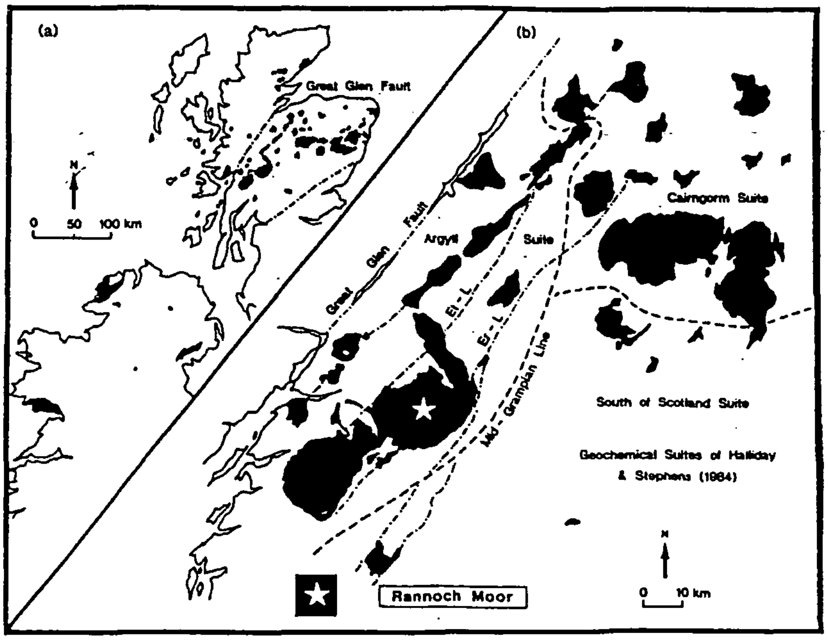


Fig. 5.1. (a) Distribution of late Caledonian granites in Scotland and Ireland. **(b)** Distribution of granitoids in the Grampian Highlands, showing location of the Rannoch Moor complex.

In the west, part of the complex has been removed by the emplacement of the Fault Intrusion of the Glencoe complex (see Ch.'s 4 & 7). This higher level emplacement phenomena cuts and obliterates a significant portion of the Rannoch Moor pluton, encorporating within the main phase of the Glencoe ring intrusion, blocks of Rannoch granodiorite (see Ch. 7).

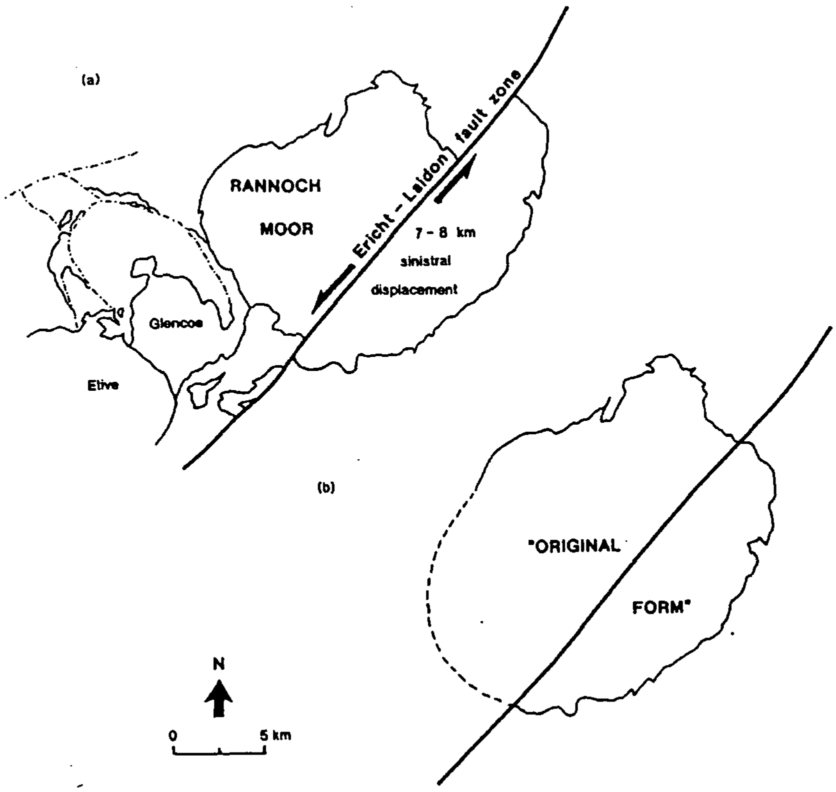


Fig. 5.2. **(a)** Map of the Rannoch Moor complex showing late sinistral offset of its margins along the NE-SW-trending Ericht-Laidon Fault. After Hinxman *et al.* (1923). **(b)** Restoration of displacement showing "original" form of pluton.

The complex was initially surveyed by Hinxman *et al.* (1923), recognising the heterogeneity of its major intrusive component (a granodioritic phase), and the development of distinct internal fabrics which they termed "flow-structures". Read's (1961) classification of emplacement style relative to the age of the pluton was partly based on observations he made within the western and southern margins of the complex, concluding that both regions possessed "forceful-type" characteristics. This led Read (1961) to conclude that the Rannoch Moor pluton was an example of "forceful" emplacement, unlike the somewhat later, "permitted" Fault Intrusion of Glencoe. The pluton received little attention until the work of Leighton (1985). This involved a reconnaissance survey to establish the extent of exposure in order to obtain sufficient representative samples to determine field, petrological and chemical variations throughout the complex.

Detailed field and microscope analysis carried out during this study, combined with pre-existing data (primarily from Leighton (1985)), has revealed that the complex can be sub-divided into six major intrusive components, which have been named here as:

G1: The Gleann Duibhe facies (sub-section 5.2.1)
Monzodiorites through to quartz-diorites

G2: The Blackwater facies (sub-section 5.2.2)
Heterogeneous granodioritic facies (major intrusive component)

G3: The Rannoch Moor Microgranites (sub-section 5.2.3)
Series of monzogranite and syenogranite sheets (minor phase)

G4: The Ciaran / Chomraidh marginal facies (sub-section 5.2.4)
Coarsely porphyritic monzogranite-syenogranite, consisting of large K-feldspar and plagioclase megacrysts (1-3 cm) in a fine-grained granodioritic groundmass

G5: The A' Chruach facies (sub-section 5.2.5)
Monzogranite-syenogranite facies

This current investigation has enabled the production of a petrography map of the distribution of internal intrusive phases of the complex (see Fig. 5.3). However, it should be noted that many of the boundaries between different intrusive phases are inferred, as some contacts are not observed due to lack of exposure in certain areas of the pluton. The petrological characteristics of these intrusive phases are described below.

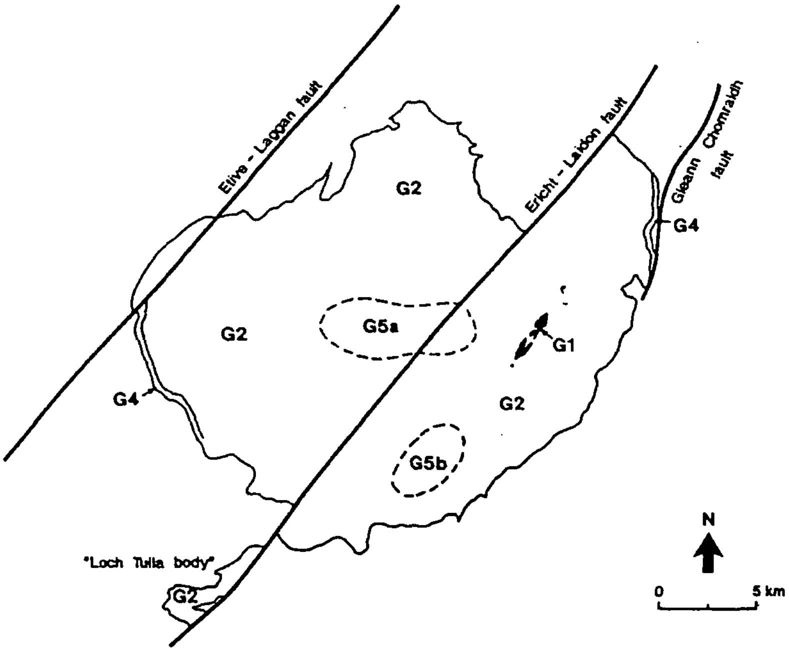


Fig. 5.3. The petrographical distribution of the major intrusive phases within the Rannoch Moor complex. It should be noted that some of the boundaries are inferred due the lack of exposure in certain parts of the pluton.

An emplacement model for the construction of the complex has never been proposed. This is probably because of two main reasons: (i) before the work of Leighton (1985) there was a general lack of informative data about the types and distribution of rocks present; and (ii) there is generally a misconceived view that exposure across the whole pluton is extremely poor. This is probably because many peoples perception of the granite is gained from traveling along the A82 across Loch Laidon and the flat, boggy areas of Rannoch Moor. The purpose of this current study was to establish: (i) the types and distribution of its internal intrusive phases; (ii) the types, distribution and intensity of fabrics which had been commented on by Hinxman *et al.* (1923); (iii) the type, distribution and magnitude of strain; (iv) the identification of local emplacement phenomena; and (v) the deformational characteristics of the surrounding country wall rocks, with particular interest in the western and eastern margins of the pluton, which had received considerable attention by Read (1961). Such information possibly leading to an understanding of the predominant processes operating during the construction of the complex.

5.2 MAJOR INTRUSIVE COMPONENTS

5.2.1 G1: The Gleann Duibhe facies

The earliest intrusive component of the Rannoch Moor complex occurs in the SE along the Gleann Duibhe fault, and takes the form of a narrow elongate sheet (approximately 2 km x 100-200 m wide) (Fig. 5.3). The facies varies from monzodiorites through to quartz-diorites.

General petrographical description:

Gleann Duibhe facies: a medium- to coarse-grained (> 2 mm) monzodiorite to quartz-diorite facies, with a porphyritic texture, containing phenocrysts of plagioclase (20-35 %) which range from 3-12 mm in length, and mafic minerals of biotite (20-30 %) and amphibole (10-30 %). The plagioclase (An 35-15) is normally (indicating high temperature component to low temperature component, i.e. An-rich plagioclase to Ab-rich plagioclase) and oscillatory (discontinuous, multiple zoning) zoned, and is often heavily altered by sericitisation. The ferromagnesian minerals often form elongate clusters. Biotite and hornblende laths range from 1 to 4 mm in length. The amphibole crystals often contain cores of biotite. These phenocryst phases are set in a groundmass of plagioclase, alkali feldspar (10-15 %), biotite and quartz (< 6 %). Biotite may be fringed by hornblende, and both may poikilitically enclose each other. Alkali feldspar is always interstitial and occurs as subhedral or anhedral crystals (< 2 mm in length). Accessories include opaques, apatite, sphene and occasionally zircon.

5.2.2 G2: The Blackwater facies

This heterogeneous granodioritic phase constitutes the largest intrusive component within the Rannoch Moor complex (Fig. 5.3). Geochemical analysis by Leighton (1985), and detailed field and microscopic analysis during this study suggests that the Blackwater facies may comprise at least two petrographically distinct units. (i) A quartz monzodioritic unit which can be divided into two sub-groups comprising a melanocratic, mafic-rich, quartz-monzodioritic phase, most of which is medium- to coarse-grained and is essentially confined to the shores of Loch Laidon, and a leucocratic, mafic-poor, quartz monzodioritic phase. The latter group is also medium- to coarse-grained, but tends to occur at the outer most periphery of G2 (Fig. 5.4), with a concentric form. (ii) A granodioritic unit which forms the bulk of G2. As with the Etive complex (see Ch. 3, sub-section 3.2.2), this G2 may comprise a number of petrographically distinct pulses, which were possibly constructed by a number of intrusive events. The granodioritic phase shows evidence of reverse zonation.

General petrographical description:

Quartz monzodioritic facies (divided into two sub-groups):
(i) a melanocratic, mafic-rich quartz monzodiorite: a medium- to coarse-grained quartz monzodiorite. Finer-grained varieties occur and are randomly distributed throughout this and other intrusive phases.

The coarser-grained variety is porphyritic, containing large tabular laths (0.5-1.5 cm long) of zoned plagioclase (40-60 %). Aggregates of hornblende (8-15 %) and biotite (10-20 %) occur, in which the crystals are generally < 1.0 mm. Hornblende often forms long prismatic crystals, which are generally between 2.5-4.0 mm in length, and are sometimes seen replacing biotite. Interstitial minerals include plagioclase, alkali feldspar (10-30 %) and quartz (5-14 %). Quartz may occur as lenticular aggregates. Accessory minerals include opaque minerals and sometimes zircon and apatite. A small amount of muscovite may occur as an alteration product.

The finer-grained variety is also somewhat porphyritic containing phenocrysts of zoned plagioclase (40-60 %) and amphibole (8-20 %). The plagioclase crystals tend to be euhedral or subhedral and range in length from 0.5 to 3.0 mm. As with the coarser-grained variety, amphibole generally forms elongate prismatic crystals (0.5-3.0 mm in length). Interstitial minerals include plagioclase, quartz (5-12 %) and alkali feldspar (10-30 %). Quartz tends to form anhedral crystals and rarely forms aggregates, unlike the coarser-grained variety. Accessory minerals include opaque minerals, small amounts of apatite and sphene, and occasionally zircon;

(ii) a leucocratic, mafic-poor, medium- to coarse-grained quartz monzodiorite. Plagioclase (oligoclase/andesine) phenocrysts (45-55 %) are tabular in form, and are generally between 0.5 to 1.5 cm in length. These are both normally and oscillatory zoned and compositionally extremely variable (An 38-An 18). The larger phenocrysts (up to 1.5 cm) tend to be oligoclase/andesine. These larger crystals generally possess distorted crystal outlines, undulose extinction, extremely complex twinning and often chlorite developed along their cleavage planes. Myrmekite is commonly associated with these phenocrysts, forming along their external margins. Smaller phenocrysts include biotite (8-17 %) and amphibole (5-12 %) which tend to form clusters up to 1.5 cm long. Biotite phenocrysts are generally subhedral and range from 2.0-3.5 mm in length. Amphibole is much more euhedral in shape, usually forming prismatic crystals ranging from 0.5-2.5 mm in length. These ferromagnesian minerals also occur as smaller crystals within the matrix, where they tend to form aggregates. Other groundmass minerals include plagioclase, perthitic alkali feldspar (14-25 %) and quartz (4-17 %). The quartz often forms aggregates which exhibit concertal textures (intergrown boundaries). Most quartz crystals have developed undulose extinction and possess recrystallisation features. Accessory minerals include opaques and small amounts of apatite and sphene. Chlorite occurs as an alteration product of hornblende, and as mentioned above, along cleavage planes within the larger plagioclase crystals.

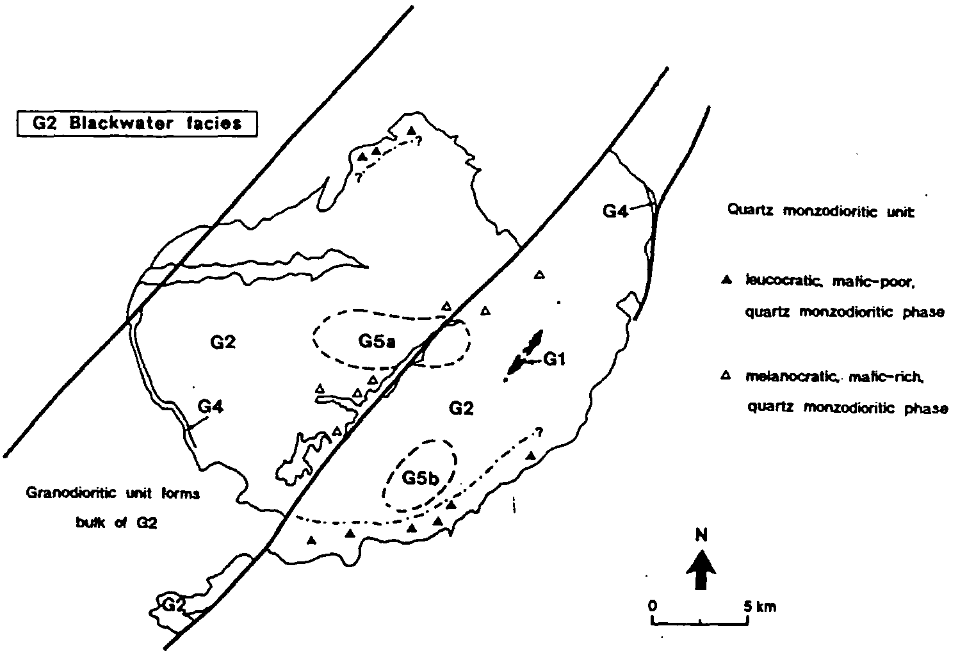


Fig. 5.4. Generalised sketch map of the distribution of petrographically distinct units which constitute the Blackwater facies (G2) of the Rannoch Moor complex.

General description of granodioritic facies: a medium- to coarse-grained, moderately porphyritic, leucocratic granodioritic phase. In hand-specimen and microscopically, rocks from the eastern part of the complex (Loch Eigheach region) can look extremely different from rocks obtained from the western part of the complex (Kingsglass region) (Fig. 5.5); however, there is no significant difference in modal mineralogy. The difference in appearance is attributed to the degree of deformation. The western part of the complex (Kingshouse high strain zone) having experienced a high degree of crystal plastic strain (CPS), whereas the eastern part was only subjected to a relatively weak CPS overprint (see sub-section 5.4.2).

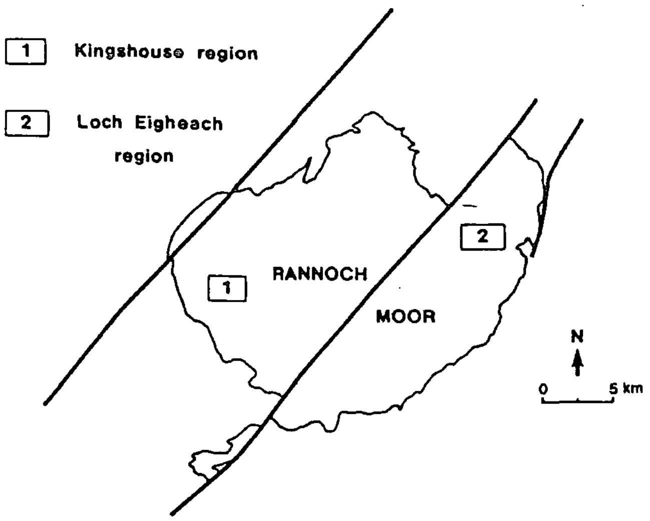


Fig. 5.5. Map of the Rannoch Moor complex showing position of the Loch Eigheach and Kingsglass regions.

Plagioclase (35-45 %) is normally and oscillatory zoned (An 15-20 with An 25-35 cores). Plagioclase phenocrysts are generally subhedral and 5-9 mm long. Within the Kingshouse region, these larger crystals have undergone quite extensive sericitisation. Biotite (8-12 %) and amphibole (5-10 %) may occur as smaller phenocrysts up to 4 mm in length, often grouped together to form mafic clusters. Within the western part of the complex (Kingshouse HSZ), the crystals which make up these aggregates tend to have irregular margins, are often bent or broken, and contain chlorite and opaque minerals along their cleavage planes. Both minerals occur within the groundmass as elongate, euhedral crystals 0.5 to 1.5 mm long. Within the Kingshouse region, these interstitial crystals generally exhibit recrystallisation textures and are often extensively chloritised. Muscovite also occurs as an alteration product. Other interstitial minerals include alkali feldspar (12-20 %) and quartz (22-30 %). Alkali feldspar occurs as anhedral crystals (< 1.5 mm), exhibiting perthitic textures and often possessing uniform extinction. Microcline is common, especially within the western part of the complex. Quartz may form individual crystals up to 2 mm in diameter, or may occur as aggregates. Within the Kingshouse region these aggregates show a high degree of recrystallisation, display concertal textures, and have often developed undulose extinction. Accessory minerals include small amounts of zircon and apatite.

5.2.3 G3: The Rannoch Moor Microgranites

This minor intrusive phase clearly cross-cuts the Blackwater facies (G2) as an extensive series of sheets and dykes. Petrographically two distinct types may occur: (i) a fine- to medium-grained syenogranite, which constitutes the largest component of G3, and (ii) a leucocratic, fine- to medium-grained monzogranite, which is characterised by a slight pink appearance. Mineralogically and texturally this phase is very similar to sheets and dykes which belong to the subsequent intrusive phases G4/G5 (see below). It is therefore, in many cases, extremely difficult to determine which intrusive phase the sheets or dykes belong to. This is further complicated by the lack of exposure within certain parts of the Rannoch Moor complex. Field relationships show that this intrusive phase clearly cross-cuts G2 and has been subsequently cross-cut by monzogranitic and syenogranitic rocks of the intrusive phases G4 and G5. The G3 sheets and dykes often show evidence of relatively moderate CPS deformation, induced predominantly by the emplacement of G5 (see sub-section 5.4.3). It was noted by Leighton (1985), that leucocratic syenogranites within the eastern part of the Rannoch Moor complex show chemical signatures very close to those exhibited by G3, (presumably the Meall Odhar syenogranitic group; Batchelor 1987) of the Etive complex.

The largest amounts of G3 occur within two zones (Fig. 5.3): (i) close to the centre of the complex along the Ericht-Laidon fault, where it has been cross-cut and disrupted by the emplacement of G5a; and (ii) a zone within the SW of the complex which has subsequently been cross-cut and disrupted by the emplacement of G5b, which is associated with the Gleann Duibhe fault.

General petrographical description:

Monzogranitic phase: a fine- to medium-grained (< 3 mm) equigranular monzogranite, slightly pink in appearance due to the presence of alkali feldspar (30-45 %). Feldspar poikilitically enclose biotite and plagioclase. Other essential minerals are plagioclase (20-25 %) and quartz (30-40 %). These alkali feldspars tends to form the largest crystals, up to 4 mm in diameter, with plagioclase (oligoclase) crystals generally < 2.5 mm in length. Quartz is always interstitial, often forming aggregates which possess undulose extinction. Biotite is sub-ordinate and may have been replaced by chlorite. Hornblende is absent. Accessories include iron ores, apatite, sphene and muscovite.

Syenogranitic phase: a leucocratic, pink, fine- to medium-grained (< 3 mm), equigranular syenogranite. Essentially composed of alkali feldspar (40-65 %), quartz (30-35 %) and plagioclase (15-20 %). Biotite is generally around 5-8 %, but may be as high as 12 %. Hornblende is sub-ordinate (1-2 %). Alkali feldspar (orthoclase) tends to form anhedral crystals up to 3.0 mm in diameter. Microcline is also present, together with alteration products such as muscovite and haematite. Quartz often occurs as a granular aggregate, possessing undulose extinction and recrystallisation features. Plagioclase (An 18-10) is often normally zoned, forms subhedral crystals (2-3 mm in length) and generally shows variable sericitisation of its cores. Biotite laths are generally < 1.5 mm and are often bent or kinked; a large percentage of these distorted crystals contain opaques along their cleavage planes and have been altered to chlorite. Accessories include muscovite, apatite and iron ores.

5.2.4 G4: The Ciaran / Chomraidh marginal facies

This is a coarsely porphyritic monzogranite-syenogranite, containing large K-feldspar and plagioclase megacrysts (1-3 cm) in a fine-grained granodioritic groundmass. This occurs as a sheet-like body, essentially in two regions (Fig. 5.3): (i) along the contact developed between the Glencoe Fault Intrusion and Rannoch G2, and in the extreme western part of the complex, particularly along the Etive-Laggan fault zone; and (ii) between the contact of G2 and the bounding Gleann Chomraidh fault, in the south-eastern part of the complex. Relatively thin, discontinuous sheets of G4 also occur along certain parts of the pluton margin.

General petrographical description:

Ciaran/Chomraidh marginal facies: a coarse-grained porphyritic monzogranite-syenogranite, containing large euhedral phenocrysts (1.0-3.0 cm) of perthitic K-feldspar (35-40 %) and plagioclase (20-25 %). These phenocryst phases generally show relatively high amounts of alteration. They are set in a groundmass of quartz (20-35 %), biotite (2-5 %) and subsidiary hornblende. Biotite and hornblende may occur as mafic knots and generally show signs of alteration to chlorite; biotite is also often mantled by iron ores. Accessory minerals include sphene, opaques, and minor amounts of zircon.

5.2.5 G5: The A' Chruach facies

As mentioned above, this intrusive phase essentially forms two elliptical/sub-elliptical monzogranite-syenogranite masses within the complex (Fig. 5.3). The smaller of the two bodies (G5b) occurs within the SW of the complex and appears to have been sited along the Gleann Duibhe fault (see Fig. 5.3); emplaced before the margins of the pluton were displaced by some 7-8 km of sinistral movement along the Ericht-Laidon fault zone (see Ch. 9). However, the position and form of G5a at the centre of the complex (Fig. 5.3) suggests that it was probably emplaced as a later event, relative to G5b, and subsequent to the main sinistral component along the Ericht-Laidon fault zone.

General petrographical description:

The A' Chruach facies: a medium- to coarse-grained equigranular monzogranite-syenogranite, with finer-grained varieties randomly dispersed throughout the two masses. Essentially composed of quartz (30-40 %), plagioclase (20-25 %), K-feldspar (30-35 %) and small amounts of biotite (2-3 %).

Within G5a, particularly in the vicinity of the Ericht-Laidon shear zone, quartz often forms aggregates, shows evidence of recrystallisation and may have developed undulose extinction. Biotite laths are often kinked or bent, have undergone extensive alteration to chlorite and have developed iron ore minerals along their cleavage planes. Often within these zones, orthoclase has been converted to microcline. Also some of the larger feldspar crystals and quartz are associated with myrmekite and have undergone quite extensive sericitisation.

5.3 GEOCHEMICAL ANALYSIS OF THE RANNOCH MOOR COMPLEX: ORIGIN AND EVOLUTION

The Rannoch Moor complex was one of twenty-five Caledonian granitic plutons which were studied isotopically (O-Sr relationships) by Harman and Halliday (1980). Their results were interpreted by Clayburn (1981) to infer that the Rannoch Moor complex contained a larger lower crustal component, and had suffered only minor contamination by local Dalradian metasedimentary upper crust, compared to the adjacent Strath Ossian complex.

The Strath Ossian pluton (Ch. 6) was originally regarded by Hinxman *et al.* (1923) as being part of the Rannoch Moor complex, separated from this granite by a NW-SE-trending metasedimentary screen (however, see below). A more detailed isotopic study has been carried out by Leighton (1985), identifying a number of important points: (i) simple crystal fractionation processes are unlikely to link the monzodioritic facies (G1) and the granodioritic facies (G2); (ii) such processes could explain the wide variation observed within the granodioritic facies (G2; monzonites-quartz monzodiorites-granodiorites-monzogranites); (iii) the isotopic data implies that the syenogranitic phases (G4/G5) are more evolved and are not part of a series related to the early intrusive phases (G1/G2) by crystal fractionation. Instead, the initial Sr ratio for the syenogranites (0.70454 +/- 5) is significantly lower than the values obtained for the granodioritic facies (0.70500-0.70503 +/- 4); suggesting either G2 was selectively contaminated with crustal material, or G4/G5 represents a change in source during the evolution of the complex. Interestingly, a similar situation has been observed with the Etive complex (as mentioned within Ch. 3), where a reversal in the general fractionation trend after G3 (Meall Odhar facies) may represent the influx of a new magmatic batch during the development of the later intrusive phases G4/G5 (Clayburn *et al.* 1983). This was also verified by Batchelor (1987) who concluded that the Cruachan (G2) and Starav (G4/G5) pulses were derived from independent parent magmas; (iv) trace elements suggest that the major intrusive phases may have been constructed by a number of distinct pulses, which were predominantly developed by crystal fractionation processes; (v) based on isotopic characteristics and distinctively high Ba and Sr abundances within the Rannoch Moor complex, compared to the lower concentrations of these elements within Strath Ossian, the two plutons appear to be distinct in terms of their age and source.

5.4 FABRIC DEVELOPMENT: EVOLUTION OF MICROSTRUCTURES

5.4.1 G1: The Gleann Duibhe facies

5.4.1.1 Pre-full crystallisation (PFC) fabrics or magmatic state fabrics

This quartz-dioritic facies possesses a well developed PFC fabric, which trends approximately NE-SW parallel to the elongation of this sheet-like body (Fig. 5.6), and dips between 44-50° towards the NW, i.e. towards the centre of the pluton. The fabric is characterised by the preferred dimensional orientation of euhedral/subhedral plagioclase phenocrysts, and by the alignment of euhedral biotite and hornblende crystals (Plate 5.1). The ferromagnesian minerals often form elongate clusters defining the PFC fabric trend.

In certain areas the fabric is somewhat complicated by the development of a 'second' PFC fabric which generally trends NW-SE and dips between 45-50° towards the SW. These fabrics do not occur together in a bimodal arrangement, but "switch" in dominance, commonly over a few metres or so. In general, the long axis of microdioritic enclaves are orientated in one particular direction parallel to the fabric trend within that particular area, e.g. Tara Mhoir Weir [NN 460 557] a relatively large population of at least 40 enclaves are orientated NE-SW, whereas within the Gleann Duibhe "waterfall section" [NN 462 558] a large number of enclaves (47) are orientated NW-SE. An interesting observation is that the X/Z mean strain (shape ratios) of these microgranitoid enclaves (from horizontal surfaces) indicate an apparent average value which is very similar for both directions: an X/Z value of 2.42 for the enclave population trending NE-SW (approximately 030°), and a mean X/Z ratio of 2.65 for the enclaves trending NW-SE (120-130°). These strain values are not restricted to both these localities (i.e. Tara Mhoir Weir and Gleann Duibhe "waterfall section") within G1, as similar strain values have been recorded on either side of this sheet-like body, generally up to 75-100 m away within the Blackwater facies (G2).

The PFC fabrics developed within G1 possibly relate to a sigmoidal PFC fabric swing developed across this region (see sub-section 5.4.2). The deflection in fabric trend across this area suggests a sinistral component of shear across a broad (approximately 200 m wide) NE-SW-trending zone of deformation. This is combined with an increase in fabric intensity towards the centre of the shear zone. The Gleann Duibhe dioritic facies (G1) is sited along and in the centre of this zone of deformation, forming a NE-SW-trending sheet-like body (Fig. 5.6). This zone of deformation, affecting fabrics both within G1 and G2 (see sub-section 5.4.2) will be referred to as the Gleann Duibhe shear zone (Fig. 5.6). The sigmoidal fabric trace across this region is attributed to a sinistral component of shear along this structure. It is envisaged that the subsequent intrusion and expansion of the intrusive phase G2 and deformation along the Gleann Duibhe shear zone resulted in the distribution of heterogeneous strain and the development of two sets of fabrics during the crystallisation of G1 within this zone. This resulted in the formation of two sets of PFC fabrics, one trending approximately NW-SE, and the other NE-SW. As deformation continued into the solid state regime, both sets of fabrics were overprinted by a NE-SW-trending CPS fabric (see below).

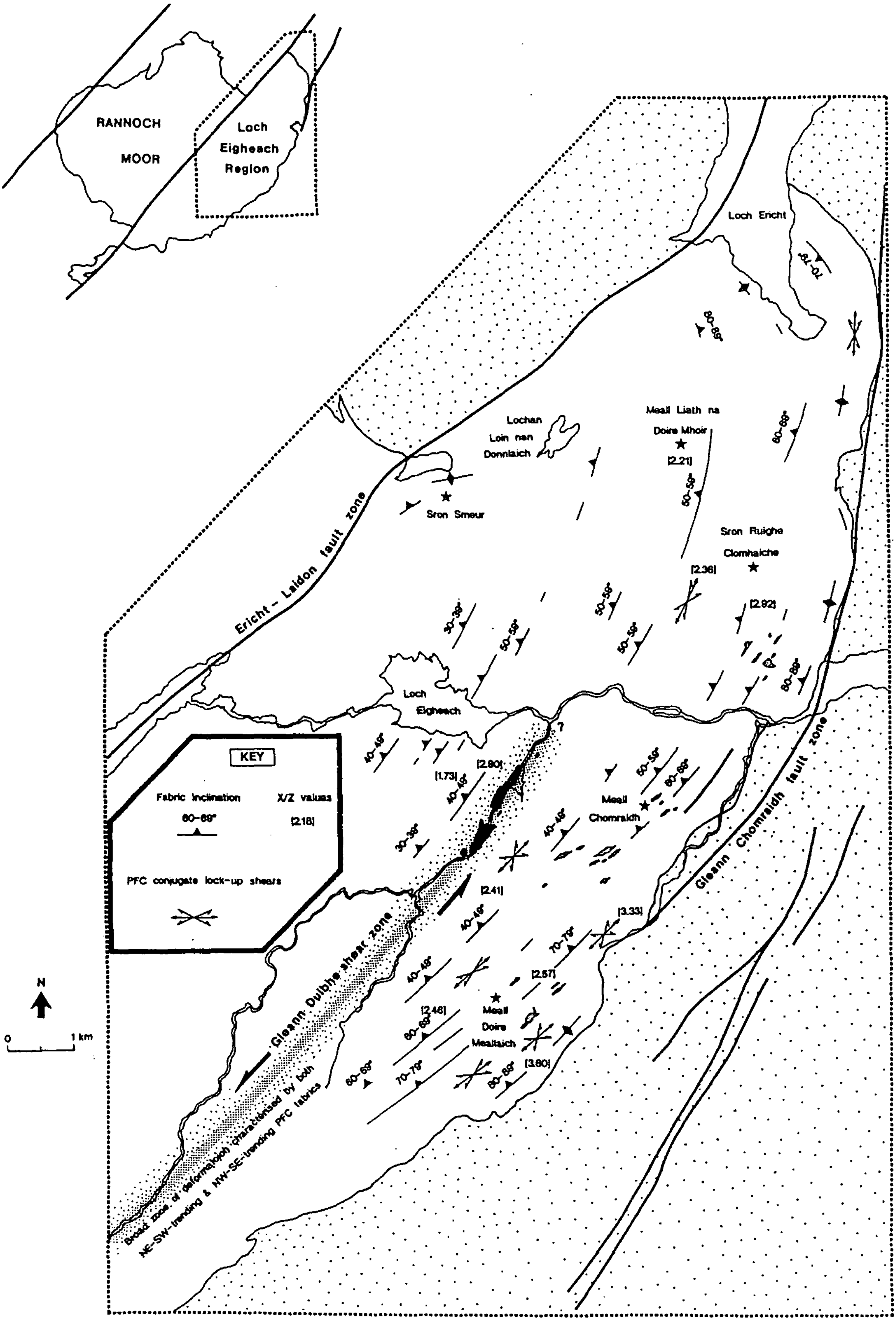


Fig. 5.6. The location of the NE-SW-trending Gleann Duibhe shear zone showing the distribution of G1 (Gleann Duibhe facies). Generalised map of fabric orientation, strain distribution and PFC 'lock-up' shears in G2 (Blackwater facies) within the Loch Eigheach region (eastern part of the complex).

Plate 5.1. Hand-specimen of G1 from the Gleann Duibhe area [NN 459 557]. It possesses a moderately developed PFC fabric defined both by plagioclase and mafic laths. It contains a weakly developed high temperature CPS overprint which can be observed in thin-section. (Field of view approximately 18 mm).

Approximately at the centre of this zone of deformation, at the Gleann Duibhe "waterfall section" [NN 462 558] (Fig. 5.6), vertical joint surfaces, perpendicular to the X-direction, enabled Y/Z ratios of the microdioritic enclaves (trending NW-SE) to be obtained. This was the only locality within this region in which a significant number of measurements could be taken in the Y/Z plane (27 measurements). The calculated K value (overall absolute mean shape) was 1.245. Due to the nature of the exposure, Y/Z ratios for the enclaves orientated NE-SW in G1 are limited, but where they do occur they also indicate a K value of around 1. The significance of such values is unclear, but it may suggest that the overall strain associated with the centre of this zone of deformation (shear zone) was essentially $K \approx 1$, plane strain. As mentioned above, the zone of deformation is approximately 200 m wide. Outside this zone, enclaves within G2 are orientated approximately NE-SW, pseudoconcentric to the margin of the pluton, and are consistently elongate disc shaped ($0 < K < 1$) indicating "flattening strains" attributed to the expansion of G2 (see sub-section 5.4.2.1). A possible explanation for the development of the two sets of fabrics within this broad (approximately 200 m wide) NE-SW-trending zone of deformation (the Gleann Duibhe shear zone), and the overall absolute mean shape values calculated from microdioritic enclaves orientated in both these directions could be:

➊ The NE-SW-trending Gleann Duibhe fault operated as a transtensional ductile shear zone, allowing and facilitating the ascent of G1 along this structure. The development of NW-SE-trending PFC fabrics, both within G1 and G2 across this zone, may infer an overall sigmoidal PFC fabric swing, implying a component of sinistral shear across this structure. This transtensional deformation across this shear zone, during the emplacement of G1, would have been associated with prolate strains (K > 1; "extensional component").

➋ During this continued deformation along the Gleann Duibhe shear zone, G2 was being emplaced at the centre of the complex by a process of *in situ* expansion (see sub-section 5.4.2.1). The deformation along the Gleann Duibhe shear zone also controlled PFC fabric development within G2 (see below), up to 75-100 m either side of the quartz-diorites (G1), i.e. the centre of the shear zone (Fig. 5.6). It is envisaged that expansion-related strains associated with the construction of G2 (see sub-section 5.4.2.1), were imposed throughout this shear zone system. Microdioritic enclaves aligned NE-SW outside this zone of deformation, within G2, may suggest that this whole region was subjected to a component of "flattening" during G2 emplacement. This may have resulted in the development of NE-SW-trending PFC fabrics both within G1 and G2. The development of two sets of PFC fabrics trending NW-SE and NE-SW, and microdioritic enclaves aligned in both these directions may suggest that the localised deformation associated with the Gleann Duibhe shear zone during the crystallisation of G1 and G2 within this zone, the whole region was also being subjected to "flattening strains" as G2 expanded. This may account for the observed plane strain values in the centre of the complex, as the extensional component (leading to "prolate strains") associated with transtensional deformation along the Gleann Duibhe shear zone, may have been 'counteracted' by a contractional component (leading to "flattening strains") imposed by the emplacement and expansion of G2 (see sub-section 5.4.2.1).

➌ As deformation continued into the solid state regime, it is likely that strains associated with deformation along the Gleann Duibhe shear zone ceased, but the flattening strains imposed by the construction of G2 persisted, resulting in both G1 and G2 in this region being overprinted by a high temperature NE-SW-trending CPS fabric (see below).

General description of microstructural features

The Gleann Duibhe facies (PFC fabrics) : This facies possesses a moderate to well developed PFC fabric easily identifiable due to its porphyritic nature. The fabric is defined by the alignment of large (3-12 mm in length) plagioclase (20-35 %) crystals, and smaller phenocrysts (1-4 mm in length) of biotite (20-30 %) and amphibole (10-30 %) laths. The ferromagnesian phenocrysts may form elongate clusters parallel to the PFC fabric trend. These phases are set in a groundmass of subhedral or anhedral alkali feldspar and quartz.

5.4.1.2 Crystal plastic strain (CPS) fabrics or solid state fabrics

The PFC fabric orientated NE-SW, parallel to the elongation of the facies, is often overprinted by a coplanar, weak to moderately developed, high temperature CPS deformation. This is generally characterised by the ductile deformation of quartz, (leading to a somewhat elongate form), and the bending and kinking of biotite laths around the stronger, resistant plagioclase crystals. This overprinting solid state fabric may have been developed as a consequence of strain being imposed by the expansion of G2 at the centre of the complex (see sub-section 5.4.2.1), continuing for a short period after all the crystal phases within G1 had fully crystallised.

5.4.2 G2: The Blackwater facies

Introduction

Within the outer parts of the Blackwater facies (G2), pseudoconcentric, inward-dipping fabrics are developed (Fig. 5.7a). Detailed fabric analysis throughout G2 shows that the pseudoconcentric foliation trajectories developed in the western (Kingsglass region) and eastern (Loch Eigheach region) parts of the complex are essentially 'continuous' with the sigmoidal fabric swing ("oblique fabrics") developed across the central parts of the pluton (Fig. 5.7a), i.e. a sigmoidal swing in the concentric fabric. The fabric swing appears to coincide with the trace of the NE-SW-trending Ericht-Laidon fault which bisects the complex (see sub-section 5.4.2.5). Fabric development within the Blackwater facies (G2) can be divided into several regions of different fabric type (see Fig. 5.7b). The changes in fabric type are progressive between these regions.

The Loch Eigheach region *Eastern part of the complex*	(sub-section 5.4.2.1)
The "northern and southern zones of sheeting and stoping" *Northern and southern parts of the complex*	(sub-section 5.4.2.2)
The Kingshouse region *Western part of the complex*	(sub-section 5.4.2.3)
The Loch Tulla region *The isolated Loch "Tulla mass"*	(sub-section 5.4.2.4)
The Ericht-Laidon fault zone *Central part of the complex*	(sub-section 5.4.2.5)

5.4.2.1 Fabric development within the eastern part of the complex (Loch Eigheach region)

5.4.2.1.1 Pre-full crystallisation (PFC) fabrics or magmatic state fabrics

Around the Loch Eigheach region, moderate to intensely developed pre-full crystallisation fabrics are developed within the eastern part of the complex (Fig. 5.6). The majority of these PFC fabrics are pseudoconcentric, parallel to the curvature of the pluton margin, and inward-dipping. Their intensity progressively increases towards the pluton contact. In general, these PFC fabrics inwardly dip at moderate angles between 36-82°, increasing in inclination towards the pluton margin. The fabric is characterised by the preferred dimensional orientation of subhedral plagioclase phenocrysts (Plates 5.2, 5.3 & 5.4), and by the alignment of biotite and hornblende laths, which have often grouped together to form elongate mafic clusters, as is common within G1 (see sub-section 5.4.1.1). The resultant fabric trace is essentially pseudoconcentric to the form of the pluton, becoming locally modified across the Gleann Duibhe shear zone where it appears to have been deflected in a sinistral fashion. Within the central part of the shear zone (Fig. 5.6), this deformation has produced a sigmoidal fabric trace, resulting in fabrics trending NW-SE and dipping towards the SE at the inclination of 42-49°. Ductile sinistral movements along the Gleann Duibhe shear zone has affected both G1 and G2 during their crystallisation. The zone of deformation is up to 300 m wide, and is characterised by two sets of PFC fabric: (i) a pseudoconcentric fabric which trends roughly NE-SW, and (ii) a NW-SE-trending fabric (part of the sigmoidal fabric swing) related to deformation along the Gleann Duibhe shear zone (Plate 5.5). They commonly "switch" in dominance over distances between 5-10 m. A similar situation was observed with fabric development within the Gleann Duibhe dioritic facies (G1; see sub-section 5.4.1.1).

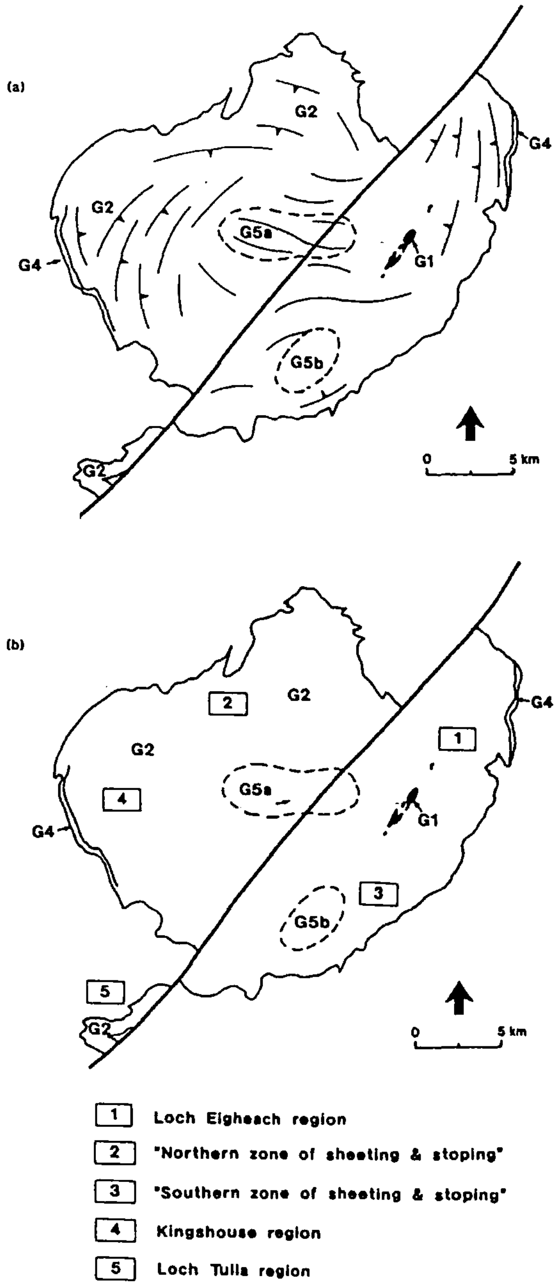


Fig. 5.7. (a) Sketch map of the Rannoch Moor pluton showing generalised internal, foliation trajectory patterns. (b) Sub-division of the Blackwater facies (G2) into several regions of different fabric type (referred to in following sub-sections).

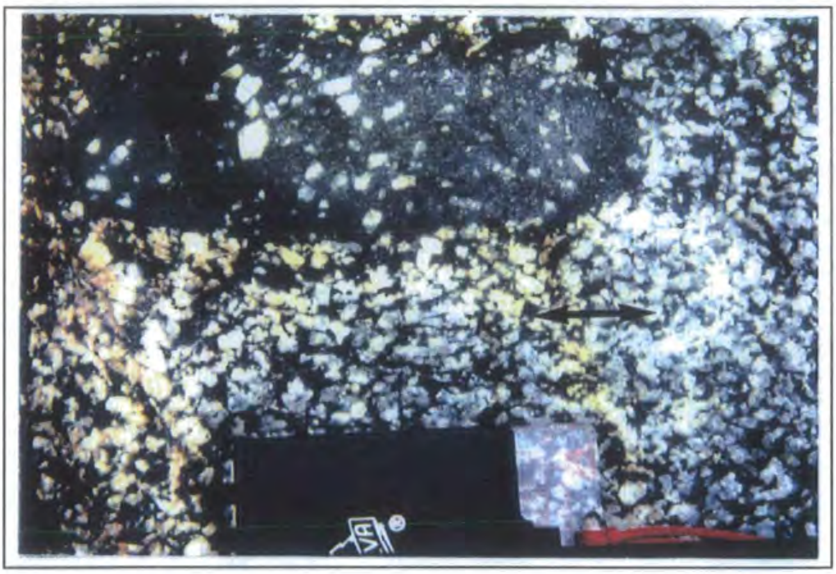


Plate 5.2. Typical outcrop of Rannoch G2 within the eastern part of the complex (Loch Eigheach region). The PFC fabric is defined by the preferred dimensional orientation of plagioclase phenocrysts. A microdioritic enclave is aligned parallel to the fabric direction. Note the 'synplutonic' contact between the enclave and host (G2). (Horizontal surface).

Plate 5.3. Hand-specimen of G2 from the Loch Eigeach region [NN 463 567]. It possesses a moderately developed PFC fabric which is defined by plagioclase phenocrysts and to a lesser extent by mafic minerals. White arrow shows fabric trend. (Yellow 'bar' is approximately 2 cm long).

Plate 5.4. Photomicrograph of hand-specimen shown in Plate 5.3. It possesses a weakly developed, high temperature CPS overprint which is generally characterised by strained undulose extinction in interstitial quartz and biotites which are slightly bent. (Field of view approximately 18 mm).

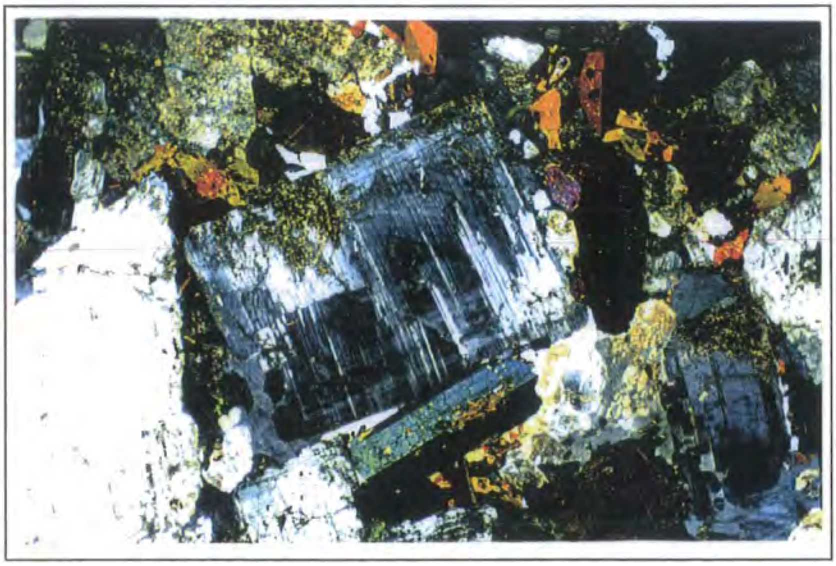


Plate 5.5. Hand-specimen of G2 from the Gleann Duibhe shear zone [NN 460 558] (Loch Eigheach region). It possesses a moderately developed PFC fabric which has been overprinted by a coplanar, weak to moderately developed CPS fabric. Note its semi-annealed texture compared to Plate 5.3.

Outside this zone of deformation, especially within the outer parts of G2, are small, discrete, conjugate, ductile shears or 'lock-up' shears (Hutton & Ingram 1992; Ingram & Hutton 1992) formed during the last stages of pre-full crystallisation deformation (Fig. 5.6). The development of these structures has been discussed in Chapter 3 (Etive complex, sub-section 3.4.2.1). As within the Etive complex, the phenocryst phases have been deflected across these discrete zones of shear, providing the sense of shear along that structure. They also tend to occur as conjugate shear sets, showing a bulk extensional component parallel to the fabric direction (Fig. 5.6). However, in Etive the width of these zones of shear tends to be fairly constant, measuring approximately 2.0 to 2.5 cm, whereas within the south-eastern part of the Rannoch Moor complex this width is much more variable, and in conjugate shear sets one 'lock-up' shear may be somewhat wider than the other. As the deformation continued down-temperature into the solid state regime, overprinting CPS fabrics were developed as the strain was imposed into these narrow zones of shear. This solid state deformation does not appear to have been uniformly distributed between both the shears of the conjugate set, but was focussed along the wider of the two. A large number of conjugate shears within this part of the complex show such an arrangement. This may suggest that during the initial development of these PFC conjugate shears, deformation was focussed equally into both zones, however, as crystallisation increased and deformation continued, there was a progressive change in the orientation of the strain imposed causing the deformation to be focussed predominantly along one of these shears. The possible reason for such development is unclear, but it may be related to the "overall gross rotational component" of the complex as it was emplaced within an overall sinistral regime (see Section 5.7). As the deformation continued down-temperature, a thin veneer of mylonite, generally < 2 mm wide, but sometimes up to 4 mm wide for the dominant shears of a conjugate set, was developed.

Along a NW-SE traverse from the outer margin of the Gleann Duibhe shear zone to the pluton contact, the inward-dipping, moderate to intensely developed pre-full crystallisation fabric developed within G2, tends to steepen and intensify towards the pluton margin. Fabrics within the central parts of the Loch Eigheach region are generally inclined (approximately 40-50°) towards the NW, and progressively steepen to > 70° close to the pluton contact (Fig. 5.6). At the pluton contact the inclination of the fabric may change around the vertical in a few places. This increase in fabric intensity towards the pluton margin is verified by an increase in X/Z ratios of microdioritic enclaves. An apparent average X/Z value of approximately 2.4 is indicated for the central part of this region, which increases to approximately 3.6, coinciding with the increase in PFC fabric intensity towards the outer contact of G2. The X-direction of these enclaves is generally parallel to the pseudoconcentric PFC fabric. As mentioned above, Y/Z ratios obtained from vertical joint surfaces, at right angles to the X-direction, indicate that the enclaves are elongate disc shaped ($0 < K < 1$), progressively becoming more oblate ($K \approx 0$) towards the pluton margin. The Y axis tends to be approximately parallel to the inclination of the dipping PFC fabric. As already mentioned in sub-section 5.4.1.1, plane strain shapes ($K \approx 1$) are common in the quartz-diorites (G1) located within the central part of the Gleann Duibhe shear zone, whereas prolate shapes ($1 < K < \infty$) are extremely rare throughout the whole region. In areas unaffected by deformation associated with the Gleann Duibhe shear zone, plane strain shapes ($K \approx 1$) have only been recorded on a few occasions.

General description of microstructural features

The Blackwater facies (PFC fabric): This granodioritic facies possesses a moderate to intensely developed PFC fabric, which is easily recognised in hand-specimen due to its porphyritic nature. Subhedral, elongate (5-9 mm long) phenocrysts of plagioclase define the fabric, together with smaller phenocrysts (up to 4 mm in length) of biotite and amphibole. The ferromagnesian minerals may form elongate clusters which help to define the fabric. These phases are set in a matrix of biotite, hornblende, alkali feldspar and quartz. The mafic minerals within the groundmass are elongate (0.5 to 1.0 mm long), euhedral crystals. In thin-section they may show a preferred dimensional orientation, suggesting that deformation may have continued during crystallisation of these interstitial phases. This seems likely due to the development of coplanar, high temperature CPS fabrics, indicating that the deformation responsible for the development of the PFC fabrics continued for a short period after the full crystallisation of G2 (see below).

Within the central parts of this region, i.e. towards the centre of the pluton, a weakly developed sub-radial lineation is generally represented by biotite crystals. Towards the centre of the complex its inclination generally becomes steeper. However, in the outer parts of G2, where the PFC fabric is much more intensely developed, biotite crystals define a moderately developed sub-horizontal stretching lineation. Strain magnitude clearly intensifies from the centre of the pluton towards its margin, suggesting that within the central parts of the complex the sub-radial lineation may represent a ‘primary fabric’ preserved in zones of relatively low strain, whereas in the outer parts of G2 this lineation has been overprinted by a sub-horizontal stretching lineation associated with the expansion of G2.

5.4.2.1.2 Crystal plastic strain (CPS) fabrics or solid state fabrics

High temperature, weak to moderately developed CPS overprint: Throughout the eastern part of the complex (Loch Eigheach region; Fig. 5.6 & 5.7), the pseudoconcentric (approximately NE-SW-trending), inward-dipping PFC fabric is overprinted by a weakly developed coplanar CPS deformation. This indicates that deformation may have continued for a short period of time after full crystallisation, leading to the slight modification of the PFC fabric. These are high temperature CPS fabrics, which are characterised by the slight internal ductile deformation of quartz (strained undulose extinction and its lenticular form) and biotite crystals (which show a slight degree of distortion in the form of bent crystals). The plagioclase phenocrysts are dominantly internally undeformed.

Within the broad zone of deformation (approximately 200 m wide) associated with the Gleann Duibhe shear zone, both sets of PFC fabric may show evidence of slight modification by solid state deformation. The PFC fabrics which are pseudoconcentric to the pluton margin (trending roughly NE-SW) generally show a greater tendency to be overprinted by CPS deformation, than the PFC fabrics orientated approximately NW-SE associated with deformation along the Gleann Duibhe shear zone. In both cases the solid state deformational overprint was coplanar leading to the enhancement of the pre-existing (PFC) fabrics.

The greater tendency for the pseudoconcentric PFC fabrics to have been overprinted by solid state deformation, compared to the PFC fabrics orientated NW-SE within the Gleann Duibhe shear zone, may suggest: (i) the deformation along the Gleann Duibhe shear zone continued across the "PFC-CPS transition" and into the solid state regime for only a relatively short period of time; whereas, (ii) the imposition of strain causing the development of the pseudoconcentric PFC fabric, continued for a greater duration into the solid state regime; and/or (iii) the strain responsible for the development of CPS fabrics, coplanar to the pre-existing pseudoconcentric fabric, may have been of a higher magnitude than the strain related to the shear component established across the Gleann Duibhe shear zone.

Localised, high to moderate temperature, moderately developed CPS fabrics: Within the outer margin of G2, in contact with the Ciaran/Chomraidh marginal facies (G4), a localised zone (approximately 5-15 m wide) of high to moderate temperature solid state deformation occurs. Quartz crystals are generally highly strained and form lenticular crystals which have undergone recrystallisation and sub-graining. Biotite laths are kinked and bent, and are often seen wrapped around resistant feldspar crystals. Many of the plagioclase phenocrysts exhibit evidence of internal ductile deformation, most commonly in the form of deformation lamellae and undulose extinction. Many of these plagioclase crystals have undergone marginal sub-graining, and recrystallisation processes may have removed magmatic features such as zoning. These microstructural features are consistent with CPS deformation occurring at relatively high to moderate temperatures, after all the constituent phases within G2 had fully crystallised.

The outer margin of the pluton within this area is essentially bounded by a major NE-SW-trending fault (Hinxman *et al.* 1923). The localised zone of high to moderate temperature solid state fabrics (described above) occur where this structure bounds the complex. This structure, named here the Gleann Chomraidh fault (Fig. 5.6), may have acted as an active ductile shear zone during the emplacement of G2. Continued deformation along this structure, for a short period after full crystallisation of G2, is likely to have resulted in the development of the localised high to moderate temperature CPS fabrics confined to this area. However, the presence of broken or fractured feldspar, and occasionally hornblende crystals, may suggest a later, somewhat low temperature, deformational event (450°C; Simpson 1985). This may be associated with the emplacement of the Ciaran/Chomraidh marginal facies (G4), a sheet-like body intruded between the contact of G2 and the bounding Gleann Chomraidh fault. It is envisaged that this fault was reactivated to allow the intrusion of G4 (see sub-section 5.4.4). During this period of reactivation, G2 may have been superimposed by a late, low temperature, solid state deformation.

Summary of general microstructural features developed within G1 and G2 in the Loch Eigheach region:

① G1 possesses two sets of PFC fabrics: (i) an inward-dipping PFC fabric, parallel to the elongation of this NE-SW-trending body; (ii) a NW-SE-trending set of fabrics which generally dip towards the SW, between 45-50°.

② Throughout this region, the predominant fabric developed within G2 is a moderate to intensely developed, inward-dipping pseudoconcentric PFC fabric which intensifies towards the pluton margin.

③ Within a broad NE-SW-trending zone (approximately 200 m wide), the centre of which coincides with the centre of the sheet-like body of quartz-diorites (G1), the PFC fabrics developed within both G1 and G2 have been somewhat complicated by the development of two sets of PFC fabrics: (i) a NE-SW-trending set which dip towards the centre of the pluton; and (ii) a NW-SE set of fabrics which generally dip towards the SW. The fabrics do not occur in a bimodal arrangement, but "switch" in dominance throughout the zone. The NW-SE-trending set of fabrics may form part of a sigmoidal fabric trace developed across this region. Its geometry may suggest a sinistral component of shear across this broad zone of deformation (named here the Gleann Duibhe shear zone).

④ The overall absolute mean shape values of microdioritic enclaves may suggest an overall plane strain ($K \approx 1$) component associated with the Gleann Duibhe shear zone. However, values obtained throughout the rest of G2 suggest K values consistently between 0 and 1 ("flattening strains"), which progressively become more oblate ($K \approx 0$) towards the pluton margin.

⑤ PFC conjugate, ductile shears more commonly developed within the outer most parts of G2, show a bulk horizontal extensional component parallel to the pervasive pseudoconcentric fabric direction.

⑥ Towards the centre of the complex, G2 may possess a relatively weakly developed, inward-dipping sub-radial lineation. However, within the outer parts of G2, where deformation is higher, a sub-horizontal stretching lineation is moderately developed.

⑦ Both G1 and G2 have been overprinted by a weak to moderately developed CPS deformation. The resultant fabric is coplanar to the pre-existing PFC fabrics developed in G1 and G2 within the Gleann Duibhe shear zone, and the (approximately NE-SW-trending) pseudoconcentric PFC fabrics developed throughout the rest of the Blackwater facies (G2). Both within G1 and G2, PFC fabrics trending NW-SE may show slight evidence of solid state deformation, but by no means to the same extent as the PFC fabrics orientated NE-SW.

⑧ Within G2, high to moderate temperature, moderately developed CPS fabrics are locally developed where the Gleann Chomraidh fault bounds the outer margin of G2. A low temperature CPS overprint may suggest that this localised zone was subjected to a low temperature deformational event.

Model proposed to account for the microstructural features developed within the Loch Eigheach region

A simple model to account for these features could be:

❶ The quartz-diorites (G1) were sited and emplaced along the NE-SW-trending Gleann Duibhe fault, which acted as a ductile shear zone (see below), leading to the development of contact parallel PFC fabrics. These fabrics were continuously modified during, and after the full crystallisation of G1, by strain related to movements along this shear zone, and deformation related to the subsequent emplacement and expansion of G2 (see below).

❷ *In situ* expansion of G2 led to the development of a pervasive pseudoconcentric PFC fabric due to the imposition of predominantly "flattening-type strains". This is verified by the three-dimensional shape of microdioritic enclaves which suggest an overall bulk shortening component.

❸ During the expansion of G2, deformation associated with the Gleann Duibhe shear zone continued, resulting in the development of a set of NW-SE-trending PFC fabrics both within G1 and G2. The inferred sigmoidal trace of these fabrics may suggest a sinistral component of shear across this structure.

The mean shape analysis of microdioritic enclaves within this deformation zone may suggest that a transtensional component (leading to "prolate strains") established across the Gleann Duibhe shear zone (to allow the emplacement of G1 along that structure), may have been 'counteracted' by "flattening-type strains" induced by the emplacement and subsequent expansion of G2. This may explain the development of two sets of fabrics, and the apparent plane strains ($K \approx 1$) observed, which are in contrast to the "flattening-type strains" predominantly developed throughout G2 outside this zone. An alternative explanation is that the Gleann Duibhe shear zone experienced a higher component of sinistral shear, producing $K \approx 1$ strains.

❹ Due to the continued imposition of expansion-related strains during the last stages of pre-full crystallisation deformation, PFC conjugate 'lock-up' shears were developed allowing bulk extension to occur parallel to the fabric direction.

❺ As the emplacement of G2 continued and the pluton body 'inflated', G1 and earlier intrusive components of G2 crystallised, resulting in the PFC fabrics being slightly modified by an overprinting CPS deformational overprint. This was most intense within a localised zone along the outer margin of G2 where the NE-SW-trending Gleann Chomraidh fault essentially bounds the pluton. It is envisaged that this structure may have been an active ductile shear zone during G2 emplacement. Continued deformation along this structure, into the solid state regime, is likely to have resulted in the development of the localised high to moderate temperature fabrics confined to this area. A lower temperature deformational overprint may suggest that this structure was reactivated during the emplacement of G4 (see sub-section 5.4.4).

5.4.2.2 Fabric development within the north and south of the complex

The north and south of the complex are characterised by relatively weak to moderately developed, inwardly-dipping PFC fabrics (Fig. 5.7). Within the outer periphery of these two zones, a large amount of sheeting and stoping of the surrounding country rock occurs. Both zones are up to 500 m wide, and will be referred to as the "northern and southern zones of sheeting and stoping" (see below).

There is quite a rapid decrease in the amount of country rock xenoliths moving from these zones of "sheeting and stoping" towards the pluton centre. The predominant fabric is an inward-dipping pseudoconcentric PFC fabric (Fig. 5.7). Strain analysis from the measurement of X/Z, and a limited number of Y/Z ratios of microdioritic enclaves indicate that flattening strains are dominant, with enclaves consistently having elongate disc shapes ($0 < K < 1$). Oblate shapes ($K \approx 0$) were not recorded, as seen in the Loch Eigheach region (see sub-section 5.4.2.1) where flattening strains progressively increased towards the pluton margin. This might be because the outer periphery of these regions appears to have been constructed by a completely different process. Instead of an expansion type process right up to the pluton contact, as seen in the Loch Eigheach region (sub-section 5.4.2.1), it appears that in the north and south, during the *in situ* expansion of G2, a localised emplacement phenomenon of sheeting and stoping was also occurring simultaneously. Moving from both zones towards the centre of the complex several changes occur: (i) The PFC fabric progressively changes from being approximately concentric to the pluton margin, to being oblique, forming an apparent continuous sigmoidal fabric trace across the Ericht-Laidon fault zone (see sub-section 5.4.2.5) (Fig. 5.7). (ii) The inclination of the fabric progressively changes from approximately vertical (generally > 80°) at the outer margin of G2, (i.e. within the zones of sheeting and stoping), to much lower values of around 45-40°, which then quite dramatically become much steeper (75-90°) within a zone of approximately 2-4 km wide across the Ericht-Laidon fault. Along this structure the fabric is generally sub-vertical, dipping between 82-90°. (iii) The lack of exposure across the central part of the pluton (as the Ericht-Laidon fault is topographically expressed by the Loch Laidon) limited the number of X/Z ratios of microdioritic enclaves recorded. However, where obtained they showed an apparent decrease in relative strain from the "zones of sheeting and stoping" (X/Z ratios ranging from 2.5-4.0) towards the pluton centre (approximately 2.0-2.5), until about 2-3 km from the Ericht-Laidon fault, where there appeared to be quite a large increase in apparent strain (X/Z ratios from 2.5 to 6.0 and possibly greater). The lack of vertical surfaces throughout this central region prevented any confident evaluation of the types of strain involved. The apparent changes in strain magnitude across this 'north-south transect' is synchronised by changes in fabric intensity, with the most intense fabrics occurring along the Ericht-Laidon fault zone (see sub-section 5.4.2.5).

In the eastern part of the complex, around the vicinity of Meall Liath na Doire Mhòir [NN 488 612] and Sròn Ruighe Clomhaiche [NN 500 592] (Fig. 5.8), G2 contains country rock rafts of psammite, which range from a few metres or so, up to 50 m in length. The PFC fabric within this region is moderately developed, predominantly sub-parallel to the pluton margin (000-020°). The fabric is defined by internally undeformed plagioclase and biotite. A 'second', weakly developed PFC fabric is occasionally observed, often as a bimodal arrangement with the predominant PFC fabric. In Sròn Ruighe Clomhaiche this 'secondary' fabric generally trends ESE-WNW (115-125°), changing towards the north, to NW-SE (135-160°) in the Meall Liath na Doine Mhóir region (Fig. 5.8). This 'secondary' fabric is generally defined by plagioclase laths. A recent detailed study of the angular relationship of such sub-fabrics developed close to the pluton margin has been carried out by McErlean (1992). These features described for the Thorr Granite (Co. Donegal), show similar characteristics to those observed within this region. As mentioned above, the predominant fabric is pseudoconcentric to the pluton contact, and is likely to have formed due to the imposition of pluton-expansion related strains associated with the *in situ* expansion of G2 (see Fig. 5.9). This would have resulted in bulk shortening ("flattening strains") perpendicular to the walls of the pluton, producing the contact parallel PFC fabric. However, the development of a 'secondary' sub-fabric during this pre-full crystallisation deformation, may suggest that this region was subjected to a shear induced component, resulting in a bimodal fabric distribution (see Ch. 1, sub-section 1.7.3; Fernandez *et al.* 1983; Fernandez 1987; Ildefonse 1987; Ildefonse & Fernandez 1988; Fernandez & Laporte 1991).

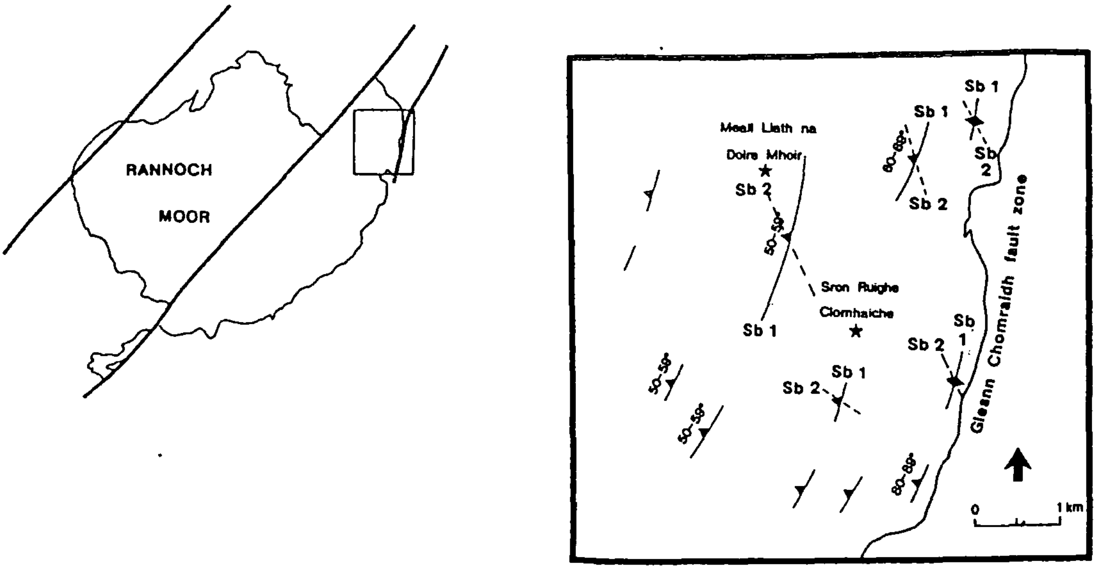


Fig. 5.8. Bimodal PFC fabrics developed within the eastern part of the Rannoch Moor complex, around the vicinity of Meall Liath na Doine Mhóir region [NN 500 592].

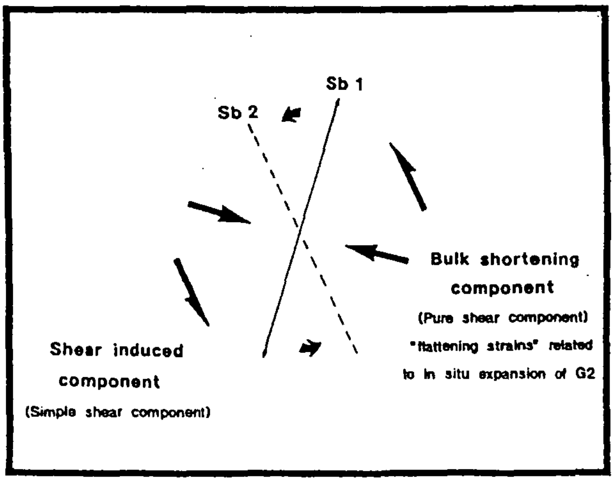


Fig. 5.9. Generalised model explaining the development of the bimodal PFC fabrics within the eastern part of the Rannoch Moor complex.

The angular relationship between the sub-fabrics may suggest a sinistral shear component during their development (Fig. 5.9). The fabric trajectory patterns across the Ericht-Laidon fault, combined with the distribution of strain throughout the complex, and its overall geometrical form, suggests that the complex was subjected to an overall, gross sinistral transpressional component during the construction of G2. It could therefore be envisaged, that as G2 was constructed by a process of *in situ* expansion, which resulted in predominantly flattening strains to be localised at its outer contact (leading to the development of pseudoconcentric fabrics), sinistral transcurrent deformation along the Ericht-Laidon fault zone, and an overall sinistral transpressive deformation being applied to the whole complex, resulted in a sinistral shear component across this region, and the development of the 'secondary' fabric. As deformation continued into the solid state regime, CPS deformation appears to have been focussed into this 'secondary' fabric direction. This is shown microstructurally by the internal ductile deformation of some of the plagioclase crystals, and in particular interstitial quartz which forms lenticular crystals which subtly define the trend of this generally coplanar CPS overprint. This solid state deformation may suggest that movements along the Ericht-Laidon shear zone continued after G2 had fully crystallised within this region.

A sinistral shear component established within this region is consistent with kinematic observations of the synplutonic rotation of regional country rock foliations into parallelism with the pluton margin (see Section 5.6). A number of sinistral, minor ductile shears are also developed within this part of G2, predominantly trending N-S to NE-SW, sub-parallel to the major Ericht-Laidon fault zone, the Gleann Duibhe shear zone and the bounding Gleann Chomraidh fault zone (Fig. 5.10a). These minor ductile shear zones were active during the crystallisation of G2, causing a gross deflection in PFC fabric trend, and sinistral offsets. These sigmoidal deflections generally range from approximately 1-2 m across. One such shear zone, located on the southern slope of Sròn Ruighe Clomhaiche [NN 498 591], is approximately 10 cm wide, 12 m long, and trends 040° clearly deflecting the PFC fabric trend in a sinistral fashion. Outside this zone of deformation the fabric trends 010-020° and is clearly internally undeformed. However, within the centre of the shear zone, a localised zone about 1.5 to 2.0 cm wide shows considerable CPS deformation leading to an annealed texture in areas of high sub-grain density. In thin-section, this deformation is exhibited by distorted feldspar crystals, possessing undulose extinction and deformation lamellae, and highly lenticular quartz crystals which have undergone internal lattice dissolution. Many quartz crystals show considerable recrystallisation and sub-graining. Biotite laths are bent and kinked, and are often wrapped around feldspar phenocrysts. These microstructural features are consistent with CPS deformation occurring at high temperatures. Microstructural features indicative of brittle, lower temperature CPS deformation are absent, indicating that deformation along this structure only continued for a relatively short period after full crystallisation of G2. Deformation along this zone has sinistrally offset a xenolithic block of psammite (Plate 5.6).

Within the vicinity of the last location, a large, approximately 4 m wide, ductile shear zone occurs [NN 499 591] (Fig. 5.10a). This has also had the affect of deflecting the PFC fabric in a sigmoidal fashion indicative of a sinistral component of shear (Fig. 5.10b). Outside this zone of deformation the PFC fabric trends 010-020°, being rotated to approximately 070° at the centre of the shear zone. The PFC fabric swing is continuous and is defined by plagioclase phenocrysts. Its geometry (Fig. 5.10b) may suggest a transpressional component of deformation during PFC fabric development across this zone. However, within this zone of deformation are two bands, approximately 2-4 cm wide, which are parallel to the PFC fabric direction within the wall rocks bounding this shear zone (Fig. 5.10b). Both bands are composed of plagioclase phenocrysts which are aligned parallel to the elongation of the band, and are enclosed by sub-parallel biotite and hornblende crystals. Both sets of fabrics within the shear zone are internally undeformed, and do not appear to cross-cut one another, but "merge" synplutonically where they meet. The geometrical relationship of these two sets of fabrics is unclear, but one possible explanation could be that the set forming the discrete bands could represent some kind of mineralogical banding, resulting in the development of a 'strain-insensitive fabric' (see Ch. 1, sub-section 1.7.2). If this is the case, it could be envisaged that as the zone was being subjected to non-coaxial progressive deformation, early phase phenocrysts, such as plagioclase and biotite outside these bands, were progressively being rotated and aligned towards the wall rocks bounding this zone of deformation; thus resulting in a sigmoidal foliation trajectory pattern typical of strain-sensitive fabrics. This would result in what could be termed as a 'continuous non-coaxial PFC fabric'. However, within the bands in which the phenocrysts are not uniformly distributed, perhaps because of mineralogical banding, the material will deform heterogeneously. As the phenocrysts of one particular 'family' are more highly concentrated, they will show a greater tendency to rotate during non-coaxial progressive deformation than the more sparsely distributed phenocrysts outside these zones. This results in the development of essentially monomineralic fabrics which lie sub-parallel to the shear plane (Fig. 5.10b). These fabrics will be referred to as 'discontinuous non-coaxial PFC fabrics' (see Ch. 1, sub-section 1.7.2).

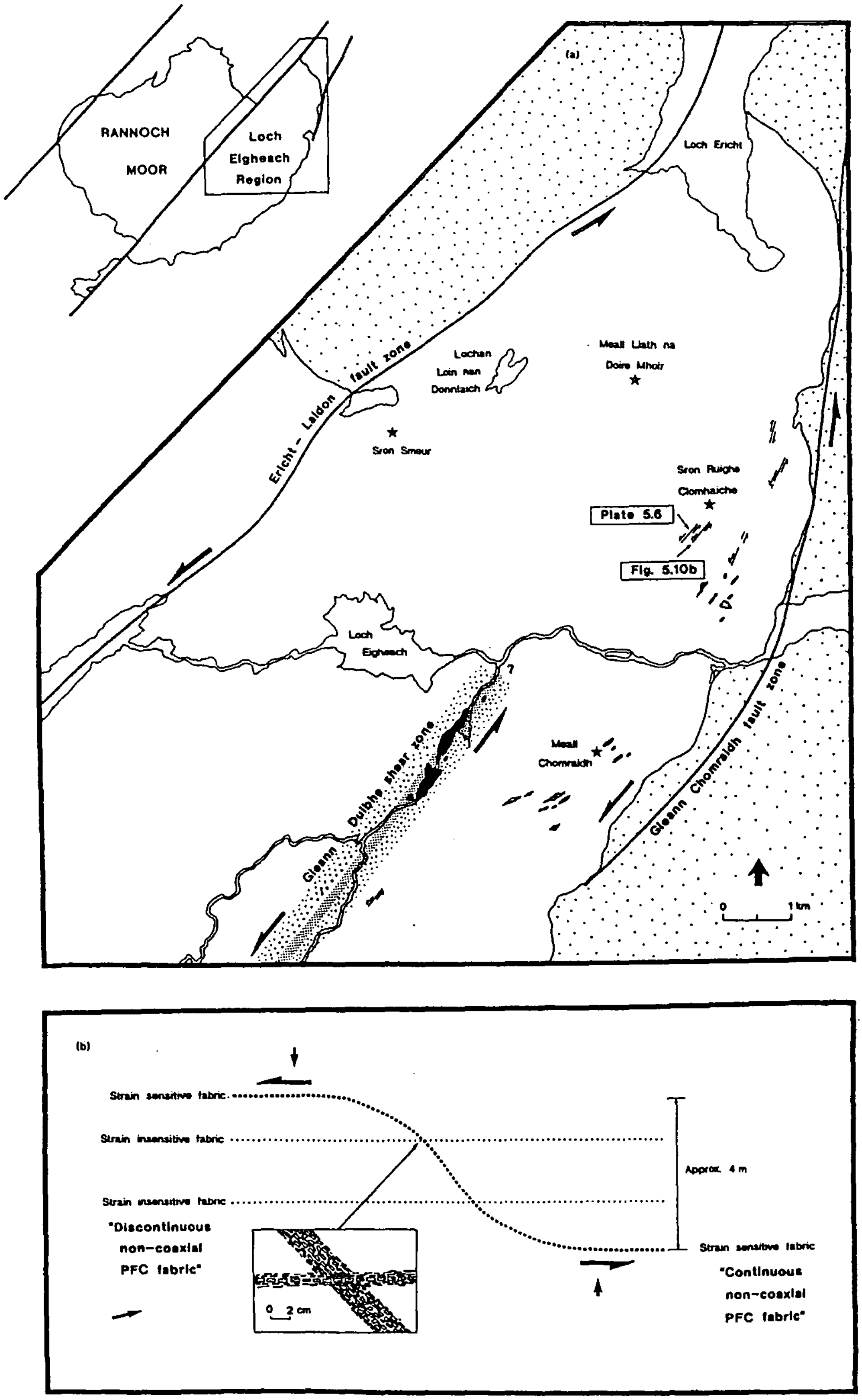


Fig. 5.10. (a) Map showing the traces of the Ericht-Laidon fault zone, the Gleann Duibhe shear zone and the bounding Gleann Chomraidh fault zone, together with the spatial distribution of several minor ductile shear zones, within the eastern part of the complex. (b) Diagrammatic sketch of a NE-SW-trending minor ductile shear zone, possibly showing geometrical relationships typical of both 'strain-sensitive' and 'strain-insensitive' fabrics (see text for explanation).

Plate 5.6. A minor sinistral ductile shear zone within the Meall Liath na Doine Mhóir region, exposed on the southern slope of Sròn Ruighe Clomhaiche [NN 498 591]. The PFC fabric developed within G2 is clearly deflected in a sinistral fashion across the shear zone. The approximate position of the shear plane is indicated by the dotted line. The xenolithic block of psammite has been sinistrally offset by this shear component. (Inclined surface, approximately 20°).

The southern zone of sheeting and stoping:

The southern zone is far more exposed than its corresponding zone in the north, and hence, will be discussed in more detail.

The nature of this southern zone of sheeting and stoping has been previously addressed by Hinxman *et al.* (1923) and France (1971), both commenting upon the intricate intrusive nature of the area and the way in which the foliation of the larger xenolithic rafts can be traced without disturbance into the surrounding country rock. The zone is approximately 400-500 m wide from the "main" pluton contact. In the Guala Moor region (Fig. 5.11), a large percentage of the granitic sheets are sub-parallel to the regional foliation within the *in situ* psammitic screens, trending approximately NE-SW. Within the larger granitic sheets (generally > 0.5 m wide) weak to moderately developed, contact parallel PFC fabrics are developed. As shown by Figure 5.11, the trend of the regional foliation of some of the country rock xenoliths, and the form and orientation of the granitic sheets suggest that both may have been rotated, from a NE-SW orientation into sub-parallelism with the 'main' pluton contact to form sigmoidal geometries. This deformation must have continued after all the phases within many of the granitic sheets had fully crystallised, as the PFC fabric in many cases has been modified by a weakly developed, high to moderate temperature overprinting CPS fabric. This solid state overprint is generally represented by: (a) the deformation of quartz to lenticular forms; and (b) the distortion of biotite laths.

A possible model accounting for the characteristics of this region, and its corresponding zone of sheeting and stoping within the north of the complex is proposed at the end of this Chapter (see Section 5.7).

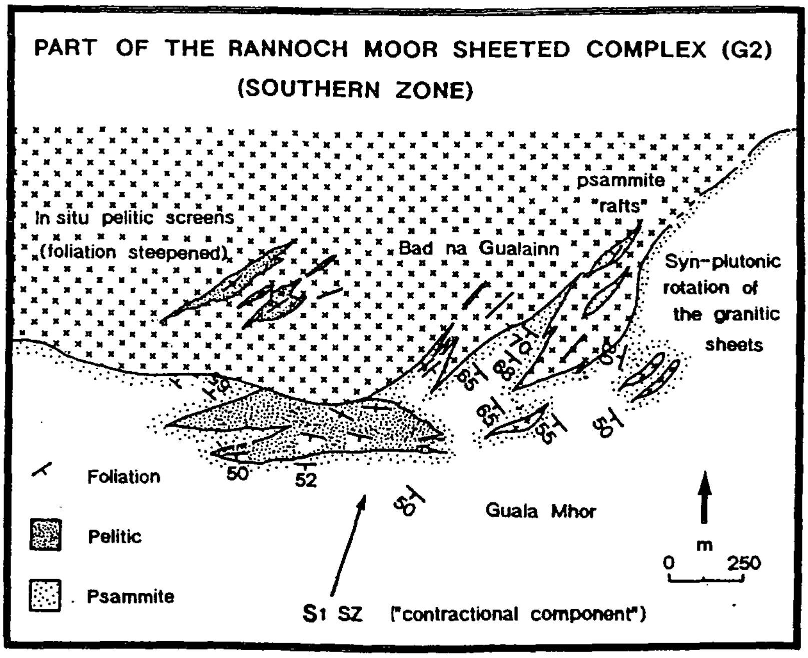


Fig. 5.11. The "southern zone of sheeting and stoping". Modified after France (1971).

The northern zone of sheeting and stoping

Structural characteristics of the northern zone of sheeting and stoping (Leum Uilleim [NN 331 640] and Carn Dearg [NN 420 659] region (see Hinxman *et al.* 1923)) are very similar to those described for the southern zone and so will not be discussed further in this Section. The northern zone will, however, receive further attention in Chapters 10 and 11, when discussing the development of these regions.

5.4.2.3 Fabric development within the western part of the complex (Kingshouse region)

Within the western part of the complex (Kingshouse region; see Fig. 5.7), the fabric trajectory pattern is very similar to that developed within the eastern part of the pluton (Loch Eigheach region). However, there are several fundamental differences: (i) In the west, the concentric fabrics are slightly oblique to the outer contact of G2, whereas in the east they are pseudoconcentric to the pluton margin. The reason for this obliquity is probably because part of the outer contact of G2 within this area has been removed by the emplacement of the Fault Intrusion of the adjacent Glencoe complex (Fig. 5.12). This is demonstrated by restoring the 7-8 km sinistral displacement of the plutons margins along the Ericht-Laidon fault zone (Hinxman *et al.* 1923; see Section 5.1), which shows that the pluton had an original elliptical form. (ii) For the equivalent corresponding zone in the east, fabrics dip from approximately 40 to 49°, whereas, in the west, fabric inclination is much steeper ranging from 62° to approximately vertical even though the 'original' contact probably occurs much further west. (iii) In the east, the fabrics are predominantly moderate to intensely developed PFC fabrics, with only a slight, high temperature, coplanar overprint (see sub-section 5.4.2.1). However, in the west the PFC fabric has been completely overprinted and/or obliterated by an intense solid state deformational overprint. This CPS deformation is microstructurally characterised by plagioclase crystals which have undergone dynamic recrystallisation and dissolution. Strong minerals such as feldspar and hornblende may be fractured, indicating deformation at temperatures of < 450°C (Simpson 1985). The larger plagioclase phenocrysts (5-9 mm long) are generally extensively sericitised, and magmatic features such as oscillatory zoning may have been completely removed in certain areas. Smaller phenocrysts of hornblende and biotite (up to 4 mm in length) often form mafic clusters. These are generally lenticular in form and may have extremely irregular margins. Both mafic minerals may be bent or broken, and often contain opaque minerals and chlorite along their cleavage planes. Interstitial crystals of biotite and hornblende (0.5 to 1.5 mm long) are extensively chloritised and have often been recrystallised to finer-grained elongate aggregates. Biotite may form stringers which wrap themselves around stronger feldspar crystals. Myrmekite is sometimes present (an intimate intergrowth of quartz and plagioclase) concentrated around the periphery of feldspar crystals, and along their twin planes. Quartz possesses strained undulose extinction, and tends to form elongate and flattened crystals or polycrystalline lenses. These microstructural features suggest that G2, within this region, was subjected to a relatively moderate to low temperature deformational event. Towards the centre of the complex this CPS deformational overprint decreases in intensity (Plates 5.7, 5.8 5.9, 5.10, 5.11 & 5.12). In these areas the solid state fabric essentially forms an 'S2' cleavage, obliquely overprinting the pre-existing PFC fabric. The PFC fabric appears to form part of the continuous, sigmoidal fabric trace which extends across the Ericht-Laidon fault zone and into the eastern part of the complex (Fig. 5.7). The obliquity of the CPS fabric to the overall fabric trajectory pattern across the pluton, implies that it is likely to have been developed by a separate, possibly unrelated deformational event (see below).

X/Z ratios of microdioritic enclaves (from horizontal surfaces) indicate an apparent increase in strain magnitude towards the outer contact of G2. X/Z values range from 2.5 to 6.3 (Fig. 5.12), coeval with an increase in dip and intensity of the CPS fabric. The X axis of the enclaves are generally sub-parallel to the concentric fabric. Y/Z ratios, where obtained, enabled an estimation of the mean shape of these enclaves, which indicates they are consistently elongate disc shaped ($0 < K < 1$) ("flattening-type strains").

An attractive explanation to account for these observed features within the western part of the complex, would be that they were formed as a consequence of the somewhat later emplacement of G5a at the centre of the complex (Fig. 5.12), after G2 had completely crystallised and cooled to some degree. Microstructural analysis of G5a (see sub-section 5.4.5) suggests that it was emplaced by a process of *in situ* expansion predominantly into this direction. This presumably could have produced the necessary expansion-related strains to cause the CPS deformation seen within the Kingshouse region. There are however, several problems with this assumption:

① The maximum expansion direction of G5a at the centre of the complex, appears to have been predominantly into an E-W direction (see sub-section 5.4.5). This would imply that expansion-related strains would have been focused into the western (Kingshouse region) and eastern (Loch Eigheach region) parts of the complex, resulting in low temperature CPS fabrics in both regions. However, in the east, PFC fabrics are only overprinted by a weakly developed, high temperature solid state overprint probably related to the continued, *in situ* expansion of G2, causing a slight CPS deformational overprint in the somewhat earlier, crystallised parts of G2 (see sub-section 5.4.2.1).

② The moderate to low temperature CPS within the Kingshouse region increases progressively towards the outer contact of G2. This appears to be opposite to what would be expected, as the highest solid state fabrics should occur adjacent to the G5a contact, and the deformational overprint should decrease moving further away from the influence of strains associated with the expansion of this intrusive phase (G5a).

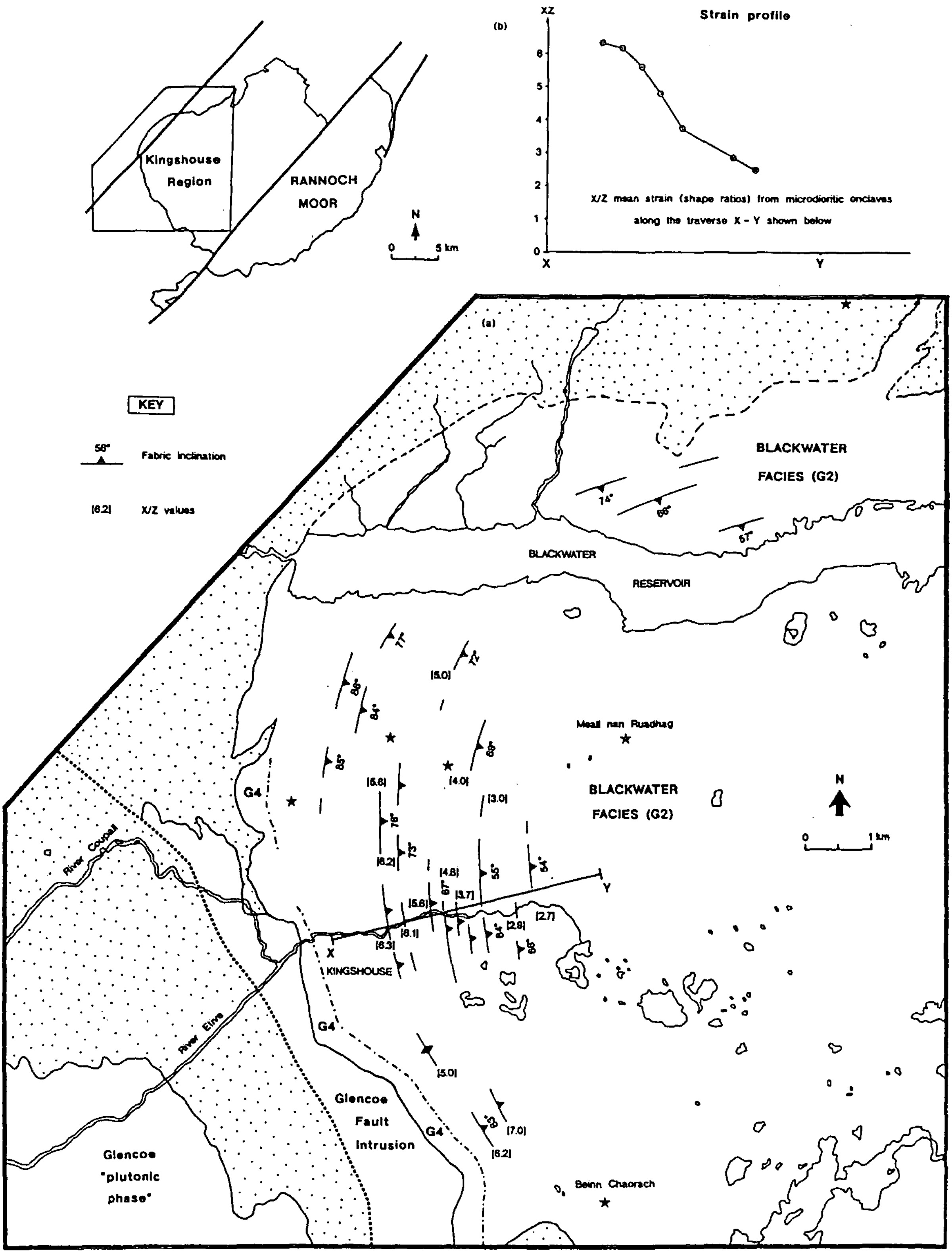


Fig. 5.12. (a) Sketch map showing fabric trajectory pattern and strain distribution within G2 throughout the Kingshouse region. (b) Strain profile along the line X-Y.

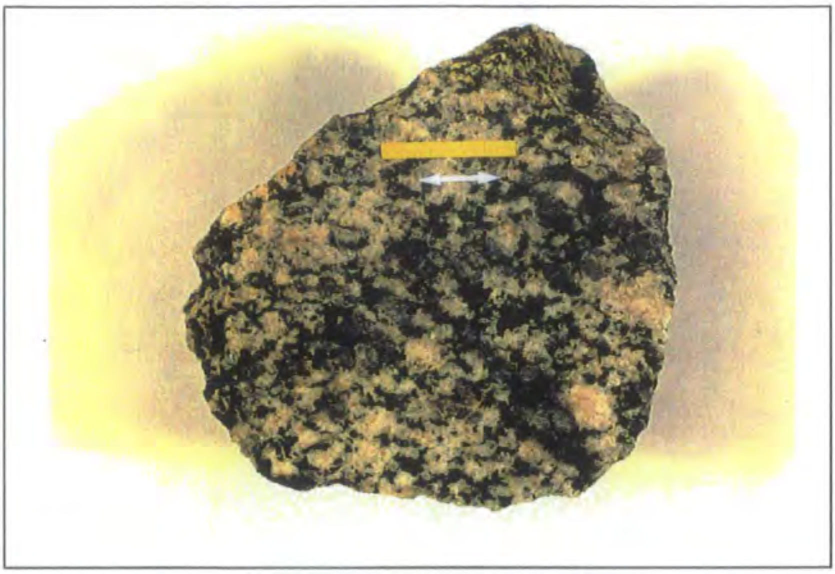


Plate 5.7. Hand-specimen of leucocratic, mafic-poor, quartz-monzodioritic phase (G2; see sub-section 5.2.2) from the White Corries area [NN 270 527] in the Kingshouse region (see Fig. 5.12 for location). It possesses a moderately developed, medium to low tempeature CPS fabric. White arrow shows fabric trend. (Yellow 'bar' is approximately 2 cm long).

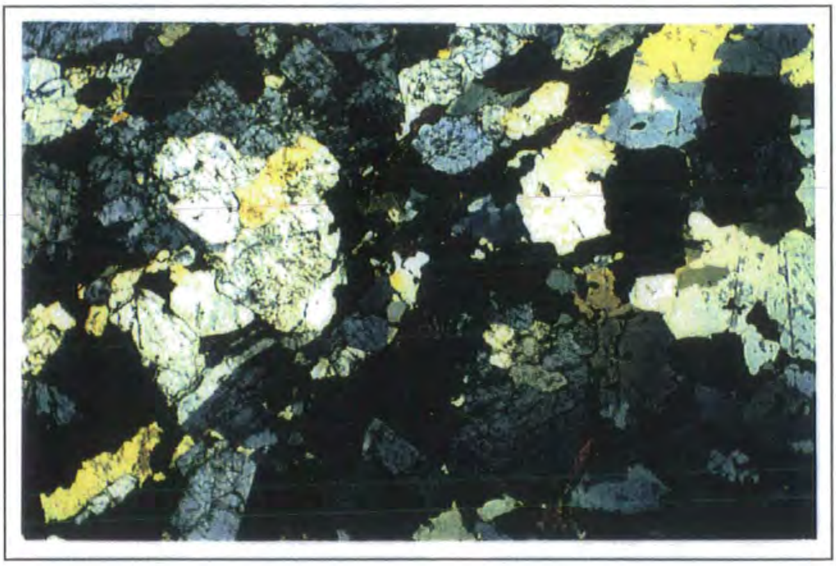


Plate 5.8. Photomicrograph of hand-specimen shown in Plate 5.7. Note how biotites may form stringers which wrap around feldspar crystals. (Field of view approximately 18 mm).

Plate 5.9. Hand-specimen of of granodioritic phase (G2; see sub-section 5.2.2) from the Kingshouse region [NN 260 548] (see Fig. 5.12 for location). It has a moderately developed, moderate to low temperature CPS fabric. White arrow shows fabric trend. (Yellow 'bar' is approximately 2 cm long).

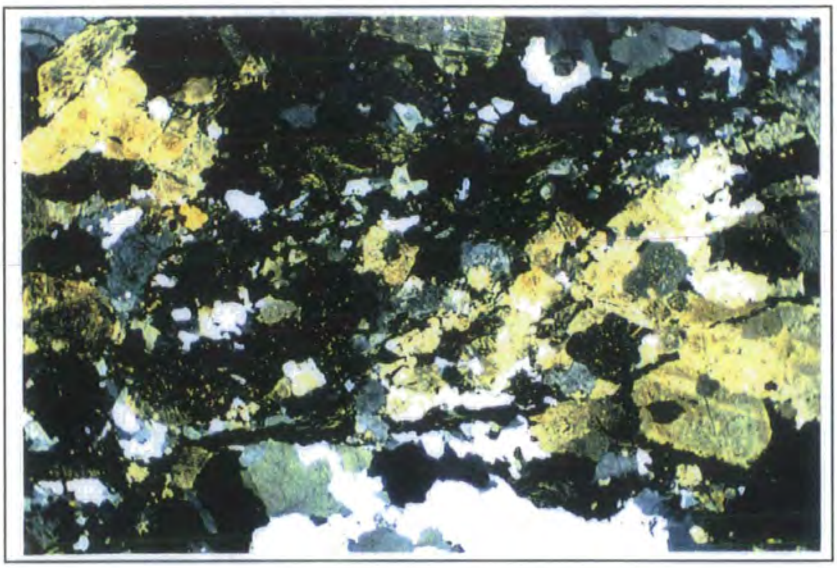


Plate 5.10. Photomicrograph of hand-specimen shown in Plate 5.9. Note the general recrystallisation to finer-grained elongate aggregates. (Field of view approximately 18 mm).

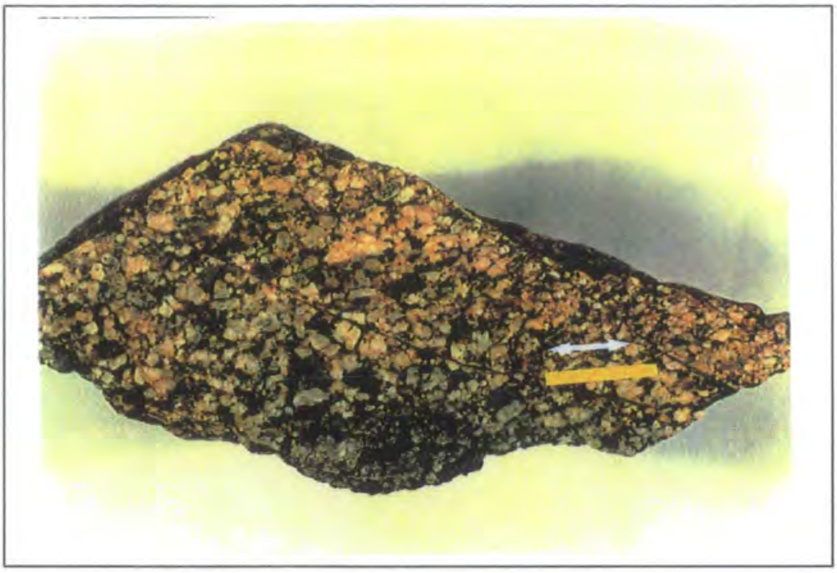


Plate 5.11. Hand-specimen of granodioritic phase (G2; see sub-section 5.2.2) from the Kingshouse region [NN 273 550] (see Fig. 5.12 for location). It possesses a weak to moderately developed moderate to low temperature solid state overprint. The fabric trend is shown by the white arrow. (Yellow 'bar' is approximately 2 cm long).

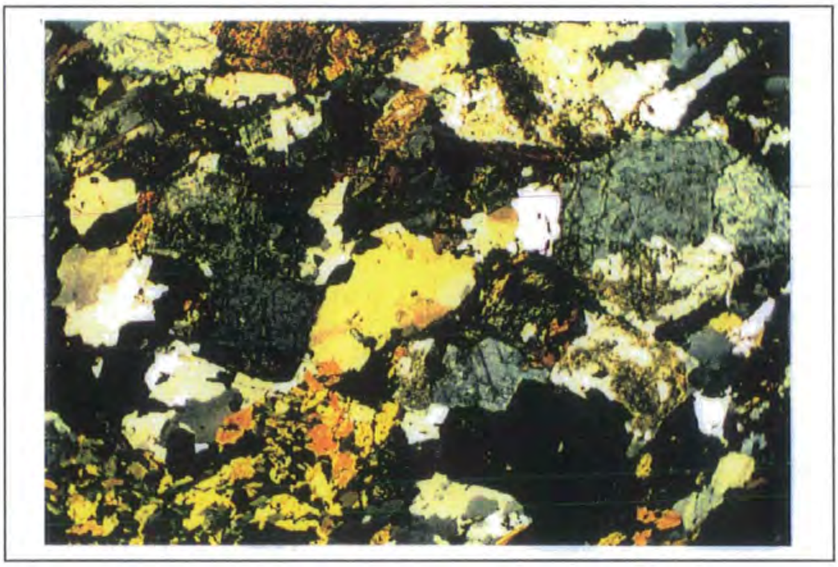


Plate 5.12. Photomicrograph of hand-specimen shown in Plate 5.11. Note the elongate form of some of the crystals. (Field of view is approximately 18 mm).

③ The Ciaran/Chomraidh marginal facies (G4) has intruded as a sheet-like body along the contact developed between the Glencoe Fault Intrusion and Rannoch G2. The "marginal phase" (G4) possesses weak to moderately developed PFC fabrics (see sub-section 5.4.4) which have not been overprinted by any significant amount of CPS deformation. The contrast in fabric types and intensity between G4 and G2, also suggests that the emplacement of G5a is unlikely to have been responsible for the development of such high magnitudes of deformation within the western part of G2.

An alternative model is that the emplacement of G4 as a marginal facies within this area (Fig. 5.12) was responsible for the moderate to low temperature deformational overprint within the Kingshouse region. Although the emplacement of G4 may have resulted in the localised development of low temperature CPS fabrics within G2 along its contacts, it is unlikely to have been responsible for the development of the solid state overprint developed throughout the Kingshouse region.

The main reason for this is because G4 also occurs within the eastern part of the complex (Loch Eigheach region), as a marginal facies emplaced along the Gleann Chomraidh fault (see Fig. 5.6). Its form and microstructural characteristics are very similar to those exhibited by the sheet-like bodies of G4 within the NW of the pluton, however, it occurs within a region which has not undergone such a pervasive low temperature deformational overprint.

An alternative, and more attractive explanation is as follows:

❶ *In situ* expansion of G2, predominantly E-W into the Loch Eigheach and Kingshouse regions respectively, produced moderate to intensely developed, inward-dipping pseudoconcentric PFC fabrics within the outer parts of G2. These are still preserved in the eastern part of the complex (Loch Eigheach region).

❷ After full crystallisation of G2, and significant cooling, the western margin of the complex (Kingshouse region) was cross-cut and removed by the intrusion of the adjacent Glencoe complex. It is envisaged that during the initial stages of the construction of the Glencoe plutonic phase, expansion-related strains (see Ch. 4) deformed the roof zone, leading to the development of peripheral ring faults which interacted with the Earth's surface (see Ch.'s 7 & 11). As the Glencoe pluton expanded, the resultant crustal block (containing part of the western margin of Rannoch G2) was moved upwards towards the free surface, accommodated along the volcanotectonic faults developed. Expansion-related strains produced during the construction of the Glencoe complex, were focussed and accommodated on the north-eastern side of the complex within the adjacent Kingshouse region, i.e. Rannoch G2. This resulted in the PFC fabrics developed within Rannoch G2 being steepened and superimposed by a moderate to low temperature, CPS deformation.

❸ During an episode(s) of little or no magma input into the Glencoe pluton, 'expansion-related strains' were exceeded by the lithostatic pressure of the crustal block, allowing the block to descend. This probably led to the Glencoe cauldron subsidence, and the emplacement of the Fault Intrusion ('ring dyke') along parts of the peripheral ring-fault structure (Fig. 5.12; see Ch. 7), between the Glencoe plutonic mass and Rannoch G2. Blocks of Rannoch Moor which exhibit a low temperature CPS fabric are seen as xenoliths within the main phase of the Glencoe Fault Intrusion ('ring intrusion'), which exhibits a pre-full crystallisation fabric of its own (Plate 5.13). As shown by Plate 5.13, the pre-existing low temperature CPS fabric developed within G2 has been clearly 'modified', particularly along the margins of the blocks, probably during their encorporation as xenoliths into the Fault Intrusion. This indicates that the moderate to low temperature CPS fabric developed within G2 is probably related to a slightly earlier deformational event. As proposed above, this may have been caused by strains related to the construction of the Glencoe plutonic phase.

❹ The Ciaran/Chomraidh marginal facies (G4) was then intruded as a sheet-like body between the Glencoe Fault Intrusion and the Blackwater facies (Rannoch G2) (Fig. 5.12).

Plate 5.13. Xenolithic blocks of Rannoch Moor G2 incorporated within the main phase of the Glencoe Fault Intrusion. Note the modification of the low temperature CPS fabric developed within G2 along the margins of the blocks. (Horizontal surface).

5.4.2.4 Fabric development within the Loch Tulla region

To the SW of the 'main' plutonic body, west of Loch Tulla, an isolated mass (6-8 km^2) of the Blackwater facies (G2) occurs (referred to as the 'Loch Tulla mass'; Fig. 13a). It may represent a 'relict' part of the western margin of G2, which was not removed by the emplacement of the Glencoe complex. It was separated from the 'main' mass by a sinistral offset across the Ericht-Laidon fault zone, displacing the pluton margin by some 7-8 km (Fig. 5.2; Hinxman *et al.* 1923).

Within the central parts of the Loch Tulla mass, PFC fabrics are preserved trending NE-SW (generally 030°), sub-parallel to the Ericht-Laidon fault zone (Fig. 5.13a). Along the Allt Toaig river section (Fig. 5.13a), moving from the central part of the mass towards its north-western margin, are many synplutonic sheets (generally < 1 m wide) of G2 and appinitic/dioritic material trending NE-SW. At the outer margin, G2 extensively sheets the country rocks. All the sheets possess contact parallel PFC fabrics (Plate 5.14).

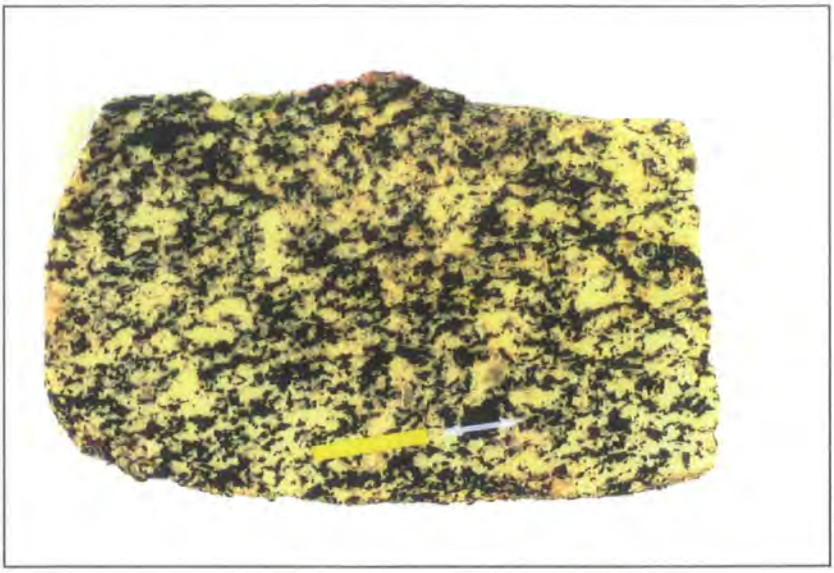


Plate 5.14. Hand-specimen of G2 from the centre of the Loch Tulla mass. Possesses a moderately developed PFC fabric. Trend of fabric is shown by white arrow. (Yellow 'bar' is approximately 2 cm long).

In parts of the main body, where G2 is more homogeneous, X/Z ratios of microdioritic enclaves give apparent values ranging from 3.29 to 3.61 (see Fig. 5.13a). In most areas the PFC fabric has been overprinted by a weak to moderately developed, solid state overprint. Whether this was produced by high temperature CPS deformation related to movements along the Ericht-Laidon fault zone, followed by a relatively lower temperature event, either by (a) later deformation along the fault zone, or (b) strains associated with the expansion of the adjacent Glencoe complex, is unclear.

Approximately 500 m from the Ericht-Laidon fault zone, within the Abhainn Shira stream section [265 424], G2 possesses an intense CPS fabric which trends NW-SE (approximately 127°) (Fig. 5.13a). Microstructurally, feldspar phenocrysts have undergone marginal sub-graining leading to an annealed texture, and recrystallisation processes have generally removed magmatic state features such as zoning. Many of these feldspar crystals, together with biotite, show evidence of internal ductile deformation. Quartz is generally highly strained, possessing undulose extinction, and forms lenticular crystals. These microstructural features may suggest that G2 was subjected to a relatively high temperature CPS deformation (Plate 5.15).

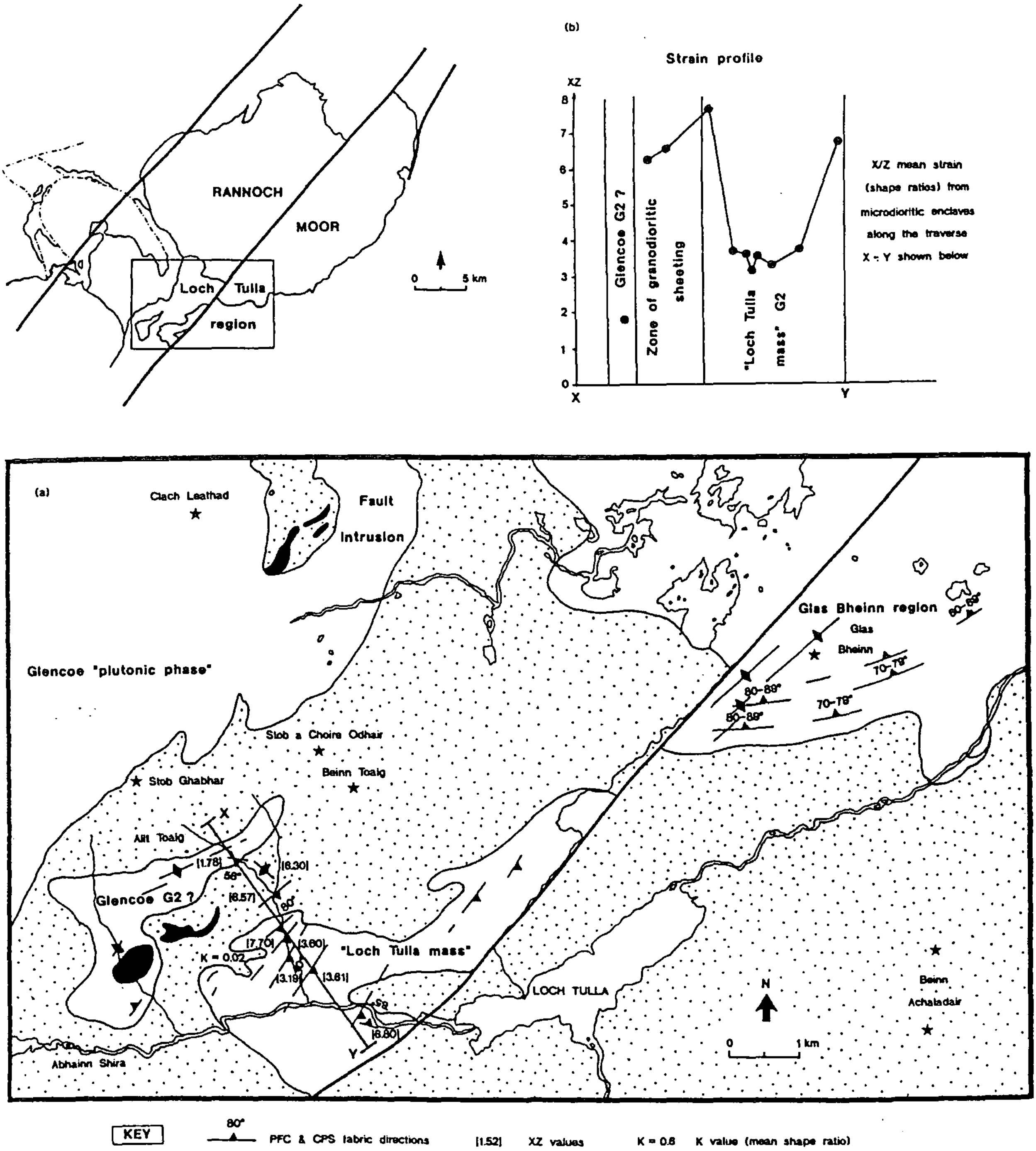


Fig. 5.13. **(a)** Fabric orientation and strain distribution throughout the Tulla mass, and within the Glas Bheinn area. **(b)** Strain profile along the Allt Toaig river section.

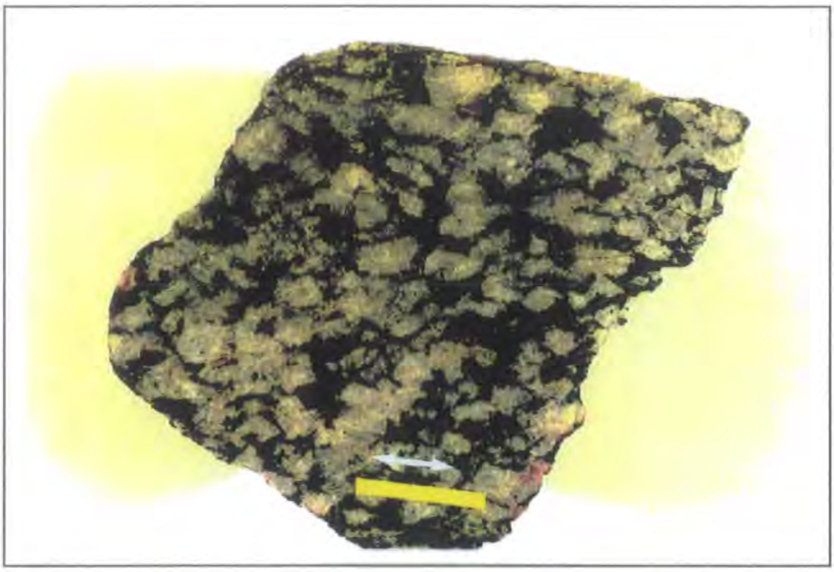


Plate 5.15. Hand-specimen of G2, approximately 500 m from the Ericht-Laidon fault zone, from the Abhainn Shira stream section [NN 265 424] ('Loch Tulla mass'). It possesses a relatively high temperature CPS overprint, giving it an annealed texture. The trend of the fabric is shown by the white arrow. (Yellow 'bar' is approximately 2 cm long).

The measurement of microdioritic enclaves within the Abhainn Shira stream section [NN 265 424], give an apparent X/Z ratio of 6.8, which is much higher than those recorded within the central parts of the Loch Tulla mass (see Fig. 5.13a & b). The presence of broken feldspar and hornblende crystals may suggest that G2 was also subjected to a significant amount of low temperature solid state deformation. It is possible that both phases of solid state deformation are associated with movements along the Ericht-Laidon fault zone. The higher temperature CPS fabric may have been produced by continued deformation along the structure, for a short period after full crystallisation of G2, and the lower temperature fabrics may have been produced during a much later deformational event along the fault zone, possibly related to the displacement of the pluton margins by some 7-8 km.

Near Mon [NN 264 416] (Fig. 5.13a), late stage, brittle deformation along the fault zone is clearly evident, and may be associated with the latter deformational event mentioned above. G2 is extremely red, highly brecciated/cataclastic, and is cross-cut by a network of quartz veins. The veins trend in two predominant directions, approximately

110° and 170°. A similar distribution of quartz veins is seen in the Glas Bheinn area [NN 327 473] (Fig. 5.13a), within the 'main' part of the pluton (Plate 5.16). This area would have presumably been the south-eastward continuation of the 'Loch Tulla mass' before the 7-8 km sinistral displacement along the Ericht-Laidon fault zone. Fabrics within the Glas Bheinn area appear to have been also overprinted by a low temperature solid state deformation, probably associated with late, brittle displacement along the Ericht-Laidon fault zone. A pervasive contact parallel PFC fabric is overprinted by CPS deformation, which is often expressed as a "second cleavage" (S_2) orientated NE-SW, sub-parallel to the Ericht-Laidon fault zone. In many places, country rock xenoliths have been deformed by these deformational events, often elongated parallel to the fabric developed within G2 (Plate 5.17).

Plate 5.16. Late stage, brittle deformation probably associated with the reactivation of the Ericht-Laidon fault zone. The photograph shows a network of quartz veins associated with this deformation in the Glas Bheinn area [NN 327 473]. Similar features occur near Mon [NN 264 416] where the isolated 'Loch Tulla mass' is bounded to the south by the Ericht-Laidon fault.

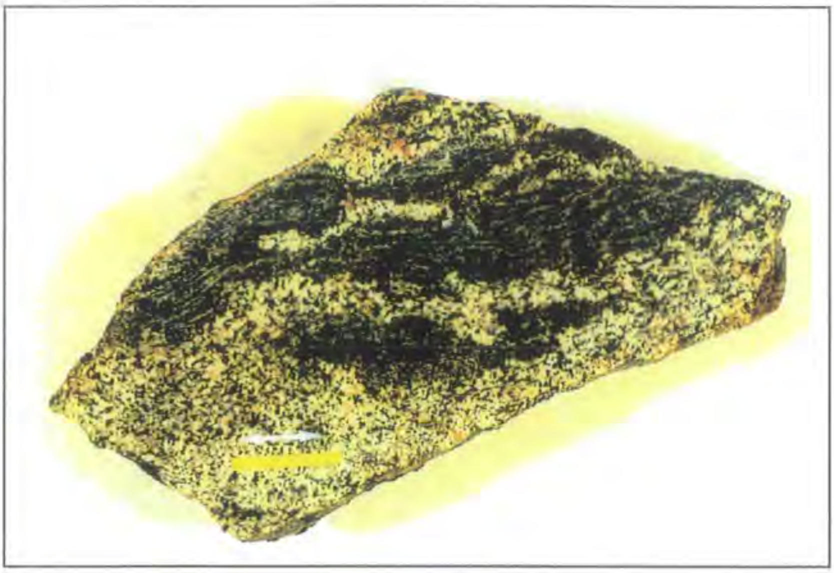


Plate 5.17. Hand-specimen of G2 from the Glas Bheinn area [NN 328 473]. G2 contains many deformed country rock xenoliths which are generally aligned parallel to the fabric developed in G2. (Yellow 'bar' is approximately 2 cm long).

Continuing along the Allt Toaig river section towards the north-western margin of the Loch Tulla mass (Fig. 5.13a), there is an apparent dramatic increase in strain approximately 100-150 m from the country rock contact. This is based on measured X/Z ratios (horizontal surfaces) of microdioritic enclaves. As mentioned above, X/Z ratios ranging from 3.29 to 3.61 have been recorded within the central parts of the main body. However, this changes dramatically from an apparent value of 3.60 to 7.70 in a distance of only about 25 m (Fig. 5.13a & b). From this point, moving towards the pluton margin (NW), X/Z ratios recorded have been 6.57 and 6.30 (Fig. 5.13a & b). A moderate number (48) of Y/Z ratios were also recorded for one of these populations, giving an apparent Y/Z ratio of 5.67. A K-value of 0.018 was determined, which implies that the enclaves are almost perfect uniaxial oblate (pancake) type ($X = Y > Z$) shapes, with K values close to zero ($K \approx 0$). Such "flattening strains " have also been recorded in the outer most parts of G2 in the Kingsglass region (see sub-section 5.4.2.3), which were attributed to strains imposed by the *in situ* expansion of the adjacent Glencoe complex. A similar situation may have also occurred within the north-western parts of the Loch Tulla mass, resulting in high flattening strains and the development of fabrics trending NE-SW approximately sub-parallel to the 'main' plutonic contact of the Glencoe complex (see Fig. 5.13a). The fabrics also appear to have been developed by low temperature CPS deformation (Plates 5.18 &

5.19), characterised by the same microstructural features observed within the Kingsglass region (see sub-section 5.4.2.3). However, unlike the Kingsglass region, many NW-SE-trending, vertical appinitic/dioritic and granodioritic sheets (generally < 1.0 m) cross-cut the Blackwater facies (G2) and the surrounding country rocks. Throughout the compositionally diverse range of sheets, contact parallel PFC fabrics are intensely developed. The sheets can be traced north-westwards throughout the country rocks to an isolated, irregular shaped body (approximately 3 km^2) of what appears to be Glencoe G2 (Clach Leathad facies) (Fig. 5.13a; see Ch. 4). The fabrics developed within this body appear to be relatively high temperature CPS fabrics, with evidence of a lower temperature deformational event (Plate 5.20).

Plate 5.18. Hand-specimen of Rannoch G2 from the north-western part of the 'Loch Tulla mass' [NN 253 437]. It possesses a low temperature CPS fabric. Note the great reduction in grain-size by this deformation, compared to G2 from the centre of the "mass" (Plate 5.14). (Yellow 'bar' is approximately 2 cm long).

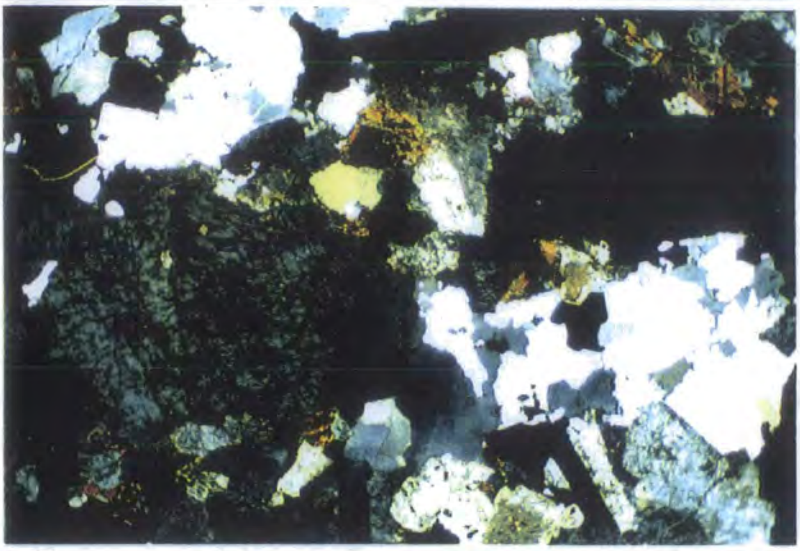


Plate 5.19. Photomicrograph of the hand-specimen shown in Plate 5.18. Many crystals have undergone recrystallisation and dissolution. (Field of view approximately 18 mm).

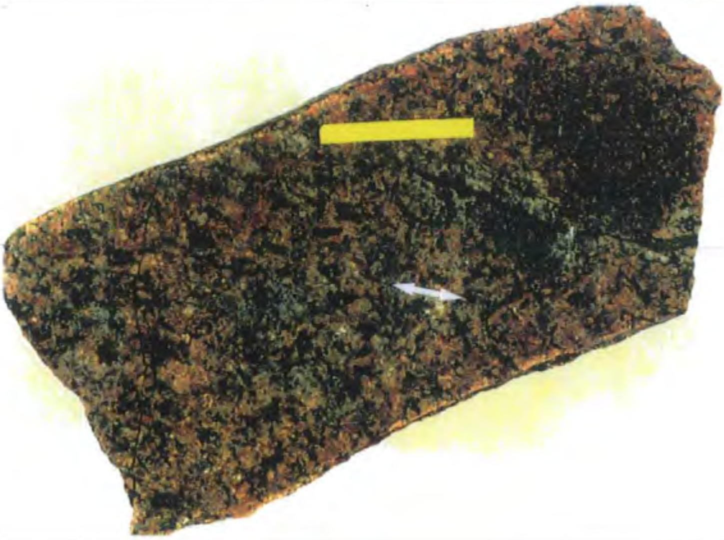


Plate 5.20. Hand-specimen of possibly Glencoe G2 from an isolated body sited between the Loch Tulla mass and the 'main body' of the Glencoe plutonic complex. It shows great simularities to the high temperature CPS fabrics developed within the Glencoe 'Lairig Gartain pulse' (see Ch. 3). (Yellow 'bar' is approximately 2 cm long).

5.4.2.5 Fabric development within the centre of the complex: along the Ericht-Laidon fault zone

As described above (see sub-section 5.4.2.2), the pseudoconcentric PFC fabric developed within the outer periphery of G2 appears to become progressively more oblique towards the centre of the complex, forming a sigmoidal fabric trajectory pattern across the Ericht-Laidon fault zone (Fig. 5.7 & 5.8). This together with information obtained from fabric and strain analysis throughout the western part of G2 implies that this structure was a major active sinistral shear zone during the construction of the Blackwater facies (G2). Continued deformation along this structure (for a short period) after full crystallisation of G2, and/or a later reactivation along this fault zone, resulted in the development of a localised zone of NE-SW-trending, weak to moderately developed CPS fabrics along this structure.

Other structures spatially associated with the Rannoch Moor complex are the Etive-Laggan, and Gleann Chomraidh faults, which partially bound the pluton in the NW and SE, respectively (Fig. 5.10). Data presented above (see also sub-section 5.4.4, "G4 emplacement") may suggest that these structures were acting as major Caledonian NE-SW-trending shear zones during the construction of the Rannoch Moor complex (and during other magmatic events associated with the emplacement of the Etive (Ch. 3), Glencoe (Ch. 4), and Strath Ossian (Ch. 6) plutons.

A simple model to account for the general distribution of fabric types, strain, and trajectories produced during the construction of G2 could be:

➊ The bisecting Ericht-Laidon fault, and the partially bounding Etive-Laggan and Gleann Chomraidh structures, were active NE-SW-trending shear zones during the *in situ* expansion of G2.

➋ Sinistral ductile deformation along these structures may have allowed magma to expand predominantly into the direction of maximum extension imposed by these controlling structures. The maximum expansion direction would have been orientated approximately E-W. This may have produced a 'primary' mineral stretching lineation, preserved within the Loch Eigheach region.

➌ As expansion and rotation of G2 continued, early pre-full crystallisation fabrics within the 'extension direction' were progressively modified, resulting in the development of a gross, sinistral sigmoidal swing across the Ericht-Laidon shear zone, and the development of intense, pseudoconcentric PFC fabrics showing high "flattening strains" within the NW (Kingshouse region) and SE (Loch Eigheach region) of the complex (the directions of maximum expansion). This resulted in the development of a sub-horizontal mineral stretching lineation. As deformation continued into the solid state regime, the fabrics were further modified and overprinted by crystal plastic strain.

④ Simultaneous sheeting and stoping along the pluton contact (in the north and south of the complex) occurs where magma was emplaced into a localised transtensional environment created within the zone of maximum shortening (constriction) of the overall system (see Ch. 10 for explanation).

5.4.3 G3: The Rannoch Moor Microgranites

G3 occurs as an extensive series of sheets and dykes, predominantly in two main areas (see sub-section 5.2.3): (i) within the SW of the complex, possibly sited along the Gleann Duibhe fault; and (ii) close to the centre of the complex along the Ericht-Laidon fault zone. In both cases, G3 has been cross-cut and disrupted by the emplacement of G5a (at the centre of the complex), and G5b (a smaller mass in the SW) (see Fig. 5.3). Solid state deformation within the syenogranites and monzogranites of G3 distinguish them from the mineralogically similar sheets and dykes of G5, which generally possess PFC fabrics (see sub-section 5.4.5). The CPS deformation within G3 is low to moderately developed and is characterised by the ductile deformation of quartz, leading to lenticular crystals, and the bending and kinking of biotite laths. The intensity of the solid state deformation tends to increase towards the main occurrences of G5. This may imply that the deformation was induced predominantly by the emplacement of G5 (see sub-section 5.4.5), after all the phases within G3 had fully crystallised.

5.4.4 G4: The Ciaran / Chomraidh marginal facies

As mentioned in sub-section 5.2.4, G4 occurs as a sheet-like body in two main regions (Fig. 5.3): (i) within the south-eastern part of the complex, between the contact of G2 and the bounding NE-SW-trending Gleann Chomraidh fault; and (ii) along the contact between the Glencoe Fault Intrusion and G2 (i.e. the Blackwater facies). Within these areas G4 generally contains a vertical, moderate to intensely developed, contact parallel (or sub-parallel) PFC fabric. The fabric is generally defined by the preferred dimensional orientation of plagioclase, K-feldspar, and biotite microphenocrysts (Plates 5.21 & 5.22).

The K-feldspar and plagioclase megacrysts (1-3 cm in length) are generally more randomly aligned.

Plate 5.21. Hand-specimen of G4 from the "marginal facies" intruded between G2 and the Glencoe Fault Intrusion [NN 263 521]. It possesses a moderately developed PFC fabric. White arrow shows fabric direction. (Yellow 'bar' is approximately 2 cm long).

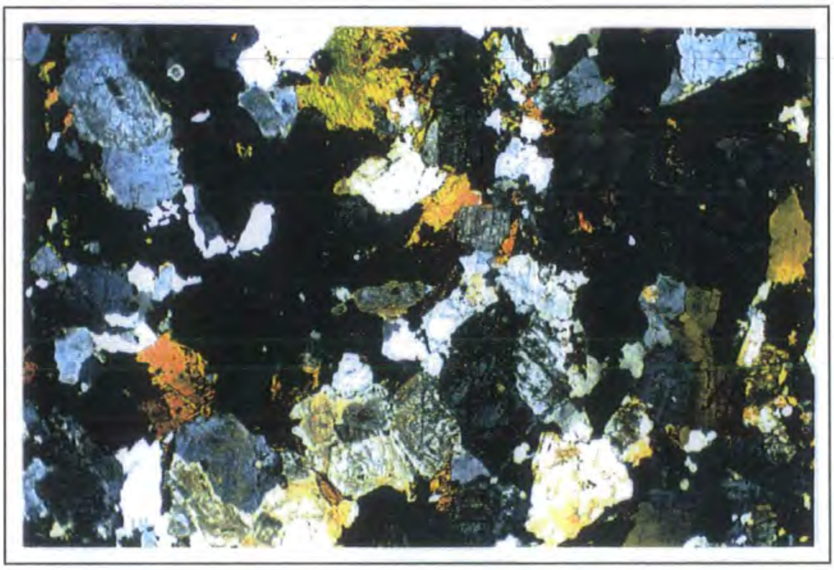


Plate 5.22. Photomicrograph of hand-specimen shown in Plate 5.21. (Field of view approximately 18 mm).

However, particularly within the central parts of these sheet-like bodies, these K-feldspar and plagioclase megacrysts may have a preferred dimensional orientation, forming a weakly developed fabric oblique to the walls of the intrusion. Both fabrics occur together in a bimodal arrangement, set in a relatively undeformed groundmass of quartz, biotite and subsidiary hornblende. The angular relationship between these sub-fabrics appears to infer a dextral sense of shear during their development, assuming that the K-feldspar and plagioclase megacrysts which have small aspect ratios would have rotated faster than the microphenocrysts of plagioclase, K-feldspar and mica which clearly have much larger aspect ratios (see Fernandez & Laporte 1991; Ch. 1, sub-section 1.7.3). However, this simple solution implying a dextral shear component during the emplacement and deformation of G4 as it crystallised, does not explain, and is not consistent with: (i) a sinistral sense of shear deduced from a number of different kinematic indicators such as the tiling of early formed phenocrysts, the sinistral deflection of the PFC fabric across psammitic 'rafts' encorporated within G4 (see below), the obliquity of PFC fabrics at the wall rock contact, and melt-filled shears, porphyroblasts, etc. developed within the adjacent country wall rocks; and (ii) the large angle of obliquity between the two sub-fabrics (generally from 50° up to 70°; Fig. 5.14a). One possible solution to account for the angular relationship between the two sub-fabrics, if formed during non-coaxial deformation with an overall component of sinistral shear, could be explained by the axial ratios of the K-feldspar and plagioclase megacrysts being around 2.5. The two-dimensional experiments by Ildefonse and Fernandez (1988) suggest that for particles with such axial ratio values, they may have undergone reverse rotation, giving the apparent affect that the particles with higher axial ratios have rotated more and faster (see Ch. 1, sub-section 1.7.3). However, these experiments show that such a phenomena will only occur at large shear strains of between 6 and 9. With geologically reasonable shear strains of $2 < \gamma < 5$ (Nicolas 1992), and X/Z ratios of microdioritic enclaves within G4 yielding values of between 3.4 to 3.7, up to a maximum of 5.9 (see Fig. 5.14), such a solution is extremely unlikely. A more feasible model might be that the "oblique fabric" represents a kind of tiling or imbrication fabric (Den Tex 1969; Blumenfeld 1983; Ch. 1, sub-section 1.7.3), developed due to the interaction of rotating crystals, causing them to pile up during non-coaxial deformation. This tiling effect essentially slows down their rotation and thus, keeps the crystals at an angle to the shear plane for a longer period of time. During crystallisation, the crystal content will progressively increase and the crystals forming the 'tiling fabric' may essentially 'lock-up', whereas phenocryst phases outside these discrete zones may be able to rotate more freely, tracking the finite strain ellipsoid, towards the shear direction (shear plane); thus, increasing the angle between the two sub-fabrics. As mentioned above, the 'oblique fabric' is generally defined by the K-feldspar and plagioclase megacrysts. This might be because this phase has crystallised late into the system, and continued to grow *in* *situ* during the development of the fabrics, causing some of these megacrysts to be 'locked' into or against the 'tiling zones' (forming the 'oblique fabric'), whereas the megacrysts outside these zones are not in the system long enough to be rotated towards the shear plane (to form the 'contact parallel PFC fabric'), and/or the degree of crystallisation at this stage causes the system to be 'choked' with crystals, preventing their rotation.

On the south-western slopes of the Beinn a' Chrùlaiste, near to the trace of the Etive-Laggan shear zone/fault [NN 241 560], the PFC fabric in G4 has been weakly overprinted by a high temperature CPS deformation. This has led to some recrystallisation, the elongation of interstitial crystals, and the kinking of biotite laths (Plates 5.23 & 5.24). These features may suggest that deformation along the Ericht-Laidon shear zone/fault continued for a short period after G4 had fully crystallised.

In the extreme NW of the complex, exposed within the Ciaran Water section (Fig. 5.14b), G4 occurs as two separate sheet-like bodies: (i) as the 'typical' marginal phase; and (ii) along the Ciaran-Ossian fault zone (see Ch. 6). Their actual width is uncertain, but in general they appear to be approximately 200-350 m wide. They are separated from each other by an intervening belt of granodioritic material (G2: the Blackwater facies). Moving from north to south along the Ciaran Water section (Fig. 5.14b), the following microstructural features have been observed:

① The G4 "marginal facies" (up to 350 m wide) possesses an intensely developed solid state deformational fabric which trends around 072°-078°, sub-parallel to the trend of the NE-SW-trending Etive-Laggan and Ciaran-Ossian fault zones. The fabric is defined by extremely lenticular and flattened quartz crystals, and highly elongate biotite laths, which are often bent and kinked around resistant plagioclase crystals.

The marginal facies can be traced from Allt an Ruadha Dheirg [NN 281 627] to Leac nan Carn [NN 308 625]. In certain areas between these two localities, particularly within the west, the PFC fabric is only slightly overprinted by solid state deformation. The fabric is generally vertical, and trends 040° to 080°, sub-parallel to its contacts and thus, the outer contact of G2. Within this region the foliation within the surrounding country wall rocks has been syn-plutonically rotated into parallelism with the pluton margin, and the intense fabric developed within G4. Whether this deformation within the country rocks was associated with the emplacement of G4, or related to the earlier construction of G2 is unclear.

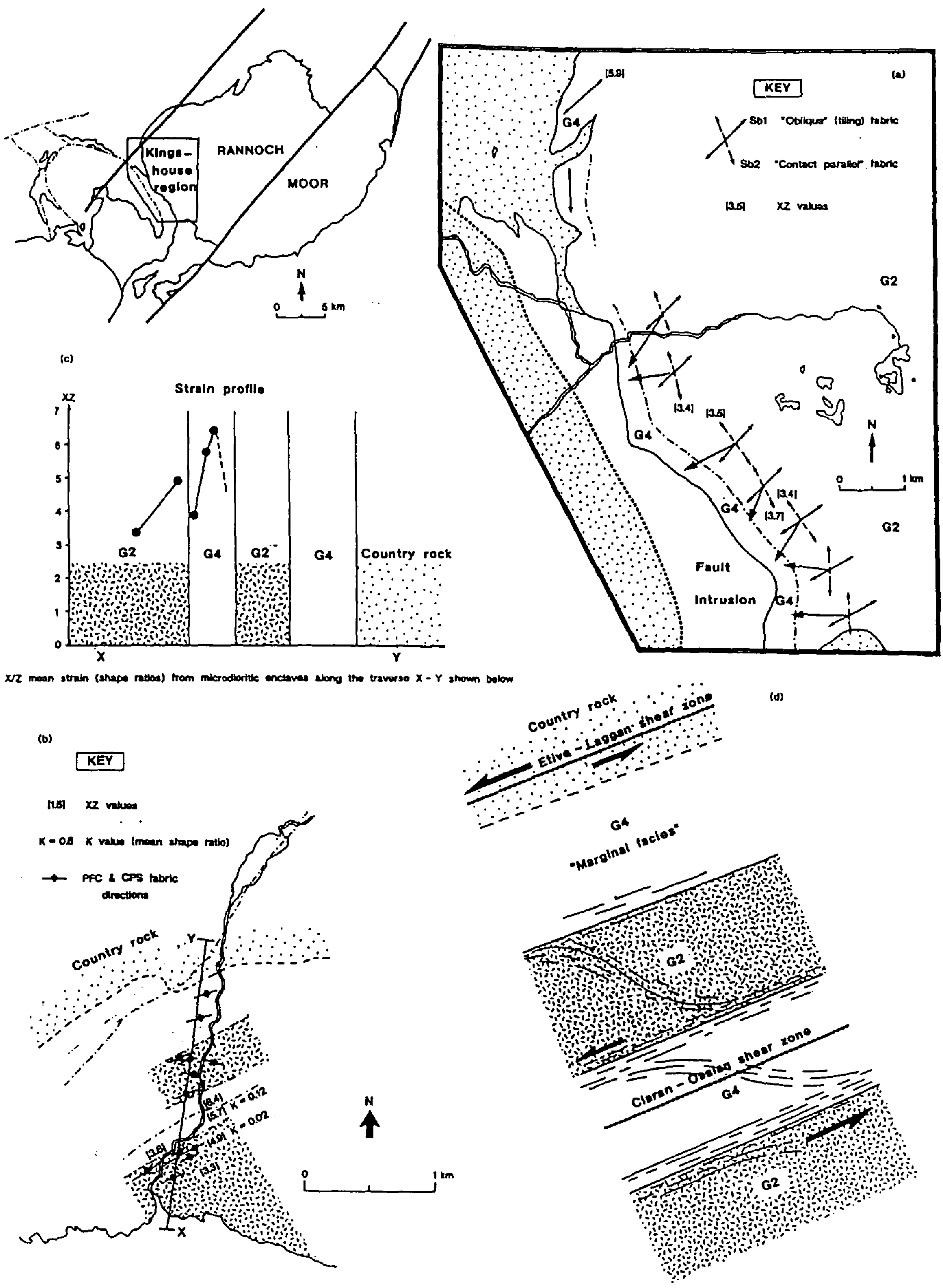


Fig. 5.14. **(a)** The 'marginal' facies of G4 along the north-western margin of the pluton (note how it has intruded between the contact of G2 and the Glencoe Fault Intrusion as a sheet-like body). The distribution of bimodal PFC fabrics are shown, together with X/Z values for microdioritic enclaves. **(b)** In the extreme NW of the complex, G4 occurs as two separate sheet-like bodies: (i) along the Ciaran-Ossian shear zone; and (ii) as the 'typical' marginal phase. Fabric geometries are shown for both G4 and G2 developed along the "Ciaran Water Section", together with X/Z values from microdioritic enclaves. **(c)** Strain profile along Ciaran Ossian section. **(d)** Generalised model for fabric development in the "Ciaran Water Section".

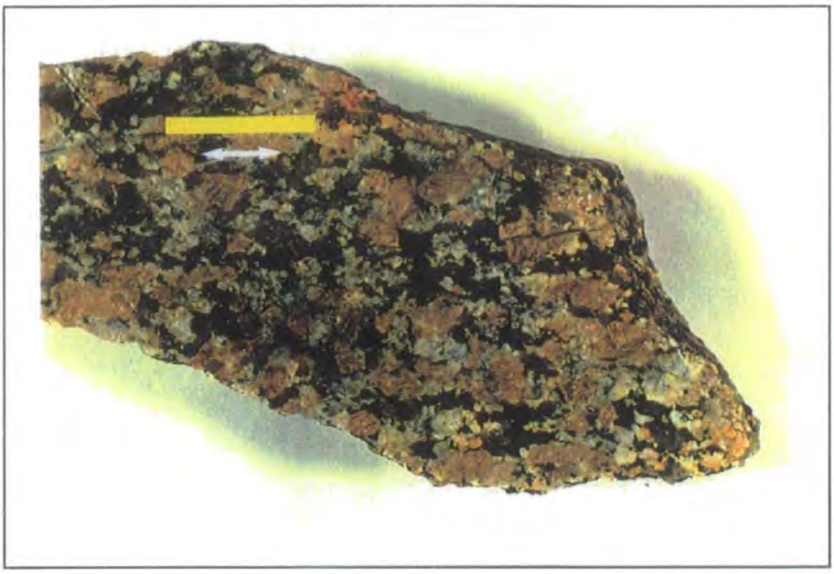
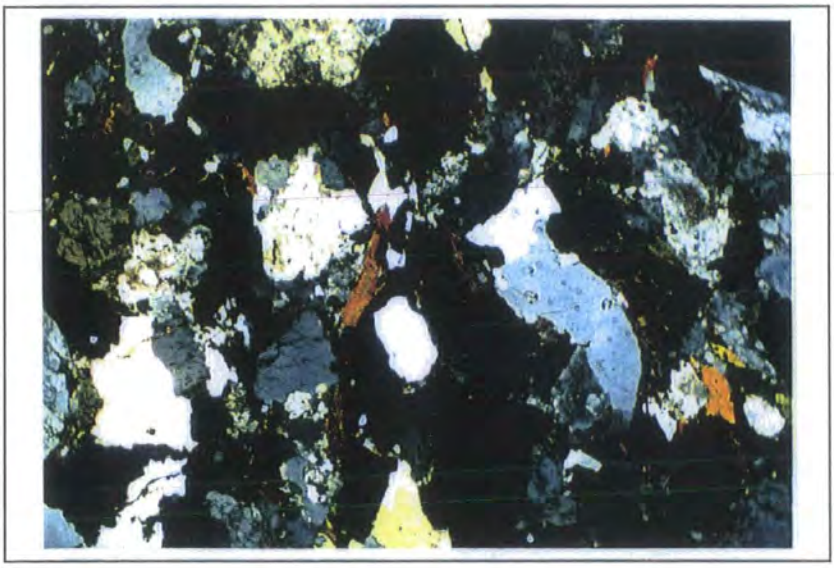


Plate 5.23. Hand-specimen of G4 from the Beinn a' Chrùlaiste area [NN 241 560]. It possesses a moderate PFC fabric which has been overprinted by a weakly developed, high temperature solid state overprint to produce a semi-annealed texture. (Yellow 'bar' is approximately 2 cm long).



late 5.24. Photomicrograph of hand-specimen shown in Plate 5.23. (Field of view approximately 18 mm).

① The G4 "marginal facies" (up to 350 m wide) possesses an intensely developed solid state deformational fabric which trends around 072°-078°, sub-parallel to the trend of the NE-SW-trending Etive-Laggan and Ciaran-Ossian fault zones. The fabric is defined by extremely lenticular and flattened quartz crystals, and highly elongate biotite laths, which are often bent and kinked around resistant plagioclase crystals.

The marginal facies can be traced from Allt an Ruadha Dheirg [NN 281 627] to Leac nan Carn [NN 308 625]. In certain areas between these two localities, particularly within the west, the PFC fabric is only slightly overprinted by solid state deformation. The fabric is generally vertical, and trends 040° to 080°, sub-parallel to its contacts and thus, the outer contact of G2. Within this region the foliation within the surrounding country wall rocks has been syn-plutonically rotated into parallelism with the pluton margin, and the intense fabric developed within G4. Whether this deformation within the country rocks was associated with the emplacement of G4, or related to the earlier construction of G2 is unclear.

② As mentioned above, 'sandwiched' between the two bodies of G4 is a zone of granodioritic material (Fig. 5.14b). Microstructural analysis of this rock suggests that it is part of the Blackwater facies (G2), which has undergone extensive modification by CPS deformation. The original fabric has been completely obliterated by an intense, low temperature solid state overprint (Plate 5.25). The resultant fabric trends oblique to the G4 sheets, consistently at 105° and becomes contact parallel within a localised zone (possibly 20-40 m wide) developed along its northern margin (the southern margin is not exposed). The geometrical orientation of this fabric may suggest that it was developed as a consequence of a strain induced sinistral shear component established across this zone during the emplacement of the two sheet-like bodies of G4 (see Fig. 5.14b), or possibly later during the solid state deformation of G4 (see below).

Plate 5.25. Hand-specimen of G2 from the "Ciaran Water Section" [NN 288 623]. It possesses an intense, low temperature solid state overprint which has 'obliterated' the pre-existing CPS fabric. (Yellow 'bar' is approximately 2 cm long).

③ The G4 body sited along the Ciaran-Ossian fault zone has also been overprinted by solid state deformation, showing similar characteristics to the 'marginal facies' to the north. The fabric trajectory pattern is very similar to that developed within the band of G2, described above, forming a sigmoidal fabric trajectory pattern indicative of sinistral shear. This combined with an apparent increase in strain towards the centre of this body, from X/Z ratios of microdioritic enclaves, and an apparent absolute mean shape value of K = 0.12, from the three-dimensional analysis of the enclaves, indicates a large flattening component across this zone. These features suggest that this zone was subjected to non-coaxial general shear (transpression) after G4 had fully crystallised, resulting in the intense low temperature CPS fabrics now observed.

④ As shown by Fig. 5.14b, the G4 body sited along the Ciaran-Ossian fault zone is bounded on both sides by G2 (Blackwater facies). Fabrics developed within G2 along these contacts are extremely intense, low temperature CPS fabrics which trend sub-parallel to the contact at approximately 040°. A K-value of 0.02 was obtained from the mean shape analysis of microdioritic enclaves within G2, again implying that this area was subjected to large "flattening strains", as inferred from enclaves within the adjacent G4 body (see above).

Model proposed for the emplacement and subsequent deformation of G4

A simple model to account for all these features could be:

❶ G4 occurs as sheet-like bodies, along the contact developed between the Glencoe Fault Intrusion and Rannoch G2 (Blackwater facies), and in proximity to the bounding faults of the complex. In the NW of the complex, two intrusions occur: (i) sited along the Ciaran-Ossian fault zone; and (ii) as a 'marginal facies' in close proximity to the Etive-Laggan fault zone (both recognised as major shear zones during the construction of the Strath Ossian complex (see Ch. 6, sub-section). In the SW of the complex, G4 occurs as a 'marginal facies', intruded between the contact of G2 and the bounding Gleann Chomraidh fault; the fault possibly acting as a major ductile shear zone during the emplacement of G2. It is envisaged that these structures were reactivated to allow the intrusion of G4, resulting in the sheets developing an intense pre-full crystallisation fabric parallel to their margins.

❷ A sinistral sense of shear along these faults is inferred from the analysis of the angular relationship between sub-fabrics developed with the 'magmatic state', and from a number of different kinematic indicators developed both within G4 and the country wall rocks. A sinistral shear component along these NE-SW-trending structures may have produced an overall transtensional environment along the NW and SE margins of the complex, allowing these zones to be exploited by magma (G4). This transtensional period of magmatism may closely coincide with the emplacement of the NE-SW-trending Etive Dyke Swarm, which may have involved a major transtensional component throughout the region (see Ch. 8). The emplacement of G4 predates the intrusion of the Etive Dyke Swarm. However, contact relationships such as cuspate/lobate margins suggests the period between the two events may have been relatively small, as G4 had not fully crystallised before being cross-cut by the dykes. It is also interesting to note, that many of these dykes are concentrated along or in the vicinity of the NE-SW-trending Etive-Laggan and Ciaran-Ossian fault zones, the same structures which are likely to have been influential during the emplacement of G4.

❸ In the extreme NW of the complex, fabric analysis and strain determinations from microdioritic enclaves suggest that after G4 had fully crystallised, it was subjected to deformation associated with movements along the Etive-Laggan and Ciaran-Ossian fault zones. The resultant low temperature CPS fabrics show clear evidence of an overall sinistral shear component during their development. Whether this solid state overprint is attributed to deformation continuing down-temperature in a 'progressive fashion', or represents a later reactivation along these structures, is unclear. However, one thing which is clear, is that this later deformational episode is not associated with transtension as envisaged during the intrusion of G4, as fabric trajectory patterns and K values indicate a large bulk shortening component across these fault zones ($K \approx 0$), inferring that these structures were transpressive during this later period of deformation.

5.4.5 G5: The A' Chruach facies

5.4.5.1 Pre-full crystallisation (PFC) fabrics or magmatic state fabrics.

As mentioned in sub-section 5.2.5, G5 occurs as two elliptical/sub-elliptical masses within the complex. The smaller of the two masses (G5b) occurs within the SW of the complex, and is sited along the Gleann Duibhe fault (Fig. 5.7a). It appears that it has been displaced by some 7-8 km along the Ericht-Laidon shear zone (see Ch. 9). However, G5a occurs at the centre of the complex, and appears to have been emplaced somewhat later, relative to G5b, and subsequent to the large sinistral offset across the Ericht-Laidon fault zone.

Both masses contain weak to moderately developed PFC fabrics which are generally vertical and pseudoconcentric to the form of the bodies. The PFC fabrics within both masses appear to intensify towards their outer margin. The PFC fabric is characterised by the alignment of plagioclase, and to a lesser extent by K-feldspar phenocrysts. The feldspar, together with essential quartz, is internally undeformed. Exceptions do occur, particularly within the central parts of the masses (see below), where there is a weak to moderate solid state overprint. Biotite may form a weak sub-horizontal mineral stretching lineation, and is often developed within the outer most parts of the bodies.

Both G5a and G5b clearly cross-cut intensely developed PFC and CPS fabrics developed within G2 (Blackwater facies). The substantial time difference between the emplacement of these two major intrusive phases (i.e. G2 and G5) is clearly demonstrated at the centre of the complex, near the summit of Stob na Cruaiche [NN 363 571], where

G5a is considerably chilled against G2, and G5a clearly cross-cuts (at high angles) the low temperature solid state fabric within G2 (Plate 5.26).

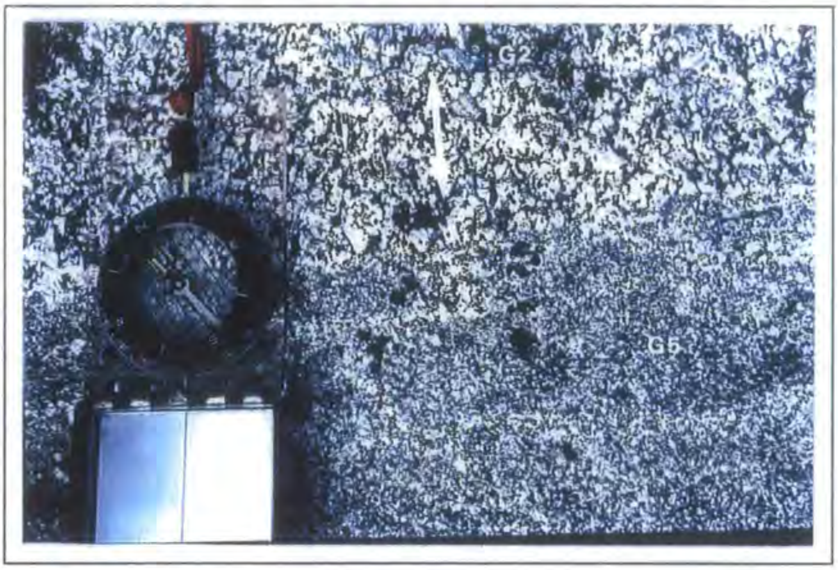


Plate 5.26. G2/G5a contact at the centre of the complex, near summit of Stob na Cruaiche [NN 363 571]. Note how G5a has cross-cut, at a high angle, the low temperature CPS fabric fabric developed within G2. The trend of the CPS fabric is shown by the white arrow. (Horizontal surface).

5.4.5.2 Crystal plastic strain (CPS) fabrics or solid state fabrics.

Along the Ericht-Laidon fault zone, and to a lesser extent along the Gleann Duibhe fault, the PFC fabric within G5 has been modified by a weak to moderately developed solid state overprint. This CPS deformation is generally localised along these structures, and exhibits the following features: (i) quartz, both essential and interstitial, may form lenticular crystals and aggregates which may show evidence of recrystallisation, and may have developed undulose extinction; (ii) some of the larger feldspar crystals are broken, and have undergone extensive sericitisation; (iii) orthoclase has sometimes been converted to microcline; (iv) feldspar and quartz is occasionally associated with myrmekite; and (v) biotite laths are often bent or kinked, and have occasionally undergone extensive alteration to chlorite.

Model proposed for the construction and subsequent deformation of G5

A simple model to account for all these features could be:

❶ Both masses, i.e. G5a and G5b, were constructed by a process of *in situ* expansion resulting in the development of pseudoconcentric PFC fabrics which intensify towards their outer contact with G2, and a generally weak sub-horizontal mineral stretching lineation.

❷ The elongate form of G5a, with its long axis trending E-W (Fig. 5.7a) may suggest that a sinistral component of shear was established across the Ericht-Laidon shear zone during its emplacement, allowing magma at the centre of the complex to expand predominantly into the direction of maximum extension imposed. Continued deformation along this structure, after G5a had fully crystallised may explain the development of the solid state deformational overprint.

5.5 TECTONIC CONTROLS ON PLUTONISM

Running through the adjacent wall rocks and in places partially bounding the pluton are the Etive-Laggan and Ciaran-Ossian faults within the NW of the complex, and the Gleann Chomraidh fault in the SE. The complex is bisected by the NE-SW-trending Ericht-Laidon fault zone (Fig. 5.15). Data presented within this Chapter, combined with information predominantly based on the recognition of 'pre-full crystallisation' and 'crystal plastic strain' fabrics developed within the adjacent granitic complexes (see Ch.'s 4 and 6) show that where these structures are spatially associated with plutons, they were acting as shear zones during magmatism. This has led to the recognition that five major Caledonian NE-SW-trending shear zones may have sited and controlled intrusive activity during the construction of the Rannoch Moor pluton. These are:

(i) the Etive-Laggan shear zone

(ii) the Ciaran-Ossian shear zone

(iii) the Ericht-Laidon shear zone

(iv) the Gleann Chomraidh fault

(v) the Gleann Duibhe shear zone

Strain distribution, fabric types and fabric trajectories associated with these structures suggest that they were active sinistral shear zones during plutonism.

The major intrusive phases of the Rannoch Moor complex appear to have been controlled by the following tectonic structures (see Fig. 5.15):

G1: The Gleann Duibhe facies

This sheet-like body of quartz-diorites appears to have been sited and emplaced along a transtensional segment of the Gleann Duibhe shear zone.

G2: The Blackwater facies

The Etive-Laggan shear zone essentially bounds the complex to the NW, and the Gleann Chomraidh fault bounds it to the SE (Fig. 5.15). The Ericht-Laidon shear zone runs through the centre of the complex. Sinistral ductile deformation along these structures, during the construction of the Rannoch Moor complex, may have allowed magma to expand predominantly into the direction of maximum extension imposed by these controlling structures. The maximum expansion direction would have been orientated approximately E-W. It is envisaged this would have resulted in the development of intense, pseudoconcentric PFC fabrics within the E and W of the complex, which intensify towards he pluton margin. Such fabrics are preserved within the eastern part of the complex (Loch Eigheach region; sub-section 5.4.2.1). The sigmoidal fabric trace across the Ericht-Laidon shear zone suggests a significant component of sinistral shear along that structure during he *in situ* expansion of G2.

The southern and northern zones of sheeting and stoping occur where magma was ntruded into a localised transtensional environment developed within the zone of maximum shortening (constriction) caused by the overall gross transpressional component mposed by the NE-SW-trending structures (see Ch. 10 for explanation).

G3: The Rannoch Moor Microgranites

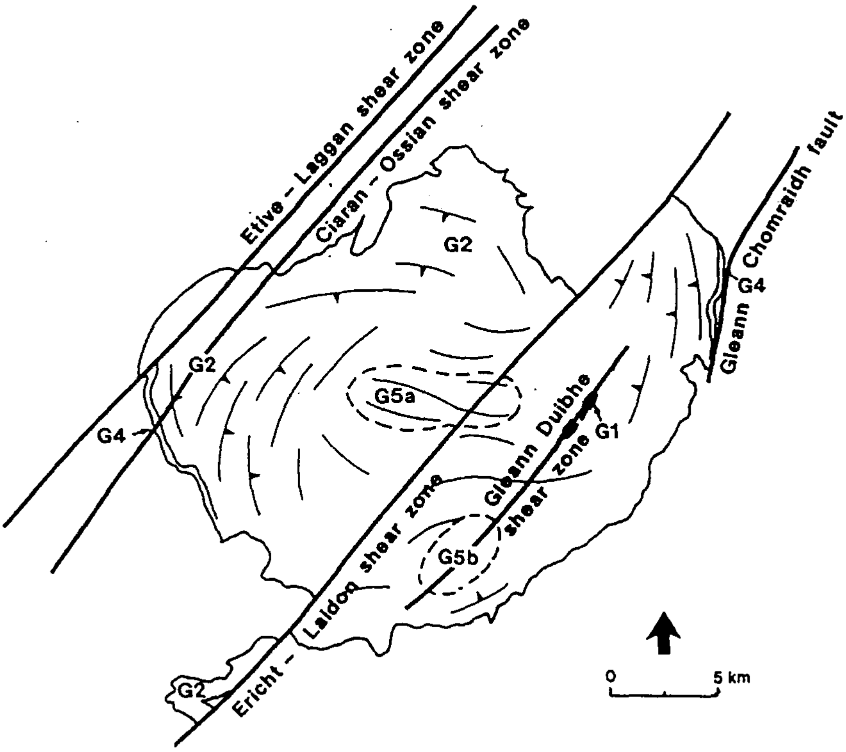
The two main occurrences of G3 may suggest that they were sited, and controlled during their emplacement by the Etive-Laggan and Gleann Duibhe shear zones.

G4: The Ciaran/Chomraidh marginal facies

Within the NW and SE of the complex, sinistral transcurrent motion along the bounding Etive-Laggan and Gleann Chomraidh structures, respectively, appears to have allowed G4 to intrude as a 'marginal facies' where they partially bound the pluton. Also within the NW of the complex, G4 occurs as a sheet-like body along the Ciaran-Ossian shear zone.

G5: The A' Chruach facies

Both the Ericht-Laidon and Gleann Duibhe shear zones appear to have been reactivated during the emplacement of G5, siting this intrusive phase, and possibly controlling its emplacement dynamics in two regions: (i) at the centre of the complex, along the Ericht-Laidon shear zone (G5a); and (ii) within the SW of the complex, along the Gleann Duibhe shear zone (G5b).

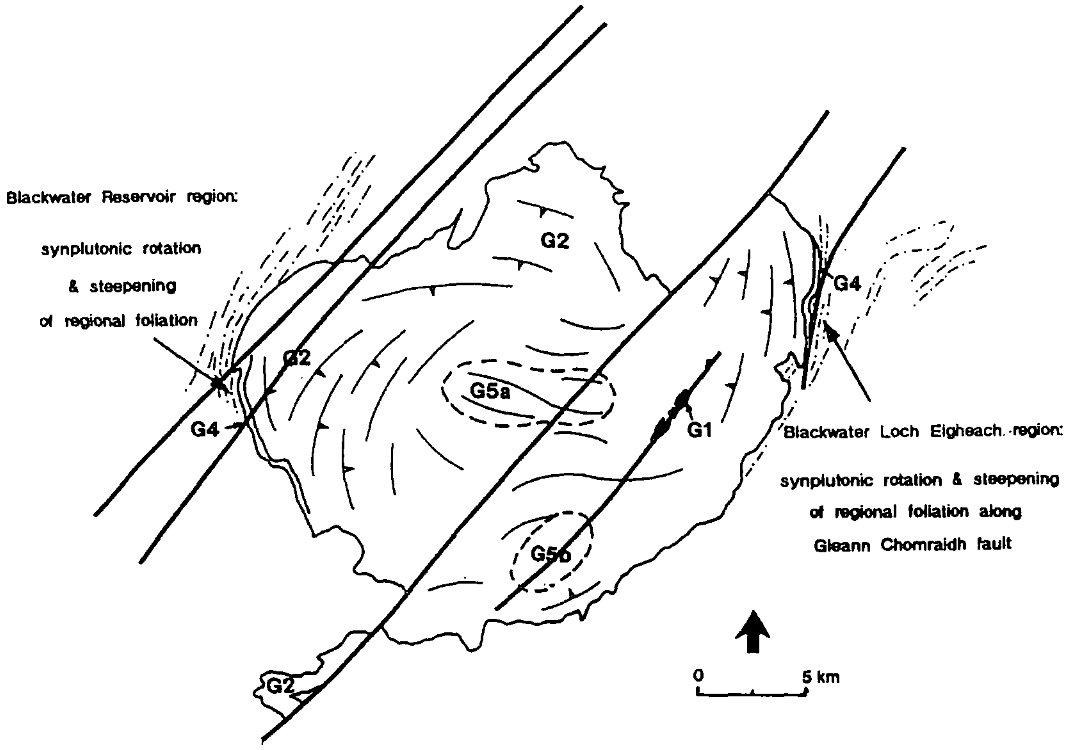


ig. 5.15. Major tectonic structures associated with the construction of the Rannoch Moor complex.

5.6 CONTACT RELATIONSHIPS AND COUNTRY ROCK DEFORMATION

As with the Etive complex (Ch. 3), which is also an elliptical complex, the outer contact of the Rannoch Moor pluton is extremely variable. It can be (a) fault controlled, as seen within the NW (Etive-Laggan shear zone) and SE (Gleann Chomraidh fault) of the complex, (b) simple and well defined, and (c) extremely complex forming an intricate relationship with the surrounding rocks, as developed within the "northern and southern zones of sheeting and stoping". Except within the NW and SE of the complex, the adjacent country rocks show little evidence of deformation associated with the construction of the Rannoch Moor complex. Both the NW and SE of the pluton correspond to the direction of maximum expansion during the construction of G2 (see sub-section 5.4.2), resulting in the development of high flattening strains shown by highly oblate enclaves and intense pseudoconcentric fabrics. Within the adjacent wall rocks to these regions, a component of ductile shortening is clearly evident. As mentioned above, within both zones, the pluton margin has been essentially controlled by the bounding NE-SW-trending Etive-Laggan shear zone in the NW, and the Gleann Chomraidh fault in the SE (Fig. 5.15). As described by Read (1956; 1961), in the south-eastern part of the complex, a 1000 m traverse from the faulted contact (Gleann Chomraidh fault) into the adjacent wall rocks shows that the regional fabrics have been synplutonically rotated and steepened towards the pluton margin (Fig. 5.16). Such features led Read (1956; 1961) to describe the pluton as exhibiting predominantly forceful characteristics, where significant ductile flow type processes have occurred within the contact aureole.

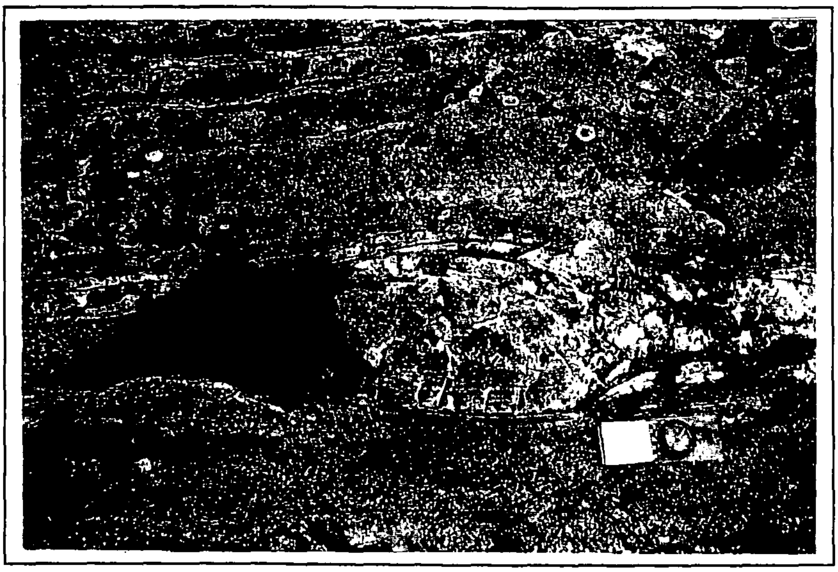
A similar situation occurs in the wall rocks within the NW of the complex. Ductile deformational characteristics and magnitudes of strain are similar to those exhibited by the south-eastern region. Within the north-western aureole, in the vicinity of the Blackwater Reservoir, regional foliations and the trace of NE-SW-trending fold structures, appear to have been synplutonically rotated into a NNE orientation forming a partially concordant contact aureole (Fig. 5.16). This ductile deformation has occurred within a zone approximately 600-800 m wide, the majority of which is composed of grey pelitic gneisses (Reservoir Schists). Following the contact of the pluton is a zone (approximately 150-200 m wide) of fine-grained quartzites (Reservoir Quartzite) and a banded psammitic gneiss with micaceous laminae (Reservoir Flags). Developed within the latter lithological unit are large, metre scale shear sense indicators in the form of σ- (Plate 5.27) and δ-type (Plate 5.28) structures, kinematically consistent with a gross sinistral rotation of the complex during the construction (expansion) of its major intrusive component, G2.



Blackwater Reservoir region: synplutonic rotation & steepening of regional foliation

Blackwater Loch Eigheach region: synplutonic rotation & steepening of regional foliation along Gleann Chomraidh fault

Fig. 5.16. Generalised model showing how the regional country rock fabrics have been synplutonically rotated within the NW and SE of the complex.



ate 5.27. A large scale σ-type structure developed within the country wall rock (Reservoir Flags) in the rth-western part of the Rannoch Moor complex (Blackwater Reservoir area). (Horizontal surface).

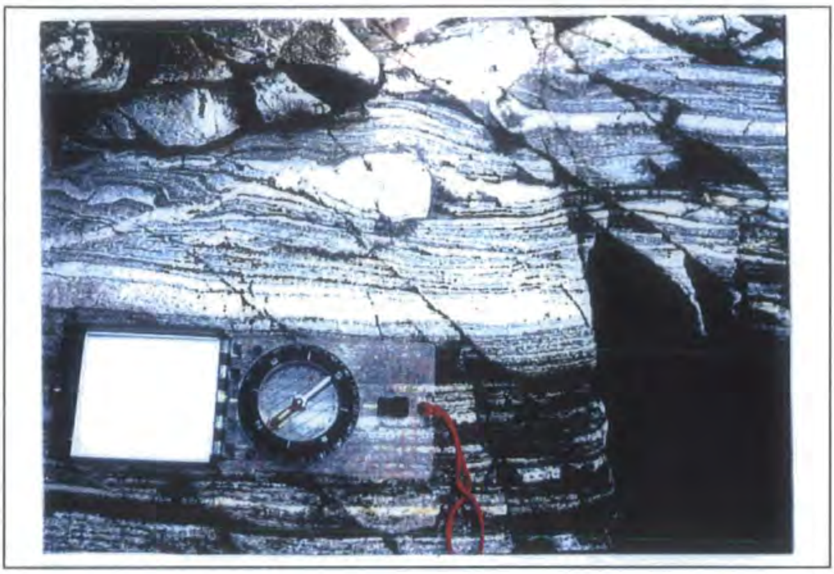


Plate 5.28. A δ-type structure developed within the country wall rock (Reservoir Flags) in the north-western part of the Rannoch Moor complex (Blackwater Reservoir area). (Horizontal surface).

Such ductile deformational structures may indicate that along the NW and SE contacts of the pluton, sinistral transcurrent motion along the bounding shear zones may have been a significant process of space creation during pluton construction. The possible mechanisms by which space was created during the construction of the Rannoch Moor complex are discussed separately in Chapter 11.

5.7 CONSTRUCTION OF THE RANNOCH MOOR COMPLEX: AN EMPLACEMENT MODEL

This Section summarises the most important features regarding the geometry of the pluton, the distribution of its internal intrusive phases, and its internal and external deformational characteristics in relation to major tectonic structures. An account of the predominant mechanisms operating during the construction of these individual intrusive phases are proposed, based on the data presented within this Chapter (see Fig. 5.17).

➊ When the late sinistral offset of some 7-8 km along the Ericht-Laidon fault zone (Hinxman *et al.* 1923) is restored, the pluton has a somewhat elliptical form (approximately 28 km x 18 km), with its long axis orientated NE-SW parallel to the regional Caledonian strike (Fig. 5.17a).

➋ Running through the adjacent wall rocks and in places partially bounding the pluton are the Etive-Laggan shear zone in the NW, and the Gleann Chomraidh fault in the SE. Running through the centre of the complex is the Ericht-Laidon shear zone (Fig. 5.17).

➌ G1 (Gleann Duibhe facies) takes the form of a narrow elongate sheet (Fig. 5.17a) along the NE-SW-trending Gleann Duibhe shear zone, within the south-eastern part of the complex. Sinistral transcurrent movements along this structure may have sited and controlled the emplacement of this quartz-dioritic facies.

➍ G2 (Blackwater facies) constitutes the largest intrusive component of the complex, and was constructed predominantly by a process of *in situ* expansion, and to a lesser extent by sheeting and stoping localised within the northern and southern most periphery of the complex (Fig. 5.17a).

An overall gross sinistral transpressional component imposed by the bounding and bisecting NE-SW-trending structures, allowed magma to expand predominantly into the direction of maximum extension imposed by these controlling structures. This maximum expansion direction was orientated approximately E-W (Fig. 5.17a), leading to the development of: (i) a steep, inward-dipping, pseudoconcentric, PFC fabric within the outer most parts of the complex, which intensifies towards the pluton margin; (ii) a sub-horizontal mineral stretching lineation; (iii) an overall bulk shortening component, shown by the three-dimensional shapes of microdioritic enclaves; and (iv) PFC conjugate, ductile shears showing a bulk horizontal extensional component parallel to the fabric direction, formed during the last stages of pre-full crystallisation due to the continued imposition of expansion-related strains. These features are preserved within the eastern part of the complex (Loch Eigheach region). Within the west (Kingshouse region) these features were subsequently modified and overprinted by the imposition of expansion-related strains related to the construction of the adjacent Glencoe complex (Fig. 5.17b).

Simultaneous sheeting and stoping along the northern and southern contact of the complex, corresponds to the regions of maximum shortening (constriction) of the overall gross sinistral transpressional system imposed by the bounding and bisecting NE-SW-trending shear zones (Fig. 5.17a). It is envisaged that this led to the development of a localised transtensional environment allowing the localised phenomena of sheeting and stoping to occur.This is addressed further in Chapter 10.

❺ The next intrusive event was the emplacement of the Rannoch Moor Microgranites (G3). This minor phase is represented by a series of monzogranitic and syenogranitic sheets and dykes. Their distribution suggests they may have been sited and localised in two areas, before being subsequently disrupted and modified by the emplacement of the A' Chruach facies (G5), which resulted in G3 being overprinted by a solid state overprint. The largest occurrence of G3 is at the centre of the complex, and has been disrupted by the emplacement of G5a (see below). Its proximity to the Ericht-Laidon shear zone may suggest that it was sited along part of this structure. A similar relationship occurs within the SW of the complex, where a localised zone of monzogranitic-syenogranitic dykes and sheets appear to have been disrupted by the emplacement of G5b (see below). This occurrence also appears to be in close association with a major tectonic structure, the NE-SW-trending Gleann Duibhe shear zone.

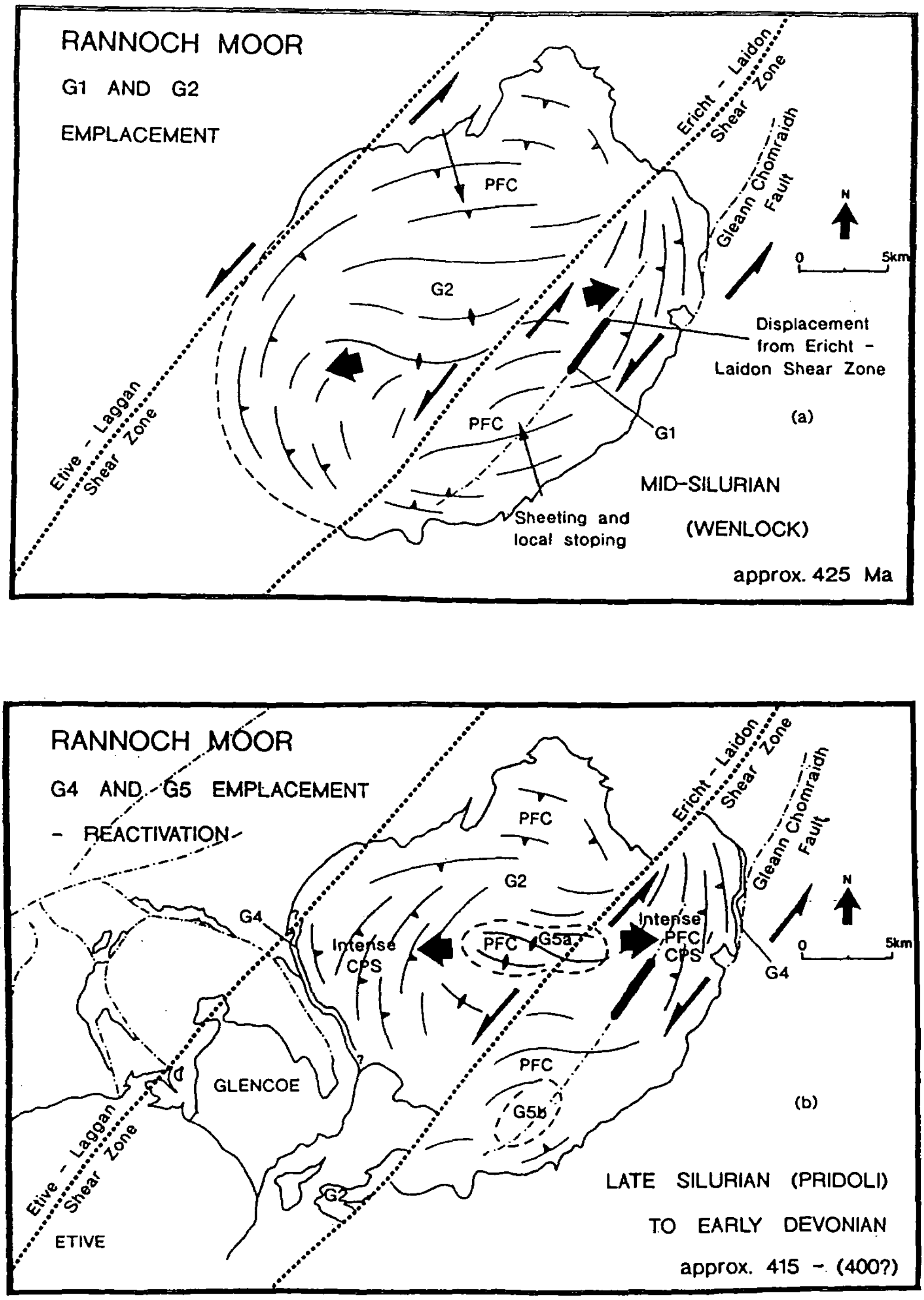
❻ This was followed by the emplacement of sheet-like bodies of G4 along the Etive-Laggan and Ciaran-Ossian shear zones within the NW, and the Gleann Chomraidh fault in the SE (Fig. 5.17b). Fabric analysis, strain determinations and the spatial distribution of G4 suggests that sinistral transcurrent motion along these bounding NE-SW-trending structures may have created a localised transtensional environment around parts of the NW and SE pluton margin, allowing G4 to intrude as a 'marginal sheet-like phase'.

❼ As with G2, the A' Chruach facies (G5a and G5b) was constructed by a process of *in situ* expansion resulting in the development of weak to moderately developed, slightly inward-dipping pseudoconcentric PFC fabrics. As with G3 (Rannoch Moor Microgranites), G5 occurs in two regions (Fig. 5.17b): (i) within the SW of the complex, along the Gleann Duibhe shear zone (G5b); and (ii) at the centre of the complex, along the Ericht-Laidon shear zone. The location of G5b suggests that it was emplaced before the 7-8 km displacement of the pluton margins along the Ericht-Laidon shear zone (see Ch. 9). Whereas, the form and position of G5a, and its fabric development, suggests that it was emplaced after this main component of displacement, but still under the influence of sinistral transcurrent deformation associated with the Ericht-Laidon shear zone, causing magma to expand predominantly E-W into the direction of maximum extension imposed by this structure.

Model proposed for the main construction of the pluton

The major intrusive component G2 was constructed by a process of *in situ* expansion whilst undergoing sinistral transpression. Magma predominantly expanded approximately E-W into the direction of maximum extension imposed by the controlling NE-SW-trending major faults and shear zones (Fig. 5.17a).

Microstructural features suggest that by the time G4 and G5 were assembled, the free surface had been lowered. This is clearly shown by the intrusion of part of G4 along the contact between the high level Glencoe Fault Intrusion and Rannoch G2 (Fig. 5.17b). A significant period of regional sinistral transtension may have occurred during the emplacement of G4. Emplacement dynamics and synplutonic relationships suggest that the Glencoe Fault Intrusion (see Ch. 7) and Etive Dyke Swarm (see Ch. 8) were emplaced during this regional extensional phase. Displacement along the bounding NE-SW-trending structures created space for Rannoch G4 at the outer margins of the complex (Fig. 5.17b). Both G5a and G5b have been constructed by a process of *in situ* expansion. The major phase G5a occurs at the centre of the complex (Fig. 5.17b) and appears to have expanded approximately into the direction of least tectonic strain imposed by the controlling NE-SW-trending shear zone/fault system.



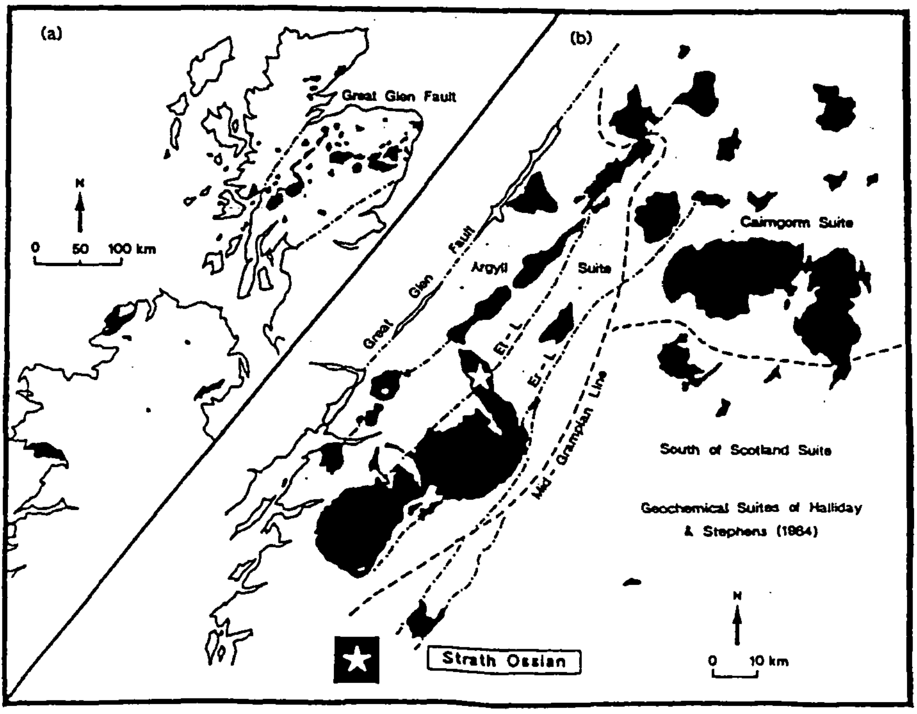
ig. 5.17: Generalised models for the emplacement of (a) G1 and G2 and (b) G4 and G5 of the Rannoch loor complex.

CHAPTER 6

THE STRATH OSSIAN COMPLEX

6.1 INTRODUCTION

The Strath Ossian igneous complex (Hinxman *et al.* 1923; Anderson 1956; Clayburn 1981; Henderson 1982; Key *et al.* 1993) is a vertical-sided, NW-SE-trending linear shaped pluton (approximately 30 km x 6 km) (Fig. 6.1). It was emplaced into the Appin and Grampian Group metasediments, at an estimated pressure of 3.2 +/- 0.5 kbars, indicating an apparent depth of 9.5 +/- 2.0 km (Key *et al.* 1993).



ig. 6.1. **(a)** Distribution of late Caledonian granites in Scotland and Ireland. **(b)** Distribution of granitoids the Grampian Highlands, showing the location of the Strath Ossian complex.

Originally, the first surveyors (Hinxman *et al.* 1923) regarded this trans-Caledonian ntrusive body as being part of the Rannoch Moor complex, separated from this granite by a NW-SE-trending metasedimentary screen (see sub-section 6.3). However, more recent studies of their isotopic characteristics (Clayburn *et al.* 1981; Leighton 1985) suggest that they are two independent intrusive masses, distinct in terms of source and age. A broad pertrographical study of the major intrusive phases has been carried out by Anderson (1956), Clayburn (1981), and Henderson (1982). A more thorough investigation by Key *et al.* (1993) has produced a detailed petrography map for the northern part of the complex (Fig. 6.2).

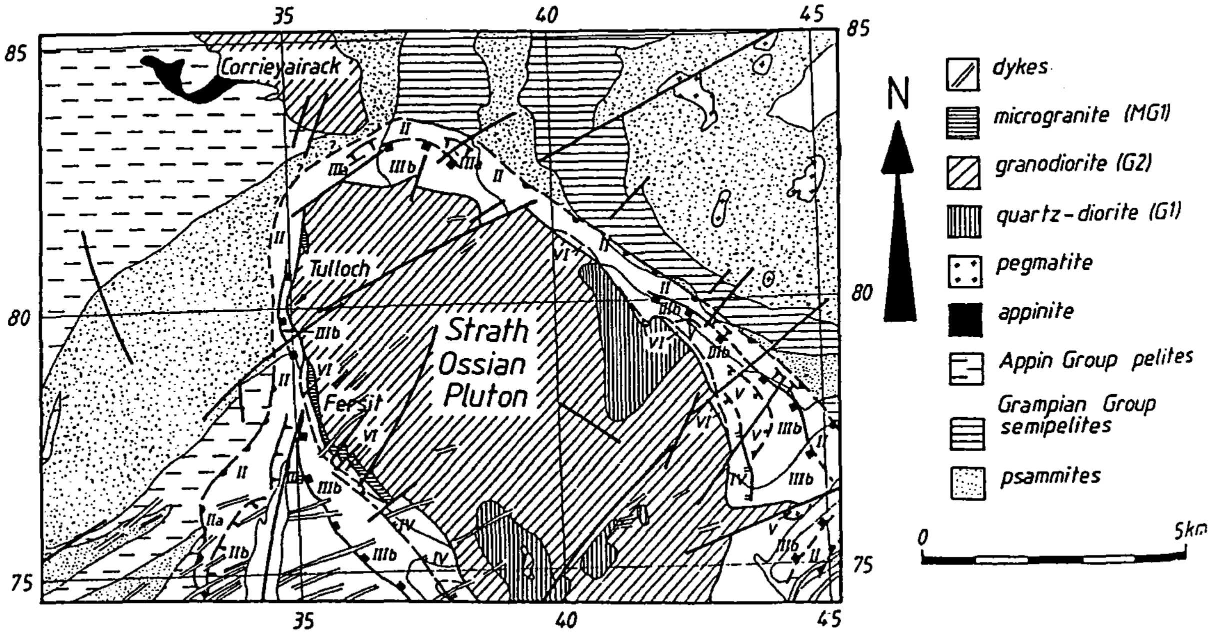


Fig. 6.2. Simplified geology map of the northern part of the Strath Ossian complex: I.A.: Inverlair Anticline; B.S.: Blackwater Syncline; L.L.A.: Loch Laggan Anticline; L.D.F.: Laggan Dam Fault. After Key *et al.* (1993).

The compilation of existing data and the result of new mapping undertaken during this tudy has revealed that the Strath Ossian pluton is a multiphase complex, consisting of five major intrusive phases (Fig. 6.3). These are named within this contribution as:

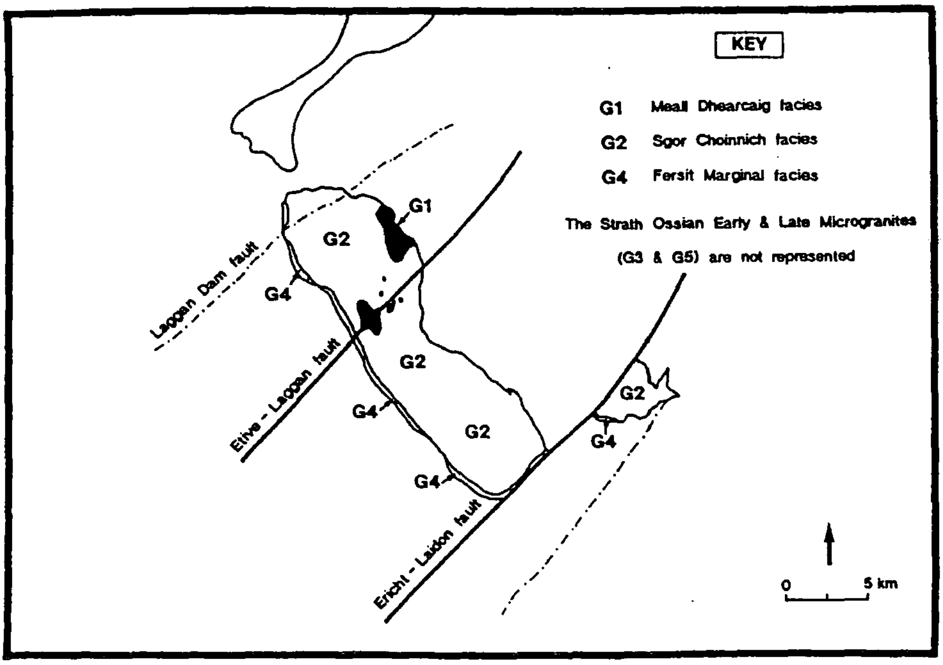
G1: The Meall Dhearcaig facies (sub-section 6.2.1)
Quartz-diorite

G2: The Sgòr Choinnich facies (sub-section 6.2.2)
Granodioritic facies

G3: The Strath Ossian Early Microgranites (sub-section 6.2.3)
Microgranite sheets

G4: The Fersit Marginal facies (sub-section 6.2.4)
Coarsely porphyritic monzogranite consisting of large (1-3 cm) tabular plagioclase and K-feldspar megacrysts

G5: The Strath Ossian Late Microgranites (sub-section 6.2.5)
Microgranite sheets and dykes



ig. 6.3. A generalised map of the petrographical distribution of the major intrusive phases within the Strath ssian complex.

The petrological characteristics of these intrusive phases are described below. These are based on detailed field and microscope analysis carried out during this current investigation, combined with observations made by Key *et al.* (1993) for the northern part of the complex.

Until quite recently, an actual emplacement model for the construction of the pluton and its internal intrusive phases had not been proposed. A model by Key *et al.* (1993) suggests that the initial emplacement of the pluton took place at its northern-most end, with magma spreading towards the ESE. The direction of spreading was controlled by a pre-existing structure, the NW-SE-trending Strath Ossian lineament (Forrest & Key 1989). The lineament has been interpreted by Forrest and Key (1989) as the trace of a major deep seated basement fracture which initially influenced facies variations during early Dalradian sedimentation, with later reactivation affecting metamorphism and igneous activity (see also Phillips *et al.* 1994; Glover *et al.* 1995; Chapter 9). The model proposed is very simplistic and provides little information regarding the mechanisms operating during the construction of the pluton, to account for the distribution and structural features of its internal intrusive phases and deformational features within the surrounding country wall rocks. This Chapter, however, hopes to address such questions, and ultimately present a model describing the predominant processes operating during the construction of the complex. This will be achieved by the integration of various data, including: (i) fabric type, orientation and intensity; (ii) relative strain from mafic microgranitoid enclaves; (iii) overall geographical distribution of facies; (iv) local emplacement phenomena; and (v) associated fabrics and strains within the adjacent country rocks.

6.2 MAJOR INTRUSIVE COMPONENTS

6.2.1 G1: The Meall Dhearcaig facies

This is the earliest intrusive component within the Strath Ossian complex, ssentially forming a NNE-SSW-trending sub-elliptical core to the complex along the tive-Laggan fault zone (Fig. 6.2 & 6.3). The distribution of this facies and its fabric evelopment (see sub-section 6.4.1) suggests that this mass was subsequently rotated and isrupted by the intrusion of G2 shortly after its emplacement, resulting in G1 forming everal discrete bodies (Fig. 6.2 & 6.3). The facies varies from medium- to coarse-grained quartz-dioritic to monzodioritic rocks which constitute the bulk of the facies, through to fine- to medium-grained appinitic compositions (Plates 6.1 & 6.2). Smaller bodies of fine-grained appinitic material through to medium-grained quartz-dioritic compositions are confined to the Uisge Labhair river section (Fig. 6.3). Compositionally, much of the material is very similar to the dioritic bodies which occur within the main mass to the north. However, some of the material is extremely appinitic to dioritic in nature and compositionally resembles the microappinitic-dioritic enclaves encorporated within G2. The majority of this dioritic phase was not emplaced as a separate intrusive event prior to G2, but occurs synplutonically as large irregular bodies encorporated within G2, or as dykes and sheets. The dyke-like bodies range in orientation from 125-175°, with the majority trending 130-140°; approximately parallel to the long axis of the pluton. Sharp and planar contacts between this dioritic 'unit' and G2 are rare (Plate 6.3), with most being irregular; including cuspate/lobate geometries (Plate 6.4). Gradational contacts are not uncommon and small digested dioritic inclusions encorporated within G2 show evidence of magma mingling processes.

late 6.1. Hand-specimen of medium-grained appinitic-type material from Uisge Labhair river section. The Suite' is extremely compositionally variable from quartz-dioritic to monzodioritic compositions (largest omponent), through to appinitic material. (Yellow 'bar' is approximately 2 cm long).

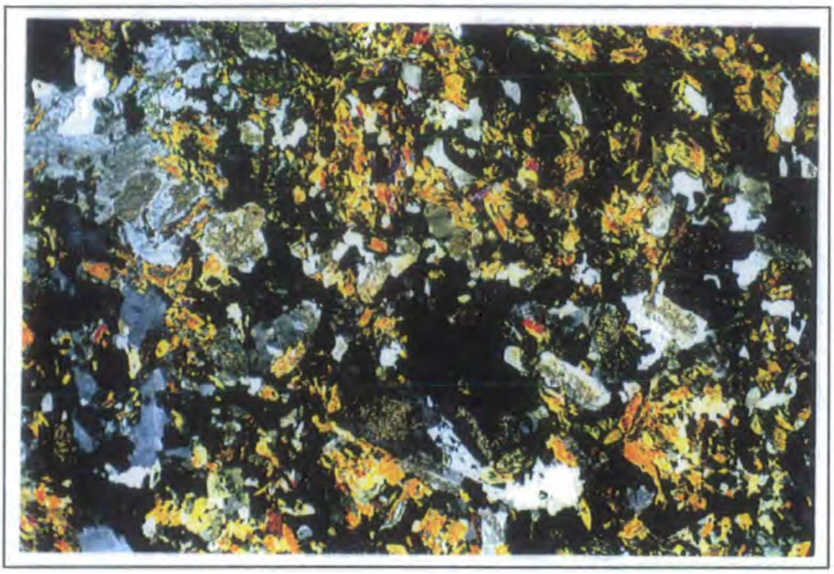


Plate 6.2. Photomicrograph of hand-specimen shown in Plate 6.1. (Field of view approximately 18 mm).

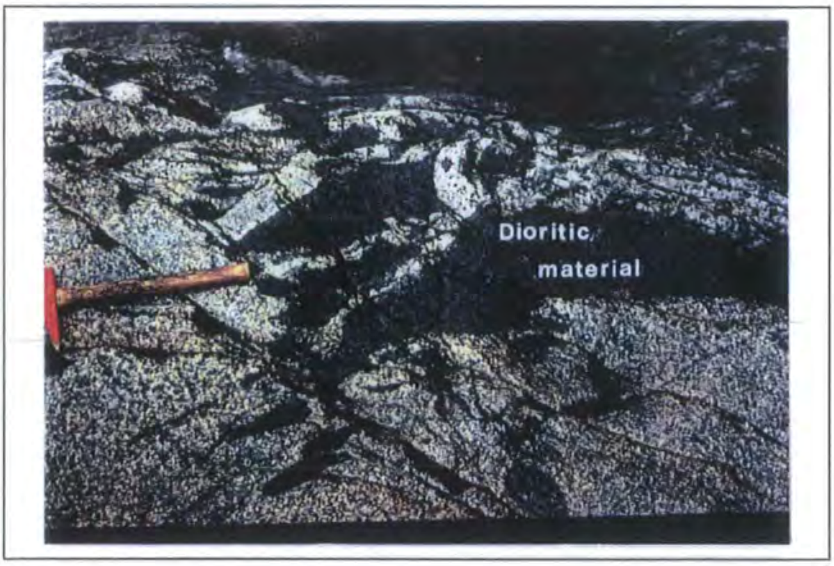


Plate 6.3. Sharp and planar contacts between G2 and dioritic material in the Uisge Labhair river section. (Horizontal surface).

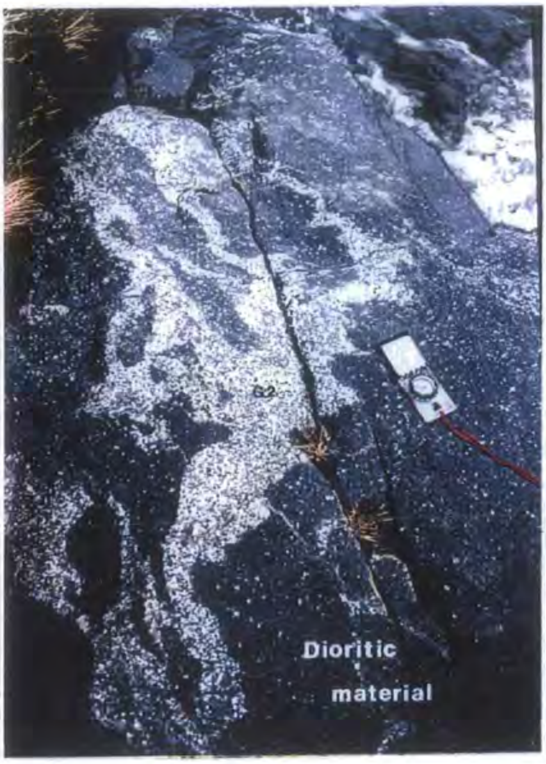


Plate 6.4. Synplutonic relationship between G2 and dioritic material in the Uisge Labhair river section. Contacts are irregular, showing cuspate/lobate geometries. (Horizontal surface).

A number of much finer-grained, microdioritic dykes cross cut G2 throughout the complex. They have extremely sharp and planar contacts, often truncating host (G2) crystals along contacts. Also, they do not trend NW-SE, as do the medium- to coarser-grained varieties, but trend roughly NE-SW. These may represent a much later dyke phase, possibly associated with either the Etive or Ben Nevis dyke swarms. However, a large majority possess a dextral shear component (Plate 6.5) which was not observed in the detailed study of the Etive Dyke Swarm in the Glen Etive region (see Ch. 8). This may mply that this phase belongs to the Ben Nevis Dyke Swarm or it represents a localised vent.

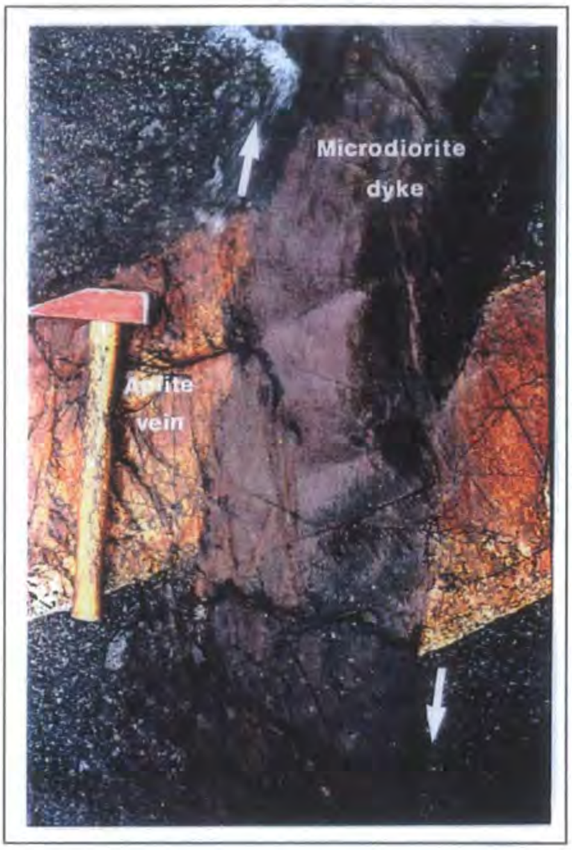


Plate 6.5. A NE-SW-trending microdiorite dyke which has displaced a large aplite vein in a dextral fashion. (Horizontal surface).

General petrographical description:

The Meall Dhearcaig facies: essentially a medium- to coarse-grained, equigranular quartz-dioritic phase. Finer-grained varieties do occur and compositionally are somewhat variable, including monzodiorites-quartz monzodiorites through to appinitic compositions. In some areas, particularly within the quartz-monzodioritic phase, plagioclase (15-35 %; including interstitial plagioclase) phenocrysts are zoned, and range from 4-12 mm in length, and are often fairly heavily altered by sericitisation. Mafic minerals include biotite (20-35 %) and amphibole (10-30 %), which occur as smaller phenocryst phases (1-4 mm in length), often showing strong evidence of alteration to chlorite and epidote. Biotite may poikilitically enclose amphibole. Alkali feldspar (5-20 %) may occur as a phenocryst phase, but in general occurs as subhedral or anhedral crystals (< 2 mm) interstitially within the groundmass, together with quartz (up to 12 %) and biotite. Accessories include opaques, sphene and apatite.

6.2.2 G2: The Sgòr Choinnich facies

This medium- to coarse-grained granodioritic phase constitutes the largest component of the Strath Ossian complex, forming a NW-SE-trending elongate body (approximately 30 km x 5-6 km) (Fig. 6.3). It is a fairly homogeneous intrusive phase, ranging from infrequent quartz-monzodiorites, through to granodioritic composition. G2 clearly extensively veins and sheets the quartz-dioritic phase (G1) which forms the sub-elliptical core at the centre of the complex.

General petrographical description:

The Sgòr Choinnich facies: essentially a medium- to coarse-grained, porphyritic, leucocratic granodiorite. Phenocryst phases include plagioclase (40-50 %), biotite (up to 15 %), amphibole (up to 10 %) and alkali feldspar (< 20 %). A large percentage of the alkali feldspar occurs interstitially within the matrix, together with plagioclase, quartz (15-25 %), biotite and hornblende.

The appearance of the granodiorite, in both hand-specimen and thin-section, changes quite considerably across the width of the intrusion. The difference is due to the development of a zone of intense, relatively low temperature crystal plastic strain, along the contact with G4, within the western part of the complex (see sub-section 6.4.2). This zone is characterised by the following features: (i) sericitisation of the feldspars is common; (ii) the longer plagioclase phenocrysts are often broken; (iii) biotites and hornblende are elongate, kinked or bent; (iv) quartz is highly strained, often forming lenticular aggregates and ribboned quartz; and (v) there is a progressive decrease in grain-size as the solid state deformation intensifies towards the G4 contact.

Within the eastern part of the complex, the granodiorite has not been effected by this later solid state deformational event (see sub-section 6.4.2), and so maintains many of its 'magmatic' features. The plagioclase (andesine to oligoclase) phenocrysts are generally subhedral up to 10 mm long, and are oscillatory zoned. Biotite and amphibole often form smaller phenocrysts up to 5 mm in length, and often group to form mafic clusters. Alkali feldspar (sometimes microperthitic) generally occurs as an interstitial phase, forming anhedral crystals < 1.5 mm. Quartz is interstitial, forming anhedral to subhedral crystals. Accessory minerals include opaques, sphene, and small amounts of zircon. Chlorite and epidote occur as common alteration products.

6.2.3 G3: The Strath Ossian Early Microgranites

Cross cutting both G1 and G2 is a minor suite of microgranitic sheets and veins with varying attitudes and orientations, which have been subsequently cross cut by the emplacement of G4. They are leucocratic, fine- to medium-grained monzogranite-syenogranite sheets, which are generally < 15 cm thick.

General petrographical description

The Strath Ossian Early Microgranites: a fine- to medium-grained, equigranular monzogranite-syenogranite facies. Essentially composed of alkali feldspar (30-40 %) (which gives it a pinkish appearance), quartz (30-45 %), plagioclase (20-25 %), biotite (up to 10 %) and subsidiary amphibole. Iron ores occur as accessory minerals.

6.2.4 G4: The Fersit Marginal facies

This is a 30-40 m wide sheet-like marginal facies of K-feldspar megacrystic granite, which has intruded predominantly along the western flank of G2 (Fig. 6.2 & 6.3). This marginal phase contains megacrysts (1-3 cm in length) of microperthitic K-feldspar and plagioclase.

General petrographical description

The Fersit marginal facies: this is a coarsely porphyritic monzogranite-syenogranitic phase, containing megacrysts of microperthitic K-feldspar (35-50 %) and plagioclase (20-25 %). These crystals are tabular, 1-3 cm in length and are generally sericitised. Smaller phenocrysts include biotite (up to 5 %) and subsidiary hornblende. These phenocryst phases are set in a groundmass of quartz (up to 35 %), biotite, and hornblende. The biotite and hornblende crystals often form mafic clusters, which have been generally highly altered to chlorite. Accessory minerals include opaques, sphene, apatite and minor amounts of zircon. Muscovite and andalusite may occur.

.2.5 G5: The Strath Ossian Late Microgranites

Cross cutting all the earlier intrusive phases (G1/G2/G3/G4) is a minor suite of nicrogranitic sheets. They have varying attitudes and orientations, but are often gently lipping. As with the G3 phase, the sheets rarely exceed 15 cm in thickness, but a few may occasionally reach up to 0.5 m in width.

General petrographical description

Minor granitic facies: a fine-grained, fairly equigranular monzogranite-syenogranite. Essentially composed of quartz (up to 45 %), alkali feldspar (30-40 %), plagioclase (20-25 %), biotite (up to 18 %) and subsidiary hornblende. Iron ore is the most predominant accessory mineral.

,3 GEOCHEMICAL ANALYSIS OF THE STRATH OSSIAN COMPLEX: ORIGIN AND EVOLUTION

Originally, the first surveyors (Hinxman *et al.* 1923) thought that the Strath Ossian luton could represent part of the Rannoch Moor complex, separated by a narrow strip of IW-SE-trending schists. This metasedimentary screen either being a rooted unit or a roof endant. Petrographically the two plutons are very similar (see Anderson 1956; Clayburn 981; Henderson 1982), however, (as mentioned in Ch. 5, Section 5.3) their isotopic haracteristics (Clayburn 1981; Leighton 1985) suggests that the two intrusive bodies are istinct in terms of age and source.

Isotopically, the primary source magma of the main phase (G2) of the Strath Ossian omplex appears to have been derived from a juvenile, mantle-source melt, which possess ome lower crustal contamination (Clayburn 1981). The relative proportions of Sr and Pb, ndicates that the magma underwent late-stage contamination by local Dalradian etasedimentary crust (see Clayburn 1981).

6.4 FABRIC DEVELOPMENT: EVOLUTION OF MICROSTRUCTURES

This Section will discuss the type of fabrics and microstructures which are common within the intrusive phases of the Strath Ossian complex, and will briefly outline the fundamental processes operating during their evolution. Within the complex a whole range of fabric types are observed; from the magmatic state, through the crystallisation transition, and into the solid state regime. It is not intended as an extensive account of the textural development and mechanisms operating during fabric evolution.

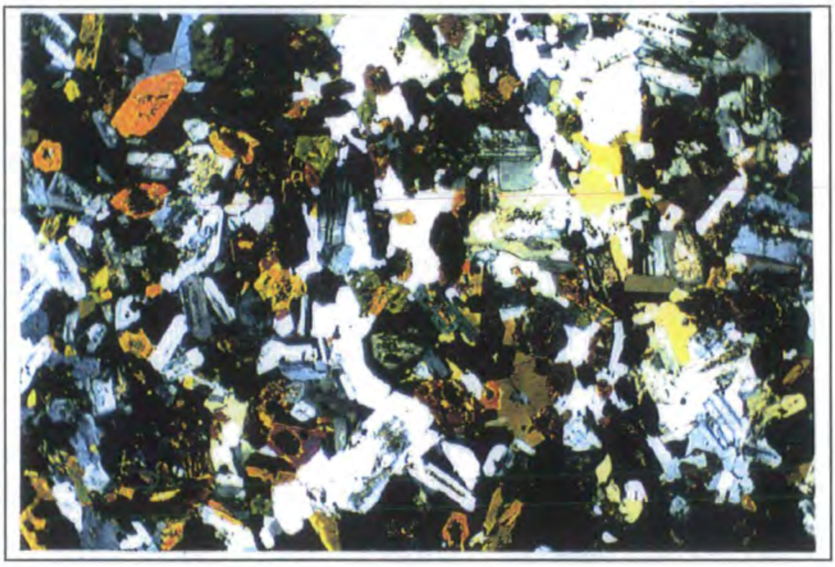
6.4.1 G1: The Meall Dhearcaig facies

6.4.1.1 Pre-full crystallisation (PFC) fabrics or magmatic state fabrics

Within the several discrete bodies of G1 at the centre of the complex (see sub-section 6.2.1) pre-full crystallisation fabrics are extremely rare. The majority of these PFC fabrics have been modified by a moderately intense solid state deformation (see sub-section 6.4.1.2), often resulting in the overprinting and obliteration of the pre-existing fabric. Where PFC fabrics are preserved, they are generally most apparent in the coarser-grained quartz-dioritic varieties (Plates 6.6 & 6.7), forming weak fabrics with various orientations.

PFC fabrics are more commonly developed within the appinitic/dioritic sheets and dykes exposed in the Uisge Labhair river section (Fig. 6.4). As mentioned in sub-section 6.2.1, a large number of these dyke-like bodies trend approximately 130-140°, sub-parallel o the long axis of the pluton. The majority of these 'dykes' possess a contact-parallel, weak to moderate PFC fabric. Most of these intrusives exhibit synplutonic relationships with G2 (see sub-section 6.2.1), and a few of these G1 sheet-like bodies, with somewhat harper, planar contacts, clearly cross cut G2. This slightly later G1 phase, is often haracterised by the development of an intense PFC fabric within the adjacent wall rocks of he G2 host.

late 6.6. Hand-specimen of G1 from one of the several discrete bodies at the centre of the complex [NN 05 748]. It possesses a moderate PFC fabric predominantly defined by plagioclase phenocrysts, which is verprinted by an oblique, weakly developed solid state overprint. The resultant CPS fabric is defined by ent, reorientated biotite laths. (Yellow 'bar' is approximately 2 cm long).



ate 6.7. Photomicrograph of hand-specimen shown in Plate 6.6. (Field of view approximately 18 mm).

General description of microstructural characteristics:

The Meall Dhearcaig facies (PFC fabrics): weak to moderately developed PFC fabrics may occur, defined by euhedral to subhedral zoned plagioclase phenocrysts (15-20 %), and microphenocrysts of biotite (20-25 %) and amphibole (10-30 %). These phases are internally undeformed and set in an undeformed matrix of alkali feldspar, quartz and biotite.

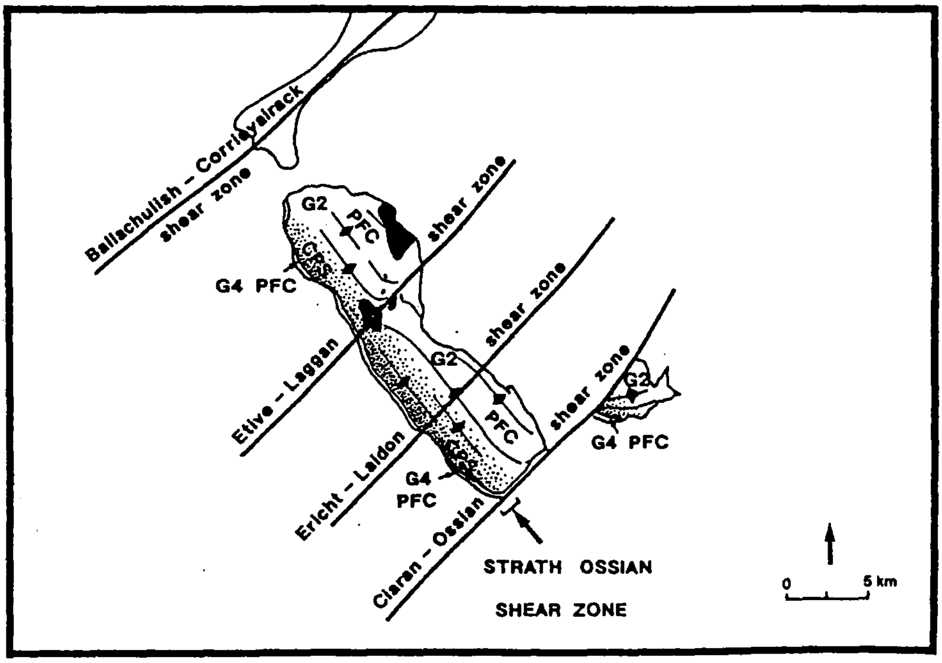
6.4.1.2 Crystal plastic strain (CPS) fabrics or solid state fabrics

At the centre of the complex, many of the discrete bodies of quartz-diorite (G1) possess a weak to moderate CPS deformational overprint. By definition, these fabrics occurred after the magma had reached its RCMP (see Ch. 1), at or below the solidus temperature of its constituent minerals. The resultant CPS fabric often obliquely overprints the pre-existing PFC fabric where the latter is preserved. The CPS fabric is defined by the elongation of quartz crystals and the reorientation of biotite crystals, and microstructural features suggest that the fabric has developed at high to moderate temperatures (see below).

General description of microstructural characteristics:

High to moderate temperature CPS fabrics within the Meall Dhearcaig facies: the majority of the quartz-dioritic phase possesses a relatively high to moderate temperature, weak to moderately developed CPS fabric. It is characterised by the internal ductile deformation of interstitial quartz (up to 12 %), producing a lenticular form and undulose extinction. Biotite (20-35 %) crystals are often bent and kinked due to deformation in the solid state. The CPS fabric is defined by the elongation of the quartz crystals and the reorientation of the biotite laths.

However, within the western part of the complex many of the isolated quartz-ioritic bodies possess a moderately intense, low temperature NW-SE-trending solid state abric (see below), whereas in the east the CPS fabrics are high to moderate temperature (as escribed above). Those in the west developed at low temperatures, and occur in a broad one of NW-SE-trending fabric orientation. This zone of deformation is approximately 0.5 m, up to 1 km wide, and extends along the western flank of the complex (see Fig. 6.4). his broad zone of deformation will be referred to as the "Strath Ossian shear zone" or the Strath Ossian lineament" within this contribution. The moderately developed, low emperature CPS deformation within G1 and G2 (see sub-section 6.4.2.2), is characterised y the development of quartz ribbons. The sigmoidal nature of these quartz ribbons implies sinistral sense of motion along the NW-SE-trending shear zone. Many of the crystals, oth phenocryst and interstitial phases, have undergone dynamic recrystallisation and issolution, leading to a reduction in grain-size and the formation of fine-grained ggregates. Plagioclase phenocrysts are often broken and fractured indicating deformation t temperatures of < 450°C (Simpson 1985). There is a progressive decrease in the amount f low temperature solid state overprint moving away from the G4/G2 contact and into the ain part of the complex; indicating that the solid state deformation was localised along the estern flank of the complex. This is verified by an apparent increase in strain from X/Z atios of microgranitoid enclaves (see Fig. 6.4). This deformation occurred after both G1 nd G2 had fully crystallised, and as discussed later, is probably due to the emplacement of 4 as a sheet-like body along the zone of shear (see sub-sections 6.4.2.2 & 6.4.4.1).



g. 6.4. Generalised map showing the distribution of PFC and CPS fabrics throughout G1 and G2 of the rath Ossian complex. It shows the position of the broad zone of deformation along the western flank of the mplex, termed here the "Strath Ossian shear zone". Major NE-SW-trending Caledonian shear zones are o shown. Representative mean X/Z values of microdioritic enclaves are shown.

General description of microstructural features:

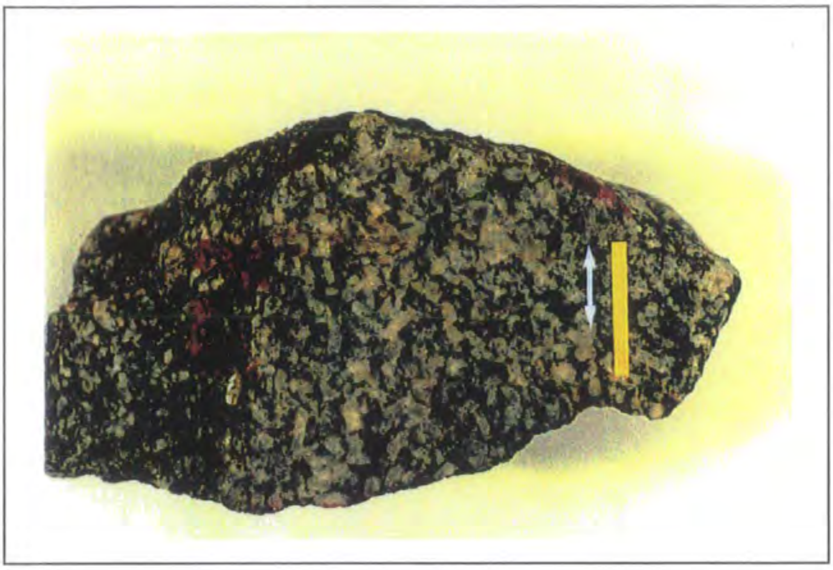
Low temperature CPS fabric within the Meall Dhearcaig facies: The most prominent microstructural feature of this fabric is the development of elongate and flattened polycrystalline quartz lenses/ribbons which tend to define the orientation of the fabric. Feldspar and hornblende phenocrysts may be fractured, indicating deformation at temperatures < 450°C (Simpson 1985). A large number of the feldspar crystals have undergone sericitisation. Interstitial feldspar, quartz and mica have often undergone recrystallisation to finer-grained aggregates. Both mica and hornblende may form extremely elongate laths, showing evidence of kinking and bending, often wrapping themselves around feldspar phenocrysts. In general there is a progressive grain-size reduction as the CPS deformation intensifies towards the G4 contact.

.4.2 G2: The Sgòr Choinnich facies

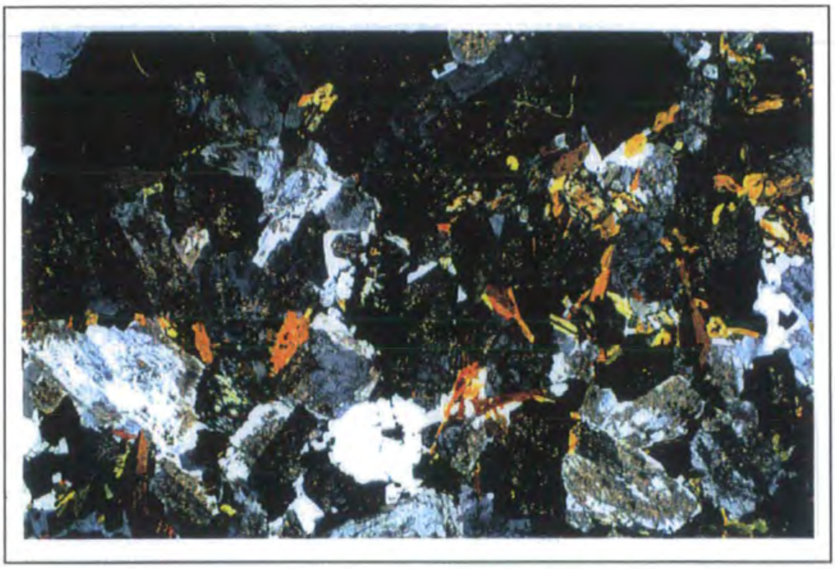
.4.2.1 Pre-full crystallisation (PFC) fabrics or magmatic state fabrics

The majority of G2 contains a pervasive, moderately developed NW-SE-trending, pproximately vertical PFC fabric (Plates 6.8 & 6.9). This is parallel to both sheets (1-2 m ide) (see Section 6.5) developed throughout the complex, and to the NW-SE-trending trath Ossian shear zone developed along the western flank of the complex, and to the verall linear trend of the pluton (Fig. 6.4). As with G1, these PFC fabrics are overprinted y NW-SE, low temperature, solid state fabrics in the west of the area; being only preserved ithout overprint in the eastern part of the complex.

The orientation of the PFC fabric is locally modified along three regional scale, NE-W-trending shear zones. These are the north-eastward continuation of: (i) the Etive-aggan shear zone (see Ch.'s 3, 4, 5 & 9), which runs through the centre of the complex; i) the Ciaran-Ossian shear zone (see Ch.'s 4, 5 & 9); and (iii), the Ericht-Laidon shear one (see Ch.'s 5 & 9) (Fig. 6.4). A sigmoidal PFC fabric trace across all three shear zones nd an intensification of the fabric indicates their influence during the emplacement of G2 nd during its crystallisation (Fig. 6.4). This deflection in PFC trend indicates a shear zone idth of approximately 0.5 to 1 km for the Etive-Laggan and Ericht-Laidon shear zones, nd approximately 0.5 to 0.75 km for the Ciaran-Ossian shear zone. At the centre of the rger shear zones the fabric has been progressively rotated to form a localised zone of NE-W-trending fabrics. However, along the Ciaran-Ossian shear zone this is somewhat more mplicated. Within the centre of the shear zone, along the Uisge Labhar river section, nes possessing PFC fabrics and microgranitoid enclaves orientated NW-SE, alternate ith zones in which the PFC fabric and microgranitoid enclaves are aligned NE-SW. The zones range from approximately 20-30 m wide, up to 45 m, and the change in fabric orientation appears to be almost instantaneous (see Fig. 6.5), suggesting an area of heterogeneous strain.



late 6.8. Hand-specimen of G2 showing a typical moderately developed PFC fabric. It possesses a slight, oplanar solid state overprint. (Yellow 'bar' is approximately 2 cm long).



ate 6.9. Photomicrograph of hand-specimen shown in Plate 6.8. (Field of view approximately 18 mm).

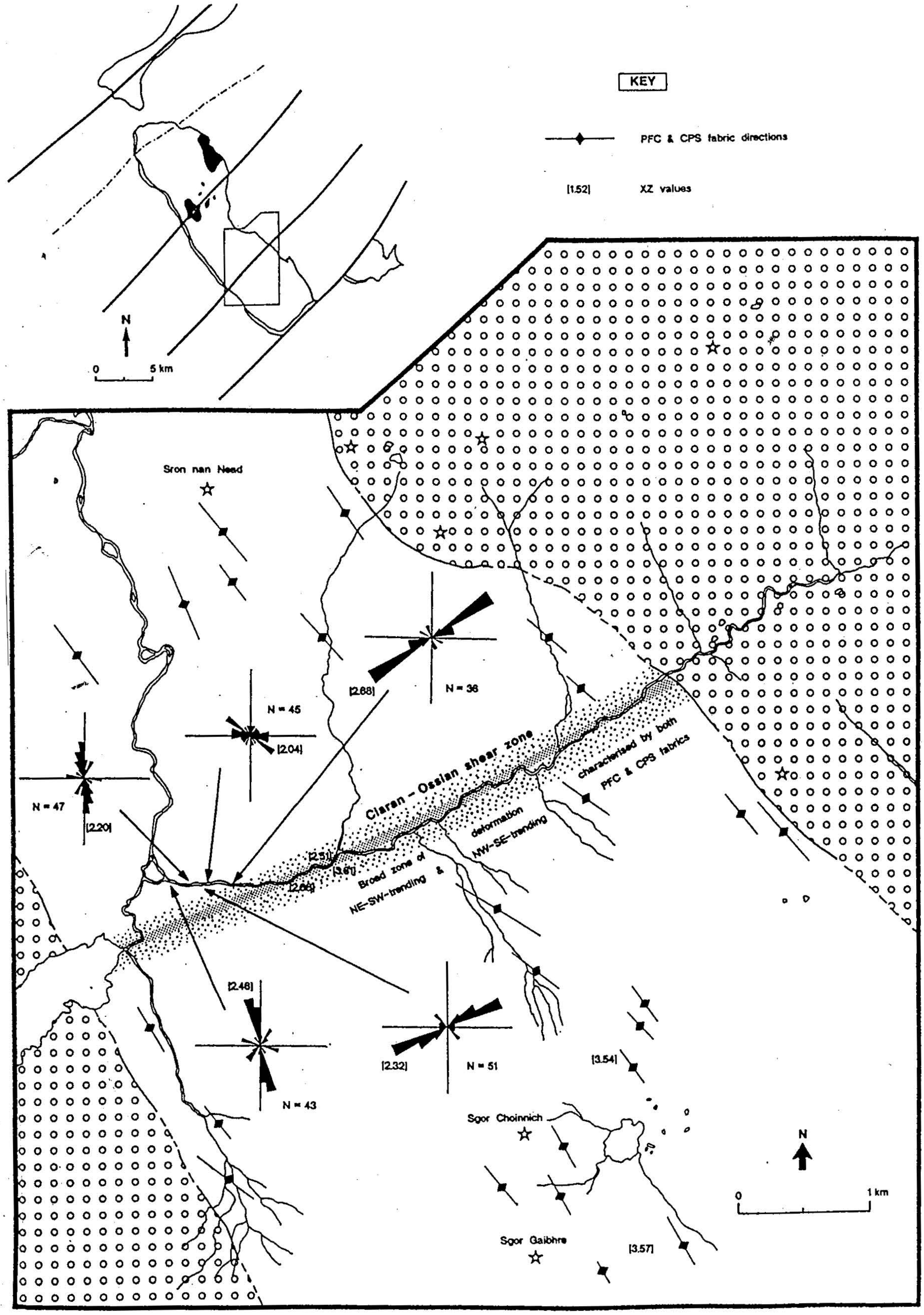


Fig. 6.5. Fabric orientation and strain distribution along the Ciaran-Ossian shear zone (Uisge Labhar river section). Rose diagrams show orientation of X-axis of microdioritic enclaves and country rock xenoliths (generally psammite).

General description of microstructural characteristics:

The Sgòr Choinnich facies (PFC fabrics): these are generally well developed throughout the central and western parts of the complex, due to the porphyritic nature of the granodioritic phase. All crystal phases are undeformed, and the fabric is predominantly defined by the alignment of plagioclase phenocrysts (40-50 %). Other phenocryst phases which are often aligned include biotite (up to 15 %), amphibole (up to 10 %), and to a lesser extent alkali feldspar (< 8 %). A large percentage of the alkali feldspar occurs as an interstitial phase with quartz (15-25 %).

A moderate to intense sub-horizontal stretching lineation is often developed, generally defined by the plagioclase and biotite crystals.

6.4.2.2 Crystal plastic strain (CPS) fabrics or solid state fabrics

As with G1, solid state fabrics are developed within G2 in a broad zone, approximately 0.5 km wide, which extends NW-SE along the western flank of the complex (the Strath Ossian shear zone; Fig. 6.5). These are NW-SE orientated, moderately developed, low temperature CPS fabrics, whose development is attributed to deformation in the Strath Ossian shear zone during the emplacement of the 30-40 m wide sheet-like marginal facies, G4 (Fig. 6.5; see sub-section 6.4.4). The resultant imposition of strain has led to the development of sinuous quartz ribbons and the fracturing of plagioclase crystals in G2. This low temperature solid state overprint is coplanar with the pre-existing PFC fabric.

During the emplacement of G4, the Ericht-Laidon shear zone was also initiated (see sub-section 6.4.4). This resulted in the localised development of a low temperature CPS fabric, trending NE-SW parallel to the zone of shear, within G2 (Fig. 6.4). This low temperature, solid state overprint indicates that G2 had fully crystallised before movements along the Ericht-Laidon shear zone were reassumed, allowing the emplacement of G4.

Relatively high to moderate temperature CPS fabrics are rare with the majority occurring locally along the Etive-Laggan and Ciaran-Ossian shear zones (Plates 6.10 & 6.11).

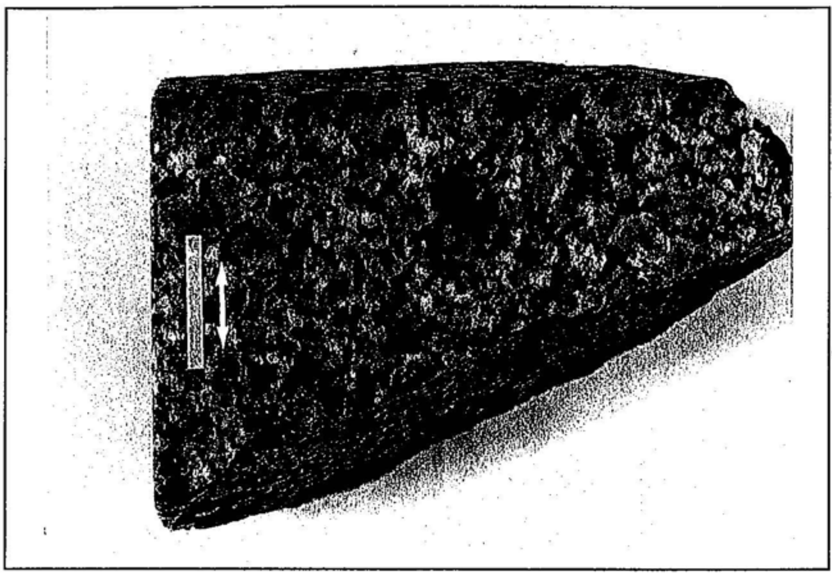


Plate 6.10. Hand-specimen of G2 from the Uisge Labhair stream section. It possesses a PFC fabric which has been overprinted by a high to moderate temperature, coplanar CPS overprint. Note its semi-annealed texture compared to Plate 6.8. (Yellow 'bar' is approximately 2 cm long).

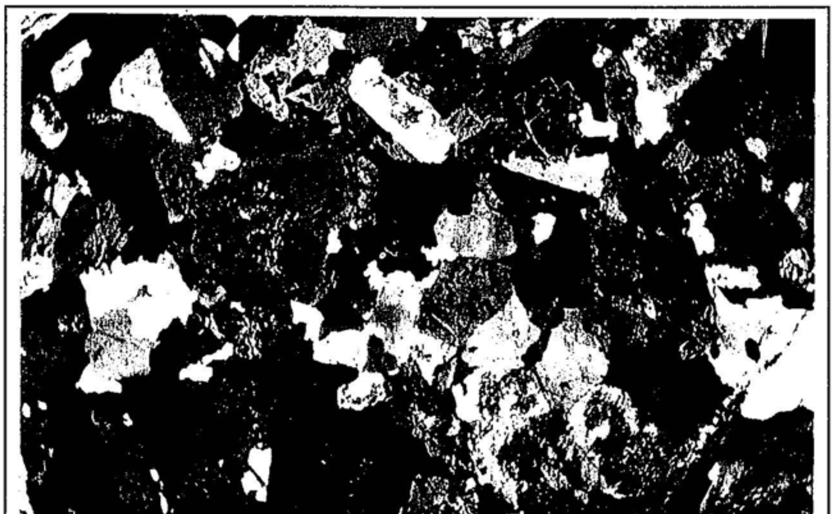


Plate 6.11. Photomicrograph of hand-specimen shown in Plate 6.10. (Field of view approximately 18 mm).

General description of microstructural characteristics:

The Sgòr Choinnich facies (CPS fabrics) : these are predominantly low temperature CPS fabrics developed within: (i) a NW-SE-trending zone approximately 0.5 km wide, along the western flank of G2; and (ii) a localised zone along the Ericht-Laidon shear zone. Both zones are characterised by plagioclase (40-50 %) and alkali feldspar (< 20 %) crystals which have undergone recrystallisation processes. Euhedral plagioclase crystals have often become subhedral by sub-graining and recrystallisation of their margins. Myrmekite is present as an intergrowth with quartz. Biotite (up to 15 %) is generally kinked and bent around the feldspar phenocrysts, forming stringers. Quartz (15-25 %) crystals have become elongate and flattened, forming polycrystalline lenses and sinuous quartz ribbons which define the CPS fabric. Many of the feldspar and hornblende crystals are fractured, indicating deformation at temperatures < 450° C (Simpson 1985). Many of the feldspars have undergone sericitisation and there is a progressive decrease in grain-size as the solid state deformation increases towards the contact with G4.

Summary of general microstructural features developed within G1 and G2:

① The major occurrence of G1 is at the centre of the complex, forming several discrete bodies. Their distribution essentially forms a sub-elliptical core to the complex. Within G1, pre-full crystallisation fabrics are extremely rare, and are generally preserved in the east of the complex where they are weakly developed and have various orientations.

② Many of the G1 bodies possess weak to moderately developed, high to moderate temperature CPS fabrics. The solid state deformation generally obliquely overprints the pre-existing (PFC) fabric.

③ The majority of G2 contains a pervasive, vertical NW-SE-trending PFC fabric, which is parallel to both sheets developed throughout the complex, and the overall linear trend of the pluton.

④ The orientation of the PFC fabric developed within G2, is locally modified along three major NE-SW-trending fault zones: the Etive-Laggan, Ciaran-Ossian and Ericht-Laidon structures. Across all three zones the PFC fabric has been deflected to form a sigmoidal fabric trace indicative of a sinistral sense of shear across these structures. This implies that these structures were acting as major sinistral ductile shear zones during the construction of G2.

⑤ Within the west of the complex, solid state deformation occurred at low temperatures. The resultant CPS fabric, developed both within G1 and G2, is characterised by the development of quartz ribbons. The sigmoidal form of the quartz ribbons suggests a sinistral sense of motion during their development. These fabrics are confined to a zone of deformation approximately 0.5-1 km wide along the western flank of the pluton (termed here the "Strath Ossian shear zone"). The fabrics trend NW-SE parallel to the orientation of the shear zone.

⑥ A low temperature, CPS fabric is also localised within G2, along the NE-SW-trending Ericht-Laidon fault zone. The resultant fabric trends NE-SW parallel to this structure.

Model proposed:

A simple model to account for all these features could be:

❶ As mentioned in sub-section 6.2.1, G1 essentially forms a NNE-SSW-trending sub-elliptical core to the complex. It is likely that it has been sited at the intersection of the Strath Ossian shear zone and the Etive-Laggan fault (Fig. 6.4) (the latter structure also acting as a major ductile shear zone during the emplacement of G1 and G2 (see sub-sections 6.4.1 & 6.4.2)).

❷ The distribution of G1 suggests that this mass was subsequently rotated and disrupted by the intrusion of G2 shortly after its emplacement, resulting in G1 forming several discrete bodies and the development of a high to moderate temperature solid state fabric.

❸ The predominant NW-SE-trending PFC fabric within G2 is parallel to both sheets developed throughout the complex, the linear trend of the pluton and to a broad zone of deformation (approximately 0.5-1 km wide) developed along the western flank of the complex, termed here the "Strath Ossian shear zone" (see below). These features, together with chilled contact relationships between sheets, may suggest that G2 was constructed by a process of multiple sheeting along the Strath Ossian shear zone, with sheets being preferentially intruded from E to W (see Section 6.5). The NW-SE-trending PFC fabric is locally modified across three regional scale, sinistral NE-SW-trending shear zones. A component of sinistral shear across the NW-SE-trending Strath Ossian shear zone (deduced from the reorientation of regional folds and ductile planar fabrics (see Section 6.6), combined with movements along the NE-SW-trending shear zones, may have produced a pull-apart structure (Fig. 6.6a), allowing G2 to be emplaced predominantly by a process of multiple sheeting along the actively transtensional Strath Ossian shear zone.

❹ The low temperature solid state fabrics developed within G1 and G2 along the western flank of the pluton (Fig. 6.6b) are attributed to a later episode of deformation along the NW-SE-trending Strath Ossian shear zone. This deformation occurred after G1 and G2 had fully crystallised, and allowed the emplacement of G4 as a sheet-like body along the Strath Ossian shear zone (see sub-section 6.4.4). Along the Ericht-Laidon fault zone, the spatial distribution of G4, and its marked swing in PFC fabric trend, (see sub-section 6.4.4.1), suggests that this structure was an active shear zone during the emplacement of G4, resulting in the development of low temperature CPS fabrics within G2, localised along this zone.

❺ Field and microstructural evidence therefore suggests that the NW-SE-trending Strath Ossian lineament, which has been interpreted by Forrest and Key (1989; see Section 6.1) as the trace of a major deep-seated basement fracture, was acting as a major ductile shear zone during the construction of the Strath Ossian complex.

6.4.3 G3: The Strath Ossian Early Microgranites

Fabrics within this phase are uncommon. However, within the NW-SE-trending zone of high strain developed within G2 (the Strath Ossian shear zone), these microgranitic sheets show microstructural evidence of ductile and brittle deformation. Quartz (30-45 %) may have been deformed to form elongate crystals, which together with the reorientation of biotite (up to 10 %) may form a very weak, low temperature CPS fabric. The fabric trends approximately NW-SE parallel to the solid state overprint developed within G2. The biotite laths are often bent, kinked and sometimes fractured around feldspar phenocrysts. Alkali feldspar (30-40 %) and plagioclase may have undergone recrystallisation and sub-graining, and the larger phenocrysts are often fractured. This low temperature solid state overprint implies that deformation occurred along the NW-SE-trending Strath Ossian shear zone after this intrusive phase had fully crystallised.

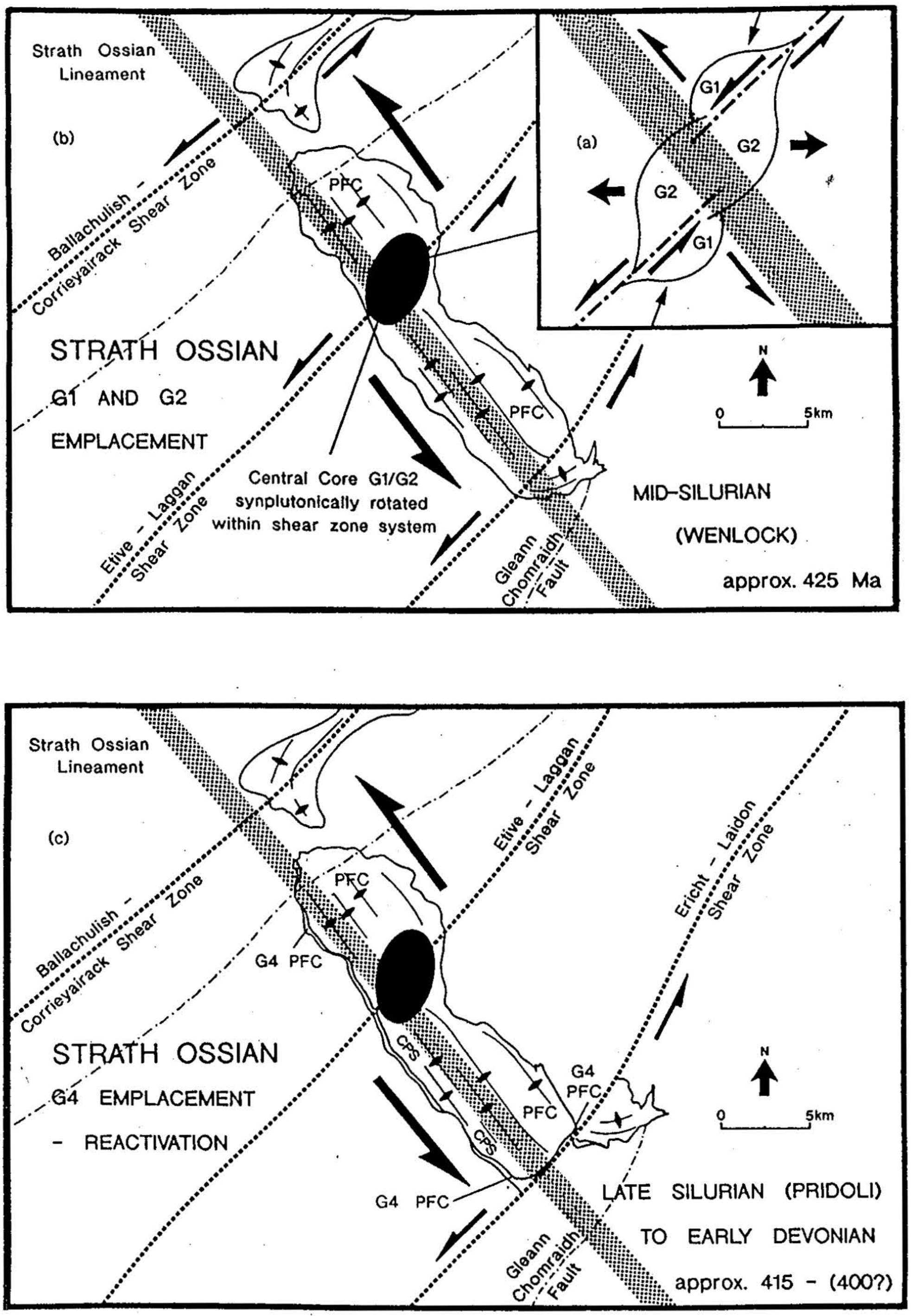


Fig. 6.6. Inset **(a)** shows an idealised model of the initial stages of G1 and G2 emplacement. Generalised model showing the distribution of PFC and CPS fabrics related to the emplacement of **(b)** G1 and G2 and **(c)** G4 of the Strath Ossian complex. (N.B. The minor Ciaran-Ossian shear zone is not shown).

6.4.4 G4: The Fersit Marginal facies:

6.4.4.1 Pre-full crystallisation (PFC) fabrics or magmatic state fabrics

This 30-40 m wide sheet-like marginal facies has predominantly intruded along the western flank of G2. It generally possesses a moderate PFC fabric (Plates 6.12 & 6.13), which is vertical and contact parallel, rotating into a NE-SW direction along the Ericht-Laidon shear zone (see Fig. 6.6b). The spatial distribution of G4 and the orientation of its PFC fabrics suggests that both the NW-SE-trending Strath Ossian shear zone and the NE-SW-trending Ericht-Laidon shear zone were active during its emplacement. This episode of movement explains the development and distribution of low temperature CPS fabrics within both G1, G2 and G3 along these zones (see sub-sections 6.4.1.2, 6.4.2.2 & 6.4.3 respectively).

> *General description of microstructural features:*
>
> *The Fersit Marginal facies (PFC fabrics) :* the fabric is generally defined by microphenocrysts of plagioclase, K-feldspar, biotite, and subsidiary hornblende. The biotite and hornblende crystals sometimes form elongate mafic clusters. The K-feldspar and plagioclase megacrysts (1-3 cm in length) are generally more randomly aligned. Along the NE-SW-trending Ericht-Laidon shear zone these megacrysts may be somewhat more aligned than along the NW-SE-trending Strath Ossian lineament, possibly suggesting that the imposition of strain was of a higher magnitude and/or the imposition of strain continued for a greater duration. It is also interesting to note, that the only CPS fabrics developed within G4 (see sub-section 6.4.4.2) occur predominantly as a weak to moderate, high temperature CPS overprint along the Ericht-Laidon shear zone, indicating movement continued along that structure, after all the constituent phases within G4 had crystallised.

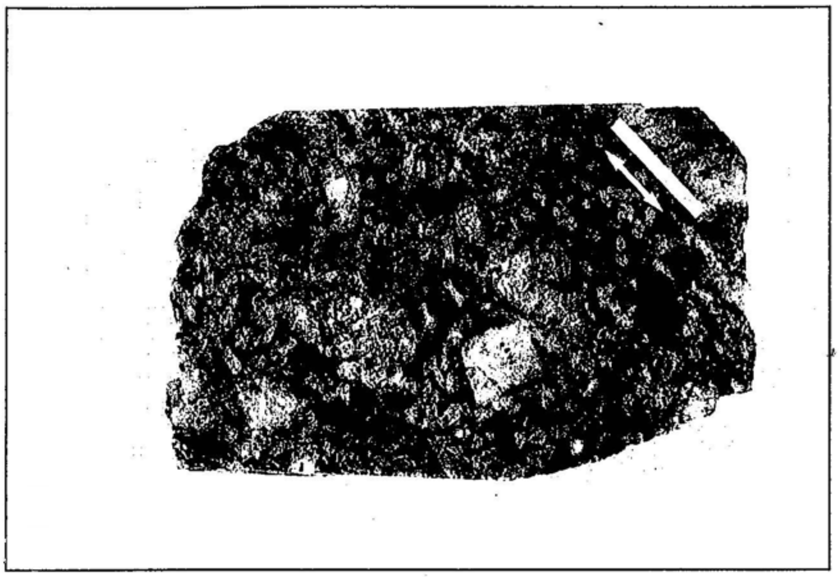


Plate 6.12. Hand-specimen of G4 from the Fersit area [NN 355 776]. It possesses a moderately developed PFC fabric which is defined predominantly by microphenocrysts of plagioclase, K-feldspar and mafics. The K feldspar and plagioclase megacrysts tend to be more randomly aligned. (Yellow 'bar' is approximately 2 cm long)

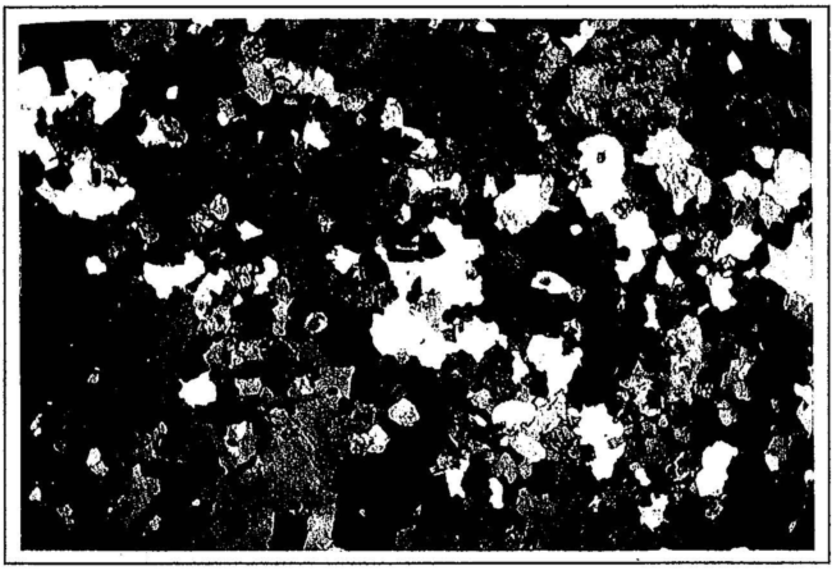


Plate 6.13. Photomicrograph of hand-specimen shown in Plate 6.12. (Field of view approximately 18 mm).

6.4.4.2 Crystal plastic strain (CPS) fabrics or solid state fabrics

As mentioned above, deformational fabrics developed within the solid state are essentially confined to the NE-SW-trending Ericht-Laidon shear zone. These are high temperature, weak to moderately developed CPS fabrics, which are coplanar to the pre-existing NE-SW-trending PFC fabric. Plagioclase and alkali feldspar megacrysts have often undergone marginal sub-graining, and recrystallisation processes have generally removed magmatic features such as zoning. Some feldspars have developed undulose extinction and deformation lamellae. Quartz crystals are generally highly strained and form lenticular crystals, which have undergone significant sub-graining and recrystallisation. Biotite laths are kinked and bent.

These features are consistent with CPS deformation at a relatively high temperature, however, the presence of broken and fractured feldspar crystals may suggest a later, low temperature, deformational event (< 450° C; Simpson 1985), associated with subsequent brittle movements along the Ericht-Laidon fault zone.

6.4.5 G5: The Strath Ossian Late Microgranites

Fabrics within this minor suite of microgranitic sheets are generally uncommon. However, the largest sheets which reach up to 0.5 m in width may possess a weak to moderately developed PFC fabric, which is defined by the alignment of alkali feldspar (30-40 %), plagioclase (20-35 %), and in particular biotite (up to 18 %) laths. The PFC fabrics are generally contact parallel. However, in a few sheets the fabric was oblique to the walls and sometimes possessed a sigmoidal form, possibly suggesting a small component of shear along its walls during its emplacement. In the majority of these cases, the sense of displacement was sinistral.

6.5 EVIDENCE FOR MULTIPLE SHEETING DURING THE EMPLACEMENT OF THE MAJOR INTRUSIVE COMPONENT, G2

The sheeted nature of G2 of the Strath Ossian complex was noted by Hinxman *et al.* (1923), suggesting similarities with the eastern part of the Rannoch Moor pluton (see Ch. 5, sub-section 5.4.2.2), where "the granite for more than a mile inward from the edge holds innumerable schist inclusions. The long axis of the larger masses, some of which are upwards of a hundred yards in length, are roughly parallel to the general strike of the arrangement. A similar complex is found on the Càrn Dearg ridge, south of Loch Ossian, and elsewhere. The same kind of plexus occurs along the margin of the Strath Ossian mass on the northern summit of Beinn Pharlagain, where the actual boundary of the granite is indeterminate, and to the north of Loch Ossian. In the last-named locality the granite envelops large masses of schist which have evidently not been disturbed, the strike of the foliation-planes being parallel to that of the schists outside the intrusion." (Hinxman *et al.* 1923)

Evidence for sheeted units within the Sgòr Choinnich facies (G2) is based on chilled contact relationships between successive sheets. The sheets on average are roughly 1 m wide and trend approximately NW-SE parallel to the Strath Ossian shear zone, and the elongation of the pluton. There is a grain-size reduction across the width of individual sheets suggesting that subsequent units were intruded against the chilled contacts of slightly earlier sheets. These relationships suggest that the sheets were preferentially intruded from east to west. Such features, together with the fabrics described in the previous sub-sections suggest that the NW-SE-trending Strath Ossian shear zone was active during the emplacement of G2. It is envisaged that this structure actively controlled the emplacement of G2 by a process of multiple sheeting along the shear zone, resulting in the development of a pervasive NW-SE-trending, vertical PFC fabric (sub-section 6.4.2.1).

6.6 SYNPLUTONIC DEFORMATION OF THE COUNTRY WALL ROCKS

The Strath Ossian pluton was emplaced into the Appin and Grampian Group metasediments, at an estimated depth of 9.5 +/- 2.0 km (Key *et al.* 1993).

Regional fold structures such as the axis of the Loch Laggan Antiform have been synplutonically rotated, from an original WSW-plunge to a steep southerly plunge as the western flank of the pluton is reached (Fig. 6.2; see Key *et al.* 1993). Fold axial traces and regional foliation trajectories mapped during this present study (Fig. 6.7; see Ch. 11) on both the eastern and western flanks of the pluton suggest that they have been synplutonically rotated during the construction of the Strath Ossian complex. This ductile deformation produced a partially concordant contact aureole, together with the possible development of slightly asymmetrical external triple points, identified by regional foliation patterns and variations of finite strain (Fig. 6.7; see Ch. 11). The rotational sense of these regional structures, from kilometre scale folds to planar fabrics, complies with the kinematic information obtained from the granitic rocks of the Strath Ossian complex; a major sinistral component along the Strath Ossian shear zone/lineament.

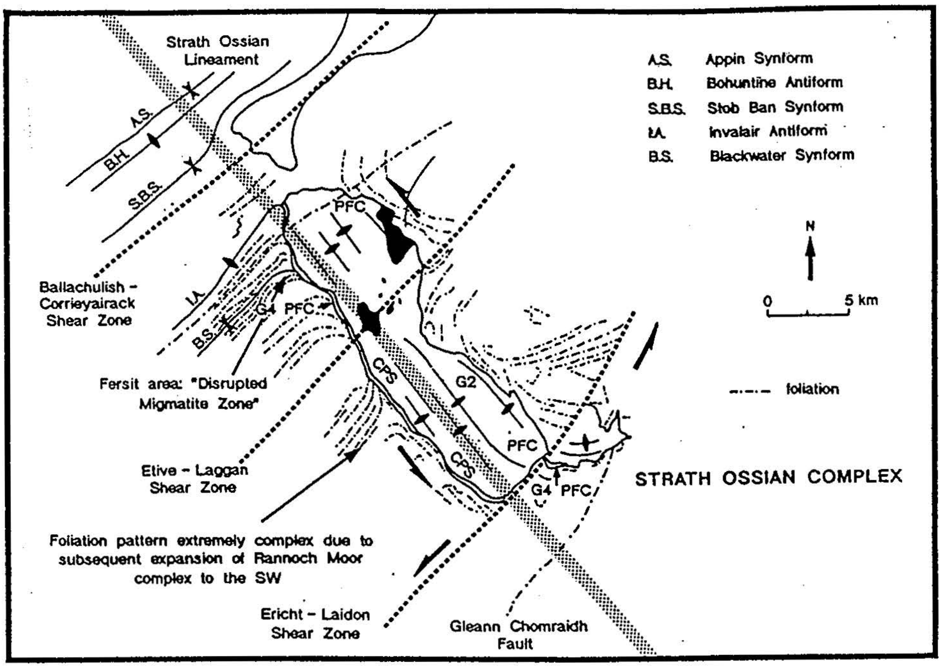


Fig. 6.7. Generalised map showing fold axial traces and regional foliation trajectories on both the eastern and western flanks of the pluton. In the extreme NW of the complex, regional fabric traces have been largely taken from Key *et al.* (1993).

Ductile deformation of the wall rocks is clearly evident along the north-western flank of the pluton, within the Fersit area (Fig. 6.7). This zone, termed here the "Disrupted Migmatite Zone", has very similar petrological and structural characteristics to that of the "Chaotic Zone" of the Ballachulish complex (see Pattison & Harte 1988; see Ch. 11). The 'Disrupted Migmatite Zone' extends for approximately 2 km and is generally between 200-300 m wide. The zone is composed of Leven Schists, which have undergone extensive migmatisation and disruption, forming angular, semipelitic and psammitic xenoliths set in a matrix of semipelitic composition. The matrix possesses an intense ductile planar fabric, trending NW-SE parallel to the contact of the pluton. Most angular xenoliths are randomly orientated, whereas some rectilinear raft type units exhibit a preferred orientation, parallel to the ductile planar fabric developed within the matrix. A sinistral sense of rotation is implied for a large number of these xenoliths, inferred by the way the ductile planar fabric within the matrix has been deflected around them.

In summary, the syn-kinematic rotation of regional structures and the development of ductile planar fabrics within the aureole of the Strath Ossian pluton, are consistent with sinistral transcurrent motion along the Strath Ossian lineament during its construction.

6.7 CONSTRUCTION OF THE STRATH OSSIAN COMPLEX: AN EMPLACEMENT MODEL

This Section summarises the most important features regarding the geometry of the pluton, the distribution of its internal intrusive phases, and its internal and external deformational characteristics in relation to major tectonic structures. An account of the predominant mechanisms operating during the construction of these individual intrusive phases are proposed, based on the data presented within this Chapter (see Fig. 6.6).

Controls on the Strath Ossian complex

❶ This is a vertical sided, linear shaped body (approximately 30 km x 6 km),markedly transverse to the regional Caledonian strike.

❷ Its long axis runs NW-SE along the Strath Ossian lineament (Forrest & Key 1989).

❸ The earliest intrusive activity is represented by the intrusion of appinite bodies at the northern most end of the Strath Ossian complex. The appinites are sited at the intersection of the Strath Ossian lineament and the Ballachulish-Corrieyairack shear zone.

This was followed by the emplacement of the Meall Dhearcaig facies (G1). These are medium- to coarse-grained quartz-dioritic to monzodioritic rocks, through to fine-grained appinitic compositions. The bulk of this facies forms a NNE-SSW-trending "sub-elliptical core" to the complex at the intersection of the Strath Ossian lineament and the Etive-Laggan fault. This "sub-elliptical core" is composed of many discrete bodies of G1, presumably originally forming a mass of quartz-diorites at the centre of the complex before being disrupted and dispersed by the emplacement of G2. High to moderate temperature CPS fabrics developed within these G1 bodies are likely to be the result of this deformation, occurring shortly after G1 had fully crystallised.

The main mass of the pluton consists of a fairly homogeneous equigranular granodiorite (G2). This facies is elongate along the lineament and has a pervasive PFC fabric trending NW-SE parallel to the long axis of the pluton. These fabrics suggest that the lineament was an active shear zone during magma intrusion, corroborated by ductile planar fabrics developed within migmatites along the western flank and the reorientation of regional folds.

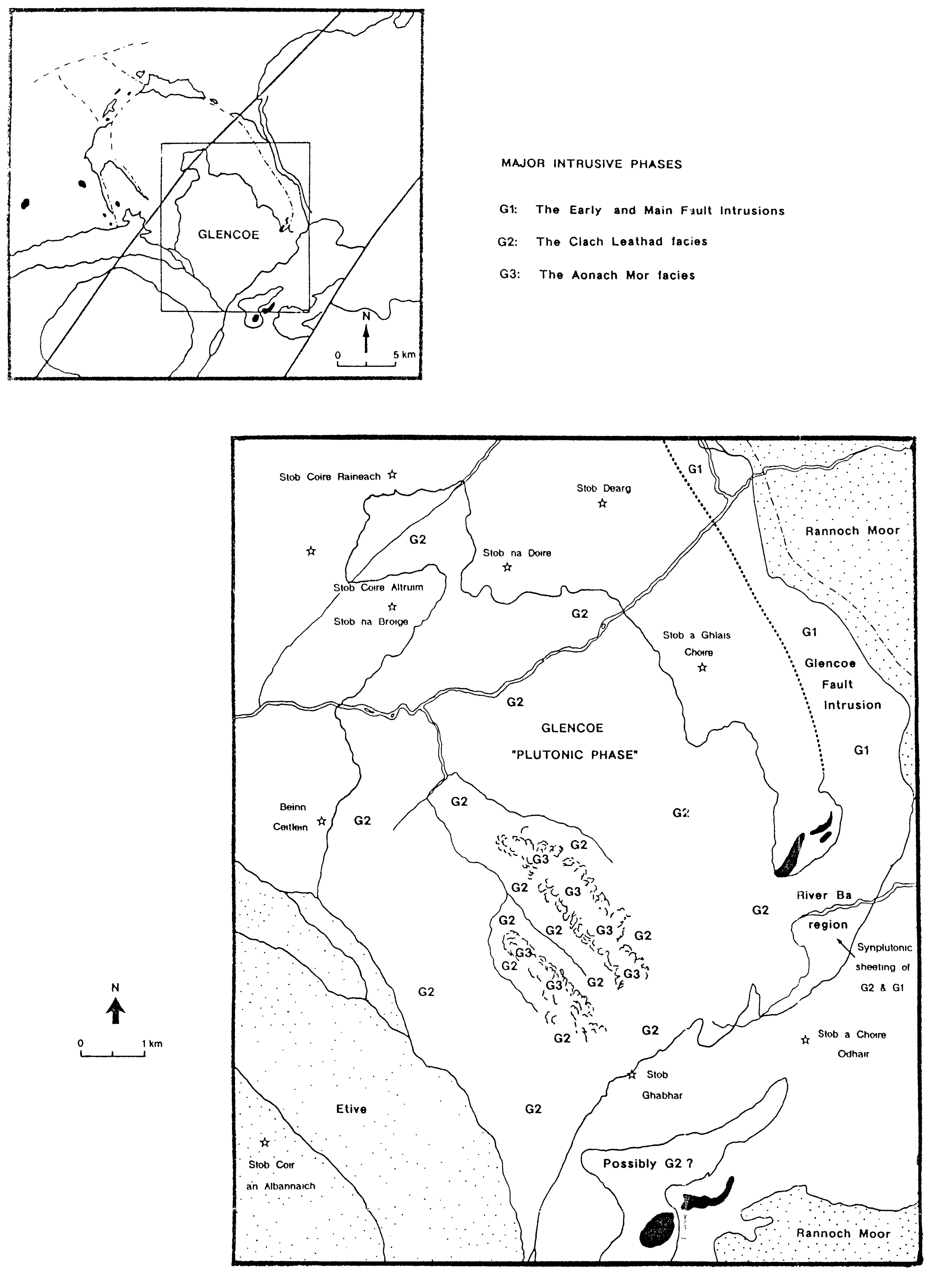
The orientation of the PFC fabric is locally modified along three regional scale, NE-SW-trending shear zones: the Etive-Laggan shear zone (0.5 to 1 km wide), the Ciaran-Ossian shear zone (0.5 to 0.75 km wide), and the Ericht-Laidon shear zone (0.5 to 1 km wide). A sigmoidal PFC fabric trace across all three shear zones and an intensification of the fabric indicates their influence during the emplacement of G2 and during its crystallisation. The complex is essentially bounded to the north by the Ballachulish-Corrieyairack shear zone (see Ch. 9) and to the south by the Ericht-Laidon shear zone. The Etive-Laggan shear zone runs through the centre of the complex. It is envisaged that the history of the Strath Ossian pluton can be explained by reactivation of the Strath Ossian lineament, which functioned as a transtensional Caledonian shear zone, interacting with the other three shear zones. Fabric analysis and field observations suggest that the NW-SE-trending Strath Ossian shear zone was actively transtensional, allowing the intrusion of G2 by a process of multiple sheeting combined with sinistral displacements along the NE-SW shear zones, producing a pull-apart structure.

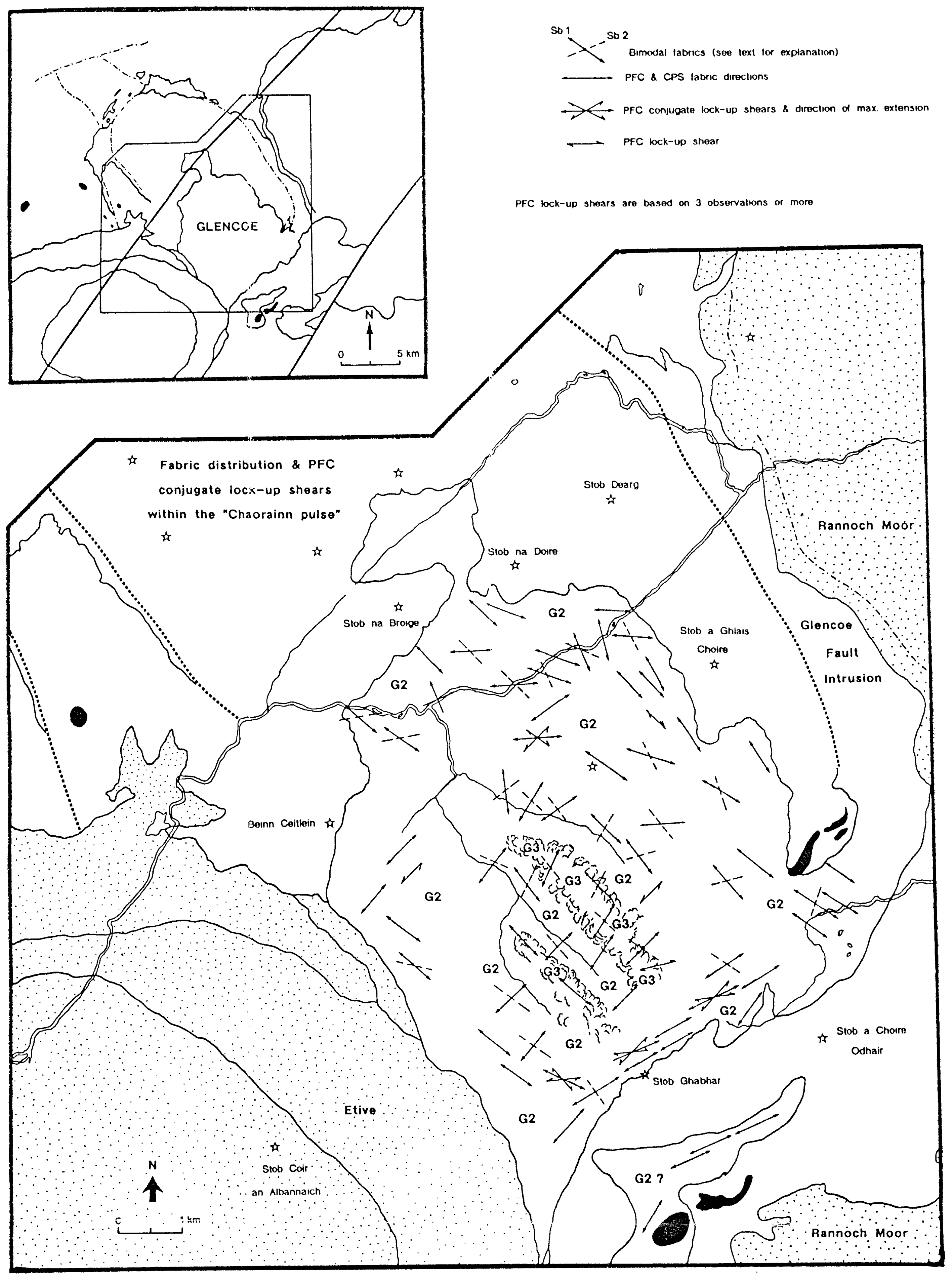
The next intrusive event was the emplacement of a minor suite of micrgranitic sheets and veins (generally < 15 cm thick), which possess varying attitudes and orientations.

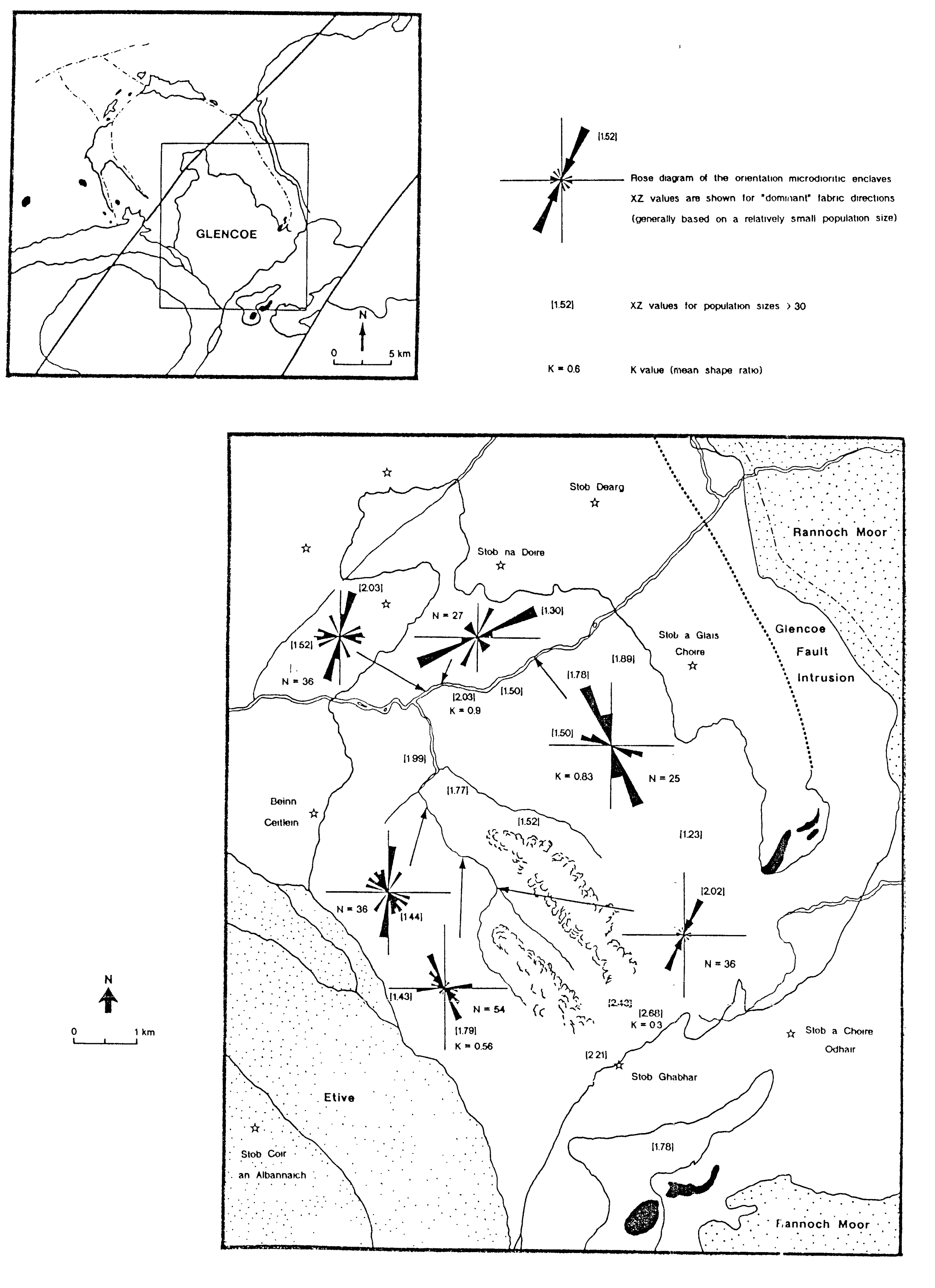
The next apparent activity along the Strath Ossian shear zone is associated with the intrusion of a 30-40 m wide sheet-like marginal facies of a K-feldspar megacrystic granite along the western flank of G2. This again possesses an intense vertical PFC fabric shown by the preferred orientation of hornblende and biotite clots and microphenocrysts of plagioclase. The megacrysts of microperthitic K-feldspar and plagioclase are generally more randomly orientated, but still possess a general NW-SE alignment. A solid state, low temperature CPS fabric developed in G1, G2 and G3, probably formed at this time. These fabrics are confined to a broad zone of deformation approximately 0.5 km wide, which extends NW-SE against G4, along the western flank of the complex. The moderately developed, low temperature CPS deformation within G1 and G2, is characterised by the development of quartz ribbons. The sigmoidal nature of these ribbons implies a sinistral sense of motion along the NW-SE-trending shear zone. Within G2, this low temperature solid state overprint is coplanar with the pre-existing NW-SE-trending PFC fabric.

The spatial distribution of G4 and the marked swing in the orientation of its PFC fabric suggests that the Ericht-Laidon shear zone was active during its intrusion. The reactivation of the Ericht-Laidon shear zone also resulted in the development of low temperature solid state fabrics within G2. This produced a localised CPS fabric trending NE-SW parallel to the zone of shear. The narrow zone of G4 along the western flank of the pluton implies that transtensional deformation across the Strath Ossian shear zone was now limited, due to the cessation of movement on the Etive-Laggan and Ballachulish-Corrieyairack systems. However, the Ericht-Laidon shear zone continued to influence the southern end of the pluton after crystallisation, by displacing it some 8 km to its present position.

The final intrusive episode was the emplacement of a minor suite of monzogranite-syenogranite sheets (G5). As with G3, they have varying attitudes and orientations, and rarely exceed 15 cm in thickness. In some of the larger sheets (up to 0.5 m wide) a PFC fabric may be developed, which occasionally exhibits a sigmoidal form. In the majority of these sheets a small sinistral component of shear along its walls during its emplacement is inferred. This may suggest that the complex as a whole was being subjected to a slight, but significant component of sinistral deformation during the emplacement of G5.







THE GLENCOE PLUTONIC COMPLEX

THE STRATH OSSIAN IGNEOUS COMPLEX

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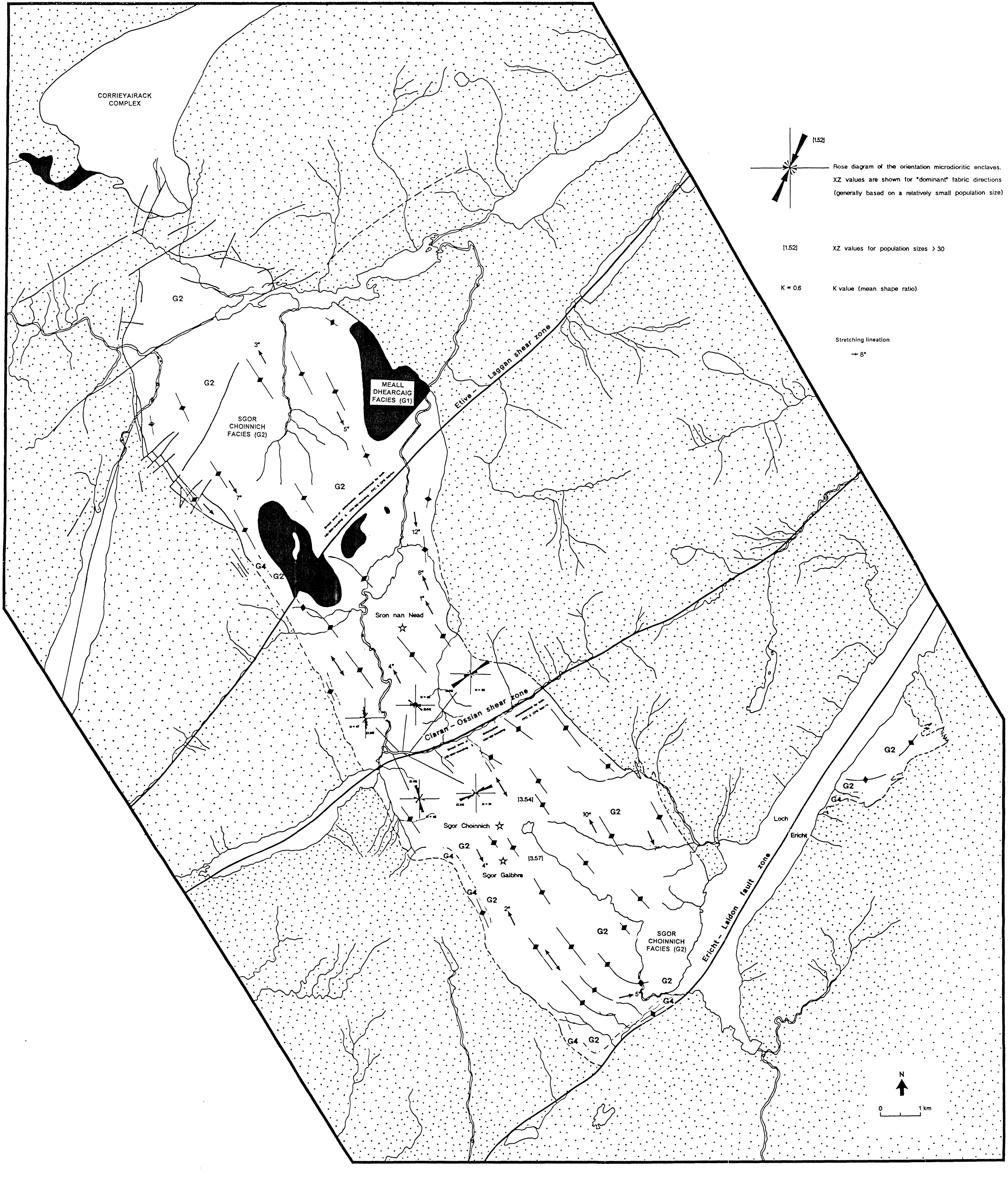
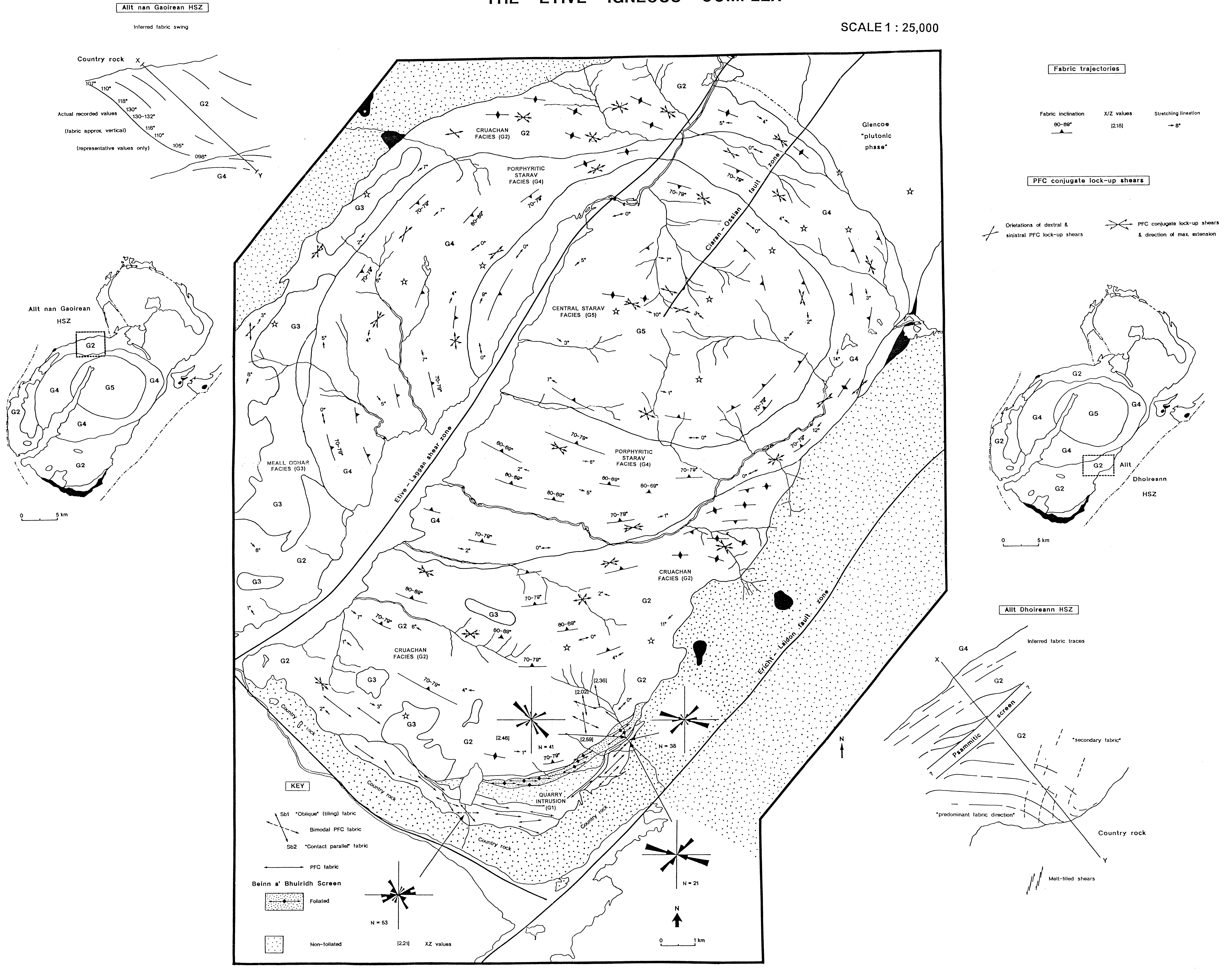


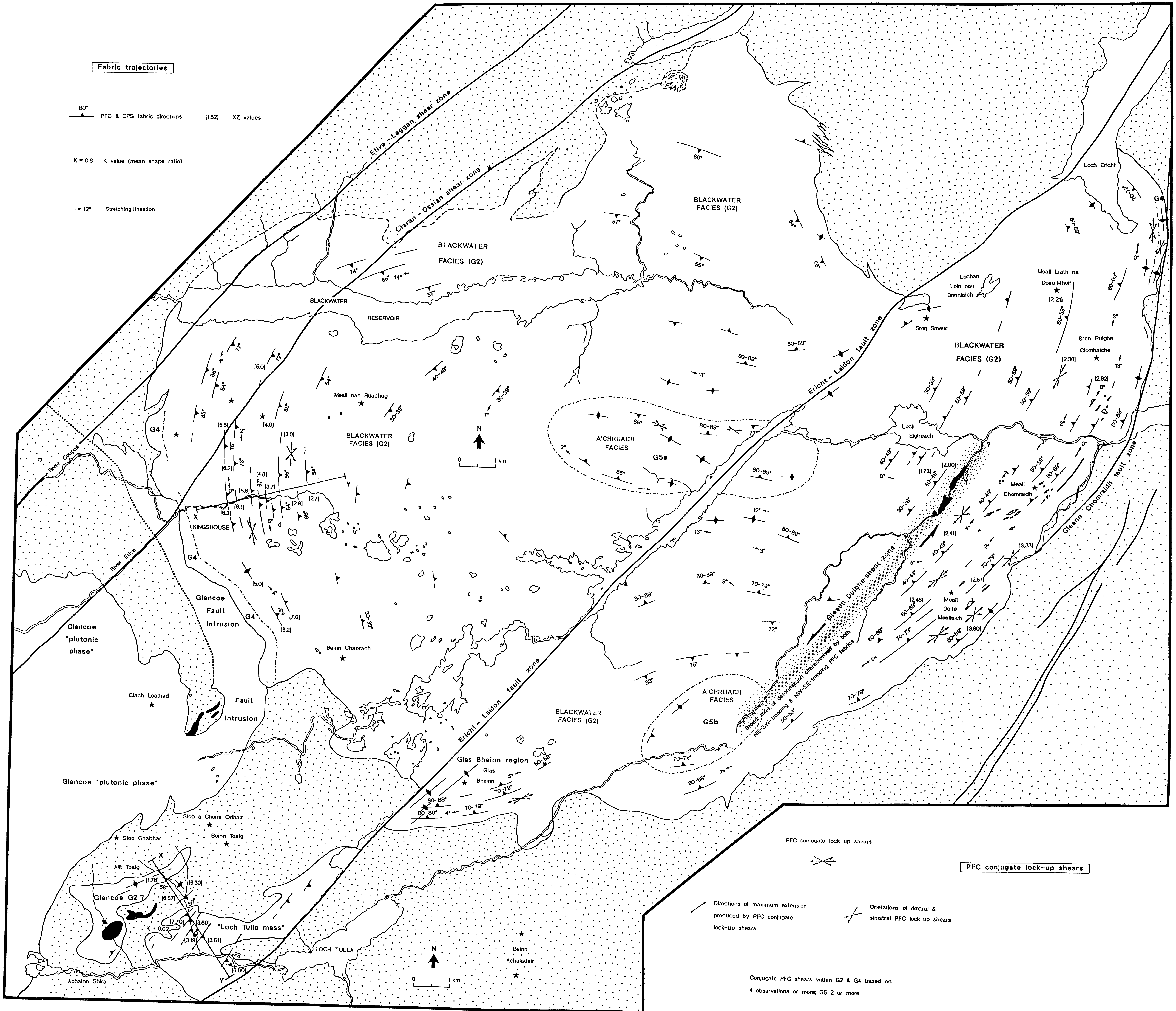
THE ETIVE IGNEOUS COMPLEX

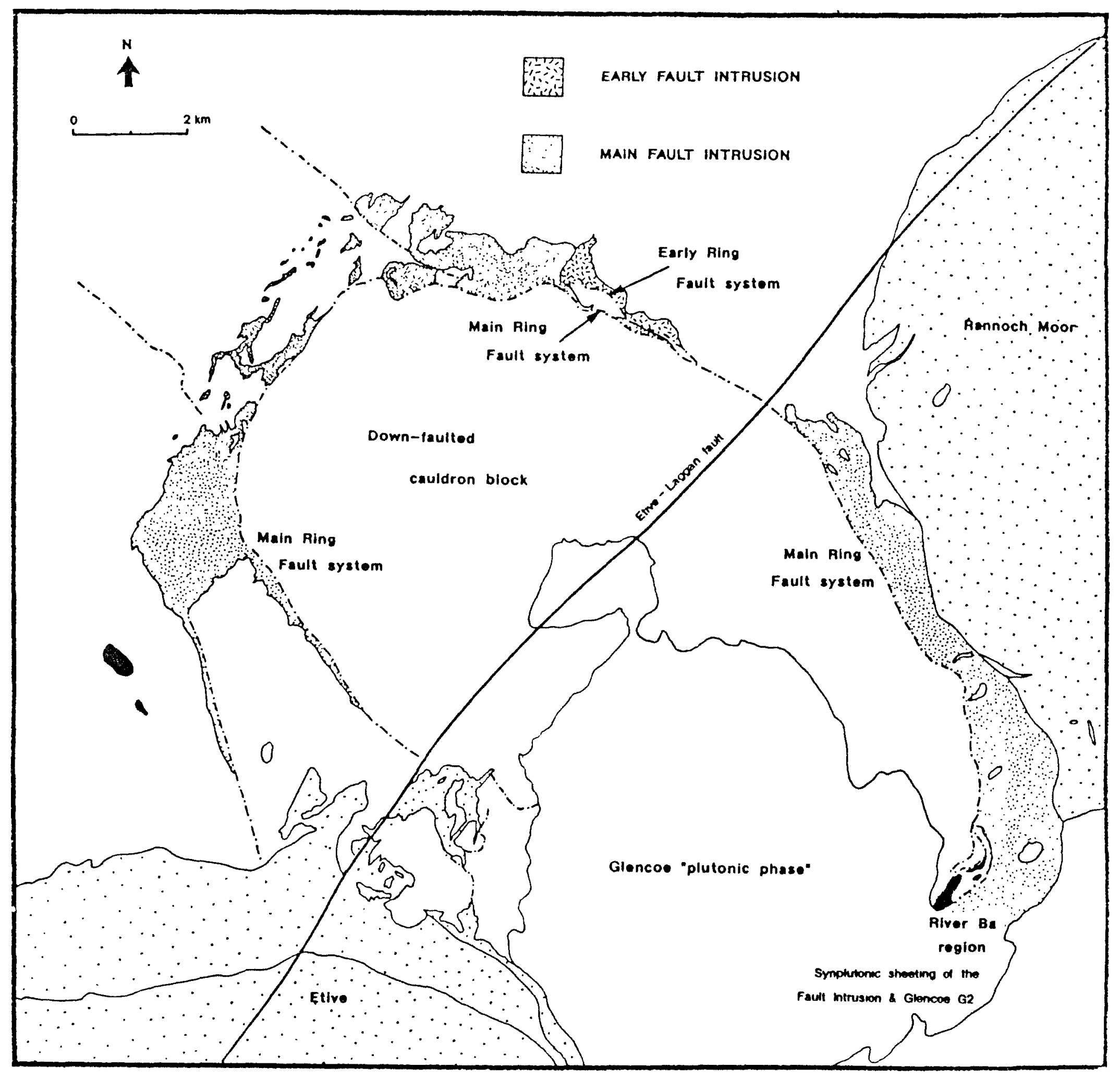
SCALE 1 : 25,000

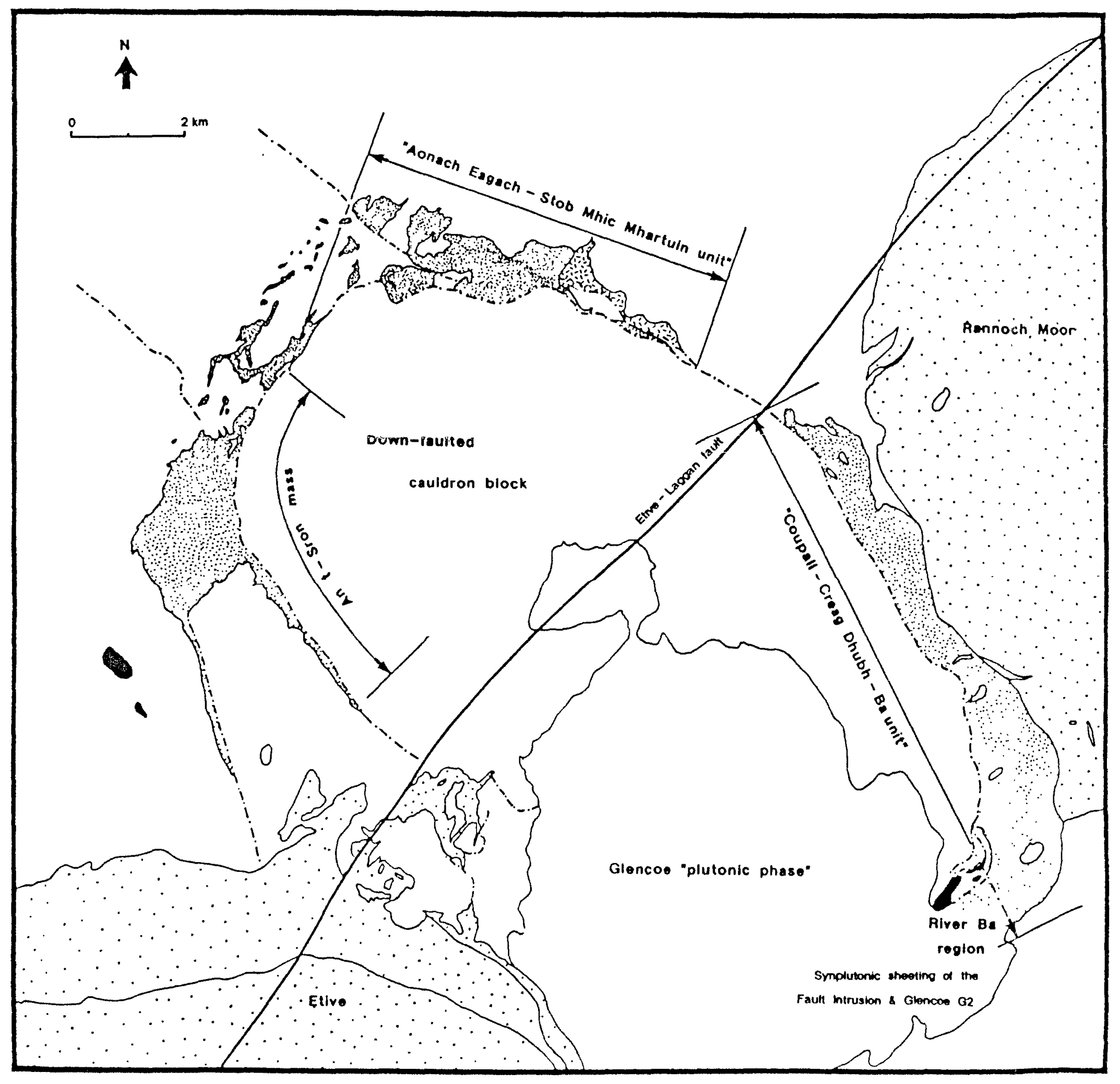


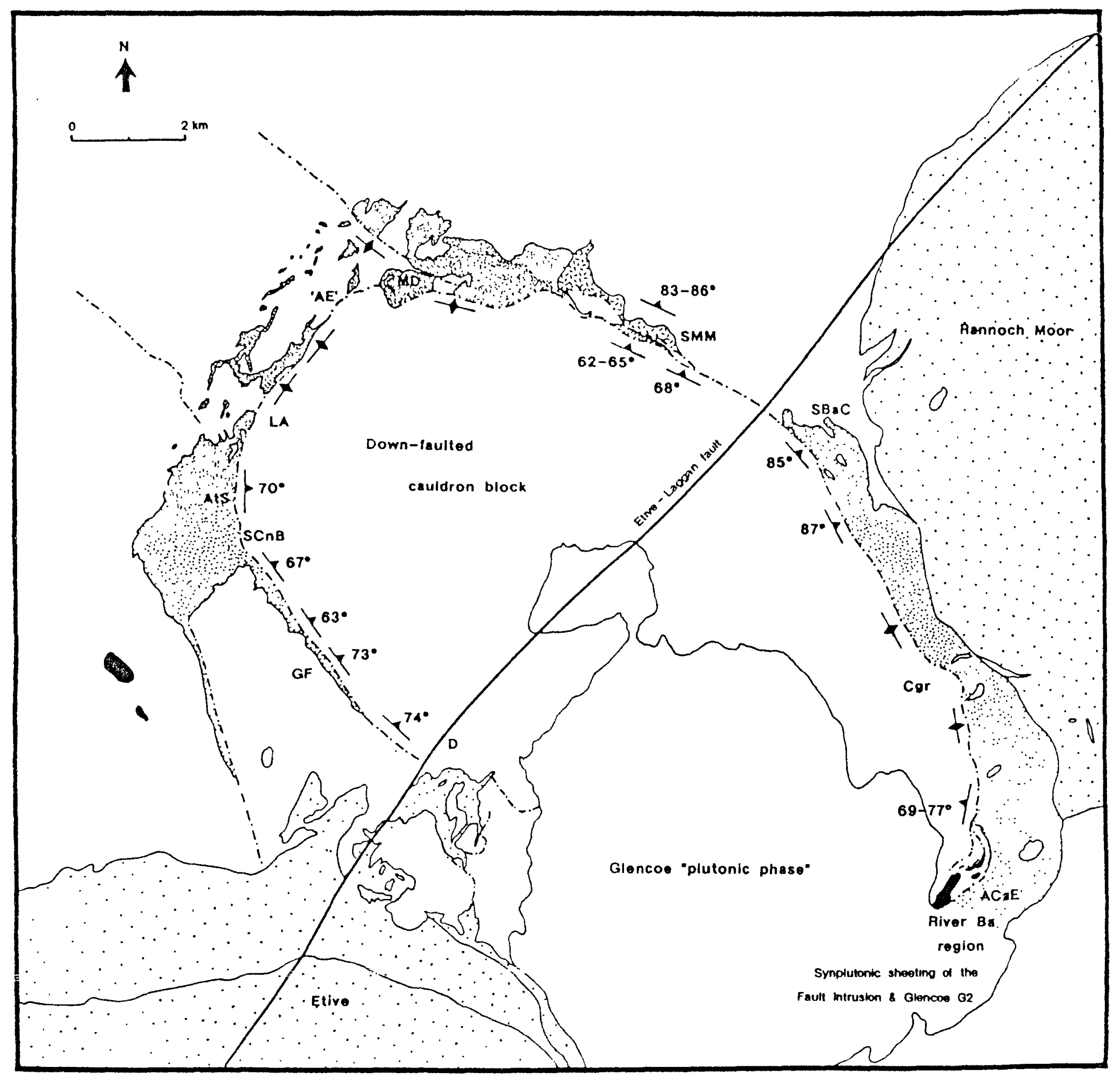
THE RANNOCH MOOR IGNEOUS COMPLEX

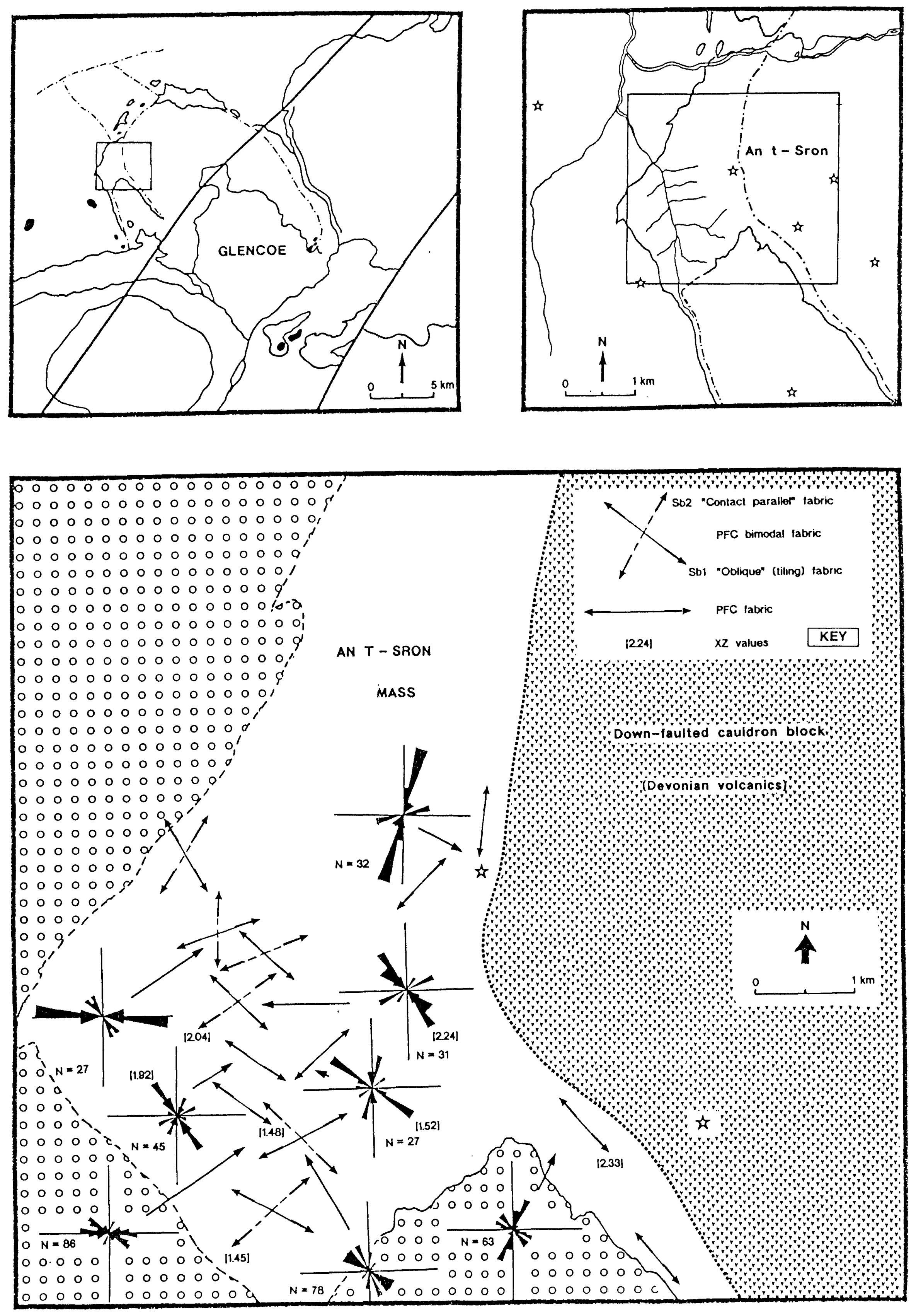
SCALE 1 : 25,000

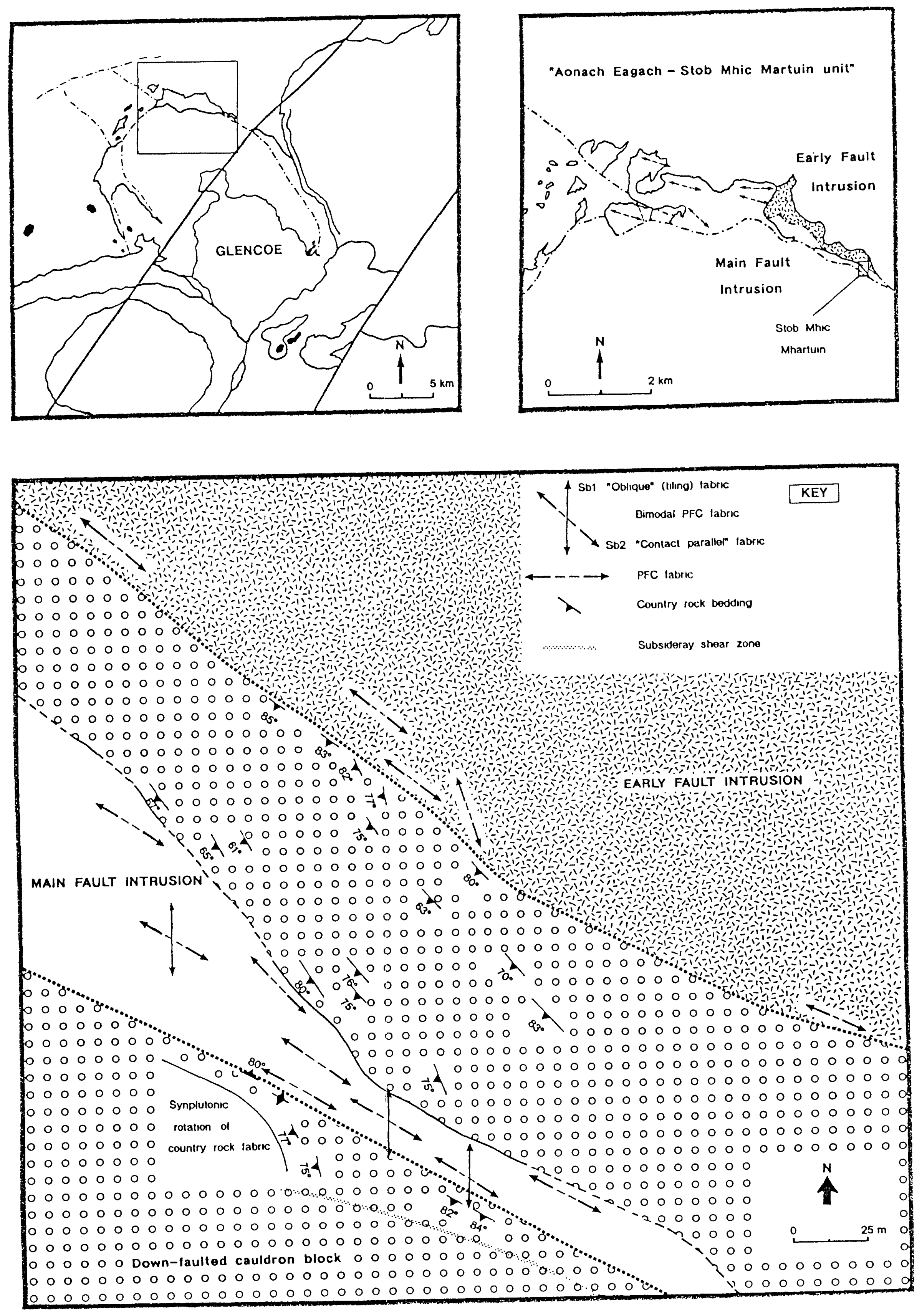


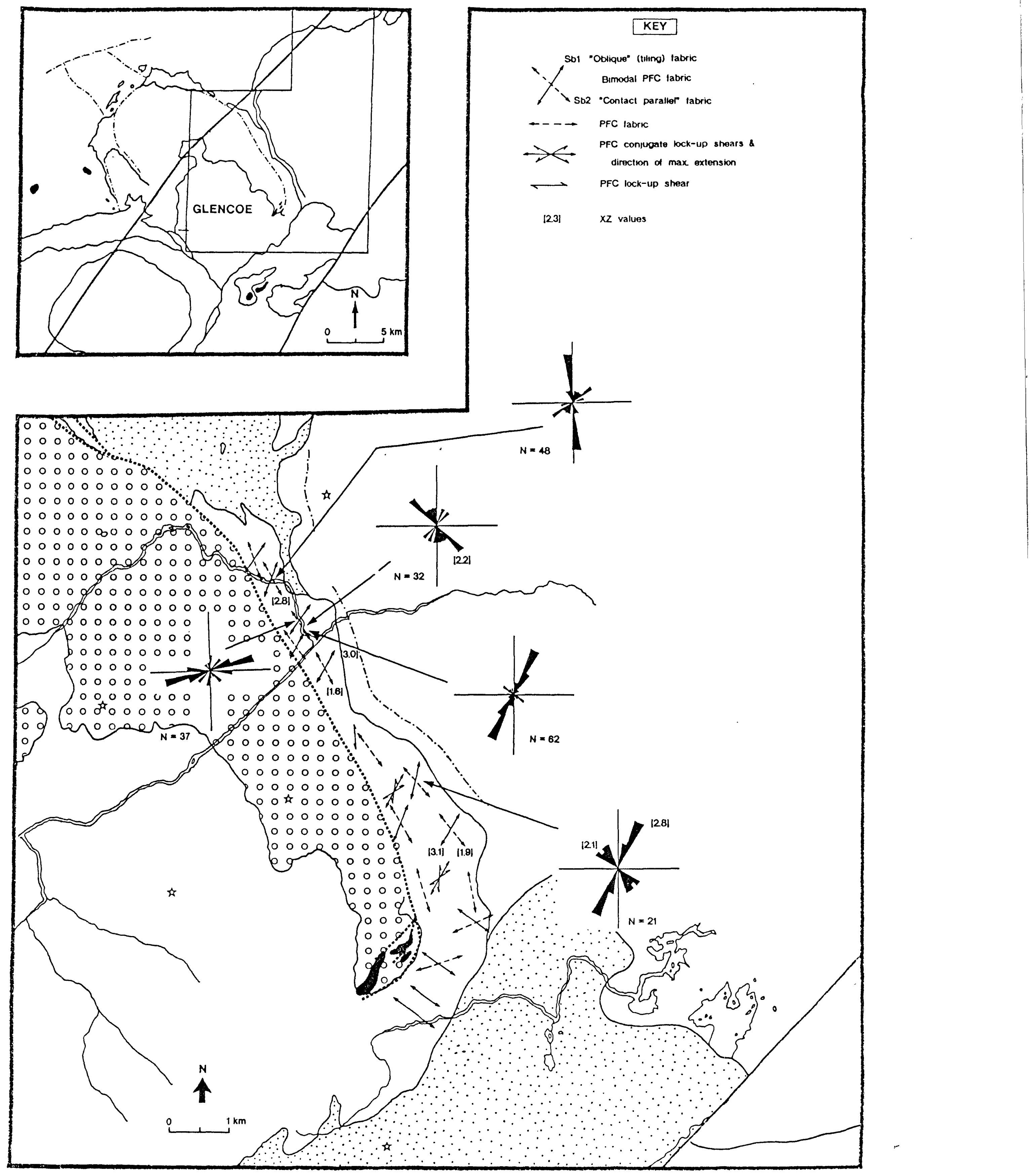












THE GLENCOE FAULT INTRUSION AND THE ETIVE QUARRY INTRUSION