IGNEOUS AND METAMORPHIC PROCESSES IN THE SHAP GRANITE AND ITS AUREOLE

by

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TO MY

MOTHER AND FATHER

ABSTRACT

The Shap Granite outcrops in eastern Cumbria, N.W. England and is a post-orogenic granite intruded during the Lower Devonian (ie 394 Ma) into rocks of Ordovician to Silurian age. It is of adamellite composition and is notable in having megacrysts of orthoclase which crystallised late (relative to the matrix) by an essentially metasomatic process. Late in it's cooling history, hydrothermal fluids resulted in alteration and mineralisation in and about the joint structures. Comparison of whole-rock element and stable isotope data between the hydrothermally-altered and non-altered granites shows that this late-stage process was isochemical and only involved localised redistribution of the available elements, the hydrothermal fluid being derived from the granite itself and acting in a closed system.

The associated suite of granitic dykes extends the chemical range of Shap granitic rocks from the restricted compositions of the granite itself (around 68%) to 62 to 77% SiO_2. Mineralogical and chemical evidence suggests that the Shap magma compositions were controlled mainly by biotite and plagioclase fractionation over much of this silica range.

The granite is intruded about much of its outcrop into rocks of the mid-Ordovician, calk-alkaline Borrowdale Volcanic Group. The aureole is 1km wide and generally displays limited contact metamorphic reactions apart from in the Blue Quarry, where higher sub-surface heat flow during the granite's intrusion resulted in localised more extreme metamorphic and some metasomatic conditions resulting in the development of garnet veins. Analysis of 61 samples from the aureole region show only very limited modifications to their original calk-alkaline chemistry. Stable isotope and the whole-rock geochemistry indicates that the contact metamorphism was essentially isochemical and that chemical interaction with the granite did not occur. Aureole metamorphic reactions took place at moderate temperatures (250 -400°C) apart from in a narrow (<100m) zone about the granite contact where temperatures may have reached close to those of the granite solidus (around 600°C).

Xenoliths from the granite Pink Quarries at Shap contain the same mineralogy as their host granite, including the megacryst orthoclase. The xenolith chemistry compares well with that of the more basic dykes, with the xenoliths forming a coherent group over the compositional range 56 to 67% SiO_2. Comparison with the country-rock chemistry shows that the xenoliths were not externally derived but probably represent quenched, more basic, comagmatic melts related to the generation of the main Shap Granite magma. Limited Sr and Nd isotope data for the xenoliths show that these isotopes were in equilibrium with the granite and lends strong support for the cogeneric origins and chemical relationships for the granites, dykes and xenoliths together.

The narrow aureole width is typical of those formed by conductive rather convective cooling with interaction with the adjacent granite limited to thermal effects and not involving the cycling of fluids through the granite or aureole as in convective pluton cooling.

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CHAPTER 1. INTRODUCTION.

1.1 Introduction

It is scarcely 50km from one side of the Lake District (Cumbria) to the other and yet in that small area there is a variety of scenery and geology almost unequalled in Britain. The region has always been a place of active mining and quarrying and particularly so during the last 200 years. During this time a natural cliff section of granite called Wasdale Crag near the village of Shap became established as a major hard rock quarry (which is now called the Pink Quarry) for the supply of building materials (Plate 1.a). The rock has since been called Shap Granite and its attractive and distinctive porphyritic texture has resulted in a high demand for its use. By the late nineteenth century, over one thousand men were employed by the Shap Granite Company for quarrying and producing dressed and polished Shap Granite.

The extensive and widespread use of the granite as a building stone has made it nationally famous and, as a consequence, the quarry and surrounding area has been a place of particular geological interest resulting in many published works concerning its geology (see section 1.3).

1.2 Location of Research Area.

The area upon which this research project is centred is approximately halfway between the towns of Penrith and Kendal on the eastern border of the Lake District National Park within the county of Cumbria (Fig.1.1). It lies immediately south of the village of Shap and to the west of the major road and rail trunk routes of N.W.England.

Although mainly within the National Park, the area

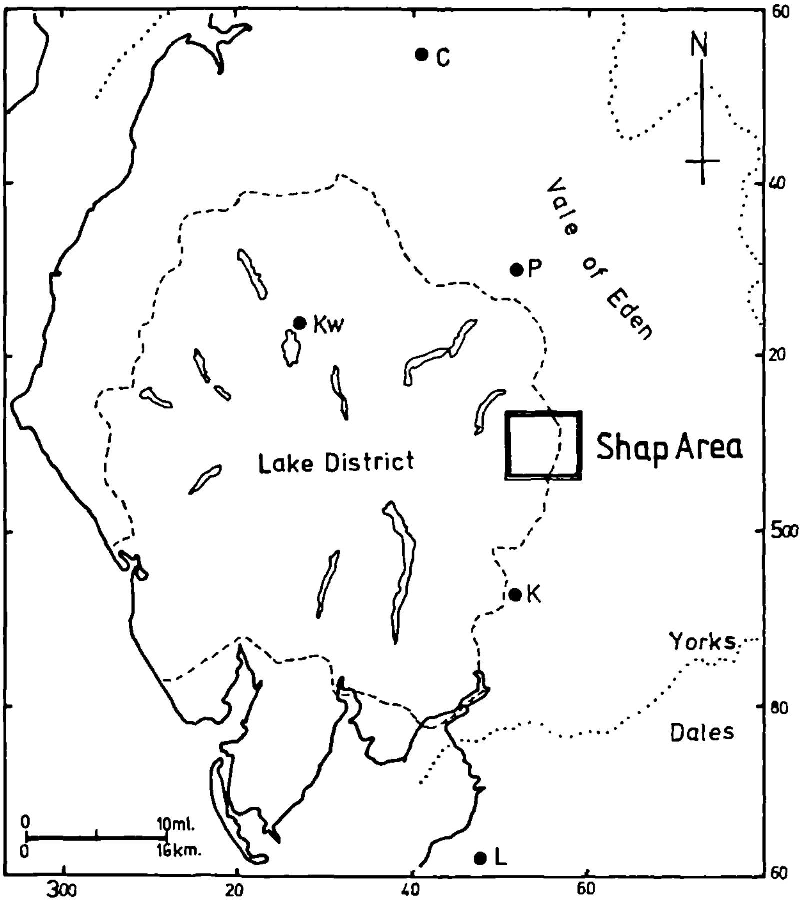


FIG. 1.1.

Location map of N.W.England showing the position of the Shap area in relation to the county boundaries of Cumbria (......), the Lake District National Park (------) and selected towns.

Carlisle (C), Penrith (P), Keswick (Kw), Kendal (K) and Lacaster (L).

PLATE 1.

PLATE 1. GRANITE FEATURES

a. Wasdale Crag viewed from the south, showing the two working faces of the granite (Pink) quarry.

b. Well developed sub-vertical joint structures at near normal intersection resulting in joint-bound granite blocks. (East wall of smaller, western working face, Pink Quarry).

c. Small xenolith and narrow aplite vein in granite. The aplite is off-set by a hydrothermal quartz vein (Pink Quarry).

d. Contact of granite, with well cleaved volcanic tuffs, now strongly hornfelsed. Note strongly cross-cutting nature of the granite relative to the fabric in the country rock.
(GR 539101)

e. Coarse grained granite dyke with pegmatitic quartz margins.
(GR 538100)

f. Near vertical fault in the main face of the Pink Quarry. The fault zone is 2 metres in width and filled with altered crushed granite. There appears to be little vertical displacement.

g. Basal Carboniferous conglomerate (the Shap Conglomerate) sitting unconformably on Silurian siltstones.
(GR 578095)

h. Small microgranite dyke in volcanic country rocks.
(GR 538102) (Sample 563)

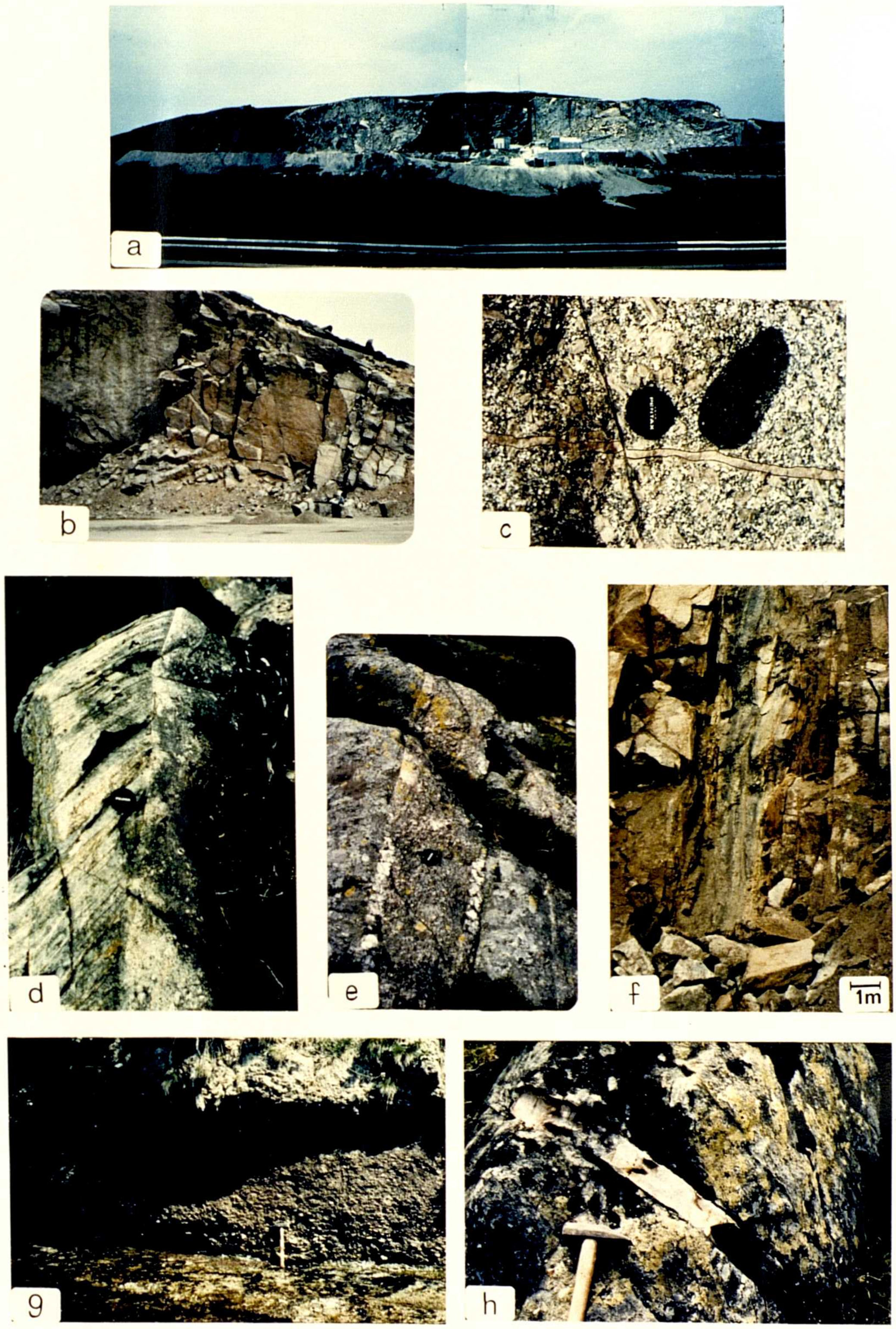


PLATE 1

is of less rugged topography than the main, more central areas of the Lake District to the west. The major topographic features of the Shap area are shown in Fig.1.2. The ground lies between 300m (1000ft) in the east and 550m (1800ft) towards the west, with Shap Fell dividing the watershed northeastwards into the River Lowther and the Vale of Eden, and, southwards into the River Lune.

Most of the area is rolling fell country with isolated crags on the higher ground. Rock exposure is restricted with most of the fell being covered with rough grass and heather upon wetland and thick peat "head". Glacial action has resulted in a rounding of the topography and a smoothing of the outcrops. This is especially evident on Shap Fell itself where low relief, glacially-striated exposures of rocks and large glacial erratic boulders are not uncommon.

1.3 Previous Work.

Geological studies of the Lake District extend over a period of nearly 120 years, with the first short publications being produced by Dakyns (1869) and Aveline (1869) prior to the first Geological Survey publications of the 1870's (eg. Ward 1876 and below). As already mentioned, Shap was one particular centre of interest, focused by the activity of granite working. Since scientific study and resulting publications in mid-Victorian times, some 60 or more articles have been published relating to the geology of the Shap Granite and the surrounding area. This list includes excursion guides, survey memoirs, research papers and theses,

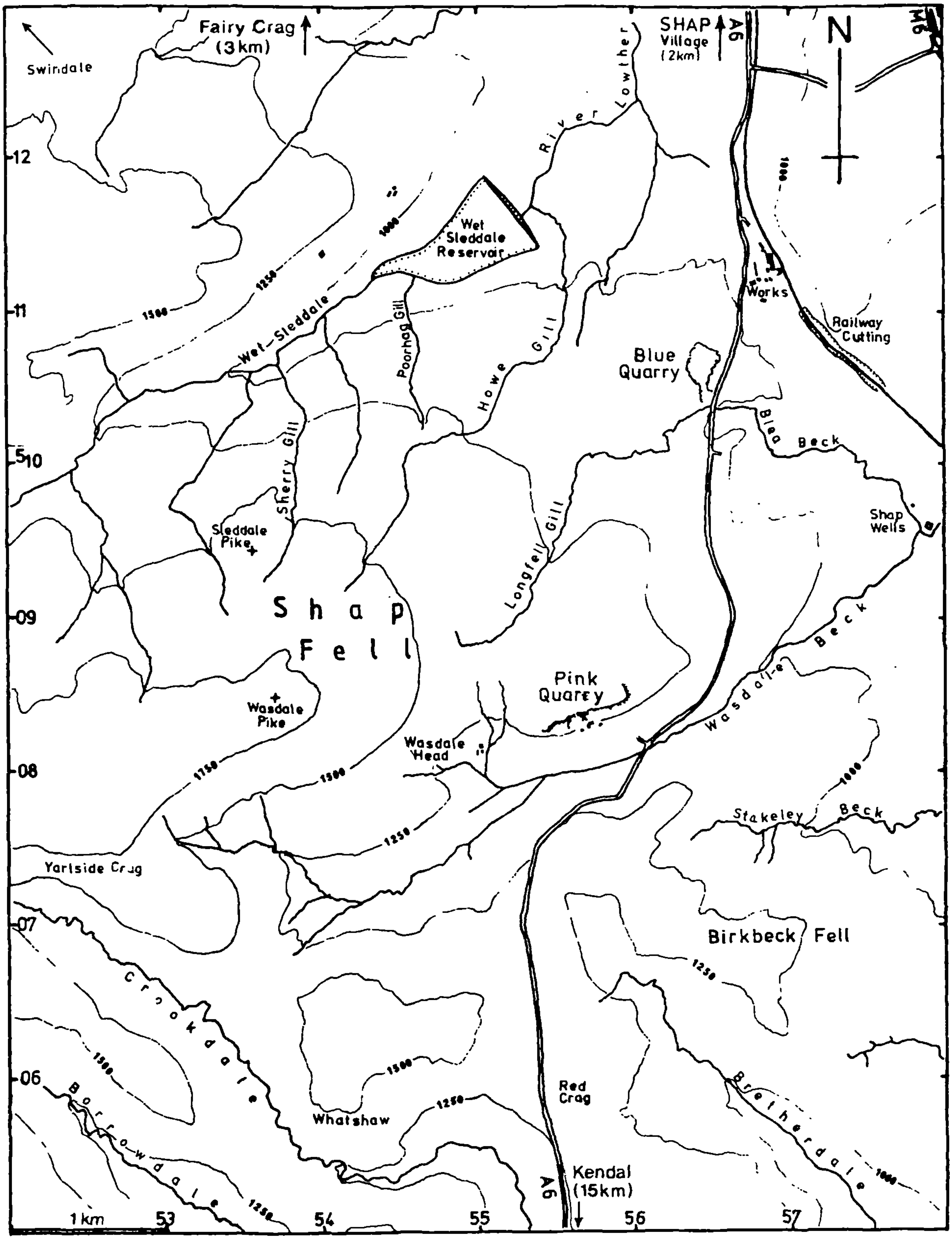


FIG. 1.2.

Topographic map of the Shap area showing the principal hills, waterways and trunk routes.

The Shap Granite and local volcanic rocks are worked at the Pink and Blue Quarries respectively.

Contours in feet above O.D.

reference books and national newspaper articles. A comprehensive list is given by Smith (1974) who cites more than 1000 publications in a bibliography of the Cumbrian geology and geomorphology which includes those of the Shap area. Of the many publications relating to Shap only about one third are specifically concerned with the Shap area alone. The remainder place the Shap geology within a broader context such as regional studies or geochemistry of granites.

Little was published prior to 50 years ago. The first significant work was the Geological Survey Memoir (Aveline et al.1872, 1888) which was the earliest organised mapping and description of the region. The memoir encompassed a much larger region stretching as far south as Kendal but it included only a very short description of the granite and local geology, not dissimilar to a short work on the granite by Nicholson (1868). Further small works were produced by Cheetham (1887) and Hutchins (1891, 1895). Cheetham (op. cit.) described the granite and associated xenoliths in the Pink Quarry and mentioned the wide distribution of the readily recognisable glacial blocks of granite scattered to the south of Shap Fell.

Hutchins (op. cit.) gave a mineralogical description of the rocks collected from the metamorphic aureole of the granite thus presenting the first documented evidence of the contact metamorphic effects produced by the granite's intrusion.

The first major detailed works are those of Harker and Marr (1891, 1893) who comprehensively described the granite and the local geology. They discussed the granite, xenoliths and associated minor intrusions (dykes and sills) and presented the first geochemical data in the form of major element oxide analyses for a granite, a xenolith and a porphyritic orthoclase feldspar. The major part of the work concentrated on descriptions of the extent and effects of thermal metamorphism in the surrounding country rocks. They concluded that there was a phase of regional metamorphism prior to the granite's intrusion and that thermal metamorphism and not chemical movement (ie. isochemical alteration) was the major process in producing the wide range of metamorphic minerals they described.

Morrison (1919) gave a petrological account of the Shap minor intrusions over a large area mainly to the south of the granite. He divided them into acid, intermediate, and basic varieties and noted that they probably vary in age of emplacement but, still relate in origin to the granite pluton itself.

Prompted by questions raised by these authors, Grantham (1928) produced the major work on the petrology of the Shap Granite. In it he presented a detailed description and a number of whole-rock analyses of the granite and its xenoliths. Noting a variation in the modal content of the porphyritic orthoclase, he divided the intrusion into 4 granite varieties which become increasingly more porphyritic and acidic with time of relative emplacement. However, he admits that most of the intrusion is of a single variety, the remainder being limited in extent. He further concluded that the xenoliths were principally assimilated local volcanic country rocks and also that the pegmatites and aplites associated with the granite are produced by differentiation of the main granite magma.

Doctoral research by Firman (1953a) resulted in a significant group of papers (1953b,1954,1957) briefly describing the metamorphic changes in the volcanic rocks about the granite. In particular, he described the development of calc-silicate mineral assemblages containing andraditic garnet and the spatial relationships of these assemblages to fissures and joints in the metamorphic aureole. He concluded that these assemblages were a result of chemical transfer (ie. metasomatism) and not of simple thermal metamorphism.

During the mid 1970s, the building of a water tunnel and gas pipe-line across Birkbeck Fell allowed an opportunity for a detailed study of a section through the Silurian sediment succession immediately south of the granite (Redfern 1979). Although mainly a sedimentolgical description, the minor intrusions and some geochemical aspects of the contact metamorphism of the area were also discussed. The works outlined above constitute the major studies of the Shap area and only a few smaller studies such as Boulter and Soper 1973 (granite emplacement), Wadge et al. 1978 (age determination) and Wager 1945, Spears 1961, Vistelius 1969, Kim 1973 and Caunt 1977 (mineralogy and geochemistry) are specific to the granite alone.

Information about the Shap Granite is found in many papers within the broader context of Cumbrian geology. These include geophysical studies (eg. Bott 1974, Lee

1984a,b, Banks and Gurbuz 1984, Piper et al. 1978, Briden and Morris 1973), and geochemical studies such as radiometric dating (eg. Gale et al.1979, Brown et al.1964) and mineralisation (Stanley and Vaughan1982, Rastall and Wilcockson 1915).

The Shap Granite is of Caledonian age and has often been referred to in geochemical studies of the Caledonian (ie. 500-380my) granitic intrusions of northern Britain. The more recent publications include Brown 1979, Brown et al. 1984, Plant et al. 1980, Simpson et al. 1979, Pidgeon and Aftalion 1978, Hampton and Taylor 1983, Hennessy 1981, Bradshaw 1967, Moorbath 1962, Hamilton et al.1980, Harmon and Halliday 1983, Halliday 1979 and Firman 1978. Many of the publications above involve the use of radiogenic isotope systematics for petrogenetic modelling to deduce the origins of Caledonian acidic plutons.

The works outlined in this section, along with those of lesser significance concerned with the Shap Granite, are discussed more fully in the relevant chapters of this work.

1.4 Simplified Geology of Field Area.

The centre of the study area is Shap Fell which is mainly underlain by the granite. Volcanic rocks (the Borrowdale Volcanic Group) of mid Ordovician age occupy much of the ground around the granite apart from to the south where sediments of Silurian age occur (Fig 2.5). Both these Palaeozoic successions have been deformed during the Caledonian Orogeny resulting in low-grade regional metamorphism and the development of folds and cleavage typical of "slate belt" structures found in the southern region of the Caledonian fold belt of Britain (ie.the Paratectonic Caledonides of Dewey 1969). A more detailed description of geology of the Shap region is given in Chapter 2.2.

1.5 Aims of Research.

Despite the many works listed in the previous section, no comprehensive geochemical study of the granite, minor intrusions and the associated rocks of the aureole has been previously undertaken. The most recent published whole rock analyses are those of Grantham (1928) who showed that there is significant chemical variation within the granite pluton. Additionally, during the past ten years the radiogenic isotopes of the granite have been briefly studied (eg. Hamilton et al.1980) though remarkably, no trace element data have been collected. Therefore, the whole suite of granites and minor intrusions was collected and analysed for major and trace elements along with analysis of selected mineral phases.

The development of porphyritic orthoclase megacrysts within granites is not uncommon and they are also found to occur within many of the associated xenoliths as well as occasionally forming in the aureole about the granite margin. As a consequence of this multivarious development, their growth has been attributed to both liquid (magmatic) and solid-state (metamorphic) processes, with megacrysts crystallising as true phenocrysts (ie. early-formed large grains crystallising from a magma) or, by replacive growth due to late-stage potassium metasomatism in a cooling granitic pluton near or below it's solidus. The possibility of one or a even a combination of these two extremes has been examined for the rocks at Shap with evidence presented in this study. The granite has also undergone a phase of intermediate to low temperature mineralisation resulting in alteration to the host granite and metalliferous and gangue mineral development in the aureole. The possible origins of the minerals and the processes of transport and deposition are also discussed.

With an examination recently of Silurian sedimentary rocks immediately south of the granite by Redfern (1979), it was decided to concentrate within this study, on the geochemistry of the volcanic aureole rocks about the remainder of the pluton (Fig.2.4). Both Harker and Marr (1891) and Firman (1953a, 1957) had analysed a small number (2 and 5 respectively) of volcanic samples from north and west of the granite. However, their shortage of data makes it difficult to relate whole-rock geochemistry to the effects of metamorphism and consequently, a collection of approximately 60 samples has been analysed to assess some of the geochemical aspects of the contact metamorphism and mineralisation.

Alteration and subsequent cooling of the granite and the aureole is usually dominated by either convective or conductive heat transfer which may be accompanied by chemical interaction between the granite and the aureole, resulting in the transfer of chemical elements and the addition and fixation of these elements, especially in the aureole.

Using the two main data sets from the granite and its aureole, along with knowledge of mineral reactions and development, it is possible to describe the relationship between the processes of granite emplacement and cooling to that of contact metamorphism. It is the examination of this overall process which has been the main aim of this research.

1.6 Field Work.

An area of approximatly 40 sq.km. was traversed in order to undertake basic mapping and sample collection within the area shown in Fig.1.2. The principle function of this work was to collect material suitable for geochemical analysis along with basic structural data, lithological descriptions and information of field relationships.

The major problem incurred was the lack of outcrop exposure (eg.Plate 11.a). As previously mentioned, most of the area is covered by vegetation or glacial debris. Consequently, outcrops are generally scattered, small in size and often showing signs of glaciation and weathering. The granite outcrops particularly tend to show such effects.

The better outcrops occur as crags on higher ground, low relief exposures on the smooth fells or as stream sections. Exceptions to this are the two large quarries worked by the Shap Granite Company within the granite (Pink Quarry) and the volcanic (Blue Quarry) rocks. (Fig.1.2).

The lack of good exposure makes mapping problematical especially in the volcanic regions where individual units (eg.lava flows, tuff horizons etc.) are virtually impossible to identify or to trace laterally.

All varieties of granite and minor types (eg.

aplites, xenoliths etc.) were collected, though the majority were from the Pink Quarry. All dykes and sills were sampled, including material from two previously unrecorded localities. This collection was supplemented by dyke samples collected by Redfern (1979) during his examination of underground excavations upon Birkbeck Fell (Fig.4.1). Samples of the Silurian sedimentary succession from south of the granite were not collected due to reasons outlined in section 1.3.

1.7 Analytical Techniques.

The preparation of samples for examination and analysis is outlined in the Appendix. All data were collected using facilities of the Dept. of Earth Sciences, Leeds University unless otherwise stated.

The major data set consists of whole-rock analyses for major and trace elements obtained by X-Ray fluorescence and mineral analyses collected by electron microprobe. The relevant machine operating conditions are given in the Appendix.

Stable isotope analysis of selected rocks and minerals was undertaken at the Scottish Universities Reactor Centre, East Kilbride, in collaboration with Dr.R.Harmon.

Although it was not intended to undertake any radiogenic isotope analysis within this project, a small number of xenolith samples were analysed for Sr and Nd isotopes by colleagues at the Isotope Laboratory of the Dept. of Earth Sciences, Leeds University (details in the Appendix).

1.8 Thesis Layout.

After a general introduction and a description of the local geology (Chapters 1 and 2 resp.), detailed descriptions of the four major groups of rocks (granites, minor intrusions, volcanics and xenoliths) constitute the central part of the thesis. Each of these four chapters gives petrographic descriptions followed by the presentation of geochemical data and a discussion of their significance. The remaining chapter brings together the entire data set into the broader context of the overall processes operating both within the granite itself and between the granite and its aureole. Much of the analytical data and descriptive details of individual samples (eg. locations, petrographic descriptions etc.) are located in the Appendices.

CHAPTER 2 REGIONAL GEOLOGY.

2.1 Cumbrian Geology.

2.1.1. Introduction.

The most important period in the geological history of Cumbria is that extending from the early Ordovician to the early Devonian. It was a time when the major Palaeozoic ocean (Iapetus) was closing, leading to continental collision between an American and a European continent, climaxing with the Caledonian Orogeny. By early Ordovician times Iapetus was probably less than 1000km wide (Faller and Briden 1978) and oceanic crust was being consumed by subduction beneath the continental crust of England. The ocean was essentially closed by the late Ordovician but true continental collision and orogenesis occurred towards the end of the Silurian. The rocks of both continental margins formed the Caledonian fold belt with strongly deformed rocks about a suture line which is thought to run along the Solway and northeastwards along the southern margin of the Southern Uplands of Scotland. The orogenic episode was completed with the emplacement of wide-spread calc-alkaline granitic plutons in central and northern Britain, in the main being of Lower Devonian age (Brown and Locke 1979).

Post-orogenic uplift and erosion of the new continental land mass followed during the Devonian and was succeeded by the transgression of a mid-European ocean and epicontinental seas during the Carboniferous. Carboniferous and later Permo-Triassic sedimentary deposition was related to the new Caledonian basement structures and basins, many of which were reactivated during the subsequent Hercynian Orogeny.

Since the Triassic period there is little evidence of geological events in Cumbria apart from the Quaternary Ice Age. Figure 2.1 shows a simplified geological succession for the Lake Disrtict with the most important time being the period 500-400Ma when three major rock groups, namely the Skiddaw Slate Group, the Borrowdale Volcanic Group and the Silurian sediments were formed. It is these three groups which constitute the major portion of the Cumbrian massif.(Fig. 2.2.).

2.1.2 The Skiddaw Slate Group (Lower Ordovician).

These are the oldest known rocks in the Lake District, comprising at least 3000m of dominantly mudstones and greywackes which are considered to be distal turbidites deposited on the continental margin of ancient Europe, with their main outcrop across the northern Lake District and smaller outcrops in the Black Combe and Cross Fell inliers. Stratigraphic division and correlation within this Group has always been problematical due to the structural complexity, poor exposures and lack of good marker horizons or index fossils. Graptolites are the principal stratigraphic fossils and show the group to be mainly Arenig in age, although Molyneux and Rushton (1984) using acritarchs and trilobites have shown some beds in the west of the area to be of a probable, older Tremadoc age. Small inliers of rocks similar to the Skiddaw Slate Group also occur in northern England at Cross Fell, Teesdale and Craven which, along with the Manx Slate turbidite sequence in the Isle of Man (also of Tremadoc-Arenig age) suggest, that rocks

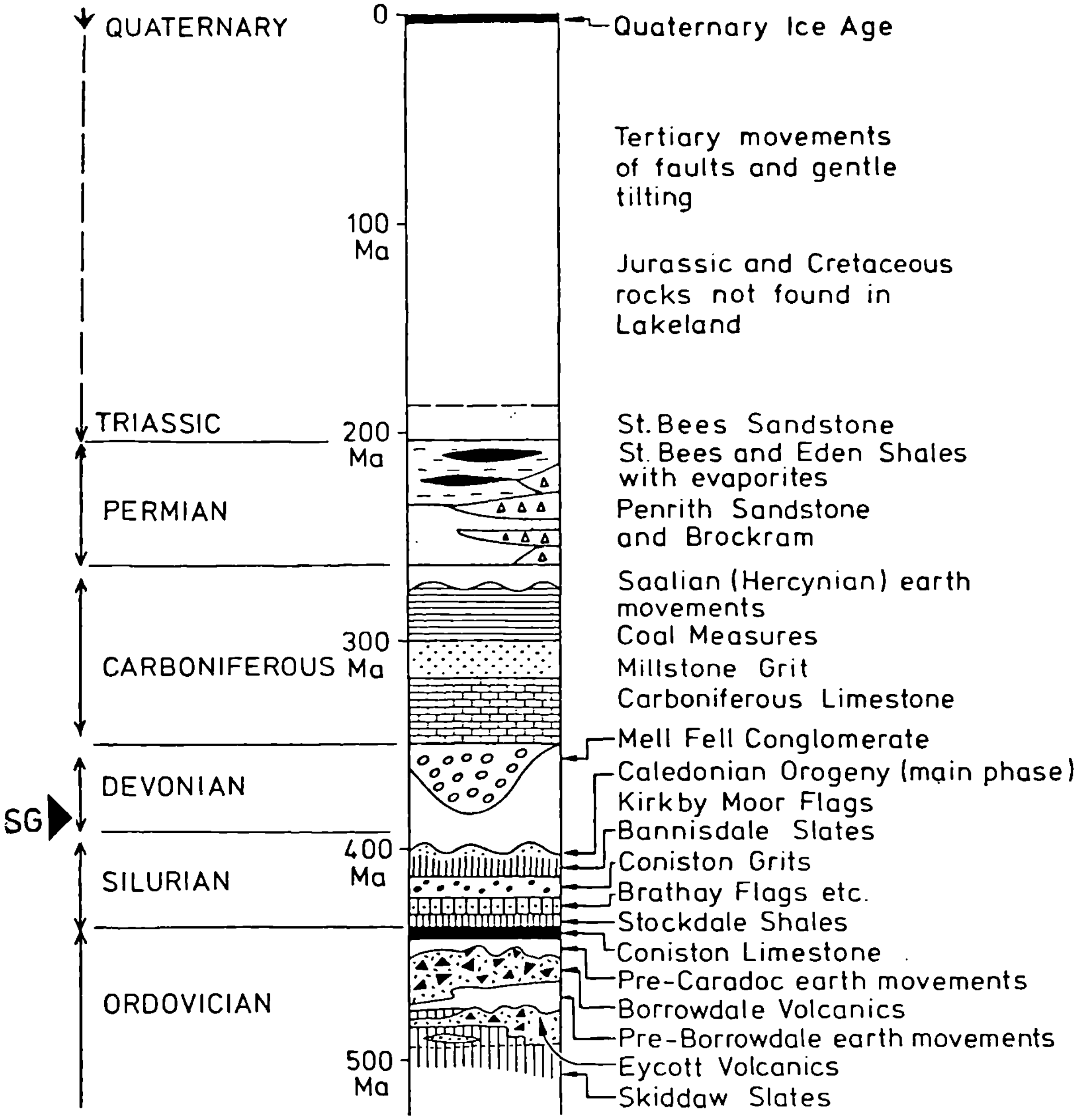


FIG. 2.1.

A generalised geological succession for Cumbria (from Moseley 1978).

SG marks the position of the Shap Granite which was intruded during the Lower Devonian and after the Caledonian Orogeny.

Only rocks of Palaeozoic age occur in the study area.

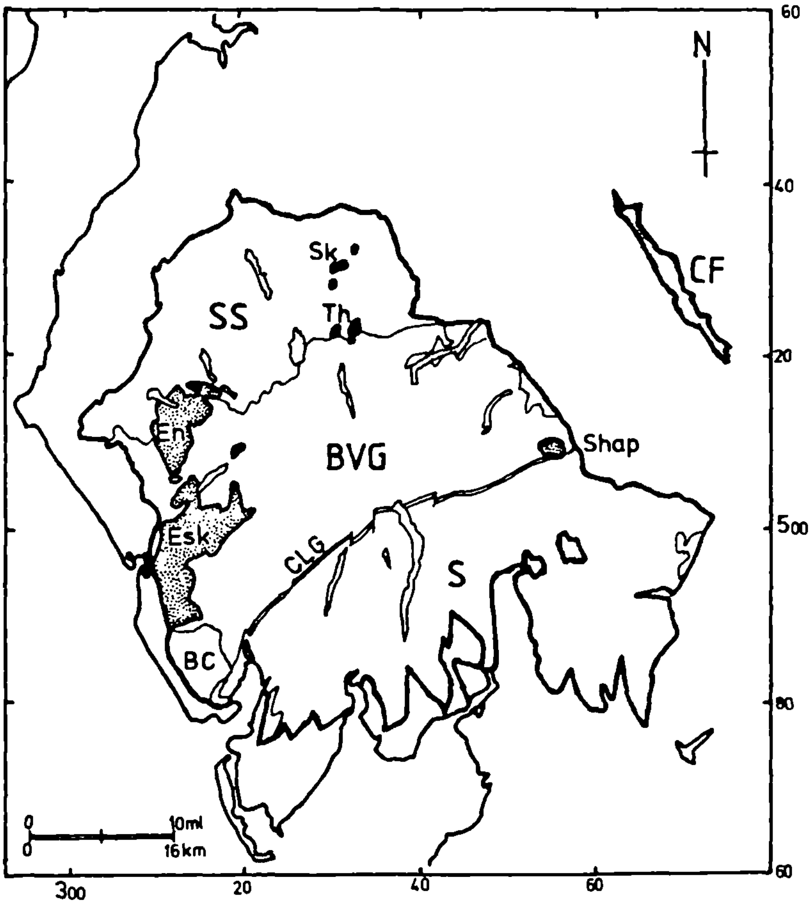


FIG. 2.2.

A simplified geological map illustrating the major 3-fold division of the Lake District into Skiddaw Slates (SS), Borrowdale Volcanic Group (BVG) and Silurian rocks (S).

Also shown is the Coniston Limestone Group (CLG) and the major granitic intrusions of Eskdale (Esk), Ennerdale (En), Skiddaw (Sk), Threlkeld (Th) and Shap.

To the north east is the Cross Fell inlier (CF) and to the south west, the Black Combe inlier (BC).

Undesignated areas are sediments of Devonian to Triassic age.

such as these may underlie much of the upper Palaeozoic cover of northern England.

Towards the top of this group, is found the Eycott Volcanic Group, which represents the earliest episode of volcanic activity in Cumbria. At one time equated with the overlying mid-Ordovician Borrowdale volcanic rocks, this Group has been shown to be distinctly older as it is interbedded with pelites which contain fossils of Arenig age (Downie and Soper 1972). These volcanics are made up of some 2500m of mainly basic lavas of a transitional tholeiitic to calc-alkaline composition (Fitton and Hughes 1970).

2.1.3. The Borrowdale Volcanic Group (Mid Ordovician).

This Group forms the craggy, mountainous areas of the central Lake District and is composed of both subaerial and subaqueous lavas and pyroclastic rocks. The total thickness exceeds 5000m and dating of samples from the lower part of the group using Nd isotopes gives mineral -rock ages of 460 Ma, showing them to be of Llandeilo age (Thirlwall and Fitton 1983). The Group includes basaltic through to rhyolitic lavas and tuffs, with the more acidic members usually ignimbritic in character. Field relationships are complex but sequences occur in broadly basic to acid cycles emanating from several small volcanic centres possibly related to a single volcano system (P.Allen pers.comm.). Associated with these rocks are basic intrusions and vent agglomerates which have been interpreted as possible feeders to the surface volcanism (eg.Nutt 1979).

Individual sequences are divided into formations which are characterised by a common association of lithologies rather than a particular rock type. An example of this is the Wrengill Andesite formation, which occurs towards the top of the Borrowdale Volcanic Group. This formation is not entirely composed of andesitic rocks, but is dominated by lavas of this composition which can be tentatively traced across central and eastern portions of the Borrowdale succession (Fig.2.3).

The composition of the Borrowdale Volcanic lavas varies from high alumina basalt to rhyolite and is of calc-alkaline character. The distribution of compositions is bimodal with a marked silica gap between basalt to andesite and dacite to rhyolite (Millward et al. 1978).

Along with Ordovician volcanic rocks in Wales and Eire, the Borrowdale (and Eycott) Volcanic Groups have been interpreted as the remnants of a volcanic zone forming in an island arc or continental margin environment above a south easterly-dipping subduction zone (Fitton and Hughes 1970).

2.1.4. The Coniston Limestone Group (Upper Ordovician).

With further closure of the Iapetus ocean, volcanic activity largely ceased and the volcanic rocks were followed unconformably by the Coniston Limestone Group of Ashgillian age. This Group oversteps the whole of the volcanic sequences to rest upon Skiddaw Slates which suggests a considerable degree of uplift and erosion prior to the Ashgill. This Group is not well represented in Cumbria, outcropping as a narrow, thin (usually less than 150m), NE to SW -trending strip of mainly calcareous sediments (Fig.2.2). McNamara (1979) has interpreted the

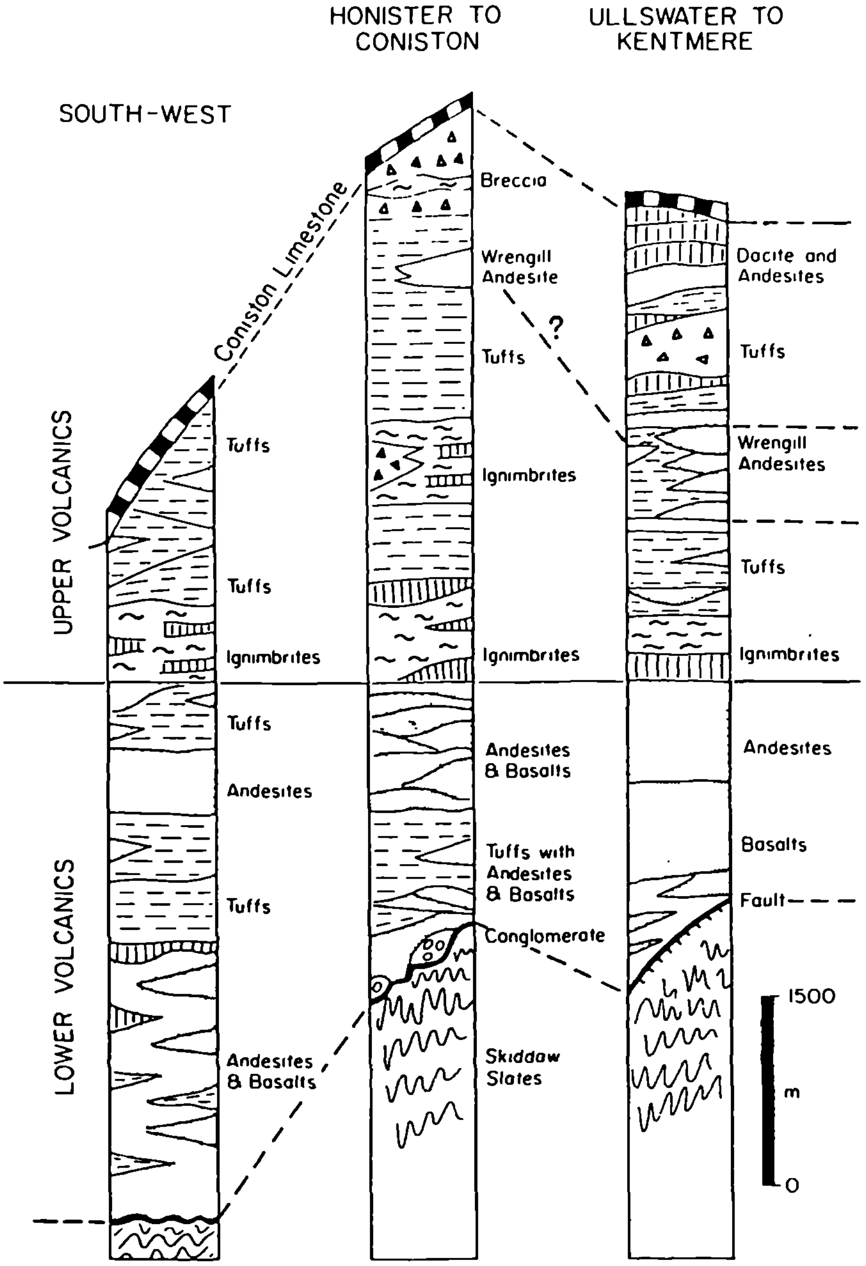


FIG. 2.3.

Comparitive simplified sections through the Borrowdale Volcanic Group in south west, central and eastern Cumbria.

High in the eastern sequence is the Wrengill Andesites which thin out to the west.

This occurrence of the Wrengill Andesites also includes the Shap region.

(After Moseley and Millward, 1982).

Group as forming in a shallow marine shelf environment. Within this sedimentary sequence is the Stockdale (or Yarlside) Rhyolite and some related felsic tuffs. This rhyolite lava has a maximum thickness of about 150m and at some localities is composed of more than one flow (Moseley and Millward 1982). Its inclusion within fossiliferous sediments of Ashgillian age has enabled attempts to date absolutely the Ashgill Period. However, the calculated Rb-Sr age of 421 Ma (Gale et al. 1979) and the subsequent revision of Palaeozoic time-scales has been brought into question by some authors (eg. McKerrow et al. 1980) who regard the use and value of acid extrusives for dating purposes as unreliable due to the possibility of Rb mobility and subsequent Rb-Sr resetting post extrusion.

2.1.5. The Silurian Sediments.

The thin Coniston Limestone Group is followed by a thick sequence of sediments of Silurian age which outcrop across much of southern Cumbria (Fig.2.2). Following the late Ordovician shallow seas, the lowermost Llandovery sediments are graptolitic and shelly shales and mudstones representing a deepening marine sequence (locally called the Stockdale Shales). This is followed in the Wenlock by further mudstones and sandstones (the Brathay Flags) eventually passing up into rocks of Ludlow age through a series of calcareous siltstones and shales (the Coldwell Beds). The Ludlow series is composed of the Coniston Grits, which are mainly fine to medium-grained turbiditic sandstones,they in turn being followed by at least 600m of mudstones and siltstones (the Bannisdale Slates). The coarser nature of the Ludlow sediments contrasts with the finer sediments of the underlying lower Silurian and is thought to represent the gradual shallowing of the marine environment (Rickards 1978). The Scout Hill Flags, some 150m of silty red-bed sediments of upper Silurian age are the culmination of the Silurian marine sequence prior to the main Caledonian deformation episode and the post orogenic,non-marine environment of the Devonian.

2.1.6. The Devonian and Carboniferous.

The end-Silurian continental collision resulted in rapid uplift and erosion in northern Britain with the subsequent widespread development of red-bed sequences. Unfossiliferous conglomerates and sandstones thought to be of Devonian age occur S.W. of Penrith (the Mell Fell Conglomerate) and within the Cross Fell inlier (the Polygenetic Conglomerate) (Wadge 1978, Arthurton and Wadge 1981).

The Mell Fell Conglomerate is some 300m or so thick and contains locally-derived Ordovician and Silurian material whilst the Polygenetic Conglomerate occurs as local pockets of coarse, clastic material of unknown thickness though sequences of up to 70m in thickness are exposed. Both conglomerates have been interpreted as alluvial fan facies depositional environments and although conclusive evidence of their age and position within the Devonian period is lacking, they are thought to be the last remnants of post-orogenic erosion of the Cumbrian massif.

Rocks of Carboniferous age unconformably overlie all the previous rock groups described. The marine transgression is thought to have covered all of Cumbria by mid Carboniferous times but further uplift and erosion during the Hercynian and Tertiary has resulted in the present outcrop of Carboniferous rocks surrounding the Lake District massif (Mitchell et al.1978). Only the lowest (Dinantian age) rocks are described here as it is these that constitute the main Carboniferous outcrop in Cumbria.

The basal unconformity is marked by the Basement Beds, a group of clastic rocks below the lowermost Carboniferous Limestones. These initially consist of red and yellow shales, sandstones and conglomerates in fining-upward sequences composed of alluvial material of local origin (Kimber 1984) which are followed by shales and fine sandstones (some calcareous) deposited in a shallow marine environment. These lowest marine horizons have been shown to be Lower Dinantian (Courceyan) in age by the use of micro-fossils (Varker and Higgins 1979). At the northern margin of the Lake District, the Basement Beds contain some 90m of basic lavas (the Cockermouth Lavas), being some five flows of olivine basalt (Eastwood et al. 1968). Recent geochemical study (MacDonald and Walker 1985) has shown the lavas to be tholeiites of very similar composition to the Dinantian lavas of Scotland and Derbyshire, thus supporting the palaeontological evidence for the Dinantian age of the Basement Beds.

Above these beds are thick, limestone-dominated horizons, also of Dinantian age which occur over much of northern England. With the termination of the Carboniferous period, continental conditions were again established with the formation of sedimentary basins during the Hercynian within which thick accumulations of Permo-Triassis sediments occur, notably along the eastern (Vale of Eden) and western (St. Bees and Whitehaven) sides of Cumbria.

2.1.7. The Granitic Intrusions.

As shown in Fig.2.2., large intrusions of granitic composition are emplaced into all three major rock groups of the Lake District. Intrusions of a similar age and composition occur throughout the Caledonian of central and northern Britain and Ireland (eg.Brown et al.1981) and a review of the intrusions of Cumbria is given by Firman (1978).

The ages of these intrusions vary between Ordovician and Lower Devonian (550 to 380Ma) and radiometric dating shows that they divide broadly into two groups, being essentially either pre-Silurian (Caledonian) or Lower Devonian (post-orogenic) in age.

In Cumbria, the Shap and Skiddaw Granites are lower Devonian in age (Wadge et al.1978 and Brown et al. 1964 resp.) whilst the remaining intrusions, the Eskdale Granite, Ennerdale Granophyre and Threlkeld Microgranite, are mid to upper Ordovician in age (Rundle 1979, 1981).

All are calc-alkaline in composition, though the older intrusions show some chemical modification and alteration due to being pre- or synorogenic in character (Firman 1978, Caunt 1984).

The Eskdale Granite covers some 90sq.km. and is mainly composed of granite, with granodioritic margins which include xenoliths of tonalite. The Ennerdale Granophyre, although poorly exposed consists almost entirely of a quartz-feldspar rock with occasional coarser, porphyritic varieties towards the margin (Clark 1963, Firman 1978). The Threlkeld Microgranite consists of three small exposures of quartz porphyry which are sufficiently similar to suggest they constitute part of a larger intrusion at depth (Caunt 1984).

The two Devonian intrusions, the Shap Granite (discussed in 2.2.4) and the Skiddaw Granite are both porphyritic granites with associated hydrothermal mineralisation. At Skiddaw the granite has limited exposure, but gravity data (Bott 1974) and an associated extensive, dome-shaped metamorphic aureole again suggests that a much larger intrusion occurs at shallow depths and that this granite has a wide flattish roof zone which has only relatively recently been exposed during the Quaternary.

Bott (op cit.) and Lee (1984a) showed that the Lake District is dominated by an E-W belt of relatively low Bouger gravity anomaly with the minima occurring over the Eskdale, Skiddaw and Shap Granites. This has been interpreted to suggest that these granites are the exposed parts of a large, composite granite batholith underlying Cumbria (Fig. 2.4). Studies further to the east have shown similar low gravity anomalies under much of northern England as well as to the west under the Isle of Man and northwards in the Southern Uplands of Scotland, where Devonian granites also outcrop (Bott 1967,1974,Bott et al. 1978, Lagois and Hipkin 1979). The implication of this data and the possible existence of widespread, unexposed granite below northern England has been supported by

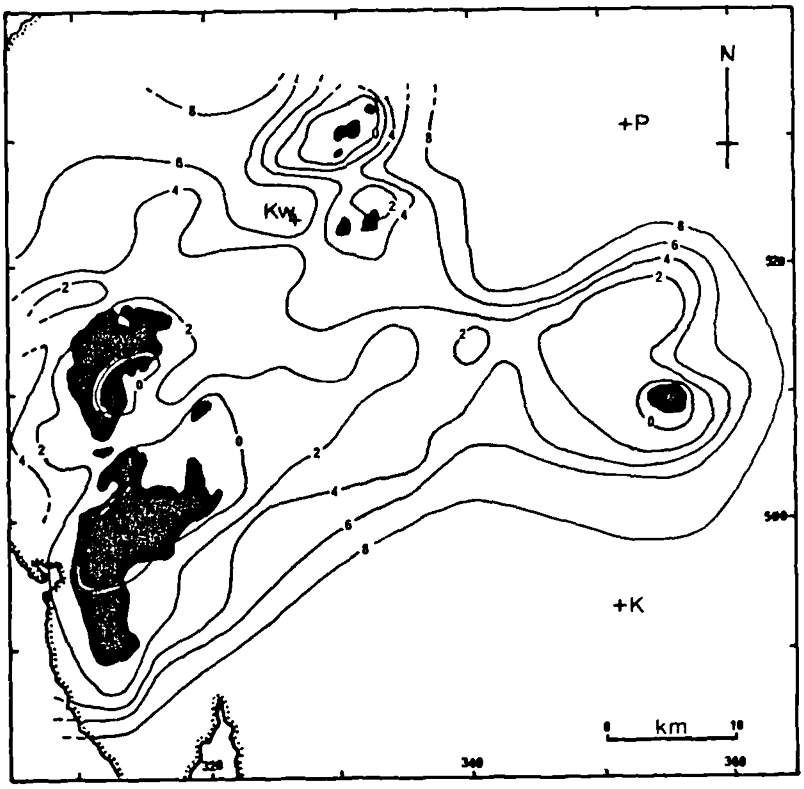


FIG. 2.4.

A generalised three-dimensional model of the subsurface Cumbrian Batholith.

Major granite outcrops are (shown in solid ornament) as in Fig. 2.2.

Contours show depth to the granite roof in km. below sea-level.

(After Lee 1984a).

drilling at Rookhope, Co.Durham, where granite (the Weardale Granite) was encounted at 390m below the local Carboniferous succession (Dunham et al. 1965).

2.2 The Shap Area.

2.2.1 Introduction.

The character of the area studied has been outlined previously (Chapter 1.4). No rocks of the Skiddaw Slate or Eycott Volcanic Groups occur within the region, although Skiddaw Slates do outcrop some 4-8km to the north and are likely to underlie much of the younger rocks of the Shap area. Apart from the granite, the area mainly consists of the Borrowdale Volcanic Group and rocks of Silurian age, divided by the narrow strip of the Coniston Limestone Group (Fig.2.5).

2.2.2 The Borrowdale Volcanic Group.

Rocks of this group occupy most of the region about the granite apart from the southern portion of the area. Harker and Marr (1891) mainly restricted their observations of the volcanic rocks at Shap to examination and descriptions of the effects of thermal contact metamorphism about the granite. They divided the local succession into 2 groups which they called the Andesitic and the Rhyolitic with the latter being a minor group of ashes and breccias occupying the area immediately east and southeast of the granite and being stratigraphically younger than the former, more widespread group.

The andesites are described as being blue and green flows which are essentially vesicular whilst the rhyolites are a pink-cream colour and often show flow lamination,

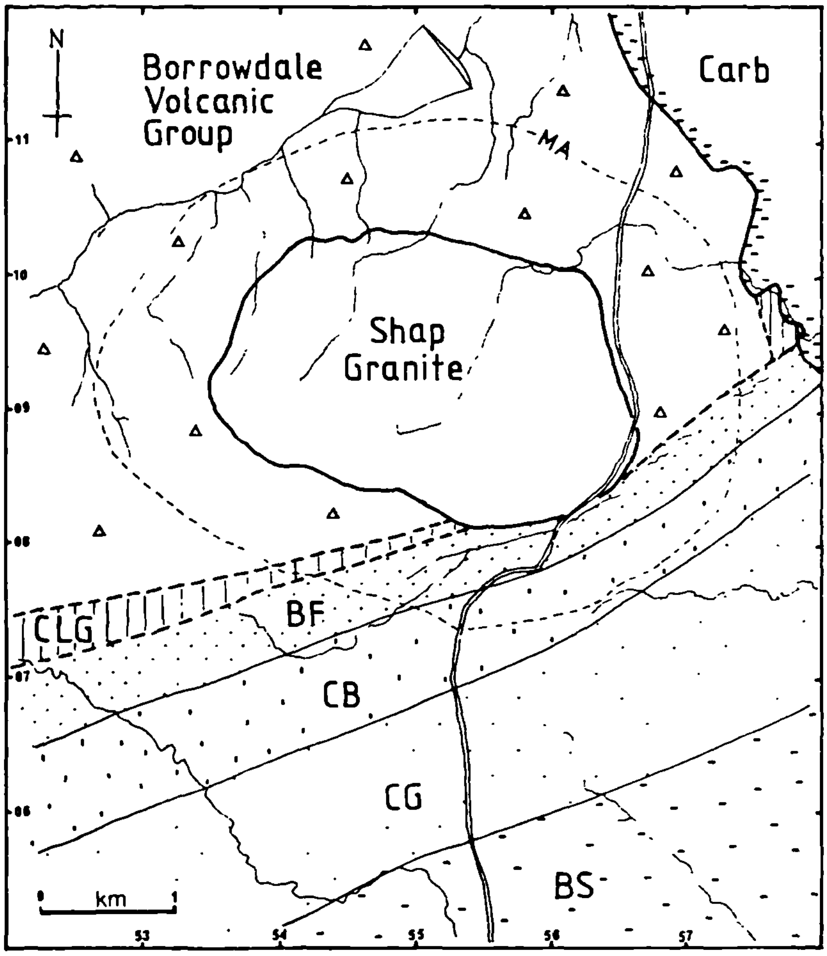


FIG. 2.5.

A simplified map of the major geological units about the Shap Granite.

The local Silurian succession is composed of the Brathay Flags (BF), Coldwell Beds (CB), Coniston Grits (CG) and Bannisdale Slates (BS).

The Borrowdale Volcanic Group, Coniston Limestone Group (CLG) and Carboniferous successions are undivided.

MA - Outer limit of the contact metamorphic aureole.

Minor intrusions and faults are omitted.

(Partly after Harker and Marr, 1891).

both groups showing limited low-grade alteration (metamorphism) due to regional Caledonian deformation. It was Mitchell (1934) who gave the first more modern description of these rocks and although he described a large area north from Shap to Haweswater (some 10km. distance), he assigned all the rocks about Shap to being the equivalent of the Wrengill Andesites, a formation of volcanics which he had previously described further to the east in the Kentmere district (Mitchell 1929).

Cross sections based on Mitchell (1934) for the Shap area are shown in Fig.2.6 showing the Wrengill Andesites to be the major volcanic formation in the region, lying directly below the Coniston Limestone Group and thus being the youngest volcanic rocks in the eastern Lake District.

Mitchell (op cit) omits an account of the Shap Rhyolites of Harker and Marr (1891) due to their poor exposure but gives a full description of the Wrengill Andesites as noted below. It is estimated that more than 90% of the rocks exposed are lavas and thin tuffs of andesitic composition with basalts and acidic rocks being infrequent. Outside the metamorphic aureole, the andesites consist of thin, blue-green aphanitic flows with occasional porphyritic horizons and thin bedded tuffs between flows. The flows are generally massive though flow brecciated and vesicular varieties are also seen. Phenocrysts are evident, the most common being plagioclase, though chlorite pseudomorphs after pyroxene can also be noted. Caledonian deformation and associated low grade metamorphism (usually below greenschist facies) has resulted in some secondary alteration of phenocrysts

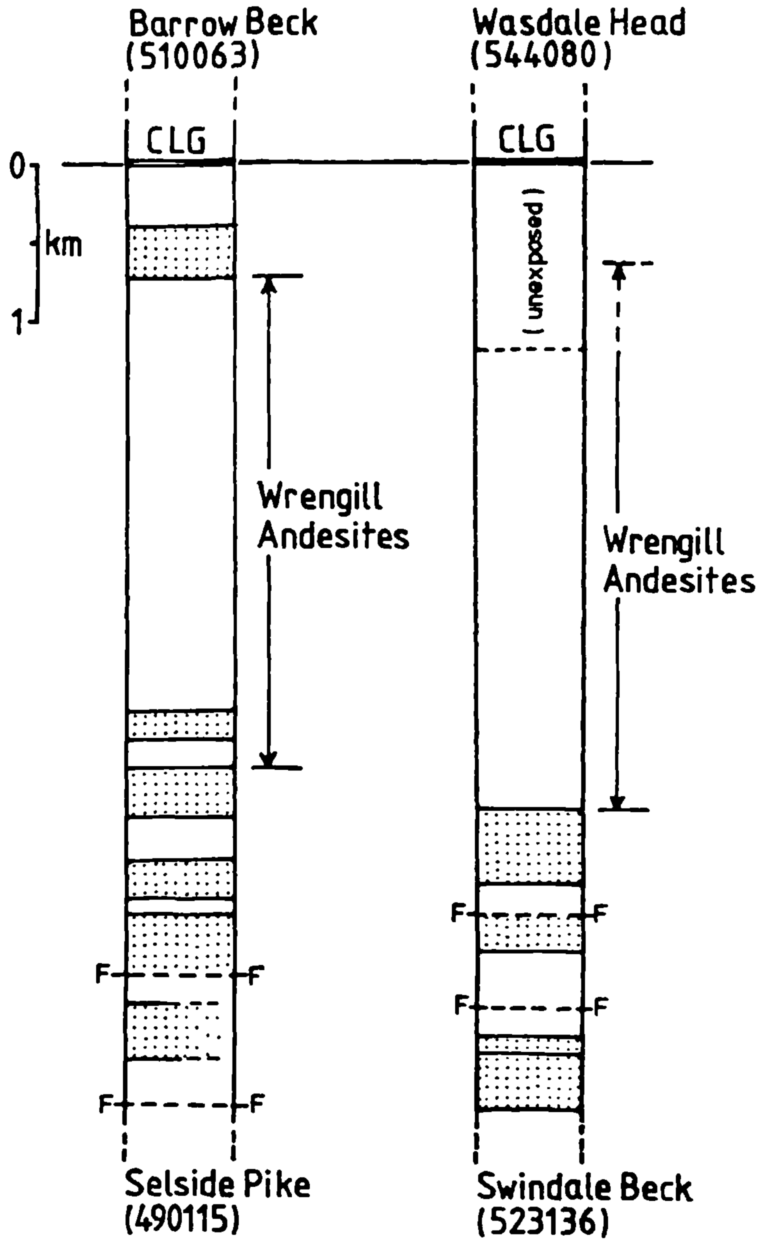


FIG. 2.6. Two simplified logs of the Borrowdale Volcanic rocks running northwards from the Shap area.

The two traverses are 4km apart and thicknesses are not corrected for dip (which is usually steep).

Pyroclastic horizons (ornamented) are interbedded with thick and thin units of lava. Many minor units and faults (F) have been omitted.

The Wrengill Andesites are unconformably overlain by the Coniston Limestone Group (CLG).

(After Mitchell 1934).

and the development of epidote in the groundmass.

Towards the granite, contact metamorphism results in hornfelsing and further epidotisation along with the development of biotite. Of particular interest has been the fissure metasomatism described by Firman (1957) which has produced garnet-bearing calc-silicate veins, which at present are only known from the Shap Blue Quarry. North-east of Wet Sleddale, good exposures of green lithic tuffs outcrop about the River Lowther. They vary from fine to coarse and are poorly-bedded and graded with some massive, coarse horizons between thinner, finer-grained beds.

The Wrengill Lavas are generally massive with the development of fracture cleavage and joints whilst the thin interbedded tuffs have a penetrative cleavage. Cleavage is always steep (>70°) and trends approximately north-eastwards apart from near the granite margin where trends have been rotated during the granite's emplacement (see section 2.2.4).

Mitchell (1934) also described regional E-W folds within the Wrengill Andesites overturning to the north which he delineated using the tuff horizons. Although some folds no doubt exist, the value of these thin tuffs as marker horizons in identifying individual folds is questioned. The best lateral exposure of volcanics in the study area is in the Blue Quarry where some 100m of continuous exposure is available. Although this exposure is within the metamorphic aureole and, as a consequence, is altered, it is still not possible to easily identify individual lava units, bedding and other structures in order to support Mitchell's fold structures.

Faulting in the area of the Borrowdale outcrop is generally normal to the regional NE-SW trends and fault breccia and shattered volcanic material can be found in some of the gills and becks running northwards off the granite. Associated with these faults are quartz and barytes veins and notably in Sherry Gill, barytes occurred in such quantity that it was briefly worked (Plate 2.a). Quartz also occurs as swarms of large veins about the aureole margin (Plate 2.b), these veins cross-cutting the local tectonic structures such as cleavage. These veins and other forms of mineralisation are further discussed in Chapter 5.

2.2.3. The Coniston Limestone and Silurian Sediments.

At Shap, the Coniston Limestone Group occurs as two isolated outcrops, one as metamorphosed rocks close to the granite margin at Wasdale Head Farm and the second, outside the metamorphic aureole in Blea Beck as a stream section near Shap Wells. At Wasdale Head, the succession only consists of the Stockdale Rhyolite and the Coniston Limestone, with the remainder of the Group cut out by faulting. Both rock types have been thermally metamorphosed by the granite. The rhyolite is pale pink or grey and very fine grained. Flow banding is evident at both outcrops but some recrystallisation due to metamorphism is noticeable at Wasdale Head. Harker and Marr (1891) describe the metamorphism of the Stockdale Rhyolite and Coniston Limestone and mention the development of garnet and wollastonite in the calcareous sediments. Unfortunately, these garnet-bearing rocks are not available for study as their outcrop is no longer

PLATE 2.

PLATE 2. COUNTRY ROCKS

a. Blocks of impure barytes from the minor workings of a small deposit in Sherry Gill.
(GR 539103)

b. Swarm of large quartz veins in distorted volcanic rocks at the margin of the metamorphic aureole by Wet Sleddale reservoir.
(GR 547112)

Structures in the Silurian rocks exposed in the A6 road section south of Shap Fell.

c. Tool marks and flute casts.
d. Flute casts.
e. Sandstone dykelets in an interbedded siltstone-fine sandstone sequence.

f. Bedding-cleavage intersections in Silurian siltstones.

g. Open E-W trending folds, typical of the minor folds on the northern limb of the Bannisdale Syncline. (Fold H of Moseley 1968)

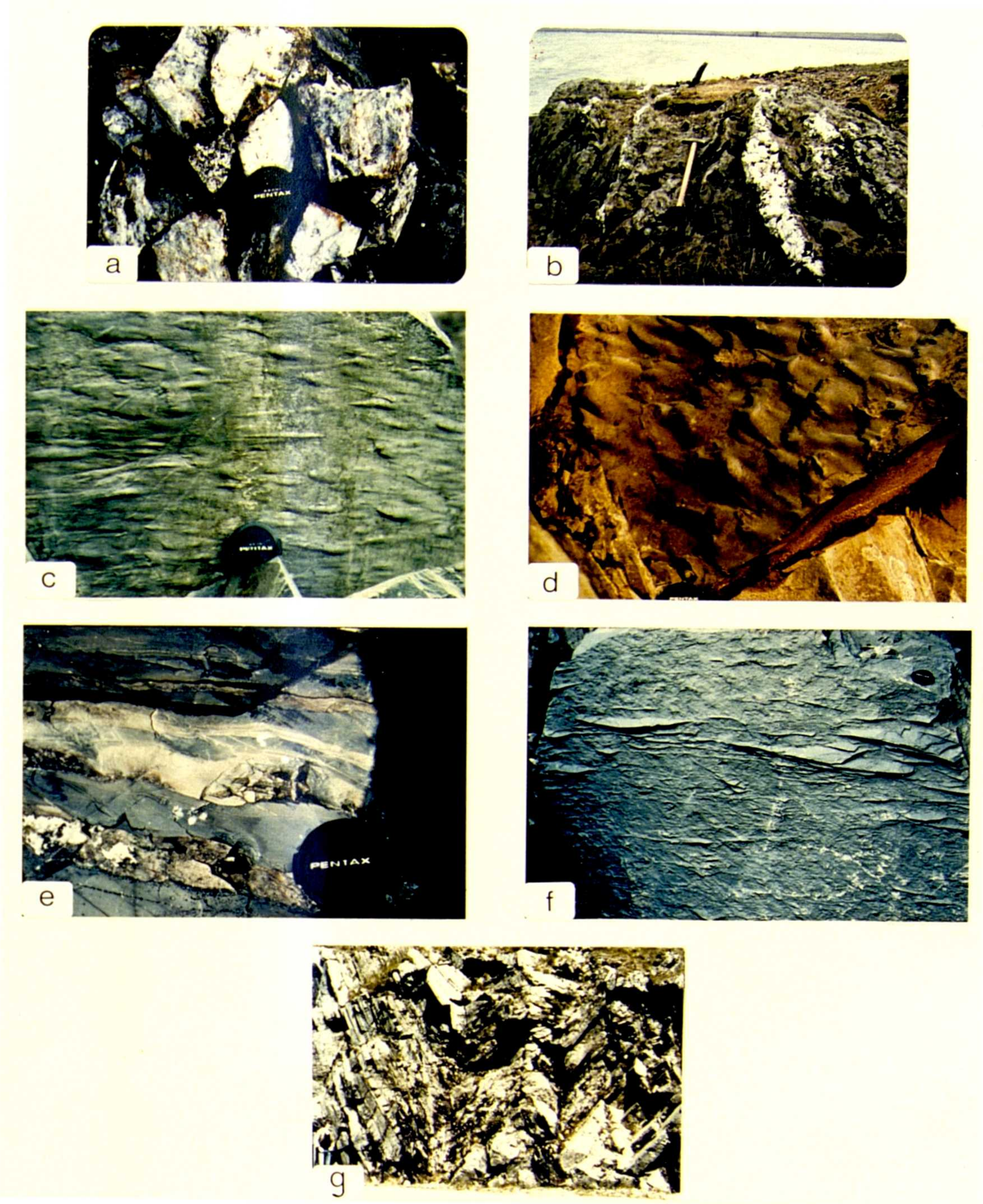


PLATE 2

visible.

The southern part of the area consists of folded and cleaved Silurian turbiditic sediments faulted against the underlying Ordovician rocks. Due to this faulting, the lowest members of the Silurian (of Llandovery age) are not found at Shap. The local succession is shown in Fig.2.5 and, as previously mentioned, has recently been studied by Redfern (1979). Moving southwards and up the sequence, the rocks become progressively finer with a decrease in the more massive greywackes and a corresponding increase in the siltstone-shale horizons. The rocks are poorly fossiliferous but display well developed erosional and depositional sedimentary structures (Plate 2.c,d,e) along with upright folding and associated tectonic structures typical of the late Silurian deformational style in Cumbria (Plate 2.g,f).

The development of these tectonic structures is discussed more fully by Moseley (1968,1972). The folds south of the granite are minor folds on the northern limb of the Bannisdale Syncline which is one of the few recognisable major Caledonian folds running across Cumbria (Moseley op cit.). This is shown in a simplified N-S section through the Shap area (Fig.2.7), which, based on geophysical evidence, shows the major spatial relationships between the granite and the local rock units.

Of particular interest to this study is that the lowest part of the Silurian succession (the Brathay Flags and Coldwell Beds) lie within the metamorphic aureole. Portions of these strata are calcareous and the

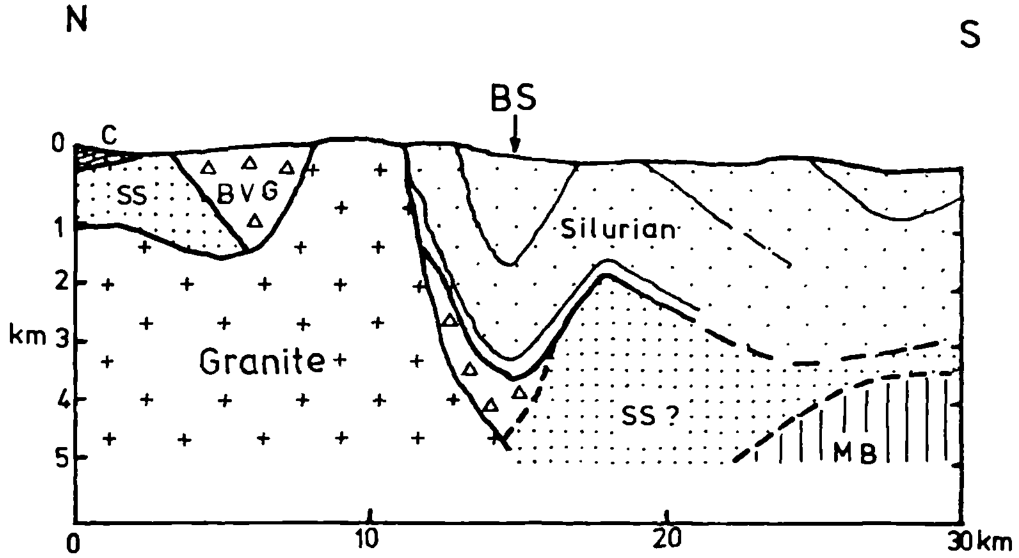


FIG. 2.7.

Geological interpretation of a 30km north-south section of the eastern Lake District showing the subsurface position of the Shap Granite and the Bannisdale Syncline (BS), and the major fold structure of the region.

Below 3km, the position of the Skiddaw Slates (SS) and the underlying basement (MB) are conjectural, designed to accommodate the aeromagnetic data.

C-Carboniferous, BVG- Borrowdale Volcanic Group.

(After Banks and Gurbuz 1984).

metamorphism and subsequent development of calc-silicate assemblages allows discussion of the metamorphic processes occurring in the aureole (see Chapter 5).

2.2.4 The Shap Granite.

The granite has an ovoid outcrop of some 7 sq. km and is the surface expression of a large area of low gravity values, suggesting that it is a small boss off the roof zone of the Cumbrian Batholith (Fig.2.7). It is the only major Cumbrian granitic intrusion to have reached stratigraphically as high as the Silurian. The granite has been precisely dated by Rb-Sr techniques at 394±4 Ma which is within error of determined K-Ar ages (Wadge op cit., Brown et al. 1964, Dodson et al. 1961) and places this granite along with those of Skiddaw and Weardale in the lowermost Devonian.

Grantham (1928) showed that the granite was largely a porphyritic adamellite composed of orthoclase perthite megacrysts (of very variable modal amounts) in a coarse matrix of quartz, orthoclase, plagioclase and biotite, with minor apatite, zircon, sphene, magnetite and pyrite as the main accessory phases.

Jointing is the major structure developed in the granite and, although occuring throughout, is best displayed in the Pink Quarries (Plate 1.b), where it facilitates quarrying operations. The joints appear to have acted as conduits for the passage of late-stage hydrothermal fluids during the granite's cooling. Dark, altered granite zones are found about the joints due to wall-rock alteration and extensive deposition of secondary minerals occurs on the joint planes (Plate 7). At its most extreme , hydrothermal alteration results in very darkened granite varieties (Plate 7) whilst further alteration eventually results in a degraded, friable red green and cream mixture of quartz and altered feldspar and mafics. Small hydrothermal quartz veins, cross-cutting the granite and not spatially related to the joint system also result in localised altered granite along with reddened margins about the vein (Plate 7).

Within the darkened granite, (termed 'Dark' granite by Grantham 1928 to distinguish it from the normal unaltered 'Light' granite), a secondary suite of minerals such as chlorite, calcite, fluorite, and sulphides has developed.

These two main varieties, (Light and Dark) constitute the majority of the granite exposed at the present level, the remainder being minor varieties such as hornblende-bearing marginal types or late-stage aplitic and pegmatitic types.

Melanocratic medium to fine-grained xenoliths appear sparingly throughout the granite (Plate 1.c). However, this may be a false impression of their abundance as they are more plentiful in the granite quarries. Xenoliths of obvious local country-rock origins are very rare. The origins and significance of the majority of xenoliths is the subject of fuller discussion in Chapter 6.

Granite dykes occur upto 5km from the granite margin and have a rudimentary radial arrangement about the granite (see Fig.4.1). They are dominantly quartz-orthoclase porphyries though a few more basic, biotite and plagioclase-rich types also occur.

2.2.5 Intrusion of the Granite.

The contact relationships of the granite are worthy of a short discussion at this point. Although geophysical evidence shows the granite to have a planar, outward-dipping contact (Fig. 2.8), detailed examination of contact zones shows many intrusive styles. The granite margin can be examined at three main sites; to the N.E. in Longfell Gill (GR 556099), to the N.W. about Sleddale Pike and Poorhag Gill (GR 537097), and north of Wasdale Farm (GR 550082). All these sites are within the volcanic succession and contacts are locally vertical and inward-dipping areas occur on a small scale in the gullies immediately behind Wasdale Farm. At all contacts, the granite has a cross-cutting relationship with the country rocks (eg. Plate 1.d) and there is no evidence of extensive stoping or assimilation at this level. As might be expected, fine-grained microgranites and quartz veins occur at the contacts along with more normal megacryst-bearing granite, though modal proportions of orthoclase and biotite in particular are very variable, as well as textural and grain-size variation (Fig.2.9).

The main intrusive style is of granitic, dyke-like apophyses running off the main granite outcrop, though these usually travel only a few metres or less into the aureole. At no time does there seem to be any connection between the major dyke suite around the granite and the granite margin, suggesting that the larger dykes were emplaced by more vertically-oriented intrusion from off a.

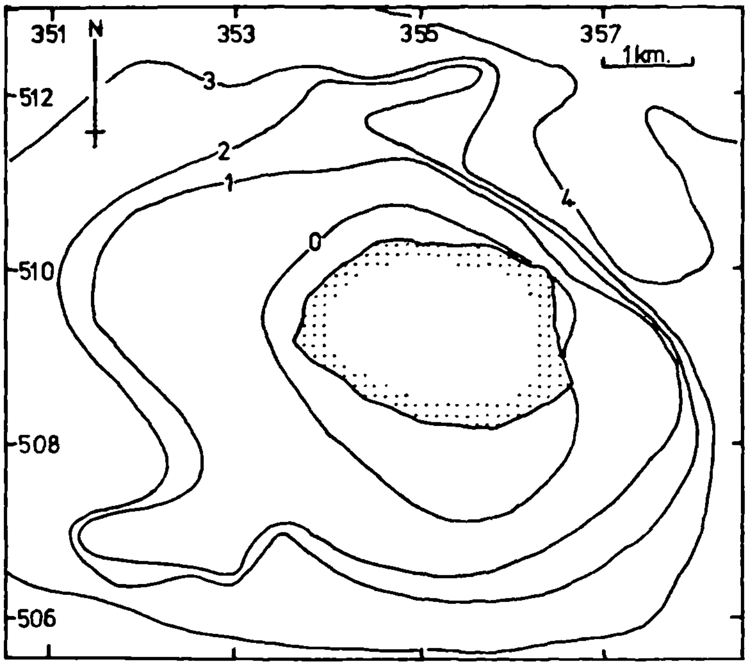


FIG. 2.8a. Three dimensional model of the Shap Granite based on gravity data.

Contours show the depth in Km below sea-level.

b.

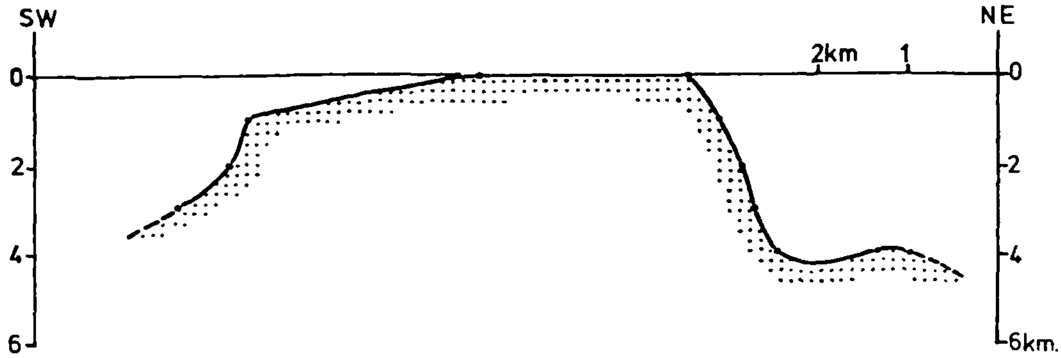


FIG. 2.8b. A NE-SW section from Fig. 2.8a showing the differing attitudes of the pluton walls.

(Both after Lee 1984a).

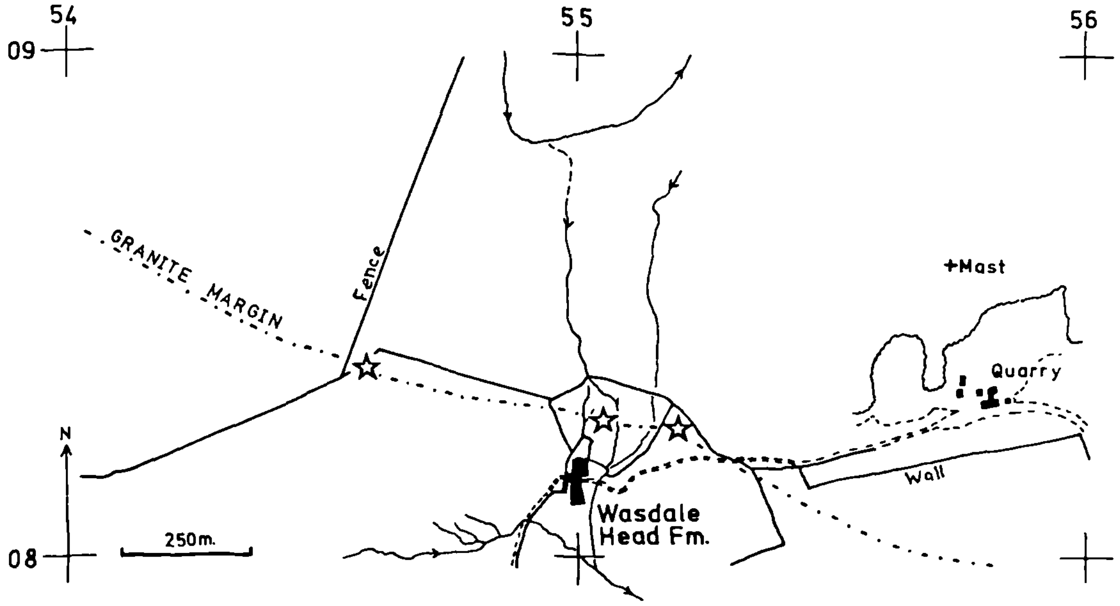


FIG. 2.9a.

Three locations (☆) about Wasdale Farm at which contact relationships between the granite and volcanic country rocks are displayed.

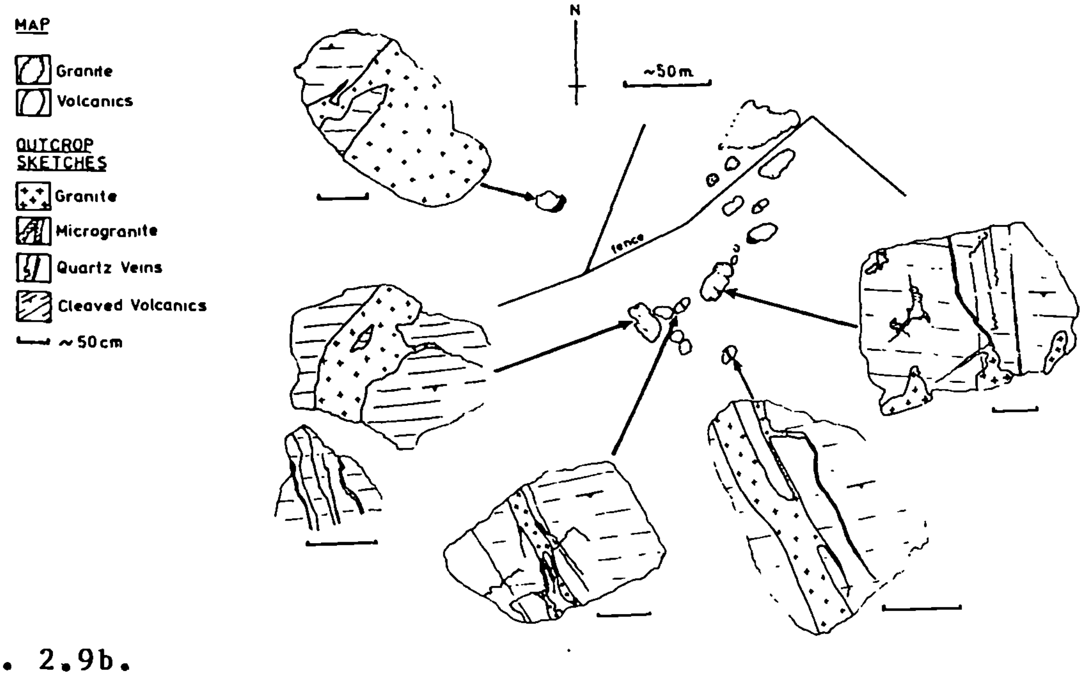


FIG. 2.9b.

Field sketches of the intrusive styles at the location to the West of Wasdale Farm.

Note the cross cutting relations of the quartz and granite veins and dykelets.

the pluton roof than as horizontal, lateral off-shoots of the granite boss.

Although the margin is mapped as a relatively smooth contact, this is a gross simplification, partly induced by poor exposure. Good lateral exposure along contacts is lacking, but outcrops about the upper reaches of Poorhag Gill show that contact zones may be more complex in some regions. The contact here is off-set by a N-S trending fault running along the gill, which somewhat complicates detailed lateral mapping. Apart from this, immediately east of the gill and south of a small cairn, isolated outcrops of both granitic and volcanic rocks are readily intermixed to such an extent that no unequivocal boundary between the two satisfies the outcrop disposition.

Details of a contact zone are shown in Plate 3. Invariably, small, narrow (<1 cm) quartz veins of short extent (<1m) appear to be the precursor to the intrusion of granitic material. Unlike the granite, these veins may intrude along the weaknesses in the country rocks such as joints or cleavage planes but are later cross-cut or themselves deformed by the subsequent emplacement of the granite. The ptygmatic folding of some quartz veins and the localised disruption of fabrics in the volcanic rocks (Plate 3.c) suggests a component of the emplacement was of a forceful ('shouldering') style in contrast to the more common cross-cutting mode.

The extent of deformation in the aureole caused by the pluton's intrusion is difficult to assess due to the pre-existance of the Caledonian tectonic structures. On a local scale, at contacts, vesicles and alteration zones in

PLATE 3.

PLATE 3. GRANITE CONTACT

a. Field Map of the Longfell Gill-Blea Beck stream exposure at the north east granite contact.
(GR 560101)

A	Deformed microgranite
B	Normal megacrystic granite
C	Deformed fabric about A
D	Small microgranite dyke
E	Deformed quartz vein
F	Xenoliths of volcanic material
G	Microgranite dyke in normal granite
H	Cross-cutting quartz veins
I	Microgranite dyke
J	Fabric in volcanic hornfels
K	Disrupted fabric

b. Microgranite contact with deformed lava with elongate and flattened vesicles producing a fabric (F). Microgranite contains small isolated orthoclase megacrysts.

c. Locality C. Distorted fabric in volcanic hornfels due to strain at granite margin.

d. Locality F. Xenoliths of volcanic rock (V) in granite (G). Fabric directions in the xenoliths correspond to those in the local country rocks suggesting that these xenoliths may be still partially afixed.

e. Locality K. Disrupted fabric in tuffaceous horizon.

f. Locality J. Partially annealed fabric in volcanic hornfels.

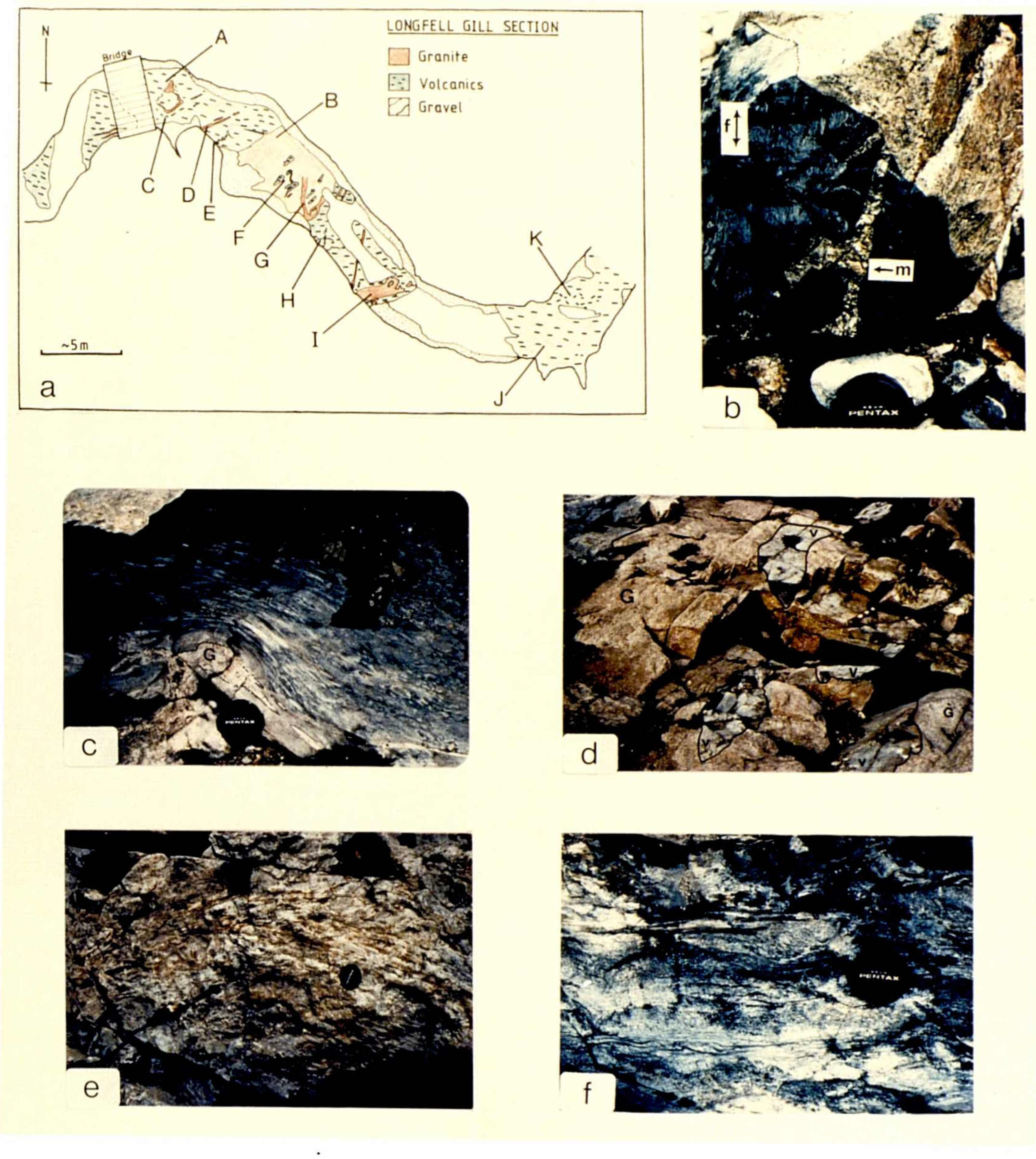

LONGFELL GILL SECTION
Granite
Volcanics
Gravel
N
Bridge
A
B
C
D
E
F
G
H
I
J
K
~5m
a
f
m
PENTAX
b
G
PENTAX
c
G
V
V
V
G
V
d
e
PENTAX
f

PLATE 3

the lavas may become more flattened or elongate when paralleling the granite margin, but this only appears to happen in the immediate vicinity of the contact. On a regional scale, Boulter and Soper (1973) showed that regions about the eastern and western margins of the granite have large deviations in the strike of tectonic fabrics (mainly cleavage) from the local NE-SW trend. Fig.2.10 shows fabric trends about the pluton and compares well with that of Boulter and Soper (op cit.). This indicates that some forceful deformation had occurred during the granite's emplacement, probably as ductile deformation taken up in the thin, well-cleaved tuffaceous horizons described previously.

There is no evidence of a marginal fabric or strain-induced structures within the granite at its contacts. Orthoclase megacrysts do not show any parallelism with the margin (suggesting a lack of flow and/or stress alignment) and xenoliths (although not commonplace at the contacts) appear unorientated and undeformed. The development of such structures is often observed in composite plutons that have developed by sequential emplacement of magma. Such marginal structures are well displayed in Criffel intrusion in southern Scotland. This, like at Shap, is a post-tectonic, lower Devonian intrusion emplaced into regionally deformed Lower Palaeozoic sediments. Here (multiple) emplacement of granite into pre-existing granodiorite has resulted in widespread fabrics in the granodiorite, paralleling the outer contact of the pluton (Plate 13.g). Lack of such structures at Shap would indicate that emplacement of individual magma pulses

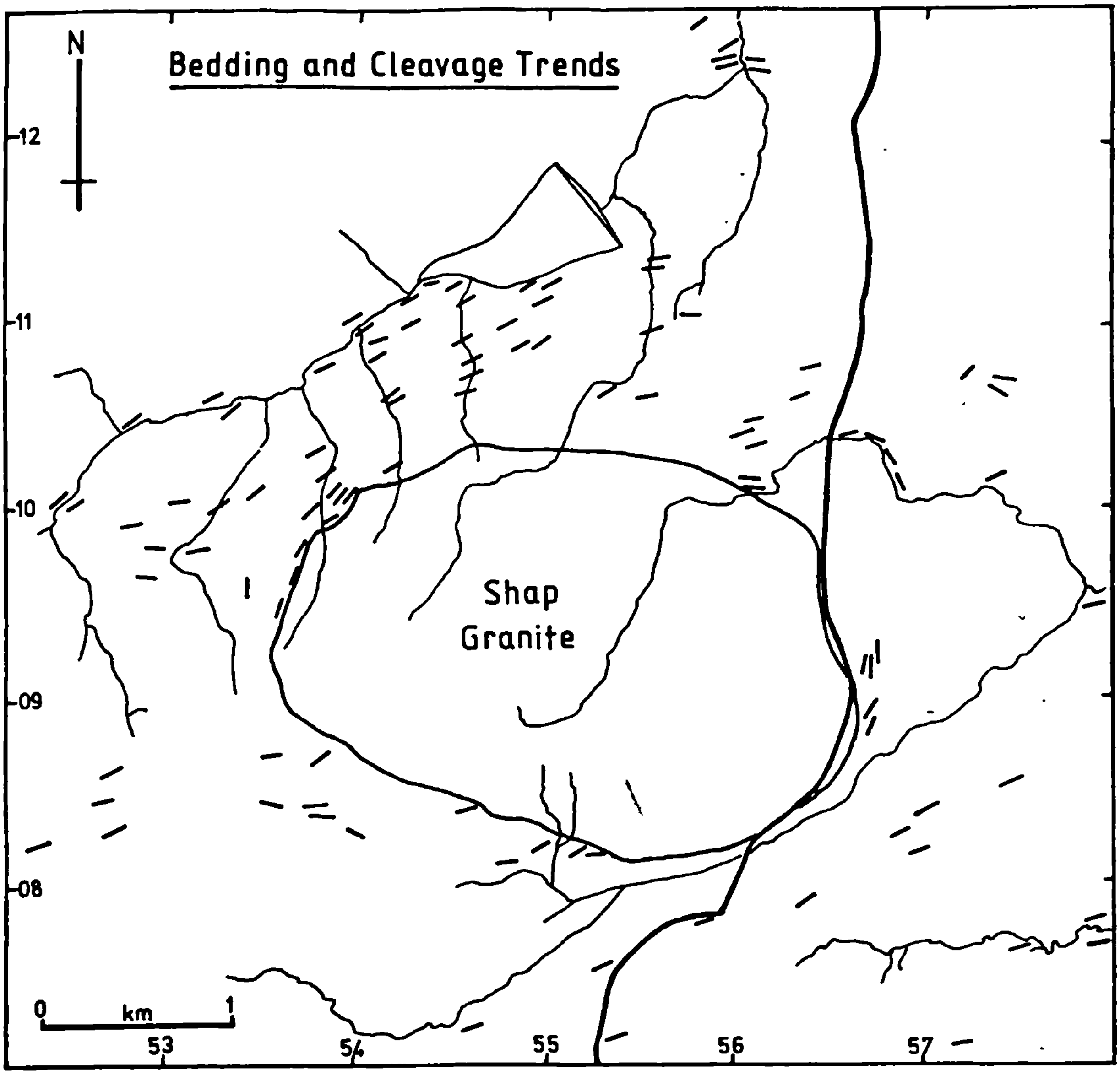


FIG. 2.10.

Trends of bedding and cleavage strike directions about the Shap Granite.

The regional trend (at approximately 060°) is deflected about the east and west contact zones.

resulting in a composite pluton has not occurred (or is not evident?) at this level of exposure. This is supported by geophysical evidence of Bott (1978) and Lee (1984a) whose gravity modelling of the granite to a depth in excess of 6km indicates no subsurface material of a differing composition to that presently exposed.

2.2.6 The Carboniferous and Granite Unroofing.

The eastern margin of the study area contains the lower members of the Carboniferous sediments which unconformably overlay both the Silurian and Ordovician successions. The lowest rocks are exposed at Shap Wells and southwards in the valley of Birk Beck and are equivalent to the Basement Beds described elsewhere in Cumbria (Sect. 2.1.6). They consist of about 10m of irregularly bedded shaly sandstones and conglomerates dipping shallowly to the east, and laying directly upon steeply bedded Silurian rocks (Plate 1.g). It has long been recognised that these rocks contain debris from the Shap Granite with fragments of the orthoclase megacrysts being very evident, along with locally-derived Silurian clasts. Above lie thick successions of Carboniferous limestone of Dinantian age.

The Basement Beds indicate that the granite was being locally eroded by the time of the Lower Carboniferous transgression which followed extensive post-orogenic erosion which had occcured during the Devonian resulting in the unroofing of the Shap Granite. A similar situation has been encounted elsewhere in northern England. Drilling of the Rookhope Borehole to encounter the Weardale Granite showed Dinantion limestones lying directly upon unroofed and weathered granite (Dunham 1967).

If one assumes these early Devonian granites were emplaced at epicrustal (1-3 Kb) depths, then large quantities of overlying Palaeozoic roof material must have been eroded during the Devonian. Evidence of large quantities of Devonian debris in northern England is lacking, the lower Carboniferous usually sitting directly on the pre-Devonian rocks. No doubt much Devonian material was extensively re-worked prior to the Carboniferous, though some remnants may still be preserved in the bottom of the deep Carboniferous basins of central and northern England or as isolated outcrops such as those mentioned in section 2.1.6.

CHAPTER 3 GRANITE PETROLOGY and GEOCHEMISTRY

3.1 Introduction.

The major granite types at Shap consist of pink orthoclase megacrysts set in a black and white matrix of mainly plagioclase, orthoclase, quartz and biotite. Grantham (1928) recognised several types of granite based on the modal proportions of these minerals and in particular, the amount of megacrysts. He named the varieties Basic and Stage 1, 2 and 3, these being a series of increasingly acid character and increasing proportion of megacrysts. Spatial division between these varieties is difficult to assess but,where in close proximity, is usually gradational suggesting that the varieties are a function of the extent of megacryst development rather than being regions of discrete granitic magmas.

The present outcrop is almost entirely of the Stage 2 type of Grantham (op cit.) which has some 20-30% megacrysts. Other varieties are minor in extent and their distribution relative to Stage 2 granite appears random. Of note is a hornblende-bearing variety of granite, known only at a single small locality at the margin near Sleddale Pike. This is the only granite type differing from the usual orthoclase-plagioclase-biotite-quartz petrology.

Aplite and quartz veins are found cross-cutting all the above varieties and these in turn are followed by a stage of pneumatolytic and hydrothermal alteration and associated mineral deposition on joints and within veins (eg. Plates 6 and 7).

3.1.1. Major Granite Varieties.

The Stage 2 granite is typically made up of 25% pink, sub to euhedral orthoclase megacrysts set in a matrix of white plagioclase (30%), pale pink orthoclase (15%), grey quartz (20%) and black biotite (10%). On the basis of the similar proportions of orthoclase and plagioclase feldspar, the granite would be classed as an adamellite. The megacrysts are perthitic, usually with simple Carlsbad twinning. They generally have random orientations although areas of weak alignment can be seen (Plate 4.a). The plagioclase and biotite are also sub to euhedral whilst the matrix orthoclase and quartz are subhedral to anhedral. Visible primary accessory minerals include sphene, magnetite and pyrite, the latter noticeably associated with the megacrysts.

Intimately associated with this typical unaltered granite ('Light' granite) is the hydrothermally altered variety ('Dark' granite). The spatial relationship between this darkened granite and the major joint systems in the granite is evident, this variety being a result of the action of hydrothermal solutions passing along the joints causing wall-rock alteration. This 'Dark' variety is like the unaltered ('Light') granite in texture and composition, but differs in having a red-grey groundmass due to alteration of the matrix plagioclase and biotite. Megacryst and matrix orthoclase are usually unaltered and it is only with more extreme alteration that the orthoclase shows signs of change, becoming reddened. The plagioclase and mafic constituents of the matrix alter further to hydrated secondary minerals such as chlorite, sericite, epidote and iron oxides. Although this is associated with the mineralisation on adjacent joint planes and minor veins, little or no mineralisation by replacement occurs within the body of the 'Dark' varieties (ie. away from the joints) which might result in a disseminated distribution of mineralisation.

3.1.2. Minor Granite Varieties.

3.1.2.1. Granites.

As previously mentioned, variations in the modal amounts of the four major constituent minerals results in minor varieties of the Shap Granite. With decreasing megacryst content, the granite takes on a greyer, more basic appearance. A single sample of a black and white granite containing no megacrysts has been found as a loose, recently-quarried block in the Pink Quarry (Plate 4.c). It was not possible to find its exact insitu location so as to assess its relationship to the major granite types, though it is thought that it may be related to the biotite-rich, megacryst-poor granites described below (section 3.1.2.3).

Megacrysts proportions are rarely less than 15% and these varieties are equivalent to Grantham's Basic and Stage 1 granites. In such varieties plagioclase and biotite are more abundant with matrix orthoclase and quartz being reduced to less than 25% of the mode. The megacrysts are of interest in that they often have narrow, pale rims, not unlike Rapakivi-textured granites. A good example of this texture was observed within a loose block on a bank of spoil immediately below the smaller, western face of the Pink Quarry. Plate 4.d shows the rimmed megacrysts within this granite which grades over about a metre into normal Stage 2

PLATE 4.

PLATE 4. GRANITE VARIETIES

a. 'Dark' variety of normal porphyritic Shap Granite with well developed orthoclase megacrysts (Pink Quarry).

b. Megacryst-rich granite. (Pink Quarry).

c. Non-porphyritic granite. (Pink Quarry). (Sample No.600)

d. Dark, megacryst-poor granite in contact with normal Shap Granite in discarded block below Pink Quarry.

e. Megacryst-poor granite from the granite margin behind Wasdale Farm, with much orthoclase development in the groundmass. (Sample No.605)

f. Similar to 4.e. Biotite-rich, megacryst-poor granite from the Wasdale Farm contact. (Sample No.606)

g. Hornblende granites from the NW contact with variable grain size and orthoclase development. All the visable dark minerals are hornblende with biotite being rare.
(GR 539100) (Sample No.523)

h. Orthoclase-rich microgranite fron near northern contact found inter-mixed with normal megacrystic granite.
(GR 545103)

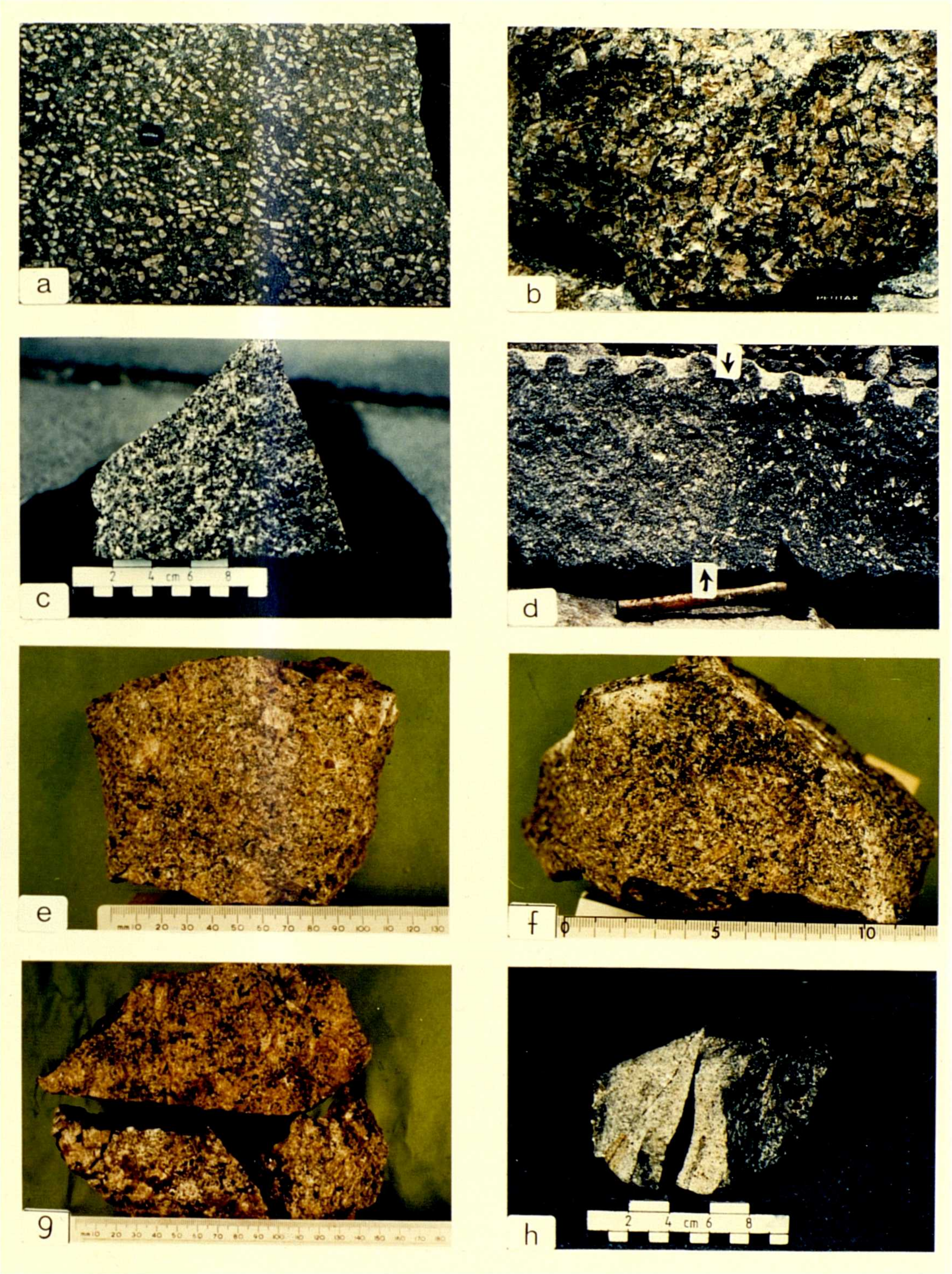

a
b
c
2 4 cm 6 8
d
e
mm 10 20 30 40 50 60 70 80 90 100 110 120 130
f
0 5 10
g
mm 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
h
2 4 cm 6 8

PLATE 4

granite with unrimmed megacrysts.

The hornblende-bearing granite is known from only one small location on the granite margin near Sleddale Pike. Its exposure is now very limited and field relationships to the main body of granite and the adjacent country rocks are difficult to ascertain. Grantham (1928) gave a full description of this granite's occurrence after he excavated the area by blasting. He stated that the hornblende granite occured as a few dyke-like apophyses off the main granite, some being over 10m long and containing xenoliths of local volcanic material. This granite is intermixed with normal biotite granite (Stage 2) and the hornblende and orthoclase are very variable in grainsize (Plate 4.g). Orthoclase appears plentiful with plagioclase and quartz less obvious than in other granites. The intermixing of the two granite types lead Grantham (op cit) to the conclusion that both types must have been liquid at near the same time and that the hornblende granite was a product of granite contamination by the digestion of local andesitic material.

About the northern contact, N.E. from Sleddale Pike across to Sherry Gill, normal megacrystic granite can be seen to be intermixed or sharply cross-cut by medium-grained, orthoclase-rich microgranite, not dissimilar to that seen at Blea Beck (Plates 3 and 6.a). Based on its grainsize and mineralogy, this granite variety appears to be intermediate between normal granite and aplite. It also is emplaced after the host megacrystic granite, occurs in relatively minor quantities and does not pass out into the country rock. Additionally, the development of megacrysts and mafic phases within it is restricted.

3.1.2.2. Aplites.

These are best displayed in the Pink Quarries and are known to occur throughout the outcrop, although they are generally restricted in extent to the margins of the intrusion. They are emplaced as straight, cross-cutting structures, post dating the other main granite phases but are themselves cross-cut by joints and faults and affected by later hydrothermal alteration. They are pale pink medium to fine grained rocks composed almost entirely of quartz and orthoclase, along with small amounts of plagioclase, biotite and pyrite (Plate 6).

Most are narrow (<2cm) and do not interact with the host granite or its megacrysts. They terminate by bifurcation until individual aplitic stringers merge with the granite matrix (Plate 6.b). An exception to this is if they are found crossing particularly biotite-rich areas of granite. Here, in what is usually an orthoclase-poor environment, the aplite vein develops less distinctly with poorly formed margins and inclusions of biotite and white feldspar (plagioclase?) (Plate 6.d). Other phenomena include quartz-rich margins to aplites (Plate 6.c) and the occurrence of pyrite, sometimes appearing as well developed euhedral grains scattered through the aplite.

Rarely aplites attain widths upto a metre and these differ in having marginal zones of an intermediate character being between normal fine-grained aplite and the coarse grained host granite (Plate 6.e). These larger aplites are less planar with more undulating granite contacts. The marginal zones are medium grained and contain more biotite than expected as well as distinctive grains of quartz (Plate

6.f). No larger aplites such as those described by Dunham et al. (1965) from the Weardale Granite (approx. 10m thick) or the Skiddaw Granite (over 3m wide, Barratt 1969) have ever been recorded from Shap.

A particular form of aplitic rock is found at a single isolated exposure towards the north of the pluton. Here, on a small outcrop, are pod-like bodies of aplitic granite within normal Stage 2 granite (Plate 6.g,h). They consist of discrete irregularly-rounded pale cream-pink bodies upto 0.5m in diameter with sharp, cross-cutting margins, which are very similar in mineralogy to the aplites described above. Careful examination and sample extraction has shown that their form is not a surface effect, but in fact they appear to be a cluster of aplite pods. This form requires a differing style of emplacement to that seen elsewhere in this and other plutons. The normal aplites cross-cut the host granite in a style which suggests that the granite was consolidated and behaved in an essentially brittle style. Conversely, the form of the pod -like bodies suggests that the granite may have been in an intermediate physical state of a more 'plastic' nature, which in turn implies that these bodies were emplaced prior to the more typical aplites but still near to the complete crystallisation of the granite.

None of the aplites show any degree of deformation or folding. This would imply that there has been no volume change in the granite mass after aplite emplacement by processes such as granite cooling (contraction) or multiple intrusion (expansion).

3.1.2.3. Biotite Banding and 'Stringers' (Schlieren).

Recently, biotite-rich bands of granite have been

PLATE 5.

PLATE 5. BIOTITE BANDING

All Examples from the Pink Quarry.

a. A biotite-rich vein in normal megacrystic granite.

b. Diffuse termination of biotite stringer.

c. Biotite banding or schlieren with well developed internal banding.

d. As in 4c. This example was 30 metres in length and internally banded throughout.

e. Specimen of biotite-rich, non-megacrystic granite band.

f. Biotite-rich band intermediate in development between 4c, d, and 4e. Note the general lack of megacryst development within these bands.

g. Pegmatitic quartz and orthoclase with biotite-rich selvage in normal granite.

h. Extreme development of 4g, with the growth of near monomineralic biotite and orthoclase zones.

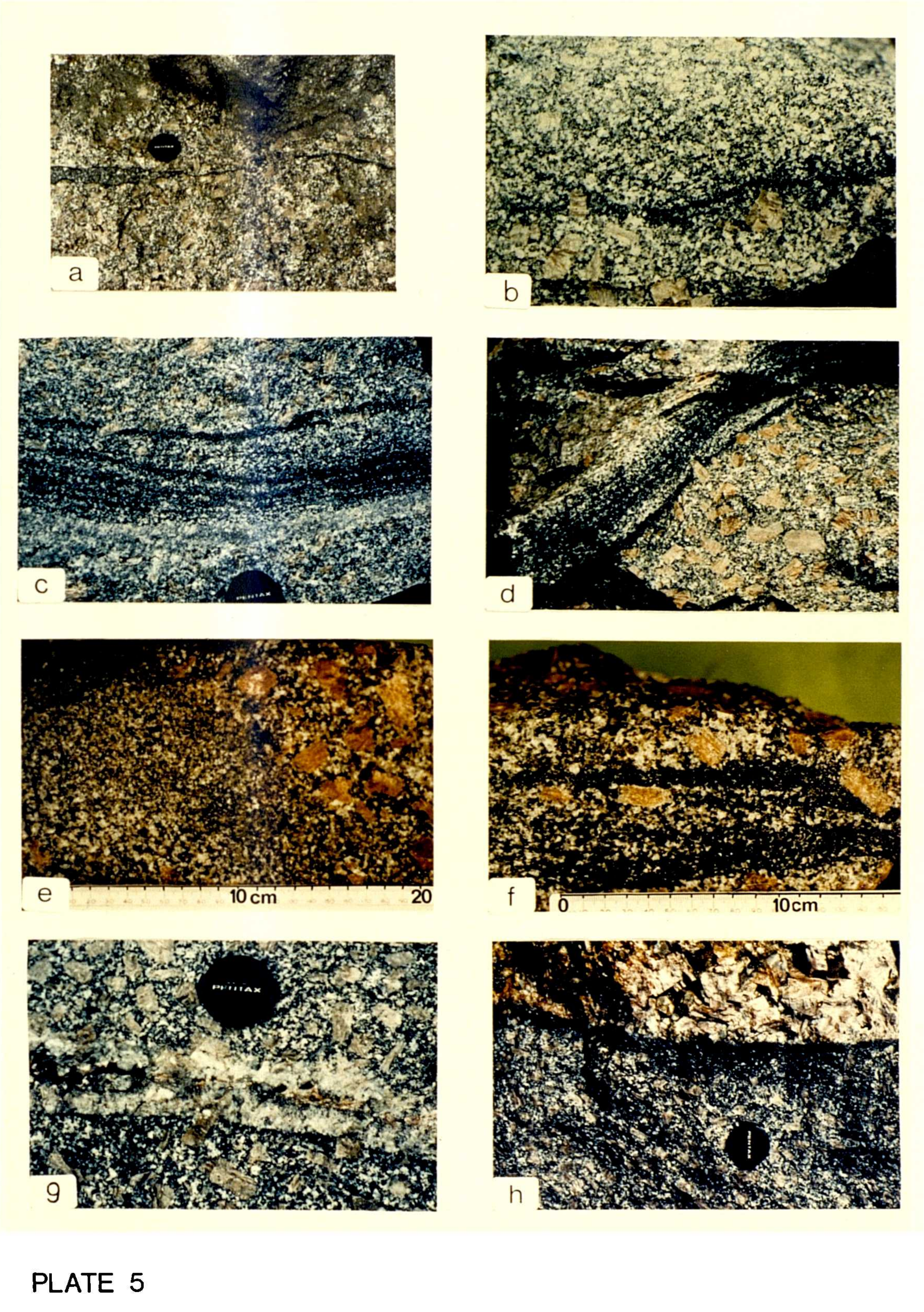


PLATE 5

PLATE 6.

PLATE 6. APLITES

a. Aplite vein in normal granite near northern contact.
(GR 543101)

b. Typical bifurcating aplite vein termination. (Pink Quarry)

c. Small aplite with quartz-rich outer margins. (Pink Quarry)
(Sample No.650)

d. Aplite crossing biotite band in normal granite. Note the weaker development of the aplite in the centre of the band.
(Pink Quarry)

e. The widest aplite vein noted at Shap with pink medium to fine grained interior and microgranite outer margins.
(Pink Quarry) (Sample No.652)

f. Close up of lower margin of 6e. Outer portions of this aplite vein are transitional in character between normal granite and typical biotite-free, fine grained aplite.

g. Microgranite/aplitic 'pods' in normal granite. Each is discrete and not a function of outcrop configuration.
(GR 547103)

h. Close up of the contact and internal structure of one of the 'pods' in 6g. (Sample No.653)

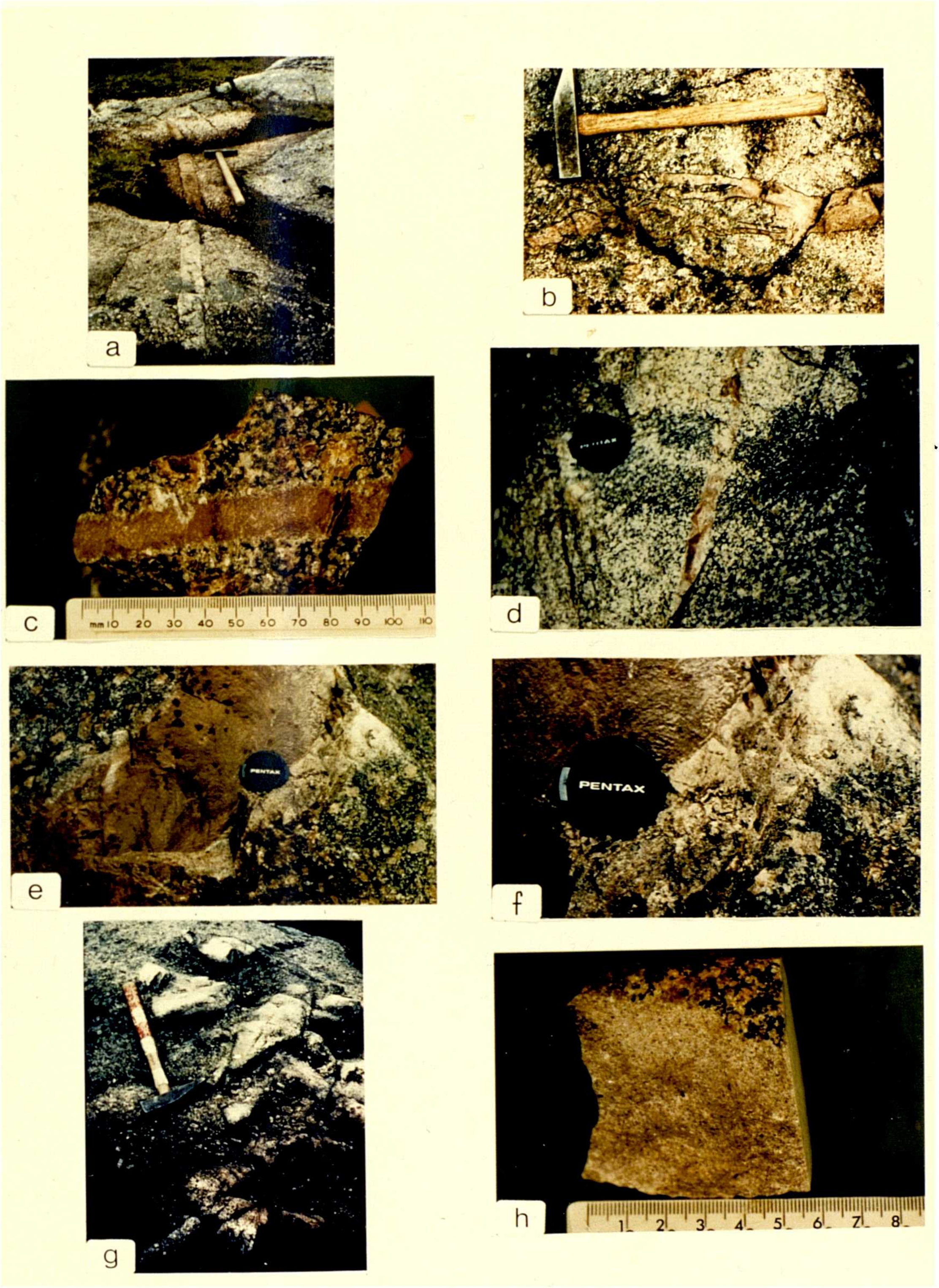

a
b
PENTAX
c
mm 10 20 30 40 50 60 70 80 90 100 110
d
PENTAX
e
PENTAX
f
g
h
1 2 3 4 5 6 7 8

PLATE 6

exposed by renewed quarrying of the wall of the main Pink Quarry. They vary in width and lateral extent ranging from thin (<0.5cm) impersistent 'stringers' upto well-developed large (macro) bands of upto 0.5m in width and 10's of metres in length (Plate 5). The macro bands show good internal minor banding, these smaller (mini) bands having both sharp and gradational contacts with the host granite (Plate 5.c,d). Like the aplites, both the macro and mini bands terminate by reduction in size, eventually diffusing into the granite matrix.

Orthoclase megacryst development is noticeably restricted or absent within the macro-bands though megacrysts can be seen to cross-cut individual stringers or mini bands indicating time relationships between the two structures, the megacrysts forming after the development of the banded structures. When they occur within the bands, the megacrysts are usually poorly developed and may show narrow, paler rims similar to those in the more basic granites and xenoliths (Plate 5.e,f).

High proportions of biotite are also found as selvages surrounding felsic veins, vugs and segregations in the granite (Plate 5.g,h). About these structures, narrow zones of biotite-rich granite develop immediately adjacent to coarse felsic accumulations of pegmatitic quartz and orthoclase. These associations of biotite and quartz/orthoclase pegmatite are not widespread and occur as small (<1m) zones, differing from the elongate banding just described. The two structures are similar in that the orthoclase and biotite seem spatially exclusive which suggests that conditions for the development of these structures were locally different from the majority of the host granite. Also, they were forming before and during megacryst development, but were completed prior to aplite emplacement. At Shap, aplites are seen to cross-cut the biotite banding whereas in the Weardale Granite, Dunham et al.(1965) described aplites cross-cutting well developed segregations of quartz-orthoclase pegmatite. Consequently, these pegmatitic segregations and veins/vugs should not be confused with the pegmatitic-like hydrothermal mineral structures described below in section 3.1.3. below.

Mafic banded structures in acid to intermediate plutons are usually termed schlieren and their formation has been attributed to many, widely-varying processes including in-situ fractionation, gravity accumulation, volatite-streaming and xenolith digestion (eg. Didier 1973 , Parsons 1979, Emeleus 1963).

3.1.3. Hydrothermal Mineralisation.

Hydrothermal action about the joint system and minor veins of the Shap Granite has resulted in a suite of secondary minerals, some of which have already been mentioned. Sulphides are the most obvious, covering large areas of joint planes, resulting in greenish oxidation products on weathered surfaces. Harker and Marr (1893) make little or no mention of this aspect of the granite, but it is covered more fully by Grantham (1928), who divides the mineralisation into various stages. Grantham (op cit) also recognises there is a pre-hydrothermal sulphide phase of pyrite (and minor molybdenite) associated with the late-stage development of the megacrysts and aplites which has been confirmed by this study. This is followed by the hydrothermal stage which is initially dominated by sulphides of mainly pyrite, molybdenite, chalcopyrite and to a lesser extent zinc-blende,galena,arsenopyrite and bismuthite. The molybdenite is notable in that it rarely occurs in association with these other ores, and, is the only one which is found to be deposited in the wall-rock upto 5cm from the joints. These facts, along with its association with the orthoclase growth, suggest that it is of an early origin, forming at higher temperatures than the main hydrothermal stage.

The gangue minerals, quartz, baryte,calcite, and haematite (granular) occur along with the sulphides, but are especially well developed in the wider joints in which they can form significant thicknesses. Grantham (op cit) describes massive and cockscomb 'crusts' upto 20cm thick along with widespread development of euhedral quartz crystals. An indication of the nature of the hydrothermal fluid involved is given by the limited existence of fluorite and tourmaline. The fluorite is usually the blue variety, though colourless types have also been noted whilst the tourmaline appears as small, dark needles. Both minerals usually occur in quartz and are also found in some of the hydrothermal quartz veins described below. The minor occurrence of these two minerals shows that there was some halogens involved in the hydrothermal event, although probably at very low concentrations.

The quartz veins contain little or no ore minerals, and in particular, are often associated with a pink colouration to the host wall-rock granite. This effect is also well seen in the xenoliths (Plate 7.a,b,c) and is thought to be a

PLATE 7.

PLATE 7. HYDROTHERMAL MINERALISATION

All Photographs from the Pink Quarry.

a. Quartz veins with feldspathic wall-rock zones in Dark granite.

b. Quartz-feldspar vein cross-cutting granite and xenolith.

c. Close-up of hydrothermal vein entering a xenolith. Note the unaffected nature of the orthoclase megacrysts in and about the veins as shown in 7a, b, and c.

d. Development of small quartz crystals on a joint plane.

e. Extremely altered and reddened granite with a quartz coating containing molybdenite (M) grains.

f. Disseminated pyrite occurring within normal granite, and not related to vein or joint development.

g. Discrete patches of pure pyrites on a joint surface.

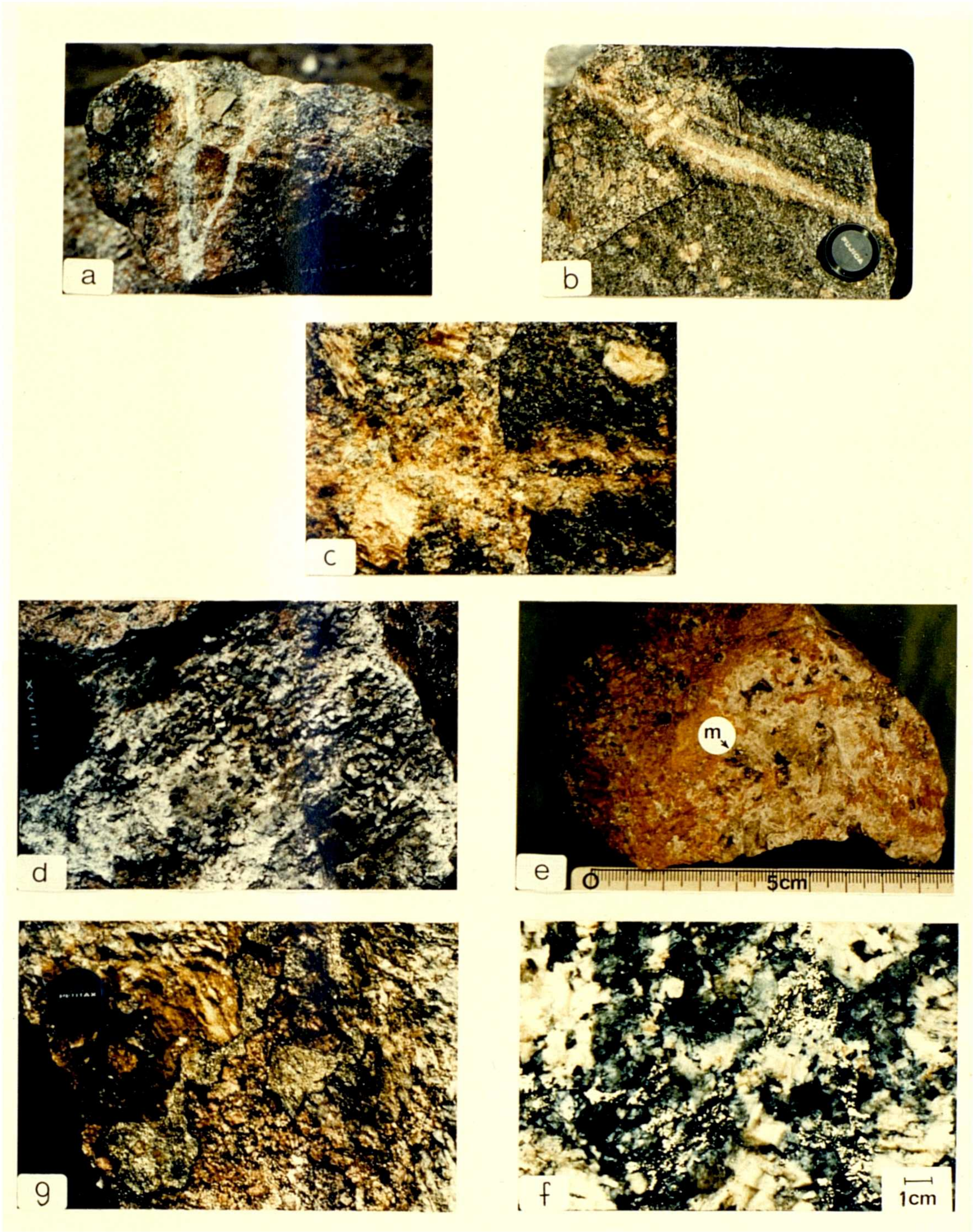


PLATE 7

similar process to that of the darkening of Light granite about the joints. It is known that these veins were probably emplaced at moderately high temperatures as they sometimes contain molybdenite. At these temperatures biotite and plagioclase become altered and quartz recrystallises. Existing orthoclase appears unaffected and the pink zonation may represent the process of iron fixation combined with the possible introduction, redistribution and further development of new orthoclase (Plate 7.b).

Plant et al.(1980) have shown that most of the Caledonian granites of northern Britain have a recognised phase of associated mineralisation. This also appears to be the case with the northern England granites where, apart from the development of hydrothermal alteration and mineralisation within the granites as described above at Shap, there is a phase of regional mineralisation which has been attributed to hydrothermal activity due to and, promoted by, the intrusion of the granites and, in particular, those of Lower Devonian age (Stanley and Vaughan 1982).

The older intrusion at Eskdale displays limited tourmalinisation and associated late-stage greisenation with topaz and fluorite development (Firman 1978). The Threlkeld Microgranite also contains tourmaline and in the more fractionated regions develops pyrite (Caunt 1984). Both these styles of late mineralisation are somewhat limited in extent when compared to the Devonian granites of Shap, Skiddaw and Weardale.

At Skiddaw, extensive greisenation has occurred in the roof zone along with tin-tungsten vein mineralisation in cross-cutting fault zones. Tourmaline, fluorite and apatite occur with a sulphide association of pyrite, arsenopyrite, sphalerite, bismuthite and molybdenite, along with the usual gangue minerals. A study by oxygen isotope and fluid inclusion techniques (Shepherd et al.1975) indicates that the hydrothermal event occurred over a wide temperature interval down to about 250-300°C and involved saline fluids.

Within the Weardale granite are minor veins of quartz with haematite and rare galena. This region is recognised as being dominated by mineralisation of the overlying Visean sediments of a Pb-Zn-fluorite association. This complicates the recognition of lower Devonian hydrothermal mineralisation in the granite. It might be expected that the Weardale Granite has a Cu-Fe-(Mo?) mineralisation style more typical of the other intrusions.

In all cases, much or most of the hydrothermal mineralisation occurred after granite consolidation. Greisenation and vein deposition has been dated with the use of Rb-Sr and K-Ar isotopic analysis of muscovites and gives a range of 385-365 ± 8 Ma at Skiddaw, whilst the resetting of plutonic micas at Weardale gives ages of 365± 8 Ma (Holland and Lambert 1972). This would imply that cooling and associated hydrothermal activity in these and the Shap granite took some 20-30 myr. since the time of their emplacement at around 400-390 Ma.

None of these granites have extensive low temperature alteration such that occurs in the Hercynian tin-tungsten granites of S.W.England. Greisenisation and sericitisation are not widespread in Caledonian granites whereas both these alteration styles along with kaolinitisation are prevalent in the Hercynian granites. These granites also show extensive effects of halogen influxes, especially boron and fluorine, an aspect of hydrothermal alteration not seen at Shap and elsewhere in Northern Britain (Fuge and Power 1969).

Many of the ore and gangue minerals found in the Shap Granite also occur in the metamorphic aureole. The description of this associated second suite of mineralisation in the aureole is given in subsequent chapters, whilst an overall model of the cooling and mineralisation of both the granite and the aureole is presented in Chapter 7.

3.2 Granite Petrography and Mineral Chemistry.

3.2.1 Introduction.

The major petrographic descriptions of Shap Granite have been by Harker and Marr (1891) and Grantham (1928). Harker and Marr (op cit) restricted themselves to a general description of the granite without reference to the effects of hydrothermal alteration or a discussion of the minor varieties such as the aplites. They recognised that orthoclase occurs as megacrysts and in the groundmass and presented a bulk analysis of a separated megacryst. Grantham (1928) gave a fuller and more accurate account of most of the granite varieties highlighting some of the minor ones.

In this study, the major phases of orthoclase, plagioclase, biotite and hornblende in Light and Hornblende granites have been analysed along with textural relationships in the many granite varieties.

PLATE 8.

PLATE 8. GRANITE PHOTOMICROGRAPHS

Scale Bar 0.5mm Unless Stated Otherwise.

a. Euhedral zircons from a normal Light granite. They appear to have no relic cores suggesting that they have grown entirely from the granite magma. (PPL)

b. Distribution of mafic phases is typically even in most granite samples. Occasionally, mafic clusters such as this composed of biotite, sphene and Fe-Ti oxides can be found.
(Slide No. 37993) (PPL)

c. Typical Shap Granite with large perthitic megacryst and late groundmass orthoclase and quartz enclosing euhedral biotite.
(Slide No. 37995) (XPL)

d. Hornblende granite with large euhedral hornblendes in an essentially quartz-orthoclase matrix along with plentiful apatite inclusions.
(Slide No. 37998) (PPL)

e. Large skeletal apatite in hornblende granite. This sample contains minor biotite, top left.
(Slide No. 39959) (PPL)

f. Typical quartz-orthoclase texture of the aplites.
(Slide No. 39960) (XPL)

g. Finer grained quartz-orthoclase texture intermediate between normal granite and aplite. Such textures are found in marginal granites such as near Wasdale Farm and suggest more rapid cooling than in the normal granites.
(Slide No. 37999) (XPL)

h. Biotite clot in marginal granite from Wasdale Farm. Note small grain size in comparison to those such as shown in 8b.
(Slide No. 38000) (PPL)

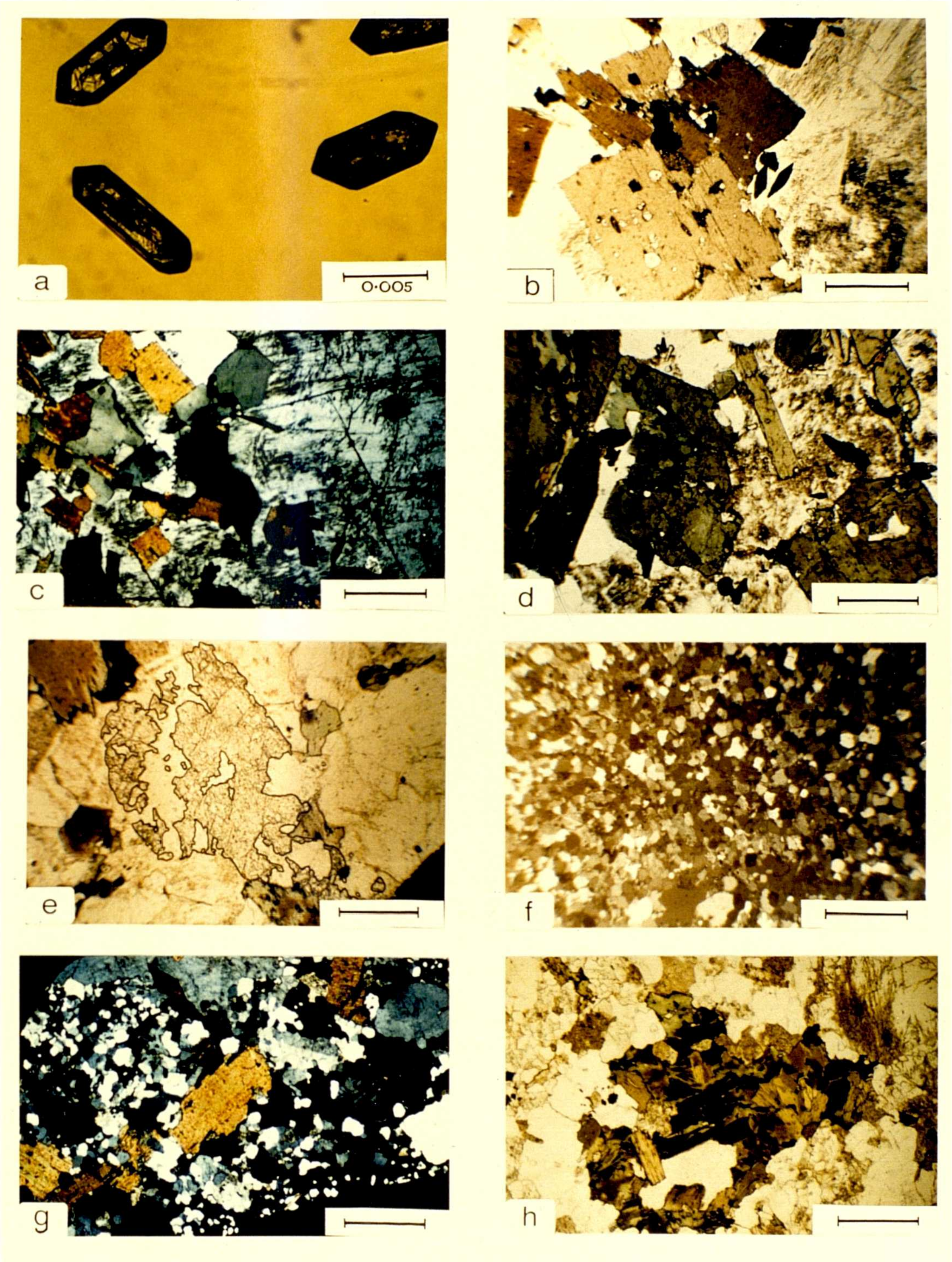


PLATE 8

3.2.2. Major Granite Types.

The earliest phases to crystallise were the accessory minerals apatite, zircon, magnetite, sphene along with rare monazite and allanite, all of which may occur indiscriminantly in most of the later phases. Apatite occurs in all sections as colourless, euhedral prisms and needles whilst zircon is also euhedral and colourless to pale yellow. Separation of zircons shows them to be free of inherited cores or other inclusions indicating that they have not been derived from the granite magma source as a restite phase (Plate 8.a). Rastall and Wilcockson (1915), whilst undertaking a study of accessory minerals in rocks of the Lake District, describe zircon in the Shap Granite as "distinctly rare", though this study has not found this to be the case apart from in the more evolved micrograniitic and aplitic types.

Magnetite is found as irregular grains in all granites and as inclusions in altered biotite and as arrays of small inclusions in sphene as zones paralleling the crystal faces. Previous study of the Fe-Ti oxides of the Shap Granite (Caunt 1977) has shown the magnetites to have a very low TiO2 (ulvospinel) content, typical of magnetites in acidic rocks (Buddington and Lindsley 1964). Rastall and Wilcockson (1915) list ilmenite as an accessory phase though Grantham (1928) and this study have not confirmed this. Some magnetites, particularly those associated with the biotite or sphene, are more titaniferous but, definite ilmenite has not been proven. Sphene occurs in varying proportions in all types of granite, being more prevalent in the more basic varieties. It varies in colour between pale yellow and deep brown, is strongly pleochroic and commonly has inclusions of magnetite. It's habit is subhedral to euhedral and it is often spatially associated with apatite and biotite.

These primary accessory minerals constitute only 2% of the normal granites (Spears 1961) and rare amongst these are allanite and monazite. Allanite occurs as small, pleochroic yellow-brown grains, usually euhedral and concentrically zoned. Monazite has only been recognised as very small rounded grains in mineral separates. Pyrite forms anhedral to euhedral grains, often associated with orthoclase and, as a consequence, is more common an accessory in later granite varieties. Other accessory minerals include chlorite, calcite, fluorite, tourmaline, muscovite (sericite) and iron oxides. Most of these are secondary, being a result of hydrothermal alteration of existing phases or crystallised from the hydrothermal fluid.

Biotite occurs in all granites although decreases in amount with increasing orthoclase and quartz. It is subhedral to euhedral and pale to dark brown in colour. Inclusions of accessory phases occur more often in biotite than in any other mineral. They include apatite, zircon (with associated pleochroic haloes), magnetite, sphene and, rarely fluorite. Chloritisation is seen in most samples though is restricted in the Light granites compared to the Dark. Clots of biotite along with apatite and sphene are occasionally seen suggesting that these minerals crystallised at about the same time and prior to the major feldspar phases. Data for biotites from a Light granite are shown in Figure 3.1a and tabulated in the Appendix. The analyses are very consistent, all the data plotting in a

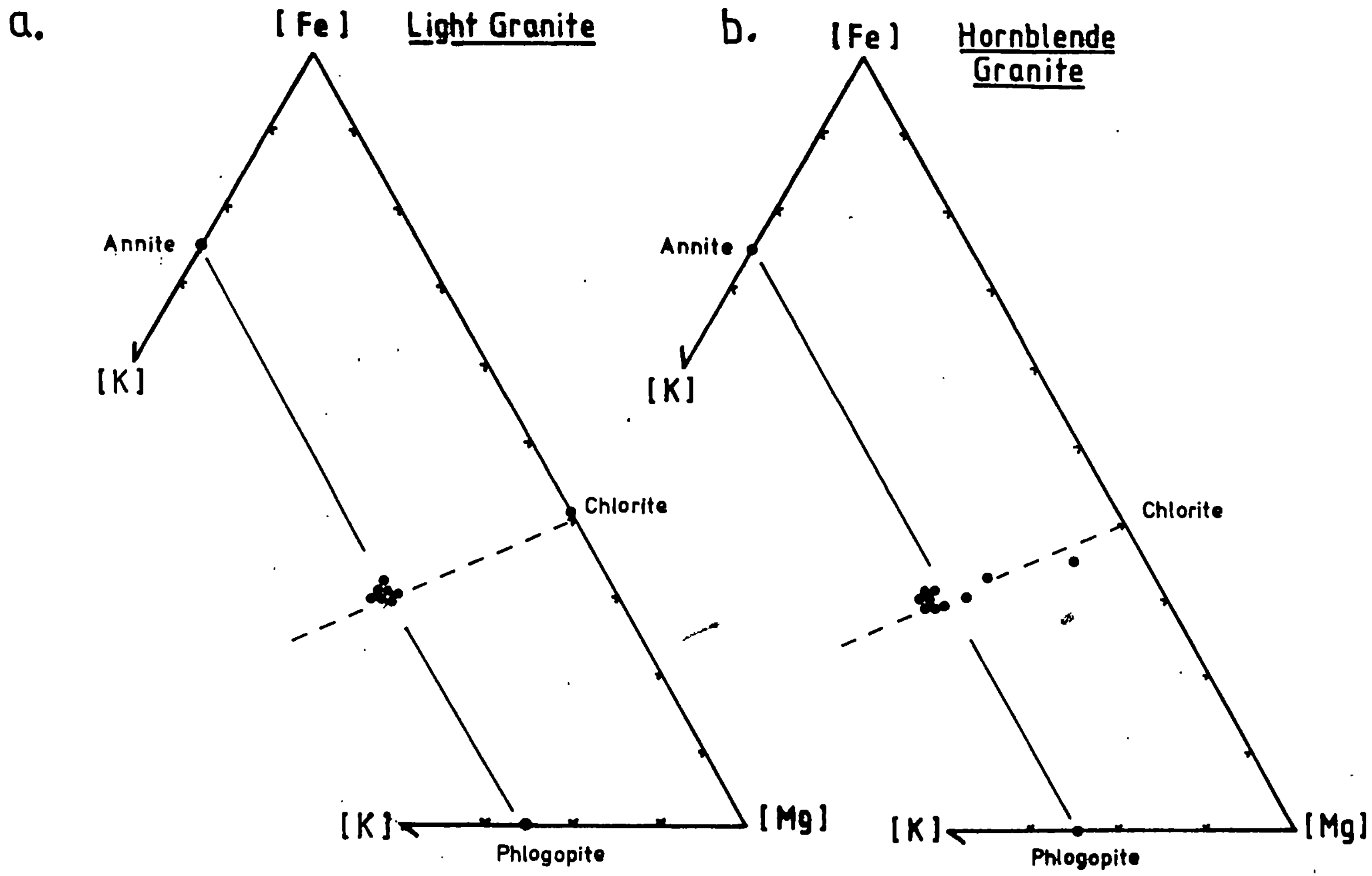


FIG. 3.1 a,b.

Biotite analyses expressed as atoms per formula unit of Fe, Mg and K.
Analyses tend to lie about the annite-phlogopite tie-line and about an Mg/Mg+Fe ratio of 0.6 (dashed line).
Chlorites after biotites are also shown.

tight group on the annite-phlogopite tie-line. Grains show no zoning, all having a near constant Mg/Mg+Fe ratio of 0.59, these being compositions typical of granitic biotites (Nockolds 1947). Very low levels of the halogen elements chlorine and fluorine have been assessed semiquantitively by microprobe. Although somewhat conjectural, fluorine appears absent, whilst chlorine levels represent only 1% of the total volatile content of the biotite. Maaloe and Wyllie (1975) stated that biotite crystallising early in the granite sequence at low pressures (<3kb) suggested increasing water content of the magma (>1.5 wt.%). This being the case, at this stage, the fluid content of the Shap magma appears to be essentially halogen-free, unless, halogens were being preferentially left in the melt during biotite formation. This is in contrast to the Hercynian granites which show large amounts of chlorine in the biotites, whilst fluorine is left in the melt to be incorporated in later phases (Alberqurque 1973, Fuge and Power 1969).

Plagioclase feldspar (Fig.3.2a and the Appendix) appears to have crystallised during or after biotite formation as inclusions of biotite occur in the larger plagioclase grains. Plagioclase is the major matrix phase sometimes constituting upto 50% of the groundmass in more basic granite types. It is euhedral, with narrow Albitic and simple Carlsbad twinning. Smaller, more irregularly-shaped plagioclase grains also occur as inclusions in the orthoclase megacrysts. Apart from the smallest grains, all the plagioclase is normally zoned from oligoclase-andesine cores to albite-oligoclase rims, the largest grains tending

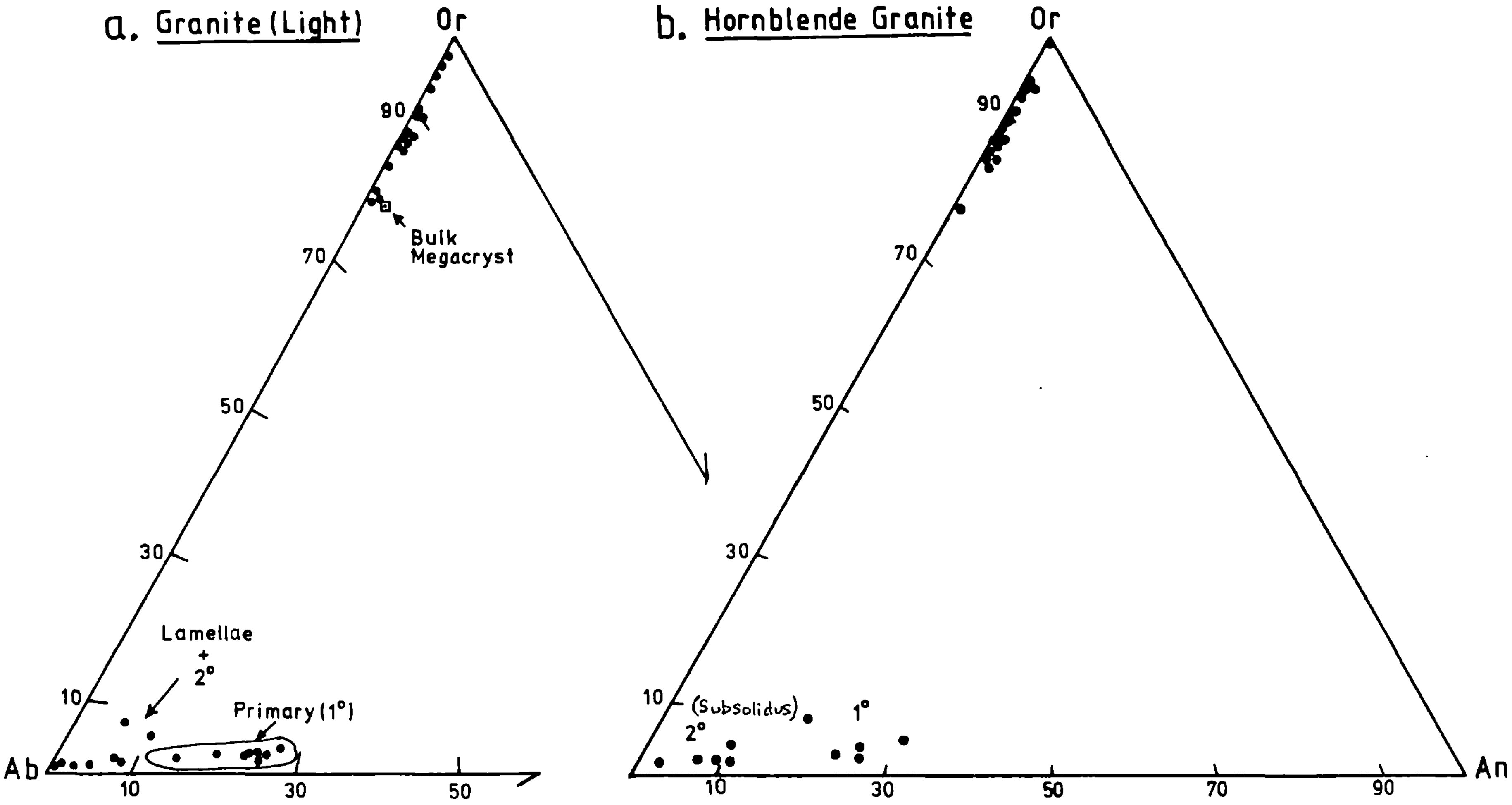


FIG. 3.2a,b.

Feldspar compositions expressed as formula end-members orthoclase (Or), albite (Ab) and anorthite (An).
Plagioclase analyses based upon optical and microprobe determinations.
Bulk megacryst composition from Spencer (1938).

to have the most anorthite-rich cores. An investigation of the zoning in plagioclase feldspars from igneous rocks by Greenwood and McTagget (1957) involved the examination of a granite sample from Shap. Although all the grains that they examined at Shap varied from oligoclase to albite in composition, the range of composition from core to margin in individual grains was found to vary. Core compositions in one grain might be An20 whilst in another be only An15 though both had the same composition of remaining zones and albitic margins. The width and correlation of individual zones between the grains examined had a low degree of variance. This led them to the conclusion that the grains with more An-rich cores crystallised earlier before eventually being joined by subsequent new plagioclase grains, all of which then crystallised zones of An14 to albite. This would imply that either the start of plagioclase crystallisation in the Shap magma occurred over a wide time (or temperature ?) interval or, grains from differing regions or compositions of the magma became mixed during crystallisation or emplacement.

Many grains show minor micaisation or cloudiness in discrete, concentric zones or as dispersed patches. The more albitic margins are usually unaltered which led Grantham (1928) to the idea that the zonal alteration occurred during crystallisation. Alternatively, as much of the alteration appears to be zonal and spatially related to the more calcic compositional zones, the alteration is thought not to be time, but compositionally dependant.

Near-pure albite is found to be associated with the margins of plagioclase and the orthoclase megacrysts, as well as small, unzoned grains in the groundmass. The development of this albite appears late in the crystallisation and much of it is no doubt related to the secondary and subsolidus effects described below.

Orthoclase appears as megacrysts and as a major constituent of the matrix. With increasing development of orthoclase and, in particular the megacrysts, biotite and plagioclase become less prevalent. The megacrysts are euhedral, with simple Carlsbad twinning and well developed perthite structures of clear albitic lamellae in the orthoclase host. Megacrysts contain inclusions of biotite, plagioclase and quartz along with minor amounts of magnetite, apatite and pyrite. All the inclusions are generally smaller than in the matrix which suggests that megacryst growth may have commenced prior to the full development of the groundmass. Both the plagioclase and biotite inclusions are of the same composition to these phases in the groundmass although tend to show less alteration. The pyrite occurs in many forms such as small 'strings' or rounded grains though is commonly euhedral cubes suggesting contemporaneous growth with the megacryst. Megacryst margins appear straight but, on closer inspection, are seen to be more irregular with orthoclase overgrowing the matrix and the minor development of small albite patches and grains. Quartz is found as rounded inclusions near the margin probably crystallising along with the late megacryst growth.

Bulk compositions of the megacrysts have been quoted by Harker and Marr (1891), Spencer (1938) and Farrand (1960). Apart from the later author (whose data lack CaO values), the data compare well with analyses from this study and a typical value is plotted in Figure 3.2a. Microprobe analysis shows large variations in the composition of the orthoclase in the megacrysts, varying between Or76 and Or99. This variation is a function of two effects. Firstly, the degree of exsolution at the point of analysis (ie.the extent of albite-orthoclase unmixing) and secondly, the physical size of the exsolution texture in comparison to the X-ray beam size. The megacrysts do not appear to have exsolved uniformly throughout a grain, with large variations in the physical state of the perthite development, visible only at high degrees of magnification. The most potassic orthoclase is usually found at the margins of the megacrysts which suggests that the latest stages of megacryst growth may have been very potassic or, that exsolution has been more extreme at the megacryst margins. Analysis of host-lamellae pairs shows the typical composition of exsolved plagioclase to be Ab95 and the host around Or88.

In the groundmass, orthoclase is anhedral, perthitic and of the same bulk and perthite compositions as the megacrysts. Grains may develop narrow albitic margins against other minerals. This orthoclase lacks inclusions apart from small grains of plagioclase and quartz. Quartz itself is mainly intergranular in the matrix or, to a lesser extent, as inclusions in orthoclase.

In the Dark granites, hydrothermal alteration results in extensive changes mainly to the biotite and plagioclase which become chloritised and sericitised respectively. Chloritisation occurs along margins and cleavages of the biotite with associated development of granular iron oxide (haematite?). Extreme alteration results in very pale chlorite or even what appears to be muscovite with very small inclusions of rutile and rarely, small blobs of fluorite. The plagioclase initially alters in zonal form as described above but eventually may become completely altered though the purest albites often remain unaffected. Sphene is generally resistant although marginal embayment is often noted and, under extreme conditions, grains may be pseudomorphed by a mixture of calcite, quartz and iron oxides. Both megacryst and groundmass orthoclase tend to remain unaffected by the hydrothermal fluids and this is supported by the fact that inclusions of biotite and plagioclase within the megacrysts are also unaltered.

3.2.3 Minor Granite Varieties.

The hornblende granite consists of the above primary minerals along with well developed hornblende. The hornblende is very variable in grainsize, though is generally large (upto 4cm in length) euhedral, elongate crystals, often twinned and forming upto 35% of some samples (Plate 8.d). Much of the matrix is microperthite orthoclase of the same composition as in the other granites (Fig.3.1b). Apatite, sphene and Fe-Ti oxides again crystallised first, followed by hornblende, biotite and plagioclase. Both apatite and sphene are more abundant whilst biotite and plagioclase are subordinate in comparison to normal granites. Apatite occurs as stumpy prisms or as large skeletal grains (Plate 8.e) and the sphene as euhedral, lozenge-shaped grains, often a very dark brown and twinned. Biotite is the same composition as before (Mg/Mg+Fe=0.59) and again has a very low halogen content.

Some grains show partial chloritisation resulting in analyses with low K2O contents (Fig. 3.1b).

Analysis of the hornblendes shows them to be typical calcic amphiboles, these being strictly termed edenites after the classification of Leake (1978), (Fig.3.3a,b). They are not compositionally zoned, although have a Mg/Mg+Fe ratio of 0.63, this being slightly higher than for the biotites. They also have similar halogen contents to the biotites in this and the Light granite (ie.<1.5% of total hydroxyl content). This implies that the hornblendes are primary phases crystallising from the magma, their slightly higher Mg content than the associated biotites supporting the notion that the hornblende formed before the biotite when Mg/Fe ratios in the magma might have been slightly higher. This is further supported by the fact that in some samples hornblende content decreases with the increasing amount of biotite.

Plagioclase is not as commonplace as in the major granite varieties but shows the same oligoclase compositions and similar zoning and alteration. Orthoclase megacrysts are erratically developed, whilst perthitic orthoclase dominates the groundmass along with interstitial quartz. Hydrothermal alteration does not appear to have affected the hornblende granite and, as a consequence, secondary minerals and alteration are rare.

The megacryst-poor granites are orthoclase and quartz rich and show patches of fine-grained material within an otherwise coarse-grained groundmass (Plate 8.g). Some quartz grains are larger than in the groundmass and appear to be rounded 'phenocrysts'. Biotite and plagioclase occur less

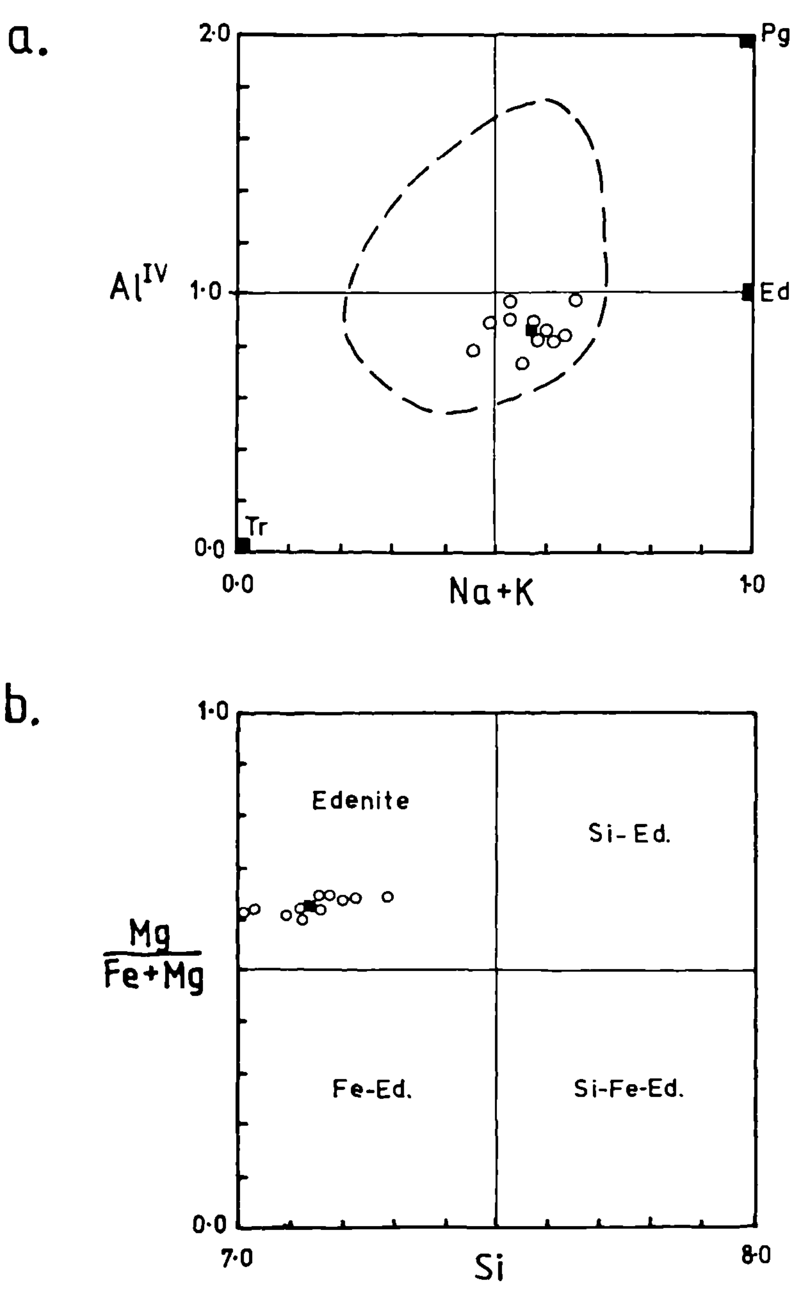


FIG. 3.3a,b.

a. Chemical variation of hornblendes expressed as Na+K and Al IV atoms per formula unit. The outlined field shows the approximate region of common igneous amphiboles.

b. Chemical variation of hornblendes expressed as Mg/Mg+Fe and Si atoms per formula unit (Total iron as FeO). The compositional regions are as defined by Leake (1978) for amphiboles with (Ca+Na) $\geqslant$ 1.34, Na $\leqslant$ 0.67.
■ Mean composition. Ed-edenite, Pg-pargasite, Tr-tremolite, Si-silicic, Fe-ferro.

Data from Appendix Table D.6.

frequently than in normal granites, the biotite being paler in comparison and the plagioclase being poorly formed albite-rich grains. This suggests that both of these minerals are towards the end of their crystallisation interval at this composition, some 2-3 wt% SiO2 above the composition of megacryst-bearing granites.

The trend of decreasing megacrysts, plagioclase, biotite and other accessory minerals along with increasing orthoclase and quartz is shown by the aplites which are essentially fine-grained, megacryst-free orthoclase-quartz-albitic plagioclase mixtures. The plagioclase shows little or no zoning and the main accessory minerals are sulphides, especially pyrite (Plate 8.f).

3.2.4 Discussion.

From the examination of the samples, an approximate order of crystallisation can be made. Apatite, zircon, magnetite and sphene appear to be the earliest phases followed by hornblende, biotite and plagioclase. The plagioclase continued crystallisation over an extended period producing normal zoning, with orthoclase and quartz being the final phases. The textural relationships in an otherwise normal granitictextured rock show the megacrysts to be late-stage and sometimes post-dating quartz growth. This implies that the megacrysts were forming from a late-stage potassic fluid in a near-consolidated matrix. Vistelius (1969) studied the textural distribution of the quartz, orthoclase and plagioclase by a statistical analysis of regular point counting. He concluded that the megacrysts grew metasomatically, there being a paucity of orthoclase as an expected late groundmass phase, though he admitted that the calculation was hampered by the probable dissolution and redistribution of some preexisting orthoclase, plagioclase and possibly biotite. Field evidence supports the textural evidence of the growth of plentiful late orthoclase;

a) Megacrysts are seen to grow in xenoliths and across granite-xenolith contacts (Chapter 6).

b). Large, euhedral orthoclase develops in late-stage cavities and vugs during the end of consolidation of the granite but prior to any hydrothermal activity (section 3.1.2.3).

c). Magmatic (as opposed to hydrothermal) sulphide development in granites is restricted to the last phases of granite consolidation (Barnes 1979). The growth of pyrite with the megacrysts is commonplace.

d). Megacryst development is remarkably uniform throughout the present granite outcrop. There appears no alignment of feldspars with the margin as might be expected from early-generated phenocrysts that would be present during the granite's emplacement. This suggests that they may have formed after emplacement.

The megacrysts in this and other granites were originally interpreted as phenocrysts. More recently, textural studies have shown that such megacrysts are usually late and metasomatic in origin. Such textures are well developed in the Hercynian granites such as those in Cornwall. There, megacrysts formed after plagioclase, biotite and some of the quartz and orthoclase and, their origins have also been attributed to potassic fluid metasomatism (eg. Stone and Austin 1961, Stone 1979). This being the case at Shap, Grantham's (1928) various stages of granite magma types can be regarded as spatial variation in the effects of metasomatism rather than being discrete bodies of magma containing variable amounts of orthoclase phenocrysts. Holmes (1921) calculated the composition of the groundmass of a specimen of Shap granite with 20% megacrysts as being 20% quartz, 42% plagioclase, 20% orthoclase and 8% biotite. Although it is likely that some quartz and orthoclase in the groundmass may have grown during megacryst growth, the bulk pre-metasomatic composition of the granite would have been more granodioritic or monzonitic. Thus the adamellite composition that is now seen is a function of two processes, the generation of a more basic magma that, with continued fractionation, has been modified by late-stage metasomatism.

3.3 Whole-Rock Geochemistry.

3.3.1 Introduction.

The generation of large, batholithic-sized quantities of granite has long been problematical with the origins of granite magmas being attributed to multivarious processes such as melting and assimilation of continental crust, subduction and within-plate magma generation, magma mixing and hybridisation. Models based upon trace element and radiogenic isotope evidence (eg. Brown et al 1984) invoke a complex mixture of processes to produce evolved granitic compositions, often with the generation of mafic to intermediate precursors to the acidic magmas. Most authors ascribe the generation of many granitic magmas to magmas of intermediate (tonalitic-granodioritic) composition undergoing fractional crystallisation often with some associated crustal assimilation although, for most models this in itself is a simplification.

Geochemical trends within the Peruvian granites of the Andean Batholith (Atherton et al. 1979) have been attributed to high-level calk-alkaline differentiation from gabbros and tonalites to alkali granites by the sequential fractionation of pyroxene, plagioclase, hornblende, sphene and apatite. Similar sequences of fractionation, dominated by plagioclase, hornblende, biotite and, lastly, minor phases appears the most widely held consensus at present for the production of granite magmas (eg. S.E.Asia,Beckinsale 1979; British Caledonian,Brown et al 1984; Pankhurst 1979). Tarney and Saunders (1979) regard this model of sequential fractionation as being too simple though admit to it being a major process involved. They argue that;

a) There is a lack of parental gabbros and diorites relative to the large volume of granitic rocks.

b) There is a small proportion of expected and recognisable cumulates.

c) The high viscosity of intermediate to acid liquids is not conducive to crystal removal during fractionation.

It is evident that care has to be taken when discussing the inferences derived from data of whole-rock granite samples which represent the end result of lengthy generation and emplacement sequences. Whether samples represent the end products of magma differentiation processes rather than say, crystal accumulation or partial melting is questionable. Evidence of liquid systems is limited. True acidic liquids such as dykes and aplites are known to be produced in association with granites and, along with evidence such as zoned and euhedral crystals (eg. plagioclase) which probably developed in a magma, and with the limitations discussed above, the geochemical data for the granitic rocks at Shap have been treated simply in relation to the development and crystallisation of the known mineral phases of amphibole, plagioclase, biotite, apatite etc..

Sixteen granite and four aplite samples have been analysed for major and trace elements. General petrological descriptions and sample locations can be found above and in the Appendix. Although not a large number of samples, due in part to the field problems outlined in chapter 1 and the general lack of variance in granite types, the samples chosen encompass all the major and minor varieties of granite found at Shap. The samples include Light granites (531,532,649), Dark granites (522,534) and a single sample of extremely altered hydrothermal granite (535). Samples from about the margin (530,602,603,605,606) and the interior (533) as well as the more uncharacteristic varieties eg. hornblende granite(523), non-porphyritic granite (600,601) etc. are also included. The aplite samples(650,651,652) include a single sample of the aplitic pods (653). A limited number of samples have been analysed for oxygen and hydrogen isotopes and these are discussed below (Section 3.4.2).

Apart from discussing internal variations and trends at Shap, comparisons are also made with other Cumbrian granites and with granitic complexes in general. In the literature, general comparisons of granite geochemistry are made with calc-alkaline data sets from volcanic provinces (eg.Cascades,U.S.A.; Carmichael 1964) or from major batholithic provinces such as the Sierra Nevada

Batholith,U.S.A. (Larsen 1948) or the Andes (Thorpe and Francis 1979). In this work, comparisons are made with Southern Uplands Granites (henceforth termed S.U.G.'s) of southwest Scotland because of the following reasons;

a) They are of similar age and style as at Shap, being typical Caledonian post-orogenic granites.

b) They are emplaced into Palaeozoic sedimentary successions of the same low-grade of regional metamorphism.

c) They display varying degrees of shallow to intermediate unroofing.

d) Geochemically they have well established calc-alkaline characteristics over a wide range of compositions (56 to 75% SiO2).

e) The varying compositions have been shown to be related by the main process of fractional crystallisation

f) Much of the available analytical data is of post-1970's age.

(Phillips 1956, Brown et al.1979, Stephens and Halliday 1979, Thirlwall unpub.data).

3.3.2 Major Elements.

Data for the Shap granites and aplites are shown in Fig. 3.4a,b and presented in the Appendix. The data are plotted against SiO2 as an index of fractionation despite the fact that the majority of granites lie between 67 and 71% SiO2, whilst the aplites form a discrete group at about 76% SiO2. Between these two groups are the petrologically intermediate varieties of non-porphyritic granites (600,601) at 72-73% SiO2. The expression of trends amongst the granite samples is tabulated in the Appendix (Table F.1) as correlation coefficients for both major and trace elements.

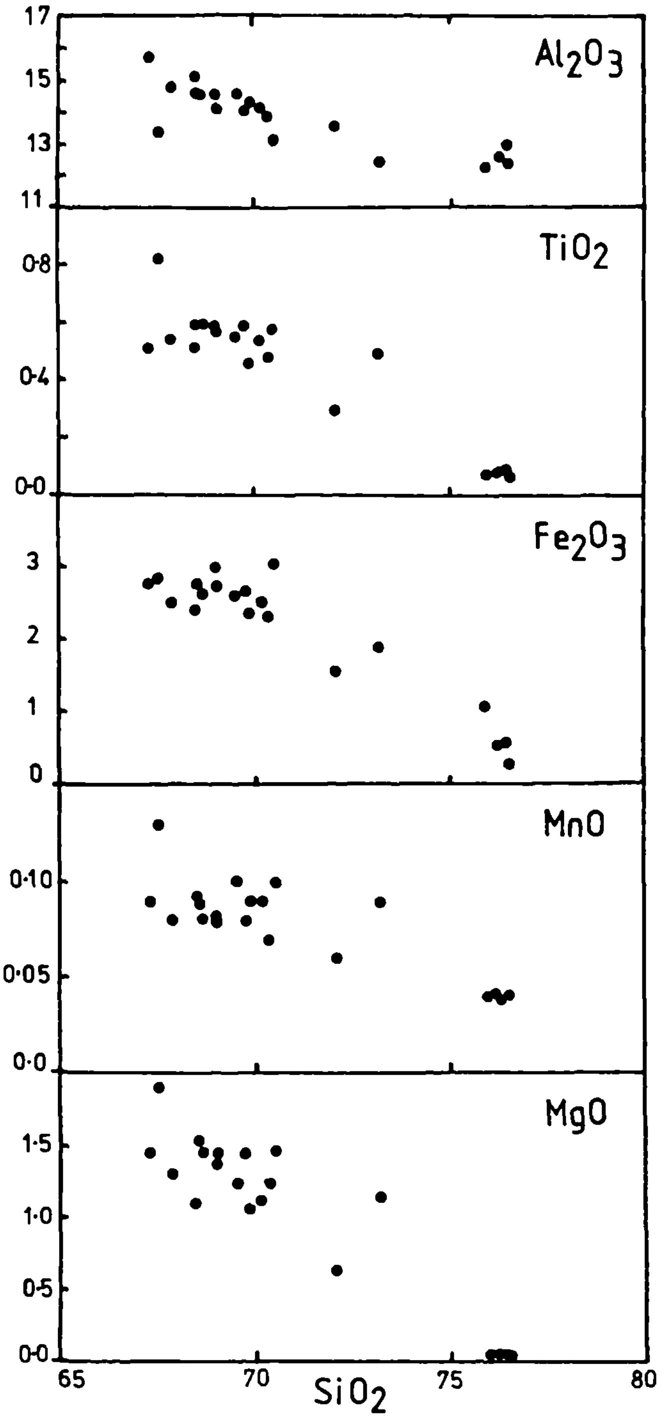


FIG. 3.4a. Granites and Alpites.

SiO2 - Major Oxides.

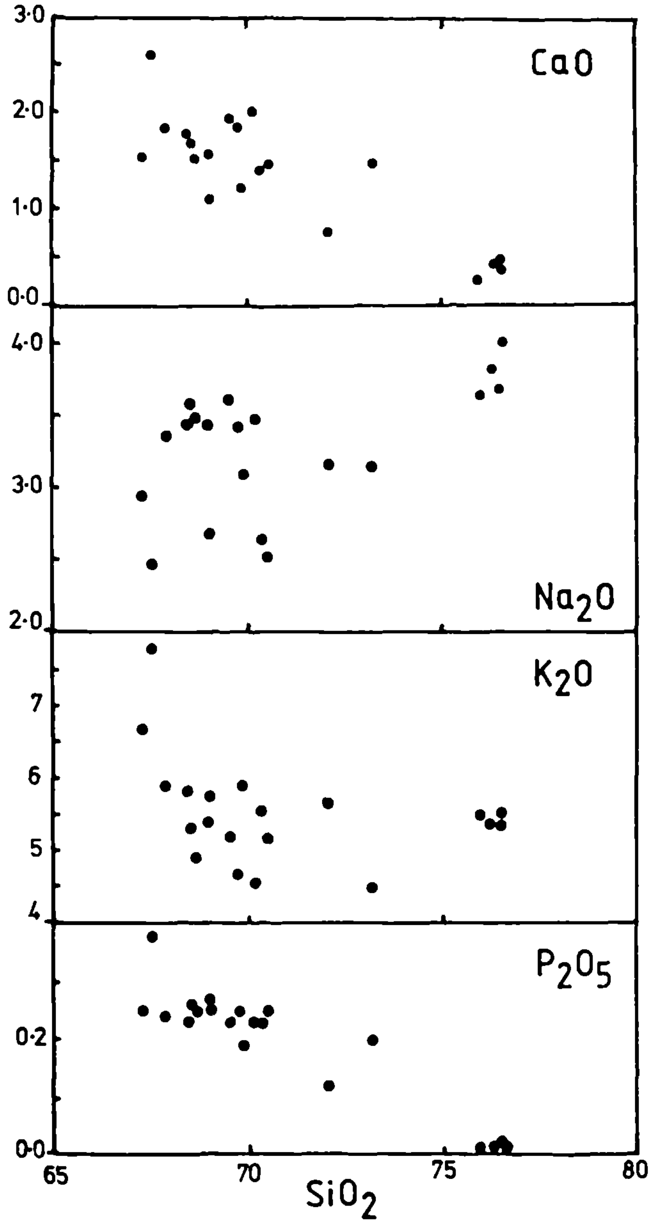


FIG. 3.4b. Granites and Aplites.

SiO2 - Major Oxides (continued).

All the major elements show trends towards the aplites suggesting that the aplites are generated from host granite.

Al2O3 reaches a minimum at about 12% indicating the completion of crystallisation of the two main aluminous phases of biotite and oligoclase, the remaining Al2O3 primarily fixed in the orthoclase.

Formation of the main mafic phases of biotite, magnetite and sphene decreases in proportion with increasing SiO2, eventually being essentially absent from the aplites, being a result of very low levels of available TiO2, Fe2O3, MnO and MgO. Continuing crystallisation of both apatite and the calcic component of the plagioclase results in correspondingly low levels of CaO and P2O5 with increasing SiO2 whilst plagioclase becomes more albitic prior to complete crystallisation as shown by the aplites which have slightly higher Na2O levels than the granite. Of interest is that the aplites have K2O levels the same as the host granite, although they are orthoclase-rich. Presumably, a possible increase in K2O from orthoclase development is offset by the lack of the other main potassic phase of biotite. This similarity in concentrations of major components such as K2O and SiO2 would also promote the lack of interaction between aplites and granite during aplite emplacement. These whole-rock trends are generally unremarkable in that they are typical of most acidic plutonic rocks and, along with the restricted SiO2 range, few inferences can be made at this point as to the production of these acid magmas.

3.3.3 Trace Elements.

3.3.3.1 Introduction.

Some eighteen trace elements have been analysed for the granites and aplites and are presented in the Appendix and Figs.3.4c,d,e. Previously, authors have used many types of trace element grouping such as mobile/immobile (eg. Pearce 1975) to assess the extent of alteration and to act as geochemical discriminants or, compatible/incompatible to model the evolution of magma compositions during melting and crystallisation processes. The use of such groupings is often dependant upon knowledge of the behaviour of these elements in magma-mineral systems and, in particular,the liquid-solid distribution coefficients (D) of the elements. Such parameters are fairly well established for basic magma compositions, especially in volcanic rocks but problems can arise when using such a system with acidic plutonic rocks for the following reasons;

a) Many acid plutonic rocks may not be the product of simple liquid-crystal evolution.

b) D-values for acidic compositions are less well constrained.

c) Plutonic bodies often show the effects of subsolidus change such that elemental values may not represent the magma compositions involved in the pluton's history.

Because of these reservations, a grouping scheme has been adopted after that of Saunders et al.,1979 who divided the trace elements into four groups. This scheme is based on the ionic character of the elements and, in particular, the ionic radius/charge ratio which results in elements in a group exhibiting similar geochemical behaviour.

Group 1 comprises the Low Field Strength (LFS) elements and equates with the Large Ion Lithophile (LIL) elements of Schilling (1973). These elements have a radius/charge ratio greater than 0.2 and include Rb, Ba, Sr, Th, U and Pb. The major oxide K2O also has a LFS character. Group 2 contains elements with a ratio less than 0.2 and these are termed High Field Strength (HFS) elements. This group includes Zr and Nb, along with the major oxides of TiO2 and P2O5. Both Group 1 and 2 elements are normally termed incompatible elements with D values less than 1. Strictly, the Rare Earth Elements (REE's) and Y also belong to the LFS Group, their ratios being greater than 0.3. Because aspects of their behaviour also resemble those of the HFS elements, they have been grouped separately into Group 3, which contains La, Ce, Nd and Y. Groups 2 and 3 comprise elements which are usually immobile during alteration whereas, the Group 1, LFS elements may be readily mobilised even at low to moderate temperature conditions, especially in the presence of a fluid.

The Transition Metal Elements (TME's), Cr, Ni, Cu, Zn, V and Sc constitute the final group, Group 4. Over basic to intermediate compositions in particular, these tend to behave compatibly along with the major oxides of Fe2O3, MgO and MnO. They generally decrease in concentration with increasing SiO2 reflecting the fractionation of mafic phases in calc-alkaline magmas. The use of this group of elements is made more difficult as some are also often mobile in hydrothermal processes associated with the secondary mineralisation of the plutonic rocks.

This grouping scheme will be used for discussion of T.E. geochemistry in this and each subsequent chapter of this work. Many trace elements show low absolute concentrations, resulting in values close to detection limits of the analytical equipment. The variation in and assessment of errors on the data along with correlation coefficients between elements are dealt with in the Appendix (Table F.1 and XRF Analytical Techniques).

3.3.3.2 The Shap Granites and Aplites

Group 1 (LFS) Elements.

Fig. 3.4c. shows that the Shap rocks have moderate to good positive (Rb, Pb,U,Th) and negative (Sr,Ba) elemental trends against SiO_2, even though absolute values have a relatively wide scatter. As expected, Rb and Sr behaviour echo K_2O and CaO respectively whilst all but Ba are behaving in an incompatible fashion being selectively incorporated into residual fractions of the granite magma during consolidation. Sr appears to be behaving compatibly being preferentially incorporated into crystallising plagioclase along with CaO and Al_2O_3. Ba has the largest ionic radius of the commoner +ve divalent ions and usually involved in isostructural replacement with Sr^{2+} , Pb^{2+}, and to a lesser extent, Ca^{2+} and K^+ within feldspars, micas, and amphibole. Within granodioritic magmas, the main carriers of Ba are biotite (1000ppm) and plagioclase (300ppm in labradorite, 100ppm in albite). At Shap, Ba appears to be behaving similarly to Sr and possibly K_2O (see above) suggesting that it is being removed from the residual liquids by Ca-bearing plagioclase (oligoclase) and biotite crystallisation. This is supported by the very low Ba values in the aplites which contain little of these two minerals.

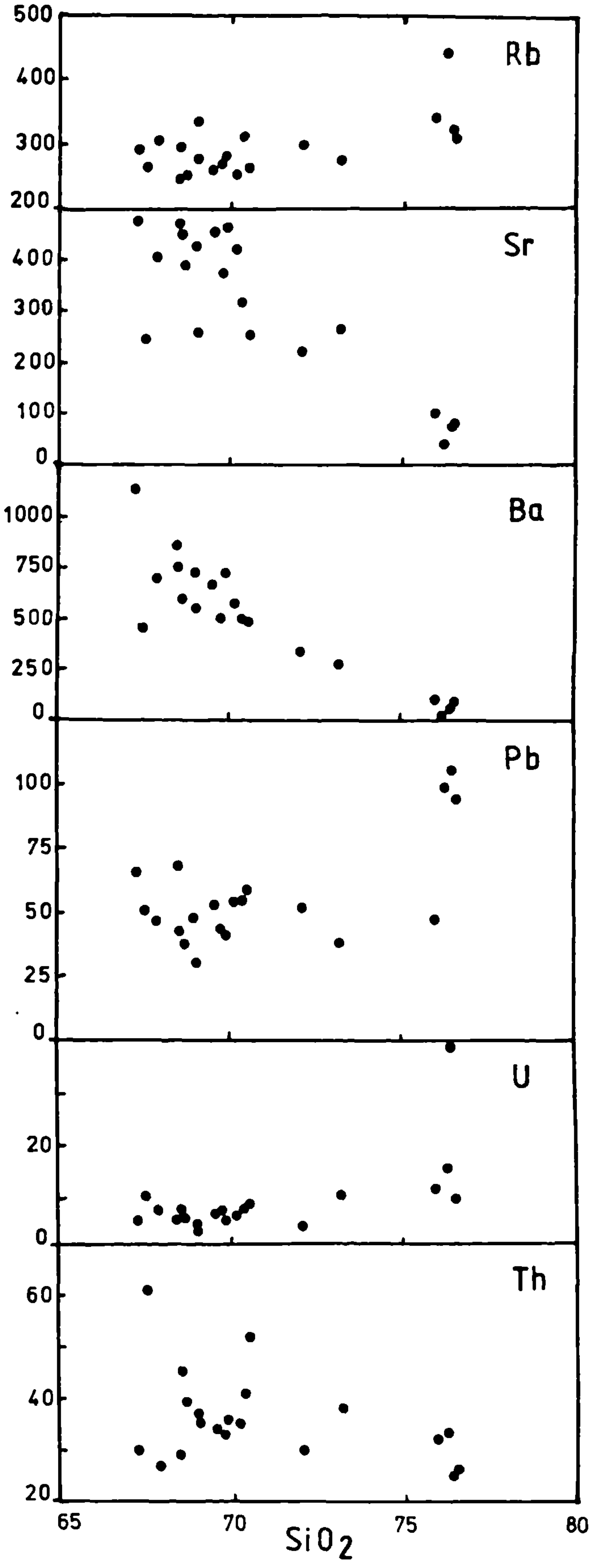


FIG. 3.4c. SiO2 - Group 1 (LFS) Elements.

Pb contents in the Shap granites are somewhat higher (25-75ppm) than in average granites (25ppm) and show incompatible behaviour as expected. Particular enrichment in the aplites indicates that orthoclase and not biotite is the likely main carrier.

The positive correlation of increasing U with SiO2 is weak, though U appears to be behaving incompatibly. Most main rock-forming minerals contain only 0 to 10ppm U, this element usually being concentrated in minor phases such as apatite, zircon or allanite. Consequently, small modal variations in these minor minerals can produce large variations in U concentration. Should such minerals not be present, as in the aplites, the U may fixed in mineral lattice defects, on grain boundaries or very rarely as isomorphous substitution in K-rich phases. It is likely that U in the aplites is fixed in such a style. The high degree of solubility and mobility of U at even low temperatures has led Webb and Brown (1984) to conclude that the analysis of near-surface samples of rocks often results in erroneous data, with upto 50% possible loss. This is due to fluid penetration and movement being principally along grain boundaries where U resides. As a consequence, U levels at Shap may be significantly higher than those values measured.

Th shows the largest proportional scatter (40-20ppm), though somewhat enriched relative to typical values for granite of around 10-30ppm. The aplites are slightly lower in Th concentration, though the negative correlation with SiO2 is weak. This element occurs as a tetravalent ion and, as with U, its precise location in a rock is often unknown.

It generally correlates positively with U, though this is not the case at Shap. The main common carriers are hornblende, then biotite, though it is enriched in the minor phases, sphene and apatite. As a consequence, the hornblende granite, which is hornblende, sphene, and apatite-rich compared to most Shap samples shows the highest Th levels, whilst the quartz-orthoclase aplites have the corresponding lowest levels.

Group 2 (HFS) Elements.

Zr and Nb show weak -ve correlations with SiO2 (Fig 3.4d) and compare well with the -ve trends shown by TiO2 and P2O5. Over basic to intermediate magma compositions Zr and Nb normally behave incompatibly, producing +ve correlations with SiO2 before eventually being fixed into zircon and sphene. At acidic compositions, the formation of these two phases during early crystallisation results in -ve trends with increasing SiO2 , an effect shown by the Shap samples. Again sample 523 shows HFS element enrichment, probably as a result of the plentiful modal sphene.

Group 3 (HFS/REE) Elements.

The REE's and Y show negative correlations in contrast to their normally incompatible behaviour in non-acidic systems which results in +ve correlations with SiO2 (Fig. 3.4d). As with the Group 2 elements, concentrations are controlled by the minor phases, especially Y and the light REE's which have an affinity for phosphorus and in particular apatite. Consequently, both groups show wide data scatter, being sensitive to small modal variations in apatite along with allanite, monazite etc.

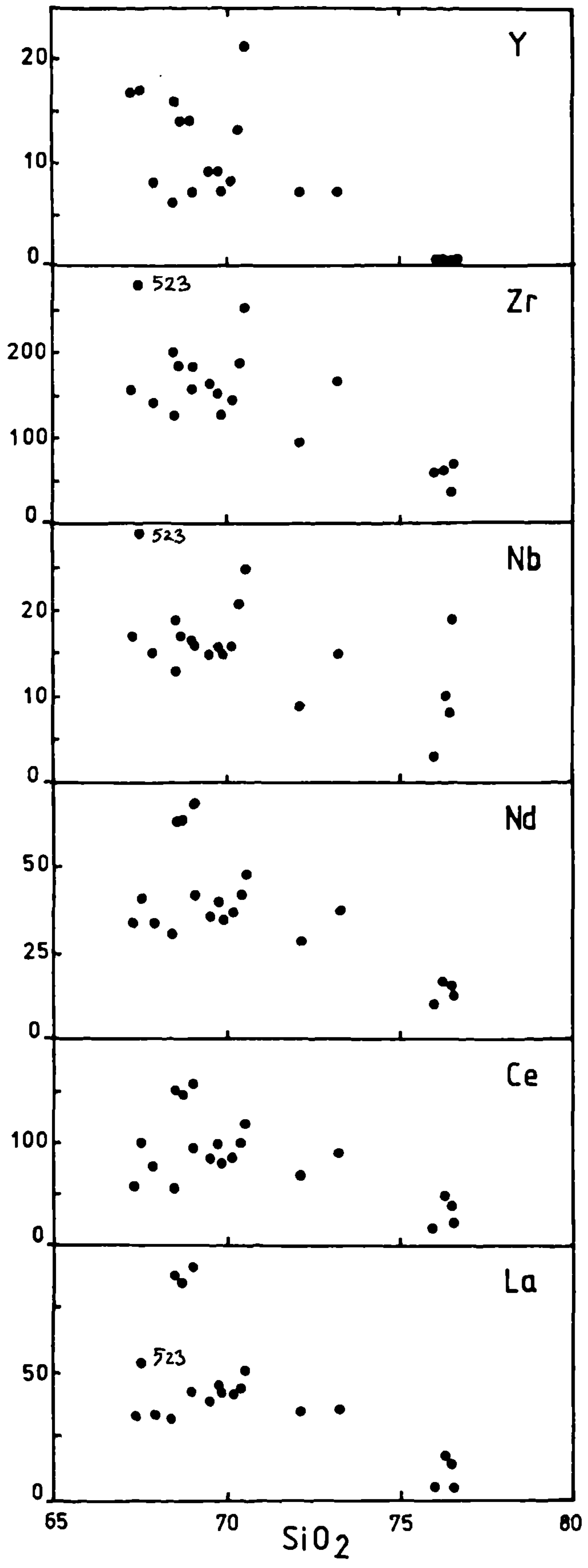


FIG. 3.4d. SiO2 - Group 2 and 3 (HFS and REE) Elements.

Group 4 (TME's).

Cr,Ni,V and Sc show good -ve variation with SiO2, with particularly low levels in the aplites (Fig. 3.4e). These elements behave compatibly being fixed in the mafic phase of biotite, magnetite and rutile, entering the 4 and 6-fold coordination sites with Fe2+, Fe3+,Ti4+,Mn2+ etc. Low absolute levels are typical in granites (and aplites) that have been produced by fractional crystallisation of pyroxene and amphibole. The case for Cu and Zn is similar; both elements replacing Fe and Mg in silicates, usually the biotite in acidic compositions. Typical levels of 40 ppm Zn and 10ppm Cu are found in the Shap granites. Viswanathan (1973) states that 70% of Zn in granites is carried by biotite in acidic rocks. Interestingly, this does appear the case at Shap as the aplites show similar or lower levels of Zn although they contain only minor biotite or mafic minerals. It is also thought that the Cu and Zn is also fixed in sulphides which are commonly found in the aplites (section 3.1.2.2).

Relative to the range of compositions of S.U.G's the trends at Shap are generally similar though a problem arises with the wide SiO2 range of the S.U.G.'s such that trends are influenced by the intermediate granodioritic compositions which do not occur at Shap. Hence the elements Zr and Nb tend to behave incompatibly in the S.U.G.'s as expected by calc-alkaline fractionation processes, although Group 3 elements behave alike in both data sets. This is also the case in the Group 4 elements all of which decrease with increasing SiO2. The S.U.G. data set for Group 1 elements lacks values for Ba and U. This apart, all the

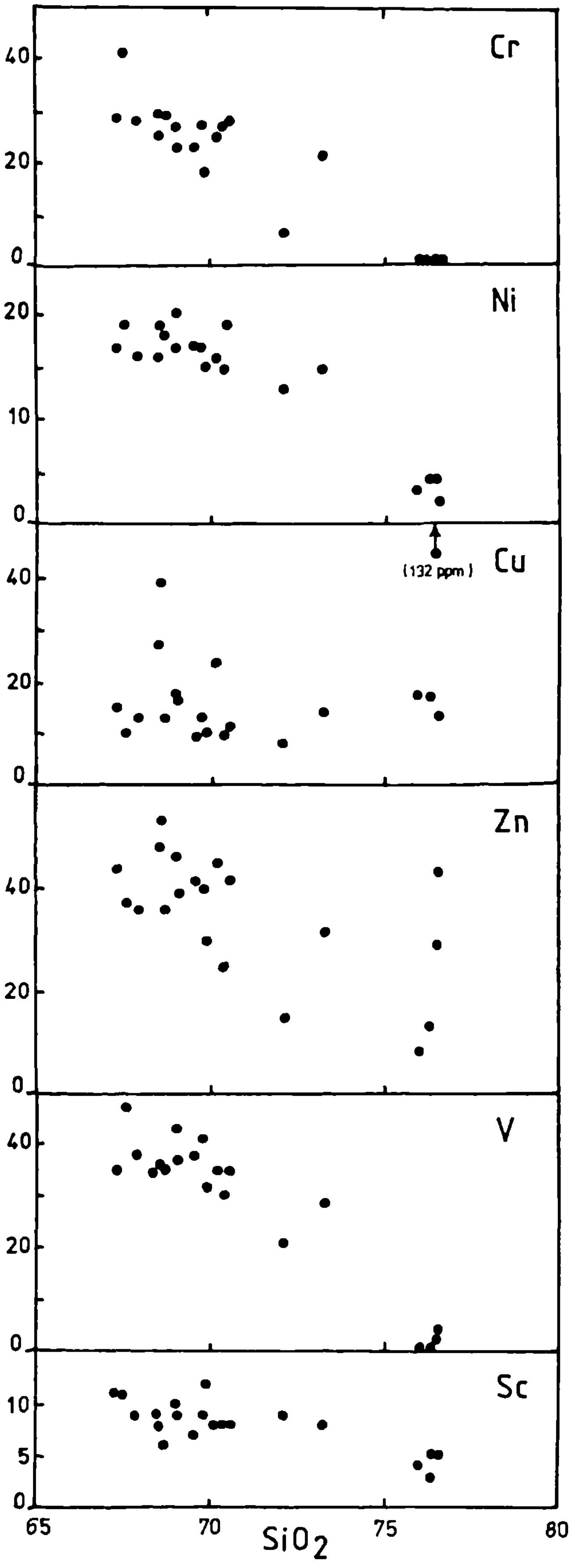


FIG. 3.4e. SiO2 - Transition Metal Elements.

remaining elements of this Group behave incompatibly except for Th, which in contrast to at Shap, behaves incompatibly as expected of all the Group 1 elements apart from Sr which usually behaves in a compatible manner along with CaO.

In conclusion, it is evident that as with the major elements, the majority of trace elements trends are a result of fractionation towards extreme acidic compositions. The non-porphyritic samples (600,601) occupy a compositional region intermediate between the granites and aplites. These rocks are not widespread (sec.3.1.2.1) but appear to form a possible continuum between what initially is a discrete division between the granites and aplites. It is not clear to which of the above granitic rocks these two samples are related. There intrusive character and finer grainsize supports aplitic affinities whilst geochemically, they appear to be related to the granites.

At these acidic compositions, minor accessory phases may become the key to elemental concentrations and distributions between granite types, especially relative to the aplites. The samples appear to be generally fresh and not to have undergone near-surface leaching, apart from the possibility of some U loss. Hydrothermal altered granite samples do not appear to show discrete chemical variations relative to the unaltered samples, suggesting an essentially isochemical alteration process. There also appears to be some sulphur-fixation of metals (Cu and Zn) in relation to the late stage consolidation of the granite especially within the aplites.

3.4 Stable Isotopes.

3.4.1 Introduction.

The composition of the stable, non-radiogenic isotopes of both oxygen and hydrogen have been analysed for Shap granites and their major hydrous phases of biotite and hornblende. For oxygen, the usual notation of $\delta O18$ has been adopted, being the variation of O18/O16 ratios in the sample relative to a standard of Standard Mean Ocean Water (SMOW). Similarly, the usual measured ratio of D/H (notation δD) has been used for hydrogen isotope values, again relative to SMOW.

Because of the wide variety of chemical conditions and compositions of magmas, the behaviour of these stable isotopes during melting and crystallisation processes is difficult to quantify. It is generally recognised that minerals have a tendency to preferentially fix either the heavy or light isotope of an element and, in particular, an increased fixation of the heavier isotope with the increasing preponderance of Si-O bonding. As a consequence, fresh igneous rocks define a trend of increasing $\delta O18$ with wt % SiO2, the normal range being +5 to +12‰ (Taylor 1968). Similarly, hydrogen values range from -50 to -120‰.

Interaction between magmatic rocks and the crustal environment such as occuring during metamorphism, hydrothermal alteration or weathering, all of which involve a fluid phase, usually results in isotopic exchange and anomalous isotopic values from the expected. Knowing isotopic values for fresh and altered rocks allows one to qualify the origins and processes undergone by samples, such as the syn- and post-emplacement history of plutons.

Fresh granitic rocks, being Si02-rich, have high δ 018 values of +8 to +15‰ and a tendency to more negative δ D values of <-50‰. Chappell and White (1974) showed that granites of predominantly differing origins have differing δ 018 signatures. Those of an igneous (termed I-type) origin have lower (usually <10 ‰) δ 018 values compared to granites with a significant sedimentary component from assimilation of continental crust (S-type).

3.4.2 The Shap Samples.

Isolated data for the Shap granite has been quoted by Harmon and Halliday (1980) and Thomas et al. (1985) and is tabulated below and shown in Fig.3.5 along with the data of this work.

Table 3.1 Stable Isotope Data - Shap Granites

Sample No.	Type	δ 018 ‰	δ D ‰	Whole Rock (WR) Mineral (M)
522	Dark	10.96	-69.9	WR
523	Horn.	11.56	-107.8	WR
531	Light	11.82	-65.2	WR
532	Light	10.95	-64.0	WR
534	Dark	10.80	-60.5	WR
	Mean	11.20	---	WR
523	Horn.	---	-81.8	M
	Bio.	---	-79.3	M
532	Bio.	---	-84.8	M
534	Bio.	---	-77.0	M
81148	Light?	10.4	---	WR Thomas et al. (1985)
Shap	Light?	11.0	---	WR Harmon and Halliday (1980)

It can be seen that the Shap samples of this work cluster about a mean value for δ018 of 11.2‰ which is not

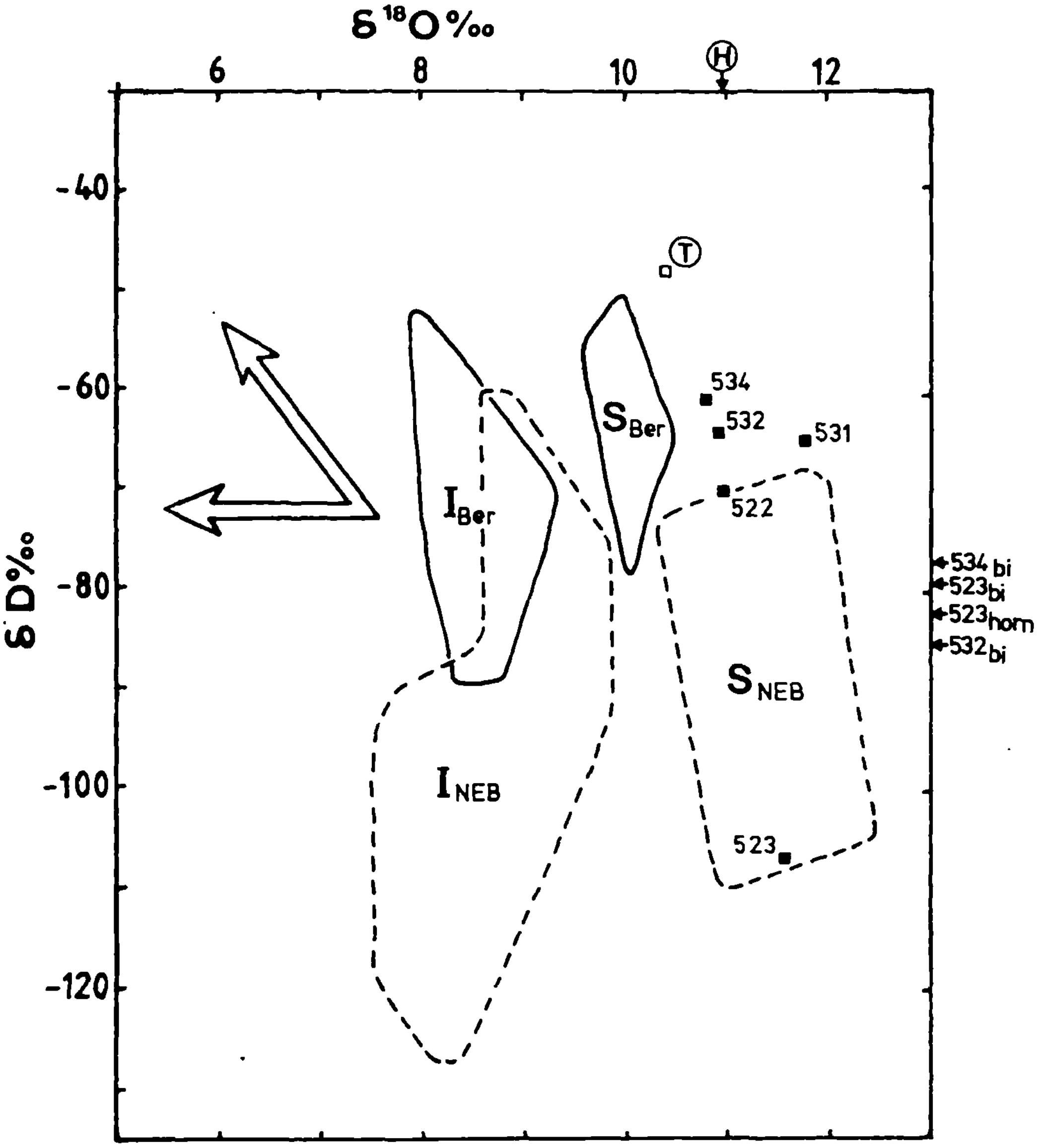


FIG. 3.5.

Oxygen and hydrogen isotopic ratios for Shap Granites and mineral separates as in Table 3.1, including Ⓣ Thomas et al. 1985 and Ⓗ Harmon and Halliday (1980).

Also shown are regions of typical S and I - type granites from the Berridale (Ber) and New England (NEB) batholiths of O'Neil and Chappell (1977) and O'Neil et al. (1977).

Secondary granite alteration results in lighter isotopic ratios as shown by the arrows.

dissimilar to the previous quoted values. The values also lie within the fields of S-type granites of Chappell and White (1974). The δ D values are also consistent with the expected range for granites apart from the very negative whole-rock value of sample 523. To assess this variation, the major hydrous phases of this and the other major granite types have been analysed for hydrogen isotopes. It can be seen that the δ D values of mineral separates for 523 are essentially the same as for the Light and the Dark granites. This suggests that this low whole-rock value for 523 is a result of some other hydrous or secondary phase although examination of this rock (see section 3.2 above) shows it to to have no other major hydrous phase and is remarkably fresh.

Of more importance is the lack of δ D variation between the Light and Dark samples. Also, the slightly chloritised biotite of 534 is of very similar value to that of 532. Both these facts indicate that the hydrothermal fluid involved in this alteration (and the associated mineralisation) was in isotopic equilibrium with the host granite and was therefore probably derived from the cooling granite. Many mineralised granitic stocks and other epicrustal intrusions such as sub-volcanic complexes show anomalous stable isotopic characters due to interaction with meteoric waters. Such waters have low values of δ O18 and δ D and produce lighter isotopic values as shown by the arrows in Fig. 3.5. No such trends are seen in the Shap samples apart from 523 which may represent some recent contamination with meteoric water from recent weathering. This effect is not seen in the other samples so it is concluded that the hydrothermal event at Shap was essentially a closed-system in character with there

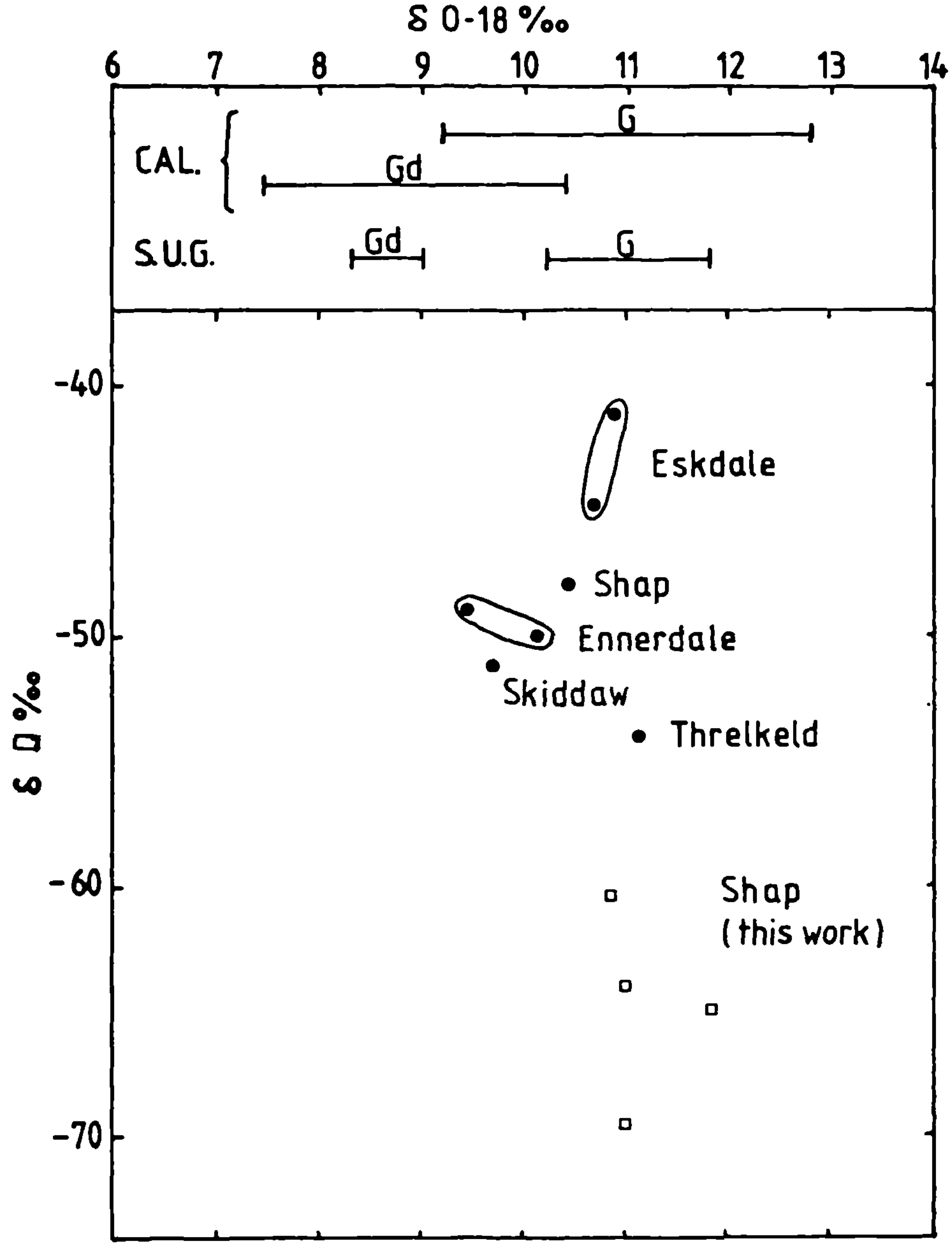


FIG. 3.6.

Stable isotope values of Cumbrian Granites from Thomas et al. (1985) and this study, and the ranges of typical Caledonian granites (G) and granodiorites (Gd) of northern Britain (CAL) and the Southern Uplands Granites (SUG).

being no fluid (or chemical ?) interaction with the surrounding country rocks.

Fig.3.6 shows the Shap samples in comparison to granodiorites and granites from the British Caledonides in general, the Southern Uplands Granites and the Cumbrian Granites. Again, there is a division between granite types about δ O18 of 9-10% though this time it relates directly to whole-rock composition, the more SiO2-rich granites (s.s.) having correspondingly higher O18 contents. All the Cumbrian intrusions have similar δ O18 values in the expected range of 9 to 12 ‰, which likely represent values somewhere near their original. No intrusions show δ D values indicative of interaction with meteoric waters or, effects of Caledonian deformation in the older plutons of Eskdale, Threlkeld and Ennerdale. The δ D values of this work are significantly lower than the Cumbrian (and Shap) granite values of Thomas et al.(1985). Inter-lab error is not thought to exceed about 5‰ (Harmon, pers. comm.) so this variation is thought to be a function of sampling styles. It is understood that Thomas et al.'s material came from boreholes which would have had little or no contact with surface meteoric water. Apart from the hornblende granite, the Shap samples for isotope study were collected from recently quarried rock and all were carefully dried to reduce any effects of contamination from near-surface waters.

3.5 Discussion

3.5.1 Normative Mineral Modes.

C.I.P.W. normative mineral modes have been calculated for all the Shap granite and aplite samples. In order to undertake the calculation, an Fe3+/Fe2+ ratio of 0.81 was assumed for all samples, this being the value for 'Light' granite analysed by wet chemical techniques (Caunt 1977). The possibility of this ratio differing from this value (in for instance, hydrothermally altered granites) has been considered but not estimated due to the low total Fe2O3 of the whole-rocks. Thus, uncertainties in the Fe3+/Fe2+ ratio would not grossly affect the extent of Fe-bearing phases relative to the felsic phases in the norm.

Data are presented in Appendix Table C.1 and Fig.3.7. The trend of many calc-alkaline systems in many tectonic environments of diminishing diopside and increasing corundum in the norm, is typified by the S.U.G.'s which define a broad but obvious similar trend between 55 and 80% SiO2. The values for Shap lie mainly in the corundum normative region and compare well with the more acid members of the S.U.G.'s as outlined by Stephens and Halliday (1979). The silica-oversaturated nature of the granites means they usually have quartz and hypersthene and corundum in the norm. This is the case at Shap apart from 523 (hornblende granite) and the aplites which both have normative diopside rather than corundum, along with also lower normative anorthite.

In the case of 523, the relatively high CaO and low Al2O3 of the sample results in a change from corundum to diopside in the norm whilst the extreme whole-rock chemistry of the aplites with their low Al2O3 and P2O5 means that normative anorthite and apatite are very low such that there is an excess of CaO in the calculation which is accommodated as diopside. The aplites also show very low hypersthene

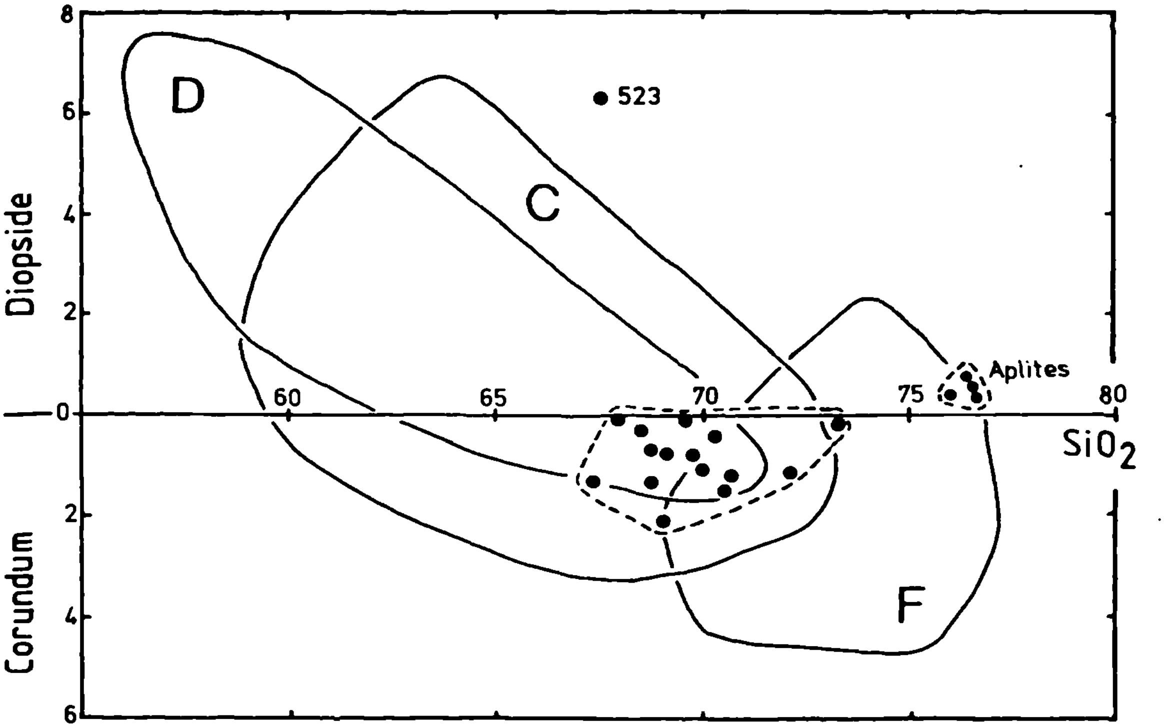


FIG. 3.7.

Normative diopside-corundum against SiO2 for Shap granites and aplites along with fields for S.U.G.'s of Doon (D), Criffel (C) and Fleet (F) after Stephens and Halliday (1979).

Most of the Shap rocks are typically corundum normative apart from sample 523 and the aplites.

values in the norm which is due to these samples having very low Fe2O3 and MgO contents.

Cawthorn et al. (1976) attributed the overall diopside to corundum trend to the dominant process of amphibole fractionation, especially over intermediate regions of SiO2. Typical amphibole (hornblende) analyses give a good possible end-member to this trend at 40-45% SiO2 and 20-30% diopside which would back-project directly along the calc-alkaline trend (Fig.3.8). This idea is further supported by the work of Pinwinski and Wyllie (1970) who found hornblende as a liquidus phase when melting corundum normative granites. Cawthorn et al. (op cit.) do not discuss the effects of fractionation at high SiO2 values where the role of amphibole becomes less dominant. Figure 3.8 shows that the diopside-corundum trend flattens out at around granodioritic compositions and remains essentially unchanged with increasing SiO2. At these acidic compositions, it is likely that crystallisation of biotite and plagioclase (An30 to An10) along with minor phases such as sphene, zircon etc. produce the increase in SiO2 and the level norm trend of Fig.3.8.

Also quoted in Appendix Table C.1 are values for the Differentiation Index (D.I.) of Thornton and Tuttle (1960). This value is calculated from the sum of normative quartz and feldspars (and feldspathoids) and in turn is based upon the idea that fractionation towards acidic compositions leads to the constituents of 'Petrogeny's Residua' System ie. the minimum melt quartz - orthoclase - albite mixture. The mean value of D.I. for the Shap granites of 84.4 is typical of adamellites and is significantly lower than for a

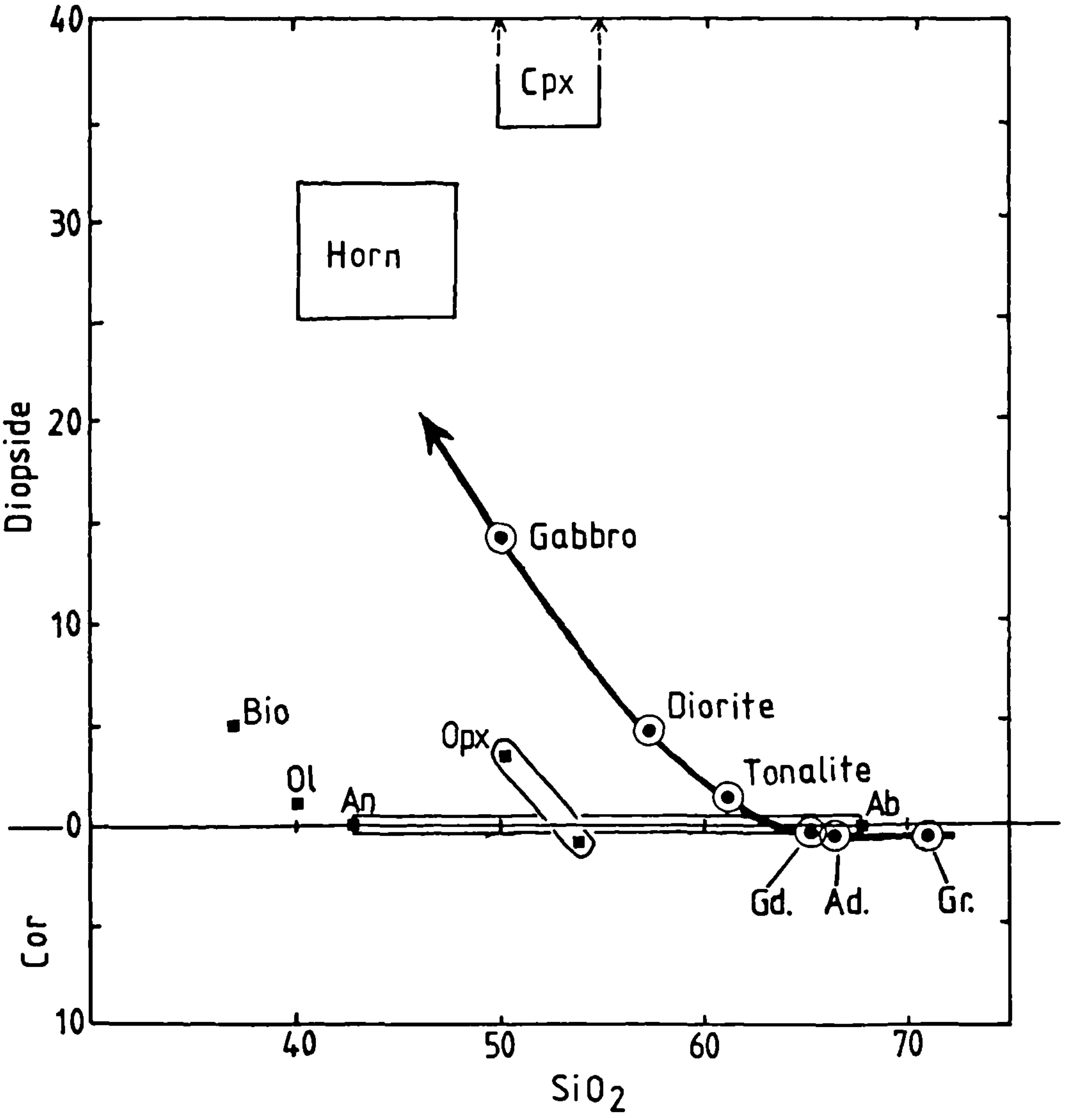


FIG. 3.8.

Normative diopside-corundum (Cor) against wt % SiO2 showing the fractionation trend shown by the typical calc-alkaline series gabbro-diorite-tonalite-granodiorite (Gd)-adamellite (Ad)-granite (Gr).

Also shown are the positions of common rock-forming silicates such as clinopyroxene (Cpx), hornblende (Horn), biotite (Bio), forsteritic olivine (Ol), orthopyroxene (Opx) and the plagioclase feldspars anorthite (An) to albite (Ab).

Back-projection of this trend supports the argument for hornblende fractionation being a dominant process in producing granitic rocks upto about 65 wt % SiO2.

Rock and mineral analyses selected from Cox et al. (1979).

granite (s.s.) value of around 90.0, reflecting the more granodioritic character of Shap Granite. The higher D.I. values for the aplites (about 96.9) give further support to aplites being extreme fractionates of the Shap magma and that the generation of granitic liquids with above about 76% SiO2 (and D.I.= 100) cannot be produced by simply the process by fractionation alone.

The process of production of high-SiO2 magmas is of interest when extended to the generation of acidic dykes (eg. quartz porphyries) which generally have high SiO2 (>72%) but differ from aplites in often having significant proportions of mafic phases and lower D.I.'s, but yet are still ascribed as being fractionates of the same granitic magma as the aplites. This variation between acid dykes and aplites is discussed further in Chapter 4 along with the relationship between the chemistry of the granites and dykes.

3.5.2 Peralkalinity.

Knowing that much of the final texture and chemistry of the granites is related to potash metasomatism, values of alkalinity (ie. molar Al2O3/Na2O+K2O+CaO) have been calculated to establish whether the development of megacrysts and the fixation of K2O has resulted in trends towards alkali enrichment ie.peralkalinity.

Mean values for Light granites are almost unity (0.98), a value typical of adamellites where the alkalis in plagioclase, orthoclase and biotite are balanced by the alumina fixed in those phases. This balance effect is typified by the aplites which although orthoclase-rich (which might be expected to promote peralkalinity) are also biotite and plagioclase-poor.

The effects of this modal variation between granites and aplites are reflected in the reduced Al2O3 and CaO contents of the aplites, whilst K2O values remain unchanged as modal biotite is replaced by an increase in orthoclase such that the resulting value of 0.98 for the aplites matches that of the host granite. Samples from about the margin (eg.602,605,606) have slightly higher values of 1.01 to 1.06. This is due to the increase in modal biotite of these samples which increases Al2O3 whilst the K2O contents remain the same as the Stage 2 granites.

The hornblende granite (523) has a low value of 0.78, due to its lower Al2O3 and high K2O and CaO content, a reflection of the amphibole along with the reduced modal biotite and increased orthoclase.

The effects of hydrothermal alteration produce a trend of increasing ratios (0.98-1.12). The Dark granites have a mean value of 0.99 showing that in respect of these four major oxides involved, the alteration is nearly isochemical with the sum of the alkalis (including CaO) being maintained by slightly reduced values of Na2O and CaO in combination with a corresponding minor increase in K2O whilst Al2O3 is essentially constant. Extreme alteration (535) results in a significantly increased ratio with Al2O3 still fixed but now there is much larger reductions in Na2O and CaO.

Overall, it should be noted that;

a) Widespread orthoclase development has not resulted in a relatively alkali-rich granite.

b) The process of hydrothermal alteration of the granites has been one of fixed alumina and, except under extreme conditions, near constant alkalis.

3.5.3 Chemical Effects of Hydrothermal Alteration.

Assessment of mineralogical and chemical differences between fresh and hydrothermally altered granites (ie. Light and Dark respectively) allows consideration of some aspects of the geochemical processes involved. The alteration results in little or no change to the orthoclase and quartz (as well as resistant accessories such as apatite, zircon, etc.) but induces extensive alteration in biotite and plagioclase and produces a bulk rock redistribution of iron (section 3.2.2). Stable isotope study confirms that the fluid involved was in stable isotopic equilibrium with the granite (section 3.4.2).

Alderton et al. (1980) examined the effects of various alteration styles on the major element whole-rock chemistry of granites. Fig.3.9 shows their regions of expected chemistry for granites that have undergone argillic, sericitic, chloritic and K-silicate alteration. Both the Light and Dark samples appear to be positioned in the region of unaltered "fresh" granites which in turn is encompassed in the broad region of chloritisation. This would suggest that much of the process of chloritisation in granites is isochemical with regard to these elements, this classification not being able to distinguish between fresh and chloritised granites except at extreme stages of alteration.

Comparison of the major and trace element variations

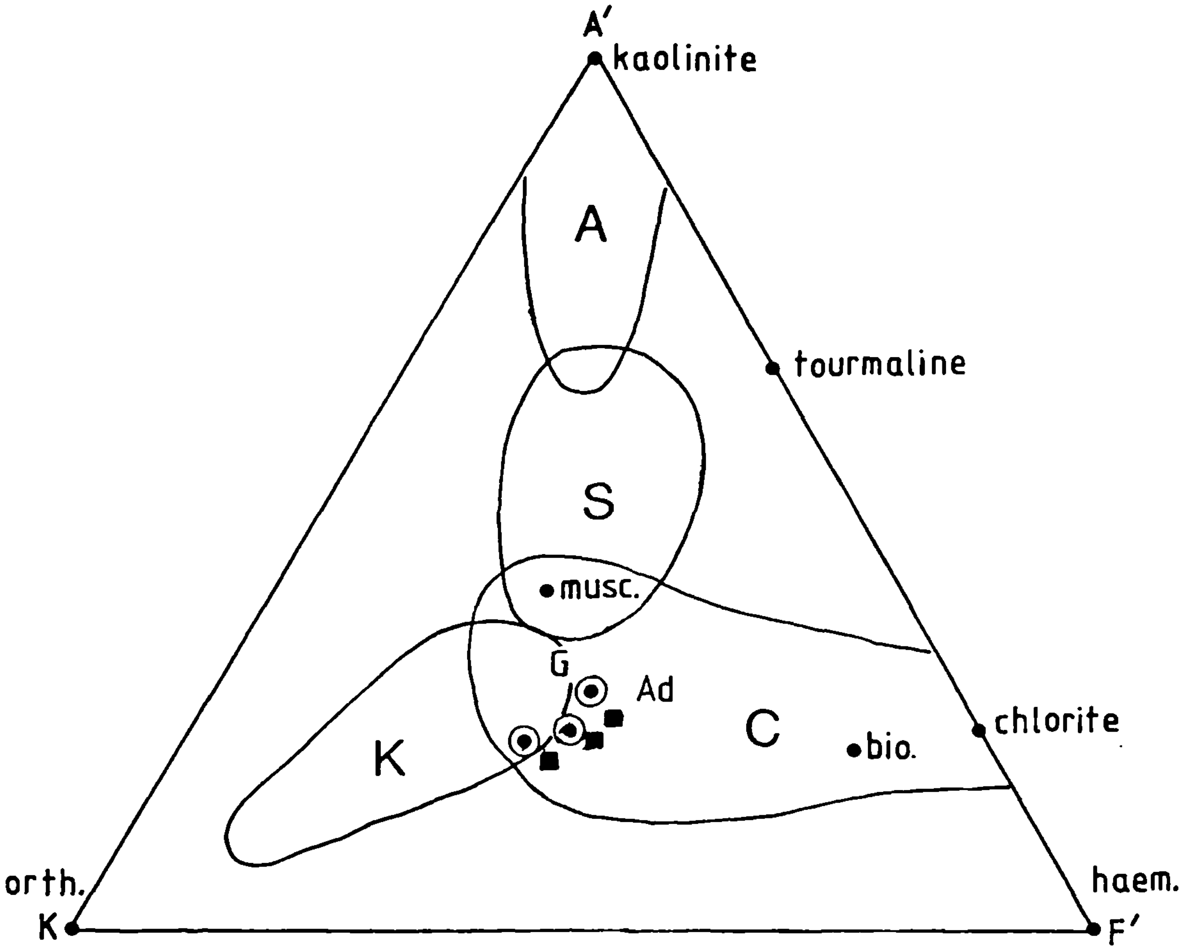


FIG. 3.9.

Fields of granite alteration (A-argillic, S-sericitic, K-K silicate, C-chloritisation) expressed as A' (Al2O3-(Na2O+K2O), K (K2O) and F (FeO+MgO+MnO).

Typical granite (G) and adamellite (Ad) define a central region of fresh rocks not dissimilar to Shap analyses for Light (◉) and Dark (■) granites.

Hydrothermal alteration at Shap appears to be confined to near-isochemical chloritisation.

(After Alderton et al. 1980).

Table 3.2 Chemical trends between average Light and Dark Granites

	Light	Dark	V.Dark	Trend		L	D	VD	T
SiO2	69.4	68.8	69.0	0	Rb	268	285	335	+
TiO2	0.53	0.56	0.57	+	Sr	450	393	261	-
Al2O3	14.6	14.4	14.1	-	Ba	701	605	553	-
Fe2O3	2.50	2.58	2.98	+	Pb	58	45	31	-
MnO	0.09	0.08	0.08	0	U	6	7	3	?
MgO	1.15	1.38	1.45	+	Th	33	30	35	0
CaO	1.92	1.85	1.10	-					
Na2O	3.55	3.40	2.67	-	Y	8	9	7	0
K2O	5.19	5.29	5.76	+	Zr	146	148	184	+?
P2O5	0.23	0.24	0.25	+?	Nb	15	16	16	0
					Nd	35	37	42	+?
LOI	0.61	0.96	1.58	+	Ce	75	88	94	+?
					La	38	40	43	+?
Cr	24	28	23	?					
Ni	16	17	20	+?	V	36	40	37	0
Cu	20	13	16	-?	Sc	8	9	9	0
Zn	45	38	39	-?					

from Light, Dark and extensively altered granite shows how the mineralogical changes effect the whole-rock chemistry. There are significant increases in MgO,K2O,P2O5, (LOI),Cr,Ni,Rb,Zr and REE's, which can be explained by modal increases in chlorite (after biotite) and the resistant phases of orthoclase, apatite, zircon and to some extent, Fe-Ti oxides and sphene. The corresponding decreases are in CaO,Na2O,Cu,Zn,Sr,Pb,and Ba reflecting the alteration of oligoclase and biotite. These decreases would suggest that the biotite alteration would act as a source of some elements involved in mineralisation, in particular, Cu and Zn and, combined with plagioclase, would also provide the Pb, Ba and Sr. Values of these LFS elements decrease by upto 35% suggesting that much of the remaining Pb and Ba in particular are still held in the orthoclase feldspar as expected. Also, release of K2O from biotite breakdown into solution would enhance the survival of potassic orthoclase (as is usually the case) apart from in regions of more extreme alteration close to the master joints where fluids were likely to be more extensive in time and volume.

Decreases in the Cu and Zn values are only some 10-20% of the initial concentration, which suggests that much of the available Cu and Zn is either in phases other than biotite or, that little leaching of these and other elements into the joint system had occurred. It is likely that only when extensive alteration occurs, which in turn eventually results in physical removal of material and greatly increased permeablity, do metallic species become readily available for movement in solution and eventual fixation about the granite. Permeability within the Dark granite does not appear dissimilar to that in unaltered granite. Increased modal hydrated phases (and LOI) shows that some hydrous input has occurred but, it is thought that much of the elements mobilised during the alteration remained fixed as new alteration products (eg. sericite) or as inter-lattice and grain-boundary phases.

It may also be likely that the hydrothermal fluid involved was not enriched in halogen species which would enable elements to be fixed into chemical complexes, allowing easier mobility and increasing concentrations of these species in the hydrothermal fluid. It is known that there is a strong correlation between available halogens and the extent of mineralisation in mineralised granites, especially in disseminated metal deposits such as porphyry-Cu complexes (Barnes 1985). This topic of mineralisation and the model proposed is discussed in Chapter 7.

3.5.4 Comparison with N.England Granites (s.l.).

Northern England is thought to be underlain by a composite batholith of which the Shap Granite is one particular outcrop in the roof zone. The granites known to constitute this batholith are Ordovician to Devonian in age and range in composition from diorites and granophyres to granites (s.s) and adamellites (Chapter 2). The more felsic members tend to be of post-orogenic age (namely Shap, Skiddaw, and Weardale) apart from the small intrusion at Threlkeld and portions of the Eskdale Granite which are both pre-Silurian in age (Rundle 1981).

Comparison of these intrusions with that at Shap is hampered by a number of factors. Firstly, whole-rock analyses for Cumbrian granitic rocks are scarce. This is typified by the fact that at Shap, little analysis has been undertaken since that of Grantham (1928). Good samples of Skiddaw Granite are minimal due to the lack of outcrop and much of the available material being very weathered. Also, of the published analyses, most have been of the greisened granite which occurs about the roof zone at Skiddaw which is unlikely to be representative of the composition of the granite as a whole (Hitchen 1934, Roberts 1983). The data set for the unexposed Weardale Granite is based on material from a single borehole although some 18 sample analyses have been published (Holland and Lambert 1970). The Ennerdale and Eskdale granites, despite being the largest Cumbrian intrusions and quite well exposed, have received little scientific attention, analyses being few and not recent (Simpson 1934, Eastwood et al.1968).

The older intrusions also show chemical modification due to limited deformation during the Silurian. This manifests itself as secondary alteration and in particular albitisation and Na metasomatism (Firman 1978, Caunt 1984). Finally, the available analyses for Cumbrian granites have been undertaken over a period of 60 years using a wide range of analytical techniques such that much of the data set is not strictly comparable. However, given these limitations, some broad comparisons can be made.

All the intrusions are of a calc-alkaline nature and define similar AFM trends to Shap (Fig.3.10). The best comparisons can be made with Skiddaw and Weardale intrusions which are of similar mineralogy and have more complete data sets. Amongst the major elements, the Shap Granite has significantly higher TiO_2, Fe_2O_3, MgO and CaO (Note the effect of higher MgO on lowering the position of the AFM trend in Fig.3.10) and lower values of SiO_2, Al_2O_3 and P_2O_5. Na_2O values are intermediate between those of Weardale (4.2%) and Skiddaw (3.2%) whilst K_2O is remarkably similar in all 3 intrusions, all having mean values close to 5.1%. In contrast to K_2O, Rb values for Shap are lower than might be expected whilst amongst the limited available trace element data Sr,Ba,Zr,Cu, and Pb values are higher, and Ni and Zn appear similar.

If we assume that the lower SiO_2 values at Shap reflect a less fractionated magma than at Skiddaw and Weardale, then this would account for the higher Fe_2O_3,TiO_2,MgO,CaO, and Sr values. In return, this implies that the Shap Granite is slightly enriched in the incompatible elements such as K_2O,Ba,Pb, and Zr relative to the other granites. Knowing

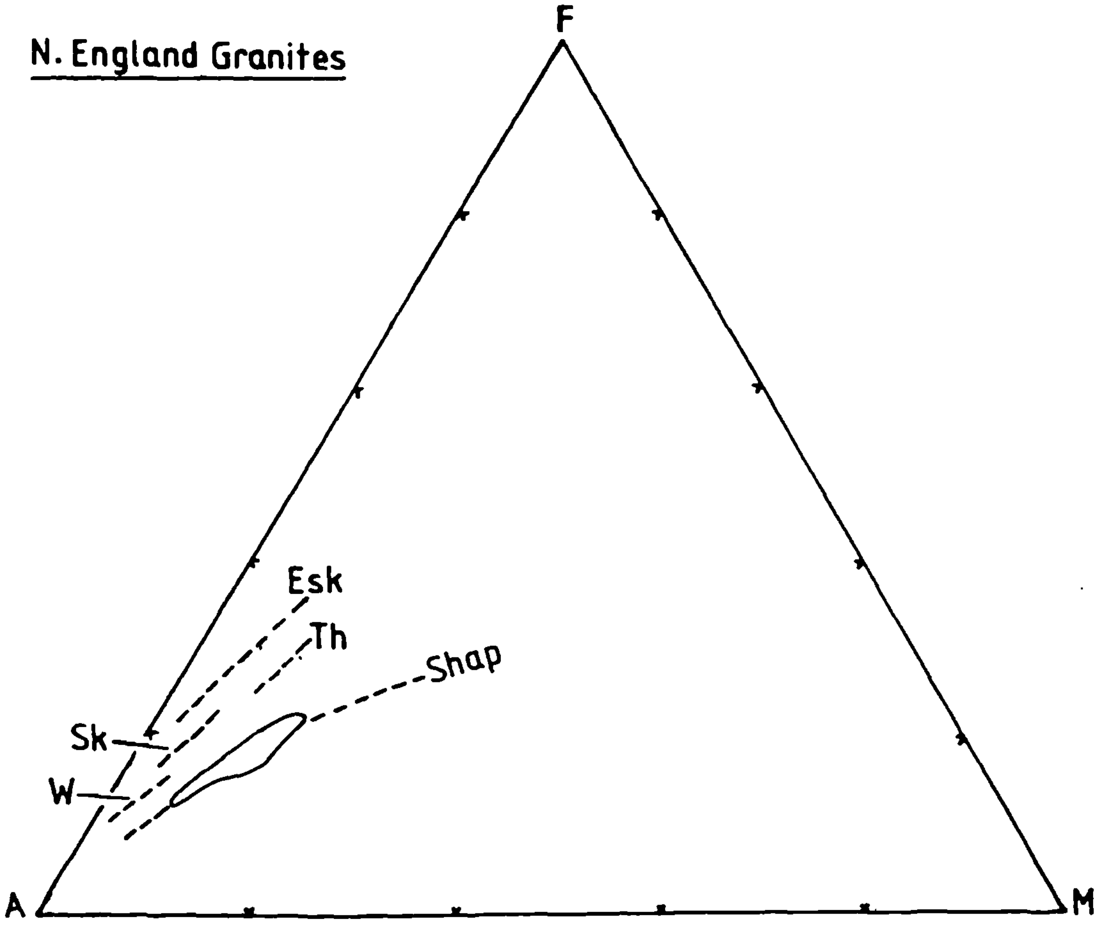


FIG. 3.10.

AFM trends of Northern England granites showing typical calc-alkaline characters.

Esk,	Eskdale (Firman 1978)
Th,	Threlkeld (Caunt 1984)
Sk,	Skiddaw (Hitchen 1934, Roberts 1983)
W,	Weardale (Holland 1967)

that the granite exposure at Shap is close to the roof zone of the batholith, it might be expected that the granites be enriched in elements associated with residual or late fractionated liquids which are themselves enriched in incompatible elements and concentrated about the roof and margins of the pluton. This argument does not appear to be the reason for this enrichment of Shap samples when compared to the depth-chemistry relationships for the other granites. For instance;

a) The Skiddaw Granite occupies the roof zone of the Cumbrian Batholith and although secondary mineralisation and greisenisation have occurred at Skiddaw, the normal granite variety at Skiddaw is not rich in incompatible elements relative to Shap and there is also no evidence to indicate that elements have been 'leached' by the secondary events or more recent weathering etc., modifying the granite's chemistry.

b) Geophysical evidence shows the Weardale Granite to have been unroofed to a similar extent to the Shap Granite. The Weardale Granite's lower incompatible element levels might be a function of the effects of pre-Carboniferous weathering that some samples show (Dunham et al.1967). Element concentrations are not thought to have been greatly affected by this event judging by Rb, an element expected to have been lost from the samples but is in fact enriched in the Weardale Granite. What is not clear is why the Weardale Granite appears Rb enriched relative to its K2O content or in comparison to the other granites of the area.

Therefore, it is thought that this relative enrichment of incompatible elements at Shap is a function of variation in original magma chemistry, this being in contrast to the idea that the magma was originally of a more granodioritic character.

3.5.5 Granite I and S-Type Classification.

Detailed mineralogical and chemical studies of granites forming major batholiths of the Tasman Orogenic Zone of eastern Australia resulted in a classification of granites by Chappell and White (1974). They proposed two major suites having differing characters due to each originating from either a sedimentary (S- type granite) or an igneous source (I-type granite). This broad scheme has been adopted and widened by other workers including an equivalent classification into magnetite and ilmenite-series granites (Ishihara 1977) as well as stable isotope classifications (eg. O'Neil et al.1977, Coleman 1979). These and other details are presented in Table 3.3 where they are compared to the Shap Granite in order to establish some broad characteristics of this intrusion.

Such a classification, involving the division of many various granite types from variable settings, into two major types has obvious limitations. Table 3.3 shows this to be the case at Shap, which appears to have either an I,S, or intermediate character. For instance, a problem arises over whether the adamellite composition typifies the nature of the Shap pluton as a whole, or whether at deeper levels granite of differing (more basic ?) composition represents the major pluton lithology. Evidence of more basic granite is generally lacking (Chapter 2) but, it is commonplace for

Table 3.3 Granite Classification.

'I' Type Character	'S' Type Character	Shap Granite	Inf.
A. Tectonic Setting and Lithologies.			
Subduction-related Batholiths eg. Andes	Continental Collision Batholiths (No obvious relationship to oceanic lithosphere subduction). eg. Cornwall	Post-Orogenic Caledonian Collision	S
Mafic to Felsic Compositions	Mainly High-SiO_2 Compositions	Adamellites only at present level	S
Tonalites and Granodiorites Prevalent	Granites s.s.	As Above	S
Igneous/Cognate Xenoliths	Metasedimentary and /or Country-Rock Xenoliths	See Chapter 6	I
Cu-Mo Provinces (eg.Porphyry-Cu's)	Sn-W Provinces	Minor Cu + Mo	I?
B. Mineralogy.			
Biotite only	Biotite + Muscovite	No Primary Muscovite	I
Hornblende	Horn. + Biotite	Hornblende Rare	S
Hornblende	Garnet	No Garnet	I
Sphene	Cordierite	No Cordierite	I
Allanite	Monazite	All. > Monz.?	I?
Magnetite	Ilmenite	Mag. >> Ilm.	I
Pyrrotite	Pyrite	Pyrite >> Po.	S
C. Geochemistry			
$Na_2O > 3.2$ % in Felsic Varieties	$Na_2O < 3.2$ % at $K_2O = 5$ %	$Na_2O = 3.65$ % at $K_2O = 5$ %	I
Peralkalinity < 1.1	Peralkalinity > 1.1	Peralk. = 0.98	I/S?
C.I.P.W. Norm Diopside or<1% Cor.	> 1 % Corundum	0.2 % Cor.	I
High Fe^{3+}/Fe^{2+} ratio	Low Fe^{3+}/Fe^{2+} ratio	$Fe^{3+}/Fe^{2+}=0.8$ (Whole-Rock)	I

O-18 < 10 ‰	O-18 > 10 ‰	O-18 = 11.2 ‰	S
Low Sr-i (<0.708)	High Sr-i (> 0.708)	Sr-i = 0.7077 (Wadge et al. 1978)	I/S?

Notes To The Above

1. This table is broadly based on aspects of the following;
   (a) Chappell and White 1974 (I and S granites)
   (b) Coleman 1979 (Stable isotopes in granites)
   (c) Beckinsale 1979 (Metallogenic granites)
   (d) Ishihara 1977 (Magnetite-Ilmenite Series granites)
2. Geochemical values for Shap Granite taken for the 'Light' variety where possible.

intrusions to be like the S.U.G.'s with a more dioritic nature at depth. If this was the case at Shap, then I-type affinities would be more prevalent.

The division of suites on the style of associated mineralisation is specifically based upon metallogenic granites (ie. granites with extensive mineral deposits) rather than mineralised granites (ie. granites with minor secondary mineralisation such as at Shap). The occurrence of molybdenite and the lack of tin-tungsten minerals at Shap would support an I-type affinity but this intrusion does not show the disseminated porphyry-Cu style mineralisation normally associated with this classification.

In many cases, both of the rock-forming or accessory minerals used in distinguishing between the two suites occur within the Shap Granite. For example, biotite and hornblende, pyrite and pyrrohtite, magnetite and ilmenite all occur at Shap but the occurrence of the latter mineral of each pair is usually relatively minor (eg. hornblende) or difficult to identify (eg. monazite). As a consequence, these mineral criteria are also somewhat subjective giving inferences of a mixed character. The geochemical parameters chosen for classification also reflect the role of either a mantle or a continental crust dominated origin. As expected, S-type granites generally have higher Al2O3, K2O, Sr-i and δO18 values relative to I-type granites. Again, these chemical criteria are not robust, with many granites commonly having both I and S characteristics reflecting the likely mixed and multivarious origins of granitic magmas (see sect. 3.3).

In favour of the scheme is its value in showing the character of granites where origins and tectonic settings are known. These broader parameters are well defined in this classification. This is also the case at Shap. The lower Devonian Caledonian plutons are a product of continental collision and post-orogenic magma genesis. As such, they do not generally show subduction-related characteristics, their magmas usually reflecting the role of crustal thickening and subsequent melting. In extreme cases, this may result in alkaline acid magmas or, those containing garnet, cordierite, muscovite etc. from extensive crustal assimilation. Neither of these extremes is the case at Shap nor for that matter, in the Caledonian granites in general. This apart, the tectonic setting does infer that the Shap Granite is likely to be more S-type than I in overall character.

3.6 Conclusions.

Based on the evidence and discussion presented above, some broad conclusions can be made at this point concerning the geochemistry of the Shap Granite.

1) The granite magma shows typical calc-alkaline trends probably generated by the fractionation of amphibole and some plagioclase from a granodioritic precursor at depth. Late-stage crystallisation resulted in crystal accumulation of both major and minor phases and late highly-evolved fractionates such as the aplites.

2) The granite is enriched in incompatible elements relative to the other granitic intrusions of northern England, an effect which is not thought to be a result of it's high level position towards the roof of the Cumbrian Batholith.

3) Although an adamellite in composition, the granite shows some chemical trends towards more granodioritic or monzonitic affinities.

4) Textural evidence supports the argument that much of the orthoclase feldspar growth and in particular,that of the megacrysts, was formed late in the magma's consolidation, representing a metasomatic style of development. Prior to this event, the magma composition would likely have been less evolved and of more intermediate composition.

5) Hydrothermal alteration occured after consolidation, with a reaction between hydrous fluids of magmatic origin and the cooling granite. This alteration and the associated mineralisation was essentially isochemical and took place as a closed system ie., remobilisation and deposition was confined to within and about the joint system of the granite.

CHAPTER 4 MINOR INTRUSIONS (DYKES).

4.1 Introduction.

Associated with the major Palaeozoic volcanism and plutonism in N.W. England are a suite of minor intrusions (dykes, sills and pipes) mostly varying between Ordovician and Devonian in age although a few are of Carboniferous to Permian age.

The broad petrological nature of these minor intrusions varies with age and the associated 'parental' igneous episode. As a consequence, the intrusions can be broadly divided into three groupings. Firstly, there are the minor intrusions associated with the Eycott and Borrowdale Volcanic Groups and the basic intrusions about Carrock Fell and Embleton in the northern Lake District (Firman 1978). These are very limited in extent and are typically basic in composition (basalts and dolerites) along with some rare albite porphyries. Caledonian deformation has resulted in their extensive alteration and, along with associated weathering, is in part responsible for their paucity relative to the large extent of the volcanic and basic plutonic rocks in the Lake District (Eastwood et al 1968).

The second and by far the largest and most widespread group of minor intrusions is that related to the Cumbrian granitic batholith. These intrusions may vary in age from Ordovician to Devonian, though the majority are likely to be syn- and post-orogenic in age and related to the major granite plutons there being very few intrusions in rocks of Carboniferous or younger age. As such, most are of acidic composition though these are often associated with more intermediate varieties as well as those of lamprophyric affinities. This second group of intrusions is distributed all over Cumbria in host rocks older than the Carboniferous and, in some areas, they outcrop plentifully. Arthurton and Wadge (1981), in describing the geology around Penrith and in particular, the Cross Fell area, mentioned the occurrence of 141 minor intrusions varying in composition from dolerites and lamprophyres through to microgranites and quartz porphyries and they attributed to the majority of them a Caledonian age.

Lastly, belonging to the third group of minor intrusions, are a few small dykes and sills thought to be Carboniferous to Permian in age. In the northern Lake District, basic dykes are found in the Devonian? sediments about Mell Fell (Capewell 1954) and further to the northwest near Cockermouth. These are thought to be contemporaneous with the Cockermouth Lavas which are tholeiitic basalts of probable Dinantian age (Firman 1978, MacDonald and Walker 1985). In eastern Cumbria, some basic dykes near Melmerby in the Cross Fell inlier have a K/Ar age of 296 Ma and these intrusions may be related to the major Carboniferous tholeiitic sills of northern England and in particular, the Whin Sill (Wadge et al 1972). A study by Nutt (1970) of the geology of the Haweswater area revealed the rare occurrence of dykes of camptonite and minette compositions, not dissimilar to those dykes described from further to the southeast at Ingleton in West Yorkshire. Nutt (op cit) attributed to these intrusions a possible Permian age.

The minor intrusions of the Shap region can be assigned to the major second group outlined above, they being mainly acidic intrusions related to the Shap Granite. Little attention has been paid to these acidic minor intrusions either at Shap or for that matter elsewhere in Cumbria. This is in contrast to the associated more basic and lamprophyric intrusions which have received a much wider examination (eg. Harker 1892, Williams 1923, Wilson and Galligan 1927, Smith 1930, Hudson 1937, Moore and Ashton 1968, Burgess and Holliday 1979, Arthurton and Wadge 1981, Nixon 1984 et al etc.) and this in turn has produced a wide spectrum of evidence and discussion concerning the age and origins of the lamprophyres in particular, and, their relationships to the acidic minor intrusions. In the Shap area, the main descriptions of the minor intrusions have been made by Morrison (1919), Harker and Marr (1891) and Redfern (1979). The major granite studies of Grantham (1928) and Firman (1953a) gave no details of these intrusions. Morrison (op cit) gave a lengthy petrological description of the intrusions occurring upto 30km south of the Shap Granite. He noted that the more acidic members occurred nearer to the granite and he attributed the complete compositional range from lamprophyre to quartz felsite as being direct offshoots of the Shap pluton. His model for the derivation of the varying magma compositions involved a complex inter-relationship between acid and basic magmas from a zoned magma chamber resulting in composite intrusions, hybrid magmas and widespread intrusion ages. Harker and Marr (1891) gave brief petrological descriptions of the intrusions upto 6km from the granite and they too noted the close relationship between the mineralogy of the Shap Granite and that of the surrounding minor intrusions, there being a lack of the more basic intrusions near to the granite. Redfern

(1979) whilst studying the Silurian sedimentary succession to the south of the granite, undertook a brief examination of the minor intrusions including the description of a small number of samples collected during the driving of two tunnels (Fig. 4.1). His study included the first analyses of these rocks and his whole-rock geochemical data confirmed that the intrusions where mainly acidic but also, that there was a wide range of compositions (51-78% SiO_2) within the area close to the granite, a range much broader than found within the Shap Granite itself.

Given this range, the intrusions were examined about the granite in order to establish the geochemical character of this mainly acidic suite for comparison with the granite data. It was hoped that the intrusions reflected variations in magma chemistry, as they were likely to have been intruded as true magmatic liquids (as opposed to crystal mushes etc.) and possibly over a range of time spanning the time of the granite's final emplacement. Consequently, geochemical variations of the granite magma might be preserved by the periodic tapping, emplacement and rapid cooling of the intrusions thus reducing some of the non-magmatic effects that might modify the chemistry of the granite such as subsolidus reequilibration, metasomatism etc. If this is the case, it would then be possible to assess to what extent the composition of the Shap Granite (and perhaps granites in general?) represents that of a magmatic liquid.

4.2 Intrusion Age, Distribution and Emplacement.

As mentioned above, although lamprophyric intrusions are lacking about the granite, they often occur in

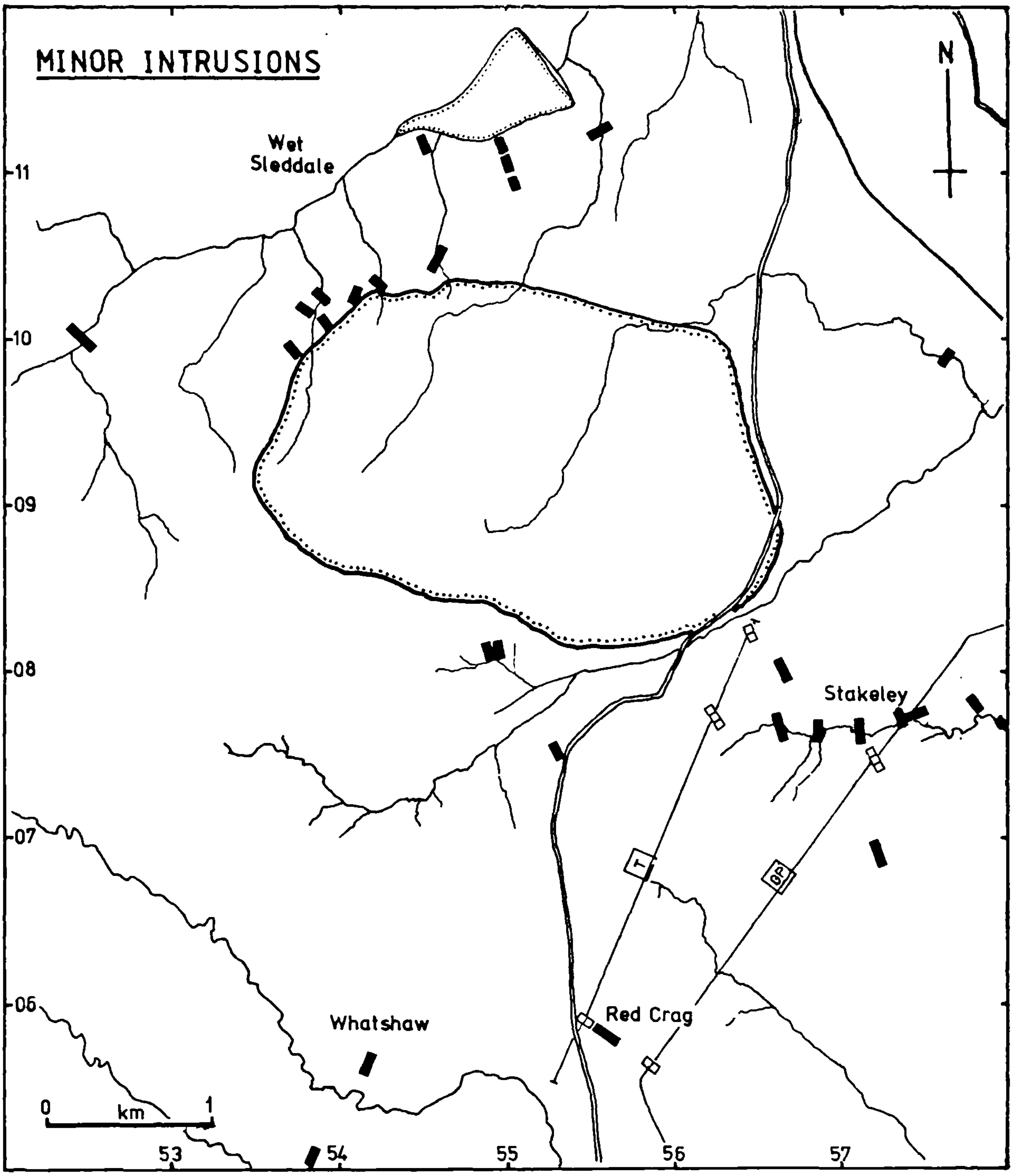


FIG. 4.1

The distribution of dykes about the Shap Granite.

Also shown is the position of the gas pipe-line (GP) and the Tunnel (T) sections through the Silurian rocks, from Redfern (1979).

association with granitoid calk-alkaline plutons (Rock 1984). Their mineralogy is typically dominated by phlogopitic mica, amphibole, olivine, pyroxene along with primary carbonates and zeolites. Both K-feldspar and intermediate plagioclase may be present though strictly these should not be phenocrysts but confined to the groundmass. Their age and origins have until recently been associated with the granite plutons , with the lamprophyres from much of northwest England being continually attributed to being 'offshoots' of the Shap Granite. The distribution of these intrusions is in fact usually away from the exposed granite plutons being associated with the areas above the deeper and less geophysically constrained regions of the roof and flanks of the granite batholith of Bott (1978) which is thought to underlie northern England. On the basis of palaeomagnetic data, Piper et al (1978) suggested that the lamprophyre intrusions of Cross Fell are of early Devonian age. A different view has been expressed by Arthurton and Wadge (1981) who recognised an end-Silurian cleavage in several of these dykes and inferred that they were intruded as a late to syn-orogenic phase towards the end of the Silurian. The incorporation of granitic xenoliths in some lamprophyres has been used as evidence for these intrusions being contemporaneous with the lower Devonian granites (Rock 1984). It is known that in northern Britain granites of Ordovician and Silurian age constitute much of the granitic batholithic mid and upper crust (eg.the Eskdale and Ennerdale granites of Cumbria) and therefore, it is possible that these xenoliths and their host lamprophyres need not be constrained to being the same or a later age than the post-orogenic granites such as Shap, Skiddaw, Weardale etc. Recently, Nixon et al (1984) gained K/Ar ages for 3 lamprophyres intruded into Ordovician and Silurian sediments about Cautley in northwest Yorkshire. Within error, they gave a mean age of 410 Ma, their ages being compatible with a single age of intrusion thought to immediately post-date the final phase of deformation in the Caledonian Orogeny and well pre-dating the main generation of the Lower Devonian granites. This evidence does not itself imply that all the lamprophyres were intruded earlier than the more common and associated acidic minor intrusions. Clearly, there was possibly more than one phase of minor intrusion activity, although until further investigation, it is presently thought that the lamprophyres are spatially but not temporally related to the acidic minor intrusions and the post-orogenic granites. The geochemical relationships are discussed below in sections 4.4 and 4.5.

The evidence for the age of the acidic intrusions is based upon field criteria, there being no absolute dating available for these minor intrusions in north England. Their disposition and petrological character suggest that they are mainly related to the Lower Devonian granite plutons. Apart from minor aplitic dykes, acidic minor intrusives are not seen to be emplaced in the host plutons suggesting that they are before or contemporaneous with the granite emplacement or that the cooling granite was a physically unsuitable medium for minor intrusions. This is in contrast to the Hercynian granites of southwest England where Darbyshire and Shepherd (1985) dated the major granite types to establish a chronology for the granite magmatism and associated mineralisation. They found that many of the associated quartz porphyry dykes (known locally as elvans) cross-cut the granite plutons and have an age range of some 10 million years and which were generally younger than the range of ages for the plutons. The aplites have ages similar to the elvans. They concluded that the elvans were not intruded as a single episode and that the distribution of elvan directions is related to the master joint configuration in the plutons. This evidence indicates that for these batholithic plutons their associated acidic dykes were emplaced after the plutons' emplacement and initial cooling. A problem then arises as to the source of this volume of granitic liquid given that the pluton was essentially consolidated.

Considering the extent and exposure of the Cumbrian granitic batholith, there appears to be a paucity of expected associated acidic minor intrusions. This is due in part to the often limited rock exposure in many areas due to coverings of drift and head along with the state of survival of intrusions, many now being in poor condition due to surface weathering. Given these limitations however, and, knowing that the acidic intrusions are likely to be found near to rather than away from pluton margins, regions about the roof zones of these plutons might be expected to contain more plentiful minor intrusions. The Skiddaw Granite of the northern Lake District has a broad, flattish roof zone, thinly covered (0-150m) by Skiddaw Slates. Detailed mapping of this area shows that minor intrusions are notably scarce (Eastwood et al 1968, Barratt 1968). Small quartz veins and aplitic offshoots are found as apophyses to the granite but less than a dozen small, acidic dykes have been mapped in a region of about 50 sq.km. Some of these dykes are found emplaced into the adjacent Carrock Fell igneous complex, which is composed of massive gabbros and granophyres. This would indicate that the intrusions do not appear to have a preference for emplacement into the much deformed sediments of the Skiddaw Slate Group as might be expected. From such evidence, it appears from the location of acidic minor intrusions is not simply a function of proximity to the host granite pluton. This factor is exemplified by the common occurrence of acidic dykes at Cross Fell (approximately 100 in number) although this region is some 2-3 km above the conjectured flanks and roof zone of the Cumbrian Batholith (Bott 1974). Brief comparison of the age and structural state of the various areas where minor intrusions occur shows that the extent and character of deformation of the host rocks of the intrusions does not appear to be a major factor in the distribution of the intrusions. It is also apparent that the style or mode of emplacement of the granite plutons did not involve the emplacement of minor intrusions as precursors or as a marginal 'front' to the upper zones of the major intrusions. This indicates that the generally sharp cross-cutting margins of the Shap Granite, with little or no evidence of stoping and/or dyke-like injection of material, along with the slight 'shouldering' of the aureole zone (Chapter 2.2.5) typifies the intrusive style of the post-orogenic granites at this crustal level.

The distribution of the minor intrusions examined about the Shap Granite is shown in Fig.4.1. It also shows the course of the two underground pipelines in which Redfern (1979) encounted some new exposures of intrusions. The Shap intrusions are all thought to be dykes rather than sills, this being in contrast to Harker and Marr (1891) who described four dykes from Stakeley Beck as being distinctly sill-like. Many of the dykes are deeply weathered and detailed field descriptions are not profitable. Their distribution is somewhat radial about the granite and they are laterally impersistent. Given the limitations of exposure, they seem to be concentrated in a region trending N-NW to S-SE. This is not dissimilar to trends of intrusions recognised from other regions such as about Skiddaw (NE and NNW, Eastwood et al 1968) and around Haweswater (NNW to W, Nutt 1970). Some insight into the reason for this was indicated by Redfern (1979) who noted that most of the dykes were intruded along fault lines, some of which showed the effects of brecciation along dyke margins due to later movement. There is no evidence of permissive intrusion or tensional fracturing of the country rocks with the dykes being emplaced into the fault structures generated by the forceful intrusion of the granite, such as might be found in a sub-volcanic environment. Therefore, the weak radial distribution of the dykes at Shap is not generally considered to be related in any way to the process of distention of the surrounding country rocks by the granite as shown by the rotation of the regional cleavage trends in the aureole (Fig.2.8).

The relationship between the direction of faults and the trends of dykes had also been noticed by Wilson and Galligan (1927) on the Howgill Fells of eastern Cumbria and by Morrison (1919) to the south of Shap. It appears that the dyke trends are related to the end-Silurian Caledonian fault system of Cumbria which generally has trends from the NW to the NE (eg. Soper and Moseley 1978, pg.52). These usually have steep inclinations and the larger examples have regional displacements of upto 2km and upto 500m near Shap (Moseley 1968). This relationship of dykes to Caledonian faults is complicated in the northern Lake District because of earlier, pre-Borrowdale deformation found to occur in the Skiddaw Slate Group (Roberts 1971). However, it is probable that fault development occurred during and after the Caledonian folding and the associated regional cleavage since these faults commonly offset the fold axes. Furthermore, minor faulting along with renewed and reactivated movement on Caledonian structures occurred during the late or post Carboniferous times in relation to the mild effects of the Hercynian Orogeny in northern England (Soper and Moseley 1978). In the Shap area, such effects can be seen as brecciation of fault-bound dykes and faulting of the granite in the Pink Quarry (Plate 1.f) and in the gills running off the northern regions of the granite. Studies of faulting in the Carboniferous rocks of northwest England show that these faults also have NW-NE trends although it is not certain to what extent the similarity of the Hercynian trends to those of Caledonian age is a function of the influence of pre-existing Caledonian structures.

Where outcrop quality permitted, dyke samples were collected for petrological examination and chemical analysis from the outcrops shown in Fig. 4.1. These samples were supplemented by a few specimens collected by Redfern from the tunnel sections. Apart from where the tunnels cross Stakeley Beck, no tunnel dyke exposures had adjacent surface outcrops directly above although some lateral connections could be made especially around Red Crag. Included in this study, but from outside the study area and not shown in Fig.4.1, is a dyke from Fairy Crag (GR 536161), some 6km. north of the granite near to the village of Rosgill. This intrusion occurs as a large outcrop adjacent to the confluence of Swindale Beck and the River Lowther. It is intruded into Skiddaw Slates and was estimated by Harker and Marr (1891) to be upto 35m in width, although present outcrop appears to be less than this. This dyke was sampled as a good example of an intrusion away from the granite and it's larger than normal width had resulted in it being noted in previous studies (eg. Harker and Marr, op cit and Nutt 1970).

A phenomenon noted by other workers is the limited occurrence of composite dykes. Lamprophyres containing felsic portions and vice versa have been described by Arthurton and Wadge (1981) as well as basic dykes intruded with and/or cross-cutting acidic dykes (eg.Wilson and Galligan 1927). Less common than these type of occurrences are the true composite dykes, usually with basic outer and felsitic inner portions. A good example at Shap occurred where the gas pipeline crosses Stakeley Beck. It was described by Morrison (1919) and Redfern (1979) as being an outer lamprophyre with an acidic interior of quartz felsite. Little remains of this dyke due to the tunneling operations although fragments of both components can be found scattered in the beck bottom. Such evidence of intimately associated acid and basic dyke compositions has been used as evidence of consanguineous coexisting magmas at the time of the pluton's emplacement involving models of hybridisation and the generation of acidic liquids from basic or lamprophyric magmas (eg. Arthurton and Wadge 1981).

4.3 Dyke Petrology.

4.3.1 Introduction.

Prior to describing the Shap dykes, a few notes on the general classification of these minor intrusions will be made. These comments will be restricted to intrusions of calk-alkaline composition as opposed to those of more alkaline or tholeiitic trends. This is particularly relevant when discussing the lamprophyres which can occur as alkaline (eg. camptonites), melilitic (eg. alnoites) and calk-alkaline groups (Rock 1984, Streckeisen 1979). Partly, the reason for this discussion is that it is thought that many of the basic dykes described from N.W. England and termed lamprophyres are in fact of a more intermediate rather than basic character being of dioritic affinities. Traditional classification of lamprophyres such as that outlined in Hatch, Wells and Wells (1968) is based upon the identification of the relative proportions of feldspar along with biotite and/or hornblende (usually as phenocryst phases) as outlined in Table 4.1 below;

By definition, lamprophyres are basic rocks (typically 40-52 wt% SiO_2) containing essential biotite and/or amphibole and/or clinopyroxene along with feldspars restricted to the groundmass (Rock 1984). Many have no compositional equivalent to the commoner volcanic or

Table 4.1 Modal Classification of Calk-Alkaline Lamprophyres

A. Traditional (eg. Hatch, Wells and Wells, 1968).

	Biotite	Hornblende
Orth> Plag	Minette	Vogesite
Plag> Orth	Kersantite	Spessartite

B. Modern (eg. Rock, 1984).

a. May contain Amphibole, Biotite=Fe-Phlogopite, Clinopyroxene,Olivine as main mafic phases.
b. Although basic in composition, may contain plentiful hydrous phases, quartz, calcite etc.
c. Strongly zoned minerals commonplace.
d. No feldspar phenocrysts.
e. Plagioclase composition less anorthitic than expected ie. An 10-40.

plutonic rocks such as basalt or gabbro. Neither are they simple varieties of these commoner rocks as many lamprophyres contain significant amounts of primary minerals such as apatite, calcite and quartz these not being normal constituents of basic calk-alkaline rocks. Many of the basic dykes of N. England described as lamprophyres have phenocryst assemblages of feldspar along with biotite and/or hornblende and, consequently, have been termed kersantite, spessartite etc. as in Table 4.1.A above. Description and analysis (eg. Arthurton and Wadge 1981) has shown some of these to be of a more intermediate character and not true lamprophyres. They should be strictly termed micro-diorite, -tonalite or -granodiorite. Dykes typical of these compositions occur about the Southern Uplands Granites and vary from microtonalite to quartz porphyry (microgranite) ranging from 62 to 74 wt.% SiO2 (R.Fuge pers.comm.). Those of intermediate compositions (<66% SiO2) are termed porphyrites and contain phenocrystal hornblende, biotite, plagioclase (An 40-10) and sphene. They are directly equivalent to the intermediate portions of the associated composite granitic plutons. By traditional classification (ie. Table 4.1) they could be called lamprophyres though this would be in error. Therefore, especially if phenocryst feldspar be evident, it is recommended that care should be taken when describing basic to intermediate minor intrusions and not simply classify them as in Table 4.1.A and call them lamprophyres but, to name them based upon the volcanic/plutonic equivalent unless contrary evidence is clear.

4.3.2 Field Description.

Apart from at Red and Fairy Crags, the Shap dykes are narrow (<2m.) in width and laterally impersistent, this factor being in part due to many dykes being offset by faulting (Fig.4.2, Plate 1.h). The more acidic varieties tend to be wider than the basic, though this may be due to the acidic dykes being more resistant to weathering. They are simple, steep-sided intrusions with straight, cross-cutting contacts, having little effect on the country rocks, either as physical disruption or contact metamorphism. The largest local dyke is Red Crag which Redfern (1979) noted in a tunnel section as being upto 8m wide and, although faulted on it's S.W. side, had a clear igneous contact on the N.E. side with an associated chilled margin and contact metamorphic effects upto 3m into the surrounding Silurian siltstones. The very wide dyke at Fairy Crag has poorly exposed contacts but contains small xenoliths of the local Skiddaw Slates, xenoliths not being a common feature of the dykes in general.

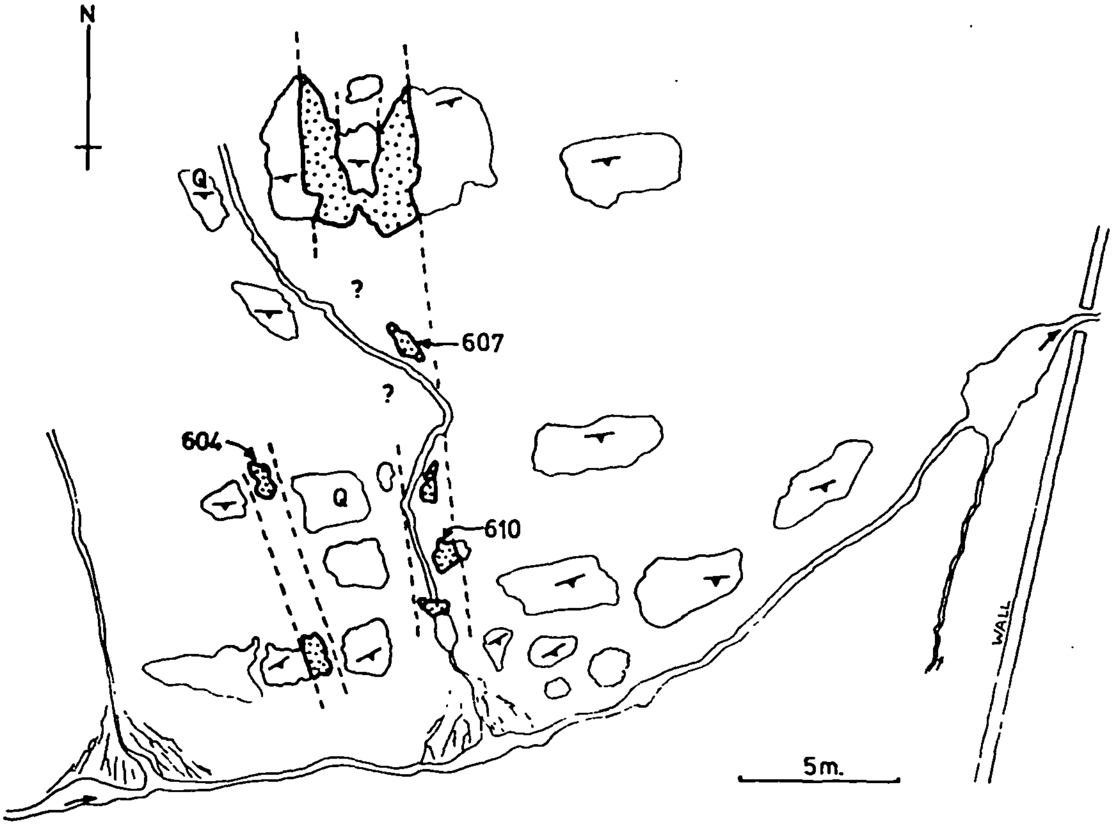


FIG. 4.2

Typical dyke exposures immediately west of Wasdale Farm, with narrow impersistent outcrops of dyke emplaced into the Upper Ordovician rocks.

Q - Quartz veins.

⊥ - Fabric trends in country rocks.

604, 607, 610 - Sample numbers.

(GR 548081).

PLATE 9.

PLATE 9. DYKE PETROLOGY AND PHOTOMICROGRAPHS.

a. Quartz-feldspar microgranite dyke with rare mafic content and poorly developed orthoclase phenocrysts in a very fine grained groundmass.
(GR 555113)

b. Feldspar microgranite. Orthoclase and plagioclase phenocrysts in a medium-grained dark grey groundmass.
(GR 571076)

c. Red-pink feldspar microgranite showing very variable phenocryst development.
(GR 545105)

d. Quartz, biotite and plagioclase phenocrysts in a very fine-grained felsitic matrix. Apart from the quartz all phases have undergone hydrothermal alteration.
(Slide No. 39909) (XPL)

e. Large euhedral biotite phenocryst in plagioclase-biotite-orthoclase-quartz granular and microphenocrystic matrix.
(Slide No. 39908) (PPL and XPL)

f. Strongly pleochroic phenocryst and groundmass biotite, typical of the less acidic dykes. Note also zoned plagioclase phenocyst (Pl).
(Slide No. 43122) (PPL)

g. Zoned brown allanite intergrown with altered biotite and sphene phenocrysts.
(Slide No. 43121) (PPL)

Scale Bar as in Plate 8.

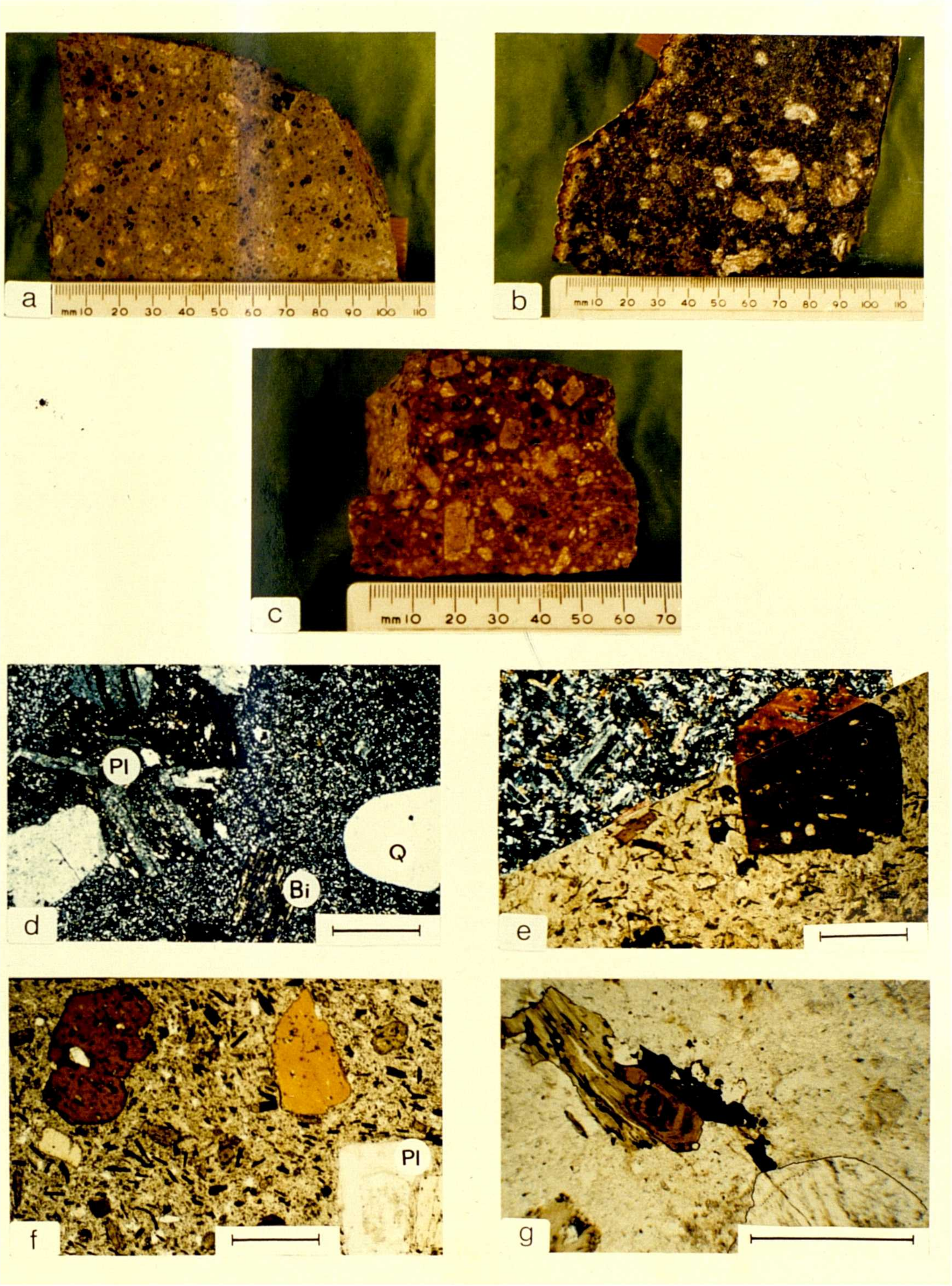

a
mm 10 20 30 40 50 60 70 80 90 100 110
b
mm 10 20 30 40 50 60 70 80 90 100 110
c
mm 10 20 30 40 50 60 70
Pl
Q
Bi
d
e
Pl
f
g

PLATE 9

The dykes vary in colour from cream through shades of orange, brick-red, pink and purple to grey (Plate 9.a,b,c). All contain recognisable phenocrysts they being one or more of orthoclase, plagioclase, quartz and biotite. The groundmasses are also very variable in texture being fine-grained, almost glassy to medium-grained and granular. Most, as expected, are acidic in character, with the coarser examples appearing similar to the Shap Granite, some with well-developed orthoclase phenocrysts showing twinning and perthite development. The less acidic varieties show a preponderance of smaller, whitish plagioclase phenocrysts in a greyer groundmass in contrast to the more acidic dykes which are often very reddish in colour and contain plentiful rounded grains of quartz. These more acidic varieties constitute over 70% of the samples, many of these being considerably more quartz-rich than the granite. Rarely, phenocrysts are almost absent. This may be due to rapid cooling on emplacement, but some of these aphyric dykes are granular in texture and are not dissimilar to the larger aplites found in the granite suggesting a less rapid cooling interval. Biotite phenocrysts and, to some extent, those of plagioclase, are the most altered and, consequently, it is difficult to assess the extent of biotite development in hand specimen, but as expected, these two are the dominant phenocrysts with increasing modal orthoclase and quartz in the more acidic dykes. This trend apart, the modal phenocryst content of plagioclase almost always exceeds that of biotite, whatever the overall dyke composition. Scattered development of secondary minerals such as calcite, white mica and sulphides can also be seen in many samples.

All the dykes appear to be in the range microgranodiorite to microgranite with no evidence of lamprophyres. Most of the dykes would be traditionally termed quartz or feldspar porphyries or felsites although this gives little indication of the range of dyke types as most contain phenocryst feldspar and could thus be called felsites. Grouping into types is difficult , but a simple division can be made between those dykes containing and those lacking quartz phenocrysts. Near to the granite, orthoclase phenocrysts are common but become less so away from the granite until at about 4km. distance they are poorly developed even in the more acidic dykes (this work, Morrison 1919). Orthoclase also appears in more variable colours than the pink form in the granite and as a consequence, identification between phenocrystal orthoclase and plagioclase is often difficult, especially as they can also be found as mixed glomerocrysts! Arthurton and Wadge (1981) divided the microgranites of the Penrith area firstly, on the basis of the presence or absence of quartz phenocrysts and secondly, on the presence of muscovite. This is not thought to be particularly useful as much of the muscovite is unlikely to be of primary origins and may relate to the extent of phenocryst alteration (esp. biotite) or hydrothermal effects rather than the overall original composition of the dyke. Certainly primary muscovite is found in the most acidic dykes, but, most of the mica in the dykes is biotite or its alteration products (eg. chlorite) and therefore it is possible that some of the muscovite-bearing dykes are more intermediate in character than they might appear. It is suggested that divisions should be made, where possible, between biotite + plagioclase, plagioclase + orthoclase (±biotite,quartz) and, orthoclase + quartz (±mica), the appearance of quartz phenocrysts and the lack of plagioclase being suitable broad group divisions.

There appears little textural variation across the dykes such as the distribution of phenocrysts and flow alignment of phenocrysts is also rare. The proportion of phenocrysts in any particular dyke does not correlate with dyke size or composition, except prehaps at the most acidic compositions where phenocrysts are less plentiful. The general lack of textural variation in the dykes is due to their small size and, as a consequence, their rapid cooling. Larger intrusions, involving considerably more magma and much slower cooling times, would no doubt develop more variable internal textures along with chilled margins and contact metamorphism. What is evident, is that these dykes were intruded as liquids and, due to their rapid cooling, were probably carrying some phenocrysts that had already crystallised in the parental magma.

4.3.3 Thin Section Description.

Some 33 dyke sections have been examined and are summarised in table form in the Appendix. Lengthy descriptions were given by Morrison (1919) and only a briefer description is given here to outline the important petrological features. As previously mentioned, the dykes are composed of the same minerals as found in the granite. Phenocrysts are of quartz, plagioclase, orthoclase and biotite set in a groundmass of the same along with chlorite, muscovite, apatite, magnetite, sphene, calcite, pyrite and allanite. Three distinct groundmass textures exist, granular, microphenocrystic and spherulitic, the former being the most prevalent, although two or all three of these may appear in one sample (Plate 9, 10).

Biotite phenocrysts are more plentiful in the less acidic dykes and at the same time, are also of a more red-brown colour suggesting that they are of a more Ti-rich composition (Deer,Howie and Zussman 1966). Where plentiful, they dominate the phenocryst assemblage and ,along with the associated groundmass biotite, can make upto 30% of the mode. The possible occurrence of hornblende with the biotite at these more basic compositions is not found. Inclusions in the biotite may be apatite, zircon and sphene. Alteration of biotite is commonplace resulting in secondary chlorite along with calcite, sericite, leucoxene, Fe-Ti oxides and more rarely, iron sulphides. The extent of alteration is very variable even within individual samples although it usually progresses along the cleavage with the ensuing volume increase causing distention of the cleavage planes. Extensive alteration results in complete chloritisation which starts as isomorphous alteration but may result in large pale green clots of fibrous chlorites. Examples of deformed biotite phenocrysts is not uncommon with grains bent, split or showing fracture zones (Plate 10). These deformations suggest that these phenocrysts had formed prior to the final emplacement of the dyke, the deformation being caused by fluxion in the dyke magma before consolidation. This would imply that some of the dykes may have been emplaced as crystal-liquid mixtures as opposed to completely crystallising when finally emplaced.

Plagioclase phenocrysts occur as glomerocrysts (Plate

PLATE 10.

PLATE 10. DYKE PHOTOMICROGRAPHS II

a. Quartz phenocrysts with narrow fine-grained rims in felsitic granular groundmass, typical of the most acidic dykes.
(Slide No. 39921) (XPL)

b. Quartz phenocrysts in a devitrified glassy groundmass.
(Slide No. 43134) (PPL)

c. Quartz phenocrysts surrounded by spherulitic groundmass of felsitic composition.
(Slide No. 39903) (XPL)

d. Quartz and plagioclase phenocrysts with spherulitic rims in a granular groundmass.
(Slide No. 39952) (XPL)

e. Pseudomorphed plagioclase phenocryst now composed of chlorite with minor albite and quartz.
(Slide No. 43132) (PPL)

f. Altered phenocryst biotite and large granular calcite (CC) clot. Note the distention of the biotite cleavage and replacement of biotite by calcite, but also that much of the adjacent biotite appears unaffected.
(Slide No. 39910) (XPL)

g. Quartz-calcite infills to hydrothermal fractures.
(Slide No. 43121) (PPL)

h. Bent, fractured and chloritised biotite phenocrysts in granular microgranitic groundmass.
(Slide No. 39911) (PPL)

Scale Bar as in Plate 8.

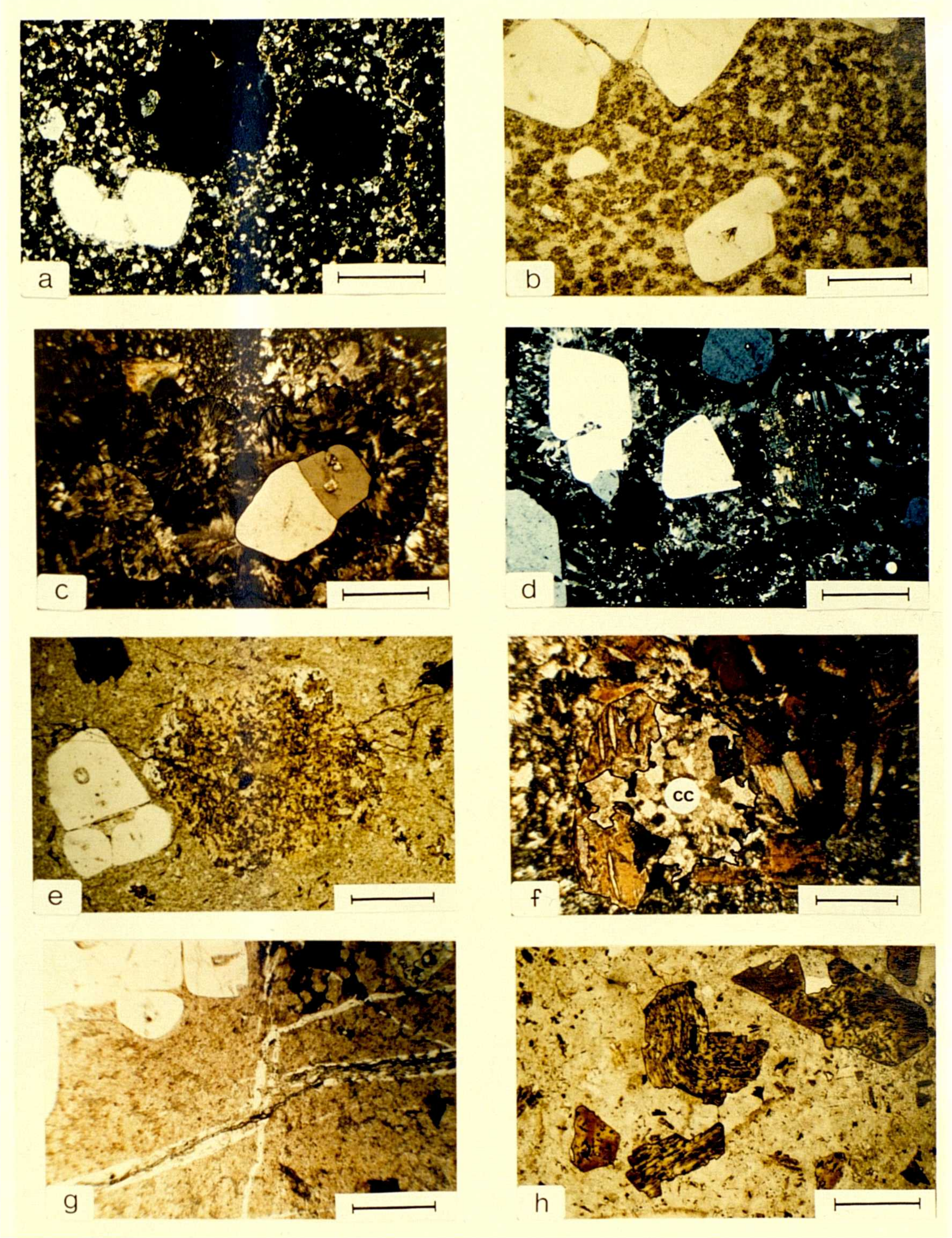


PLATE 10

9.d) as well as individual grains and are mainly in the composition An30-10 though rarely attain An40. Many have overgrowths of clear albite or orthoclase especially in the more acidic dykes. Twinning is usually combined Carlsbad-albite and there is often well developed oscillatory normal zoning, highlighted by zones of secondary sericitic alteration. The phenocrysts may overgrow small biotite phenocrysts and have quartz inclusions in the outer portions of the plagioclase sometimes aligned with the cleavage of the feldspar. As with the biotite, secondary alteration of both phenocryst and groundmass plagioclase is commonplace with the development of albite, calcite, chlorite, quartz and sericite. With increasing acidity plagioclase phenocrysts become restricted and orthoclase appears. Well developed orthoclase phenocrysts are not common except in the most acidic dykes. Arthurton and Wadge (1981) say that this is because these are particularly altered but, as shown in the granite and in the Shap dykes, this does not appear to be the reason. It is thought that the reason is that the orthoclase phenocryst development was generally limited with orthoclase growth being late in a dyke's consolidation and as a consequence, mainly restricted to the groundmass. Orthoclase phenocrysts appear similar to those in the granite showing perthite development, Carlsbad twinning and inclusions of small biotite and plagioclase grains and plentiful quartz blebs. In these more acidic dykes, with decreasing biotite and plagioclase, quartz joins orthoclase as a phenocryst phase, it being very variable in size and often occurring as clots or glomerocrysts (Plate 10). It is rarely the sole phenocryst phase and they are generally rounded in shape with embayed or resorbed margins and often surrounded by very fine-grained groundmass or radiating clusters of feldspar (orthoclase) and quartz mixtures (Plate 10.c).

Other phenocrysts are not common although muscovite can be found in the most acidic dykes, forming after the feldspar. It is more common in the groundmass or as an alteration product. Early formed small phenocrysts of apatite, zircon, sphene, allanite and magnetite are also seen (Plate 9.g). The groundmass may contain all the previously mentioned minerals though quartz and feldspar dominate. Arthurton and Wadge (1981) suggest that groundmass quartz is present only in rocks that contain quartz phenocrysts, but this does not appear to be the case at Shap. All but one (sample 521) of the thin sections examined across the composition range contain quartz no doubt promoted in the more basic dykes by the crystallisation of biotite which has a lower SiO_2 content (35-40%) than its host magma. Groundmass textures are usually a mixture of lattice-like biotite or feldspar microphenocrysts set in a granular felsic matrix. The plagioclase is usually more albitic than the equivalent phenocrysts. Other textures include equigranular mosaics of quartz and feldspar as well as spherulitic and devitrification structures (Plate 10). Based on the above textural evidence, the order of crystallisation in the dykes is thought to be plagioclase, biotite, (allanite?), orthoclase, quartz and muscovite with the minor phases such as apatite, zircon and sphene probably preceding all the major phenocryst phases. There is no evidence of the involvement of hornblende.

Alteration appears in all the samples to a varying extent, mainly affecting the phenocrysts but also the groundmass. Chlorite, calcite, white mica, quartz and pyrite are the most common secondary minerals and they are also associated with late-stage veining (Plate 10.g). This alteration is restricted to within the dykes and unaffects the wall rocks, it being caused by autopneumatolysis as volatiles are released during the emplacement and relatively rapid cooling of the dyke magmas. The extent of alteration, veining or the type of groundmass texture shows no consistent variation with dyke size or composition, suggesting that the dykes were emplaced and underwent cooling at differing rates.

4.4 Dyke Geochemistry

4.4.1 Introduction

Some 28 dykes, including 8 from the Redfern collection, were analysed for major and trace elements and the data are listed in the Appendix and in Figs. 4.3a-e. They range from 51 to 77 wt% SiO2, although the majority are of similar or more acidic compositions to the Shap Granite being microgranodiorites and granites. They correspond in range to the granite and its aplites, there being a weak bimodal distribution about 67 and 74 wt% SiO2. Comparison with the granite-aplite data shows a good overlap and an extension of the chemical trends shown by the granite in Chapter 3. Variation in the extent of alteration and phenocryst development results in a wider scatter of the data but the trends are still readily apparent. This supports the idea that the secondary alteration was essentially isochemical and because of this, inferences can still be made concerning

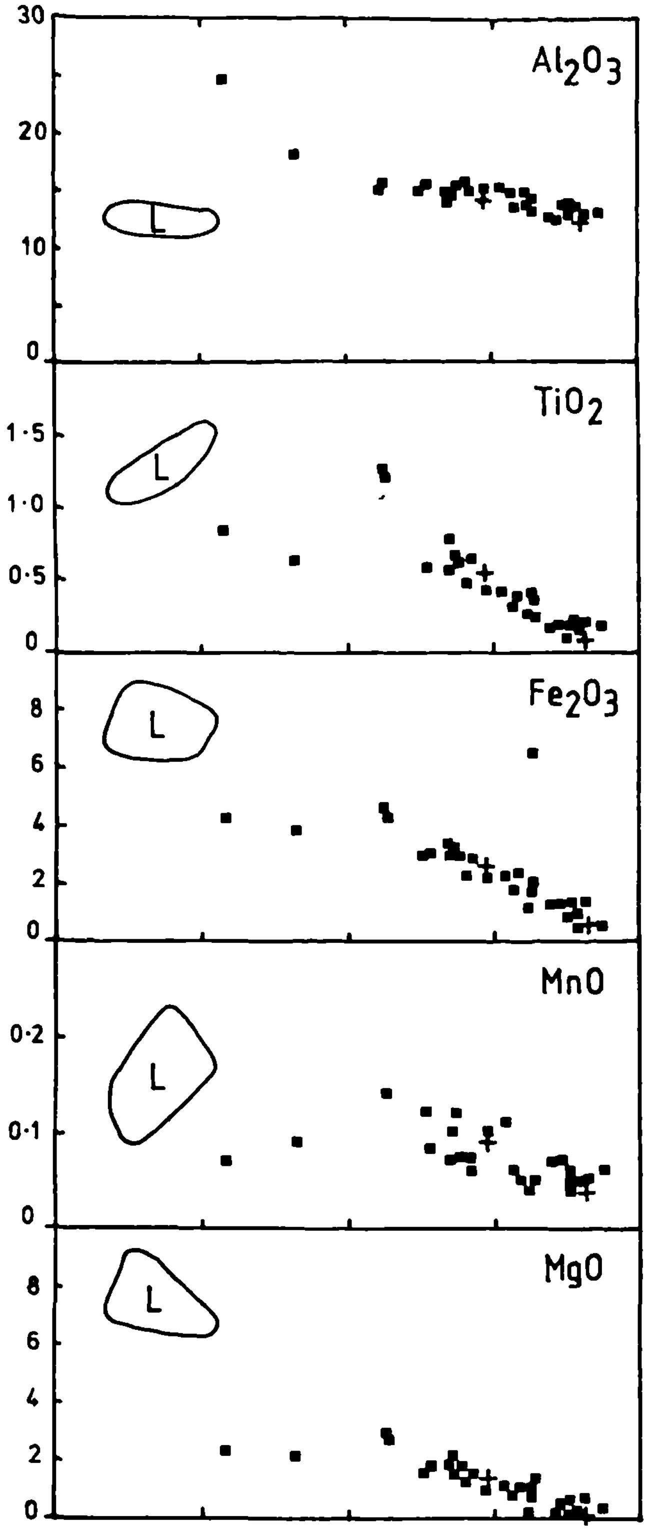


FIG. 4.3a

Dyke Analyses. SiO2 - Major Oxides.

Also shown is the field of typical lamprophyres (L) from **Appendix Table B.4** and the positions of average granite and aplite (+).

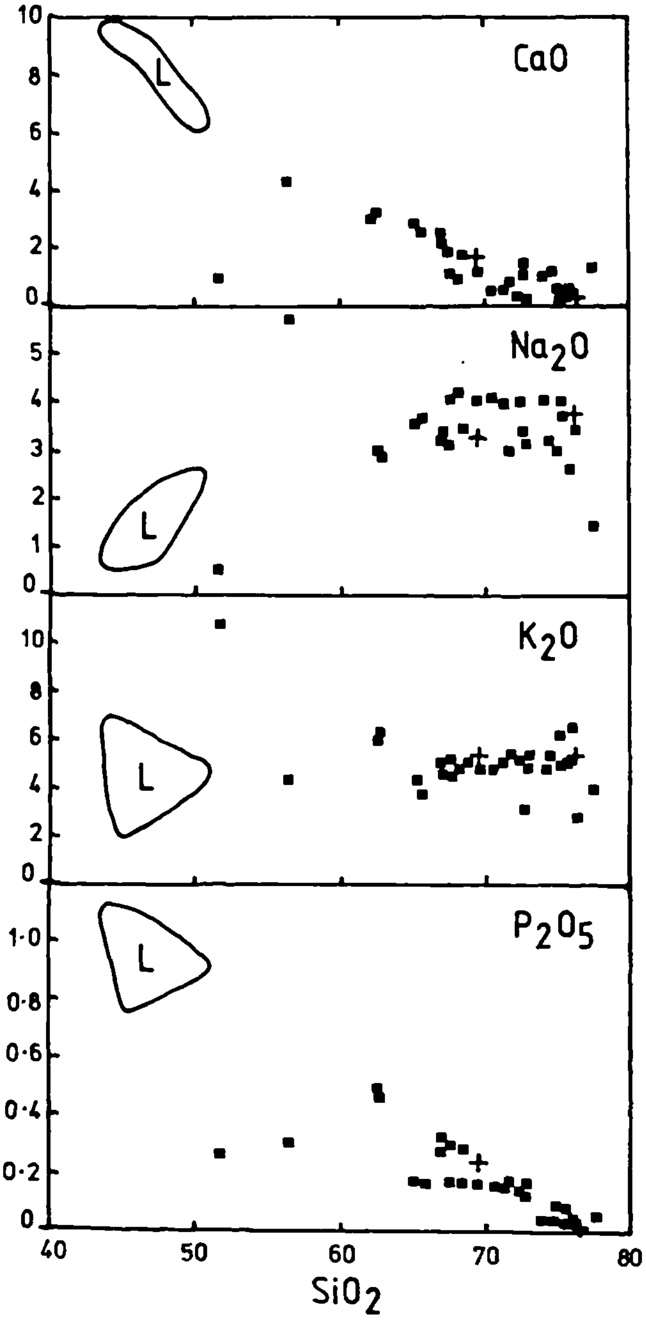


FIG. 4.3b

SiO2 - Major Oxides (continued).

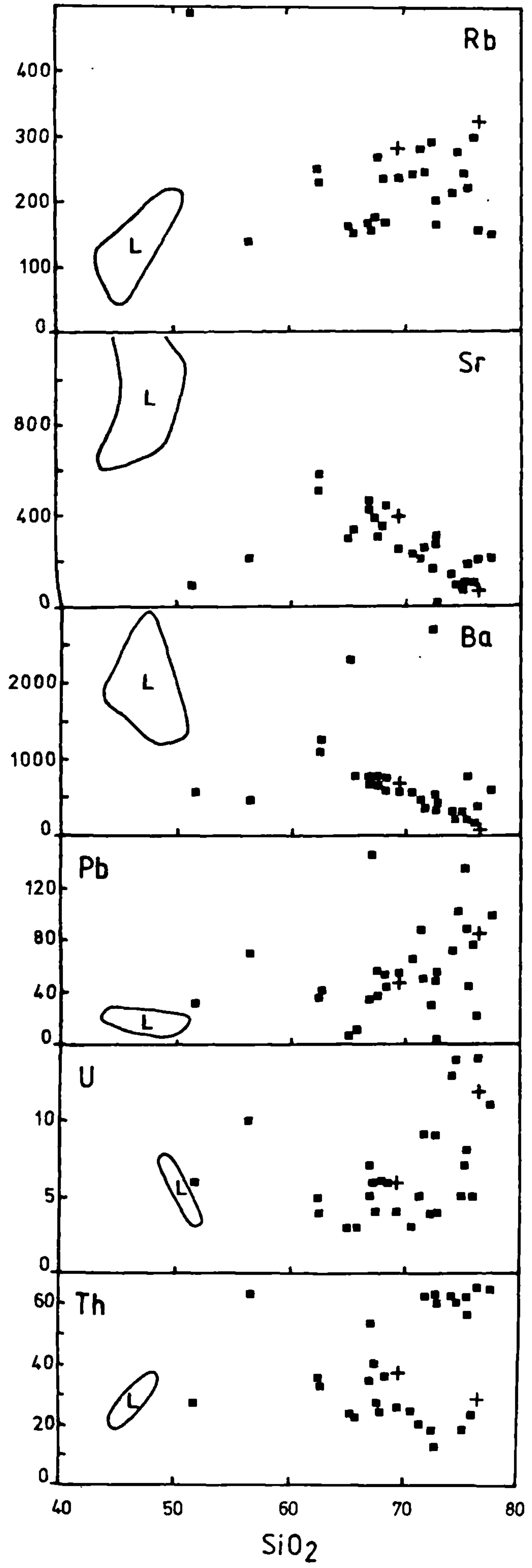


FIG. 4.3c

SiO2 - Group 1 (LFS) elements.

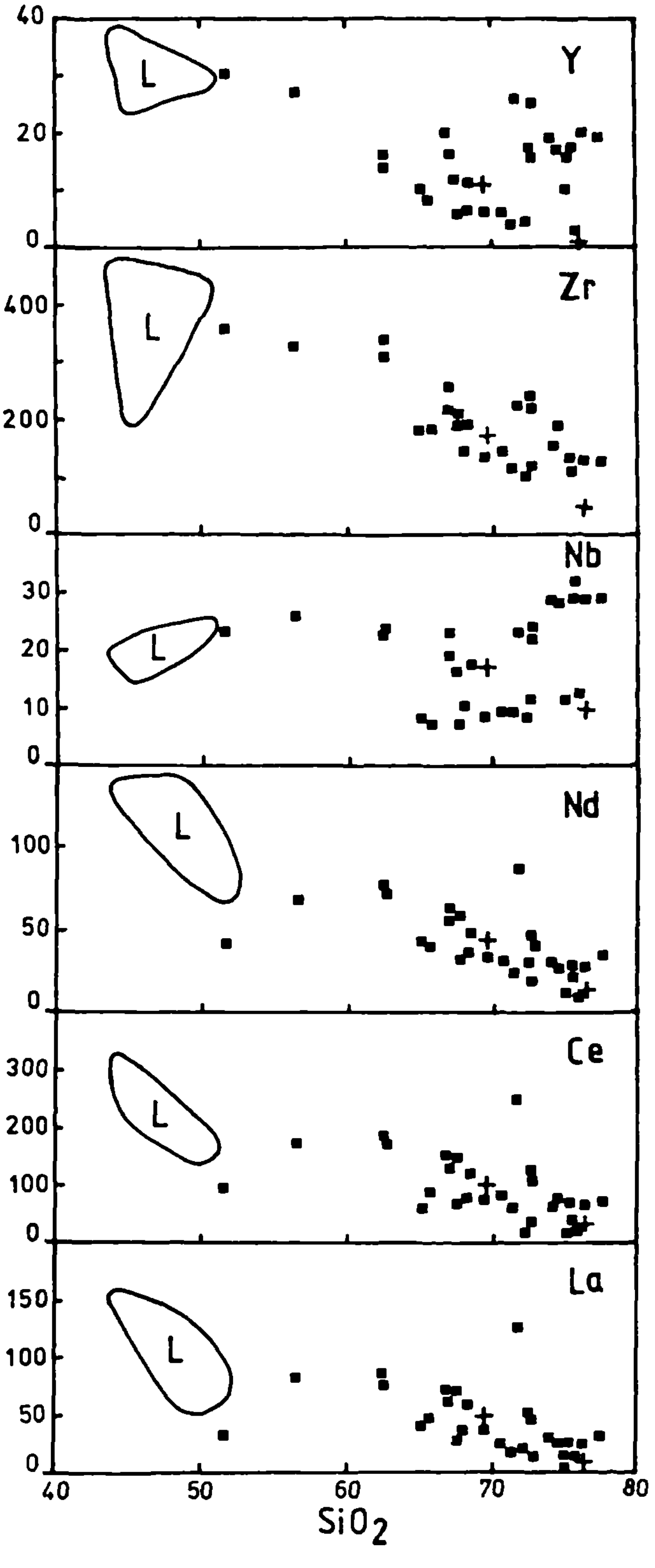


FIG. 4.3d

SiO2 - Group 2 and 3 (HFS/REE) elements.

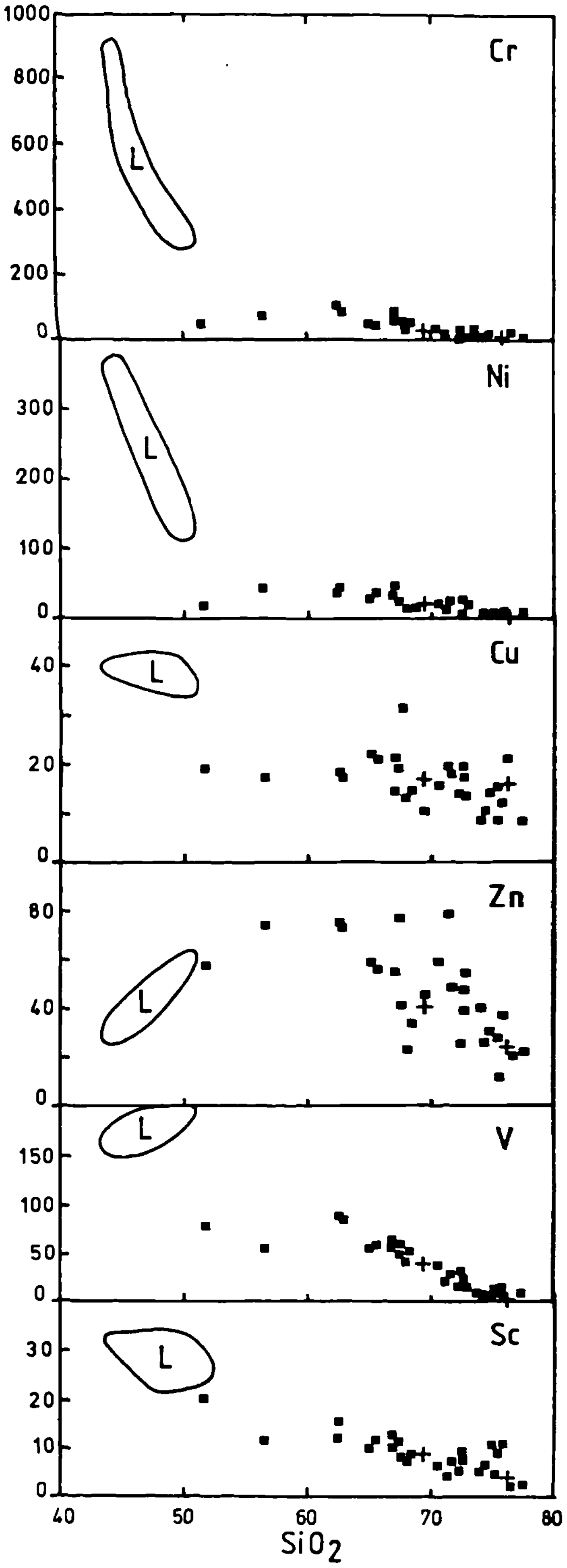


FIG. 4.3e

SiO2 - Group 4 (Transition Metal) elements.

the geochemical character of the dyke and granite magma.

4.4.2. Major Elements.

The main group of dykes varies from 65% (614) to 77% (609) SiO_2 with no obvious compositional gap as seen between the granites and the aplites. Samples 608 and 611 have a slightly lower (62%) SiO_2 content but correspond well with the main trends and, occurring close to the granite, are likely to be direct offshoots of the pluton and as such, probably define an approximate lower SiO_2 limit to the possible range of granite magma compositions found at this structural level. Similarly, 77% SiO_2 represents the most evolved magma compositions found at Shap, not dissimilar to that of the late-stage aplites. The two most basic samples (521,514; 51 and 56 wt% SiO_2 resp.) are anomalous when compared to the main dyke trends. Sample 514, described as a lamprophyre by Redfern (1979), does not relate to the field of typical lamprophyres but has a composition more alike the microdiorites or porphyrites associated with the granites of southern Scotland (R.Fuge, pers.comm.). It has particularly high Na_2O and slightly lower TiO_2, Fe_2O_3, MnO and MgO than expected suggesting partial chemical alteration. Similar arguments can be used to explain 521, this sample perhaps being an altered lamprophyre having very low CaO combined with very high K_2O (10.8%). These samples apart, the main trends all support those shown by the granites, being typical of calk-alkaline fractionation with decreasing Al_2O_3, CaO, P_2O_5 and transition metal oxides along with weakly increasing alkalis. Lack of evidence of amphibole suggests that these trends are likely to mainly be a function of biotite and plagioclase development.

4.4.3. Trace Elements.

The Group 1 elements (LFS) show a wide scatter against SiO_2 although generally confirm the trends shown by the granites, especially by Sr and Ba (-ve correlation) and to a lesser extent, Rb (+ve correlation), supporting the idea of biotite and feldspar controlling magma compositions. As in the granites, the dykes show high Pb levels (upto 145 ppm) though even at high SiO_2 levels have wide ranges in concentrations (0-135ppm) due partly to the variable extent of orthoclase development (the likely main carrier for Pb) and the effects of the secondary alteration.

The Group 2 elements (HFS) Zr and Nb along with the Group 3 (HFS/REE) elements show weak negative trends against SiO_2 along with large data scatter. As concentrations of these elements are controlled mainly by the minor mineral phases present (zircon, apatite, sphene, allanite etc.) data scatter will result due to small modal variations of these minerals. Above about 70% SiO_2, these phases are generally scarce but, discrete small grains of allanite can be found in many samples and where more prevalent, may cause high REE contents (eg 607).

The Transition Metal Elements (TME's) of Cr, Ni, V and Sc all occur at low concentrations but define negative trends with SiO_2, being a reflection of the low modal contents of mafic minerals apart from biotite. Cu and Zn also display weak negative correlations with SiO_2. Zn concentrations reach twice those found in the granites especially in the biotite-rich dykes, supporting the idea that this phase is the main carrier for Zn at these compositions. Zn and Cu levels are still significant (10-30ppm) in the more acidic dykes where biotite is less common indicating a second or minor carrier present, probably metal oxides or sulphides.

4.4.4. Normative Mineral Modes.

As with the granites, C.I.P.W. mineral modes have been calculated for the Shap dykes along with a selection of other minor intrusives from northern England. Fe3+/Fe2+ ratios have been estimated based on the analysis of available data of similar dykes including those of Arthurton and Wadge (1981), Rock (1984) and Fuge (pers.comm.). The ratio increases with wt% SiO2, from 0.5 at 50% to 1.4 at 75%, and the calculated norms are given in the Appendix. All the dyke data from Shap and elsewhere have been plotted on the normative diopside-corundum against wt% SiO2 diagram (Fig.4.4) as introduced in chapter 3.

The Shap dykes show a large scatter which corresponds with the fields of granites from Fig.3.7 and the fractionation trend shown by the S.U.G.'s. The lamprophyres display no trend, being very widely scattered. This is in part due to the role of CO2 in the norm calculation. Lamprophyres usually contain significant though variable amounts of CO2 which is allotted to CaO at the beginning of the norm calculation. This then results in immediate changes in the calculated amount of possible normative diopside (and anorthite) which is dependant on the available CaO. The lack of CO2 in more evolved compositions does not cause this possible early amendment in the norm calculation. Secondly, the lack of lamprophyre trends supports the fact that lamprophyric magmas are probably not the function of a

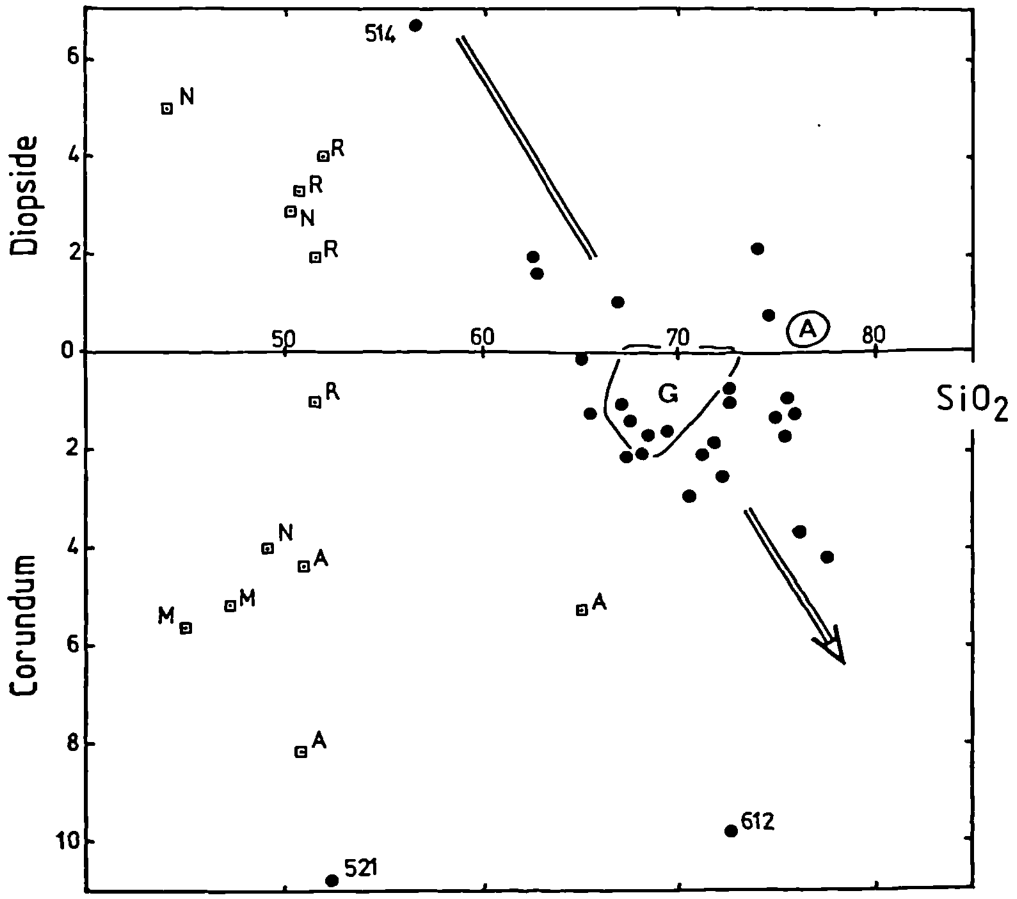


FIG. 4.4

Normative corundum-diopside against wt % SiO2.

The majority of the Shap dykes (●) lie about the field of Shap Granites (G) and aplites (A) and the S.U.G.'s trend (⟹) from Fig. 3.7

Northern England Lamprophyres (⊡) form an unrelated and very scattered low SiO2 region compared to the granitic dykes.

Data from	A	Arthurton and Wadge (1981) Burgess and Holliday (1979)
	M	MacDonald et al. (1985)
	N	Nixon et al. (1984)
	R	Rock (1984)

simple melt generation process or crystal fractionation but are generated in a way significantly differing from that of the Shap and other evolved dykes (see discussion below).

The array of the Shap dykes shows that the magma compositions are indeed controlled by biotite and feldspar (see also Fig.3.8). The most acidic dykes show some normative variation from the aplites. The aplites are all diopside normative, reversing an otherwise negative norm trend against increasing SiO2. Some dykes on the other hand continue to display increasing corundum normative trends, probably due to the decreasing modal biotite. The aplites lack biotite in contrast to some dykes which contain small (but significant) amounts of biotite or chlorite at these high SiO2 levels. Biotite growth can be suppressed by decreasing volatile levels during crystallisation of a granite magma. Most of the dykes had some volatile content (hence the hydrous primary and alteration minerals) in contrast to the aplites which were emplaced after granite magma consolidation. It is therefore thought that the dykes of similar composition to the aplites were wet melts relative to the essentially drier aplitic melts, the volatiles in the main Shap pluton being fixed into the secondary hydrothermal mineralisation and pegmatites. This implies that the most acidic dykes can be produced by simple crystal fractionation (mainly by biotite control) from the main granite magma, whilst the aplite composition is a function of the effects of the granite magma dewatering during cooling. It is also likely that these two differing evolved compositions were emplaced at differing times, the dykes being prior to the aplites.

4.4.5 Inter-Element Trends.

As mentioned in Chapter 3.3.1, the Southern Uplands Granites (S.U.G.'s) are used to compare possible fractionation trends over a range of compositions in plutonic granites at Shap. The composition range (56-75% SiO2) of the S.U.G.'s is similar to that of the Shap granites and dykes. The typical calk-alkaline trend of the S.U.G.'s is shown in Fig.4.5a and compares well with the somewhat restricted range of Shap granites (Fig.4.5b). When extended by the dyke data, the Shap trend is further enhanced (Fig.4.5c). The S.U.G. trend is attributed to magma evolution dominated by amphibole and plagioclase crystal fractionation (section 3.3.1.) but, even with the combining of all the Shap data, the AFM trend is unknown at low SiO2 values and, as such, it cannot be assumed that amphibole and feldspar fractionation has occurred. At more evolved compositions, amphibole control is less important and, as a consequence, the AFM diagram at higher alkali and lower MgO and FeO compositions becomes less sensitive. With this in mind, the data can be plotted to compare the trends of a suite of evolved rocks by using the incompatible trace elements which increase in content in such rocks. Bouseily and Sokkary (1979) used the triangular plot Rb-Sr-Ba to predict the differentiation path from diorites through 'normal' granites to 'strongly differentiated' granites. They showed that with plagioclase fractionation, Sr decreased along with a Ba increase until after granodiorite compositions when Rb rapidly increased due to biotite and orthoclase accumulation. Their diagram shows that the path of fractionation follows the outer portions of the plot,

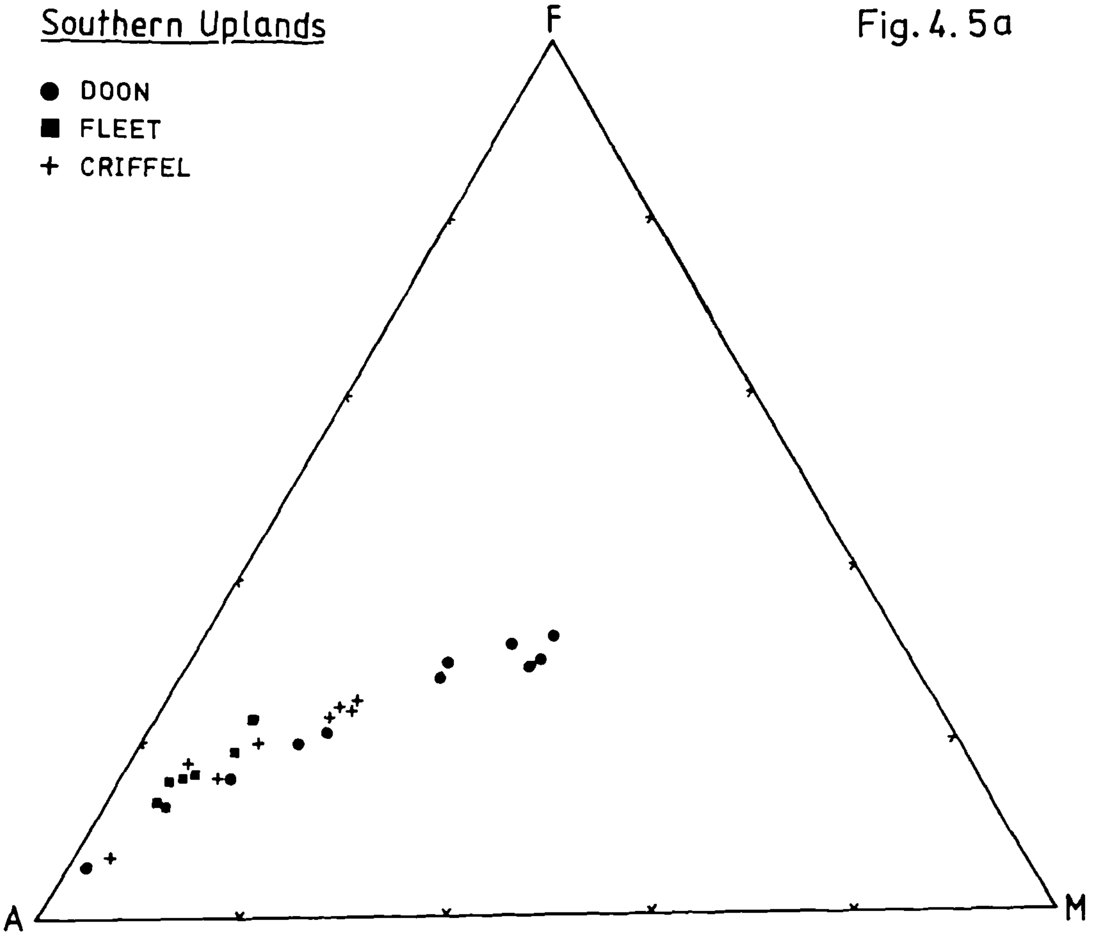


Fig. 4.5a

Southern Uplands

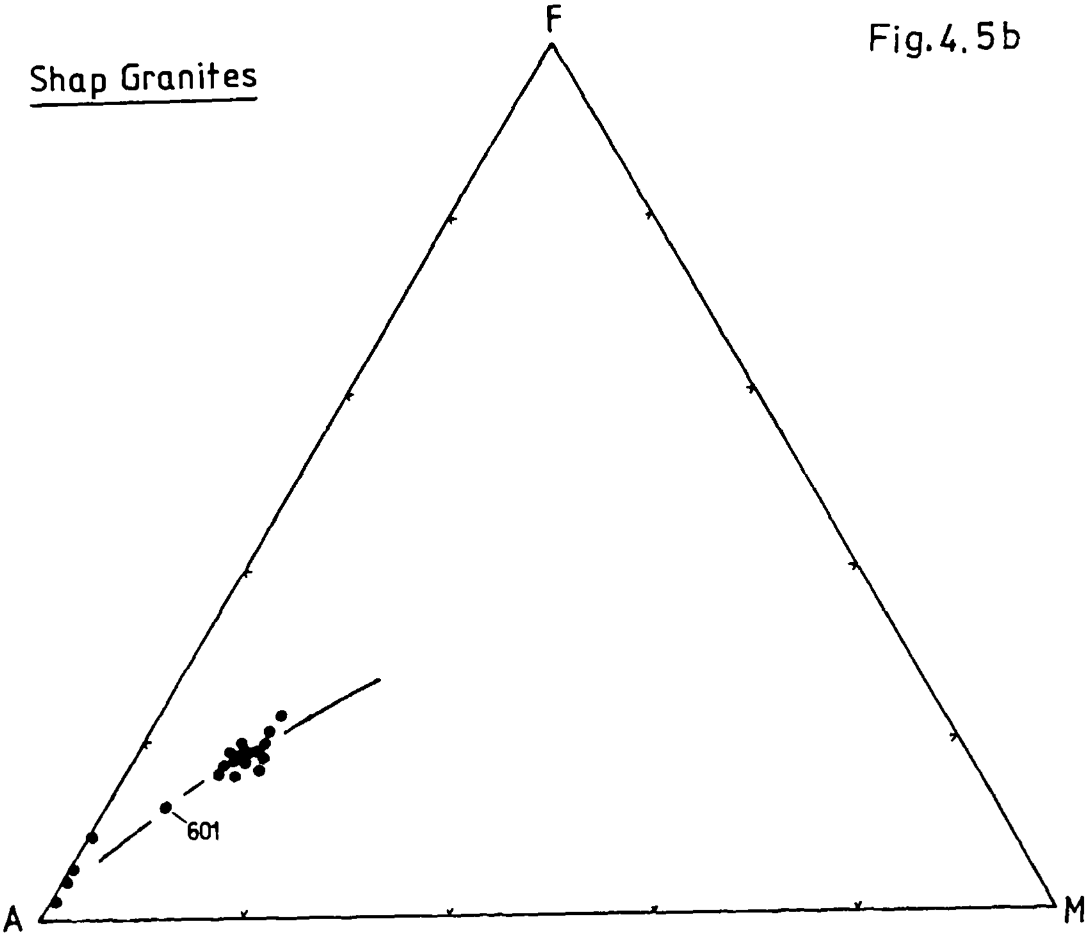
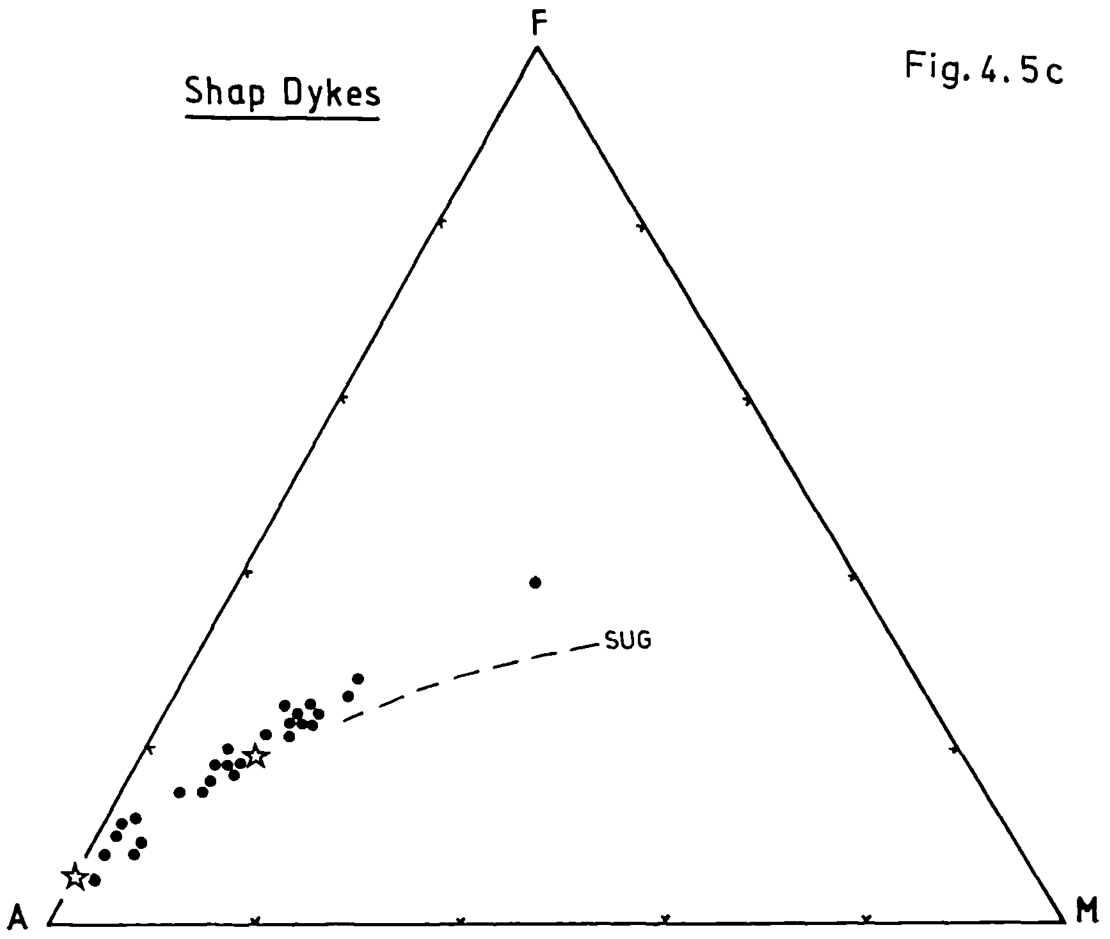


Fig. 4.5b

Shap Granites



FIGS. 4.5 a,b,c.

FIG. 4.5a

Typical calc-alkaline AFM trend of the Southern Upland Granites.

Data from Stephens and Halliday (1980), Parslow (1980) and Thirlwall (pers. comm.).

FIG. 4.5b

Limited trend shown by the Shap granites and aplites. Note the intermediate character of sample 601 (non-porphyritic granite).

FIG. 4.5c

AFM trend of the Shap dykes in comparison to that of the Southern Upland Granites (S.U.G.) and average Shap Granite and aplite (☆).

with 'anomalous' granites occupying the more central regions (Fig.4.6a). This is thought to be an unrealistic simplification of the actual case, their trend only occuring in cases of extreme fractionation in order to greatly reduce Sr levels along with the rapid increase in Ba concentrations over intermediate compositions. This is not typical of calk-alkaline fractionation and the more normal case is exemplified by the S.U.G.'s which define a broad arcuate trend over the range diorite to granite (Fig.4.6a). The region of extreme evolution resulting in aplites has been approximated using the limited trace element data for aplites which occur within various host granites such as those at Skiddaw (Barratt 1968), Weardale (Holland 1967) and Hercynian granites (Neiva 1975). The Shap granites plot adjacent to the S.U.G. field, but show little trend apart from increasing Rb at near constant Sr levels. Again the granodioritic nature of these Shap granites is expressed as generally higher relative proportions of Sr to Ba and Rb in comparison to the S.U.G.'s. The same can be said of the aplites which at even these extreme compositions are still Sr rich compared to the other aplite data. The dyke data on this plot again shows a large scatter (Fig. 4.6b). Much of the data occupies the regions of the Shap and S.U.G. granites as expected but a number of points are worth further comment. Firstly, the most evolved dyke compositions do not now compare well with the aplites but show lower Rb and Sr and higher Ba levels suggesting that these two types of evolved composition were produced by differing processes. Secondly, some samples have unexpectedly high Ba levels which tends to pull their

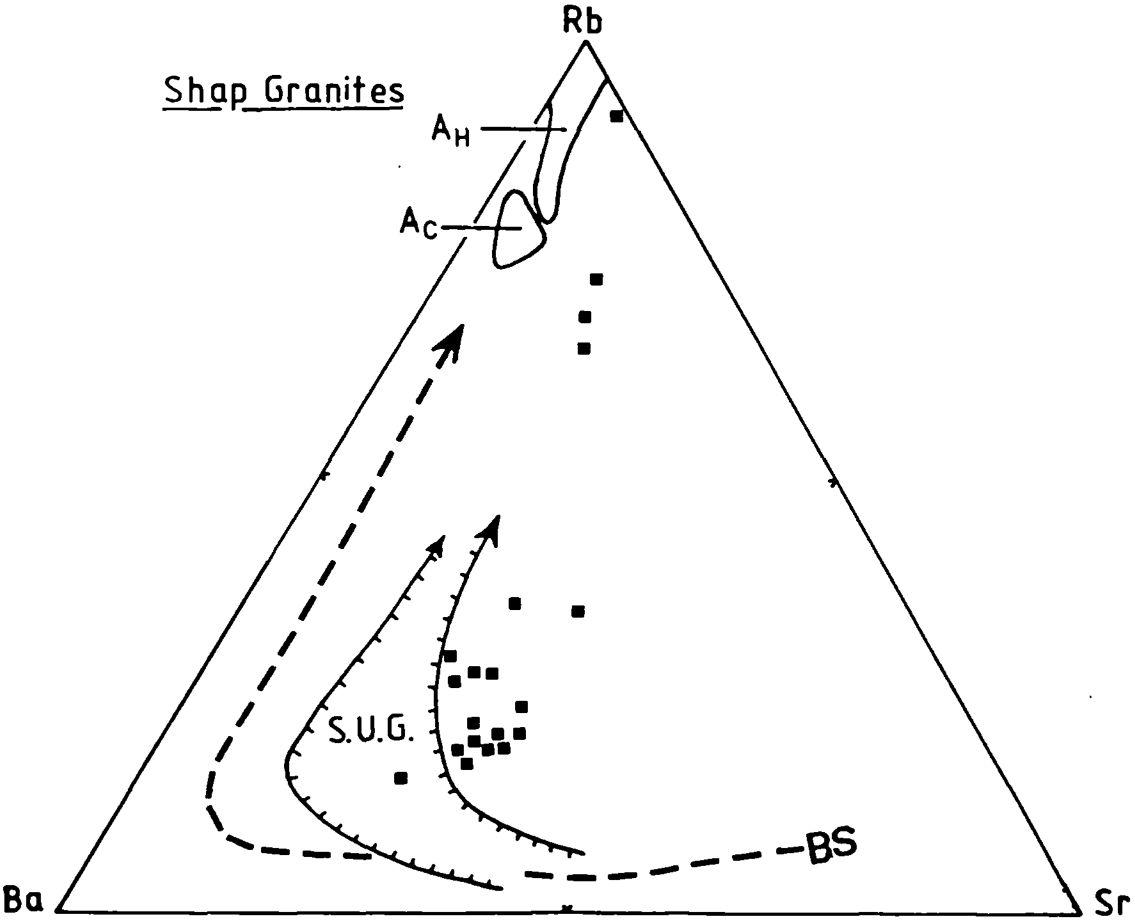


FIG. 4.6a.

Shap granite and aplite data (■) plotted on the Sr-Ba-Rb differentiation diagram of Bouseily and Sokkary (1979).

Their trend of extreme differentiation (BS) contrasts with that thought more typical of the field of Southern Uplands Granites (S.U.G.).

A_H -Hercynian aplites (Neiva, 1975)
A_C -Caledonian aplites (see text).

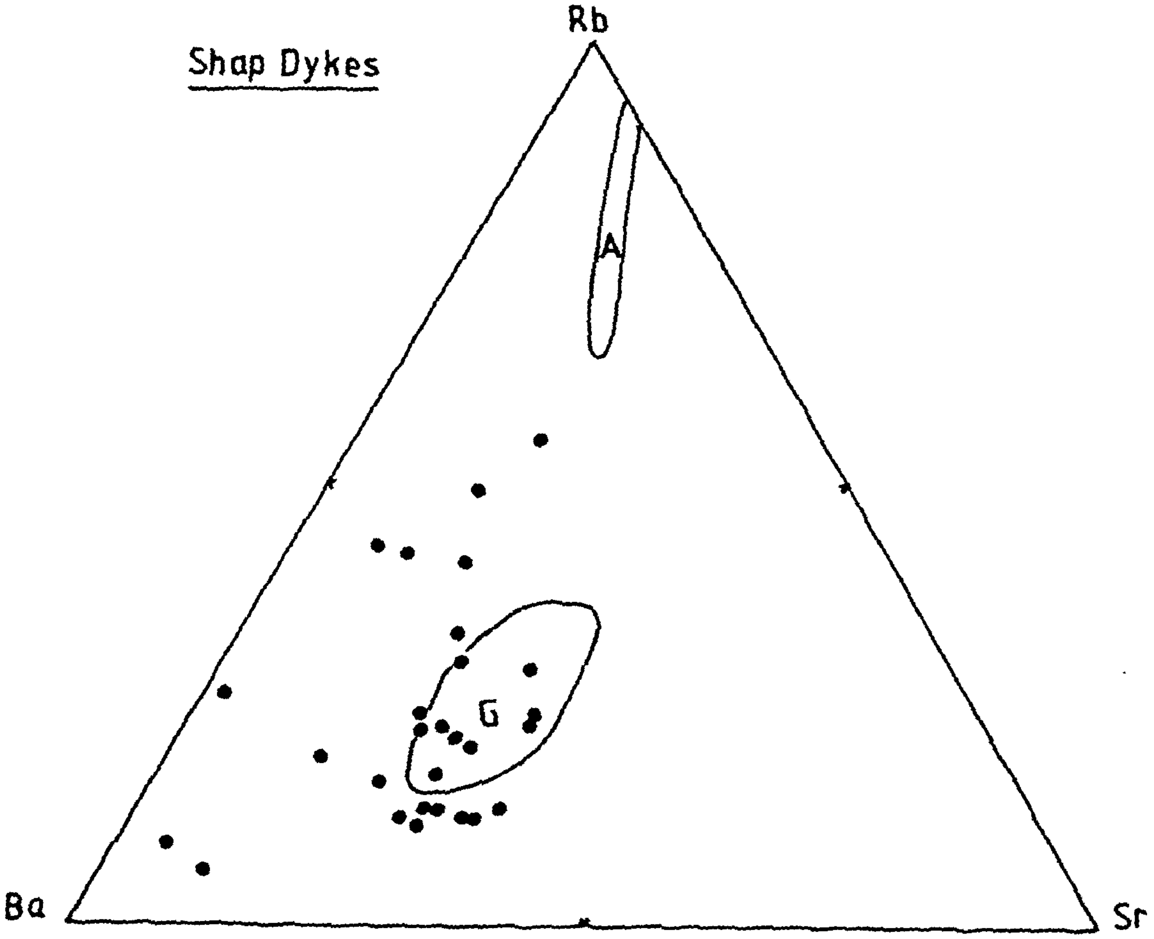


FIG. 4.6b

Shap dyke compositions (●) on the Sr-Ba-Rb diagram of Bouseily and Sokkary (1979), in comparison with the regions of Shap Granite (G) and Aplites (A) from Fig. 4.6a.

position on the plot away from the region of the dykes even though their Sr and Rb levels are not anomalous. This is thought to be due to the fixation of Ba in some dykes, this not being the case in the aplites and granites where some of the Ba is released from the system to be later deposited in the hydrothermal event. Thirdly, there is minor overall evolution in the relative Sr content indicating little involvement of Ca-bearing plagioclase in the magma evolution at these compositions.

4.5 Discussion.

4.5.1 Relationship Between the Dykes and the Lamprophyres.

Although spatially and somewhat temporally related (Section 4.2) the Shap dykes do not appear to be chemically or petrologically related to the dykes of lamprophyric composition. Recent chemical modelling has resulted in a multi-component origin for calk-alkaline lamprophyres derived from various mantle processes. Macdonald et al (1985) invoke a depleted mantle source melt promoted by an H2O-rich subduction zone component along with a CO2-rich phase from a degassing mantle, resulting in a magma not unlike a K-rich basalt (Rock 1984). Thus it appears that these melts involve the action of subduction-related processes, in contrast to the production of the post-orogenic granitic magmas. Although showing some calk-alkaline affinities, back-projection of the granitic trends does not support a chemical link with the lamprophyres being parental to calk-alkaline dykes of intermediate or acidic composition. The intermediate composition porphyrites of south Scotland also show a 'silica gap' with the associated local lamprophyres and therefore have been attributed to a distinct differentiation process from a basic, non-lamprophyric magma of a 57 to 63% SiO_2 range (Barnes et al, 1986). This composition matches the most basic of the plutonic rocks of the S.U.G.'s and it is thought that this is more likely to be the initial magma composition for the generation of the diorite to granite dykes and plutons seen in Scotland and Cumbria. As yet, the origins of this melt have not been constrained with multivarious models being presented to account for the geochemical data of these and other Caledonian granites and dykes (eg. Chapter 3.3.1.).

4.5.2 The Crystallisation of the Shap Granitic Magma.

Given the relatively limited geochemical range of the Shap samples with the evidence cited above and in Chapter 3, the chemistry of the Shap granitic rocks can be discussed. The crystallisation sequence does not appear to involve hornblende though prior to around 63% SiO_2 it may have been a major fractionating phase. The stability of amphibole is such that at low pressures (<3kb) and moderate temperatures (<850°C) hornblende is not found and biotite with plagioclase become the main fractionating silicate phases. Consequently, hornblende tends to be restricted to intermediate compositions either emplaced rapidly (to reduce possible resorption and reequilibration) or at greater depths than the more evolved plutons.

A study by Maaloe and Wyllie (1975) analysed the crystallisation sequence of a granite (SiO_2=71%) over a range of temperatures and H_2O contents at 2kb (Fig.4.7). They concluded that granitic magmas were essentially H_2O-undersaturated throughout most of their emplacement histories, with the progressive crystallisation eventually

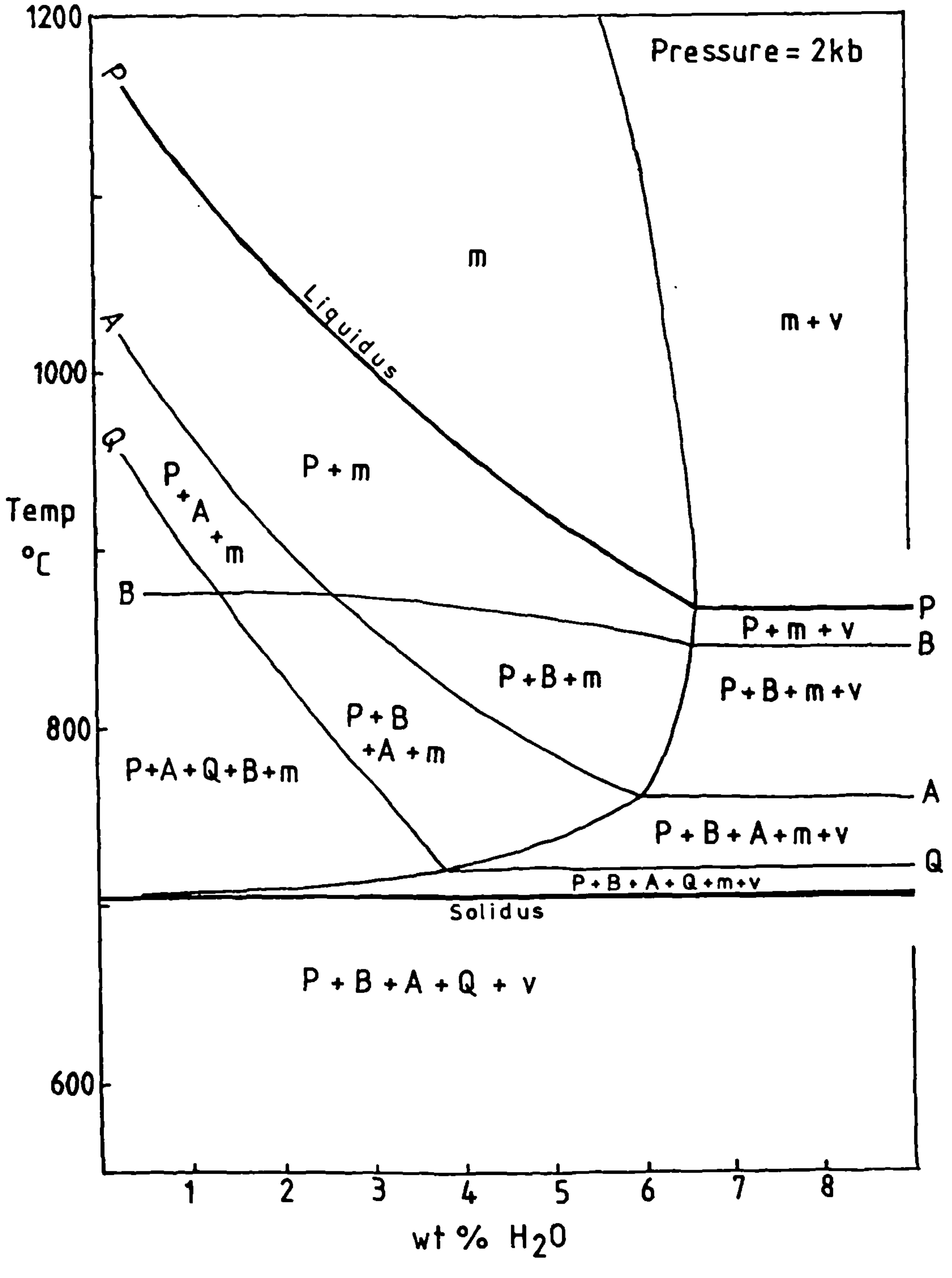


FIG. 4.7

The stability fields of the four phase granite system derived from experimental determination of crystallisation of a granite by Maaloe and Wyllie (1975).

P-plagioclase, B-biotite, A-alkali feldspar, Q-quartz, m-melt, v-vapour.

producing H2O saturation conditions about the upper portions of large granite plutons. The crystallisation sequence was found to be dependant on the water content of the melt. At contents less than 2.5 wt%, biotite crystallised last after magnetite, feldspar and quartz. This is in contrast to the sequence established at Shap of magnetite, plagioclase, biotite, alkali feldspar and quartz which is shown in Fig.4.7 to occur when the H2O content exceeds 2.5 wt%. Both relatively low temperature and high H2O contents promote late order crystallisation of orthoclase. It is perhaps under these conditions that metasomatic orthoclase can develop resulting in textures as seen in the Shap Granite. It is also of interest to note that orthoclase phenocryst development in the dykes of similar composition to the granite (ie 67% SiO2) is not commonplace. This may be due to orthoclase crystallisation being suppressed by very high H2O contents in the dykes or alternatively, gives support to the case for the orthoclase megacrysts in the granite not being phenocrysts but being of metasomatic origin.

4.5.3 The Case for Evolved Felsitic Magmas.

Given the significant production of minor intrusive magma more acidic than the parental granitic pluton, a problem arises given that the pluton itself represents the most evolved state of the parental granitic magma. This has not thought to be a problem in the production of volcanic acidic liquids (eg rhyolites, pumices etc.) these being the product of the upper portions of strongly fractionated and zoned magma chambers. Dacites and rhyolites often contain hornblende and plagioclase phenocrysts suggesting higher temperatures (>1000 C) and wider crystallisation intervals

(Stormer and Carmichael 1970) for magma evolution than found in granitic plutonic systems (Section 4.5.2). The comparison of geochemical data of various acidic igneous rocks by Miller and Mittlefehldt (1984) has led them to the conclusion that both volcanic and plutonic rocks are the product of fractional crystallisation. Their main evidence is the strong geochemical similarity of compositional trends in most acidic igneous rock sequences, suggesting a major overall common mechanism. These trends are consistent with the dominant process of fractional crystallisation, with the resulting chemical imprint surviving later stages of the cooling history. They reject crystal settling in favour of magma compositions being determined by in-situ crystallisation and mineral accumulation. Although this fits many of the requirements of the plutonic system, problems arise with very extensive crystallisation and fractionation (prehaps upto 90% for some early phases?) which is required to explain the chemical trends. Also, the production of essentially crystal-poor liquids in appreciable quantities from a magma that has already undergone extensive crystallisation requires an effective crystal-liquid separation process. Mineral packing when crystallisation exceeds 50-60% makes effective melt separation difficult and sluggish (Marsh 1981).

Therefore the extent of dyke and aplite production is dependant upon the overall physical cooling character of the host pluton, the many factors include depth of magma emplacement, order of crystallisation, rate of cooling, volatile accumulation and the occurrence of a metasomatic event all of which of course are themselves also interdependant. Importantly, the dyke magma production must have occurred prior to the megacryst development in the granite, which suggests that the metasomatism must have occurred after the granite magma's evolution, the metasomatic event being essentially isochemical and within a closed-system.

4.6 Conclusions.

1. The dykes about the Shap Granite are coeval with it's emplacement and are a product of the same overall magma generation process.
2. Most of the dykes are of a similar or more acidic composition to the granite. When less acidic, the dykes are of a dioritic rather than a lamprophyric character.
3. The lamprophyres are a distinct earlier and non-related magmatic event to the associated acidic minor intrusions.
4. The aplites and acidic dykes both represent extreme fractionates of the granitic magma but differ in time of production and the effects of the volatile component in the cooling host magma.
5. Compositions of the granites and dykes are mainly controlled by the effects of biotite and plagioclase fractionation.
6. Geochemically, granitic liquids can be envisaged as behaving in the typical calk-alkaline model of crystal-liquid interaction. Physical constraints make this model an over-simplification.

CHAPTER 5 THE BORROWDALE VOLCANICS.

5.1 Introduction.

The two major studies of the volcanic rocks about the Shap Granite were by Harker and Marr (1891, 1893) and Firman (1953a, 1954, 1957), both of which included detailed petrological descriptions of the effects of metamorphism and an associated metasomatic event resulting in the development of garnet-bearing veins (Firman 1957). This part of the study is specifically concerned with the evidence for the physical and chemical alteration in the aureole, representing the overall process of metamorphism and granite-country rock interaction. Harker and Marr did not discuss the geochemistry and Firman (1953a) analysed only a small number of samples (5) upto 1500m from the granite to try and assess whether chemical movement had occurred on a regional scale.

All available outcrops were examined in the aureole, though much of the area has very restricted exposure (Plate 11a). The general nature of the region is outlined in Chapter 2.2.2., being mainly massive lavas with thinner interbedded tuffs. Unfortunately, individual units cannot be traced laterally across the aureole so as to facilitate the study of variations in the effects of metamorphism in a single selected horizon.

The extent of regional metamorphism of the Shap area and Cumbria as a whole has been assessed by studies in the Paratectonic Caledonides which extend from southern Scotland to Wales (Dewey 1969). Oliver and Leggett (1980) defined the regional (burial) metamorphic grade of the Southern

Uplands based on the local metabasalts and greywackes. The metabasalts developed the most diagnostic assemblages containing albite, chlorite, sericite and haematite but lacking epidote. This assemblage defines a wide range of metamorphic grade from zeolite to greenschist facies. Their conclusion was that much of the lowest zeolite-grade material had been removed by post-orogenic erosion and that the regional metamorphic grade was essentially of the prehnite-pumpellyite facies.

In the Welsh sector of the paratectonic Caledonides the Ordovician metabasites are also mainly at the prehnite-pumpellyite facies with limited areas being at a slightly higher grade of the lower greenschist facies. Much of the original igneous textures were retained along with many original mineral phases. The metamorphism resulted in secondary prehnite, pumpellyite, chlorite, sericite, calcite and sphene along with actinolite and epidote (clinozoisite) in the limited higher grade areas. (Bevins and Rowbotham 1983). This suggested that the Welsh area presently exposed attained metamorphic conditions in the region of 275-375°C and 1-5kb.

Similar metamorphic grades have been quoted by Thomas et al (1985) for the Lake District. Prehnite-pumpellyite facies metamorphism has been defined for the Eycott and Borrowdale Volcanic Groups based upon chlorite, clinozoisite, prehnite and pumpellyite in the basic rocks and a less definitive assemblage of quartz, chlorite, carbonate and sericite in the acidic volcanics with a maximum temperature of metamorphism of about 350°C. In the sedimentary successions the same metamorphic conditions have been defined by a study of illite crystallinity (Weber 1972). Apart from the secondary mineralogy, much of the original minerals and fabrics are retained in the Cumbrian rocks and in connection with the Borrowdale Volcanic Group are discussed below (5.2.1).

The limit of the contact metamorphic aureole at Shap was first recognised by Harker and Marr (1893) and their definition is still valid. The outer margin of the aureole in the volcanic rocks is represented by the development of biotite and in the Silurian sediments by new muscovite and biotite. Although it is somewhat difficult to delimit the outer aureole to the east and west of the granite due to poorer exposures, the aureole has a regular disposition about the granite being 900-1000m in width (Fig.2.4). Subsurface modelling of the granite shows that there is a disparity between aureole disposition and the granite form. Both Bott (1974) and Lee (1984a) have modelled gravity data and show the granite pluton to probably have a much steeper wall to the north east (Fig.2.6). The aureole is relatively well defined in this region and there is no indication of the expected narrower aureole to the north east. This phenomena has been previously noted (eg. Redfern 1979) and yet remains unresolved, although possible explanation is given below in section 5.4.

5.2. Petrology.

5.2.1. The Borrowdale Volcanic Group In General.

Despite the restriction of this study to mainly within the metamorphic aureole it is necessary to briefly discuss the petrological state of the volcanic rocks prior to contact metamorphism. This allows one to assess the original mineral phases present (such as phenocrysts) and to try and recognise whether secondary minerals have been developed during regional or contact metamorphism.

As stated before, the Borrowdale Volcanics are generally below greenschist grade. Regional metamorphism has tended to affect the pyroclastic rocks to a greater extent than the lavas and subsequently much of the discussion is based upon the lavas which show less penetrative deformation and recrystallisation.

Fitton (1971) examined a wide range of volcanic samples from across the whole of Cumbria and covering the full range of compositions of basalt to rhyolite. The basalts are sparsely porphyritic with relic ortho and clinopyroxene along with rare olivine and labradorite plagioclase. The basaltic andesites and andesites contain orthopyroxene and plentiful plagioclase but no olivine and little or no clinopyroxene. The intermediate rocks (andesite-dacite) have increasing plagioclase and decreasing pyroxene contents along with phenocryst almandine-pyrope garnet in limited horizons. Acidic lavas are generally restricted in number, most rocks of this composition being ignimbritic or tuffaceous, but where examined they contain potassium and albitic feldspar phenocrysts along with quartz. Microphenocrysts of magnetite, zircon and apatite occur in all compositions. Fitton (op.cit.) did not recognise any primary amphibole. Some of the phenocryst phases are essentially intact apart from the pyroxenes and olivine which are invariably altered and pseudomorphed by chlorite, quartz and iron oxides. Nutt (1970) in studying the

Haweswater region to the north of Shap also recognised altered ortho and clinopyroxene along with phenocryst plagioclase of a wide compositional range (An70-40). Primary and secondary phases are similar to those of Fitton (1971) apart from the possible recognition of brown amphibole and the lack of garnet and olivine phenocrysts. Again the more basic rocks show much secondary development of chlorite after pyroxene and with calcite, quartz and albite alteration in both the phenocrysts and groundmass and the devitrification of the groundmass glass. Amygdales contain chlorite, quartz and calcite but it is not known to what extent the assemblage is primary rather than a result of the regional metamorphism.

5.2.2. Volcanics of the Shap Region.

The general nature of the Shap volcanic rocks is described in chapter 2.2.2. The rocks within the aureole display wide variations in texture and mineralogy, including the development of the garnet-bearing veins, pyritisation, quartz vein swarms etc.. These various aspects of metamorphism and mineralisation are mainly related to the granite's intrusion, but will be discussed separately.

5.2.2.1. The Contact Metamorphism.

The major description of the contact metamorphism was by Harker and Marr (1881) who recognised the main phases produced by the thermal metamorphism within the lavas and tuffs. The most obvious changes produced by thermal metamorphism is the extent of hornfelsing and recrystallisation as the aureole is traversed. Within a metre of the granite the rock is completely recrystallised to such an extent that with the associated increase in grain size new mineral phases are readily apparent. Within 10m of the granite the amount of recrystallisation becomes more variable though is usually still very extensive, the rocks retaining little of the original mineralogy and displaying disrupted and annealed modifications to the fabrics such as the penetrative and fracture cleavage (Plate 3). Examination of rock thin sections from around the aureole shows that there is an inner zone of high crystallisation appearing as granular hornfels occupying a narrow region adjacent to the granite and of less than 100m width and mainly within 15m of the granite (Fig.5.1.). Further away from the granite out to the aureole margin the extent of the recrystallisation rarely approaches 40% and much of the aureole is occupied by rocks displaying much of their original igneous and deformational fabrics (Plate 12). There is not a smooth gradation between the inner highly crystalline zone and the remainder of the aureole, but it appears to be an abrupt change representing a significant physical character of the granite-country rock interaction.

Examination of thin sections from the aureole supports much of the mineralogical descriptions of these previous authors and only the most significant details are outlined here. The thermal metamorphism of the andesites produces a biotite-quartz-plagioclase hornfels in which the plagioclase phenocrysts survive relative to the mafic phenocrysts which usually appear as biotite-chlorite patches along with quartz, calcite and Fe-oxides (Plate 12c,d.). The extent of alteration of these phenocrysts can vary within individual samples. No original pyroxene phenocrysts have been

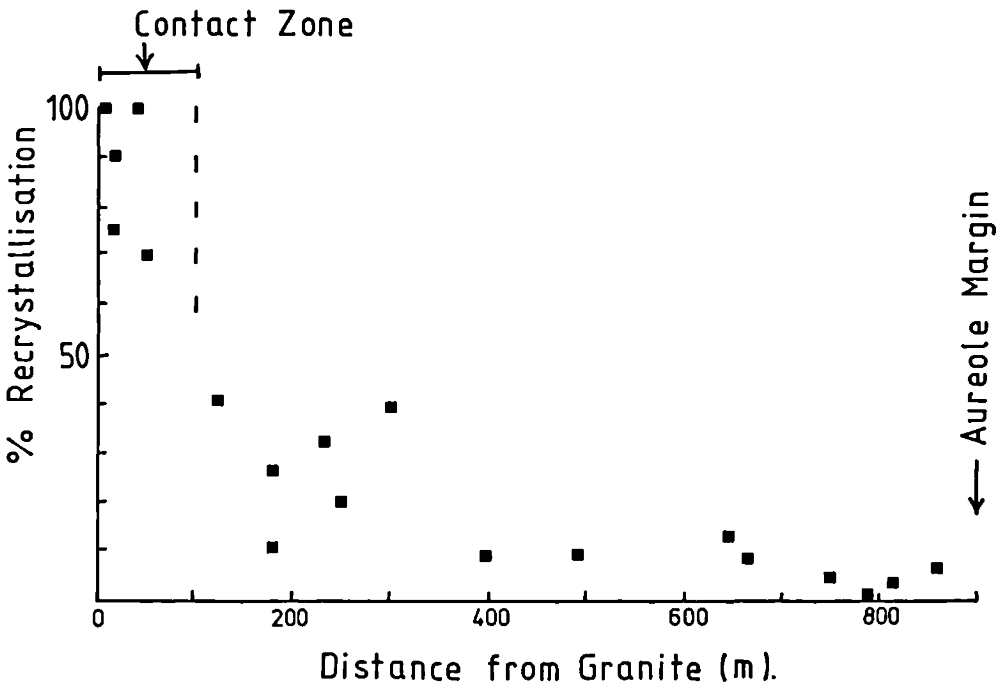


FIG. 5.1

Extent of recrystallisation due to contact metamorphism in the volcanic rocks about the Shap Granite.

Note the narrow zone of high % recrystallisation within less than 100m of the granite.

recognised although biotite pseudomorphs and plentiful patches of chlorite can be seen in the most basic samples (eg. 626). Biotite development is nearly ubiquitous being the most characteristic metamorphic product in all but the most basaltic and rhyolitic rocks, occurring mainly as mafic phenocryst pseudomorphs (eg. 626) or as a major constituent of the groundmass (Plate 12.d,e). Apart from biotite, the alteration of mafic phases also produces some small grains of sphene and Fe-oxides. Occasionally biotite may show some chloritisation due to later alteration but this is not widespread (eg. 616). Metamorphic chlorite occurs in many samples apart from near the granite contact. As mentioned it is plentiful in the most basic rocks (eg. 626) but also in Blue Quarry exposures, here being associated with the garnet vein development (644). Although many of the rocks have developed a greenish hue, the development of epidote is not as widespread as expected. As with the chlorite, it is mainly found in the basaltic rocks (eg. 626) or in the Blue Quarry where it is plentiful in many samples (eg. 644) (Plate 12.h). Quartz has been found in all samples apart from a basalt (626) and it is often associated with the parts of a sample showing the most extreme alteration, such as the altered phenocrysts or with the biotite in the groundmass where it displays alignment which defines the fabric (Plate 12.e).

Amphibole is not generally developed but is found in some vesicles and in rocks from the Blue Quarry. Metamorphic reactions appear to have taken place readily in the vesicles with the initial quartz-chlorite-calcite assemblage reacting to produce amphibole (hornblende) as well as epidote,

PLATE 11.

PLATE 11. VOLCANIC PETROLOGY

a. View eastwards from Tongue Rigg down Wet Sleddale. The ground to the right of the river valley and the reservoir is occupied by the poorly exposed volcanic rocks of the metamorphic aureole. Towards the skyline are workings in the Carboniferous Limestone.

b. Weathered surface of andesite showing plentiful plagioclase phenocrysts, somewhat aligned by later Caledonian deformation. (GR 542106)

c. Plagioclase phyric andesite showing little deformation. This sample is essentially unaltered and lies outside the metamorphic aureole. (GR 525084)

d. Highly vesicular andesite. (Blue Quarry)

e. Disseminated pyrite in andesite hornfels. (Blue Quarry)

f. Epidote-quartz veins in outcrops in Blea Beck north-west of the Shap Wells Hotel. (GR 570101)

g,h. Brittle fracturing filled with low temperature hydrothermal minerals and associated wall-rock alteration. (Blue Quarry)

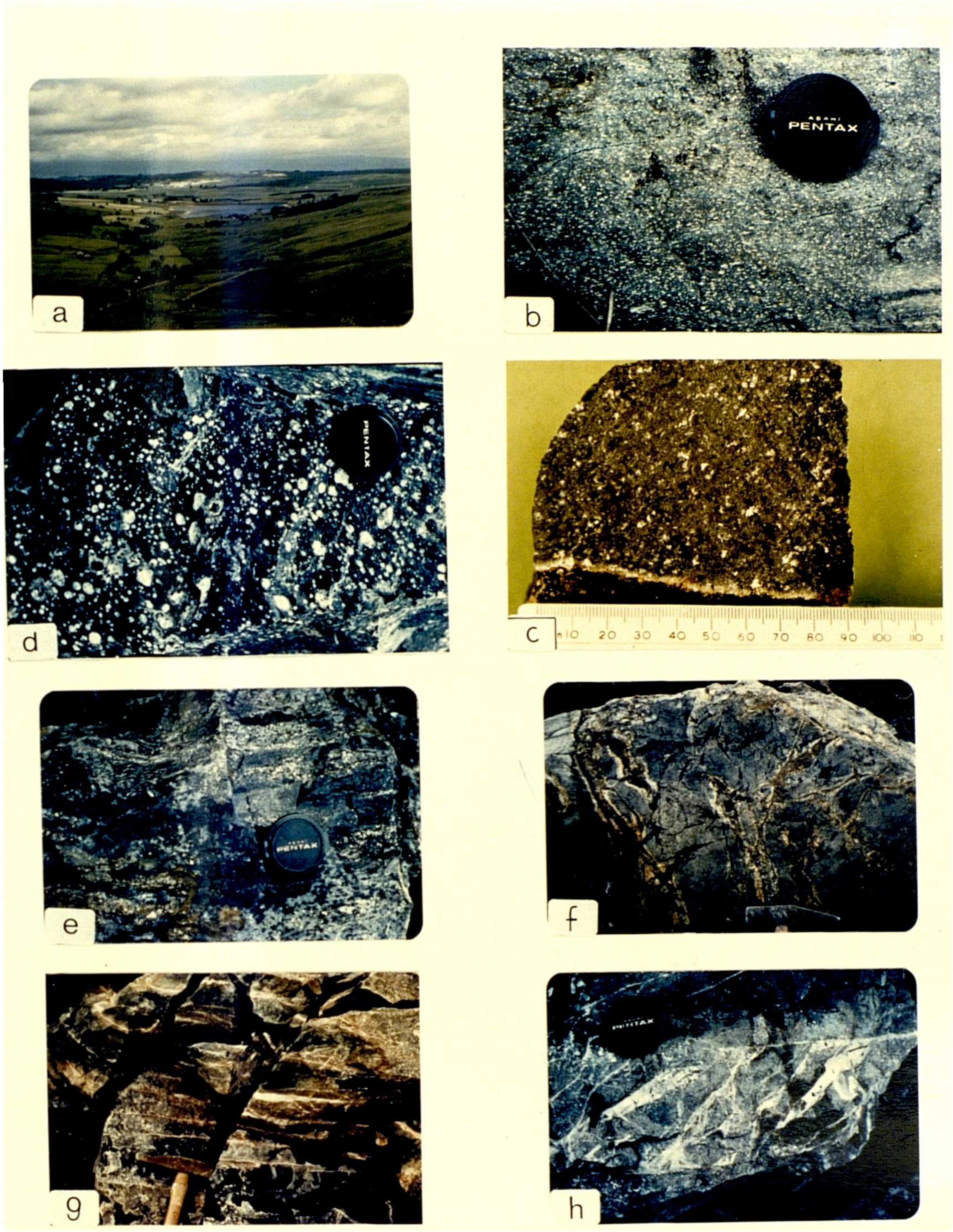

a
b
ASAHI PENTAX
d
PENTAX
c
10 20 30 40 50 60 70 80 90 100 110
e
PENTAX
f
g
h
PENTAX

PLATE 11

PLATE 12.

PLATE 12. VOLCANIC PHOTOMICROGRAPHS

a. Partial metamorphic recrystallisation and increase in grain size in an andesitic clastic tuff.
(Section No. 43116) (XPL)

b. As in 12a, complete recrystallisation of a tuff? producing a granular hornfels of dacitic composition. Sample from Wasdale Farm granite contact,
(Section No. 43113) (XPL)

c. Complete recrystallisation in contact hornfels resulting in secondary biotite and quartz with minor orthoclase although rock has a bulk composition of an andesite.
(Section No. 41525) (XPL)

d. Near complete recrystallisation with relic phenocryst outlines of biotite in an andesite some 60m. from the granite.
(Section No. 41526) (PPL and XPL)

e. Recrystallised lava? with a strong quartz-biotite fabric and pyritisation. This sample is from the NE contact zone (see Plate 3) and no indication of original petrography remains. It is thought that the fabric was produced during the granites intrusion.
(Section No. 43120) (PPL)

f. The vesicle infill of an andesite some 230m from the granite. The metamorphosed vesicle now contains quartz, chlorite and minor amphibole.
(Section No. 43115) (PPL)

g. Extensive recrystallisation and formation of quartz-epidote-pyrite mixture in an andesite 50m from the granite.
(Section No. 41521) (XPL)

h. Andesite from the Blue Quarry showing somewhat atypical metamorphic mineral development associated with the garnet veins, some 490m from the granite. Calcite-epidote-quartz intergrowth along with minor chlorite.
(Section No. 43130) (PPL)

Scale Bar as in Plate 8.

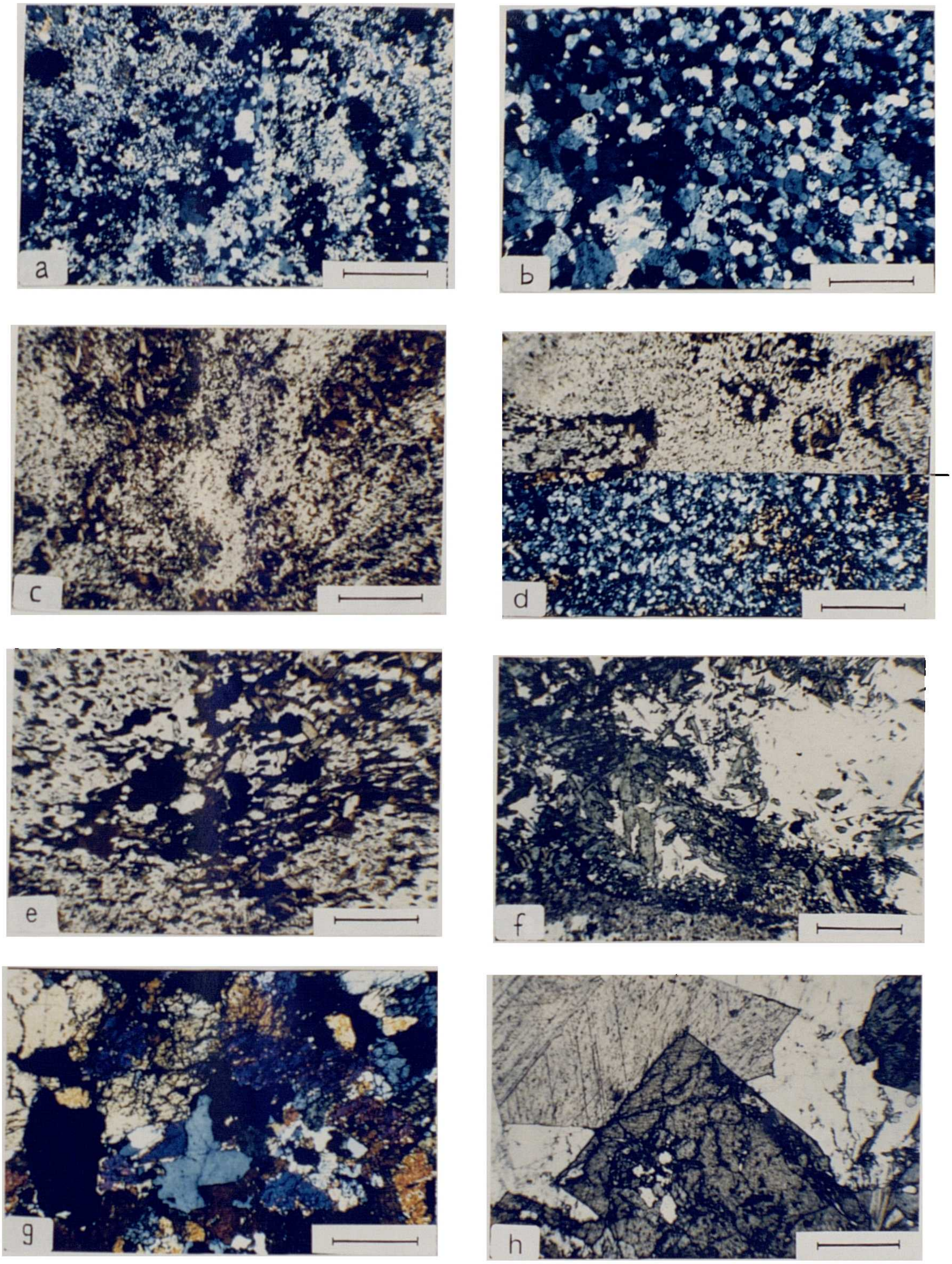


PLATE 12

clinopyroxene?, pyrite and less frequently, albite (Plate 12.f). Near the contact vesicles may also contain biotite. Minor chemical-interaction between the infilled vesicles and their host produces narrow light-coloured reaction zones which contain quartz and feldspar.

The groundmass of the aureole rocks is mainly equigranular biotite and quartz but where biotite is less developed may simply show alteration to a fine-grained mixture of chlorite, biotite, calcite, sericite and quartz. Near the granite contact additional phases might include magnetite, albite and epidote with the rare development of orthoclase and sillimanite in the most extreme cases (Firman 1953a).

The tuffs recrystallise readily and are usually biotite and quartz rich , along with rarer hornblende, epidote and feldspar.

The most acidic rocks develop much secondary feldspar and generally lack amphibole, epidote and to a lesser extent, biotite. Firman (1953a) described both andalusite and sillimanite from rhyolitic rocks near the granite contact.

A feature at some localities is the development of green reaction zones about pre-existing joints (Plate 11.f). Unmetamorphosed joints contain quartz, chlorite, and calcite and as with the vesicles this assemblage metamorphoses to produce epidote. Extreme epidotisation and wall-rock reaction is seen in the Blue Quarry in association with the garnet veins and this feature is described separately.

5.2.2.2. The Garnet-Bearing Veins.

As mentioned above some metamorphic mineral development is particularly notable in the Blue Quarry, especially about its southern exposures. Here, amphibole,chlorite and epidote growth is readily apparent along with a large range of other minerals including garnet, clinopyroxene, actinolite, orthoclase and a collection of low temperature hydrothermal metal oxide, sulphide, carbonate and hydrated silicate minerals (Firman 1957).

Firman (op.cit.) gives an excellent description of this Blue Quarry mineral suite and plentiful examples of this material can still be found. This suite has not been recorded anywhere else in the volcanic rocks of the aureole and its composition and singular location makes it atypical of the general metamorphism in the aureole.

The garnet is of andradite-grossular composition and is associated with other calc-silicate minerals including epidote, clinopyroxene (Ca46 Mg31 Fe23) and hornblende in vein structures. The overall assemblage and the extent and range of associated minerals has been attributed by Firman (1957) to extensive fissure metasomatism in and about pre-granite fractures and cleavages. Evidence from the vesicles suggests that calc-silicate reactions are favoured by the availability of quartz and calcite. Firman (1978) suggests that much of the required material was derived from the wall-rock interaction, along with pre-granite quartz-calcite-chlorite in the veins. The extent of later post-garnet vein hydrothermal mineralisation suggests that there was a localised input of material from the adjacent granite. Only in this region have minerals such as galena, sphalerite, nacrite, malachite, pectolite, saponite, psilomelane been recorded (Firman 1957). Other minerals such as magnetite, pyrite, chalcopyrite, haematite, molybdenite, arsenopyrite, barytes and quartz can be found elswhere in the aureole as discrete veins and accumulations but the age of much of this mineralisation is less clear and cannot be simply attributed to the granite metamorphism/metasomatism event.

5.2.2.3. Mineralisation.

Although Firman (1978) related the distribution of the Cumbrian epigenetic mineralisation to the form of the Cumbrian Batholith there appears no obvious spatial distribution of the major metal veins to the various regions of the batholith or the granite outcrops. There is an apparent lack of major veins about the Shap region even though this area lies upon a ridge of the roof zone of the batholith (Bott 1974) where the thermal effects of the batholith emplacement might be expected to be significant in the production of mineral veins. Elsewhere, veins are found above both the inferred roof and wall zones of the batholith with the veins occurring mainly in both the Borrowdale Volcanic and Skiddaw Slate Groups. There is a notable lack of them in the Silurian sediments of south Cumbria even though these rocks are underlain by the broad south wall of the batholith.

Many of the minerals such as pyrite, arsenopyrite, barytes and molybdenite are found in the granite and, along with the others described from the aureole and Blue Quarry, they have been attributed to fluids emanating from the granite during a low temperature, hydrothermal fluid infiltration event after the main phase of the thermal metamorphism. Firman (1957) describes calcite, pyrite, haematite and magnetite within the calc-silicate veins along with chalcopyrite, sphalerite, galena, calcite, and quartz in extensional cracks and joints. Pyrite can be found in small veins and disseminated granules in many regions of the aureole.

It is difficult to attribute a time of formation of groups of associated minerals to either a single or multiple events. Apart from a few small quartz and calcite veins, all the main mineralisation cross-cuts Caledonian deformation (ie end-Silurian) fabrics in the country rocks and some near the granite contact appear deformed by 'shouldering' by the granite. The main phase of mineralisation in Cumbria has been assigned to being related to the Cumbrian Batholith but Stanley and Vaughan (1982) have recognised 8 periods of mineralisation in Cumbria between the lower Devonian and the Jurassic (ie. 400-180 Ma). They attribute the main metal sulphides to the leaching of granites by circulating solutions at around 400°C during the Lower Devonian and Ba-Pb-Zn mineralisation to a later, Lower Carboniferous event possibly at temperatures less than 250°C. On the other hand, Dagger (1977) attributed the copper mineralisation in Cumbria to redistribution of elements in volcanic rocks. This simplified two-fold division of the main mineralisation in Cumbria does not account for what is seen at Shap where the two suites of minerals can be seen to be intimately related in time.

Independent evidence of the timing of Cumbrian mineralisation includes a K/Ar study of clays from mineral deposits by Ineson and Mitchell (1974). They found that there was a well recognised low temperature stage associated with the higher temperature, Lower Devonian sulphide mineralisation which thus would support the evidence seen at Shap. Moorbath (1962) calculated lead isotope model ages of 365± 80Ma for galenas from the Blue Quarry. This would appear to support a single age for all the mineralisation about the Shap Granite but for the fact that allowing for the quoted errors these galenas could have been produced during the main phase of Pb-Zn mineralisation thought to be at 275 Ma. (Ineson and Mitchell 1974) or 360-300 Ma (Stanley and Vaughan 1982).

It is notable that the barytes deposit in Sherry Gill north of the granite occupies a N-S trending fault. There are many similar faults in the region such as seen in the Pink Quarry (Plate 1.f) and as described in the previous chapter. These structures are thought to be Lower Carboniferous in age being related to a suite of such faults that are found in northern England and related to the Pb-Zn-Ba deposits of the region. It is therefore suggested that the Sherry Gill deposit, although small by commercial standards, is also of Lower Carboniferous age and represents mineralisation about the Shap Granite not directly related to the granite's intrusion. Recognition of other such younger veins and structures at Shap is difficult and division of mineral suites between granite-related and non-related is not possible without much detailed study. Thus it is likely that some of the low temperature and gangue mineralisation seen about the Shap Granite is not due to the thermal and chemical effects of the granite's intrusion. Secondly, the mineralisation cannot be simply attributed to redistribution of elements from the volcanic rocks themselves or addition from the granite as similar mineralisation is found in sedimentary rocks and the mineralisation event in the granite was essentially isochemical. (Chapter 3).

5.2.2.4.Geophysical Evidence.

Gravity and magnetic studies in the Shap region lend support to the understanding of the Shap aureole. Both Locke and Brown (1978) and Lee (1984a) showed the steep gradient wall on the north east of the Shap pluton directly below the Blue Quarry region (Fig.2.6). Locke and Browne (op.cit.) suggested that this might be a fault-controlled effect as a similar structure was modelled immediately to the south west of the granite about the fault contact between the Silurian and Upper Ordovician sediments. Rathore and Kafay (1986) measured the magnetic susceptibility of 12 samples from about the granite, 5 of which lay within the volcanic rocks of the aureole. They recognised the regional Caledonian fabric (trending NE-SW with a steep dip to the SE) which was overprinted in two regions, in the Blue Quarry and about the granite contact zone. The fabric in the Blue Quarry was found to be distinctly different from elswhere in the aureole being the strongest and most variable susceptibilities measured, this being attributed to the development of new granular magnetite along with a magnetite vein in the Quarry. (R.Firman pers.comm.). Apart from in this region, the volcanic rocks were magnetically 'quiet' indicating the presence of little original magnetite in the aureole rocks. All the studies recognised high induced magnetism in close proximity to the granite (<20 metres) due to the production of new large magnetite grains and, Locke and Brown (op.cit.) proposed that it came from the breakdown of biotite with the released potassium being refixed as associated orthoclase. The calculated Curie Point of 580°C for the new magnetite indicated that temperatures in these contact rocks attained levels close to those of the granite solidus itself and magnetic fabric studies (Rathore and Kafay 1986) showed that strain and a resulting new fabric occurred close to the contact.

5.2.2.5. The Silurian and Upper Ordovician Rocks.

Although not studied in this work, the rocks in the aureole to the south of the granite give some indication of the metamorphic effects about the granite. In the Silurian sediments Harker and Marr (1891) recognised the development of biotite spotting over a range of 900-300 metres from the granite becoming increasingly developed approaching the granite. Hornfelsing resulted in the recrystallisation of quartz and the growth of new albitic plagioclase. In the more aluminous horizons andalusite and sillimanite are found close to the contact in Wasdale Beck. Minor Fe-sulphides, calcite veins and barytes were attributed by Redfern (1979) to localised leaching of elements from the Silurian rocks by both hydrothermal and ground-water fluids during and after the granite's emplacement, the fluids being driven in a convective style by the heat from the pluton.

In the calcareous horizons of the Silurian Coldwell Beds metamorphic calc-silicate minerals can be found with the development of tremolite and diopside. The calcareous Upper Ordovician Coniston Limestone Group in the aureole at Wasdale Farm develop a wider assemblage of calc-silicate minerals including tremolite, diopside, idocrase, grossular garnet and wollastonite, and with complete recrystallisation of the original textures. The purer limestone horizons recrystallise to a grey saccharoidal marble, the lack of associated quartz not allowing calc-silicate reactions to occur. This dependence of the development or non-development of metamorphic minerals on the original rock composition indicated to Harker and Marr (1893) that even at this close proximity to the granite at Wasdale Farm there was no chemical transfer of material from the granite but the metamorphism was essentially thermal and isochemical. As with sillimanite, the occurrence of wollastonite again suggests that high (>400^{o}C) temperatures were reached near to the granite. (See sections 5.4. below.).

The Stockdale Rhyolite also outcrops at Wasdale Farm and shows the quartz-feldspar fabric to be completely recrystallised. Devitrification textures are destroyed and some fractures and joints show partial annealing with quartz cements. Two analyses by Harker and Marr (1891) showed a 1% increase in SiO2 compared to the same rhyolite from the type section at Stockdale. This difference is not thought to be significant due to the age and low number of the analyses used in the comparison and the likelihood of some chemical variation along the rhyolite flow. More recently Gale et al. (1979) dated the rhyolite by Rb/Sr methods and showed that the rhyolite gave a significant age with low errors. Their samples included three rocks from near Wasdale Farm, being well within the Shap metamorphic aureole. Interestingly, these samples fitted well onto the Rb-Sr isochron such that they inferred that Rb-Sr systematics of the whole flow had not been disrupted by subsequent loss or gain of Rb or Sr.

This has since been questioned by Compston et al. (1982), but it is still apparent that the samples from within the aureole appear chemically intact. The rhyolite has a wide original Rb/Sr ratio variation anyway and perhaps surprisingly, the Wasdale Farm samples have a wider variation in Sr than Rb. (M.Thirlwall pers.comm.), any expected metamorphic mobilisation of the Rb not apparently having occurred.

5.3. Geochemistry.

5.3.1. The Borrowdale Volcanic Group in General.

The major geochemical studies of the Borrowdale Volcanic Group were by Fitton (1971, 1972) and Millward (1976) who analysed a total of 249 rocks, the averages being presented in Millward et al. (1978). Small numbers of localised samples have also been published by Hadfield and Whiteside (1936), Nutt (1970, 1979) and Thirlwall and Fitton (1983). Some 97 analyses from the southern outcrop of the volcanics were undertaken by Numan (1974) but remain unpublished at present.

The rocks range from 47-78% SiO2 (ie basalt to rhyolite) but are dominated by andesite and basaltic andesite compositions (68% of the total analyses) with basalts (9%) and rhyolites (8%) being uncommon. Fitton (1972) recognised their calc-alkaline affinity and attributed the whole group to an island-arc or continental margin environment above a S.E.-dipping Caledonian Benioff zone. The lavas, ignimbrites and pyroclastic deposits all have overlapping fields of a typical calc-alkaline nature with AFM trends showing low Fe enrichment with increasing differentiation (Fig.5.2). Fe/Mg ratios vary from about 2

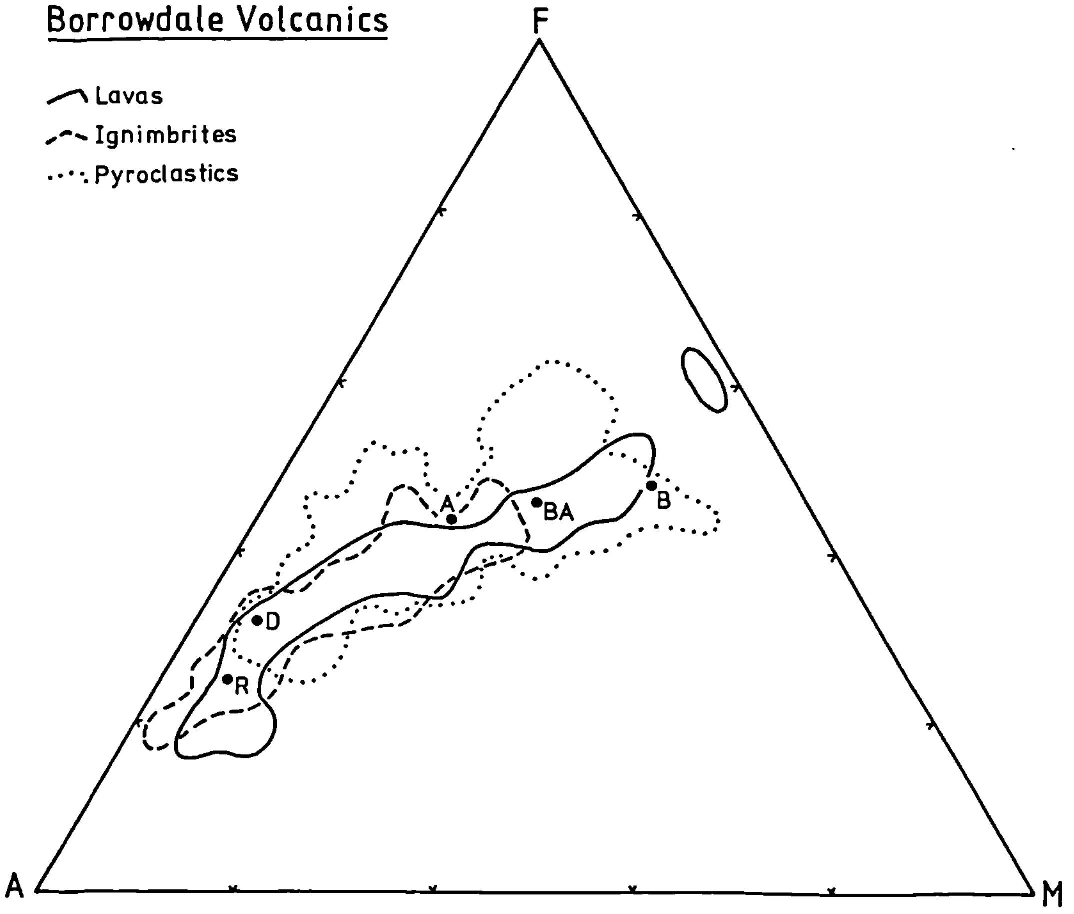


FIG. 5.2

AFM trends of the Borrowdale Volcanic Group (BVG) showing typical calc-alkaline character.

Also shown are the positions of average BVG basalt (B), basaltic andesite (BA), andesite (A), dacite (D) and rhyolite (R).

After Millward et al (1978).

for the basalts to 15 for the acid lavas. The elemental trends are dominated by pyroxene and plagioclase crystal fractionation over the range of basaltic andesite to dacite. All rocks in this range have large negative europium anomalies in their REE patterns and inverse correlations of Sr with increasing SiO_2 (Moseley and Millward 1982). The Borrowdale Volcanic Group as a whole is relatively enriched in incompatible elements such as K, Rb, Zr, Nb, Pb, Th etc. when compared to many similar modern or ancient calc-alkaline volcanic sequences (Millward et al. 1978) and the high K_2O/Na_2O ratios more consistent with continental margin volcanic provinces (Jakes and White 1972).

The basic rocks have low MgO, Ni and Cr contents but the good correlation between the Fe/Mg ratio and Ni or Cr indicates the limited involvement of pyroxene, olivine and possibly spinel in the initial evolution of the Group. There is little evidence of parental or unfractionated basic volcanics. Rocks with significantly lower Fe/Mg ratios and higher Ni and Cr are rare but have been reported from the Ullswater area (GR NY4323) (Moseley and Millward 1982) and have been found in this study at Shap. (See below.).

The Group as a whole displays obvious inter-elemental trends but show large ranges in concentrations and inter-element scatter. Whether this a primary character of the Group or a function of secondary alteration or post-eruption modification effects (eg Caledonian deformation, weathering etc.) is difficult to assess. It is now thought that the rocks have erupted from a small number of (if not a single) volcanic centres (P.Allen pers.comm.) and therefore might be expected to have relatively consistent trends reflecting a centralised magma generation process.

Millward's (1976) study of the ignimbrites stated that only Ni, Cr and Nb have been unaffected by post-depositional mineralogical changes whilst Thirlwall and Fitton (1983) suggested that many of the acidic lavas have been chemically reset, with a lack of correlation between mobile and immobile incompatible elements. (eg. Rb and Zr resp.). Nutt (1979) cites the wide variation of K2O/Na2O ratios (0.3 to 2.1) as being due to alkali mobility, the 'normal' value being >1 (Moseley and Millward 1982).

Evidence of chemical change in the pre-Silurian granites (Firman 1978), Caunt (1984) showed that the Caledonian deformation has affected Na2O levels in these intrusions and consequently this is also likely to have occurred in the dacitic and rhyolitic volcanic rocks, especially in the ignimbritic and pyroclastic members which have undergone the most pervasive deformation.

The case for the value of analysing the volcanic rocks is that low grade metamorphism and deformation does not appear to disrupt values and trends for the majority of the elements and consequently, primary geochemical variations can be assessed and the processes involved recognised. Models of classification and normalisation of volcanic suites using 'immobile' elements are widespread (eg. Cann 1970, Morrison 1978, Pearce 1979, Shervais 1982.) and although usually concerned with basaltic rocks, the elements selected can be used for all compositions. Favoured elements include Ti, Cr, Y, Zr, Nb, and the REE's, and when used in plotting data from the Borrowdale Volcanic Group do not significantly reduce scatter on inter-element diagrams.

This would imply that much of the scatter is real and a character of the original volcanic compositions and not later alteration.

The elemental trends are dominated by the process of crystal fractionation of pyroxene and plagioclase. There is little evidence of magma compositions being affected by garnet or hornblende fractionation and the high total REE content of the lavas supports this. The extent of crustal contamination or assimilation is not within the scope of this work but xenoliths of crustal or cumulate origin are not found in the Borrowdale Volcanic Group except as very local high-level unassimilated crustal xenoliths , probably incorporated during the final stages of eruption. The sub-volcanic nature of the crust during the eruption of the Group is difficult to assess but Sm/Nd studies of the garnet bearing lavas (Thirlwall and Fitton 1983) seems to indicate that incorporation of Skiddaw Slates may have promoted garnet phenocryst formation in these particular rocks. Also, the high concentrations of incompatible elements might be due to assimilation or contamination by continental crustal materials during magma evolution.

There is no silica gap in the group and basic and acidic rocks are interbedded throughout the succession and Millward (1979) found widespread chemical variation even within single ignimbritic unit which he attributed to zoned magma chambers producing comagmatic eruptions of all compositions.

5.3.2. The Shap Volcanic Rocks.

5.3.2.1 Introduction.

Sixty one volcanic samples from about the Shap Granite

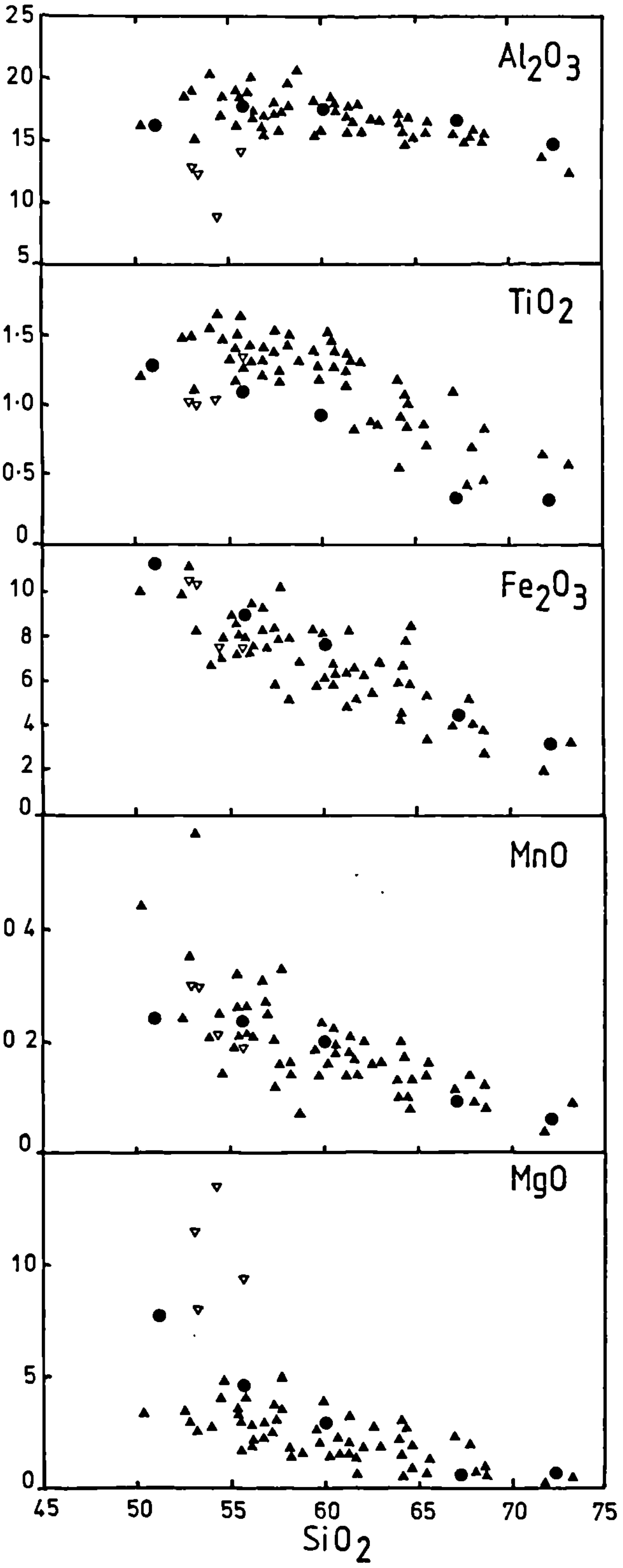


FIG. 5.4a

Shap Volcanics.

SiO2 - Major Oxides
● Average BVG analyses as in
Fig. 5.2 and Appendix Table B4.
▽ High MgO Samples

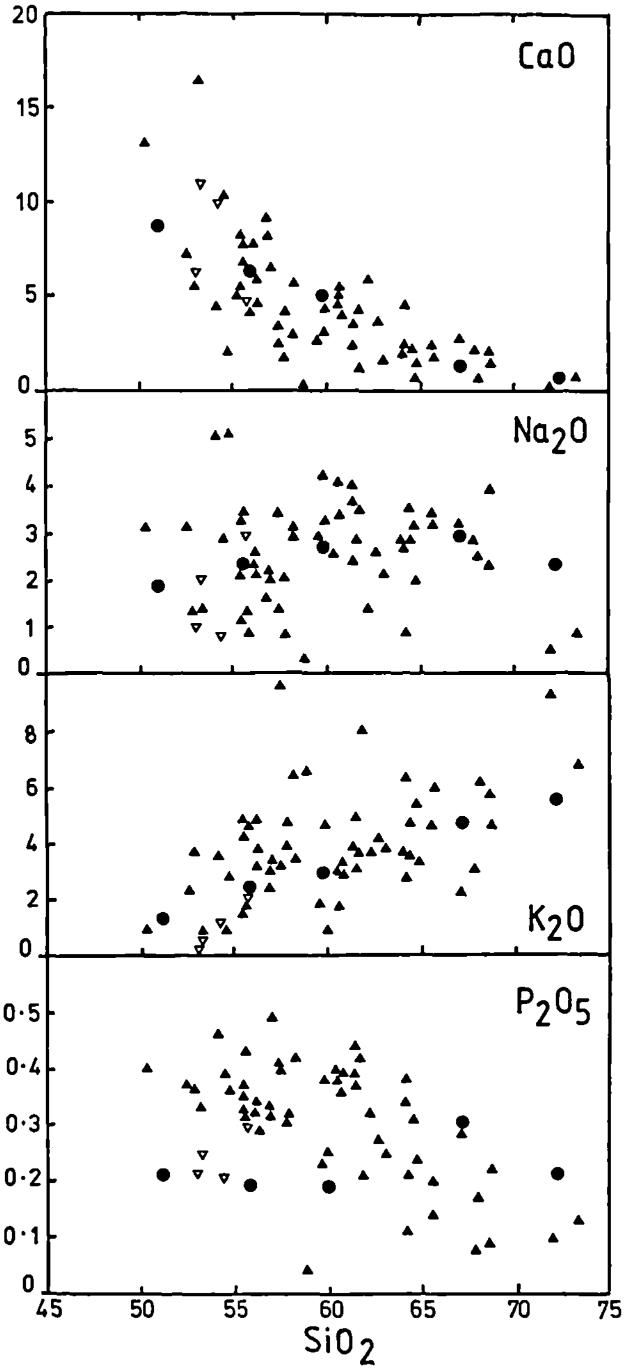


FIG. 5.4b.

SiO2 - Major Oxides (continued).

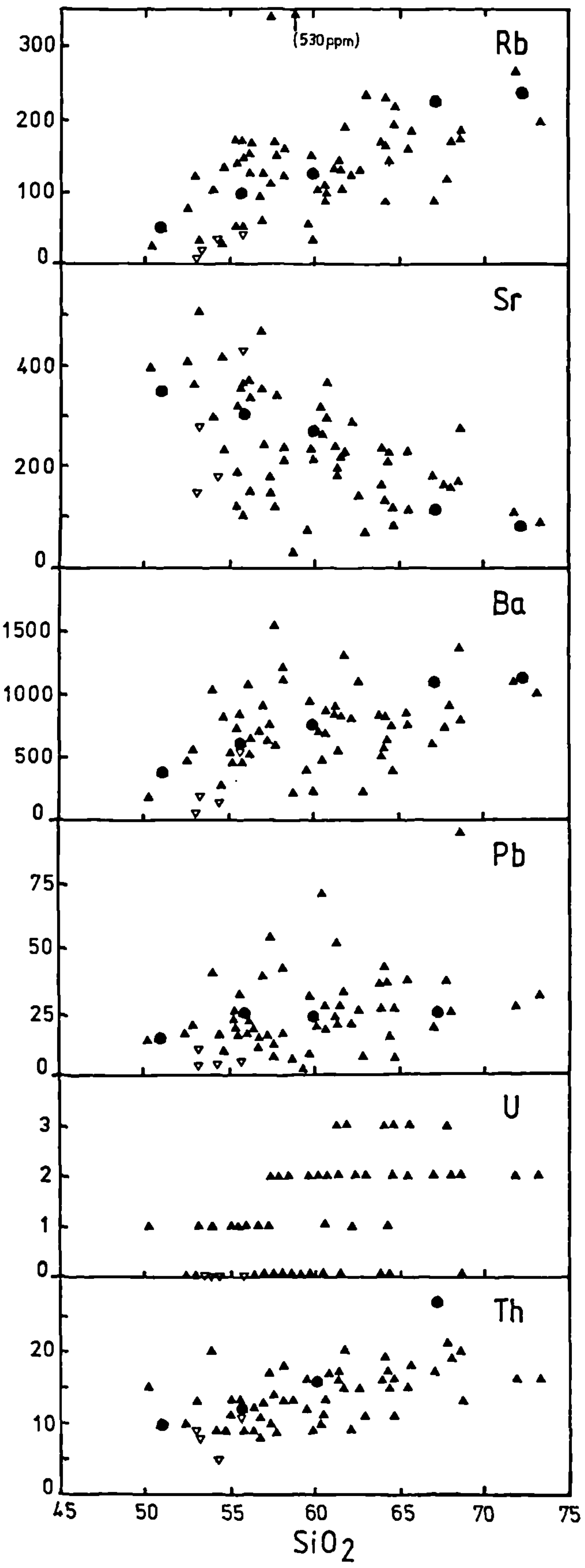


FIG. 5.4c

SiO2 - Group 1 (LFS) elements.

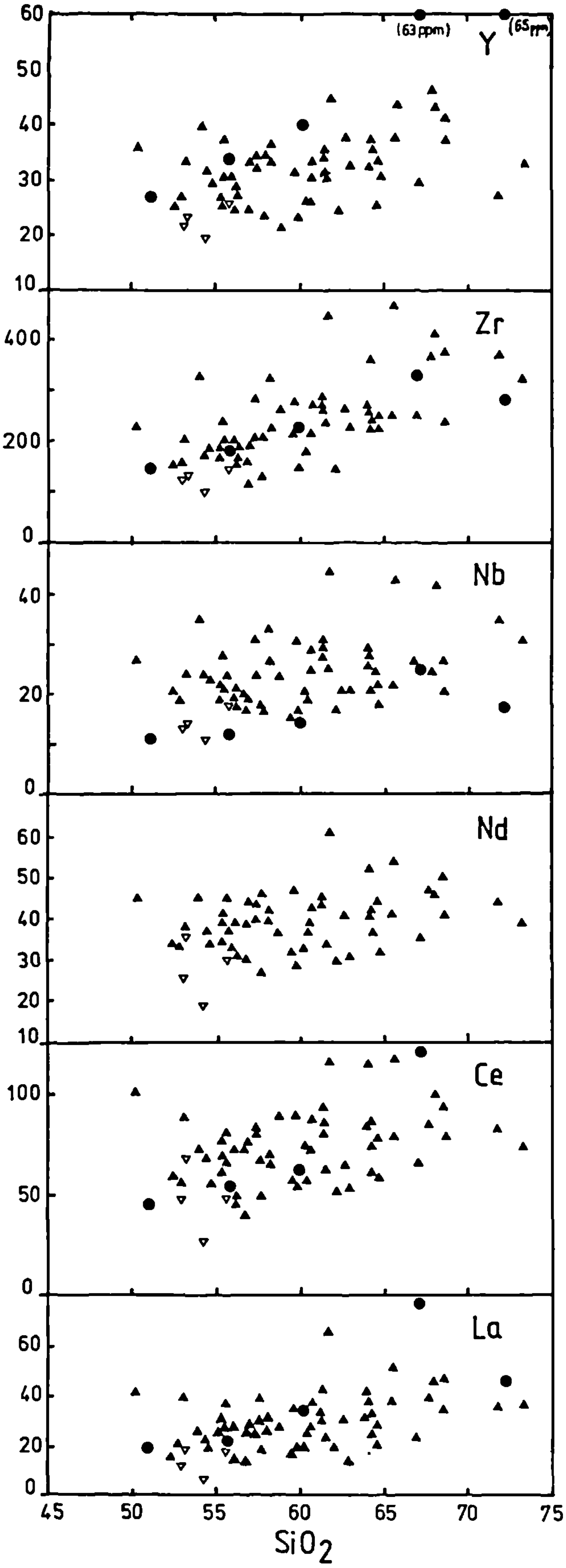


FIG. 5.4d

SiO2 - Group 2 and 3 (HFS/REE) elements.

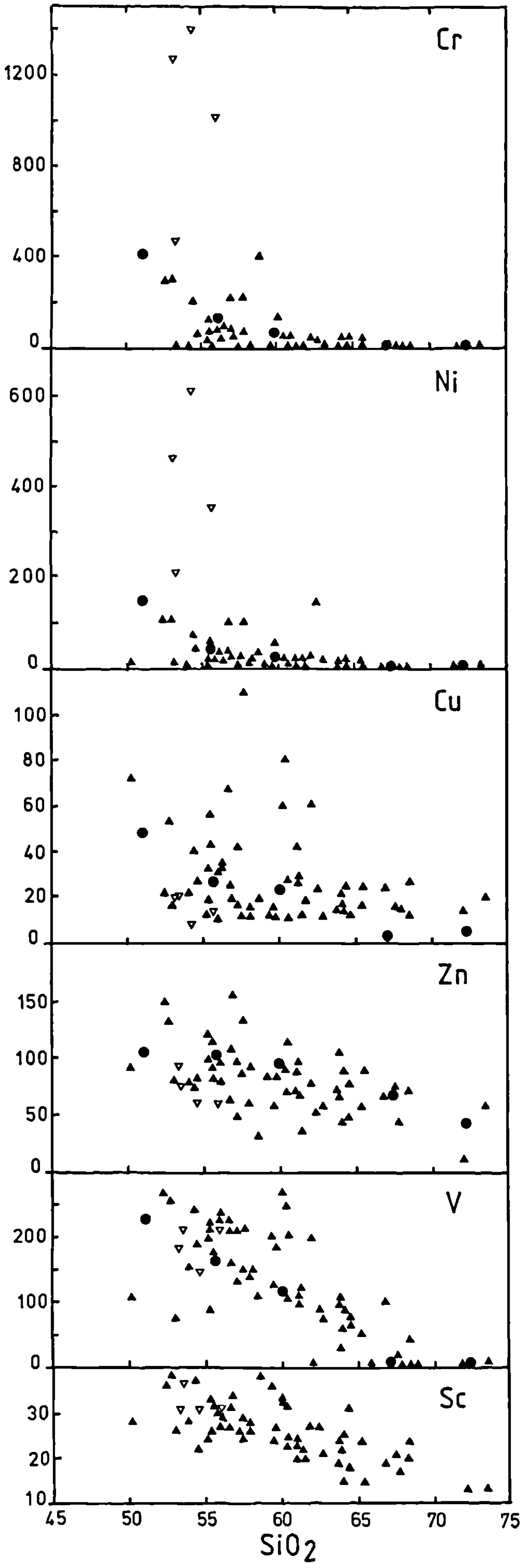


FIG. 5.4e

SiO2 - Group 4 (Transition Metal) elements.

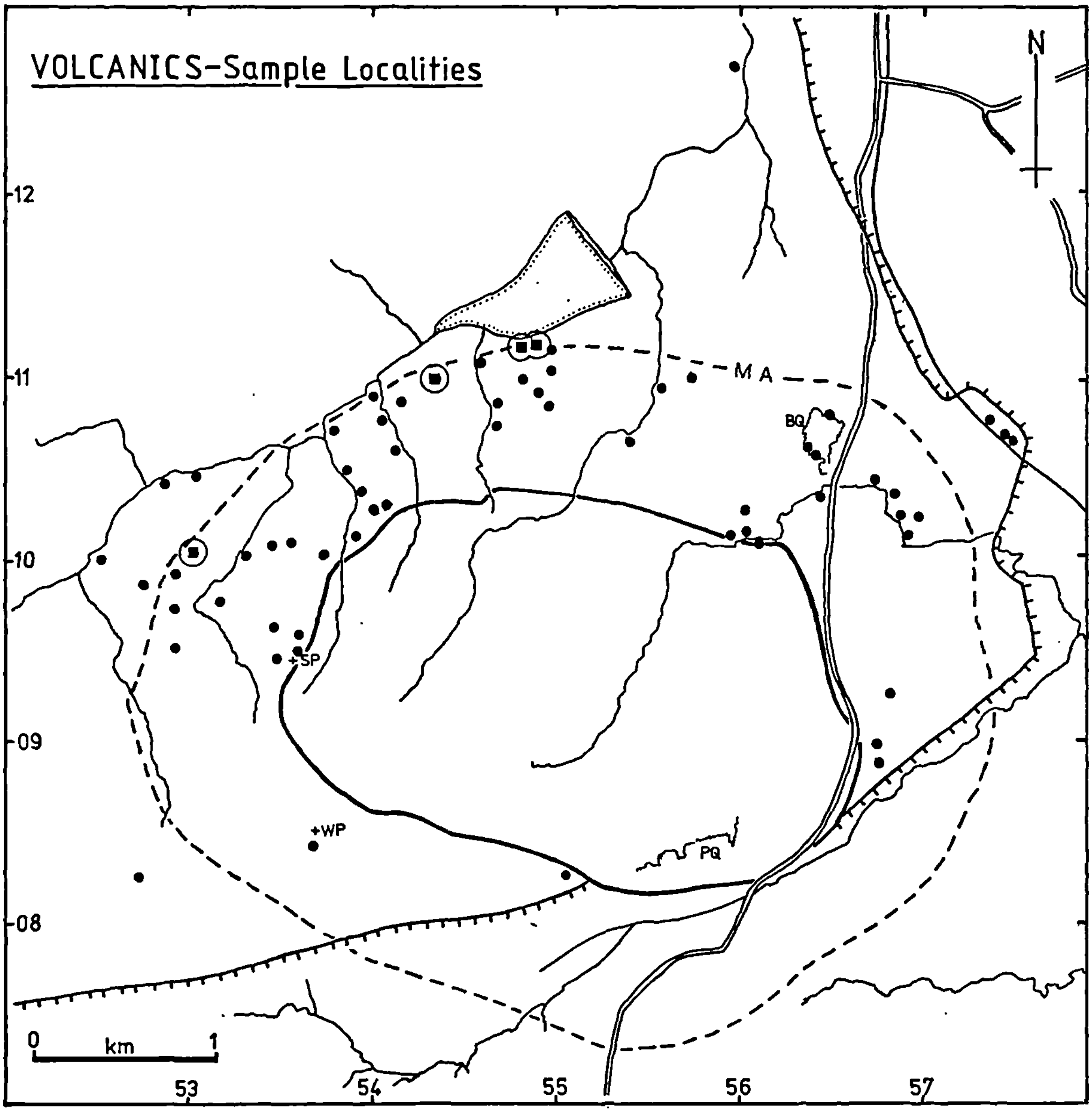


FIG. 5.3

Locations of the volcanic samples analysed in this study.

Ringed locations are of the high-MgO rocks. (■)

MA - Metamorphic aureole.(---) BQ Blue Quarry

+SP - Sleddale Pike PQ Pink Quarry

+WP - Wasdale Pike.

were analysed for major and trace elements and the data are presented in the Appendix and Figs.5.4a-e. Eight of these samples were also analysed for stable isotopes. The location of samples is shown in Fig.5.3 and shows an uneven distribution with a lack of samples to the south west of the granite. There has been a deliberate emphasis on rocks within the aureole, with only 8 samples from outside this region. Rocks showing more extreme alteration such as those containing garnet veins and hydrothermal mineralisation (especially pyritisation) were not analysed but those showing effects such as epidotisation and vesicle metamorphism were included. Samples were mainly drawn from the lavas (which are better exposed than the pyroclastic horizons), although some recrystallised tuffs were included. They were found to vary from 50 to 73 wt % SiO2 (ie. basalt to rhyolite) with andesitic compositions dominating the region (57% of samples) along with basaltic andesites (15%) and dacites (23%).

Care has been taken in discussing the chemistry of these rocks given that they are mainly from the aureole and consequently may have undergone some chemical modification such that conclusions cannot always be drawn from the data. An example of this is the plotting of the data in Figs.5.4a-e against SiO2 which might be expected to be an unreliable index of variation for such a suite of rocks. Examination of Fig.5.4a-e indicates that the samples show good trends of inter-element variation and that using SiO2 as in previous chapters, is not found to create difficulties of interpretation of the data. Further support of this is the fact that correlation coefficients (Appendix, Table F.1) indicate coherent chemical trends against SiO2 and also that there is a good comparison between the Shap data and the average analyses of Borrowdale Volcanic Group rocks of Millward et al. 1978.

It is also apparent that the majority of the data reflect the original chemical composition of the rocks, much of the inter-element scatter being typical of the Borrowdale Volcanics as a whole (section 5.3.1.) and not a function of the contact metamorphism. This so, it is suggested that the metamorphism is generally isochemical apart from isolated samples such as those from granite contact zones.

5.3.2.2. Major Elements.

There is a compositional continuum across the SiO2 range and the data compares well with the trends of the average analyses of Millward et al. 1978. Analyses show typical calc-alkaline variation with well-developed -ve. correlations against SiO2 for all major elements apart from the alkalis. Four samples in particular were found to be significantly different from the main suite of rocks by having generally lower Al2O3, TiO2, P2O5 and higher MgO. Apart from these (which are discussed in section 5.4.2) the trends are typical of those produced by pyroxene and plagioclase crystal fractionation. The basic rocks show low MgO (<5%) and P2O5 appears to behave more regularly than shown by the trend of Millward et al (1978) indicating the possibility of minor apatite fractionation. The alkalis show the broadest scatter, especially Na2O which has no apparent trend and K2O that has a weak +ve. correlation (see Appendix Table F.1). This scatter effect is typical of all Borrowdale Volcanic analyses and not primarily a function of the

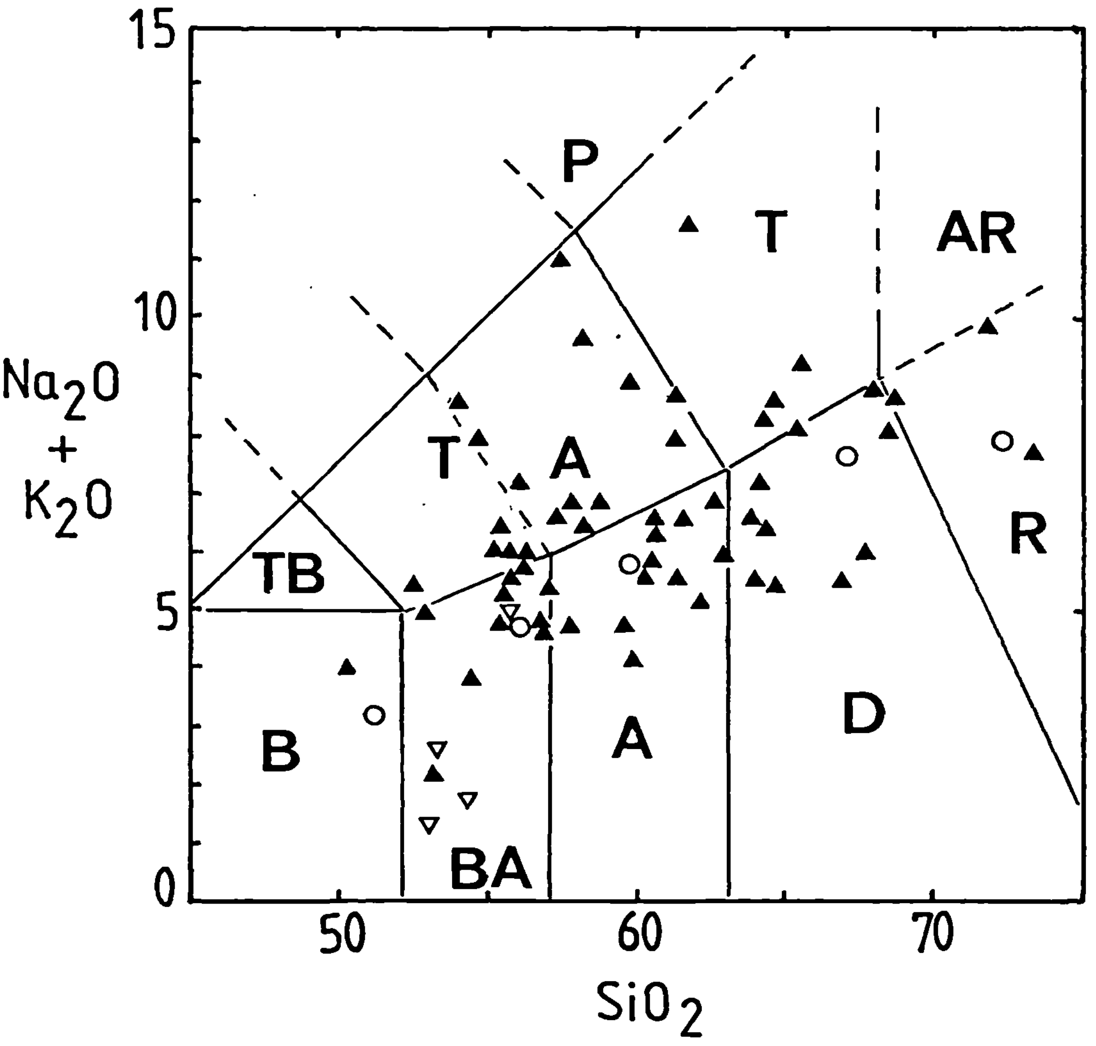


FIG. 5.5

SiO2 - alkalis volcanic classification diagram of the IUGS.

Note the apparently alkali-rich nature of the Shap volcanics (▲).

▽ - High MgO Shap volcanics.

○ - Borrowdale Volcanic Group average (see Fig. 5.2) .

B, BA, A, D, R as in Fig. 5.2

TB -trachy basalt, TA -trachy andesite, T -trachyte, AR - alkali rhyolite, P -phonolite.

contact metamorphism. The plot of SiO_2 against total alkalis ($Na_2O + K_2O$) (Fig. 5.5) shows the compositions of the Shap Volcanics based upon the I.U.G.S. classification scheme. The rocks have a generally alkali-rich nature with many analyses showing a tendency towards trachytic compositions in terms of the classification in Fig.5.5 although sample 536 with 9.60% K_2O is excessively enriched in K_2O, being a granite contact sample. However, most of the andesite samples would be classed as medium-K to high-K rocks by Gill (1981) who divided orogenic andesites from subduction-related volcanism using SiO_2-K_2O.

5.3.2.3. Trace Elements.

The group I (LFS) elements (Fig.5.4c) show +ve correlations with increasing SiO_2, apart from Sr which has an expected -ve. correlation due to plagioclase fractionation. The Rb trend shows remarkably little scatter over a wide range (0-300ppm) with only two samples (536 and 633) departing from the trend with >300ppm Rb which suggests that this expectedly mobile element has remained fixed in the aureole, presumably within the metamorphic biotite. Similarly, U although at low concentrations (<4ppm) has not been leached from the aureole and still shows a weak +ve. correlation with SiO_2 typical of Group 1 elements which (apart from Sr) behave incompatibly in basic to intermediate calc-alkaline volcanic sequences.

The Group 2 elements (HFS) such as Zr, Y, Nb, and REE's all behave incompatibly except perhaps at the most acidic compositions (ie.>70% SiO_2) where possible limited apatite and zircon fractionation may occur. These elements are among those chosen as being immobile during hydrothermal and alteration processes in volcanic rocks (as noted in 5.3.1. above), and, given that this is so at Shap, the concentrations represent original values. Again the samples show +ve. correlations with SiO2 but also a large scatter and a broad range at any given composition.

The Transition Metal Elements (T.M.E.'s) all show low values in the Shap rocks apart from the Ni and Cr of the four high-MgO samples (Fig.5.4e) which have upto 6-fold increases in these two elements. All behave compatibly being partitioned into ferromagnesian minerals which separate early in the chemical evolution of the suite. Many values for Cr and Ni are close to the analytical detection limit even at 55% SiO2, suggesting that extensive fractionation has occurred in order to produce the basic volcanics of the Shap area, there being little evidence of non-evolved volcanic rocks. The largest data scatter occurs with Cu which varies between 10 and 110ppm over the andesitic compositions. This is thought to possibly reflect the effects of minor mineralisation in aureole samples, but it is recognised that concentration of chalcophile elements such as Cu and Zn in subduction-related lavas are generally more variable than in lavas from other tectonic provinces (Davidson 1984).

The enrichment of the Borrowdale Volcanic Group in elements that behave incompatibly tends to suggest affinities to within-plate, continental volcanism. Figs.5.6a and b. show how the Shap basalts and andesites occupy the region between arc and within-plate volcanism based on tectonic discrimination diagrams (Pearce and Cann 1973, Pearce and Gale 1977). Such evidence suggests that the

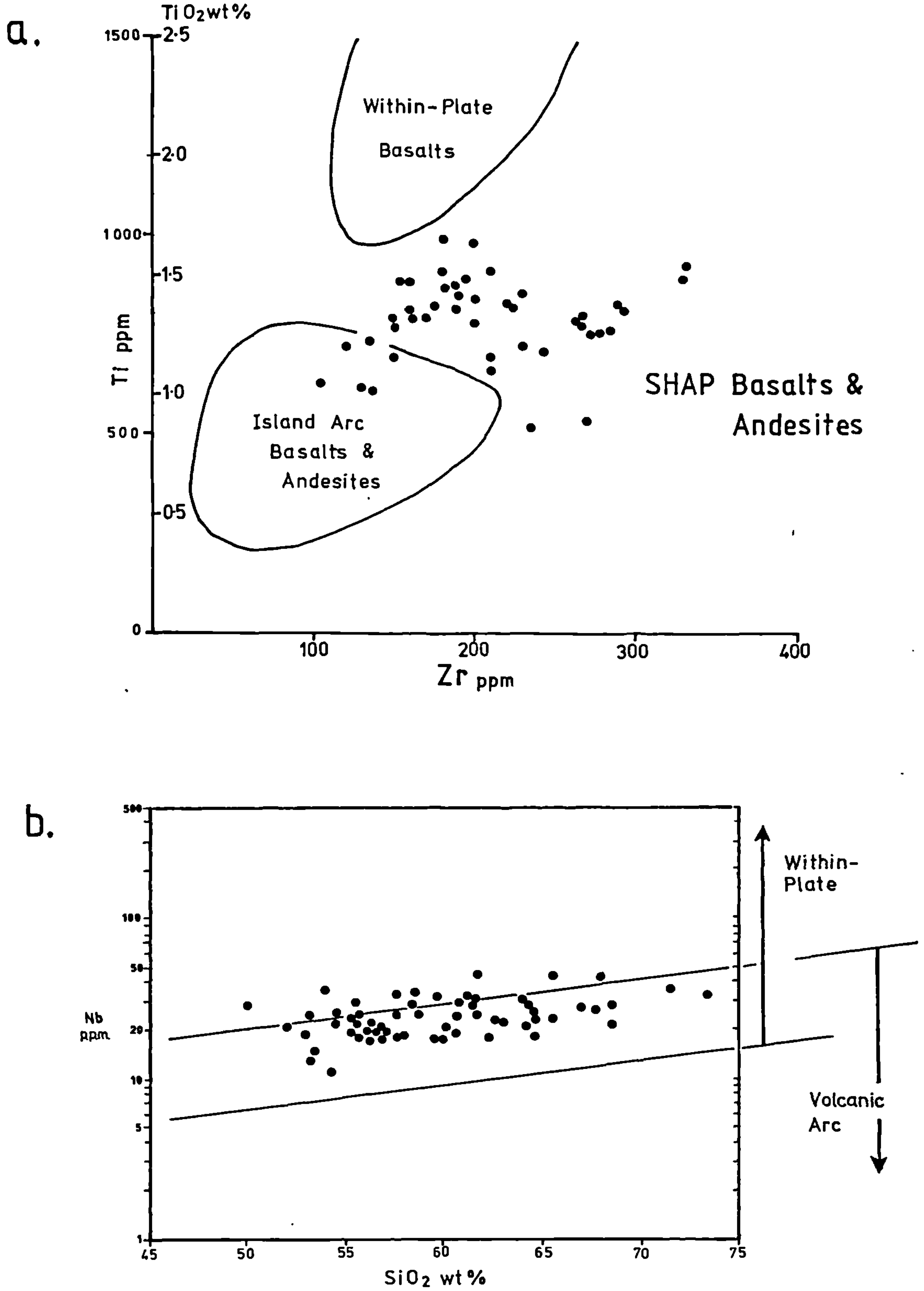


FIG. 5.6

a. Ti - Zr discrimination diagram (Pearce and Cann 1973).

b. Nb - SiO2 discrimination diagram (Pearce and Gale 1977).

Borrowdale Volcanics were erupted in a continental margin rather than island arc environment. The discussion concerning the evidence and nature of the underlying sub-Borrowdale volcanic crust is beyond the scope of this work, but at present only the Skiddaw Slate Group of sediments are known to underlie the Borrowdale Volcanics. There is some evidence of their being involved in the characterisation of the volcanic's chemistry (Thirlwall and Fitton 1983) but it is thought that such magma enrichment in incompatible elements as seen in Fig.5.6 is a function of deeper crustal effects than is indicated by the present relative high level positions of the Skiddaw Slate and Borrowdale Volcanic Groups.

5.3.2.4. Stable Isotopes.

Eight volcanic samples were analysed for oxygen isotopes, six of which were also analysed for hydrogen. Samples were chosen to traverse the metamorphic aureole from the contact to a distance of about 900m from the granite, and encompass a range of compositions from basaltic andesite to dacite. The data are presented below and show a wide range in δO18 (8.1 to 10.8‰) and δD (-54 to -85‰).

A recent isotopic study of low-grade alteration of Cumbrian Palaeozoic rocks by Thomas et al. (1985) also involved the analysis of 24 volcanic samples of unquoted composition. They also found a wide range in isotopic composition (6.2 to 10.9‰ and -37 to -56‰) not dissimilar to that of Shap. They stated that the Lake District volcanic rocks were relatively enriched in O18 compared to fresh, unaltered rocks due to fluid-rock interaction during burial

Table 5.1 Stable Isotope Data-Shap Volcanics.

Sample No.	% SiO2	Dist. (m)	δO18 ‰	δD ‰
536	57.4	0	9.70	-70.2
538	53.1	100	9.11	nd
540	61.3	540	10.65	nd
542	64.0	380	10.40	-63.7
543	55.4	900	8.91	-85.3
545	53.0	750	8.11	-71.4
546	64.1	500	10.79	-54.5
547	67.0	350	10.83	-55.9

Dist.(m) : Distance in metres from the Granite
nd : Not Determined

metamorphism, the fluid being enriched in δD and of lower δO18 values.

The values of unaltered volcanic rocks have traditionally been taken from such work as Taylor (1968), who reviewed the isotope geochemistry of igneous rocks. Taylor (op cit) showed that δO18 values for such fresh rocks increased from around 6‰ to 12‰ with increasing %SiO2 (see Chapter 3.4.1) due to the affinity of O18 for Si-O bonded oxygen. Consequently, rocks such as andesites have been assigned δO18 values of around 6 to 8‰. More recent stable isotope studies of volcanic rocks (eg. Davidson 1984) show this to be a misleading assumption and that fresh rocks of the same composition from the same volcanic centres can have widely differing δO18 values. In order to reduce the effects of the possible isotopic correlation with composition Garlick (1966) introduced a chemical index based on the ratios of the major oxides to which δO18 values could be normalised. In this way, non-magmatic isotopic effects on the δO18 value of a sample such as hydrothermal alteration or weathering become more evident.

Davidson (1984) analysed the oxygen isotopes of 28 fresh island arc volcanic samples during a geochemical investigation of the Lesser Antilles. His samples also covered the compositions basalt to dacite and ranged in values from 6 to 14‰ (Fig.5.7.a). When 'corrected' by the Garlick Index, those fresh samples still showed a wide span of δ018 values with andesites ranging in value from δ018 5 to 10‰. It is therefore evident that samples not having 018 values as traditionally expected do not necessarily have to have undergone isotopic change by interaction with a fluid with a different isotope character (eg. seawater, meteoric water, hydrothermal fluids etc.) but can have variable isotopic characteristics inherited during the magma generation process (Davidson 1984).

The intention at Shap was to identify whether there had been a stable isotopic change in the aureole volcanic rocks due to the granite's intrusion. There are many documented accounts of pluton-country rock interaction resulting in stable isotopic modification in the country rocks (eg. Forester and Taylor 1976, Lipman and Friedman 1975, Nagy and Parmentier 1982, Sheppard 1977, Sheppard and Gustafson 1976, Taylor 1971, Taylor and Forester 1971,1979.). Fluid interactions between plutons and their surroundings as described by the above authors usually involved a fluid emanating from the intrusion or the mobilisation of a fluid already in the country rocks such as meteoric water. The mobilisation of such fluids usually required the heat of the pluton to establish a thermal gradient along which the fluids would travel. In well developed cases, convective fluid motion might be established resulting in fluids repeatedly passing through both the pluton and the country

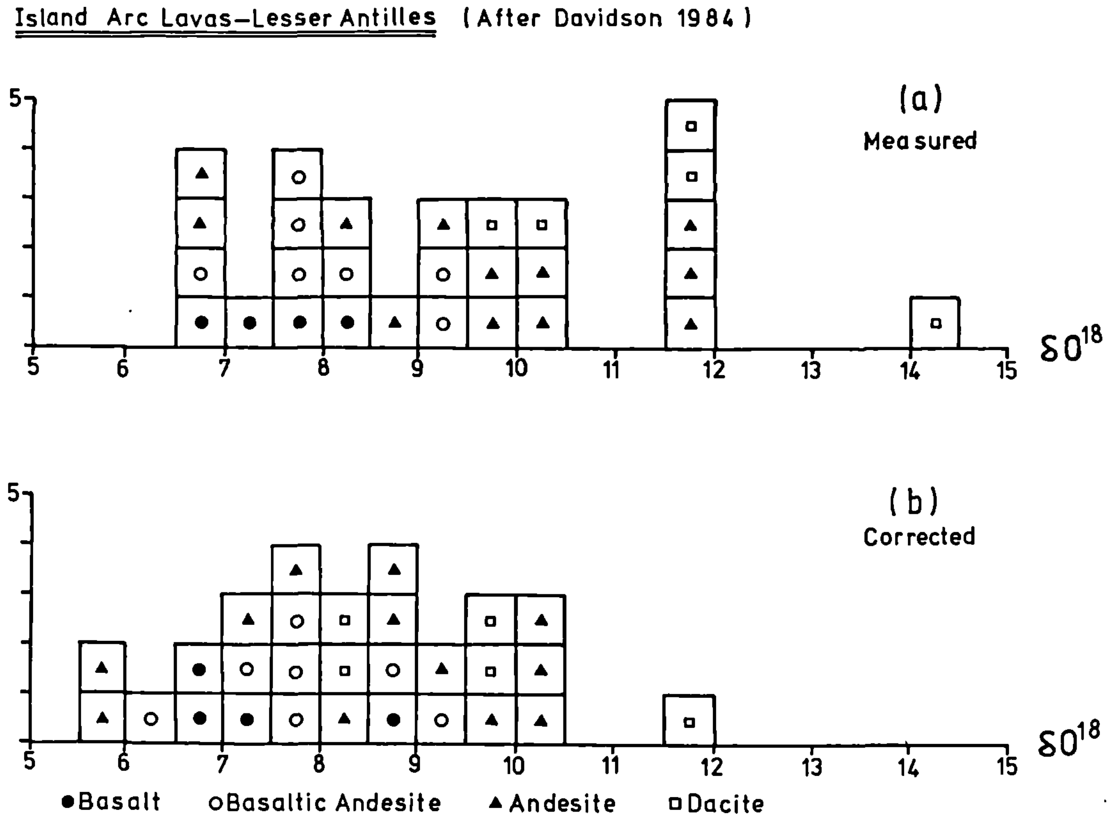


FIG. 5.7

Whole-rock isotope data of a suite of basaltic to dacitic modern volcanic rocks from the Lesser Antilles. (After Davidson 1984).

The range is wider than expected from traditional studies (eg. Taylor 1968), even when corrected by the Garlick Index for fractionation effects.

rocks. Such interaction then modifies the isotopic composition of either one or both of the pluton and the country rocks. It has already been stated (Chapter 3) that the granite and it's hydrothermal alteration at Shap are isotopically the same, the alteration occurring in a closed system. For the Shap volcanic samples the plot of δO18 and δD compositions against position in the aureole (Fig. 5.8) shows a weak trend of increasing isotopic values from those expected for intermediate volcanics (eg. δO18 8‰) to those of the granite (eg. δO18 11‰) as the contact is approached, with the possibility of an apparent isotopic 'mixing line' across the aureole. A similar trend is shown by δD where isotope values approach the isotopic composition of the Shap Granite (Fig 5.9a). However, both effects are not real but are actually a function of the whole-rock geochemistry of the samples. Plotting δO18 against selected elements (Fig. 5.9b) shows an unequivocal correlation between isotope composition and original chemical composition of the sample.

Thus the δO18-distance trend is purely an accidental function of the data. From these analyses, it can be seen that there has been no input of magmatic or hydrothermal fluids from the granite into the aureole. There is also no evidence of any other isotopically distinct fluid (eg meteoric water) being involved. Consequently, hydration and dehydration metamorphic reactions in the aureole occurred with a fluid in isotopic equilibrium with the host volcanic rocks and which was present prior to the granite's intrusion.

Thomas et al. (1985) have suggested that the Borrowdale Volcanics had possibly interacted with seawater which had

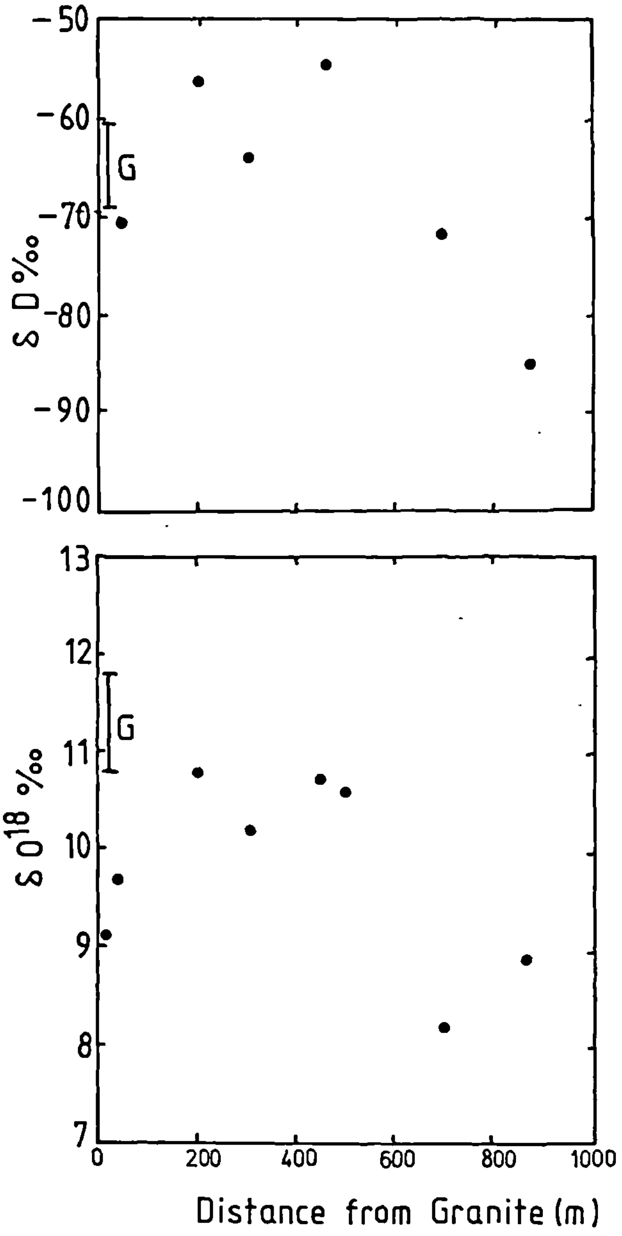
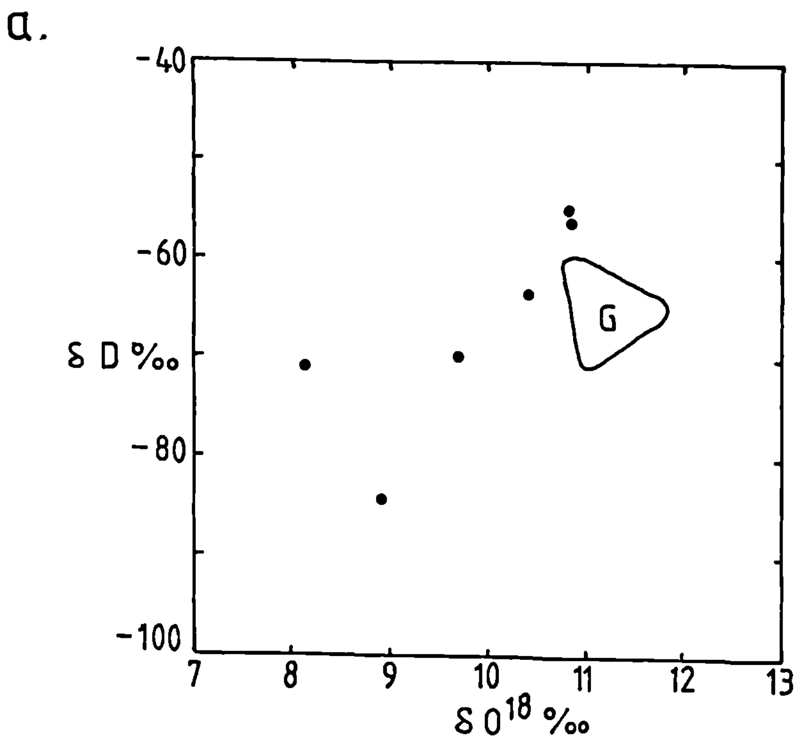


FIG. 5.8

Variation in stable isotope ratios in the Shap volcanics relative to position in the metamorphic aureole.

G - isotopic range of the Shap Granite.



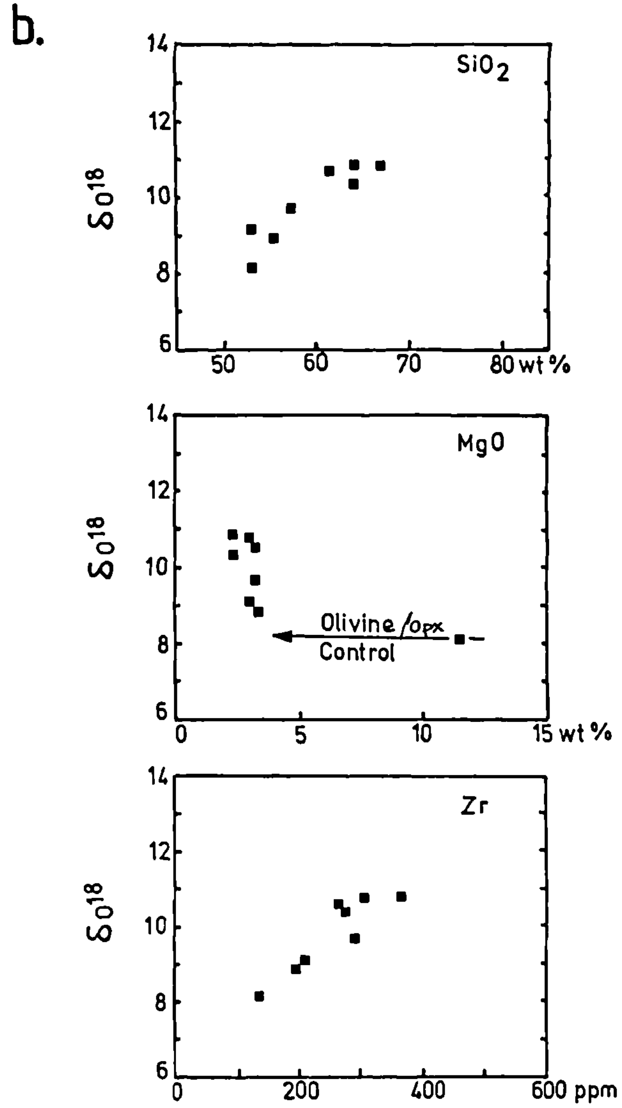


FIG. 5.9a

Stable isotope variation in the Shap volcanics relative to the granite (G).

FIG. 5.9b

Examples of variation in δO^{18} with Chemistry.

mostly been driven off during Caledonian burial and deformation. Any remaining water in the volcanics was incorporated into secondary epidote and chlorite in the volcanics and underwent equilibriation by isotopic exchange with the remaining host minerals until attaining the isotopic values we measure today.

5.4. Discussion.

5.4.1. Evidence of Chemical Addition.

Although most of the samples show broad but coherent elemental trends, some isolated examples of single samples with significantly higher than average concentrations of some elements is evident from examination of Figs. 5.4a-e. A number of samples were deliberately collected from very close to the granite margin in order to try to establish whether any chemical transfer had occurred at or near the contact. Firman (1953a) suggested that a reciprocal exchange of certain elements had occurred over a few centimetres at the granite-country rock junction. He also thought that elements had been mobilised in the aureole by 'granite fluids' involving Si, Na, K and possibly Ti, Fe, Ca, and Al, with Na, K, and Ca particularly involved at the granite contacts.

A more recent study by Roberts (1983) about the Skiddaw Granite roof zone and its associated hornfels indicated that a hydrothermal fluid from the granite introduced K2O upto 15m into the Skiddaw Slate country rocks, the process leaching upto 85% of the Na2O from the hornfels. The fluid input promoted retrograde metamorphic reactions (eg. biotite to muscovite, cordierite to chlorite) which involved the bulk transfer of K, Na, Al, Mg, Fe. Some of these elements may have been fixed locally in metal oxides and sulphides but the relocation of others, especially the Na2O is not known. A fluid inclusion study of the associated quartz and mineral veins of Skiddaw (Shepperd et al., 1976) shows the hydrothermal fluid to lack associated halogens and in contrast to Roberts (op.cit.) appears to be a brine of a non-magmatic composition, the fluid not emanating from the granite but generated from the surrounding sediments

Barratt's (1969) study of the Skiddaw Granite area attributed the retrograde reactions in the sediments about the granite contact to alkali metasomatism involving K, Rb, Li, and Pb introduced from the granite. His zone of metasomatism was narrower than of Roberts (1983), being only 30cm wide.

Evidence of chemical addition at Shap is very limited. Eight samples were collected within 40m of the granite, of which half were from within less than 1m of the contact. Within this group there was found to be enrichments in Pb, Ba, K2O and Rb, though usually not in large increases over normal expected levels. The overall scatter in data does not allow an appreciation of Na2O variation at the contact and the extent of hydration (assessed as loss on Ignition) appears similar to that of the rest of the aureole. Loss on Ignition for the aureole samples is not high (1.50 ± 0.82 (1.s.d.) wt %), the values being not dissimilar to those for fresh rocks. Anomalous levels of elements are also found away from the contact, examples being Na2O (sample 630 at 920m, 639 at 1150m), Rb (633 at 310m) and Ba (616 at 650m, 641 at 1000m). From this it is apparent that there is little chemical change at the granite margin, an aspect of the granite-aureole interaction supported by the other chemical and stable isotope results presented above. It is of interest to note that the elements involved in variations in chemistry near the contact are those likely to be involved in the metasomatic development of orthoclase in the granite, being enriched in the later stages of the granite's consolidation. This being so, any transfer of these elements to the contact zone from the granite would have occurred at near or above solidus temperatures. Any hydrothermal fluid in the granite does not appear to have migrated into the aureole except perhaps in the region of the Blue Quarry.

The extent of alteration, chemical reaction and mineralisation in the Blue Quarry suggests that this atypical zone is a product of differing conditions to the remainder of the aureole. Geophysical evidence (Fig. 2.8) indicates that the Shap Granite has a steep northeasterly-dipping wall unlike the remainder of the pluton. The consequence of this is that the heat flow through the country rocks above the pluton wall would be expected to be higher in this region than elsewhere, which in consequence would promote metamorphism and chemical movement. The development of the garnet veins and widespread mineralisation at this location would also probably require the input of a fluid phase and extra chemical components. Neither the granite nor the local volcanic country rocks appear to have been leached sufficiently to have provided all the required materials. It is possible that they may have been scavenged from the underlying rocks into which the granite was emplaced. Cross-sections based on available surface and geophysical evidence (eg. Fig. 2.7) show the

Shap region to be underlain by Skiddaw Slate Group sediments below a thin (<2km) local covering of volcanic rocks. Such a pile of sediments may have been the source rocks from which some of the chemical material involved in the reactions now seen in the Blue Quarry area was obtained. The origin of any transporting fluid involved in this process is not known but is likely to have been gained from the underlying granite or sediments rather than the volcanic rocks.

5.4.2. The High MgO Volcanic Samples.

Rocks with the more primitive characteristic of high MgO are not common in the Borrowdale Volcanic Group. Four examples were found at Shap (545,550,551,558) to be significantly enriched in MgO, Ni, and Cr. Thin section examination has shown them to be mainly composed of secondary chlorite and relic minor plagioclase and Fe-Ti oxides such that evidence of much of the original mineralogy is lacking. Based on the observations of chemical trends in the Borrowdale Volcanic Group in general it is likely that this rock would be a basalt with pyroxene ± olivine ± spinel ± plagioclase as its mineral composition. Comparison with selected elements of the average basalt of Millward et al. (1978) below, shows poor correspondence for MgO, Ni, Cr, and with the basaltic andesite, but similarities in concentrations of other elements. High MgO, Ni, Cr andesites are known to occur in Pacific island arcs within mainly tholeiitic volcanic sequences. They are also characterised by relatively high SiO2 (55%) and olivine and pyroxene mineralogies with little or no plagioclase feldspar (Hickey and Frey, 1982). They are usually associated with the early stages of arc volcanism which is in contrast to the Wrengill

Andesite formation at Shap which occupies the upper stratigraphic portions of the Borrowdale Volcanic Group.

Table 5.2 Comparison of the High MgO Shap Volcanics
to Average Borrowdale Volcanic Group
Basalt and Basaltic Andesite (Millward et al 1978)
and to Typical Boninites (Hickey and Frey 1982)

		545	550	551	558	Bas.	B.And.	Bon.
%	SiO2	53	54	55	53	51	56	57
	MgO	12	14	9	8	8	5	13
	TiO2	1.0	1.0	1.3	1.0	1.3	1.1	<0.3
	CaO	6	10	10	11	9	7	8
	K2O	0.3	1.0	2.1	0.6	1.3	2.4	0.5
ppm	Cr	1270	1397	1018	47	410	123	1250
	Ni	463	611	352	206	145	38	320
	Rb	7	34	42	18	49	97	10
	Sr	146	180	431	279	346	310	89
	Ba	40	133	550	164	349	586	31
	Y	22	20	26	24	27	34	6
	Zr	131	104	151	137	141	179	33

When compared with an average boninite calculated from Hickey and Frey (op.cit.) (Table 5.2), the Shap rocks show some similarites in SiO2, MgO, Ni and Cr but poor correlation with most of the other elements especially the incompatible elements such as Ba, Y, Zr. Given that the Shap rocks are of calc-alkaline character, this relative enrichment in incompatible elements compared to the tholeiitic boninites is not surprising. Therefore it is thought that the four Shap rocks are not boninitic in character but represent basalts or basaltic andesites, that contain accumulations of fractionating phases, probably olivine or orthopyroxene with some spinels, producing some non-typical concentrations of especially high MgO. This apart, they do not appear to represent a less fractionated or parental magma composition to the more typical Borrowdale Volcanics.

5.4.3. Metamorphic Reactions in the Shap Aureole.

The more basic volcanic rocks show the most useful metamorphic reactions with the generation of calc-silicate phases along with biotite, plagioclase, quartz etc. The major chemical components and the constituent minerals of these metabasic rocks can be plotted on an ACF diagram which allow representation of the paragenetic relations among the more abundant mineral phases. Minerals found at Shap are plotted in Fig.5.10a and also shown is the compositional region of typical calk-alkaline basalts and andesites. Traditionally, metamorphic grades in contact metamorphism have been named after the equivalent regional metamorphic terms (eg. greenschist, amphibolite etc.) especially where the contact metamorphism is essentially thermal and isochemical, which is the case at Shap. All reactions have been predicted to have occurred at relatively low pressures (<3kb). Within the aureole biotite, chlorite, and epidote represent the lowest facies of metamorphism, being albite-epidote hornfels or prehnite-pumpellyite to lower greenschist. Quartz and biotite are usually present in both facies apart from near the granite contact where biotite breakdown may occur.

With increasing grade (to greenschist), actinolite and plagioclase (Ab-rich) can be produced which at the generally highest facies (amphibolite), then react to produce hornblende and to a lesser extent clinopyroxene and garnet. This facies may be exceeded by a high temperature pyroxene hornfels facies which may also contain biotite, plagioclase, quartz and hornblende but can only be accurately

FIG. 5.10 a & b.

FIG. 5.10a

ACF tie-line diagrams of the calc-silicate minerals in metamorphosed basic volcanic rocks.

(a) The various phases found in the Shap area volcanics.

Also shown is the field of the composition of basalts and andesites. (Miyashiro 1973).

(b) Assemblages typical of low grade regional metamorphism.

(c) Minerals typical of medium to high grade contact metamorphism of basic rocks.

All diagrams have excess SiO2 and the plagioclase has an albite component.

A $Al_2O_3 - (Na_2O + K_2O)$, C $CaO - \frac{10}{3} P_2O_5$, F $MgO + FeO - (Fe_2O_3 + TiO_2)$

FIG. 5.10b.

SiO2-CaO-MgO (+H2O and CO2) tie-line diagrams to illustrate the progressive decarbonation reactions in the calcareous sediments in the Shap metamorphic aureole, representing the equivalent of original (a) greenschist (b) and lower amphibolite(C)facies with wollastonite-diopside representing the highest local metamorphic grade.

MgO -rich phases not included.

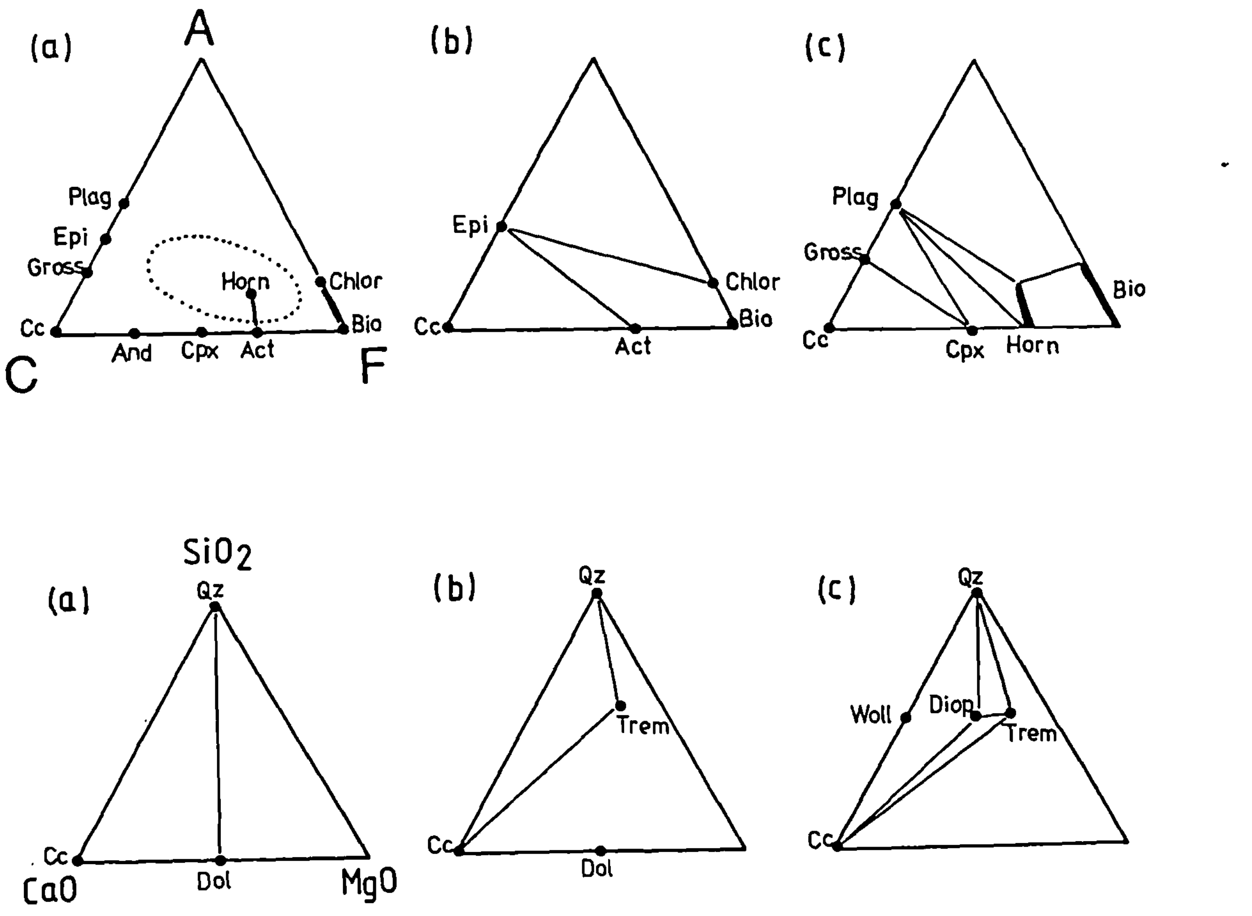

(a)
A
Plag
Epi
Gross
Horn
Chlor
Bio
Cc
And
Cpx
Act
C
F
(b)
Epi
Chlor
Bio
Cc
Act
(c)
Plag
Gross
Bio
Cc
Cpx
Horn
SiO2
(a)
Qz
Cc
CaO
Dol
MgO
(b)
Qz
Trem
Cc
Dol
(c)
Qz
Woll
Diop
Trem
Cc

FIG. 5,10 a & b.

characterised by the occurrence of diopsidic pyroxene which has not been identified at Shap.

Estimation of reaction temperatures is difficult as most phases show non-simple compositions some with associated solid solution. Reaction curves are usually based on pure end-member components which may grossly simplify the actual case. Given this limitation Miyashiro (1973) quotes some approximate temperatures for metabasic reactions at low pressure.

Na-zeolite + Quartz = Albite + H2O (180°C)
Epidote + Quartz = Garnet + Anorthite + H2O (400°C)
Epidote + Albite = Ca-rich Plagioclase (500°C)

The reaction noted near the contact of
Biotite = Orthoclase + Magnetite + H2O
has been studied by Wones and Eugster (1965) but was found to be critically dependant on oxygen fugacity and the Fe/Mg ratio of the biotite. The stability of biotite was found to range over 400° to 800°C and it is not profitable to attempt to estimate metamorphic temperatures from this reaction. What can be noted is that temperatures of reactions in the metabasites appear to be at or above 400°C near the granite.

The calc-silicate reactions and the production of tremolite, diopside and wollastonite in the calcareous Silurian and Upper Ordovician sediments allow a more definite temperature assessment to be made. Again reactions can be shown on a triangular plot, (Fig.5.10b). The lowest facies (greenschist) results in the development of tremolite from reaction between quartz and dolomite. At low amphibolite facies, tremolite reacts to produce diopside. The highest grade noted at Shap is defined by the production of wollastonite. The temperature at which these reactions occur is critically dependent on the composition of the fluid phase which is taken as a H2O-CO2 mixture. Curves for the above reactions are shown in Fig.5.11 and for the lower metamorphic grades they are not particularly sensitive to pressure. It can be seen that with very H2O-rich fluids (ie XCO2 <0.1) reactions to form tremolite or diopside can be of the order of 100°C below typical estimates of formation temperatures of about 450°C and 500°C respectively. The variation in fluid composition is very critical in predicting the reaction temperature to produce wollastonite. As it can be seen in Fig. 5.11, this may vary between 400°C and 730°C, the slope of the reaction curve being very steep relative to the other reactions. Given these limitations, the growth of wollastonite suggests temperature near the granite (eg. at Wasdale Farm) of the order of 400° C and likely in excess of 500°C.

Lastly, the production of sillimanite in some aluminous Silurian sediments is also an indication of relatively high metamorphic temperatures in the aureole. The aluminosilicate triple point of about 550° C defines the lower temperature limit of sillimanite stability (Richardson et al. 1969). This point is taken at 5kb, and, assuming a pressure in the Shap aureole of <3kb, the appearance of sillimanite near the granite would suggest that temperatures may have locally reached in excess of 600°C.

To summarise, it is not possible to accurately define metamorphic conditions within the aureole at Shap apart from to say that much of the aureole appears to have remained at moderately low temperature (<300°C) except for near to the

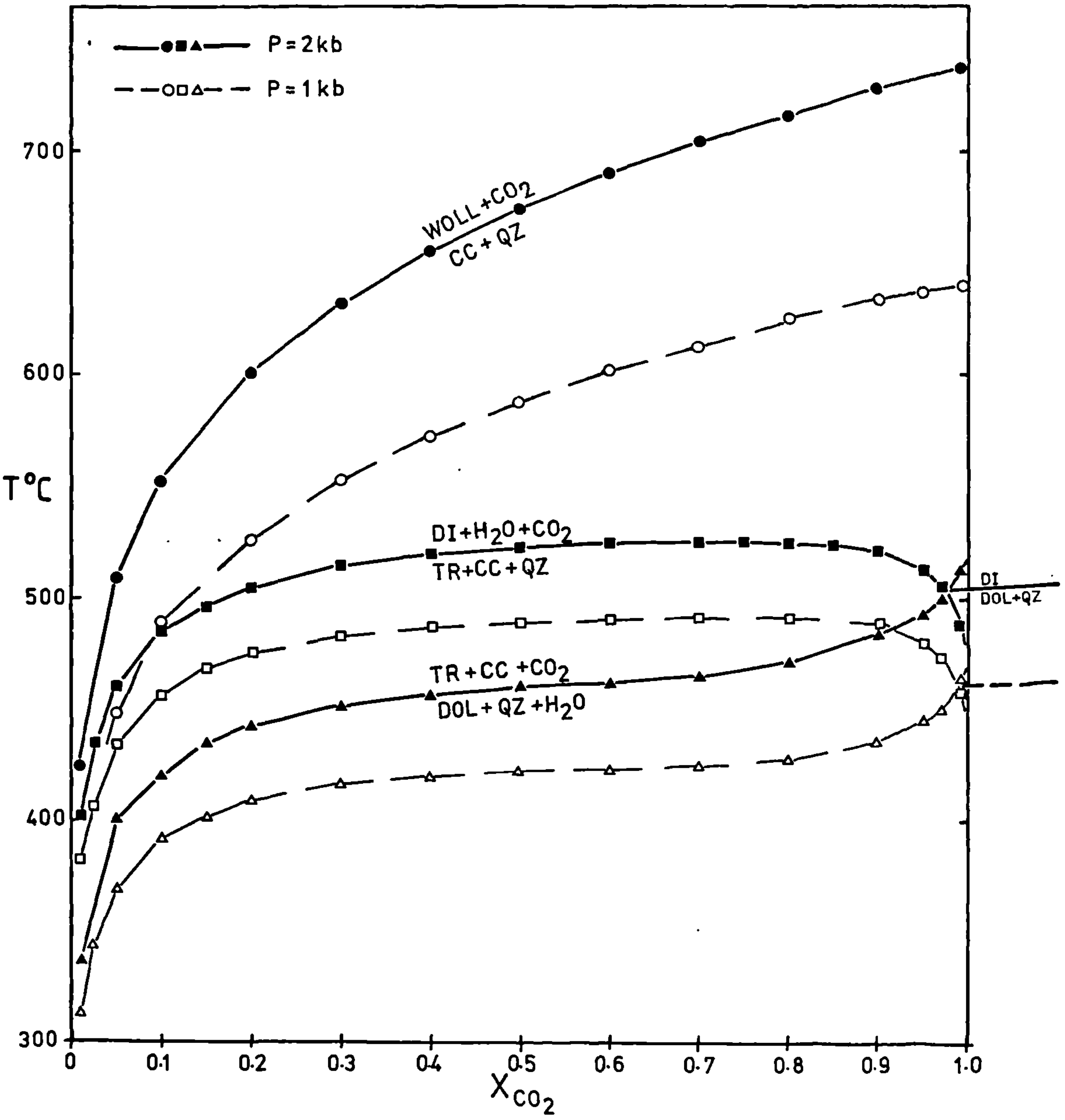


FIG. 5.11

T-X CO_2 diagram showing the calc-silicate curves at 1 and 2kb involving wollastonite (WOLL), diopside (DI), tremolite (TR), dolomite (DOL), calcite (CC), quartz (QZ), H2O and CO2.

Curves calculated by the method of Powell (1978).

contact with the pluton where temperatures reached values similar to those of the granite magma.

5.5. Conclusions.

1. The volcanic rocks at Shap are dominantly andesitic in composition and chemically are typical of the calc-alkaline Borrowdale Volcanic Group as a whole.

2. Contact metamorphism has resulted in calc-silicate assemblages overprinting an otherwise low-grade regional metamorphism.

3. Chemical interaction between the granite and the country rocks is minimal apart from the localised effects at the contact.

4. Chemical and isotopic evidence shows the metamorphism to be essentially isochemical and thermal.

5. The development of garnet veins in the Blue Quarry is thought to be atypical and to represent a localised metamorphic/metasomatic event promoted by relatively high heat flow.

6. Estimates of aureole temperatures suggest that strong thermal metamorphism was restricted to a narrow zone adjacent to the granite.

CHAPTER 6 XENOLITHS.

6.1 Introduction.

The occurrence of xenoliths and their general character at Shap has already been mentioned (Chapter 2.2.4). They are best displayed in the Pink Quarries where they are not uncommon. Elsewhere they are difficult to locate though small (>15cm) examples have been found about the northern margin of the granite. The xenoliths described in this study are of a similar character being mainly rounded, melanocratic, medium or fine-grained rocks of variable size (Plate 1.c, and Plate 13). Less commonly, coarse-grained varieties not dissimilar to the granite can also be seen. A striking feature of many xenoliths is that they contain orthoclase megacrysts of similar type to those in the granite. Evidence of obvious sedimentary or volcanic country rocks was not found although these have been noted on rare occasions by other workers (eg. Grantham 1928, R. Firman, pers. comm.). The presence of xenoliths at Shap has long been of interest with early descriptions by Phillips (1880, 1882) who noted the growth of orthoclase across granite-xenolith contacts, a feature which is readily seen in the granite quarries (Plate 13.d). Harker and Marr (1891) gave a short petrological account of the xenoliths similar to that of Phillips (op. cit.). They noticed the megacrysts in the xenoliths were often more outlined than in the granite and that the highly altered fragments of country rock never contained orthoclase megacrysts. Additionally, their samples had considerably higher specific gravity (density) than the granite thought to be due to the abundant apatite, sphene, and biotite which this and other xenoliths contained. Plagioclase feldspar was found to be concentrically zoned and some of the orthoclase megacrysts to have plagioclase and quartz-rich borders or rims.

Grantham (1928) further described and analysed a few xenoliths which included a calc-silicate hornfels which was thought to be an andesitic inclusion from the volcanic country rocks. He also described xenoliths of an intermediate character between the typical dark, fine-grained varieties and the host granite, these xenoliths being termed 'early basic granite'. The calc-silicate hornfels xenolith contained diopside, wollastonite, chlorite, sericite, pyrite and quartz, an assemblage not unlike those described in Chapter 5 for the calcareous meta-sediments. The hornfelsed volcanic rock (57% SiO_2) contained a high proportion of biotite as well as hornblende, sphene, magnetite, epidote, granular feldspar and quartz. The description of the more typical basic xenoliths does not differ significantly from that of Harker and Marr (1893) with the abundance of plagioclase, biotite, sphene and apatite being again described. An interesting feature is the hydrothermal alteration within the xenoliths. When transected by hydrothermal veins, groundmass plagioclase and also the white rims of the megacrysts become reddened. As in the granite, this reddening is due to the plagioclase and biotite alteration which appears to leave the megacrysts unaffected (Plate 7c). Grantham (1928) concluded his xenolith description with the observation that the rounded character of the xenoliths suggested extensive corrosion and granitisation of locally-derived volcanic (andesitic) material and that this process contaminated the granite to produce the high content of biotite and sphene found in the granite.

Such an interactive relationship between xenolith and host was investigated by Farrand (1960) who measured the variation in some elements as a xenolith was traversed. The data from the Shap sample was such that no firm conclusions could be drawn about any chemical exchange that might have taken place. All the above descriptions, apart from those of Phillips (1880, 1882),presented compositional data for the orthoclase megacrysts showing that orthoclase composition in the granite and xenoliths was so similar as to suggest simultaneous growth in both media, this fact being supported by occurrence of megacrysts across granite-xenolith contacts.

Work on xenoliths in other Caledonian granites is generally lacking, apart from recent geochemical research in the Southern Upland Granites and the Criffel intrusion in particular. A detailed study by Halliday et al. 1980, involved the geochemical analysis of the Criffel Granite, its xenoliths and surrounding Palaeozoic sedimentary country rocks, including the determination of oxygen and strontium isotopic ratios. It was not found possible to link chemically the origins of the xenoliths to the country rocks and consequently they were attributed to material intruded into the granite at depth.

A comparative study to that at Criffel has been undertaken at Shap and is presented in section 6.3. The origin of the Shap xenoliths has usually been attributed to assimilation of local country-rock material but, if this is not the case, then the xenoliths represent a component of the granite magma system which when understood might allow a further insight into the generation and emplacement of other similar granite plutons. The origin of xenoliths in granites has been reviewed by Didier (1973) and Vernon (1983) both of whom described xenoliths from a purely petrographical/textural approach. Vernon (1983) attributed most of the xenoliths in granites to being microgranitoid enclaves produced by magma mixing and quenching. If this is so, more detailed geochemical study of granite xenoliths is required as these processes have not usually been attributed to granite pluton systems.

6.2 Xenolith Petrology.

The descriptions of Grantham (1928) give a full account of the petrology of the xenoliths and only the main points need to be noted here.

The development of orthoclase megacrysts is very variable and their shape and size is also less regular than in the granite (Plate 13). Rimming by albitic feldspar is commonplace, sometimes constituting much of the bulk of the megacryst and representing significant plagioclase development after orthoclase. The groundmass is mainly composed of plagioclase, biotite, and quartz all of which can sometimes be phenocrystic in nature. The plagioclase may appear in sizes approaching the orthoclase

PLATE 13

PLATE 13. XENOLITHS

All Samples from the Pink Quarry apart from 13g.

a. A typical group of xenoliths showing a large size variation and rounded outlines.

b. Xenolith with erratic development of orthoclase megacrysts relative to the host granite. The smaller white grains are plagioclase.

c. An atypical xenolith composed mainly of biotite and lacking feldspar. There is also a weak longitudinal fabric.

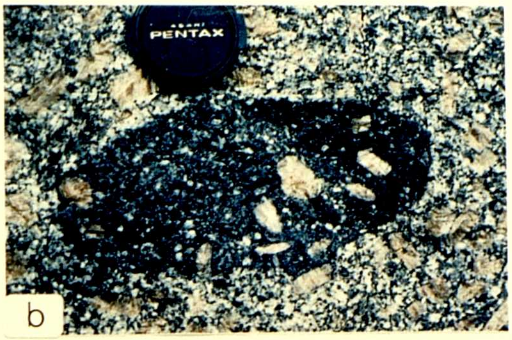
d. Orthoclase megacrysts growing across a granite-xenolith contact.

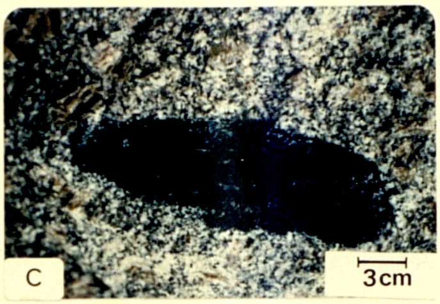
e. Xenolith showing a less sharp contact with host granite and further orthoclase and plagioclase growth relative to xenoliths such as those shown in 13a. The megacrysts have very narrow white plagioclase rims.

f. Extreme feldspar development producing a texture intermediate between typical xenoliths and granite. Note the extensive white albitic rimming to many of the orthoclase megacrysts.
(Sample No.615)

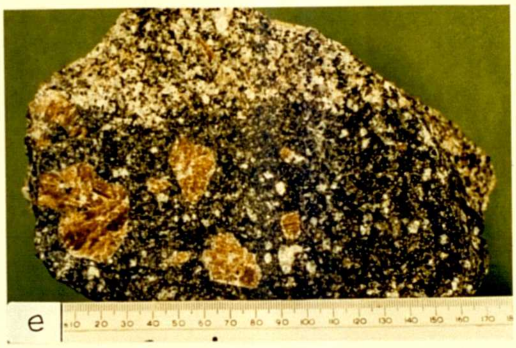
g. Deformed quartz vein and xenolith in the marginal foliated granodiorite of the Criffel Granite, Scottish Southern Uplands. (Airdrie Hill, near Dalbeattie, Dumfries. GR 945586)

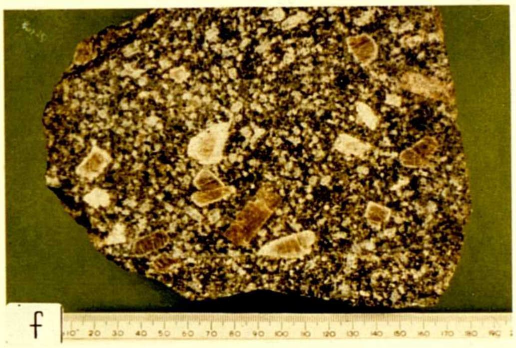

a


b


c


d


e


f


g

PLATE 13

although is generally much smaller and more evenly distributed. Both glassy and white-coloured grains of plagioclase can be found in most xenoliths and both types are rarely euhedral in shape. Biotite is the most abundant mineral giving the xenoliths their darker appearance. Large flakes can be numerous and along with small grains in the groundmass, are evenly distributed throughout the xenoliths. Small clots of biotite can sometimes be seen associated with magnetite. Quartz may also occur as composite grains but is usually restricted to the granular matrix with the other phases. Minor minerals visible in hand specimen include apatite, sphene and pyrite.

More significant features are seen in thin section examination. The orthoclase megacrysts are texturally similar to those in the granite with minor inclusions of altered plagioclase and less frequently, sphene and quartz. Megacrystic orthoclase is normally microperthitic, with small albitic plagioclase lamellae sometimes oriented relative to the orthoclase cleavage. The exsolved albite may also accumulate in patches. Rims of albite form on many orthoclase margins (Plate 14.f) and are very variable in texture and width. Inclusions in the albite rims are less common but they have a particularly interesting feature in that they contain the hydrated silicate, prehnite (Plate 14.e). This cannot be detected except by microprobe techniques, both the albite and prehnite being indistinguishable by optical microscope. No other record of such prehnite-bearing albitic overgrowths

PLATE 14

PLATE 14. XENOLITH PHOTOMICROGRAPHS

a. A zoned albite-oligoclase phenocryst in a granular matrix dominated by biotite and plagioclase.
(Slide No. 38001) (XPL)

b. Xenolith matrix rich in biotite, sphene (Sp)and apatite (Ap). The apatite here occurs as large rounded prisms and to a lesser extent as small acicular grains.
(Slide No. 39914) (PPL)

c. A clot of pale green flakes of hornblende (H) in a matrix including plentiful sphene (Sp) and biotite.
(PPL)

d. Hornblende (H) surrounded by biotite (Bi). This feature has only been seen on one occassion.
(Slide No. 39914) (PPL)

e. Microprobe photomicrographs of the margin of a megacryst. The core is of perthitic orthoclase overgrown by a rim of albite (dark grey) with prehnite (Pr) intergrowths (pale grey). Note also the sharp composition contact between the core and the rim.

Scale Bar 0.2mm

f., g. Typical overgrowths of albite (Ab) rims on potassium feldspar (Kf) or plagioclase (Pl). Contact between phases appear chequer-board (14f) or complex (14g) in contrast to that shown in 14e.
(Slide Nos. 37994, 39969 resp.) (XPL)

Scale Bar as in Plate 8

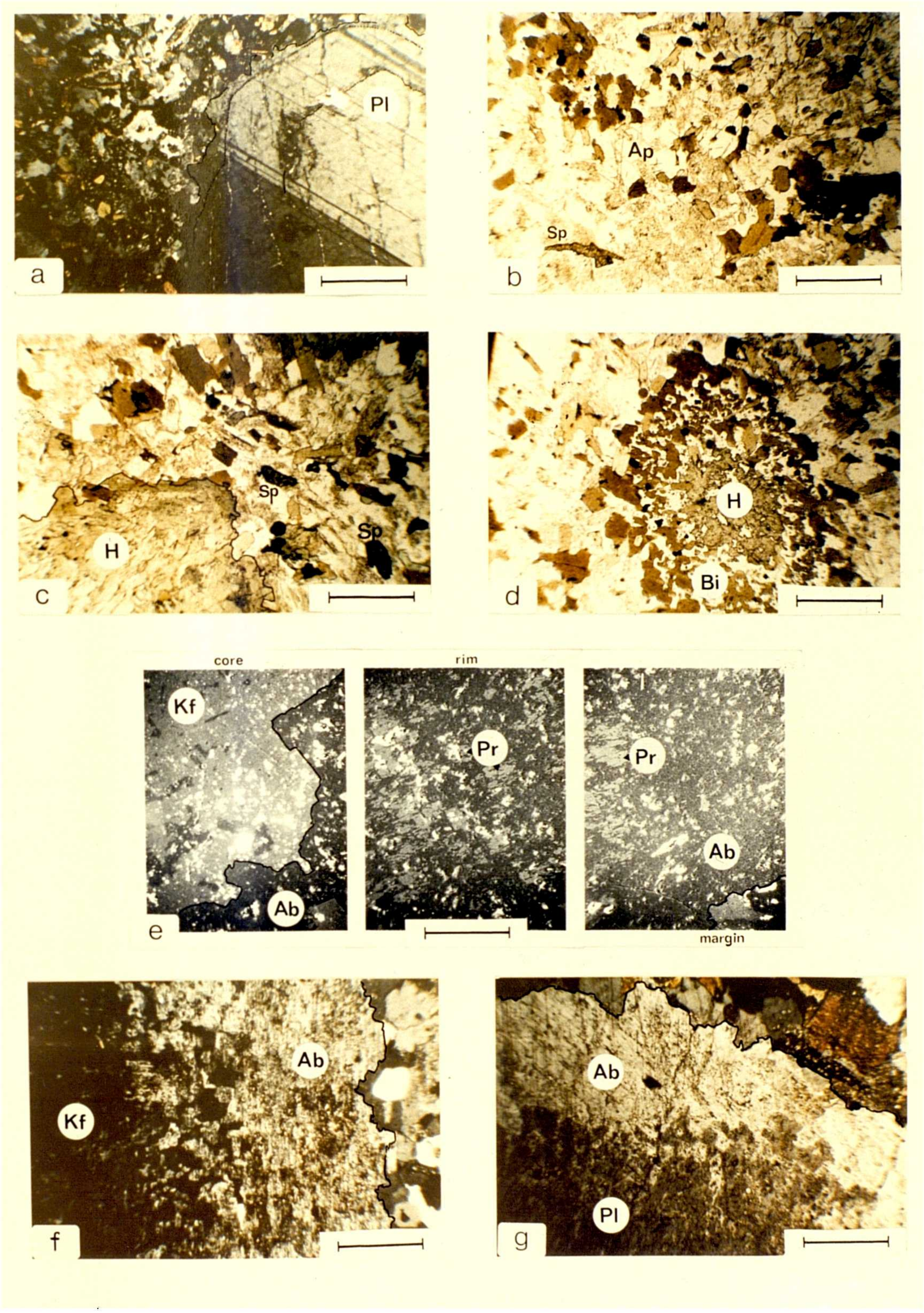

a
Pl
b
Ap
Sp
c
H
Sp
Sp
d
H
Bi
core
rim
Kf
Ab
Pr
Pr
Ab
margin
e
f
Kf
Ab
g
Ab
Pl

PLATE 14

have been found although the common occurrence of rimmed feldspars in igneous and metamorphic rocks would suggest that albite-prehnite intergrowths are more common than is thought. Apart from the orthoclase megacrysts, plagioclase is often the main phenocryst mineral with large zoned grains and glomerocrysts being common. Zonation is similar to that in the granite plagioclases, where it is often high-lighted by internal zones of secondary white micaceous alteration. Mica may also proceed down cracks and cleavage planes (Plate 14.a). The largest grains have normal compositional zoning varying over as much as 20% An. Albitic twinning is characteristic and late albite overgrowths in optical continuity give rounded outlines to the euhedral shaped zoned cores. These albitic rims again contain prehnite although this characteristic is better developed in the wider rims.

Biotite is plentiful throughout all the xenoliths and shows little chloritisation. Its pleochroism is the same as in the granite suggesting a similarity in composition between the two rock types. Many grains are euhedral with inclusions of large apatite grains and some zircon. Clots of biotite are more recognisable in thin section, these often being associated with sphene, apatite, magnetite and less commonly, hornblende. The hornblende is not common but when noted it is often surrounded by fine-grained biotite clots (eg. Fig.14.d) both minerals then possessing many inclusions of quartz. Hornblende grains are anhedral and have variable pleochroism either pale green-grey green or yellow green-yellow brown. Some grains show simple longitudinal twinning.

Sphene and apatite are plentiful, occurring as inclusion in many phases and as major constituents of the groundmass. The sphene is usually subhedral with high relief and strong pleochroism. Iron ore inclusions are very common. The apatite appears as stumpy prisms and needles, with acicular apatite often being found as inclusions in quartz. Magnetite is localised with biotite as opposed to being evenly distributed.

The groundmass contains all the above minerals (including some orthoclase) but is mainly composed of biotite, albitic plagioclase and quartz. The quartz may form rounded clusters of grains with triple junctions. These clusters have perhaps three or four large central grains with many intermediate sized grains around. It is usually interstitial between the biotite and plagioclase and may enclose small grains of biotite, it being late in crystallisation. The order of crystallisation appears to be apatite, zircon and magnetite and perhaps sphene followed by plagioclase, biotite and lastly, quartz and orthoclase. This sequence matches that in the granite and the dykes and the textural evidence suggests that the xenoliths have crystallised from a magma rather than being altered or granitised pieces of country rock.

6.3 Mineral Chemistry.

Feldspar, biotite, chlorite and prehnite have been analysed and the data are presented in Fig.6.1 and Appendix Tables E1-4. The large zoned grains of plagioclase vary between An28 and An1 but are typically around An25 (ie. oligoclase). It is thought that more anorthitic plagioclase perhaps upto An40 might also occur but alteration and albitisation results in poor compositional determinations. Albite rims and granular albite in the groundmass are also varied in composition, sometimes attaining the pure albitic form. Exsolved albite lamellae in the orthoclase perthites appeared to contain a significant potassium component but this may represent an overlap effect during microprobe analysis. Comparison between the granite feldspars in Fig.3.2 and those in Fig.6.1.a shows near identical compositions for both the orthoclase and plagioclase components in each rock type. A bulk analysis for the orthoclase in the xenoliths was not made, the data in Fig.6.1.a representing the orthoclase host. Similarly, the biotite and chlorite analyses shown in Fig.6.1.b match those of the granite (Fig.3.1), with the biotites again clustering about the annite-phlogopite join. Many analyses show lower K_2O contents than expected for biotite but these grains were not apparently chloritised when examined optically.

The prehnites were found to be associated with some of the purest albites and 8 analyses are given in Appendix Table E4. This selection comes from analyses within many differing albitic rims both on orthoclase and plagioclase. Given this, they show remarkably constant compositions and compare well with other analyses (eg. Deer et al. 1960). Compositions of immediately adjacent albite showed more variation (eg. An1 to An9). The prehnite appeared similar in texture to the albite exsolution in the orthoclase but

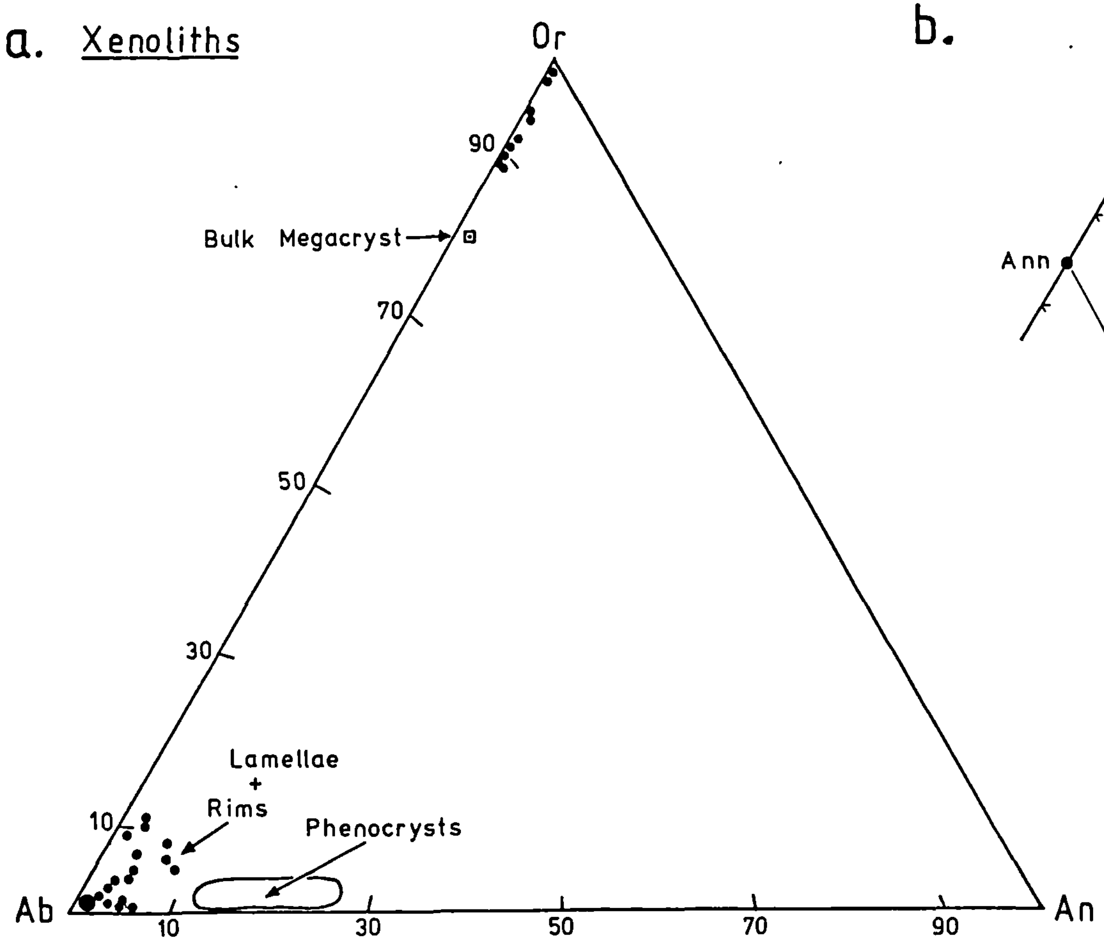


FIG. 6.1a Feldspar Compositions.

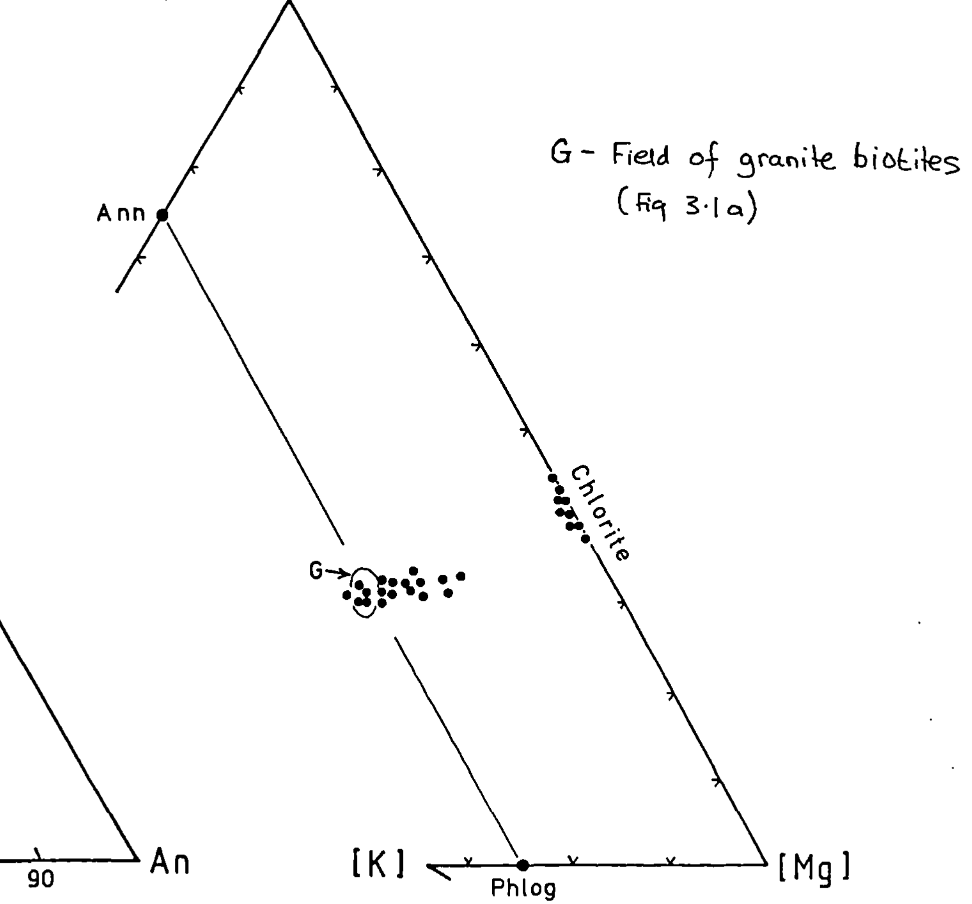


FIG. 6.1b Biotite and Chlorite Compositions.

it is not clear whether it has exsolved from or intergrown within the associated albite.

6.4 Whole-Rock Geochemistry.

6.4.1 Introduction.

The petrology of the xenoliths clearly shows similarities to the host granite and yet the origins of the Shap xenoliths have not previously been investigated by geochemical whole-rock analysis in order to compare the xenoliths with the granite and country rock chemistries. As part of the review of the granite and aureole geochemistry presented in this study, 18 xenolith samples were analysed in order to assess whether their origins could be constrained geochemically and also to discover if they had been chemically modified by inclusion in the granite as suggested by Farrand (1960). The data are presented in Fig.6.2.a-e and are again plotted against SiO_2 for comparitive purposes. Also shown in these figures are the compositional fields for granites(G), aplites (A) and Borrowdale Volcanics (V) of the Shap area, taken from the Figs.3.4.a-e and 5.4.a-e respectively. The field of volcanics encompasses over 90% of the available data, with the extreme compositions not being incorporated.

The xenoliths were chosen to include as many variable textures and compositions as possible, ranging from those lacking feldspar development (eg. Plate 13.c) through the more typical megacryst-bearing dark varieties to the very coarse grained highly feldspathic types (Plate 13.f). As megacryst development in most cases was very variable in distribution within any one of the more typical xenoliths (Plate 13.b) care was taken to collect near complete xenoliths by bulk sampling and extensive trimming. In this way it was hoped to reduce the chemical effects of the variable modal megacryst content.

6.4.2 Major Elements.

It is readily apparent from Figs.6.2.a,b that one sample (505) is distinct from the others in having a very high SiO2 content of 80%. It was not apparent that this sample was different from the remaining samples apart from that it contained little feldspar. It was similar in having a dark, biotite-rich fine-grained appearance with typical rounded outlines. This sample was probably originally a sedimentary rock that has since been extensively altered to biotite. It is consistently low in all major and trace elements apart from those associated with its possible modification by the process of granitisation. Being of such an extreme composition, it allows an assessment of granitisation and, in particular, which elements are fixed during this process. Consequently, the chemistry of this sample is usually discussed separately and will not be referred to in this section concerning the chemical characteristics of the remaining samples which form a coherent group.

The 17 samples show a wide range in composition from 56 to 68% SiO2. The highly feldspathic type (Plate 13.f and sample 615) and, to a lesser extent 529, lie in or close to the region of Shap Granites, with 615 being geochemically indistinguishable from the granite. The

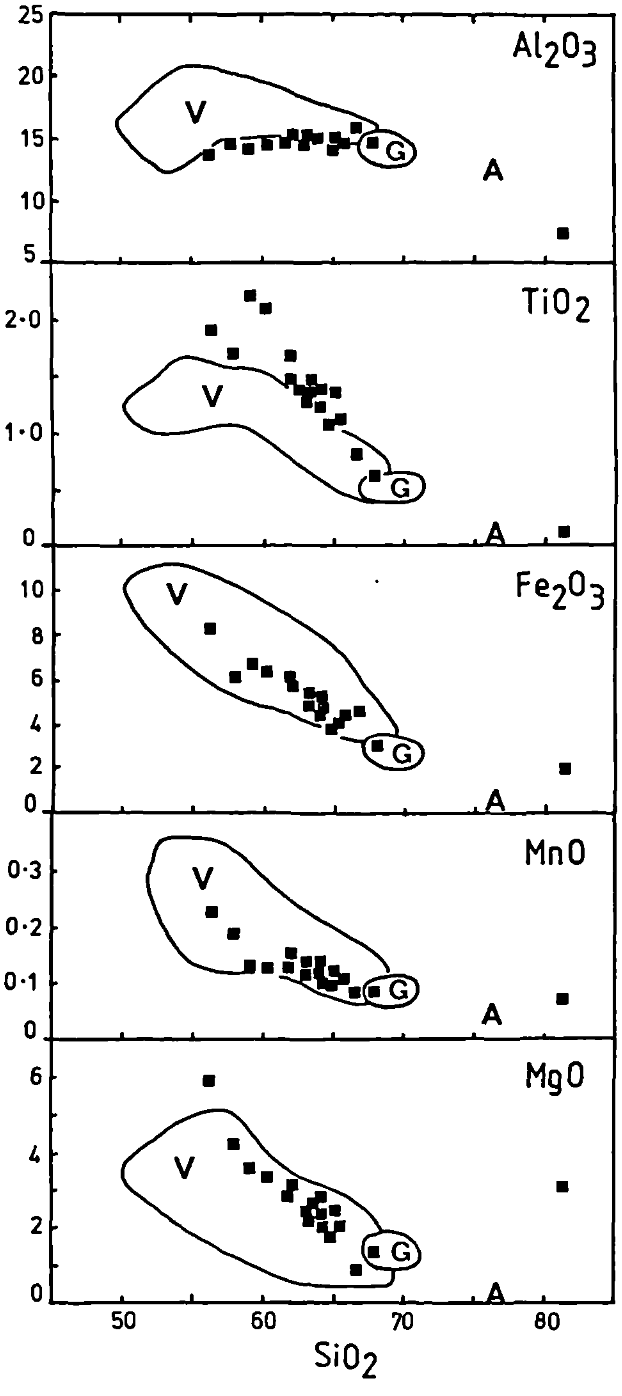


FIG. 6.2a

Xenoliths. SiO2 - Major Oxides.

Also shown are the compositional regions of Shap Granites (G), aplites (A) and local volcanic rocks (V).

other samples show remarkably coherent trends against SiO2 with generally high correlation coefficients (Appendix Table F1). There is some overlap with the volcanic field apart from Al2O3, TiO2 and P2O5 which lie outside this region. Comparison with trends shown by the dykes (Fig.4.3.a-e) shows many similarities in correlation except for Al2O3 which shows -ve slope for the dykes and K2O which shows near constant values in the dykes but a +ve correlation trend in the xenoliths.

Closer examination of the xenolith data shows that the four most basic samples (525,526,656,657) apart from defining the lower limit of SiO2 form a partially discrete group particularly with respect to TiO2 and P2O5.

6.4.3 Trace Elements.

Trace element data are plotted in Figs.6.2c,d,e., and like the major oxides, the xenoliths show a disparity with the compositions of the local volcanics. The Group 1 elements have scattered distributions which lack trends with SiO2 apart from Sr which has a weak -ve correlation. Of the four low SiO2 samples, the two most basic (<58% SiO2) deviate from the trend by having lower Sr contents than expected which would suggest a lack of plagioclase in the sample. Similarly, these 2 rocks have slightly lower CaO and Al2O3? than the other two samples of this group. The remaining Group 1 elements have concentrations with the same range as the host granite, a feature not generally shown by the other elements. From this it is inferred that this character of their compositions is related to interaction with the granite and the fixation

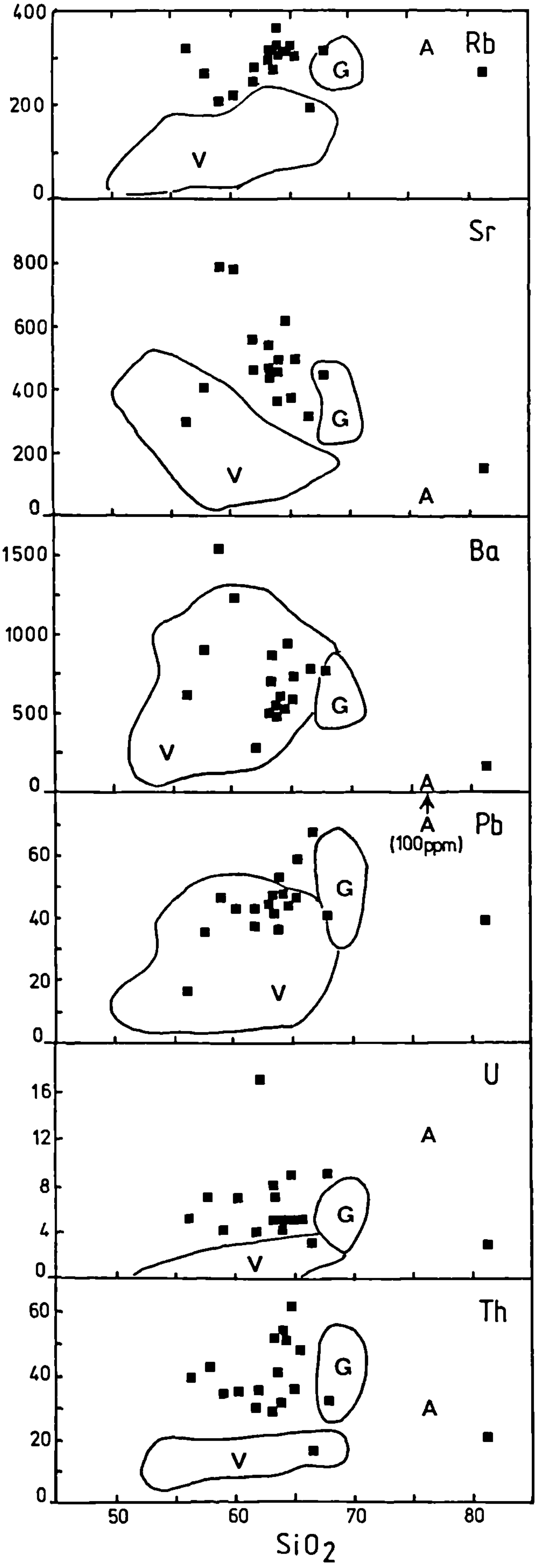


FIG. 6.2c

SiO2 - Group 1 (LFS) Elements.

of these elements is occurring in newly generated phases such as biotite and feldspar. Pb and Rb values in the high SiO2 sample also suggests that these phases are fixing much of the Group 1 elements in the xenoliths and that the concentrations of these elements are not purely a function of the xenolith's original composition.

The Group 2 and 3 elements (HFS and REE) have -ve correlations with increasing SiO2. Again there is little relation between the xenoliths and the local volcanic rocks and apart from samples 615 and 505, the xenoliths are enriched in these elements, the trend and higher concentrations not being a character related to the granite or country rocks. Consequently, this is a feature of the original xenolith compositions. The trends are similar to those in the dykes (Fig.4.3e) but the xenoliths show much less scatter of the data apart from the REE content of the basic samples which again form a distinct group from the remainder. Given that elements such as Y and Zr are generally immobile during alteration, the good correlation of the trends suggests that the rocks are related to a single evolutionary process.

Group 4 elements support the evidence seen in the previous grouping with all but Cu having good -ve correlations with SiO2. The Cu appears to be fixed in large amounts relative to the granite. Many xenoliths show limited pyritisation but concentrations upto 100ppm require the Cu to be fixed by an abundant mineral phase. Only biotite would satisfy this requirement.

The overlap with the volcanic compositions is of

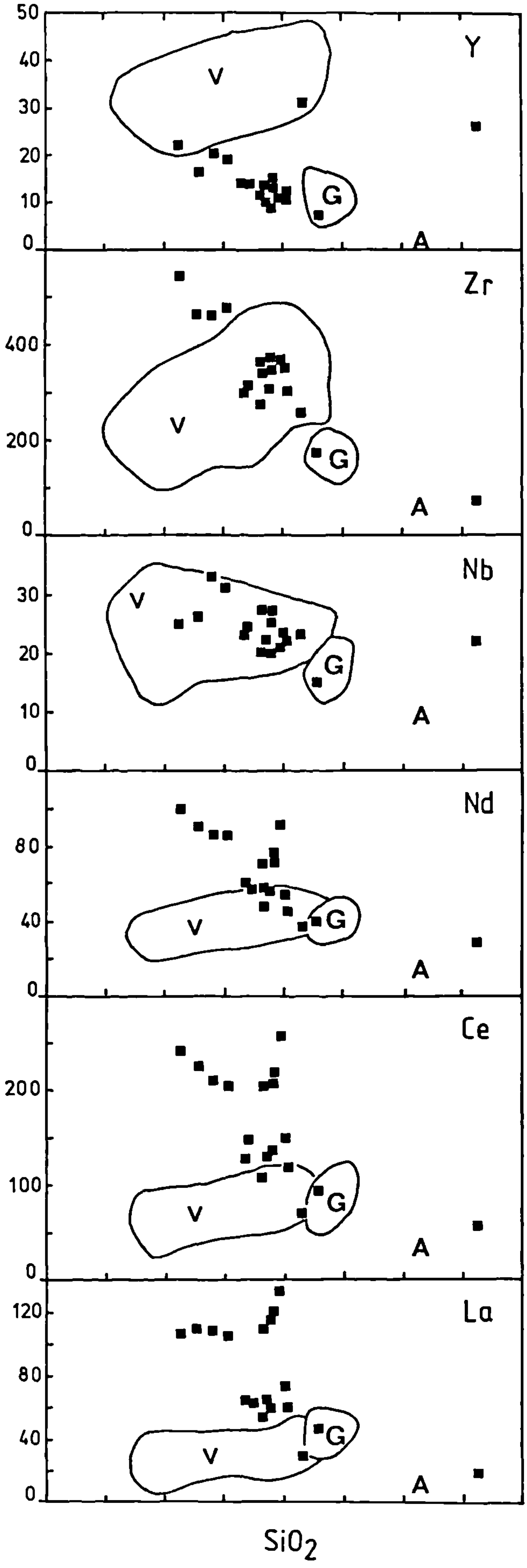


FIG. 6.2d

SiO2 - Groups 2 & 3 (HFS/REE) Elements.

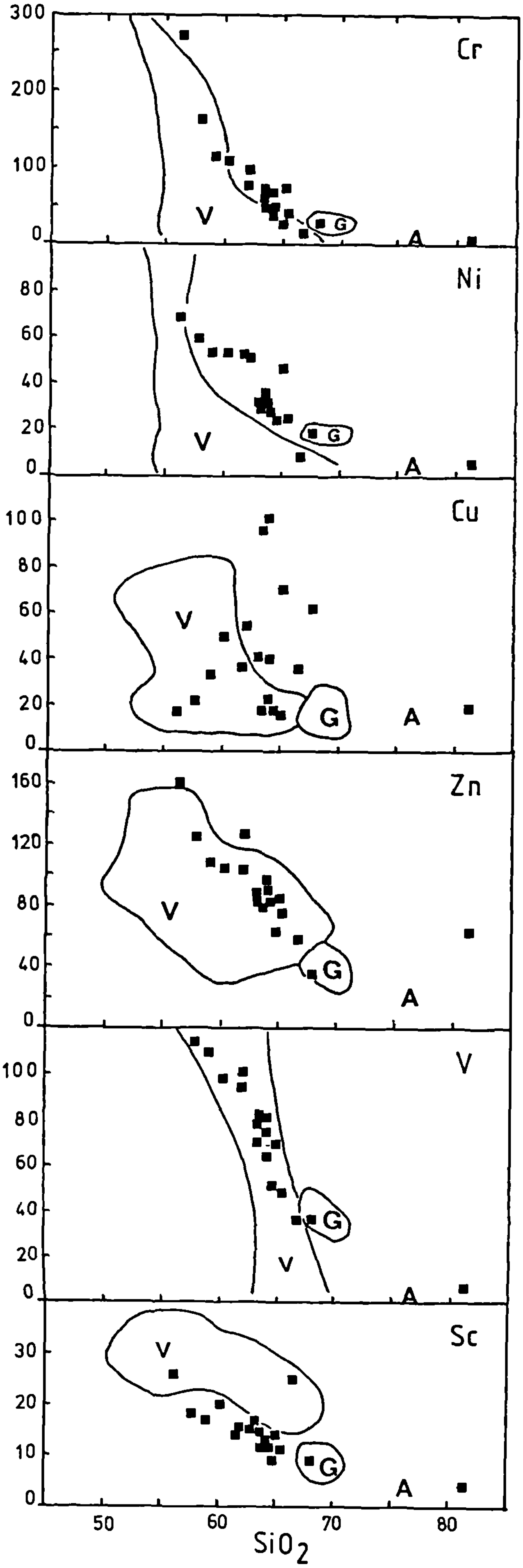


FIG. 6.2e

SiO2 - Group 4 (Transition Metal) Elements.

variable extent but is generally poor apart from for Zn and V. Again the immobile elements such as Cr and Ni behave coherently and suggest a unifying process over the range of xenolith compositions. Trends for all Group 4 elements correspond well with those of the dyke data although the dykes have lower Cr and Ni contents.

From the above information it can be seen that the xenoliths do not relate compositionally to the local volcanic material and therefore that they are not country rocks incorporated during the granite's intrusion. The general correlation of most elements over the range of 55 to 70% SiO2 is very similar in many respects to the evolutionary trend defined by the dyke and granite data which represents liquid fractionation and crystal accumulation dominated by biotite and plagioclase. The high SiO2 end of the xenolith data corresponds to the field of Shap Granites such that the granite composition may well represent the limit of the process which characterises the geochemistry of the xenoliths. Given these relationships between the granite, dyke and xenolith chemistry, it is apparent that the xenoliths are generated during the granite magma evolution and that the basic xenoliths at 56% SiO2 might define the least evolved magma compositions seen at Shap. This extends the lower range from that defined by the dykes (at 62% SiO2) and, combined with the aplites and most evolved dykes, extends the range of granitic (s.l.) compositions at Shap from 56 to 78% SiO2. This spread of compositions is similar to that seen in the Southern Uplands Granites (Chapter 3.3.1) of 56 to

75 % SiO_2 where all compositions are represented by plutonic rocks and can be related to a unified magmatic process. Thus it may be possible to model what is apparently a limited range of granite (s.s) compositions such as at Shap by including geochemical data from associated xenoliths and minor intrusions.

Plotting the xenolith data on simple diagrams to represent magma evolution such as AFM (Fig.6.3) shows that the xenoliths define a calc-alkaline trend between that of the volcanics and of the granites and dykes. Given that the xenolith trend is not a function of mixing (ie. granitisation) of local volcanic rocks, the disparity between the xenoliths and granites in this particular diagram is a function of difference in the mineral modes of the two sets of rocks. The xenoliths, at any given composition, have a slightly higher Fe/Mg ratio than the equivalent granites and dykes which is thought to be due to the high proportion of biotite in the xenoliths.

Back-projection of the main geochemical trends to 50% SiO_2 shows the possible parental magma prior to biotite formation to probably have a too high Fe/Mg ratio. Calc-alkaline magmas such SiO_2 levels would be expected to have lower Fe/Mg ratios and consequently, lower than around 56% SiO_2, the evolution of the magma composition cannot be assessed using the mineral phases we see presently (ie biotite, plagioclase, hornblende?). Therefore, it is possible that this lower limit of 56% SiO_2 represents the parental magma composition for the Shap (and SUG's) Granites which rose in the crust until becoming

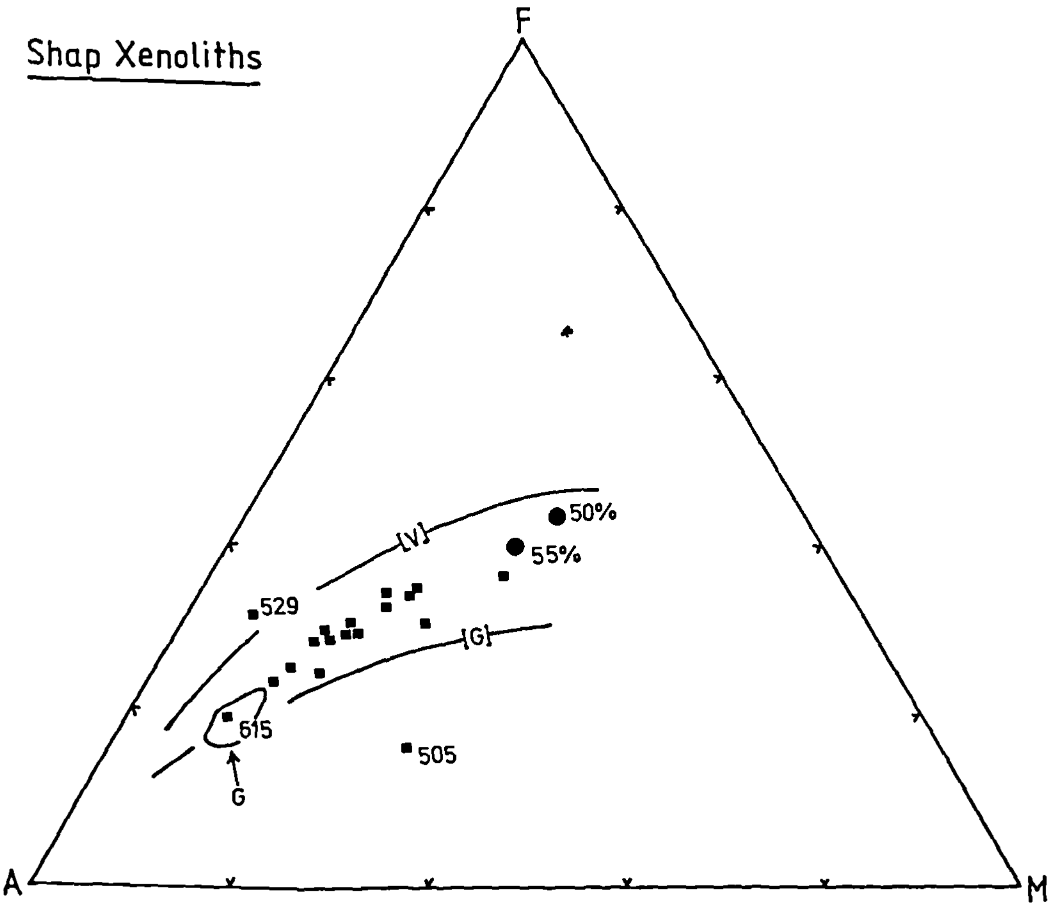


FIG. 6.3

AFM trends shown by the xenoliths (■), granites (+ dykes) (G), and volcanics (V).

● Projected compositions of xenoliths at 50 and 55% SiO2.

fractionated into more acidic compositions during ascent into the mid-upper crust.

6.6.4 Stable Isotopes.

Two samples (501,504) were analysed for oxygen isotopes (δO18 10.81 and 10.62‰ respectively). These samples have SiO2 concentrations of 63.3 and 63.8%. Their isotope values are generally between those of the volcanics and the granites and therefore, these data could be interpretated in terms of granitisation of volcanic country rocks. However, given that the xenoliths are probably magmatic, their lower δO18 compared to the granite is more likely to be due to their slightly less evolved chemistry. Nevertheless, the similarity between the granite and xenolith chemistry and their δO18 values makes it effectively impossible to say whether the δO18 of the xenoliths reflects their original composition or has been modified by the slightly higher δO18 composition of the granite. It can be tentatively stated that these samples have not equilibrated (with respect to oxygen isotopes) with the host granite, as the granite (Light variety) is usually some 0.5‰ higher in δO18.

6.4.5. Radiogenic Isotopes.

Six xenolith samples (501-506 inclusive) were analysed for strontium (Sr) isotopes (by P.Betton) and the data are presented below in Table 6.1

When plotted as Sr87/Sr86 against Rb87/Sr86 the results form an isochron with a large age error of 404 ± 39 Ma and an initial ratio of 0.7068 ± 4 (Fig. 6.4). These

Table 6.1 Strontium Isotope Data - Shap Xenoliths.

Sample No.	Rb/Sr	Rb87/Sr87	Sr86/Sr87
501	0.62	1.78973	0.71655
502	0.87	0.87366	0.72074
503	1.01	2.94497	0.72263
504	0.61	0.61694	0.71742
505	1.76	5.27756	0.73678
506	0.55	1.56395	0.71606

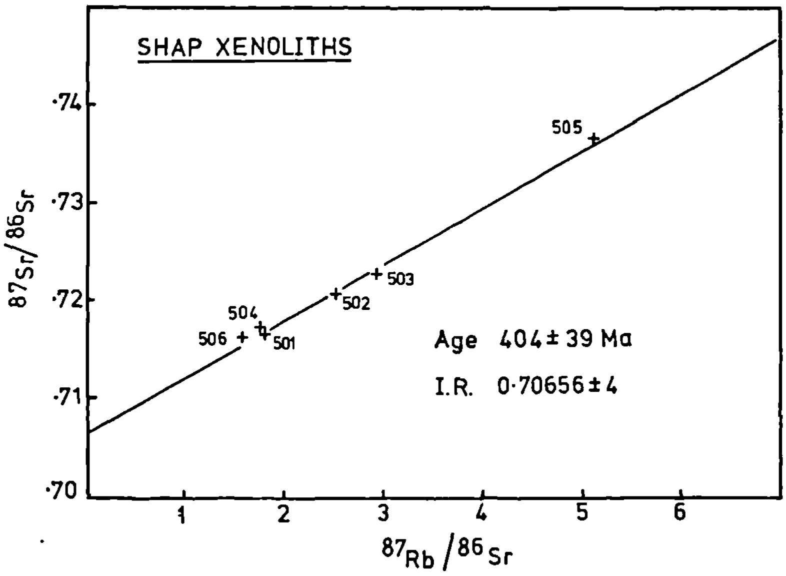
results are similar to those of the host granite of 394 ± 3 Ma and 0.70767 ± 10 (Wadge et al. 1978). The xenoliths group about a small range of isotope values (Sr87/Sr86 of 0.715-0.722, Rb87/Sr86 of 1.6-3.0) which correspond to the ranges for Shap granites given by Wadge et al. (op. cit.) (eg. 0.717-0.733 and 1.7-2.2 respectively).

The Shap samples have Rb/Sr ratios of 0.55 to 1.01 apart from sample 505 whose ratio is 1.76 and reflects the normal Rb and low Sr of a granitised sediment now containing plentiful biotite and minor orthoclase. Two conclusions can be drawn from the isotope data. Firstly, the xenoliths derived from the country rocks may have equilibrated with the host magma such that Sr isotope evidence cannot resolve their origins with certainty. Secondly, xenoliths can produce an isochron which represents a real age for the Sr isotope evolution of the magma. This may be due to re-equilibration as in sample 505 or, as is the case for the remaining samples, that they represent granitic material with the same initial Sr isotope values as the granite, but a range of Rb/Sr ratios.

Studies of the Criffel granite intrusion in the

Southern Uplands by Halliday et al (1980) included the analyses of xenoliths as well as the granite. The xenoliths were described as porphyritic microgranites varying in composition from granodiorite and quartz monzonite through to granite, and mainly being more mafic than their host and with elevated alkali compositions (eg. Rb). As at Shap, the xenoliths appear to be igneous in origin. Isochron regression of Halliday et al.'s data is shown in Fig.6.4b and the resulting isochron age and initial ratio corresponds well with that of the host Criffel granite (397-407 Ma and 0.705-0.707) as determined by Halliday et al (op.cit.). The Criffel xenoliths are similar to those at Shap and were thought by Halliday et al. (op.cit.) to represent material intruded into the granite at depth. The isotopic character of the local metasediments did not relate to that of the xenoliths although no obvious country-rock xenoliths were analysed in their study of the granite.

Studies of the neodymium isotopic evidence for the provenance of Caledonian granites included a single analysis of a granite from Shap by Hamilton et al. (1980). With this as a comparison, 3 xenoliths were analysed for Nd isotopes on the author's behalf (by J.Davidson and R.Jones). Although not undertaken in detail, comparison of the Nd143/Nd144 ratios of the xenoliths with that of Hamilton et al (op. cit.) distinguishes between comagmatic xenoliths and those of an external, non-magmatic origin. This is due to the fact that Nd is stable during alteration processes and as a consequence, isotopic values a.



b.

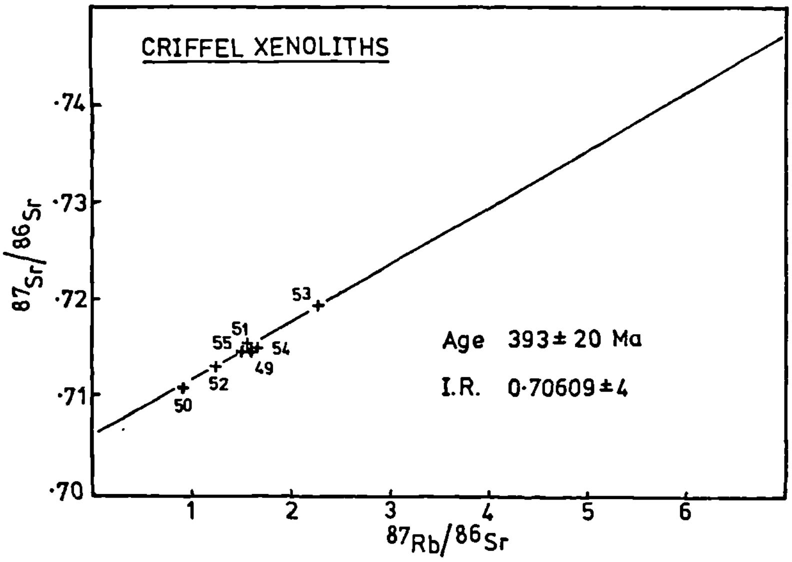


FIG. 6.4a

Sr isotope isochron for the Shap xenoliths.

FIG. 6.4b

Sr isotope isochron for the Criffel Granite xenoliths after Halliday et al. (1980).

remain intact so as to reflect the xenolith's probable origins.

Table 6.2 Neodymium Isotope Data - Shap Xenoliths and Granite.

Sample No.	Nd143/Nd144	
502	0.512138 +/- 26	This Study
504	0.512175 +/- 23	" "
505	0.512607 +/- 21	" "
CCR8	0.512261 +/- 30	Hamilton et al. (1980).

The three xenoliths analysed include sample 505 and comparison of the xenoliths with the data of Hamilton et al. (op.cit.) shows this sample to be distinctly different. Samples 502 and 504 have Nd ratios that compare with the value of the host granite. Therefore, it is thought that these two samples are typical of the main xenolith group, their isotopic character indicating that they are related to the Shap granite evolution.

6.5 Discussion.

6.5.1 Feldspar Development in the Xenoliths.

Much of the plagioclase in the xenoliths is well zoned and represents crystal growth in a liquid. The orthoclase megacryst growth was late in the xenolith history and must have occurred during or after the ascent and emplacement of the xenoliths into their present position. Whole-rock data shows that the required potassium was introduced from the granite until concentrations were similar between the two rock types. As with the granites and schlieren, the development of orthoclase is related to that of the biotite, these being the major K-bearing phases. As a consequence, an inverse correlation can be seen between biotite and orthoclase development such that in the xenoliths, which are richer in biotite (such as the more basic xenoliths or the incorporated sedimentary material), megacryst development is restricted. Such rocks may already have relatively high K_2O contents due to their biotite rich nature such that K_2O contents are similar to those in the granite. Consequently, no chemical concentration gradient exists in order to facilitate K_2O introduction to the xenoliths.

The formation of rimmed feldspars has been attributed to many processes including exsolution from the orthoclase core (Dawes 1966), magma mixing (Hibbard 1981) and metasomatic activity (Elders 1968). It is unlikely that much or in fact any rims were formed by exsolution as this would result in extreme alteration of the orthoclase core composition especially in xenoliths such as shown in Plate 13.f. Where relatively wide rims have developed, the process is more likely to be due to two effects. Firstly, if the xenoliths represent more basic material from below, then on rising upwards into the upper zones of the pluton, pH_2O might be expected to rise causing the solidus and solvus of the 2 feldspar system to intersect such that orthoclase and plagioclase might form at the same time. Secondly, Hibbard (1981) suggests that the xenoliths may represent mafic materials which have been quenched and which results in plagioclase of a range of compositions being forced to crystallise rapidly. Such rims can range from albite to oligoclase in composition. At Shap, the rims are generally albite but, the associated prehnite may represent the original calcic component of the expected oligoclase.

The exact origins and development of the albite-prehnite intergrowths are not known. There is little information on igneous prehnite occurrences although its origins in the metamorphic environment are better understood. The formation of prehnite is limited by its stability which is generally below about 400°C in most environments (Fig.6.5) and at pressures of <3kb, is likely to be some 50°C lower. At 100°C above these temperatures is the reaction of anorthite breaking down to prehnite, and it is thought that this reaction in a plagioclase of intermediate composition might produce an associated albite-rich plagioclase not unlike that we see with the prehnite.

6.5.2 Xenolith Origins.

Suggested possible origins for xenoliths in granites include:

1. Residue from partial melting at source (ie,.restite)
2. Stoped fragments of country rock.
3. Fragments of an earlier but unrelated igneous complex at depth.
4. Cumulates from the pluton magma reservoir.
5. Magma intruded into the granitic melt from below.

Evidence presented so far indicates that 1 and 2 are not likely origins for the Shap xenoliths. Number 3 would

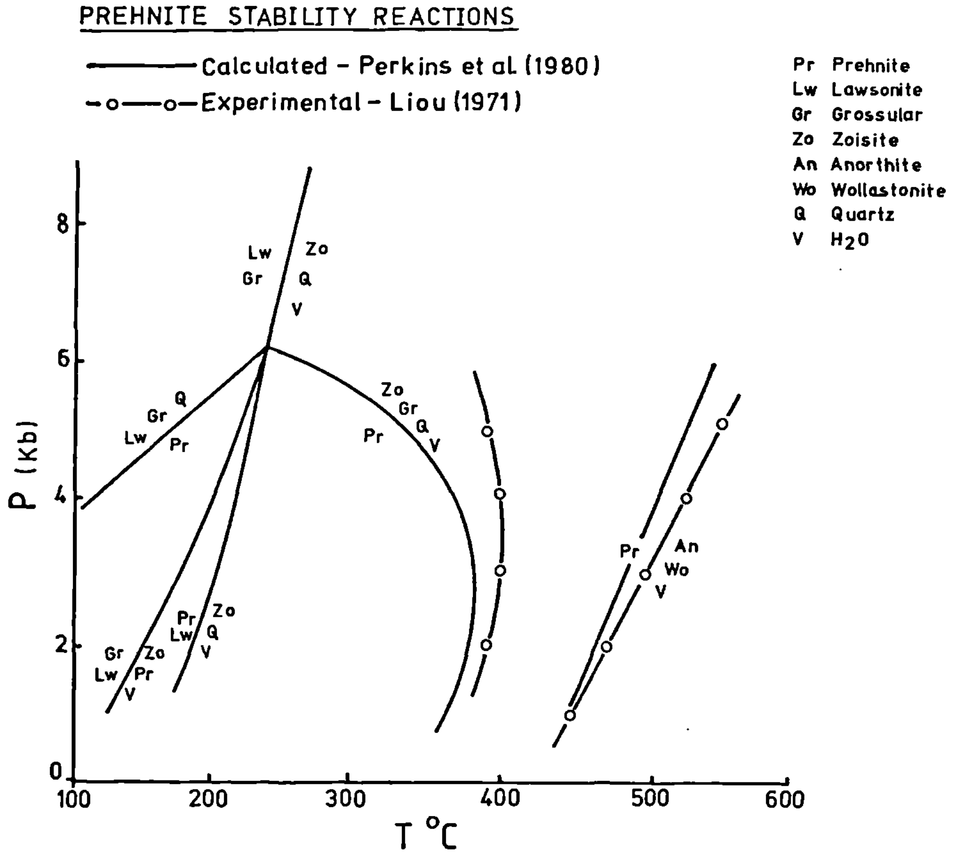


FIG. 6.5

Prehnite Stability reactions after Liou (1981) and Perkins et al (1980).

be difficult to recognise unless the fragments were geochemically distinct, had angular outlines suggesting forceful incorporation or, were of a coarse grain size such that they represented pre-crystallised igneous material incorporated into the granite melt at depth.

Three aspects of the Shap xenoliths that need to be considered in assessing their possible origins is that they are rounded in shape, fine-grained in character and enriched in TiO_2, P_2O_5 relative to the expected concentrations of these elements at these SiO_2 compositions. The rounded shape and smooth, sharp contacts with the host granite indicates that the two were physically discrete and unalike when they were brought together. Mineral zoning and xenolith composition suggests that the xenoliths were at one time magmatic and contained phenocrysts of plagioclase and biotite. The generally medium to fine grain size indicates undercooling or chilling which resulted in features such as acicular apatite which is not seen in the coarser grained varieties or the granite. Such arguments do not support a cumulate origin for the xenoliths although they do have a high content of mineral phases such as apatite, sphene etc. which would be crystallising early in the granite's solidification sequence.

An enrichment in TiO_2 and P_2O_5 is a feature notable of immiscible igneous systems. Several kinds of globular structures in igneous rocks have been interpreted as evidence of magmas separating into two phases of differing composition. Such structures have been described as being

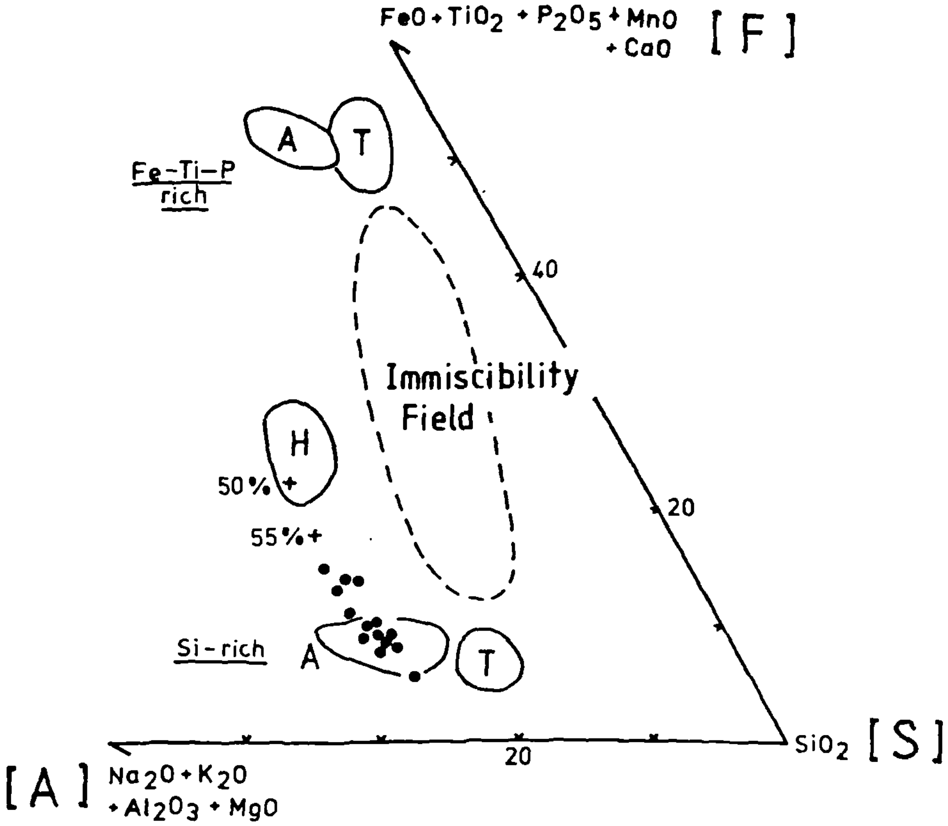


FIG. 6.6

FSA diagram showing the regions of Fe-rich and Si-rich immiscible silicate components in alkalic (A) and tholeiitic (T) rocks. (Philpotts, 1982)

Immiscible fractions are found in hosts (H) with an intermediate chemical character.

The Shap xenoliths (●) and projected compositions to 50% SiO2 (+) do not appear to show the chemical effects of immiscibility.

immiscible silicate liquids and are found in many varying rock types including alkaline lamprophyres, tholeiitic basalts, andesites and gabbros (Philpotts 1982). The separated liquids have distinct chemistries divided by an immiscibility field. One liquid is Si+Na+K-rich and the other Fe+Ti+P-rich. The Si-rich liquid in natural systems has the simple composition of a granite. The Fe-rich phase is more extreme, usually being equivalent to a composition involving pyroxene + fayalite + ilmenite + magnetite and sphene. In general, the higher the silica content of the original whole rock, the less the compositional difference between the two phases. To test the possibility of immiscibility trends in the xenolith chemistry, the whole-rock data was plotted on an FSA diagram as defined by Philpotts (op. cit.) (Fig.6.6). If the xenoliths showed immiscibility characteristics the data would trend towards the Fe-Ti-P-rich portion of the plot. Fig. 6.6 shows that although the xenoliths are enriched in $TiO2$ and $P2O5$, they do not show indications that their chemistry is in part due to immiscibility processes at depth as there is no apparent trend towards the Fe-rich region. On the other hand, immiscibility would explain a number of the physical features that these enclaves possess such as their rounded to ovoid shape, their grainsize, apatite-sphene abundance and the lack of chemical reaction with their hosts.

6.6 Conclusions.

1. The xenoliths at Shap define a coherent group over a range of 56 to 67% SiO2.

2. They are generally chemically distinct from the granite apart from the selected elements K2O, Rb and Pb which may have been introduced from the granite during orthoclase development.

3. It is likely that the xenoliths were melts emplaced from lower in the pluton and related to the generation of the Shap magmas as a whole.

4. Country rock xenoliths are rare and are readily recognisable by their individual compositions which do not equilibrate with the host granite by interaction or granitisation.

CHAPTER 7. PROCESSES AND CONCLUSIONS.

7.1 Processes in the Granite.

A number of textural and chemical effects seen in the granite have been briefly described in Chapter 3 and are worth further discussion to show the multi-various nature of the processes occuring in the granite during its emplacement and cooling.

7.1.1 The biotite banding and schlieren.

These structures are well developed in the Pink Quarries but have not been regularly seen in the past and so it is thought that they are not commonplace in the Shap Granite. As they are not seen in three-dimensions, but only in the quarry faces, it is difficult to establish their true form and extent.

Similar structures have been described from plutonic intrusions varying in composition from gabbro to granite. Structures most similar to those at Shap tend only to be found in granitic rocks over the granodiorite to alkali granite and syenite range.

Wilshire (1967) described marginal zones of steeply dipping biotite-rich, mafic layered structures in a granodiorite. These mafic layers were upto 1m thick and 30m long and also had internal crystal size grading. He attributed their formation to flow sorting during vertical sheer flow about the pluton margins during emplacement.

Structures somewhat similar to those at Shap are also shown in Fig.7.1 having been described from granites in

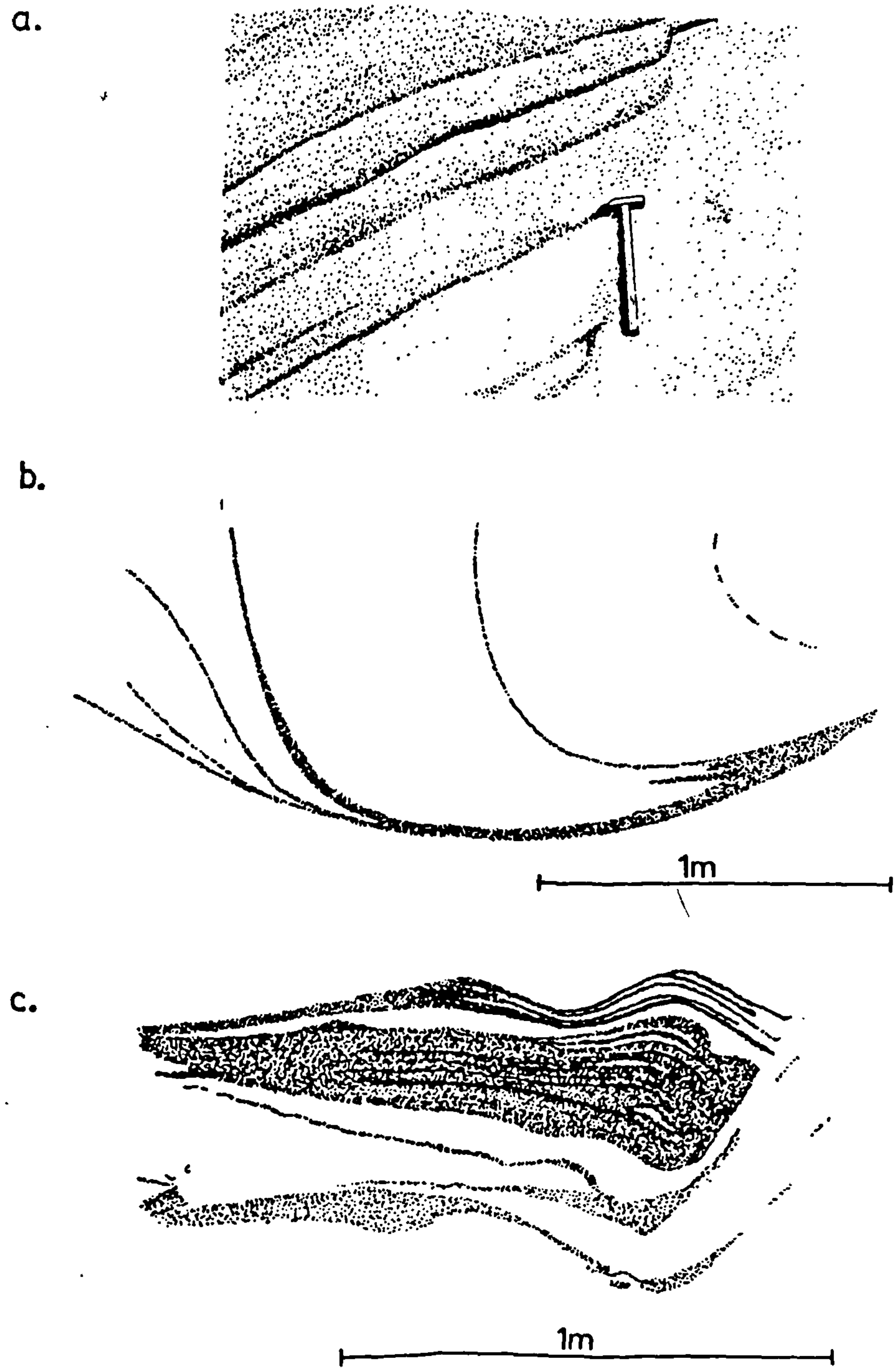


FIG. 7.1

Examples of biotite-rich layers and schlieren in granites from S.W. Greenland (after Harry and Emeleus, 1960)

Greenland by Harry and Emeleus (1960). Again, the biotite layers are restricted to the outer portions of these granites and are composed of biotite, sphene, allanite, apatite, and opaques. Of interest is the ubiquitous occurrence of fluorite, which they attributed to a high halogen-bearing volatile content in the magma, producing unusually fluid conditions. They concluded that the layers developed in a similar fashion to the cumulate layering formed in basic plutons by crystal accumulation. The formation of these layers with their sometimes curvaceous forms was thought to involve the action of magmatic currents.

Sorensen (1969) described such banded structures in peralkaline syenite intrusions and attributed them to differential settling and intermittent crystallisation in a volatile-rich magma. He suggested that temperature gradients produce convective motion to cause magma currents and, intermittent loss of volatiles from the roof and marginal zones produces local density gradients and recurrence of crystallisation and thus produce the layering. Such vapour loss results in super-cooling and rapid cumulus nucleation.

Parsons (1979) attributed these structures in sialic plutons to a number of inter-related processes and requirements as outlined below.

1. Low viscosity is required in the melt and is promoted by high halogen (fluorine) contents,

2. Mineral grading is mainly a chemical rather than mechanical process and is dictated by nucleation and

growth rates.

3. The melt requires highly sensitive pH2O fluctuations with near-stagnent magma conditions to allow banded structures to accumulate.

4. Increasing pH2O promotes mafic rather than feldspathic growth.

At Shap, the occurrence of biotite layered structures would suggest that the magma was not extensively crystallised when it was emplaced this level such that the biotite layers could form. The similarity in biotite compositions in the biotite bands and the granite shows that chemical equilibrium was maintained on this scale. The configuration of the orthoclase megacrysts about the bands again shows them to be late in the crystallisation of the granite.

There is little evidence of high halogen contents in the Shap Granite apart from the occurence of minor fluorite. Consequently, it is not thought that the Shap magma had a high fluidity suitable for more widespread development of these structures. It is also not known whether they are localised with respect to the margins of the granite. Biotite banding such as this described from Shap is not recorded from other British granites. Their general lack of occurrence in this and other Caledonian granites suggests that this is not a major process in the consolidation of these granites.

7.1.2 High temperature pyritisation.

Fe-pyrite is often found to occur away from the regions of hydrothermal mineralisation occuring in the granite itself in association with the megacrysts. Here it occurs as inclusions, forming at the same time as the orthoclase.

There is little information on the solubility of sulphur in magmatic conditions in comparison to that known for hydrothermal systems. Given these limitations, the general behaviour of sulphur in magmas is to increase in concentration with increasing fractionation. The production of sulphides and lowering of sulphur solubility is promoted in silicate liquids by falling temperature and increasing silica (Maclean 1969). It is not known whether the sulphur is associated with the silicate melt or the accompaning hydrous fluid phases. Hydrothermal studies have shown that dissolved sulphur is separated from a hydrous phase by volatile loss or rapid pressure reduction. Thus, the loss of volatiles during the late-stage consolidation when the orthoclase megacrysts were forming would result in any sulphur undergoing rapid increases in concentration which would promote high temperature sulphide formation (Burnham 1979).

The reactions involving granitic minerals in association with sulphur can be shown to be dependent on the relative activities of oxygen and sulphur. Assuming excess H2O and SiO2, reactions can be written between K2O-Al2O3-FeO-O2-S2 which encompass the phases pyrite (Py), pyrrhotite (Po), magnetite (Mag), haematite (Haem), annite (Bio) and orthoclase (Orth).

1. 3Py + 4O = Mag + 6S.
2. Bio + 6S = Orth + 3Py + H2O + $\frac{3}{2}$O

3. Bio + O = Orth + Mag + H2O
4. 3Po + 4O = Mag + 3S
5. FeS + S = FeS2
6. Bio + 3S = Orth + 3FeS + H2O
7. 2Mag + O = 3Haem
8. 2Py + 3O = 1Haem + 2S
9. Bio + O = Orth + 3/2 Haem + 2H2O.

The above reactions are shown in Fig7.2 and demonstrate two features in the granite. Firstly, the crystallising granite represented by the mixture biotite-magnetite-orthoclase, will intersect the stability field of pyrite or pyrite + orthoclase with increasing activity of sulphur, a feature which is thought to represent the high temperature growth of pyrite with orthoclase. Secondly, the oxidation reactions of biotite are promoted by increasing activity of oxygen such that biotite breakdown to orthoclase+magnetite (as seen in the contact rocks in the aureole) or, biotite to haematite, which is one of the hydrothermal reactions occurring in the granite. From this, it is possible to see that the hydrothermal pyritisation must ocurr whilst sulphur levels are still relatively high. With decreasing temperature and increasing oxidation haematite will become the stable Fe phase. Thus, the haematite formation, producing the darkened appearance to the hydrothermally altered granite, occurred during or after pyritisation about the joints. The alteration of granitic biotite to chlorite + Fe-oxides has been researched by Eggleton and Banfield (1985) who have outlined the conditions of this reaction.

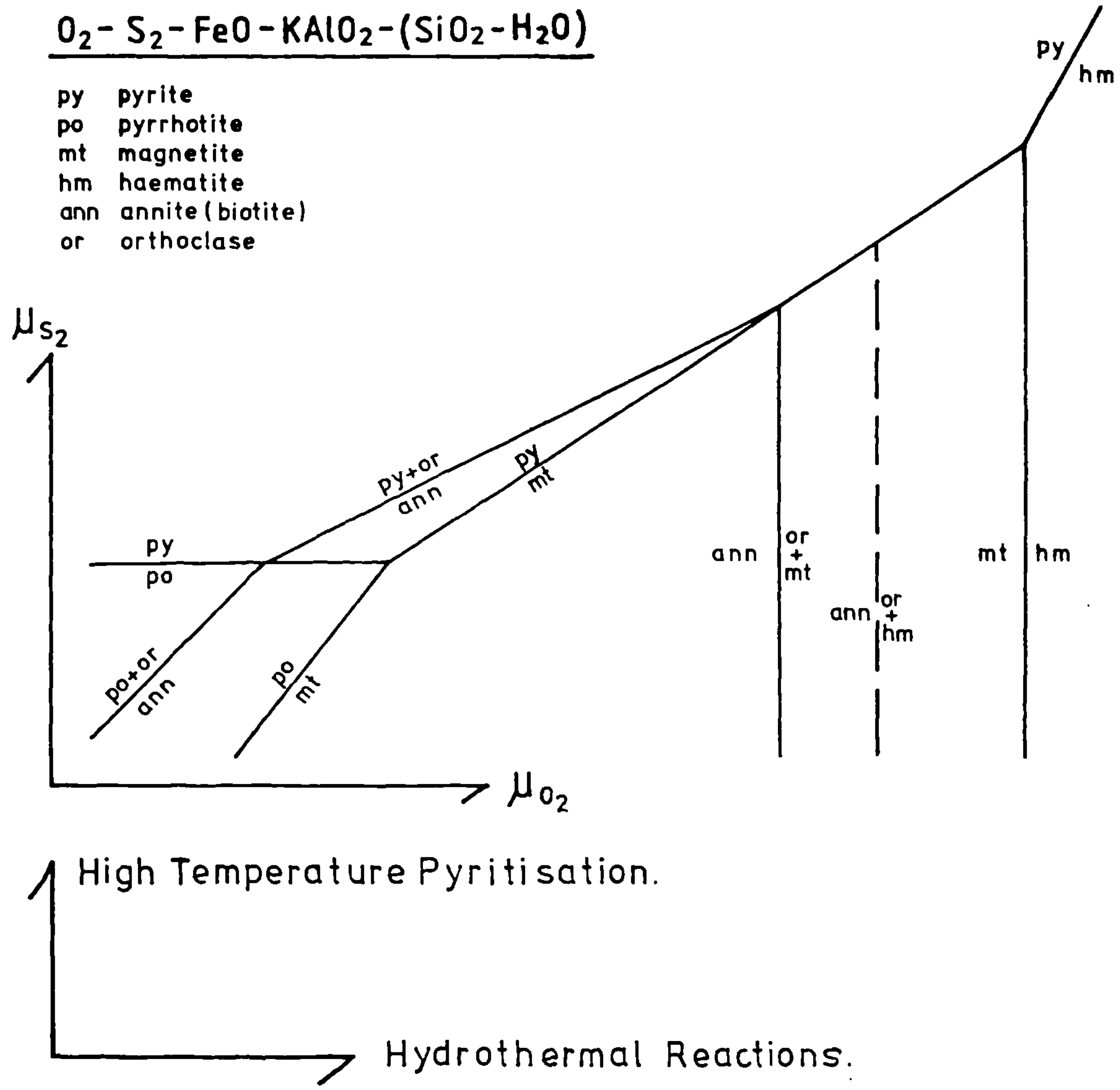


FIG. 7.2

The inter-reactions between orthoclase, biotite, Fe-sulphides and Fe-oxides relative to the activity (expressed as chemical potential μ) of sulphur and oxygen.

Reactions are as in the text.

The activity of the two species varies during the cooling of the granite resulting in two sets of reactions, pyritisation and oxidation.

The biotite-chlorite reaction occurs at around 340° C and the loss of K from the interlayer structure results in a volume reduction of 35%. The reaction is usually associated with plagioclase alteration to sericite which involves an increasing volume change. The Fe3+/Fe2+ ratio in the biotites and secondary chlorites remains almost the same but, Fe and Ti are almost completely lost from the biotite during the breakdown reation. Thus, extensive chloritisation will produce large quantities of haematite, which is the effect seen at Shap.

7.2 Processes in the Aureole.

The aureole at Shap shows little interaction with the granite apart from very close to the contact where extensive recrystallisation and some limited chemical input has occurred. The aureole shows virtually no effects of bulk fluid transfer such that elemental and stable isotopic values remain intact. Studies of various granite contact aureoles show that hydrothermal alteration and chemical modification in the aureole requires high fluid/rock interaction over an extended time and temperature interval. Such effects are produced by repeated cycling of fluids by convective circulation driven by the heat of granite. The fluid (usually essentially H_2O) enhances chemical transfer resulting in widespread variation in compositional characteristics in both the granite and aureole (Parmentier and Schedl, 1981).

In contrast, the aureole at Shap is characterised by non-convective, ie. conductive, cooling which produces narrow, relatively high temperature aureoles which are chemically unaltered. The heat anomaly of such intrusions is not convected upwards to the same extent as in convective cooling. (Nagy and Parmentier, 1982). Modelling of conductive heat transfer suggests that narrow aureoles are always formed and that wide aureoles can only be generated by fluid flow assistance. Fig.7.3 shows a compilation of available data for intrusions of known size (surface radius), aureole width and stable isotopic character. The intrusions include Hercynian and Caledonian granites, Cretaceous and Tertiary granites of Japan and Greenland, porphyry-Cu granites from the Americas and sub-volcanic plutonic complexes such as at Skaergaard and Skye.

It can be seen that the intrusions with depleted or anomalous isotopic values have wide aureoles relative to their pluton radius due to their cooling by convection. In contrast, the plutons with intact isotopic values have consistently narrow aureoles whose width appears to be independent of the pluton size. The Shap Granite conforms to the region of conductively cooled plutons although it's small radius (due to the limited extent of it's unroofing) makes this characterisation less clear in Fig.7.3. Based on the nature of aureoles of conductively cooled intrusions, one would expect little difference in the aureole width at Shap even at deeper levels as the largest intrusions shown in Fig.7.3 still have relatively narrow aureoles.

7.3 Conclusions.

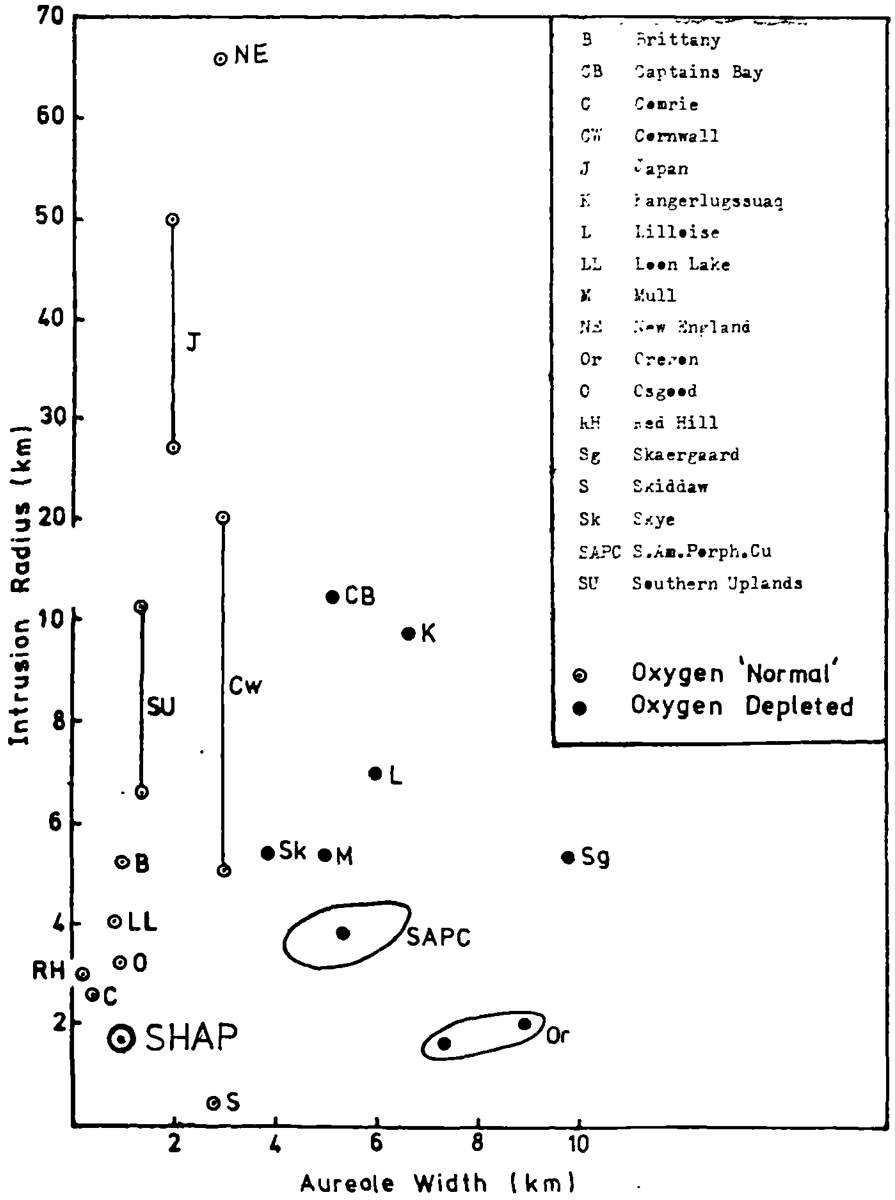


FIG. 7.3

Intrusion radius against width of metamorphic aureole for various plutonic rocks.

Data From:

Albarede et al. (1980)
Foland and Friedman (1977)
Forester and Taylor (1976,1977)
O'Neil et al. (1977)
Pankhurst, Beckinsale and Brooks (1976)
Perfit and Lawrence (1979)
Shieh, Schwarcz and Shaw (1976)
Taylor and Epstein (1963)
Taylor and Forester (1971,1979)
Taylor and O'Neil (1977)

The geochemical character of the Caledonian Shap Granite and its aureole has been examined using all available rock types. The results have been evaluated to recognise the major processes of granite intrusion and associated metamorphism and cooling.

The granite appears to have been generated by crystal fractionation of a magma of around 56% SiO_2 and continued evolving until reaching an adamellite composition. Further limited fractionation produced extreme felsitic dyke and aplitic compositions. Orthoclase growth was suppressed until late in the granite's crystallisation resulting in megacryst development in both the granites and xenoliths. The xenoliths are products of the same magma evolution, being comagmatic micrograjnites incorporated during magmas emplacement. Late hydrothermal alteration in the granite was isochemical and involved local distribution of released elements about the joint planes.

Interaction with the calc-alkaline volcanic rocks of the aureole was very limited and was generally restricted to isochemical thermal metamorphism over a narrow zone of conductive cooling. This style of cooling is thought to be typical of Caledonian granites generally and is markedly different from that seen in sub-volcanic and mineralised granites such as porphyry deposits.

With this data set, it is still not possible to draw unequivocal conclusions concerning the fractionation of the Shap magma. If further study can show that some xenoliths represent less evolved compositions then they should be included in studies of plutonic granites.

Chemical hydration-dehydration reactions in the metamorphic aureoles can be modelled using stable isotopes. The use of hydrogen isotopes (which are more sensitive to reactions than oxygen) on rocks and their minerals would allow greater understanding of the hydrothermal and metamorphic processes involved. It is only recently that mineral-H_2O systematics for hydrogen fractionation have been evaluated (eg. Graham et al. 1980) and their use in studying processes in aureoles has yet to be undertaken.

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APPENDIX

Location of Analysed Samples.

Sample Number (XRF)	Location (Grid Ref)	Comment
Granites.		
522	P.Q.	Dark
523	537098	Hornblende
530	551083	Wasdale Gully
531	P.Q.	Light
532	P.Q.	Light
533	549088	
534	P.Q.	Dark
535	P.Q.	V.Altered
561	550084	
600	P.Q.	
601	543103	
602	539088	
603	552083	
605	550083	Wasdale Farm
606	550083	" "
649	P.Q.	Light
650	P.Q.	Aplite
651	P.Q.	"
652	P.Q.	"
653	547103	Aplitic Pod
Xenoliths.		
501	P.Q.	
502	P.Q.	
503	P.Q.	
505	P.Q.	
506	P.Q.	
524	P.Q.	
525	P.Q.	
526	P.Q.	
527	P.Q.	
528	P.Q.	
529	550083	
615	P.Q.	
656	P.Q.	
657	P.Q.	
658	P.Q.	
659	P.Q.	
660	P.Q.	
Dykes		
507	574077	
508	567080	
509	572077	
510	556059	Red Crag
511	568076	
512	571076	
513	571076	
514		N-QP79
515	Stakeley	N-GP21
516		N-QP13
517	and	N-QP12
518		N-GP20
519	Birkbeck	N-GP23
520		N-QP80
521	576097?	N-SW62
562	539103	
563	537102	
604	548081	Wasdale Farm
607	548080	
608	545112	
609	552075	
610	548080	Wasdale Farm
611	545112	
612	548161	Fairy Crag
613	546105	
614	525101	
654	543057	Watshaw Pike
655	550112	

Sample Number (XRF)	Location (Grid Ref)	Comment
Volcanics.		
536	535094	
537	536095	
538	538100	
539	529095	
540	531097	
541	534096	
542	535101	
543	528099	
544	528097	
545	530101	
546	533101	
547	536101	
548	549111	
549	548112	
550	548112	
551	547112	
552	545111	
553	540109	
554	542106	
555	541102	
556	541101	
557	539101	
558	543110	
559	538104	
560	539103	
616	567104	
617	567104	
618	568103	
619	568103	
620	568102	
621	546107	
622	546108	
623	541109	
624	540108	
625	548110	
626	549109	
627	550109	
628	555109	
629	553106	
630	557110	
631	561103	
632	560126	
633	567091	
634	567088	
635	567089	
636	550084	
637	527083	
638	537085	
639	525101	
640	529105	
641	530105	
642	538108	
643	B.Q.	
644	B.Q.	
645	B.Q.	
646	560101	Blea Beck
647	560101	" "
648	560101	" "
661	574107	Shap Summit Railway Cutting
662	574107	
663	574107	

P.Q. Pink Quarry; B.Q. Blue Quarry

N- Nottingham University Sample Number (Dr.P.Redfern).

Table A.1

Thin Sections-Location of Samples.

T.S. Number	Rock Type	Location	Comment	XRF Number
37993	G	P.Q.	Light	531
94	X	P.Q.		501
95	G	P.Q.	Light	532
96	G	P.Q.	Dark	522
97	G	P.Q.	Dark	534
98	G	537098	Hornblende	523
99	G	550083	Wasdale Farm	606
38000	G	551083	" "	-
01	X	P.Q.		503
02	G	537098	Hornblende	-
03	D	556059	Red Crag	510
04	D	567080	Stakeley Beck	508
05	D	568076	" "	-
06	D	569076	" "	511
07	D	568076	" "	-
08	D	571076	" "	513
09	D	571076	" "	-
39910	D	571076	" "	512
11	D	572077	" "	509
12	D	573077	" "	507
13	X	P.Q.		527
14	X	P.Q.		524
15	G	P.Q.	Few Megacrysts	-
16	G	P.Q.	Rare Megacrysts	600
17	G	536094	Sleddale Pike	-
18	X	546084	Wasdale Farm	529
19	G	546084	" "	-
39920	D	Stakeley	N-GP8	-
21	D	Red Crag?	N-T2350	-
22	D	Stakeley	N-GP10	-
39950	D	Birkbeck	N-QP13	516
51	D	Wet Sleddale	N-WS28	-
52	D	Birkbeck	N-QP12	517
53	D	"	N-QP77	-
54	D	Stakeley	N-GP20	518
55	D	Shap Wells	N-SW62	521
56	D	Stakeley	N-GP3	-
57	D	571077	Stakeley	-
58	X	P.Q.		528
59	G	537098	Hornblende	-
39960	G	P.Q.	Aplite	651
61	G	P.Q.	Dark	-
62	G	P.Q.	Rare Megacrysts	-
63	D	539103		562
64	D	539102		563
65	D	555114		-
66	G	Bramcrag	T.M.G.	-
67	V	B.Q.		-
68	V	B.Q.		-
69	X	542100		-
41520	V	548112		550
21	V	538103		555
22	V	549112		548
23	V	533102		546
24	V	530101		545
25	V	535095		536
26	V	536096		537
27	V	569102		620
28	V	549109		626
29	V	554106		629
41530	V	568091		633
31	V	548110		625
43113	V	550084		636
14	V	550109		627
15	V	560103		631
16	V	566089		635
17	V	567104		617
18	V	546108		622
19	V	567105		616
43120	V	560100	N.E.Contact	648
21	D	548081	Wasdale Head	610
22	D	545112		608
23	D	548081		604
24	D	541057		654
25	X	P.Q.		-
26	X	P.Q.		615
27	D	546105		613
28	D	550113		655
29	V	565107	Blue Quarry	643
43130	V	565107	" "	644
31	V	564106	" "	645
32	D	534160		612
33	D	526102		614
34	D	553075		609
35	G	543103		601
36	G	553083		603
37	G	547103	Granite Pod	653

Rock Types: G, Granites and Aplites
X, Xenoliths; D, Dykes; V, Volcanics.
P.Q. Pink Quarry; B.Q. Blue Quarry.
T.M.G. Threlkeld Microgranite.
N- Nottingham University Sample Number (Dr.P.Redfern).

Table A.2

Table A.3

Dyke Petrology.

Thin Sect. Number	SiO_2 %	Colour	Phenocrysts				Groundmass									
			Q	:Or	:Pl	:Bi	Texture G,Mp,Sp	Mineralogy Q	:Or	:Pl	:Bi	:Ch	:Ap	:Cc	:Py	:ASA
39903	75	PlPink	2	1	4	3	G+Sp	+	+	?	-	+	+	-	-	-
39904	68	PlGrey	3	3	1	2	G+Mp	+	?	+	-	+	?	-	-	+
39905	-	Grey	3	1	2	4	G+Mp	+	+	+	-	+	+	-	-	-
39906	69	Grey	1	3	2	4	G+Mp	+	?	+	M	+	?	+	-	-
39907	-	Grey	1	-	2	3	G+Mp	+	-	+	M	+	+	+	-	-
39908	-	DkGrey	-	-	1	2	G+Mp	+	?	+	+	-	+	-	-	?
39909	-	Pink	1	3	2	4	G	+	?	?	-	-	?	-	-	-
39910	-	DkGrey	3	4	1	2	G+Mp	+	?	?	-	+	+	+	+	-
39911	67	GrPink	3	?	1	2	G+Sp	+	?	?	+	+	+	-	-	+
39912	68	Grey	?	3	1	2	G+Sp	+	?	+	+	+	+	+	-	+
39920	-	BrPink	1	3	2	4	G	+	?	+	-	+	+	-	+	-
39921	-	OrPink	1	3	2	3	G	+	?	+	-	?	?	?	+	-
39922	65	Grey	-	-	1	2	G	+	?	+	-	+	+	+	+	-
39950	74	Pink	1	2	3	4	G+Sp	+	?	?	-	+	+	+	-	-
39951	-	BrGrey	2	3	1	4	G	+	+	+	+	+	+	-	?	?
39952	74	Pink	1	3	2	4	G+Sp	+	?	+	-	+	+	+	-	?
39953	-	CrGrey	1	2	3	4	G	+	+	+	+	+	+	-	-	-
39954	68	PlGrey	1	?	?	2	G	+	?	+	+	+	+	?	-	+
39955	52	DkGrey	-	-	1	?	Mp	-	-	+	+	-	-	-	-	-
39956	-	Pink	1	3	2	4	G	+	?	?	+	M	+	-	-	-
39957	-	GrPink	4	1	2	3	G+Mp	+	?	?	+	+	+	+	?	+
39963	75	Pink	-	-	-	-	G	+	+	+	+	+	+	-	-	-
39964	76	Pink	-	-	-	-	G	+	+	+	+	+	?	-	-	-
39965	-	GrPink	1	3	4	2	G	+	?	?	-	+	+	+	-	-
43121	72	Pink	1	2	2	3	G	+	?	?	+	-	+	-	-	+
43122	62	Grey	3	2	1	4	G+Mp	+	?	?	+	+	+	-	-	+
43123	73	Grey	2	3	1	3	G	+	+	?	+	-	+	-	-	+
43124	65	GrPink	-	-	-	?	G	+	+	+	M	+	?	?	+	-
43127	72	Pink	1	1	2	3	G	+	+	+	+	-	?	-	-	-
43128	67	GrPink	2	1	3	4	G	+	?	+	+	+	+	-	-	-
43132	73	Pink	1	-	-	?	G	+	?	?	-	+	-	-	-	?
43133	65	DkPink	-	-	-	-	G	+	?	+	+	+	+	-	-	-
43134	77	PlGrey	1	2	2	3	G	+	?	?	-	+	-	-	-	+

Colour: Pl,Pale; Dk,Dark; Gr,Grey; Br,Brown; Or,Orange; Cr,Cream.
Phenocrysts: Q,Quartz; Or,Orthoclase; Pl,Plagioclase; Bi,Biotite.
In Order of Occurrence (1,2,3,4).
? Uncertain
- Not Present.
Groundmass: Texture: G,Granular; Mp, Microphenocrystic;
Sp,Spherulitic.
Ch,Chlorite; Ap,Apatite; Cc,Calcite; Py,Pyrite;
ASA, One or more of Allanite/Sphene/Amphibole;
M,White Mica (Muscovite) after Biotite or Chlorite

Shap Granites

Rock No.	522	523	530	531	532	533	534	535	561
Si02	67.91	67.54	67.31	70.17	68.49	69.01	69.77	69.04	69.88
Ti02	0.54	0.82	0.51	0.54	0.51	0.58	0.59	0.57	0.46
Al203	14.79	13.35	15.70	14.12	15.10	14.58	14.09	14.10	14.31
Fe203	2.51	2.83	2.76	2.52	2.40	2.73	2.64	2.98	2.36
Mn0	0.08	0.13	0.09	0.09	0.09	0.08	0.08	0.08	0.09
Mg0	1.31	1.91	1.45	1.12	1.10	1.37	1.45	1.45	1.06
Ca0	1.84	2.61	1.55	2.02	1.78	1.59	1.86	1.10	1.23
Na20	3.36	2.46	2.94	3.48	3.57	3.44	3.43	2.67	3.10
K20	5.92	7.80	6.67	4.54	5.84	5.40	4.67	5.76	5.91
P205	0.24	0.38	0.25	0.23	0.23	0.27	0.25	0.25	0.19
LOI	0.96	0.45	0.77	0.64	0.48	0.60	0.95	1.58	0.82
Total	99.47	100.30	99.99	99.48	99.59	99.66	99.79	99.58	99.42
Cr	28	41	28	25	25	27	27	23	18
Co	9	8	14	10	5	10	11	12	9
Ni	16	19	17	16	16	17	17	20	15
Cu	13	10	15	24	27	17	13	16	10
Zn	36	37	44	45	48	46	40	39	30
Rb	303	265	292	251	296	279	267	335	282
Sr	408	246	477	422	473	427	378	261	464
Y	8	17	17	8	6	14	9	7	7
Zr	141	280	158	146	129	158	154	184	127
Nb	15	29	17	16	13	16	16	16	15
Pb	47	51	66	54	68	48	43	31	42
Ba	703	454	1137	573	862	737	506	553	724
U	7	10	5	6	5	4	7	3	5
Th	27	61	30	35	29	37	33	35	36
Nd	34	41	34	37	31	68	40	42	35
Ce	76	101	58	86	56	158	99	94	81
La	34	54	33	42	32	91	45	43	43
V	38	47	35	35	35	43	41	37	32
Sc	9	11	11	8	9	10	9	9	12
Rb/Sr	0.74	1.08	0.61	0.59	0.63	0.65	0.71	1.28	0.61
K/Rb	162	244	190	150	164	161	145	143	174
Y/Zr	0.06	0.06	0.11	0.05	0.05	0.09	0.06	0.04	0.06
K20/Na20	1.76	3.17	2.27	1.30	1.64	1.57	1.36	2.16	1.91
K/Ba	70	143	49	66	56	61	77	86	68
Rb/Ba	0.43	0.58	0.26	0.44	0.34	0.38	0.53	0.61	0.39
Zr/Nb	9.40	9.66	9.29	9.12	9.92	9.87	9.62	11.50	8.47
Na20+K20	9.28	10.26	9.61	8.02	9.41	8.84	8.10	8.43	9.01
Peralk	0.968	0.775	1.056	0.987	0.979	1.013	1.001	1.117	1.042

Table B.1

Shap Granites (cont.)

Rock No.	600	601	602	603	605	606	649
SiO_2	73.21	72.09	68.68	70.37	68.55	70.53	69.54
TiO_2	0.49	0.29	0.59	0.48	0.59	0.58	0.55
Al_2O_3	12.43	13.53	14.49	13.88	14.61	13.13	14.57
Fe_2O_3	1.90	1.55	2.60	2.33	2.76	3.05	2.59
MnO	0.09	0.06	0.08	0.07	0.09	0.10	0.10
MgO	1.14	0.62	1.46	1.24	1.53	1.47	1.24
CaO	1.49	0.76	1.53	1.42	1.70	1.45	1.95
Na_2O	3.15	3.17	3.48	2.64	3.46	2.52	3.60
K_2O	4.48	5.67	4.89	5.57	5.31	5.18	5.19
P_2O_5	0.20	0.12	0.25	0.23	0.26	0.25	0.23
LOI	1.10	1.81	1.05	1.55	1.00	1.24	0.72
Total	99.67	99.67	99.10	99.79	99.85	99.52	100.28
Cr	21	6	29	27	29	28	23
Co	62	54	48	37	43	49	10
Ni	15	13	18	15	19	19	17
Cu	14	8	13	10	39	11	9
Zn	32	15	36	25	53	42	41
Rb	273	297	250	311	246	260	258
Sr	269	223	392	320	453	256	456
Y	7	7	14	13	16	21	9
Zr	166	95	185	188	202	251	162
Nb	15	9	17	21	19	25	15
Pb	38	52	38	55	43	59	53
Ba	269	339	596	505	756	494	668
U	10	4	5	7	7	8	6
Th	38	30	39	41	45	52	34
Nd	38	29	64	42	64	48	36
Ce	90	67	149	100	151	119	84
La	36	35	85	44	88	51	39
V	29	21	35	30	36	35	38
Sc	8	9	6	8	8	8	7
Rb/Sr	1.01	1.33	0.64	0.97	0.54	1.02	0.57
K/Rb	136	158	162	149	179	165	167
Y/Zr	0.04	0.07	0.08	0.07	0.08	0.08	0.06
K_2O/Na_2O	1.42	1.79	1.41	2.11	1.53	2.06	1.44
K/Ba	138	139	68	92	58	87	64
Rb/Ba	1.01	0.88	0.42	0.62	0.33	0.53	0.39
Zr/Nb	11.07	10.56	10.88	8.95	10.63	10.04	10.80
Na_2O+K_2O	7.63	8.84	8.37	8.21	8.77	7.70	8.79
Peralk	0.976	1.063	1.050	1.072	1.006	1.060	0.966

Table B.1 (cont.)

Shap Aplites

Rock No.	650	651	652	653
SiO2	75.98	76.46	76.27	76.54
TiO2	0.07	0.09	0.08	0.07
Al2O3	12.23	12.43	12.51	12.92
Fe2O3	1.07	0.56	0.53	0.25
MnO	0.04	0.04	0.04	0.04
MgO	0.01	0.03	0.05	0.04
CaO	0.26	0.45	0.44	0.41
Na2O	3.63	3.68	3.82	3.99
K2O	5.49	5.36	5.37	5.52
P2O5	0	0	0	0.02
LOI	0.89	0.64	0.50	0.60
Total	99.67	99.74	99.62	100.40
Cr	0	0	0	0
Co	80	81	69	66
Ni	3	4	4	2
Cu	17	132	17	13
Zn	8	29	13	43
Rb	337	319	439	308
Sr	95	69	39	75
Y	0	0	0	0
Zr	55	34	59	65
Nb	3	8	10	19
Pb	47	105	98	94
Ba	96	58	0	71
U	11	39	15	9
Th	32	25	33	26
Nd	10	16	16	12
Ce	17	38	48	22
La	5	14	17	5
y	0	2	0	4
Sc	4	5	3	5
Rb/Sr	3.55	4.62	11.26	4.11
K/Rb	135	139	102	149
Y/Zr	0	0	0	0
K2O/Na2O	1.51	1.46	1.41	1.38
K/Ba	475	767	0	645
Rb/Ba	3.51	5.50	0	4.34
Zr/Nb	18.33	4.25	5.90	3.42
Na2O+K2O	9.12	9.04	9.19	9.51
Peralk	0.968	0.981	0.970	0.973

Table B.1 (cont.)

Shap Dykes (Acidic, 64 to 78 % SiO2)

Rock No.	507	508	509	510	511	512	513	515	516
SiO2	66.94	67.98	68.31	75.25	69.34	66.87	75.38	70.52	74.37
TiO2	0.76	0.46	0.63	0.16	0.42	0.55	0.19	0.40	0.16
Al2O3	14.75	15.28	14.92	12.89	14.91	13.76	13.41	15.11	12.43
Fe2O3	3.22	2.23	2.77	1.11	2.23	3.04	0.94	2.16	1.20
MnO	0.07	0.07	0.06	0.05	0.10	0.10	0.05	0.11	0.07
CaO	2.12	0.87	1.64	0.07	1.10	2.28	0.25	0.37	1.07
Na2O	3.26	4.12	3.42	3.96	3.98	3.18	3.68	4.07	3.15
K2O	4.75	4.83	4.95	5.00	4.77	5.05	5.05	4.87	5.30
P2O5	0.31	0.17	0.28	0.04	0.16	0.28	0.07	0.16	0.04
LOI	1.70	1.89	1.49	0.87	2.28	2.35	1.04	1.97	1.78
Total	99.72	99.15	99.86	99.69	100.32	99.42	100.57	100.80	99.91
Cr	53	24	34	0	17	75	12	19	1
Co	14	7	10	4	8	15	2	11	5
Ni	30	13	15	3	18	44	8	17	7
Cu	21	13	14	8	10	14	15	15	10
Zn	309	22	33	27	44	54	11	58	25
Rb	157	231	166	217	233	163	218	239	273
Sr	428	344	438	97	244	443	178	222	85
Y	16	6	11	16	6	20	17	6	17
Zr	218	144	193	132	135	256	109	145	189
Nb	19	10	17	29	8	23	32	9	29
Pb	145	53	44	88	52	37	43	65	102
Ba	734	595	740	217	604	660	757	532	199
U	5	6	6	7	4	7	8	3	14
Th	34	24	36	62	25	53	56	24	60
Nd	55	34	48	27	33	62	22	30	27
Ce	131	73	115	61	72	146	33	76	67
La	62	35	58	25	37	69	14	25	25
V	60	38	50	5	37	54	10	35	7
Sc	12	7	8	4	9	10	9	6	6
Rb/Sr	0.37	0.67	0.38	2.24	0.95	0.37	1.22	1.08	3.21
K/Rb	251	174	248	191	170	257	192	169	161
Y/Zr	0.07	0.04	0.06	0.12	0.04	0.08	0.16	0.04	0.09
K2O/Na2O	1.46	1.17	1.45	1.26	1.20	1.59	1.37	1.20	1.68
K/Ba	54	67	56	191	66	64	55	76	221
Rb/Ba	0.21	0.39	0.22	1.00	0.39	0.25	0.29	0.45	1.37
Zr/Nb	11.47	14.40	11.35	4.55	16.87	11.13	3.41	16.11	6.52
Na2O+K2O	8.01	8.95	8.37	8.96	8.75	8.23	8.73	8.94	8.45
Peralk	1.027	1.125	1.069	1.070	1.088	0.927	1.120	1.196	0.966

Table B.2

Shap Dykes (Acidic cont.).

Rock No.	517	518	519	520	562	563	604	607	609
SiO_2	73.96	67.54	71.24	76.19	74.99	75.81	72.55	71.53	77.36
TiO_2	0.17	0.61	0.31	0.16	0.03	0.12	0.36	0.37	0.16
Al_2O_3	12.56	15.18	14.56	12.81	13.38	13.11	13.68	13.37	12.82
Fe_2O_3	1.19	2.98	1.75	1.20	0.83	0.47	1.97	2.24	0.49
MnO	0.07	0.07	0.06	0.05	0.06	0.05	0.05	0.05	0.06
MgO	0.27	1.70	0.72	0.66	0.15	0.17	1.05	0.93	0.32
CaO	0.99	1.04	0.45	0.37	0.37	0.44	1.33	0.72	1.22
Na_2O	3.99	4.07	3.98	3.42	2.97	2.56	3.14	2.97	1.38
K_2O	4.89	4.55	5.11	2.74	6.17	6.48	5.00	5.34	4.00
P_2O_5	0.04	0.17	0.15	0.04	0.08	0.04	0.15	0.16	0.05
LOI	1.44	1.98	1.67	2.34	0.78	0.75	1.12	1.75	1.38
Total	99.57	99.90	100.01	99.99	99.87	100.01	100.42	99.43	99.67
Cr	0	42	9	0	0	0	17	13	0
Co	3	9	9	6	0	4	42	44	27
Ni	5	24	10	8	4	4	15	17	6
Cu	8	31	19	21	14	12	19	18	8
Zn	39	41	78	20	29	36	54	48	21
Rb	210	266	279	152	239	294	198	243	147
Sr	134	304	210	195	69	97	289	252	205
Y	19	6	4	20	10	3	25	26	19
Zr	154	191	115	127	42	54	220	226	128
Nb	29	7	9	29	11	12	24	23	29
Pb	72	54	87	20	135	77	54	50	98
Ba	295	643	428	361	265	140	385	340	572
U	13	4	5	14	5	5	9	9	11
Th	62	27	20	65	18	23	61	62	64
Nd	29	33	23	28	11	11	42	87	34
Ce	64	70	58	61	15	27	106	246	67
La	27	28	17	22	4	9	47	125	32
V	7	55	19	8	4	5	22	26	7
Sc	5	8	4	2	10	10	7	7	2
Rb/Sr	1.57	0.87	1.33	0.78	3.46	3.03	0.69	0.96	0.72
K/Rb	193	142	152	150	214	183	210	182	226
Y/Zr	0.12	0.03	0.03	0.16	0.24	0.06	0.11	0.12	0.15
K_2O/Na_2O	1.22	1.12	1.28	0.80	2.08	2.53	1.59	1.80	2.90
K/Ba	137	59	99	63	193	384	108	130	58
Rb/Ba	0.71	0.41	0.65	0.42	0.90	2.10	0.51	0.71	0.26
Zr/Nb	5.31	27.29	12.79	4.38	3.82	4.50	9.17	9.83	4.41
Na_2O+K_2O	8.87	8.62	9.09	6.16	9.14	9.04	8.14	8.31	5.38
Peralk	0.921	1.124	1.129	1.383	1.094	1.090	1.053	1.117	1.454

Table B.2 (cont.)

Shap Dykes (Acidic cont.).

Rock No.	610	612	613	614	654	655
SiO2	72.48	72.55	72.21	64.99	65.47	67.31
TiO2	0.39	0.24	0.26	0.54	0.57	0.65
Al2O3	13.36	13.57	14.70	14.92	15.30	14.51
Fe2O3	1.74	6.40	1.05	2.92	2.97	3.17
MnO	0.05	0.29	0.04	0.12	0.08	0.12
MgO	0.95	0.76	0.19	1.57	1.69	1.49
CaO	1.02	0.15	0.21	2.64	2.46	1.79
Na2O	3.34	0.19	3.99	3.51	3.59	3.07
K2O	5.18	3.12	5.19	4.35	3.77	5.13
P2O5	0.15	0.11	0.14	0.17	0.17	0.29
LOI	1.46	2.77	1.45	3.94	3.84	2.14
Total	100.13	100.16	99.43	99.68	99.92	99.23
Cr	20	0	0	42	46	43
Cd	63	34	50	37	31	30
Ni	20	5	6	26	32	23
Cu	14	17	14	22	21	19
Zn	46	38	24	58	55	76
Rb	199	162	289	161	147	168
Sr	272	10	165	289	328	382
Y	17	16	4	10	9	12
Zr	238	116	100	181	183	217
Nb	22	11	8	8	7	16
Pb	50	0	29	6	9	37
Ba	356	452	2700	2290	761	745
U	9	4	4	3	3	6
Th	62	12	18	23	22	40
Nd	46	19	30	41	37	58
Ce	116	28	16	58	84	146
La	48	14	18	41	45	70
V	28	14	15	54	55	50
Sc	9	7	5	10	11	11
Rb/Sr	0.73	16.20	1.75	0.56	0.45	0.44
K/Rb	216	160	149	224	213	253
Y/Zr	0.07	0.14	0.04	0.06	0.04	0.06
K2O/Na2O	1.55	16.42	1.30	1.24	1.05	1.67
K/Ba	121	57	16	16	41	57
Rb/Ba	0.56	0.36	0.11	0.07	0.19	0.23
Zr/Nb	10.82	10.55	12.50	22.62	26.14	13.56
Na2O+K2O	8.52	3.31	9.18	7.86	7.36	8.20
Peralk	1.031	3.425	1.170	0.976	1.058	1.047

Table B.2 (cont.)

Shap Dykes (Basic to Intermediate, 51 to 63 % SiO2)

Rock No.	514	521	608	611
SiO2	56.36	51.52	62.47	62.39
TiO2	0.63	0.82	1.20	1.73
Al2O3	18.03	24.58	15.17	14.75
Fe2O3	3.79	4.22	4.34	4.58
MnO	0.09	0.07	0.14	0.14
MgO	2.11	2.25	2.69	2.71
CaO	4.22	0.96	3.00	2.98
Na2O	5.73	0.49	2.98	2.93
K2O	4.35	10.78	6.24	6.01
P2O5	0.30	0.26	0.46	0.49
LOI	4.58	4.03	1.16	1.18
Total	100.19	99.99	99.85	99.40
Cr	71	41	84	93
Co	12	14	37	32
Ni	42	17	37	38
Cu	17	19	18	18
Zn	74	57	73	75
Rb	135	496	228	248
Sr	218	92	586	509
Y	27	30	16	14
Zr	331	360	311	339
Nb	26	23	23	23
Pb	70	31	39	36
Ba	461	567	1247	1084
U	10	6	4	5
Th	63	27	33	35
Nd	69	42	73	76
Ce	171	93	172	182
La	82	32	77	86
V	53	76	83	86
Sc	11	20	15	12
Rb/Sr	0.62	5.39	0.39	0.49
K/Rb	267	180	227	201
Y/Zr	0.08	0.08	0.05	0.04
K2O/Na2O	0.76	22.00	2.09	2.05
K/Ba	78	158	42	46
Rb/Ba	0.29	0.87	0.18	0.23
Zr/Nb	12.73	15.65	13.52	14.74
Na2O+K2O	10.08	11.27	9.22	8.94
Peralk	0.827	1.729	0.887	0.881

Table B.2 (cont.)

Northern England Lamprophyres.

				Arthurton + Wadge	Burgess + Holliday		Macdonald et al.	
	Nixon et al.1984			AW,1991	BH,1979		MacD,1985	
Rock No.	5160	5161	5163	Kers.	Kers.	Min.	Mica Lamp.	Kers.
SiO_2	48.89	50.22	44.20	65.10	50.80	50.90	47.30	45.10
TiO_2	1.45	1.53	1.11	0.48	1.35	1.25	1.23	1.25
Al_2O_3	12.08	12.27	12.84	15.00	14.12	12.95	12.06	12.92
Fe_2O_3	6.69	7.45	6.84	3.42	7.73	7.12	7.29	8.62
MnO	0.19	0.17	0.13	0.17	0.24	0.72	0.22	0.21
MgO	6.62	6.66	7.13	2.38	7.21	6.54	8.00	9.09
CaO	7.46	6.39	9.45	2.35	5.16	4.34	8.31	9.05
Na_2O	2.29	2.46	0.69	5.30	2.40	1.50	1.20	1.74
K_2O	4.03	4.66	6.53	1.05	1.91	5.74	4.59	2.61
P_2O_5	0.90	0.91	1.10	0.27	0.82	0.89	1.03	0.80
LOI	8.45	5.65	8.54	4.19	8.11	7.44	8.96	8.54
Total	99.05	98.37	98.56	99.71	99.85	99.39	100.19	99.93
Cr	317	307	877	75	290	200	442	570
Co	31	38	34	20	18	20	40	42
Ni	136	129	362	44	150	85	259	291
Cu	41	36	40	230	18	10	-	-
Zn	54	60	30	-	-	-	-	-
Rb	198	202	119	-	-	-	-	-
Sr	750	1039	641	270	500	410	982	2111
Y	31	29	36	-	-	-	32	26
Zr	447	428	467	66	140	140	294	212
Nb	24	24	19	-	-	-	19	17
Pb	11	17	21	-	-	-	-	-
Ba	1285	1464	1815	110	1400	2400	2892	2191
U	-	-	-	-	-	-	-	-
Th	-	-	-	-	-	-	35	23
Nd	89	93	136	-	-	-	-	-
Ce	162	171	306	-	-	-	243	225
La	60	62	154	-	-	-	-	-
V	191	197	164	<10	25	<10	165	186
Sc	27	31	32	-	-	-	-	-
Rb/Sr	0.26	0.19	0.19	-	-	-	0.13	0.03
K/Rb	169	191	456	-	-	-	305	401
Y/Zr	0.07	0.07	0.08	-	-	-	0.11	0.12
K_2O/Na_2O	1.76	1.89	9.46	0.20	0.80	3.83	3.83	1.50
K/Ba	26	26	30	79	11	20	13	10
Rb/Ba	0.15	0.14	0.07	-	-	-	0.04	0.02
Zr/Nb	18.62	17.83	24.58	-	-	-	15.47	12.47
Na_2O+K_2O	6.32	7.12	7.22	6.35	4.31	7.24	5.79	4.35
Peralk	0.557	0.593	0.506	1.062	0.917	0.782	0.547	0.583

Table B.3

Average Calc-Alk. Lamprophyres (Rock 1985)

Rock Type	Minette	Vogesite	Kers.	Spess.	Mean Lamp.
SiO2	51.36	50.70	51.45	51.94	51.54
TiO2	1.46	1.44	1.16	1.36	1.31
Al2O3	12.65	14.01	14.77	15.22	14.29
Fe2O3	7.14	9.40	7.68	8.39	7.88
MnO	0.14	0.17	0.12	0.14	0.14
MgO	7.27	7.41	6.24	6.85	6.69
CaO	6.37	6.83	5.99	7.04	6.44
Na2O	1.91	2.76	2.95	3.19	2.68
K2O	6.08	4.19	3.36	2.40	3.88
P2O5	1.09	0.77	0.66	0.44	0.72
LOI	-	-	-	-	-
Total	95.46	96.68	94.38	96.37	95.75

No Trace Element Data Available.

K2O/Na2O	3.18	1.52	1.14	0.75	1.45
Na2O+K2O	7.99	6.95	6.31	5.59	6.56
Peralk	0.594	0.652	0.762	0.737	0.703

Table B.3 (cont.)

Shap Volcanics

Rock No.	536	537	538	539	540	541	542	543	544
SiO2	57.38	59.73	53.14	61.26	61.34	56.01	63.97	55.36	61.57
TiO2	1.37	1.27	1.10	1.24	1.13	1.34	1.17	1.49	1.33
Al2O3	17.94	18.01	15.19	16.87	15.61	17.57	16.31	18.74	16.46
Fe2O3	5.80	5.69	8.21	6.33	8.24	7.24	5.88	8.48	6.41
MnO	0.17	0.14	0.57	0.18	0.21	0.21	0.13	0.19	0.17
MgO	3.19	2.05	2.61	2.06	3.17	1.97	2.25	3.26	1.51
CaO	2.37	2.95	16.40	3.49	3.47	7.71	2.12	5.41	4.17
Na2O	1.36	4.21	1.36	4.04	2.42	2.34	2.84	2.16	2.84
K2O	9.60	4.66	0.83	3.89	3.10	4.81	3.68	4.24	3.70
P2O5	0.40	0.38	0.33	0.39	0.37	0.32	0.38	0.37	0.42
LOI	0.84	1.21	0.77	0.59	1.07	0.82	1.55	0.77	1.08
Total	100.35	100.32	100.53	100.34	100.15	100.36	100.28	100.47	99.65
Cr	2	0	0	2	0	81	0	31	0
Co	19	17	17	22	20	22	17	33	22
Ni	10	6	6	4	4	29	4	20	9
Cu	16	14	17	26	28	31	15	12	12
Zn	49	57	80	88	97	79	72	96	68
Rb	347	149	31	132	139	151	166	139	103
Sr	141	233	511	236	192	368	161	186	218
Y	33	32	34	35	32	25	33	27	31
Zr	289	285	209	273	267	162	272	195	242
Nb	31	31	24	30	28	19	29	22	25
Pb	53	30	4	21	19	21	25	22	26
Ba	737	927	151	866	536	1055	510	537	810
U	2	2	1	3	2	0	0	1	0
Th	17	16	13	17	16	9	16	11	15
Nd	44	47	38	44	44	33	41	34	34
Ce	81	89	88	80	93	50	85	61	62
La	29	35	40	34	43	25	32	24	24
V	132	126	73	110	99	214	98	201	120
Sc	26	24	26	23	20	30	19	24	22
Distance	0	60	100	680	540	180	380	900	775
Rb/Sr	2.46	0.64	0.06	0.56	0.72	0.41	1.03	0.75	0.47
K/Rb	230	260	222	245	185	264	184	253	298
Y/Zr	0.11	0.11	0.16	0.13	0.12	0.15	0.12	0.14	0.13
K2O/Na2O	7.06	1.11	0.61	0.96	1.29	2.06	1.30	1.96	1.30
K/Ba	108	42	46	37	48	38	60	66	38
Rb/Ba	0.47	0.16	0.21	0.15	0.26	0.14	0.33	0.26	0.13
Zr/Nb	9.32	9.19	8.71	9.10	9.54	8.53	9.38	8.86	9.68
Na2O+K2O	10.96	8.87	2.19	7.93	5.52	7.15	6.52	6.40	6.54
Peralk	1.059	1.039	0.461	0.981	1.144	0.762	1.304	1.043	1.013

Table B.4

Shap Volcanics (cont.)

Rock No.	546	547	548	549	552	553	554	555	556
SiO2	64.11	67.01	67.74	52.48	62.59	55.38	55.61	56.74	56.11
TiO2	0.54	1.08	0.41	1.47	0.88	1.36	1.63	1.32	1.42
Al2O3	16.58	15.47	15.20	18.57	16.60	18.65	18.54	15.90	17.25
Fe2O3	4.32	4.27	5.13	9.84	5.44	8.56	8.03	8.20	9.41
MnO	0.20	0.11	0.14	0.24	0.16	0.26	0.26	0.31	0.21
MgO	2.96	2.27	1.95	3.43	2.77	3.53	1.74	2.31	2.89
CaO	2.22	2.71	2.13	7.11	3.62	4.92	6.64	9.10	5.89
Na2O	0.84	3.18	2.84	3.10	2.62	1.13	1.30	1.62	2.59
K2O	6.35	2.24	3.13	2.31	4.16	4.85	4.66	3.08	3.20
P2O5	0.11	0.29	0.08	0.37	0.27	0.31	0.43	0.33	0.34
LOI	1.69	1.11	1.15	1.07	0.66	1.02	1.43	0.89	0.82
Total	99.92	99.75	99.90	100.00	99.76	99.96	100.27	99.80	100.16
Cr	8	0	0	289	24	67	7	80	90
Co	11	16	16	35	27	28	25	33	31
Ni	11	5	4	104	143	23	15	34	22
Cu	13	23	15	21	23	18	42	67	33
Zn	66	67	74	149	53	97	114	63	99
Rb	230	87	117	76	129	170	144	92	125
Sr	132	180	161	408	138	117	358	351	333
Y	38	30	47	26	38	26	31	25	28
Zr	366	256	370	155	271	189	201	162	191
Nb	26	26	25	21	21	19	24	20	21
Pb	41	18	36	16	24	18	31	10	16
Ba	558	584	724	460	1083	698	825	704	505
U	3	2	3	0	2	1	1	1	0
Th	19	17	21	10	15	13	12	11	12
Nd	42	35	47	34	41	39	45	39	39
Ce	86	66	85	59	64	67	81	75	72
La	38	23	40	16	31	28	37	26	28
V	29	101	16	270	87	200	221	227	229
Sc	22	19	21	36	27	33	26	27	29
Distance	500	350	730	830	680	780	400	50	10
Rb/Sr	1.74	0.48	0.73	0.19	0.93	1.45	0.40	0.26	0.38
K/Rb	229	214	222	252	268	237	269	278	213
Y/Zr	0.10	0.12	0.13	0.17	0.14	0.14	0.15	0.15	0.15
K2O/Na2O	7.56	0.70	1.10	0.75	1.59	4.29	3.58	1.90	1.24
K/Ba	94	32	36	42	32	58	47	36	53
Rb/Ba	0.41	0.15	0.16	0.17	0.12	0.24	0.17	0.13	0.25
Zr/Nb	14.08	9.85	14.80	7.38	12.90	9.95	8.37	8.10	9.10
Na2O+K2O	7.19	5.42	5.97	5.41	6.78	5.98	5.96	4.70	5.79
Peralk	1.349	1.230	1.274	0.905	1.079	1.162	0.963	0.705	0.936

Table B.4 (cont.)

Shap Volcanics (cont.)

Rock No.	557	559	560	616	617	619	620	621	622
SiO_2	58.14	56.98	64.06	61.70	65.57	67.99	56.18	61.34	60.65
TiO_2	1.49	1.40	1.16	0.80	0.70	0.69	1.32	1.35	1.26
Al_2O_3	19.53	17.06	16.82	17.77	16.45	15.50	20.06	17.71	17.27
Fe_2O_3	5.06	7.43	4.20	5.11	3.35	4.02	7.41	4.85	6.23
MnO	0.14	0.25	0.10	0.14	0.16	0.09	0.21	0.14	0.19
MgO	1.80	2.41	1.54	0.63	1.33	0.73	2.13	1.63	2.21
CaO	2.93	6.44	4.45	1.06	1.69	0.57	4.50	2.33	4.01
Na_2O	3.17	2.01	2.69	3.48	3.17	2.51	2.12	3.67	3.37
K_2O	6.44	3.34	2.81	8.06	6.01	6.23	3.79	4.97	3.16
P_2O_5	0.42	0.49	0.34	0.21	0.14	0.17	0.29	0.44	0.39
LOI	0.79	1.84	1.18	1.04	1.13	1.68	1.84	1.26	1.23
Total	99.92	99.64	99.34	100.00	99.69	100.18	99.85	99.68	99.97
Cr	1	50	0	0	0	0	40	0	3
Co	20	21	21	22	23	27	41	33	30
Ni	7	22	8	4	4	4	21	8	7
Cu	16	19	21	18	24	15	34	41	11
Zn	60	156	106	37	89	44	79	69	113
Rb	158	124	84	190	182	168	166	128	95
Sr	209	239	231	225	112	159	145	186	293
Y	37	34	33	45	44	44	29	36	34
Zr	328	198	265	453	474	417	170	293	277
Nb	33	19	28	45	43	42	18	31	29
Pb	41	38	35	31	378	24	17	51	26
Ba	1186	885	819	1277	740	897	628	815	858
U	0	1	0	3	3	2	0	2	2
Th	18	13	16	20	18	19	9	16	17
Nd	40	44	52	61	54	46	31	45	43
Ce	69	76	115	116	117	100	46	85	87
La	31	29	42	66	51	46	15	31	37
V	148	162	106	5	4	6	240	112	107
Sc	28	34	24	20	15	17	27	24	23
Distance	50	500	300	650	670	670	680	350	420
Rb/Sr	0.76	0.52	0.36	0.84	1.62	1.06	1.14	0.69	0.32
K/Rb	338	224	278	352	274	308	190	322	276
Y/Zr	0.11	0.17	0.12	0.10	0.09	0.11	0.17	0.12	0.12
K_2O/Na_2O	2.03	1.66	1.04	2.32	1.90	2.48	1.79	1.35	0.94
K/Ba	45	31	28	52	67	58	50	51	31
Rb/Ba	0.13	0.14	0.10	0.15	0.25	0.19	0.26	0.16	0.11
Zr/Nb	9.94	10.42	9.46	10.07	11.02	9.93	9.44	9.45	9.55
Na_2O+K_2O	9.61	5.35	5.50	11.54	9.18	8.74	5.91	8.64	6.53
Peralk	1.115	0.916	1.081	1.085	1.112	1.302	1.272	1.132	1.063

Table B.4 (cont.)

Shap Volcanics (cont.)

Rock No.	623	624	625	626	627	628	629	630	631
SiO2	54.41	57.34	64.37	50.25	55.38	60.61	55.53	53.98	57.69
TiO2	1.64	1.53	1.06	1.20	1.17	1.38	1.37	1.54	1.23
Al2O3	16.89	17.12	14.46	16.26	16.10	17.20	18.11	20.37	15.68
Fe2O3	7.19	9.27	7.75	10.00	8.80	6.71	7.29	6.62	10.18
MnO	0.25	0.20	0.17	0.44	0.32	0.18	0.21	0.21	0.33
MgO	3.98	3.80	2.67	3.35	3.27	1.57	3.04	2.71	3.57
CaO	10.39	3.36	1.98	13.11	8.23	5.00	7.71	4.38	4.15
Na2O	2.89	3.43	2.85	3.11	3.25	3.41	3.46	5.04	0.81
K2O	0.91	3.22	3.51	0.89	1.57	2.96	1.77	3.50	3.91
P2O5	0.39	0.41	0.31	0.40	0.35	0.36	0.32	0.46	0.32
LOI	1.08	1.16	1.21	0.96	1.86	1.31	1.06	1.03	2.05
Total	99.95	99.85	100.32	99.97	100.32	100.69	99.89	99.85	99.91
Cr	207	8	0	0	0	3	125	2	218
Co	40	35	32	38	36	30	42	24	50
Ni	72	17	7	7	5	7	53	5	98
Cu	40	42	24	71	32	27	56	21	109
Zn	74	97	88	91	120	70	97	78	132
Rb	29	110	143	23	51	89	51	103	149
Sr	414	177	210	394	318	366	355	295	339
Y	32	35	26	36	38	31	31	40	24
Zr	182	211	229	231	244	223	177	332	134
Nb	24	24	25	27	28	25	21	35	17
Pb	15	15	14	13	23	18	17	39	11
Ba	255	611	623	169	468	683	473	1018	580
U	0	0	1	1	1	1	1	1	0
Th	9	10	15	15	13	13	13	20	9
Nd	37	40	37	45	41	39	34	45	27
Ce	68	79	61	101	77	72	68	72	49
La	23	25	25	42	31	27	24	26	19
V	242	210	82	105	85	204	215	154	213
Sc	37	26	15	28	24	25	33	28	29
Distance	760	760	700	500	500	760	450	920	230
Rb/Sr	0.07	0.62	0.68	0.06	0.16	0.24	0.14	0.35	0.44
K/Rb	260	243	204	321	256	276	288	282	218
Y/Zr	0.18	0.17	0.11	0.16	0.16	0.14	0.18	0.12	0.18
K2O/Na2O	0.31	0.94	1.23	0.29	0.48	0.87	0.51	0.69	4.83
K/Ba	30	44	47	44	28	36	31	29	56
Rb/Ba	0.11	0.18	0.23	0.14	0.11	0.13	0.11	0.10	0.26
Zr/Nb	7.58	8.79	9.16	8.56	8.71	8.92	8.43	9.49	7.88
Na2O+K2O	3.80	6.65	6.36	4.00	4.82	6.37	5.23	8.54	4.72
Peralk	0.690	1.124	1.197	0.544	0.732	0.961	0.838	1.017	1.196

Table B.4 (cont.)

Shap Volcanics (cont.)

Rock No.	632	633	634	635	636	637	639	640	641
SiO2	59.54	58.72	64.66	62.92	68.62	58.15	54.63	59.84	57.65
TiO2	1.38	1.31	0.83	0.86	0.80	1.42	1.46	1.16	1.15
Al2O3	15.25	20.56	14.93	16.39	15.48	17.64	18.45	15.53	17.31
Fe2O3	8.17	6.83	8.41	6.79	2.76	7.80	7.93	7.98	7.76
MnO	0.19	0.07	0.13	0.16	0.08	0.16	0.14	0.23	0.16
MgO	2.65	1.62	1.91	1.85	0.53	1.54	4.76	3.91	4.97
CaO	2.55	0.05	1.39	1.55	1.41	5.65	2.02	4.35	1.76
Na2O	2.93	0.25	1.99	2.10	3.89	2.97	5.07	3.26	2.06
K2O	1.70	6.57	3.38	3.84	4.69	3.47	2.86	0.84	4.73
P2O5	0.23	0.04	0.24	0.25	0.22	0.42	0.36	0.25	0.31
LOI	5.18	3.85	2.14	3.44	1.64	0.99	2.62	2.73	2.35
Total	99.86	99.87	100.01	100.18	100.13	100.21	100.30	100.90	100.21
Cr	13	399	17	15	1	8	56	132	66
Co	32	24	33	29	37	36	33	37	30
Ni	5	33	13	15	7	11	40	53	16
Cu	11	19	13	11	26	12	27	12	12
Zn	84	32	77	57	431	92	81	83	86
Rb	56	530	216	233	188	119	134	32	167
Sr	68	22	79	64	274	234	231	213	114
Y	32	22	31	33	38	34	30	24	35
Zr	219	266	227	234	248	234	188	152	212
Nb	16	24	18	21	21	27	23	17	18
Pb	0	5	6	6	231	15	8	7	6
Ba	377	200	369	204	784	1088	791	207	1532
U	0	0	2	2	0	2	0	0	2
Th	12	13	11	11	13	13	9	9	14
Nd	32	37	32	31	41	42	34	29	46
Ce	57	89	59	53	79	65	55	55	67
La	18	28	21	14	35	26	21	19	39
V	201	110	64	73	45	139	188	185	151
Sc	36	38	18	21	24	26	22	27	25
Distance	2500	310	200	180	1	1120	1150	1110	1000
Rb/Sr	0.82	24.09	2.73	3.64	0.69	0.51	0.58	0.15	1.46
K/Rb	265	103	130	137	207	242	177	218	235
Y/Zr	0.15	0.08	0.14	0.14	0.15	0.15	0.16	0.16	0.17
K2O/Na2O	0.61	26.28	1.70	1.83	1.21	1.17	0.56	0.26	2.30
K/Ba	39	273	76	156	50	26	30	34	26
Rb/Ba	0.15	2.65	0.59	1.14	0.24	0.11	0.17	0.15	0.11
Zr/Nb	13.69	11.08	12.61	11.14	11.81	8.67	8.17	8.94	11.78
Na2O+K2O	4.72	6.82	5.37	5.94	8.58	6.44	7.93	4.10	6.79
Peralk	1.332	2.701	1.579	1.572	1.103	0.933	1.221	1.095	1.479

Table B.4 (cont.)

Shap Volcanics (cont.)

Rock No.	642	643	644	645	646	647	648	661	662
SiO2	55.73	60.29	56.78	52.84	60.48	68.53	62.12	64.23	65.48
TiO2	1.30	1.52	1.20	1.47	1.45	0.44	1.30	0.90	0.84
Al2O3	18.49	18.28	15.40	18.76	17.80	15.00	15.49	15.85	15.59
Fe2O3	7.90	5.99	9.19	11.08	5.87	3.79	6.18	6.57	5.31
MnO	0.26	0.16	0.27	0.35	0.22	0.12	0.20	0.10	0.14
MgO	4.07	1.54	2.92	2.87	1.57	0.79	1.89	0.63	0.70
CaO	4.17	4.77	8.16	5.53	4.66	2.01	5.85	1.86	2.30
Na2O	0.85	2.56	2.21	1.32	4.08	2.27	1.37	3.53	3.41
K2O	4.65	3.04	2.40	3.67	1.75	5.76	3.70	4.75	4.64
P2O5	0.32	0.40	0.32	0.36	0.38	0.09	0.32	0.21	0.20
LOI	1.51	1.30	1.31	1.64	1.54	0.78	1.25	1.34	1.30
Total	99.25	99.85	100.16	99.91	99.82	99.60	99.68	99.97	99.91
Cr	55	46	217	293	46	0	44	44	23
Co	31	28	48	49	33	23	38	22	30
Ni	17	20	98	104	20	4	23	8	11
Cu	12	60	24	53	80	12	60	16	16
Zn	82	92	106	131	91	71	78	43	58
Rb	170	102	59	122	107	172	123	162	158
Sr	97	316	467	362	261	169	286	227	226
Y	31	27	25	27	27	42	25	36	38
Zr	198	180	118	160	182	379	150	246	257
Nb	18	21	17	19	19	27	17	21	22
Pb	15	19	14	18	70	94	19	35	36
Ba	565	698	690	534	456	1361	786	813	833
U	1	2	0	0	0	2	1	0	2
Th	12	10	8	9	11	20	9	17	15
Nd	37	33	30	33	37	50	30	42	41
Ce	65	57	39	56	73	94	51	74	79
La	27	20	14	21	26	47	20	33	38
V	176	271	210	257	249	1	199	61	53
Sc	32	33	31	38	32	20	27	25	24
Distance	740	810	490	490	1	1	1	1375	1375
Rb/Sr	1.75	0.32	0.13	0.34	0.41	1.02	0.43	0.71	0.70
K/Rb	227	247	338	250	136	278	250	243	244
Y/Zr	0.16	0.15	0.21	0.17	0.15	0.11	0.17	0.15	0.15
K2O/Na2O	5.47	1.19	1.09	2.78	0.43	2.54	2.70	1.35	1.36
K/Ba	69	36	29	57	32	35	39	48	46
Rb/Ba	0.30	0.15	0.09	0.23	0.23	0.13	0.16	0.20	0.19
Zr/Nb	11.00	8.57	6.94	8.42	9.58	14.04	8.82	11.71	11.68
Na2O+K2O	5.50	5.60	4.61	4.99	5.83	8.03	5.07	8.28	8.05
Peralk	1.320	1.130	0.731	1.158	1.042	1.101	0.917	1.106	1.053

Table B.4 (cont.)

Shap Volcanics (cont.) (High MgO,Ni,Cr Rocks) (Acid).

Rock No.	663	545	550	551	558	618	638
SiO2	64.57	53.01	54.30	55.69	53.24	71.82	73.27
TiO2	1.00	1.03	1.04	1.29	1.02	0.64	0.57
Al2O3	16.59	12.88	8.82	14.03	12.33	13.64	12.39
Fe2O3	5.81	10.50	7.46	7.42	10.45	1.91	3.23
MnO	0.08	0.30	0.21	0.19	0.30	0.04	0.09
MgO	0.84	11.53	13.56	9.38	7.95	0.14	0.49
CaO	0.62	6.27	10.19	4.71	10.91	0.09	0.63
Na2O	3.12	1.02	0.82	2.97	2.03	0.51	0.88
K2O	5.43	0.25	1.00	2.06	0.61	9.31	6.80
P2O5	0.24	0.22	0.21	0.30	0.25	0.10	0.13
LOI	1.89	3.21	1.39	1.95	0.78	1.65	1.29
Total	100.19	100.24	99.01	99.99	99.87	99.86	99.78
Cr	46	1270	1397	1018	471	0	0
Co	25	59	35	40	47	51	27
Ni	11	463	611	352	206	5	4
Cu	13	19	8	13	20	14	19
Zn	47	93	61	59	78	10	57
Rb	192	7	34	42	18	267	196
Sr	116	146	180	431	279	108	87
Y	34	22	20	26	24	28	34
Zr	255	131	104	151	137	373	329
Nb	22	13	11	18	14	35	31
Pb	25	4	4	5	10	26	30
Ba	738	40	133	550	164	1088	987
U	3	0	0	0	0	2	2
Th	16	9	5	11	8	16	16
Nd	44	26	19	30	36	44	39
Ce	77	48	27	48	68	83	74
La	29	13	6	18	19	36	37
V	76	186	146	218	211	6	6
Sc	31	31	31	31	37	13	13
Distance	1375	750	830	820	850	670	290
Pb/Sr	1.66	0.05	0.19	0.10	0.06	2.47	2.25
K/Rb	235	296	244	407	281	289	288
Y/Zr	0.13	0.17	0.19	0.17	0.18	0.08	0.10
K2O/Na2O	1.74	0.25	1.22	0.69	0.30	18.25	7.73
K/Ba	61	52	62	31	31	71	57
Rb/Ba	0.26	0.17	0.26	0.08	0.11	0.25	0.20
Zr/Nb	11.59	10.08	9.45	8.39	9.79	10.66	10.61
Na2O+K2O	8.55	1.27	1.82	5.03	2.64	9.82	7.68
Peralk	1.367	0.965	0.421	0.895	0.517	1.231	1.245

Table B.4 (cont.)

Borrowdale Volcanics (Averages, Millward et al;1978)

Rock Type.	Basalt	B-And.	Andesite	Dacite	Dacite	Rhyolite
SiO_2	51.04	55.74	59.98	67.50	66.77	72.21
TiO_2	1.29	1.09	0.91	0.31	0.33	0.31
Al_2O_3	16.25	17.81	17.76	16.60	16.46	14.72
Fe_2O_3	11.11	8.84	7.54	4.22	4.37	3.17
MnO	0.24	0.24	0.20	0.09	0.10	0.06
MgO	7.73	4.63	2.83	0.62	0.55	0.75
CaO	8.68	6.53	4.75	1.12	1.35	0.58
Na_2O	1.88	2.32	2.67	3.00	2.83	2.36
K_2O	1.33	2.42	2.97	4.60	4.84	5.55
P_2O_5	0.21	0.19	0.19	0.30	0.29	0.21
LOI	-	-	-	-	-	-
Total	99.77	99.81	99.80	98.36	97.89	99.92
Cr	410	123	62	5	6	3
Co	-	-	-	-	-	-
Ni	145	38	22	2	2	2
Cu	48	26	23	-	-	5
Zn	104	101	96	69	-	43
Rb	49	97	124	218	232	237
Sr	346	310	270	101	122	85
Y	27	34	40	63	64	65
Zr	141	179	227	315	340	282
Nb	11	12	14	25	25	17
Pb	14	23	22	23	24	-
Ba	349	586	747	1057	1072	1096
U	-	-	-	-	-	-
Th	10	12	16	26	28	-
Nd	-	-	-	-	-	-
Ce	45	54	62	118	124	-
La	19	22	35	76	77	46
V	231	171	119	13	-	8
Sc	-	-	-	-	-	-
Rb/Sr	0.14	0.31	0.46	2.16	1.90	2.79
K/Rb	225	207	199	175	173	194
Y/Zr	0.19	0.19	0.18	0.20	0.19	0.23
K_2O/Na_2O	0.71	1.04	1.11	1.53	1.71	2.35
K/Ba	32	34	33	36	37	42
Rb/Ba	0.14	0.17	0.17	0.21	0.22	0.22
Zr/Nb	12.82	14.92	16.21	12.60	13.60	16.59
Na_2O+K_2O	3.21	4.74	5.64	7.60	7.67	7.91
Peralk	0.801	0.973	1.094	1.389	1.333	1.345

Table B.4 (cont.)

Shap Xenoliths

Rock No.	501	502	503	504	505	506	524	527	528
SiO2	63.34	64.87	63.69	63.84	81.05	63.03	65.19	63.15	63.79
TiO2	1.43	1.35	1.34	1.25	0.09	1.31	1.11	1.33	1.37
Al2O3	14.96	14.08	15.07	14.87	7.28	15.21	14.95	14.62	14.95
Fe2O3	4.91	3.94	4.96	4.64	1.82	5.07	4.22	4.90	5.02
MnO	0.12	0.12	0.11	0.12	0.07	0.13	0.11	0.12	0.13
MgO	2.63	2.40	2.72	2.10	3.05	2.54	2.00	2.26	2.21
CaO	2.49	2.61	2.24	2.86	0.22	2.84	2.50	2.93	2.92
Na2O	3.07	3.28	3.42	3.59	1.17	3.74	3.56	3.69	3.66
K2O	4.81	4.88	4.46	4.59	4.19	4.12	5.37	4.52	4.59
P2O5	0.50	0.56	0.48	0.53	0.01	0.46	0.47	0.55	0.55
LOI	1.19	1.45	1.58	1.03	0.70	1.18	0.73	1.40	0.77
Total	99.46	99.55	100.07	99.43	99.65	99.63	100.21	99.48	99.96
Cr	69	71	65	35	4	62	38	47	46
Co	19	18	20	19	3	23	15	20	18
Ni	35	46	30	27	4	31	24	30	28
Cu	18	16	22	40	19	41	70	96	101
Zn	81	84	94	84	62	84	76	89	89
Rb	278	325	365	306	268	298	309	312	317
Sr	449	372	362	496	152	541	501	463	458
Y	10	11	9	13	26	11	12	13	14
Zr	337	350	305	345	65	272	301	364	370
Nb	22	23	20	25	22	20	22	27	27
Pb	42	46	36	53	39	45	59	46	53
Ba	860	581	560	553	168	695	726	503	507
U	7	5	5	5	3	8	5	5	5
Th	41	36	31	54	21	29	48	52	54
Nd	56	55	55	73	28	47	45	71	74
Ce	131	149	134	212	56	108	119	207	216
La	63	73	60	120	19	53	60	110	115
V	81	69	81	64	5	79	48	70	75
Sc	15	14	12	12	4	15	11	16	13
Rb/Sr	0.62	0.87	1.01	0.62	1.76	0.55	0.62	0.67	0.69
K/Rb	144	125	101	125	130	115	144	120	120
Y/Zr	0.03	0.03	0.03	0.04	0.40	0.04	0.04	0.04	0.04
K2O/Na2O	1.57	1.49	1.30	1.28	3.58	1.10	1.51	1.22	1.25
K/Ba	46	70	66	69	207	49	61	75	75
Rb/Ba	0.32	0.56	0.65	0.55	1.60	0.43	0.43	0.62	0.63
Zr/Nb	15.32	15.22	15.25	13.80	2.95	13.60	13.68	13.48	13.70
Na2O+K2O	7.88	8.16	7.88	8.18	5.36	7.86	8.93	8.21	8.25
Peralk	1.012	0.913	1.038	0.926	1.061	0.965	0.922	0.898	0.918

Table B.5

	Shap Xenoliths (cont.)					Shap Xenoliths (Basic)			
	529	615	658	659	660	525	526	656	657
SiO2	66.44	67.66	64.54	61.83	61.63	60.05	58.84	56.00	57.59
TiO2	0.79	0.60	1.09	1.49	1.68	2.12	2.22	1.92	1.70
Al2O3	15.77	14.57	14.67	14.98	14.73	14.44	14.17	13.73	14.53
Fe2O3	4.49	2.90	3.76	5.69	5.96	6.36	6.64	8.18	5.97
MnO	0.08	0.08	0.10	0.15	0.13	0.13	0.13	0.23	0.19
MgO	0.78	1.34	1.71	3.02	2.88	3.35	3.56	5.88	4.22
CaO	2.56	1.90	2.52	2.95	3.65	4.28	4.44	3.93	3.98
Na2O	3.61	3.52	3.39	4.21	3.86	3.63	3.33	3.52	3.36
K2O	4.22	5.51	5.46	3.13	3.28	3.48	4.07	3.32	4.29
P2O5	0.21	0.23	0.50	0.48	0.58	0.88	0.91	0.92	0.86
LOI	0.74	1.29	1.72	1.41	1.46	0.80	1.08	1.99	2.59
Total	99.70	99.60	99.46	99.34	99.84	99.52	99.40	99.42	99.28
Cr	14	27	24	96	75	108	113	275	162
Co	14	50	34	37	42	25	25	47	39
Ni	7	17	24	53	53	53	53	68	60
Cu	36	62	17	54	36	49	33	17	21
Zn	56	33	62	126	102	104	108	160	125
Rb	192	316	314	280	251	223	208	318	266
Sr	311	449	620	464	560	788	791	297	411
Y	31	7	11	14	14	19	20	22	16
Zr	254	168	365	308	300	474	461	544	461
Nb	23	15	21	24	23	31	33	25	26
Pb	68	41	45	43	37	43	47	16	35
Ba	784	768	949	270	801	1228	1544	599	899
U	3	9	9	17	4	7	4	5	7
Th	16	32	62	35	30	35	34	39	42
Nd	37	39	92	57	58	86	86	100	91
Ce	68	94	258	150	130	207	211	243	227
La	29	46	133	63	63	105	109	106	110
V	35	35	51	101	94	98	109	214	114
Sc	25	9	9	15	14	20	17	26	18
Rb/Sr	0.62	0.70	0.51	0.60	0.45	0.28	0.26	1.07	0.65
K/Rb	182	145	144	93	108	130	162	87	134
Y/Zr	0.12	0.04	0.03	0.05	0.05	0.04	0.04	0.04	0.03
K2O/Na2O	1.17	1.57	1.61	0.74	0.85	0.96	1.22	1.00	1.28
K/Ba	45	60	48	96	34	24	22	46	40
Rb/Ba	0.24	0.41	0.33	1.04	0.31	0.18	0.13	0.53	0.30
Zr/Nb	11.04	11.20	17.38	12.83	13.04	15.29	13.97	21.76	17.73
Na2O+K2O	7.83	9.03	8.85	7.34	7.14	7.11	7.40	6.64	7.65
Peralk	1.040	0.958	0.913	0.956	0.891	0.824	0.789	0.848	0.835

Table B.5 (cont.)

C.I.P.W. Normative Mineral Modes.

Shap Granites

Rock No.	522	523	530	531	532	533	534	535	561
Q	20.1	17.4	19.3	26.8	20.2	23.2	26.1	27.2	25.1
Or	35.0	46.1	39.4	26.8	34.6	31.9	27.6	34.0	34.9
Ab	28.4	20.8	24.9	29.4	30.2	29.1	29.0	22.6	26.2
An	7.6	2.4	6.1	8.5	7.3	6.1	7.6	3.8	4.9
Cor	0.1	-	1.4	0.4	0.2	0.8	0.6	2.1	1.0
Di	-	6.4	-	-	-	-	-	-	-
Woll	-	-	-	-	-	-	-	-	-
Hyp	4.2	2.4	4.7	3.7	3.6	4.3	4.5	4.7	3.5
Mag	1.6	1.8	1.8	1.7	1.6	1.7	1.7	1.9	1.5
Ilm	1.0	1.6	1.0	1.0	1.0	1.1	1.1	1.1	0.9
Apa	0.6	0.9	0.6	0.5	0.5	0.6	0.6	0.6	0.4
D.I.	83.5	84.3	83.6	83.0	85.0	94.2	82.7	83.8	86.2

								Shap Aplites			
Rock No.	600	601	602	603	605	606	649	650	651	652	653
Q	33.2	29.5	24.6	29.1	22.5	30.9	22.9	33.6	33.6	32.6	31.5
Or	26.5	33.5	28.9	32.9	31.4	30.6	30.7	32.5	31.7	31.7	32.6
Ab	26.7	26.8	29.4	22.3	29.3	21.3	30.5	30.7	31.1	32.3	33.8
An	6.1	3.0	6.0	5.5	6.7	5.6	8.2	0.9	1.6	1.1	1.1
Cor	0.2	1.1	1.3	1.5	0.7	1.3	-	-	-	-	-
Di	-	-	-	-	-	-	-	0.4	0.6	0.8	0.4
Woll	-	-	-	-	-	-	-	-	-	0.1	0.1
Hyp	3.4	2.1	4.4	3.9	4.8	4.9	4.0	0.5	-	-	-
Mag	1.3	1.0	1.7	1.5	1.8	2.0	1.7	0.7	0.4	0.4	0.4
Ilm	0.9	0.6	1.1	0.9	1.1	1.1	1.0	0.1	0.2	0.2	0.1
Apa	0.5	0.3	0.6	0.5	0.6	0.6	0.5	-	-	-	-
D.I.	86.4	89.8	82.9	84.3	83.2	82.8	84.1	96.8	96.4	96.6	97.9

Table C.1

Shap Dykes

Rock No.	507	508	509	510	511	512	513	514	515
Q	23.2	22.1	24.5	32.6	24.2	21.9	33.6	-	26.1
Or	28.1	28.5	29.3	29.6	28.2	29.9	29.9	25.7	28.8
Ab	27.6	34.9	28.9	33.5	33.7	26.9	31.1	42.3	34.4
An	8.5	3.2	6.3	0.1	4.4	8.4	0.8	10.6	0.8
Neph	-	-	-	-	-	-	-	3.4	-
Cor	1.4	2.1	1.6	0.9	1.6	-	1.6	-	2.9
Di	-	-	-	-	-	1.0	-	6.7	-
Woll	-	-	-	-	-	-	-	-	-
Hyp	5.1	3.6	4.0	0.8	3.2	5.3	1.3	-	3.0
Ol	-	-	-	-	-	-	-	2.7	-
Mag	2.3	1.6	2.0	0.9	1.6	2.2	0.8	2.4	1.7
Haem	-	-	-	-	-	-	-	-	-
Ilm	1.4	0.9	1.2	0.3	0.8	1.0	0.4	1.2	0.8
Apa	0.7	0.4	0.7	0.1	0.4	0.7	0.2	0.7	0.4
Cc	-	-	-	-	-	-	-	-	-
D.I.	78.9	85.5	82.7	95.7	86.1	78.7	94.6	68.0	89.3

Rock No.	516	517	518	519	520	521	562	563	604
Q	33.1	30.1	21.9	26.8	44.1	1.8	33.2	35.0	31.0
Or	31.3	28.8	26.9	30.2	16.2	63.7	36.5	38.3	29.6
Ab	26.7	33.8	34.4	33.7	28.9	4.2	25.1	21.7	26.6
An	4.1	2.0	4.1	1.3	1.6	3.1	1.3	1.9	5.6
Neph	-	-	-	-	-	-	-	-	-
Cor	-	-	2.1	2.0	3.6	11.0	1.3	1.2	1.0
Di	0.8	2.1	-	-	-	-	-	-	-
Woll	-	0.1	-	-	-	-	-	-	-
Hyp	0.8	-	4.8	2.1	1.8	7.6	0.7	0.4	2.9
Ol	-	-	-	-	-	-	-	-	-
Mag	0.9	0.9	2.2	1.4	1.0	2.5	0.7	0.4	1.6
Haem	-	-	-	-	-	-	-	-	-
Ilm	0.3	0.3	1.2	0.6	0.3	1.6	0.2	0.2	0.7
Apa	0.1	0.1	0.4	0.4	0.1	0.6	0.2	0.1	0.4
Cc	-	-	-	-	-	-	-	-	-
D.I.	91.1	92.7	83.2	90.7	89.2	69.7	94.8	95.0	87.2

Rock No.	607	608	609	610	611	612	613	614	654	655
Q	31.2	12.1	51.1	30.0	13.2	57.2	28.8	20.0	22.5	24.2
Or	31.6	36.9	23.6	30.6	35.5	18.4	30.7	25.7	22.3	30.3
Ab	25.1	25.2	11.7	28.3	24.8	1.6	33.8	29.7	30.4	26.0
An	2.5	9.6	5.7	4.1	9.4	-	0.1	12.0	11.1	7.0
Neph	-	-	-	-	-	-	-	-	-	-
Cor	1.8	-	4.1	0.8	-	9.9	2.5	0.1	1.3	1.4
Di	-	1.8	-	-	1.7	-	-	-	-	-
Woll	-	-	-	-	-	-	-	-	-	-
Hyp	2.7	7.0	0.8	2.5	7.1	4.5	0.6	4.7	4.9	4.5
Ol	-	-	-	-	-	-	-	-	-	-
Mag	1.7	2.8	0.4	1.4	3.0	5.1	0.8	2.1	2.2	2.3
Haem	-	-	-	-	-	-	-	-	-	-
Ilm	0.7	2.3	0.3	0.7	2.3	0.5	0.5	1.0	1.1	1.2
Apa	0.4	1.1	0.1	0.4	1.1	0.3	0.3	0.4	0.4	0.7
Cc	-	-	-	-	-	-	-	-	-	-
D.I.	87.9	74.2	86.4	88.9	73.5	77.2	93.3	75.4	75.2	80.5

Table C.2

Northern England Lamprophyres (As Page 307-8)

	AW	BH		Nixon			McD	
Rock No.	Kers.	Kers.	Min.	5160	5161	5163	M.Lamp.	Kers.
Q	24.9	15.6	7.5	8.7	1.8	-	10.8	9.5
Or	6.2	11.3	33.9	23.8	27.5	38.6	27.1	15.4
Ab	44.8	20.3	12.7	19.4	20.8	5.8	10.2	14.7
An	-	-	-	-	8.7	12.7	-	4.4
Neph	-	-	-	-	-	-	-	-
Cor	5.2	8.1	4.3	4.0	-	-	5.1	5.6
Di	-	-	-	-	2.9	5.0	-	-
Woll	-	-	-	-	-	-	-	-
Hyp	9.8	25.1	22.8	20.1	19.3	5.1	19.9	22.6
Ol	-	-	-	-	-	10.3	-	-
Mag	0.9	2.3	2.6	3.6	4.1	3.7	4.5	0.7
Haem	-	-	-	-	-	-	1.9	7.0
Ilm	0.9	2.6	2.4	2.8	2.9	2.1	2.3	2.4
Apa	0.6	1.9	2.1	2.1	2.1	2.6	2.4	1.9
Cc	3.7	7.3	10.5	11.6	4.8	7.5	15.6	12.7
D.I.	75.9	47.2	54.1	51.9	50.1	44.4	48.1	39.6

Average Calc-Alkaline Lamprophyres (Rock 1985)

Rock No.	Min.	Vog.	Kers.	Spess.
Q	0.9	-	5.9	1.7
Or	35.9	24.8	19.9	14.2
Ab	16.2	23.4	25.0	27.0
An	8.0	13.5	14.4	20.1
Neph	-	-	-	-
Cor	-	-	1.0	-
Di	1.9	3.2	-	4.0
Woll	-	-	-	-
Hyp	20.0	17.4	15.5	20.8
Ol	-	2.9	-	-
Mag	4.4	4.9	5.5	4.3
Haem	-	-	1.3	-
Ilm	2.8	2.7	2.2	2.6
Apa	2.5	1.8	1.5	1.0
Cc	5.1	4.1	4.0	2.5
D.I.	53.0	48.2	50.8	42.9

Table C.2 (cont.)

Orthoclase Analyses - Shap Light Granite. (Perthite host compositions for megacryst and matrix orthoclase) - Sample 531, 532, 649

Oxide %	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO2	64.87	65.17	65.01	64.86	65.35	65.66	64.39	64.97	64.81	64.69	64.41	64.93	64.16	63.58	65.00	63.90	64.87
Al2O3	18.60	19.03	18.71	18.67	18.89	18.87	18.92	18.66	19.10	18.63	19.13	18.81	18.21	18.60	18.60	18.55	18.85
FeO	0.09	0.05	0.07	0.12	0.14	0.11	0.06	0.09	0.05	0.01	0.12	0.12	0.08	0.29	0.11	0.0	0.09
MnO	0.07	0.07	0.05	0.0	0.01	0.0	0.0	0.10	0.0	0.0	0.0	0.0	0.12	0.08	0.06	0.08	0.0
CaO	0.18	0.01	0.04	0.05	0.06	0.02	0.05	0.11	0.0	0.07	0.0	0.16	0.14	0.07	0.06	0.0	0.07
Na2O	2.53	2.32	2.30	1.93	1.67	1.63	1.60	1.60	1.56	1.43	1.21	1.03	0.99	0.70	0.36	0.39	0.18
K2O	13.11	13.51	13.54	14.59	14.91	14.59	14.65	14.99	14.57	15.23	15.27	15.38	15.23	15.63	15.21	16.17	16.48
Total	99.63	100.15	99.72	100.23	101.04	100.87	99.67	100.51	100.08	100.05	100.14	100.42	98.94	98.96	99.39	99.08	100.53
Formula : 8 Oxygens																	
Si	2.98	2.98	2.98	2.98	2.98	2.99	2.97	2.98	2.97	2.98	2.97	2.98	2.99	2.97	3.00	2.98	2.98
Al	1.01	1.03	1.01	1.01	1.02	1.01	1.03	1.01	1.03	1.01	1.04	1.02	1.00	1.02	1.01	1.02	1.02
Fe	0.0	0.0	0.0	0.0	0.01	0.0	0.0	0.0	0.0	0.0	0.01	0.01	0.0	0.01	0.0	0.0	0.0
Mn	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.0	0.0	0.0	0.0
Ca	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.0	0.0	0.0	0.01	0.01	0.0	0.0	0.0	0.0
Na	0.23	0.21	0.21	0.17	0.15	0.14	0.14	0.14	0.14	0.13	0.11	0.09	0.09	0.06	0.03	0.04	0.02
K	0.77	0.79	0.79	0.86	0.87	0.85	0.86	0.88	0.85	0.90	0.90	0.90	0.91	0.93	0.90	0.96	0.97
Total	5.00	5.00	5.00	5.02	5.02	4.99	5.00	5.02	5.00	5.02	5.02	5.01	5.01	5.00	4.94	5.00	4.99
Mol %																	
An	0.9	0.0	0.2	0.2	0.3	0.1	0.2	0.5	0.0	0.4	0.0	0.8	0.7	0.4	0.3	0.0	0.3
Ab	22.4	20.7	20.5	16.7	14.5	14.5	14.2	13.8	14.0	12.5	10.7	9.2	9.0	6.4	3.5	3.6	1.6
Or	76.7	79.3	79.3	83.1	85.2	85.4	85.6	85.7	86.0	87.1	89.3	90.0	90.3	93.2	96.2	96.4	98.1

Table D.1

Biotite Analyses - Shap 'Light' Granite - Sample 531, 532

Oxide %	1	2	3	4	5	6	7	8	9
SiO2	36.58	37.27	37.18	37.40	37.54	37.18	37.97	37.00	37.90
TiO2	3.39	4.04	3.79	3.98	3.59	3.86	4.07	3.44	3.91
Al2O3	14.23	13.37	13.96	13.39	13.99	13.47	14.04	14.40	13.98
Cr2O3	0.06	0.02	0.03	0.0	0.12	0.09	0.07	0.06	0.08
FeO	17.75	16.49	17.22	16.75	16.54	17.29	16.54	17.95	16.45
MnO	0.53	0.55	0.53	0.60	0.43	0.54	0.52	0.54	0.58
MgO	12.89	13.03	13.15	13.32	13.28	13.27	12.86	13.05	13.29
CaO	0.11	0.0	0.06	0.02	0.0	0.0	0.05	0.11	0.0
Na2O	0.11	0.36	0.27	0.20	0.60	0.21	0.04	0.12	0.07
K2O	9.39	9.94	9.22	9.79	9.75	9.96	9.82	9.50	9.80
NiO	0.0	0.0	0.02	0.0	0.08	0.03	0.04	0.0	0.0
ClO	-	0.06	0.09	0.08	-	0.06	0.04	-	0.11
Total	95.04	95.11	95.52	95.53	95.93	95.95	96.05	96.15	96.29

Formula : 22 Oxygens

Si	5.58	5.67	5.62	5.66	5.65	5.63	5.69	5.58	5.67
Ti	0.39	0.46	0.43	0.45	0.41	0.44	0.46	0.39	0.44
Al	2.56	2.40	2.49	2.39	2.48	2.40	2.48	2.56	2.47
Cr	0.01	0.0	0.03	0.0	0.01	0.01	0.01	0.01	0.01
Fe	2.26	2.10	2.18	2.12	2.08	2.19	2.07	2.26	2.06
Mn	0.07	0.07	0.07	0.08	0.06	0.07	0.07	0.07	0.07
Mg	2.93	2.95	2.97	3.01	2.98	2.99	2.87	2.93	2.97
Ca	0.02	0.0	0.01	0.0	0.0	0.0	0.01	0.02	0.0
Na	0.03	0.11	0.08	0.06	0.18	0.06	0.01	0.03	0.02
K	1.83	1.93	1.78	1.89	1.87	1.92	1.88	1.83	1.87
Ni	0.0	0.0	0.0	0.0	0.01	0.0	0.01	0.0	0.02
Total	15.68	15.68	15.65	15.67	15.72	15.72	15.55	15.68	15.59

Table D.2

10	11	12	13	14	15	16	17	18	19	20	21	mean	Chlorite
37.38	37.06	37.64	37.27	37.66	38.32	38.31	37.68	37.45	37.97	38.38	37.81	37.57	28.88
3.56	3.98	3.44	3.93	3.98	3.79	3.99	4.10	3.83	4.01	3.73	4.57	3.86	0.11
13.73	13.89	14.90	13.94	14.03	13.88	13.40	14.11	14.43	13.84	13.56	14.08	13.93	17.91
0.07	0.09	0.05	0.07	0.07	0.01	0.12	0.10	0.10	0.0	0.06	0.0	0.06	0.0
16.75	16.84	16.24	16.85	16.44	16.57	17.26	16.68	17.15	16.55	17.05	17.17	16.87	21.77
0.44	0.52	0.66	0.43	0.46	0.36	0.53	0.43	0.58	0.52	0.60	0.65	0.52	0.69
13.80	13.51	13.71	13.34	13.69	13.81	13.42	13.36	13.19	13.62	13.58	12.97	13.34	18.04
0.0	0.01	0.05	0.15	0.17	0.01	0.03	0.0	0.04	0.07	0.03	0.0	0.04	0.04
0.87	0.60	0.41	0.74	0.49	0.49	0.01	0.41	0.39	0.58	0.22	0.23	0.35	0.46
9.66	9.95	9.50	9.89	9.67	9.60	9.87	10.07	9.83	9.79	9.91	9.74	9.75	0.07
0.05	0.02	0.10	0.0	0.0	0.01	0.0	0.04	0.0	0.09	0.05	0.05	0.03	0.0
-	0.0	-	0.09	0.10	-	0.03	0.01	0.04	0.02	-	0.06	0.06	0.01
96.40	96.48	96.69	96.69	96.76	96.64	96.97	96.99	97.04	97.06	97.16	97.32	96.38	87.97
5.62	5.57	5.60	5.59	5.62	5.69	5.71	5.61	5.59	5.65	5.70	5.62	5.63	5.95
0.40	0.45	0.38	0.44	0.45	0.42	0.45	0.46	0.43	0.45	0.42	0.51	0.43	0.02
2.43	2.46	2.61	2.47	2.47	2.43	2.35	2.48	2.54	2.43	2.38	2.47	2.46	4.35
0.01	0.01	0.01	0.01	0.01	0.0	0.01	0.01	0.01	0.0	0.01	0.0	0.01	0.0
2.11	2.12	2.02	2.11	2.05	2.06	2.15	2.08	2.14	2.06	2.12	2.13	2.12	3.75
0.06	0.07	0.08	0.05	0.06	0.05	0.07	0.06	0.07	0.07	0.08	0.08	0.07	0.12
3.09	3.03	3.04	2.98	3.04	3.06	2.98	2.97	2.93	3.02	3.01	2.87	2.98	5.55
0.0	0.0	0.01	0.02	0.03	0.0	0.01	0.0	0.01	0.01	0.01	0.0	0.01	0.01
0.24	0.18	0.12	0.21	0.14	0.14	0.0	0.12	0.11	0.17	0.06	0.07	0.10	0.18
1.86	1.91	1.80	1.89	1.84	1.82	1.88	1.91	1.87	1.66	1.88	1.85	1.82	0.02
0.01	0.0	0.01	0.0	0.0	0.0	0.0	0.01	0.0	0.01	0.01	0.01	0.0	0.0
15.81	15.79	15.67	15.79	15.70	15.66	15.60	15.70	15.70	15.71	15.66	15.59	15.63	19.96

Table D.2 (cont.)

Orthoclase Feldspars - Hornblende Granite. (Perthitic megacryst + matrix compositions) - Sample 523

Oxide %	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO2	63.59	63.23	64.01	63.09	63.67	63.62	64.26	63.82	64.24	64.27	65.27	64.51	65.29	65.29
Al2O3	17.72	17.72	17.92	17.72	18.07	17.97	18.28	18.03	18.02	18.18	18.87	18.51	18.42	19.24
FeO	0.13	0.0	0.06	0.11	0.21	0.0	0.11	0.18	0.11	0.02	0.21	0.06	0.15	0.11
CaO	0.0	0.0	0.0	0.0	0.09	0.01	0.0	0.04	0.0	0.0	0.09	0.11	0.0	0.03
Na2O	1.51	1.82	0.53	0.55	1.49	0.0	1.38	0.73	0.55	1.46	2.58	1.53	1.18	1.45
K2O	14.08	13.89	15.45	15.94	14.48	16.87	14.69	15.98	16.14	15.29	12.35	15.67	15.63	15.27
Total	97.02	97.05	97.06	97.40	97.99	98.46	98.72	98.78	99.05	99.21	99.36	100.39	100.67	101.39
Formula : 8 Oxygens														
Si	3.01	3.00	3.01	3.00	2.99	3.00	2.99	2.99	3.00	2.99	2.98	2.98	2.99	2.97
Al	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	0.99	1.00	1.02	1.01	1.00	1.03
Fe	0.01	0.0	0.0	0.0	0.01	0.0	0.0	0.01	0.0	0.0	0.01	0.0	0.01	0.0
Ca	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.01	0.0	0.0
Na	0.14	0.17	0.05	0.05	0.14	0.0	0.13	0.07	0.05	0.13	0.23	0.14	0.11	0.13
K	0.85	0.84	0.93	0.97	0.87	1.01	0.87	0.96	0.96	0.91	0.72	0.92	0.91	0.89
Total	4.99	4.99	4.98	5.01	5.00	5.01	5.00	5.02	5.01	5.02	4.96	5.05	5.01	5.02
Mol %														
An	0.0	0.0	0.0	0.0	0.4	0.1	0.0	0.2	0.0	0.0	0.5	0.6	0.0	0.1
Ab	14.0	16.6	4.9	5.0	13.5	0.0	12.5	6.5	4.9	12.6	23.9	12.9	10.3	12.6
Or	86.0	83.4	95.1	95.0	86.1	99.9	87.5	93.3	95.1	87.4	75.6	86.5	89.7	87.3

Table D.3

Plagioclase Feldspars - Hornblende Granite (1° plagioclases) - Sample 523

Oxide %	1	2	3	4	5	6	7	8
SiO_2	62.25	59.99	61.20	60.42	62.63	66.31	66.13	62.97
Al_2O_3	21.66	23.81	23.21	25.77	23.14	21.45	21.55	23.33
FeO	0.25	0.25	0.33	0.64	0.36	0.14	0.29	0.33
CaO	3.40	5.23	4.78	1.03	4.47	1.95	1.17	3.10
Na_2O	8.27	8.04	8.30	7.45	8.70	10.08	10.35	9.20
K_2O	1.38	0.88	0.45	3.46	0.68	0.25	0.86	1.45
Total	97.21	98.19	98.27	98.77	99.99	100.17	100.35	100.38
Formula : 8 Oxygens								
Si	2.83	2.72	2.76	2.72	2.78	2.90	2.90	2.79
Al	1.16	1.27	1.24	1.37	1.21	1.11	1.11	1.22
Fe	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01
Ca	0.12	0.25	0.25	0.05	0.21	0.09	0.06	0.15
Na	0.73	0.71	0.73	0.65	0.75	0.86	0.88	0.79
K	0.08	0.05	0.03	0.20	0.04	0.01	0.05	0.08
Total	4.98	5.01	4.99	5.02	5.00	4.97	5.00	5.04
Mol %								
An	17.0	25.1	23.5	5.6	21.3	9.0	5.6	14.4
Ab	74.8	69.8	73.9	72.3	74.8	89.0	89.5	77.5
Or	8.2	5.1	2.6	22.1	2.9	1.4	4.9	8.1

Table D.4

Biotite Analyses - Hornblende Granite - Sample 523

Oxide %	1	2	3	4	5	6	7	8	9c	10c	11c
SiO_2	36.86	37.35	37.54	37.96	37.71	37.46	38.46	38.92	33.27	35.08	37.24
TiO_2	3.58	3.30	2.97	2.71	3.24	3.89	3.47	3.12	1.26	2.88	3.31
Al_2O_3	12.40	12.45	12.87	12.76	13.17	12.83	13.48	13.89	15.18	13.60	13.22
Cr_2O_3	0.06	0.09	0.14	0.0	0.08	0.09	0.05	0.0	0.0	0.09	0.09
FeO	15.98	17.09	15.95	15.97	16.74	17.11	16.05	16.45	18.87	17.54	16.95
MnO	0.48	0.44	0.52	0.63	0.61	0.47	0.42	0.70	0.75	0.67	0.50
MgO	13.38	13.04	13.62	14.04	13.02	12.88	13.60	14.04	17.38	14.15	14.71
CaO	0.0	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.52	0.01	0.02
Na_2O	0.31	0.13	0.11	0.48	0.0	0.0	0.55	0.71	0.24	0.37	0.09
K_2O	9.77	9.34	9.76	9.79	9.87	9.87	9.90	9.75	2.83	6.77	8.29
NiO	0.0	0.0	0.0	0.03	0.08	0.06	0.13	0.0	0.03	0.0	0.02
ClO	0.05	0.03	0.11	0.03	0.03	0.03	0.10	0.02	0.01	0.06	0.10
Total	92.86	93.25	93.58	94.40	94.55	94.68	96.21	97.60	90.37	91.15	94.56

Formula : 22 Oxygens

	1	2	3	4	5	6	7	8	9c	10c	11c
Si	5.74	5.79	5.78	5.80	5.76	5.73	5.75	5.74	5.22	5.53	5.65
Ti	0.42	0.36	0.34	0.31	0.37	0.45	0.39	0.35	0.15	0.34	0.38
Al	2.28	2.27	2.34	2.30	2.37	2.31	2.38	2.41	2.81	2.53	2.37
Cr	0.01	0.01	0.02	0.0	0.01	0.01	0.01	0.0	0.01	0.0	0.01
Fe	2.08	2.21	2.05	2.04	2.14	2.19	2.01	2.03	2.48	2.31	2.15
Mn	0.06	0.06	0.07	0.08	0.08	0.06	0.05	0.09	0.10	0.09	0.07
Mg	3.10	3.01	3.13	3.20	2.97	2.94	3.03	3.09	4.07	3.33	3.33
Ca	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.09	0.0	0.0
Na	0.09	0.04	0.03	0.14	0.0	0.0	0.16	0.20	0.07	0.12	0.03
K	1.94	1.85	1.92	1.91	1.92	1.93	1.89	1.83	0.57	1.36	1.61
Ni	0.0	0.0	0.0	0.0	0.01	0.01	0.02	0.0	0.0	0.0	0.0
Total	15.72	15.62	15.63	15.77	15.63	15.62	15.69	15.73	15.55	15.60	15.59

Table D.5

Hornblende Analyses - Hornblende Granite - Sample 523

Oxide %	1	2	3	4	5	6	7	8	9	10	11	Mean
SiO2	48.81	47.64	48.01	46.86	47.56	48.56	47.61	48.53	48.35	49.30	47.53	48.07
TiO2	0.58	0.95	0.88	1.07	1.02	0.90	0.93	0.91	0.64	0.82	1.09	0.89
Al2O3	4.38	5.84	5.06	6.17	5.86	5.36	5.94	5.30	5.16	5.12	6.13	5.48
Cr2O3	0.01	0.03	0.0	0.0	0.11	0.06	0.08	0.19	0.05	0.08	0.01	0.01
FeO	13.76	14.13	14.07	15.35	14.78	13.69	15.22	13.80	14.50	14.35	14.85	14.41
MnO	0.79	0.80	0.65	0.85	0.75	0.73	0.79	0.67	0.76	0.69	0.77	0.75
MgO	14.02	13.01	13.88	12.73	12.82	13.53	12.72	13.74	13.56	13.83	13.36	13.38
CaO	12.08	12.01	12.00	11.95	12.18	12.23	12.03	12.04	12.17	12.33	12.15	12.11
Na2O	1.60	1.46	1.73	1.29	1.15	1.59	1.38	1.65	2.07	1.15	1.83	1.54
K2O	0.45	0.79	0.53	0.76	0.79	0.66	0.70	0.74	0.66	0.69	0.75	0.68
NiO	0.11	0.0	0.0	0.0	0.15	0.04	0.03	0.0	0.0	0.0	0.0	0.03
ClO	0.06	0.05	0.0	0.03	0.03	0.0	0.05	0.07	0.08	0.03	0.04	0.04
Total	96.64	96.70	96.80	97.06	97.19	97.33	97.47	97.64	97.99	98.39	98.51	97.43

Formula : 23 Oxygens

Si	7.28	7.13	7.16	7.03	7.10	7.19	7.10	7.17	7.16	7.22	7.02	7.14
Ti	0.07	0.11	0.10	0.12	0.11	0.10	0.10	0.10	0.07	0.09	0.12	0.10
Al	0.77	1.03	0.89	1.09	1.03	0.94	1.04	0.92	0.90	0.88	1.07	0.96
Cr	0.0	0.0	0.0	0.0	0.01	0.01	0.01	0.02	0.01	0.01	0.0	0.01
Fe	1.72	1.77	1.76	1.93	1.85	1.70	1.90	1.71	1.80	1.76	1.83	1.79
Mn	0.10	0.10	0.08	0.11	0.10	0.09	0.10	0.08	0.10	0.09	0.10	0.09
Mg	3.12	2.90	3.09	2.85	2.85	2.99	2.83	3.03	3.00	3.02	2.94	2.96
Ca	1.93	1.93	1.92	1.92	1.95	1.94	1.92	1.91	1.93	1.94	1.92	1.93
Na	0.46	0.42	0.50	0.38	0.33	0.46	0.40	0.47	0.59	0.33	0.52	0.44
Ni	0.01	0.0	0.0	0.0	0.02	0.0	0.0	0.0	0.0	0.0	0.14	0.13
Total	15.54	15.54	15.60	15.56	15.50	15.53	15.54	15.56	15.68	15.46	15.66	15.56
Al VI	0.05	0.16	0.05	0.12	0.13	0.12	0.14	0.10	0.06	0.11	0.08	0.10
Al IV	0.72	0.87	0.84	0.97	0.90	0.81	0.90	0.83	0.84	0.78	0.98	0.86
Na+K+Ca	2.48	2.50	2.52	2.44	2.43	2.52	2.46	2.52	2.65	2.39	2.59	2.50
Mg/Mg+Fe	0.65	0.62	0.64	0.60	0.61	0.64	0.60	0.64	0.63	0.63	0.62	0.62

Table D.6

Plagioclase Analyses - Xenoliths. - Samples 501,503,506.

Oxide %	Oligoclases (1° zoned 'phenocrysts')								Albites (Rim compositions to 1° plagioclases)									
SiO_2	61.89	60.78	61.69	60.84	61.74	61.33	61.37	:	64.15	64.73	66.25	65.38	64.19	66.95	67.68	67.61	68.09	68.08
Al_2O_3	22.81	23.91	24.98	24.58	24.52	24.22	24.29	:	21.84	21.19	20.76	21.65	22.46	20.74	19.25	19.88	19.39	19.87
FeO	0.22	0.19	0.18	0.11	0.09	0.11	0.11	:	0.44	0.04	0.08	0.0	0.09	0.0	0.07	0.06	0.09	0.11
MnO	0.04	0.0	0.05	0.10	0.0	0.07	0.07	:	0.07	0.03	0.15	0.08	0.03	0.0	0.01	0.0	0.01	0.0
CaO	5.75	5.42	5.15	5.43	5.31	4.87	4.87	:	2.09	1.79	1.06	1.90	1.00	0.67	0.11	0.08	0.07	0.0
Na_2O	8.13	8.35	8.33	8.96	8.83	8.59	9.00	:	9.83	10.43	11.54	10.65	10.33	11.94	11.71	12.10	11.87	12.47
K_2O	0.52	0.44	0.26	0.41	0.45	0.31	0.31	:	0.91	0.27	0.16	0.26	1.26	0.14	0.09	0.05	0.14	0.02
Total	99.36	99.09	100.64	100.43	100.94	99.50	100.02	:	99.33	98.48	100.00	99.92	99.36	100.44	99.12	99.78	99.66	100.55
Formula : 8 Oxygens																		
Si	2.76	2.73	2.72	2.70	2.72	2.73	2.73	:	2.84	2.89	2.91	2.88	2.84	2.94	2.99	2.97	2.99	2.97
Al	1.22	1.27	1.30	1.29	1.27	1.27	1.27	:	1.16	1.12	1.08	1.12	1.19	1.06	1.00	1.03	1.00	1.02
Fe	0.01	0.01	0.01	0.0	0.0	0.0	0.0	:	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mn	0.0	0.0	0.0	0.0	0.0	0.0	0.0	:	0.0	0.0	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ca	0.28	0.26	0.24	0.26	0.25	0.23	0.23	:	0.10	0.09	0.05	0.09	0.05	0.03	0.01	0.0	0.0	0.0
Na	0.71	0.73	0.71	0.77	0.76	0.74	0.78	:	0.86	0.90	0.98	0.91	0.90	1.00	1.00	1.03	1.01	1.05
K	0.03	0.03	0.02	0.02	0.03	0.02	0.02	:	0.05	0.02	0.01	0.01	0.07	0.01	0.01	0.0	0.01	0.0
Total	5.01	5.03	5.00	5.04	5.03	4.99	5.03	:	5.03	5.02	5.04	5.01	5.05	5.04	5.01	5.03	5.01	5.04
Mol %																		
An	27.3	25.7	25.1	24.6	24.3	23.4	22.6	:	10.0	8.5	4.6	8.8	4.7	3.0	0.5	0.3	0.3	0.0
Ab	69.8	71.8	73.4	73.2	73.2	74.8	75.7	:	84.9	89.9	94.4	89.8	88.2	96.2	95.0	99.4	98.9	99.9
Or	2.9	2.5	1.5	2.2	2.5	1.2	1.7	:	5.1	1.6	0.8	1.4	7.1	0.8	0.5	0.3	0.8	0.1

Table E.1

Biotites - Xenoliths Samples 501, 503

Oxide %	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO2	36.95	37.24	37.38	39.51	36.92	37.01	37.27	37.41	35.68	36.87	35.44	37.29	35.47	35.71	35.75	34.55
TiO2	4.02	3.94	4.14	3.18	3.68	3.54	3.38	3.12	3.30	3.20	2.98	3.07	2.45	2.36	2.80	2.59
Al2O3	13.78	13.19	13.82	14.70	13.72	14.32	14.77	14.39	14.81	14.23	14.54	15.28	13.78	15.12	14.88	14.72
Cr2O3	0.06	0.11	0.0	0.03	0.0	0.0	0.0	0.06	0.0	0.04	0.0	0.01	0.08	0.0	0.0	0.06
FeO	16.92	16.71	17.12	16.73	17.07	17.48	17.20	17.07	17.60	16.87	16.58	17.54	17.50	16.87	17.72	18.40
MnO	0.58	0.54	0.57	0.55	0.49	0.49	0.56	0.51	0.51	0.46	0.60	0.50	0.49	0.50	0.54	0.48
MgO	13.36	12.79	13.09	14.10	13.81	13.54	14.11	14.13	14.47	14.46	14.66	14.72	14.07	15.44	15.87	16.19
CaO	0.09	0.08	0.08	0.05	0.09	0.23	0.04	0.11	0.20	0.08	0.09	0.0	0.13	1.09	0.01	0.17
Na2O	0.52	0.11	0.21	0.19	0.14	0.17	0.18	0.34	0.42	0.23	0.35	0.63	0.60	0.55	0.28	0.0
K2O	10.10	9.65	9.62	9.44	8.87	6.37	8.43	8.10	7.53	7.33	7.16	7.31	6.96	6.22	6.34	5.33
NiO	0.03	0.02	0.02	0.0	0.04	0.09	0.04	0.0	0.03	0.02	0.02	0.0	0.01	0.0	0.11	0.01
ClO	0.04	0.04	0.12	0.01	0.14	0.04	0.06	0.11	0.08	0.09	0.03	-	0.05	0.07	0.05	0.02
Total	96.43	94.41	96.16	97.49	94.96	95.26	96.04	95.33	94.62	93.87	92.44	96.30	91.59	93.92	94.35	92.53

Formula : 22 Oxygens

Si:	5.57	5.70	5.63	5.66	5.61	5.59	5.57	5.62	5.43	5.60	5.48	5.53	5.56	5.42	5.41	5.33
Ti	0.46	0.45	0.47	0.35	0.42	0.40	0.38	0.35	0.38	0.37	0.35	0.34	0.29	0.27	0.32	0.30
Al	2.45	2.38	2.45	2.55	2.46	2.55	2.60	2.55	2.65	2.55	2.65	2.66	2.55	2.71	2.65	2.68
Cr	0.01	0.01	0.0	0.0	0.0	0.0	0.0	0.01	0.0	0.01	0.0	0.0	0.01	0.0	0.0	0.01
Fe	2.13	2.14	2.16	2.06	2.17	2.21	2.15	2.15	2.24	2.14	2.14	2.17	2.30	2.14	2.24	2.37
Mn	0.07	0.07	0.07	0.07	0.06	0.06	0.07	0.07	0.07	0.06	0.08	0.06	0.07	0.06	0.07	0.06
Mg	3.00	2.92	2.94	3.09	3.13	3.05	3.14	3.17	3.28	3.27	3.38	3.25	3.29	3.49	3.58	3.72
Ca	0.02	0.01	0.01	0.01	0.02	0.04	0.01	0.02	0.03	0.01	0.02	0.0	0.02	0.18	0.0	0.03
Na	0.20	0.03	0.06	0.05	0.04	0.05	0.05	0.10	0.12	0.07	0.11	0.18	0.18	0.16	0.08	0.0
K	1.94	1.89	1.85	1.77	1.72	1.61	1.61	1.55	1.46	1.42	1.41	1.38	1.39	1.21	1.23	1.05
Ni	0.0	0.0	0.0	0.0	0.01	0.01	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.0
Total	15.80	15.61	15.64	15.62	15.62	15.57	15.59	15.57	15.66	15.50	15.61	15.58	15.66	15.64	15.60	15.55

Table E.2

Chlorites - Xenoliths - Samples 501,503

Oxide %	1	2	3	4	5	6	7	8	9	mean
SiO2	27.20	28.46	28.04	30.41	28.55	30.44	29.74	29.43	30.44	29.19
TiO2	0.15	0.02	0.0	0.02	0.09	0.14	0.0	0.05	0.11	0.06
Al2O3	20.83	18.89	20.20	17.24	20.03	17.53	19.83	19.94	17.74	19.14
Cr2O3	0.03	0.01	0.03	0.0	0.0	0.03	0.04	0.0	0.04	0.02
FeO	20.36	21.77	22.12	21.36	21.98	21.59	21.97	22.58	22.16	21.77
MnO	0.73	0.60	0.65	0.69	0.64	0.75	0.66	0.76	0.56	0.67
MgO	16.73	17.96	16.86	18.41	17.57	18.72	18.44	17.76	19.16	17.96
CaO	0.0	0.03	0.0	0.06	0.09	0.11	0.0	0.0	0.06	0.04
Na2O	0.08	0.12	0.12	0.40	0.32	0.0	0.0	0.40	0.75	0.24
K2C	0.06	0.04	0.06	0.04	0.05	0.07	0.03	0.02	0.08	0.05
NiO	0.0	0.09	0.08	0.0	0.03	0.04	0.03	0.04	0.0	0.03
ClO	0.0	0.05	0.0	0.01	0.04	0.0	0.0	0.0	0.01	0.01
Total	86.17	88.03	88.15	88.64	89.39	89.40	90.74	90.98	91.10	89.18

Formula : 28 Oxygens

Si	5.68	5.86	5.76	6.18	5.78	6.14	5.90	5.86	6.05	5.91
Ti	0.02	0.0	0.0	0.0	0.01	0.02	0.0	0.01	0.02	0.01
Al	5.12	4.58	4.89	4.13	4.78	4.17	4.64	4.68	4.16	4.57
Cr	0.01	0.0	0.01	0.0	0.0	0.0	0.01	0.0	0.01	0.0
Fe	3.55	3.75	3.80	3.63	3.72	3.64	3.65	3.76	3.68	3.69
Mn	0.13	0.10	0.11	0.12	0.11	0.13	0.11	0.13	0.09	0.11
Mg	5.20	5.51	5.17	5.58	5.31	5.63	5.46	5.27	5.68	5.42
Ca	0.0	0.01	0.0	0.01	0.02	0.02	0.0	0.0	0.01	0.01
Na	0.03	0.05	0.05	0.16	0.13	0.0	0.0	0.16	0.29	0.10
K	0.02	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01
Ni	0.0	0.01	0.01	0.0	0.0	0.01	0.0	0.01	0.0	0.0
Total	19.76	19.88	19.82	19.83	19.88	19.77	19.78	19.87	20.01	19.83

Table E.3

Prehnites - Xenoliths White, plag-rich rims, - Samples 501, 503.

Oxide %	1	2	3	4	5	6	7	8	mean
SiO_2	44.14	44.45	45.00	44.39	44.47	45.32	45.05	45.04	44.73
TiO_2	0.10	0.04	0.0	0.0	0.0	0.13	0.12	0.07	0.06
Al_2O_3	24.31	25.03	25.35	25.28	24.55	25.40	24.64	25.05	24.95
FeO	0.23	0.33	0.21	0.31	0.33	0.20	0.31	0.08	0.25
MnO	0.0	0.05	0.0	0.10	0.0	0.08	0.08	0.01	0.04
CaO	26.26	26.71	27.22	26.90	27.21	27.21	26.94	26.07	26.82
Na_2O	0.0	0.04	0.0	0.0	0.0	0.27	0.31	0.35	0.12
K_2O	0.03	0.0	0.06	0.06	0.09	0.02	0.08	0.03	0.05
Total	95.07	96.65	97.84	97.04	96.65	98.63	97.53	96.70	97.02

Formula : 22 Oxygens

	1	2	3	4	5	6	7	8	mean
Si	6.08	6.03	6.03	6.00	6.04	6.03	6.07	6.03	6.04
Ti	0.01	0.0	0.0	0.0	0.0	0.01	0.01	0.01	0.01
Al	3.95	4.00	4.00	4.03	3.93	3.98	3.91	3.99	3.97
Fe	0.03	0.04	0.02	0.04	0.04	0.02	0.04	0.01	0.03
Mn	0.0	0.01	0.0	0.01	0.0	0.01	0.01	0.0	0.01
Ca	3.87	3.88	3.91	3.89	3.96	3.88	3.89	3.77	3.88
Na	0.0	0.01	0.0	0.0	0.0	0.07	0.08	0.09	0.03
K	0.01	0.0	0.01	0.01	0.02	0.0	0.01	0.01	0.01
Total	13.95	13.97	13.97	13.98	13.99	14.00	14.02	13.91	13.97

Table E.4

Table F.1

Correlation Coefficients between SiO2 and all other elements.

G-Granites and Aplites, D-Dykes, X-Xenoliths, V-Volcanics

	Al2O3	TiO2	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5
G	-0.85	-0.92	-0.93	-0.83	-0.92	-0.85	0.52	-0.32	-0.85
D	-0.86	-0.78	-0.69	-0.23	-0.87	-0.68	0.00	-0.49	-0.75
X	-0.71	-0.90	-0/89	-0.77	-0.47	-0.93	-0.73	0.34	-0.92
V	-0.29	-0.72	-0.82	-0.71	-0.55	-0.71	0.02	0.51	-0.56

	LOI	Cr	Ni	Cu	Zn	Rb	Sr	Y	Zr
G	-0.10	-0.66	-0.89	0.38	-0.60	0.59	-0.87	-0.35	-0.76
D	-0.67	-0.64	-0.70	-0.42	-0.31	-0.29	-0.40	-0.23	-0.81
X	-0.53	-0.72	-0.82	-0.01	-0.70	0.05	-0.51	0.18	-0.89
V	0.00	-0.44	-0.36	-0.26	-0.05	0.39	-0.50	0.44	0.64

	Nb	Pb	Ba	U	Th	Nd	Ce	La	V	Sc
G	-0.44	0.63	-0.88	0.61	-0.39	-0.72	-0.64	-0.68	-0.92	-0.79
D	0.11	0.34	-0.25	0.33	0.24	-0.56	-0.49	-0.47	-0.87	-0.80
X	-0.45	0.28	-0.51	-0.20	-0.30	-0.74	-0.67	-0.61	-0.81	-0.69
V	0.41	0.34	0.40	0.60	0.56	0.36	0.36	0.43	-0.73	-0.71

ANALYTICAL TECHNIQUES.

SAMPLE COLLECTION and PREPARATION.

Poor exposure and the prevalence of weathered outcrops resulted in the adoption of two methods of sample collection, initial preparation and selection for analysis. Apart from the traditional style of collection of hand specimens selected at the outcrop, it was also found necessary to collect large block samples. These samples of rock were removed from outcrops and split and dressed at the university. Where removal of weathered surfaces and joints proved difficult, samples were cored using a bench mounted 1 inch diamond-tipped rock drill designed to prepare palaeomagnetic samples. The cores were then topped and tailed and any internal weathered portions cut out. This second method (coring) proved particularly useful for the volcanic samples.

Powder Preparation.

Cleaned samples were selected in representative sizes to ensure that a homogeneous rock specimen was analysed with a larger quantity of the coarser grained rocks being chosen. Rocks were split on a hydraulic vice and then reduced to chips in a percussion steel mortar or jaw crusher. 50 to 100 gms of chips (<2mm across) were crushed in an agate-lined tema mill until the powder was <100 mesh. The powder samples were then stored in labelled glass bottles. All powders were oven dried at a low temperature prior to analytical use.

X.R.F. ANALYSIS.

Preparation of Glass Discs (Major Elements).

0.4gm of rock powder was accurately weighed into a platinum crucible. This was diluted 10:1 by 4gm of pre-dried lithium borate spectroflux. Powder and flux were well homogenised, covered with a platinum lid and fused in an furnace for 30 minutes at 1000°C. After cooling, the fusion mixture was reweighed and made up to the original weight (4.4gm) with more flux. Loss in weight was noted in order to calculate Loss on Ignition (LOI). The fusion mixture was remelted over a Bunsen burner and stirred to ensure homogeneity. The melt was then rapidly cast into a copper ring sitting on a hot-plate and compressed under an aluminium plunger. After cooling, the glass discs were trimmed, labelled and stored in polythene bags to prevent hydration.

Loss on ignition was also calculated by firing a small amount of rock powder of known weight within a ceramic crucible in the oven at 1000°C for 30 minutes. After cooling the sample was reweighed and the weight loss calculated. This loss was expressed as a percentage of the original sample weight prior to firing.

Preparation of Pressed Powder Pellets.(Trace Elements).

About 15gms of rock powder was mixed with about 2mls of Moviol agglutinate. The mixture was then compressed within a toughened steel jacket to a pressure of 10 tons psi for 10 seconds. The resulting pellet was dried in a low temperature oven for 30 minutes, then labelled and stored in a polythene bag. Shortly before analysis, the pellets were placed in a vacuum dessicator. The pellets were held in the XRF sample holder by means of 6 micron mylor film which was effectively invisable to the X-ray radiation.

XRF Machine Conditions.

Samples were analysed using the Phillips PW1400 x-ray fluorescence spectrometer of the Dept. of Earth Sciences, University of Leeds under the guidance of Mr. Alan Gray. Running conditions are shown in the adjacent table. Two cycles of measurements were run to allow calculation of any machine drift.. All the raw count data were corrected for mass absorption and matrix effects by computer. The effect of machine drift was corrected for by reference to an internal standard which always occupied one of the four sample holders. Standards used in this work were USGS G-2 (granite), USGS GSP (granodiorite) and USGS AGV (andesite).

Absolute errors on the resulting analysis are difficult to define but continual laboratory monitering allow valid estimates of expected errors to be stated

X.R.F. Measuring Characteristics.

Measuring program 1. Rhodium target with power set at 40 kV by 60 mA

Element	line	Collimator	Detector	Crystal	time (secs)
Na	Ka	Coarse	Flow	TlAP	320
Mg	Ka	Coarse	Flow	TlAP	40
Al	Ka	Coarse	Flow	PET	30
Si	Ka	Coarse	Flow	InSb	20
P	Ka	Coarse	Flow	Ge	20
K	Ka	Fine	Flow	LiF 200	8
Ca	Ka	Fine	Flow	LiF 200	8
Ti	Ka	Fine	Flow	LiF 200	8
Mn	Ka	Fine	Flow	LiF 200	8
Fe	Ka	Fine	Flow	LiF 200	4

Measuring program 2. Rhodium target with power set at 80 kV by 30 mA

Element	line	Collimator	Detector	Crystal	time (secs)
Cr	Ka	Fine	Flow	LiF 200	80
Co	Ka	Fine	Flow	LiF 220	80
Ni	Ka	Fine	Flow	LiF 200	80
Cu	Ka	Fine	Flow	LiF 200	80
Zn	Ka	Fine	Scint	LiF 200	80
Rb	Ka	Fine	Scint	LiF 200	80
Sr	Ka	Fine	Scint	LiF 200	80
Y	Ka	Fine	Scint	LiF 200	80
Zr	Ka	Fine	Scint	LiF 200	80
Nb	Ka	Fine	Scint	LiF 220	80
Ba	Ka	Fine	Scint	LiF 220	80
Pb	Lb	Fine	Scint	LiF 200	80

Measuring program 3. Rhodium target with power set at 80 kV by 30 mA

Element	line	Collimator	Detector	Crystal	time (secs)
Ga	Ka	Fine	Scint	LiF 200	400
Th	La	Fine	Scint	LiF 220	400
U	La	Fine	Scint	LiF 200	400

Measuring program 4. Rhodium target with power set at 50 kV by 50 mA

Element	line	Collimator	Detector	Crystal	time (secs)
Sc	Ka	Fine	Flow	LiF 200	400
V	Ka	Fine	Flow	LiF 220	160
La	La	Coarse	Flow	LiF 200	400
Ce	Lb	Coarse	Flow	LiF 200	400
Nd	La	Coarse	Flow	LiF 200	400

Estimated Errors on XRF Data.

	wt%		ppm		ppm
SiO2	0.5	Cr	10	U	5
Al2O3	0.2	Ni	5	Th	4
TiO2	0.1	Zn	5	Sc	2
Fe2O3	0.05	Cu	10	V	5
MgO	0.1	Rb	5	Pb	10
MnO	0.05	Sr	5	Ba	25
CaO	0.1	Y	5	Nd	10
Na2O	0.3	Zr	15	Ce	10
K2O	0.05	Nb	5	La	10
P2O5	0.05				

Notes.

a. High errors MgO and Na2O due to poor excitation and high absorption (low mass no.).
Na2O due to Li flux impurities.
Cr and Cu due to tube contamination.
Zr and Y due to Sr and Rb interference.
REE's due to inter-element interference.

b. Machine precision and operator reproducibility are a factor of 10 below the errors (see Davidson 1984 for details).

ELECTRON MICROPROBE ANALYSIS.

The mineral analyses presented in this work were measured on the Joel JXA-50A probe (which is fitted with an energy-dispersive Link 860 Series 2 system) under the guidance of Dr. Eric Condliffe. All ZAF corrections were made on-line. The elements analysed were calibrated to the following standards:

The beam current used was approximately 1 nanoamp, the accelerating voltage was 20kV and the count time was 100 secs. Mineral analyses were formulated to a standard number of oxygens by computer.

Microrobe Calibration Standards.

Si	Wollastonite
Al	Corundum
Ti	Rutile
Fe	Fe metal
Mn	Rhodonite
Mg	MgO
Ca	Wollastonite
Na	Jadeite
K	Orthoclase

STABLE ISOTOPE ANALYSIS.

Stable isotope (oxygen and hydrogen) analysis was undertaken at the Scottish Universities Reactor Centre, East Kilbride in collaboration with Dr. R. Harmon.

Oxygen was extracted from samples by reaction with BrF_5 in nickel bombs and converted to CO_2 by passage over graphite at dull red heat in the presence of a platinum catalyst (Clayton and Mayeda 1963). Isotopic ratios were measured in the CO_2 gas using an A.W.R.E. Aldermaston McKinney-Nier type mass spectrometer. Ratios (S) are reported relative to SMOW (Standard Mean Ocean Water) as defined from the Snowbird Quartz (+16.20‰) and African Glass (+9.60‰) standards. Overall precision and reproducibility are slightly over 0.1‰ .

For hydrogen extraction, whole-rock samples of 400mg and mineral separates of 100mg were pre-heated in a platinum crucible at 150°C to remove absorbed water. The sample was then completely dehydrated at over 1100° C in a uranium furnace. Precision on the data are around 3 ‰ but reproducibility was considerably poorer.

SR and ND ISOTOPE ANALYSIS.

Limited analysis was undertaken on the author's behalf by Dr. Peter Betton (Sr) and Drs Jon Davidson and Richard Jones (Nd) using a VG MM30 spectrometer at the University of Leeds. Samples were run against standards NBS 987 (Sr) and the La Jolla and BCR-1 standards (Nd). Sample preparation, extraction and machine operating conditions were as outlined in Davidson (1984).