PETROCHEMISTRY AND ENGINEERING PROPERTIES
OF THE
HELMSDALE GRANITE INTRUSIONS

By

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To my wife Flora and my children
Makan and Rosa, for their love,
devotion and encouragement, without
which I could not have completed
this thesis.

MEMORANDUM

The material presented in this thesis summarizes the results of the research work undertaken in the Department of Geology, University of Glasgow, under the supervision of Dr C.D. Gribble.

The results and ideas presented in this thesis are the the result of independent work by the author and any previously published or unpublished results of other workers are fully acknowledged in the text.

ABSTRACT

The study of the petrochemistry of the Helmsdale granite intrusions, NE Scotland, reveals that the Helmsdale granite consists of two granitic intrusions; an outer, early, coarser-grained porphyritic pink granite (CGP) and the inner, finer-grained type (FG). Major and trace elements show dissimilarities between the FG and the CGP types, with the former having higher iron, MgO and TiO_2, and lower silica contents. Plagioclase and biotite removal appear to be the minerals changing the magma composition towards the later differentiated CGP type.

Both granites were subjected to weathering and hydrothermal alteration, although the latter is commonly confined to the zones of intense high K alteration within the FG type (inner intrusion). Ratios such as Na_2O/K_2O, $Al_2O_3/(SiO_2+Al_2O_3)$, $(Na_2O+K_2O+CaO+MgO)/Al_2O_3$, Fe_2O_3/FeO and microfracture index (FI) have been found to be particularly useful as indices of physical and chemical weathering of the granites.

Various British standard tests are employed to assess the suitability of the Helmsdale granite aggregates for engineering purposes including roadstone and concrete making. The CGP samples generally have lower strength and slightly better AAV, PSV values than the FG samples type.

Apart from badly weathered materials (such as in Eldrable Burn) the Helmsdale granites appear to have the same strength as the Peterhead granite and are slightly below the rest of the granites of Scotland. The AAV values of 3-6% obtained show an acceptable level for aggregate to be used for most highway and trunk road running surfaces whereas the PSV results, on the other hand, suggest that aggregate from the Helmsdale granites can be used for site C with satisfactory performances. Aggregates from the Helmsdale granites are also suitable for most concrete mixtures and satisfactory performances will be achieved except for the purposes of heavy duty concrete floors.

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LIST OF CONTENTS

Page

CHAPTER SIX - CORRELATION

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

CHAPTER ONE

INTRODUCTION

1.1. Objective and tasks

Investigation of the mechanical properties of aggregate has occupied many researchers for some time now. Only in recent years, some of the in-service results have shown that some slightly altered aggregates which passed all standard mechanical tests at the time of their use in construction failed well before their expected life span, as the materials deteriorated badly through further chemical and mineralogical alteration. Such observations suggest that current methods of evaluating some aggregates for engineering purposes (especially for pavement construction) may not always give direct information on the future mineralogical, textural and chemical alterations that are likely to occur as a result of special conditions. Consequently, further attempts were made by a few researchers to include geochemical analyses in their assessment of aggregate properties for a better understanding of the possible future behaviour of altered rock and fresh aggregate for construction purposes.

The present study is another attempt in that direction to follow the existing methods but using a slightly different approach.

The Helmsdale granite in North Scotland, which is a late Caledonian granite (Newer granite), was chosen for this study. It consists of two grain size varieties: the outer part is a coarser-grained porphyritic granite (1 to 4mm long) and the inner part is finer grained (about 1mm). Both granites have been subjected to the same weathering and hydrothermal alteration processes, although the hydrothermal effects are confined to the zones of intense alteration mainly within the finer grained type. This is a situation where all factors such as weathering, hydrothermal alteration, different grain sizes occur together within one magma source.

The main objective of this study is to assemble various geochemical, petrographical and engineering properties of aggregates from each granite type of the Helmsdale intrusions so that correlation can be made between the results obtained to satisfy the following points.

1). The effects of the geochemical changes (due to either the weathering processes or original variation) on the aggregate engineering behaviour,

2). identification of criteria which could be used to anticipate the likely behaviour of aggregate while in service,

3). assessment of the suitability of the Helmsdale granites as aggregate for engineering purposes, and

4). provision of enough information for further research for future workers.

1.2. Previous research and project development on the study of fresh and weathered rocks as suitable aggregate.

Over the last two decades the production of aggregates for construction has been the largest of the extractive industries in Britain. Although much of the aggregate produced goes into the manufacture of concrete, which is generally considered as the premier building and civil engineering construction material, the road industry also uses a substantial amount of aggregate to build highway and motorway networks to accommodate the continuously increasing traffic flows in the United Kingdom. Therefore, the quality of aggregate plays an important factor upon its selection for particular engineering purposes.

In the United Kingdom the selection of aggregate is usually based on several factors among which the result of mechanical property tests is the most important. A series of tests were outlined, modified and eventually standardized by different research and Governmental bodies which all defined aggregate quality. The available literature shows that the engineering behaviour of an aggregate depends mainly on the genesis and degree of weathering of bedrock. Weinert (1958) was probably one of the first to demonstrate the significance of weathering effects upon the physical properties of aggregate. Based on the study of igneous rocks for road foundation purposes in South Africa, Weinert (1964) showed that fresh aggregate has substantially higher strength (higher 10% fines value) than a badly disintegrated one. Dhir et al. (1971) and Ramsay et al. (1974) point out that the strength of aggregate is related directly to the petrology and inherent fabric characteristics of the rock. Subsequently they showed that existing strength tests (AIV and ACV) can be modified to measure new indices that they called "aggregate impact and crushing value residue". These values have been shown to be consistent and more sensitive indicators of the influence of the shape on the fresh rock aggregate strength than the standard test procedures. Hartley (1968, 1974) also showed that petrography has a considerable influence on the mechanical properties of aggregate and its durability while in service. He concluded that the main factors causing a reduction in the strength of igneous rocks are an increase in porosity, grain size and proportion of soft minerals due to chemical alteration of primary rock forming minerals. Hosking (1969) used the term "durability" for surfacing aggregates, followed by more work by Hartley (1974) who used this term for roadstone in the sense of "long lasting", by which they include properties such as resistance to wear, weathering and to any other factor that might impare long life in a road surface.

[illegible] →Nevertheless, most of the valuable information about weathering and its effect on aggregate physical properties and method of quarrying in Britain comes from extensive research studies carried out by a number of workers in south west England and, to a lesser extent, in the north east of Scotland, where the majority of rock quarried shows some significant amount of weathering which the subsequent engineering test revealed clearly the loss of physical performance with the increasing of weathering grades (Ramsay 1965; Ramsay et al. 1974; Dhir et al. 1971; Fookes et al. 1971; Dearman 1974a, 1974b, 1976; Dearman et al. 1976; Irfan 1977; Irfan and Dearman 1978). Only recently an attempt was made to assess the aggregate properties of weathered granite based on criteria obtained from a combination of geochemistry and aggregate physical properties analyses (Moore 1979; Moore and Gribble 1980). They concluded that, based on analyses of certain oxides like Na_2O and CaO and the Fe_2O_3/FeO ratio, the engineering properties of aggregate containing weathered and fresh material could be estimated without the necessity of actually carrying out the engineering tests.

Results of field and laboratory tests have also shown that in some cases the existing standard aggregate tests do not give information on the mineralogical or textural alterations that may occur in an aggregate used for road, pavement or concrete. Hence any prediction of the durability of already decomposed rock aggregates used for engineering purposes should take into account not only the state of weathering of the material at the time of selection, but the mode of construction, the environmental conditions and any potential alteration that the material may undergo while in service.

Although the problem of finding such criteria remains basically unsolved, there are some methods of study which may reveal much information useful to the engineer towards possible anticipation of the future behaviour of aggregate while in service. These include visual inspection supported by petrographic studies based on microscopic slides (Irfan and Dearman 1978) or X-ray diffraction (XRD); differential thermal analyses may also be useful particularly when the presence of deleterious minerals (clay minerals) is suspected (Gidigasu 1974).

The following generalizations, however, appear valid on the basis of previous studies of weathered rock for engineering purposes:

1). Weathering is a process controlled by several factors: a) the environmental condition which itself is dominated by climate and topography of the area, b) the properties of the rock material, including chemical composition, fabric, texture and permeability, and c) the properties of the rock mass, especially the homogeneity of the rock mass and discontinuity patterns.

2). Several weathering classifications for engineering purposes are in existence. a) Those qualitative classifications based on the degree of decomposition which can be determined by visual inspection together with the results of a number of relatively simple index tests such as the degree of the breakdown of the constituent minerals, hardness, and their strength. (Moye 1955; Little 1969; Anon 1970 and

1972; Dearman 1976). This type of classification has many limitations making it an unreliable method for predicting the mechanical properties and associated engineering behaviour of rocks. b) The second group of classification is a quantitative one based on variation in physical properties related to the degree of weathering, using cheap and simple field and laboratory test techniques (Hamrol 1961; Iliev 1967; Broch and Frankline 1972). This type of classification has its limitations too, in that it is relative, depending on a knowledge of the physical properties of the fresh substance. c) And finally, an alternative approach to quantitative classification has been attempted based on standard petrographic techniques to evaluate the successive stages in the mineralogical and textural changes brought about by weathering processes (Mielen 1961; Weinert 1964, 1968; Dixon 1969; Merriam et al. 1970; Oradera et al. 1978; Irfan and Dearman 1978).

All existing classifications of weathered rocks for engineering purposes consist of five principal divisions and different numbers of subdivisions. In Table 1.1 one of such classifications is shown (from Irfan and Dearman 1978).

1.3. Statement of problems

Problems related to this study were as follows:

1). In the geochemistry part of the study, one of the main problems was to find suitable sampling techniques which would provide sufficient fresh samples for geochemical study, since the greater part of the area under investigation is covered by vegetation and deep drift except for those outcrops along the relatively closely spaced river systems. Samples were also collected from two quarry faces and road cuts. The

Class	Grade	Description of material and mass	Index properties			
			Strength	RQD (%)	Rock : soil (% rock)	Effective porosity
Fresh	I	No visible sign of material weathering. Near boundary with Grade II some slight discolouration on major defects	Very high	Very high 90–100	95–100	
Slightly weathered	II	Discolouration indicates weathering of rock material and defect surfaces.	Range from very high for IIi to 50–60% of fresh rock strength for IIiv.	75–90	90–95	5% increase from rock rock
a. Partly stained	IIi IIii	Defect surfaces, only, discoloured Discolouration penetrates inwards from defects. Less than 50% discolouration by volume.				
b. Completely stained	IIiii IIiv	More than 50% discolouration 100% discolouration				
Moderately weathered	III	Less than 50% of material decomposed and disintegrated to a weakly cohesive friable intact soil. Core rock discoloured, weakened.	30% of fresh rock strength	40–75	60–90	7% increase from fresh rock
Highly weathered	IV	More than 50% of material decomposed and disintegrated to a weakly cohesive friable intact soil. Rock cores discoloured and weakened.	15% of fresh rock strength	10–40	30–60	10% increase from fresh rock
Completely weathered	V	Intact friable soil which may be weakly cohesive. Soil has fabric of parent rock.	Extremely low	0–10	0–30	20% increase from fresh rock
Residual soil	VI	Friable soil with original rock fabric completely destroyed.	Extremely low	0	0	>20

TABLE 1.1: Classification of weathered crystalline rocks (After Irfan and Dearman 1978).

collection of relatively fresh and unweathered samples was particularly important for geochemical study in order to distinguish the original variation from those due to subsequent chemical weathering, since interpretation of geochemical analyses of the undetected altered samples could be misleading.

2. In the engineering part of the study the major problem was during aggregate test procedure, since some of the samples were badly weathered and the results obtained from some standard tests were misleading. Therefore, some of the test procedures were either modified slightly where it was possible (e.g. in the case of AIV test), or an alternative test was chosen instead. In the latter case, the aggregate crushing value test results (ACV) proved not to be sensitive enough for more weathered samples, hence a 10% fines value test was used instead which appeared to be more reliable for both weak and strong aggregates.

CHAPTER TWO

HISTORICAL GEOLOGY

2.1 The Caledonian Granites of the British Isles and their Petrography

The term "Caledonian" is used to cover the events which took place from c. 700Ma to c. 400Ma ago as a result of subduction and plate collision associated with the closure of the Iapetus Ocean during early Palaeozoic time (Dewey 1969). The Caledonian events in Britain can be divided into five distinct structural-stratigraphic provinces (Figure 2.1).

H.H. Read, in his classic paper of 1961, proposed two fold-belts during the British Caledonides; namely the pre-Silurian metamorphic belt, "the early Caledonides" and the late-Silurian non-metamorphic belt "the late Caledonides".

A number of granitic and dioritic intrusions were emplaced within the Caledonian foldbelt, varying in size from small stocks and sheet-like bodies to large batholiths. On the basis of field petrography and structural evidence, Read (1961) classified the British Caledonian intrusions into two temporal groups:-

A. Deformed and metamorphosed (<u>the Older Granites and Migmatites</u>).

B. Undeformed and post metamorphosed (<u>the Newer Granites</u>).

Among the Newer Granites Read recognised two different modes of emplacement, namely:

FIGURE 2.1: Sketch map of Scotland showing:

a) The five physiographic/structural stratigraphic provinces of the Caledonian orogenic belt in Britain

b) The location and distribution of the Caledonian granites

c) Major tectonic features in northern England and Scotland

Intrusions are numbered as follows:

1. Helmsdale
2. Lairg
3. Migdale
4. Fearn
5. Glenelg-Ratagain
6. Cluanie
7. Strontian
8. Ross of Mull
9. Strichen
10. Peterhead
11. Ardclach
12. Ben Rinnes
13. Moy
14. Foyers
15. Monadhliath
16. Cairngorm
17. Glen Cairn and Lochnagar
18. Hill of Fare
19. Mt. Battock
20. Corrieyairack
21. Ben Nevis
22. Strath Ossian
23. Ballachulish
24. Moor of Rannoch
25. Etive
26. Glen Fyne
27. Distinkhorn
28. Loch Doon
29. Cairnsmore of Fleet
30. Criffel

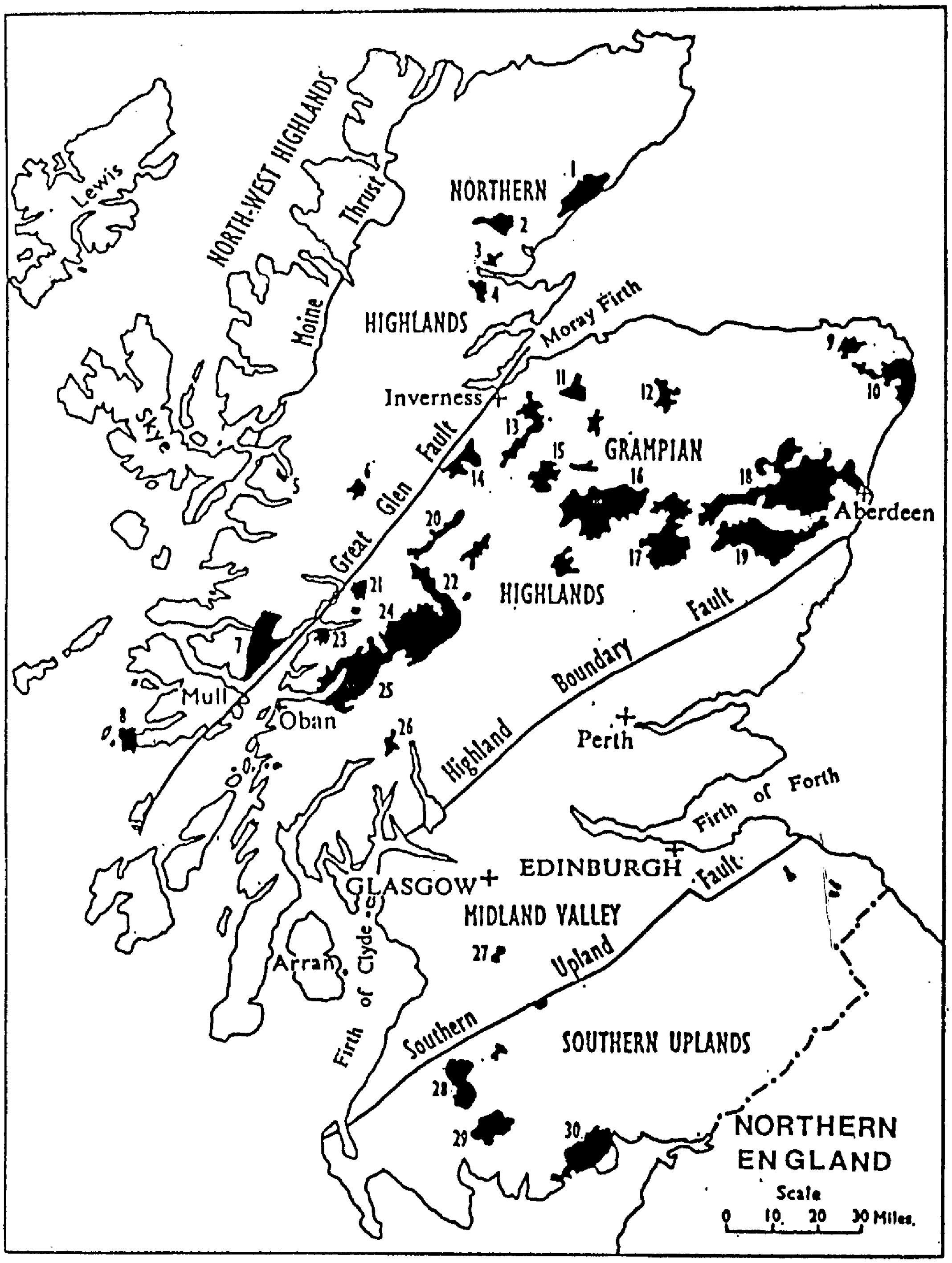


FIGURE 2.1. Sketch map of Scotland

B.1. Forceful (or active) granites, characterized by marginal deformation of country rocks and formation of contact migmatites.

B.2. Permitted (or passive) granites, which were emplaced by mechanical processes such as ring faults or cauldron subsidence. These granites are younger than the forceful granites.

Later radiometric age determinations however, provided information which disagreed in part with Read's classification. In particular, it was found not to be possible to distinguish age differences between B_1 and B_2 granites (Brown et al. 1968).

In studies of batholith emplacement, Phillips et al. (1976) and Pitcher (1978, 1979) demonstrated that Caledonian events in Britain were strongly influenced by the closure of the Iapetus Ocean. This hypothesis was supported by the researches of Brown (1979), Johnstone et al. (1979), Simpson et al. (1979), Watson and Plant (1979), who considered that a major change in granite magmatism took place between the B_1 and B_2 episodes (that is, between Newer forceful and Newer permitted types) which correlated with the final closure of the Iapetus Ocean. At that time, during subsequent crustal relaxation, the final Caledonian granite magmas were emplaced.

Brown and Locke (1979), divided the British Caledonian intrusions into two distinct age divisions, based on structural and petrochemical evidence, each of which is further subdivided spatially according to their position in relation to the ENE-WSW Iapetus Ocean suture. The main divisions are as follows:

1). An Older, pre-Silurian group comprising Read's Older granites and also his Newer 'forceful' granites. They show low concentration of incompatible elements, high Sr contents, high K/Rb ratios; low volume and low mobility magmas intruded under compressive conditions, consisting of migmatitic diorites and tonalites.

2). A Younger, Siluro-Devonian group comprising Read's Newer 'permitted' granites, with variable, and , in some cases, extremely incompatible element enrichments, including low K/Rb ratios; large intrusive volumes and mobile magmas intruded into a tensional post-tectonic regime following the Iapetus Ocean closure, consisting of granodiorites and adamellites.

The spatial subdivisions of groups 1). and 2). above are based on different isotopic and geophysical characteristics between intrusions emplaced on each side of the suture, and are given below:

1 - Northwest to Southwest.

The northwestern granites (1N) have small gravity and magmatic anomalies, high initial $^{87}Sr/^{86}Sr$ ratios and inherited zircons. They were probably produced by a partial fusion process involving Proterozoic continental crust and mantle-derived melts. The southwestern granites (1S) have similar geophysical properties but lack the isotopic characteristics of crustal melting.

2 - Northwest to Southwest.

The group 2 granites, are generally separated from those of group 1 by low initial $^{87}Sr/^{86}Sr$ ratios, and large negative residual gravity and aeromagnetic anomalies. The northwestern granites (2N) have gravity anomaly values of -32mgal (Etive intrusion), whereas the southwestern granites (2S) have lower values of -28mgal (Weardale intrusion). The 2N group also shows higher values for the aeromagnetic anomalies. This evidence suggests that magma genesis occurred in the upper mantle, or crustal underplate, with the 2N granites, rising through Lewisian basement and the 2S group rising through crust devoid of such basement material.

More recent work by Pankhurst and Sutherland (1982), showed difficulties in separating the Newer granites and they produced a different classification by grouping these granites according to the time of emplacement as follows:

1). Early to mid Ordovician granites - emplaced in NE Scotland (e.g. Strichen, Longmanhill, Aberchirder, Kennethmont and Auchedly).

2). Late Ordovician and early Silurian granites (e.g. Garabal Hill, Ratagain, Strontian and Foyers complexes, Rogart, Ballachuilish. Cluanie, Helmsdale and Moor of Rannoch).

3). Granites emplaced in Lower Old Red Sandstone times or earlier. (e.g. the ring complex of Glen Coe, Etive and Ben Nevis).

Although the provenance of the British Caledonian granitoids is by no means clear, the results from the Lithospheric Seismic Profile of Britain (LISPB) project, (Bamford and Prodehl, 1977; Bamford et al. 1978), and Harmon (1983) show that there is a distinct difference in upper crust composition on either side of the Highland Border Fault Zone (Fig. 2.2). North of the Highland Border granitoid magmas were emplaced into Moine rocks and Dalradian metasediments of greenschist or higher metamorphic grade overlying a subduction zone considered to dip northwards (Wright 1976; Phillips et al. 1976; Van Breemen and Bluck 1981). South of the Border, however, the magmas were intruded

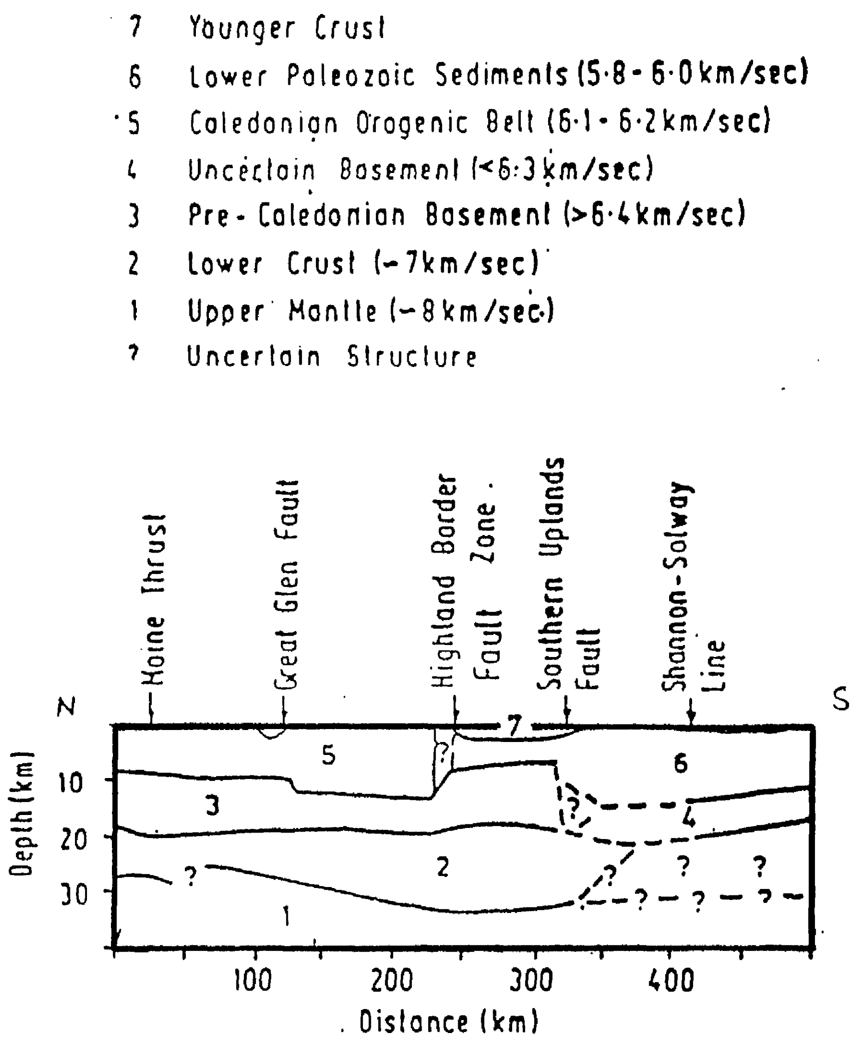


FIGURE 2.2. Crustal cross-section through northern England and Scotland after Banford et al. (1977) modified to indicate that the pre-Caledonian basement has not been identified south of the Highland Border Fracture Zone.

into weakly metamorphosed, immature, Lower Palaeozoic geosynclinal sediments overlying a subduction zone considered to dip southwards (Bott 1974; Phillips *et al*. 1976). The Midland Valley links these two regions.

2.2. Classification of the Caledonian granites based on geochronological results.

Over recent years, there has been growing interest in the use of radiogenic and stable isotope systems in the study of Caledonian magmatism.

Sr-isotopic data (Long 1964; Bell 1968; Pankhurst 1974; Busrewil *et al*. 1975; Pankhurst and Pidgeon 1976) showed that the granites could be divided into 3 groups, as follows: (see also Table 1).

1. Pre-tectonic Older granites.
2. Syn-tectonic granites.
3. Post-tectonic granites which include:
    a) Newer forceful granites and
    b) Newer last granitoids.

From the Sr isotope data and results on Sr and O isotopic data (Halliday *et al*. 1979; Pankhurst 1979; Hamilton *et al*. 1980; Harmon and Halliday 1980; Clayburn 1981) the following points can be made:

1. The pre-tectonic Older granites and the syn-tectonic granites have a wide range of both oxygen-isotope values, and Sr/Sr ratios which are all greater than 0.710.

2. All the post-tectonic group have a large oxygen-isotope range, but whereas the Newer forceful granites have a large

Sr/Sr ratio range of from 0.704 to 0.718, the Newer last granitoids have a small Sr/Sr ratio range of from 0.705 to 0.707. This, together with the I-type character of the Newer last granitoids suggests that they were derived from a mantle or lower crustal source.

U-Pb zircon studies (Pankhurst and Pidgeon 1976; Pidgeon and Aftalion 1978; Halliday et al. 1979) also support the grouping described above.

The Older granites and the Newer Forceful granitoids north of the Highland Border Fault Zone contain relict zircons in which the $^{207}Pb/^{203}Pb$ and U-Pb ages of 1500Ma are greater than the emplacement ages of the granites (Pidgeon and Johnston 1974; Pidgeon and Aftalion 1978). These earlier ages define a previous magmatic event during which the zircon originally crystallized. The presence of these 'inherited' zircons in almost all granites north of the Highland Border Fault Zone, and the absence of such zircons from granites of the Southern Uplands and Northern England suggests that 1) the Highland granites were partly derived from partial melting either of ancient Archaean basement or of younger Proterozoic Upper crust; and 2) the Southern Uplands and Northern England granites were partly derived from the partial melting of Lower Palaeozoic sediments (Pidgeon and Aftalion 1978; Harmon 1983).

Pb-isotope analyses of feldspars from a limited number of the Caledonian granites (Blaxland et al. 1979; Clayburn 1981) also suggested a lower crustal component for some of the granites north of the Highland Border Fault Zone. Furthermore, lead from feldspar becomes increasingly radiogenic southwards, suggesting the presence of older basement to the north and its absence to the south

(Blaxland et al. 1979).

δ^{18} Oxygen and Sr isotopic data for Caledonian granites with a wide spread of ages and compositions show a $\delta^{18}O$ range of from 3.9 to 14.4% and Sr/Sr ratios ranging from 0.7037 to 0.7196 (Table 2.1). Harmon (1983) concluded that there was no clear distinction between S-type and I-type granitoids as was seen in the Balaeozoic granites of Australia (O'Neil and Chappel 1977).

Plutons between 430 and 390Ma in age occurred south of the Highland Border Fault Zone and have a restricted range both in O- and Sr-isotope values with $\delta^{18}O$ values varying from 10.2 to 11.5% and $^{87}Sr/^{86}Sr$ ratios varying from 0.7052 to 0.7088. These isotopic parameters increase as the compositions change from diorite to granodiorite and finally peraluminous granite (that is, from intermediate to acid). However granitoids occurring north of the Highland Border Fault Zone exhibit a large variation in both age and isotopic composition, with no clear dependence of either $\delta^{18}O$ or $^{87}Sr/^{86}Sr$ ratios on their chemical composition. According to Harmon (1983), the isotopic data show no significant geographical trends as was suggested by Brown and Hennesey (1978), and that such variations in the isotopic composition were independent of age and style of emplacement.

Harmon (1983) also plotted $\delta^{18}O$ values against $^{87}Sr/^{86}Sr$ ratios for 38 British Caledonian granites and 2 Lower Old Red Sandstone granite boulder clasts for which both O- and Sr-isotopic composition were known (Fig. 2.3). Figure 2.3 shows that no simple correlation between O- and Sr-isotopic composition exists for the Caledonian granitoids. Previously, Taylor and Silver (1978) had shown that such correlation existed for the Peninsular Ranges batholith. However if

	No.	Age(Ma)	$\delta^{18}O$ (‰ SMOW)	$(^{87}Sr/^{86}Sr)_i$
By geographic province				
1. Northwest Highlands	7	400-555	6.6-14.4	0.7048-0.7100
2. Grampian Highlands	32	391-514	4.1-12.1	0.7037-0.7190
(a) Northeast Scotland	17	404-480	7.1-12.1	0.7059-0.7180
(b) Central Highlands	6	408-514	8.0-11.0	0.7062-0.7196
(c) Western Highlands	9	391-439	4.1-9.8	0.7037-0.7079
3. Midland Valley	1	390	7.9	0.7043
4. Southern Uplands	3	392-408	7.8-11.9	0.7042-0.7076
5. Northern England	4	390-459	3.9-11.5	0.7061-0.7088
By tectonic style				
1. Pre-Tectonic (Older) granitoids	3	> 480	6.6-11.0	0.7100-0.7190
2. Syn-Tectonic granitoids	9	450-480	9.2-12.1	0.7106-0.7196
3. Post-Tectonic granitoids	35	< 450	3.9-14.4	0.7037-0.7184
Newer Forceful granitoids	28	390-439	7.3-14.4	0.7037-0.7184
Newer Last granitoids	7	390-415	3.9-11.1	0.7048-0.7069

TABLE 2.1: Ranges for $^{18}O/^{16}O$ and $(^{87}Sr/^{86}Sr)_i$ ratios in the British Caledonian Granites (after Harmon 1983)

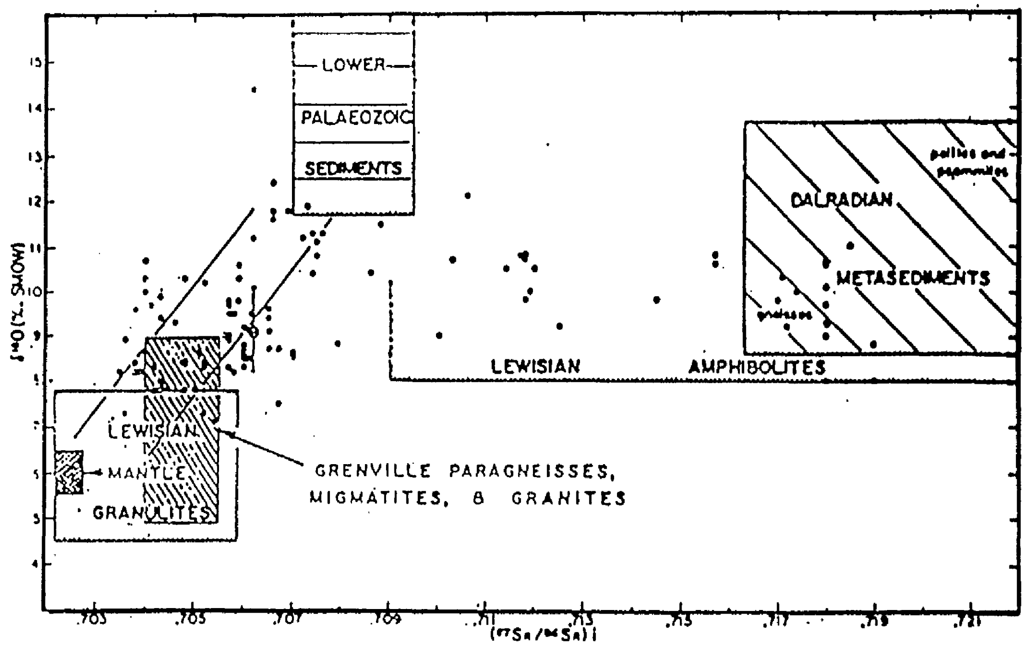


FIGURE 2.3. Diagram of $\delta^{18}O$ versus $(^{87}Sr/^{86}Sr)_i$ for 38 British Caledonian granitoids and 2 granite boulders showing the range of isotopic compositions for various possible source regions as well as the $\delta^{18}O$ versus $(^{87}Sr/^{86}Sr)_i$ trend for the Peninsular Ranges Batholith observed by Taylor and Silver (1978), (After Harmon 1983).

more restricted geographical areas are examined (Figs 2.4, 2.5), important trends in O- and Sr-isotopic data can be seen, and based on this Harmon (1983) was able to separate British Caledonian granites into 5 restricted geographical areas, information on some of which is given in more detail as follows:

1. Northwest Highlands (Table 2.1).

The Ratagan-Glenelg, Cluanie, Ross of Mull and Bonar Bridge intrusions are similar to other post-tectonic granitoids north of the Highland Border Fault Zone for which a primitive deep-seated source, contaminated by upper crust at a late stage is inferred. The Strontian Complex has a lower $\delta^{18}O$ content and inherited zircons which suggests a mantle-like source for the early tonalite and granodiorite, followed by crustal assimilation and fractional crystallization to produce the $\delta^{18}O$ and ^{87}Sr-enriched biotite granite. The oldest Caledonian granite, Cairn Chuinneag, has $\delta^{18}O$ values of 6.6 to 9.1‰, an $^{87}Sr/^{86}Sr$ ratio of 0.710 and a strong 'inherited' zircon component which indicate derivation from older Proterozoic crust. The Helmsdale granite has extremely high $\delta^{18}O$ values of 11.6 to 14.4‰, which are the highest values found in the Caledonian granites. These values may be interpreted as locally enriched $\delta^{18}O$ values due to the alteration of the intrusion during hydrothermal U-Pb-Ba-F mineralization.

2. Northeast Scotland (Fig. 2.4a; 2a in Table 2.1).

The Oxygen and Sr-isotopic compositions of the granites of NE Scotland are similar to those of the Central Highlands. The Hill of Fare Complex, the only Newer Last granitoid in this area is similar to other Newer last granitoids (Etive, Cairngorm and Lochnagar) suggesting primary derivation from a deep-seated source. However, a minor

FIGURE 2.4. Diagram of $\delta^{18}O$ versus ($^{87}Sr/^{86}Sr$) in British Caledonian granitoids from restricted geographic areas:

(2a) Northeast Scotland

(2b) The Central Highlands

ABBREVIATIONS:

LPS = Lower Palaeozoic Sediments

GR = Grenville Paragneisses

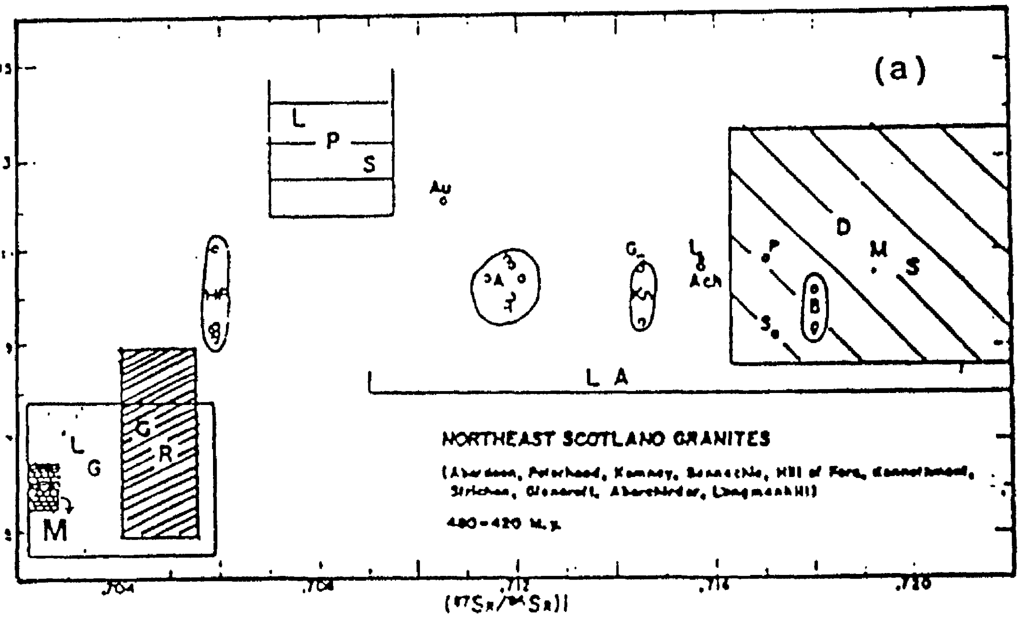
M = Mantle

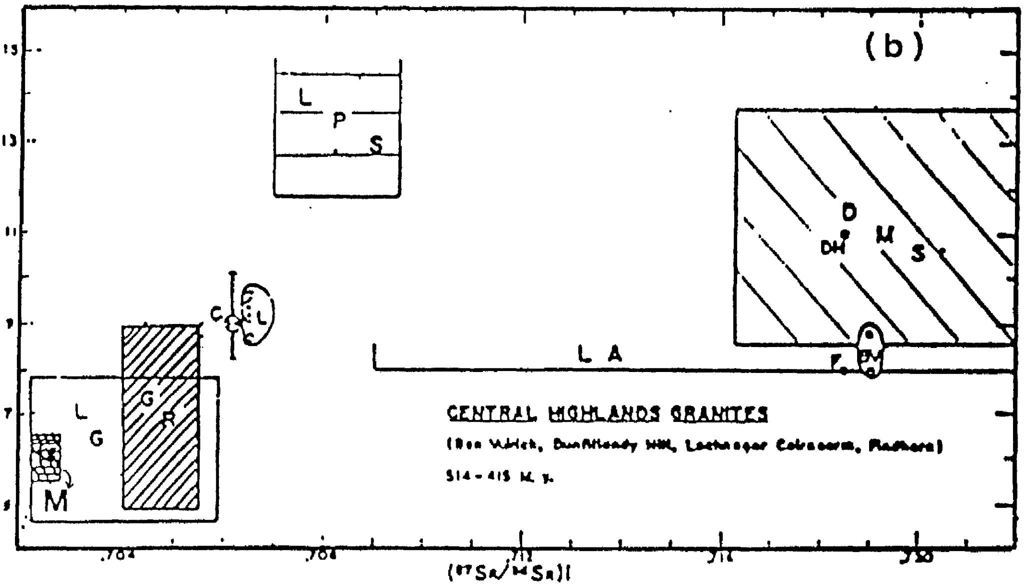
LG = Lewisian Granulites

LA = Lewisian Amphibolites

DMS = Dalradian Metasediments

LC = Lower Crust


(a)
$\delta^{18}O$ (‰ SMOW)
15
13
11
9
7
5
.704
.708
.712
.716
.720
$(^{87}Sr/^{86}Sr)_I$
L
P
S
Au
A
G
L
Ach
D
M
S
P
B
S
L A
L
G
G
R
M
NORTHEAST SCOTLAND GRANITES
(Aberdeen, Peterhead, Kemnay, Bennachie, Hill of Fare, Cannonthmont, Strichen, Glenervil, Aberchirder, Longmanhill)
480-420 M. y.


(b)
$\delta^{18}O$ (‰ SMOW)
15
13
11
9
7
5
.704
.708
.712
.716
.720
$(^{87}Sr/^{86}Sr)_I$
L
P
S
D
DH
M
S
C
L
L A
F
L
G
G
R
M
CENTRAL HIGHLANDS GRANITES
(Ben Vuirich, Dunfallandy Hill, Lochnagar Cairngorm, Redhouse)
514-415 M. y.

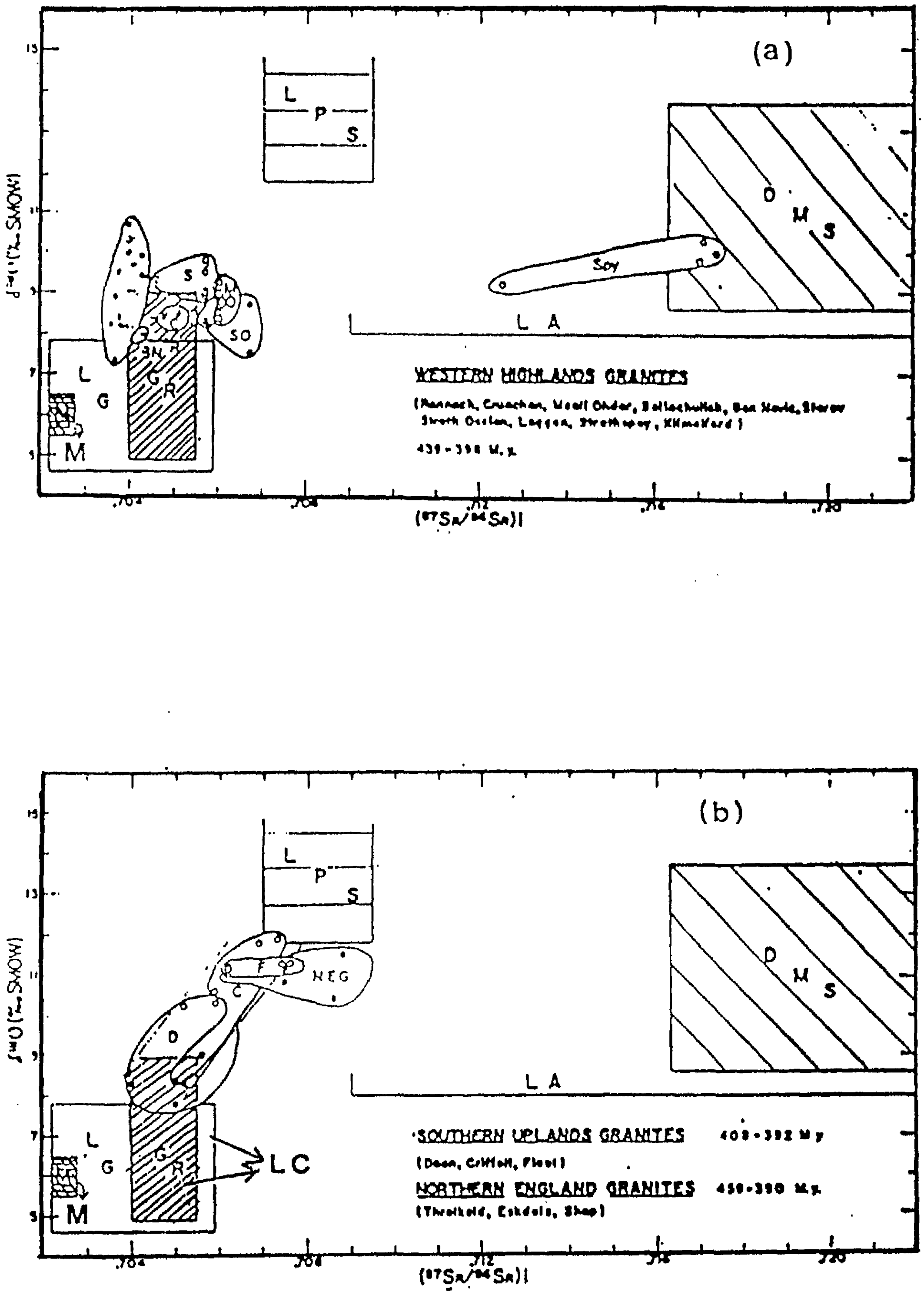


FIGURE 2.5. Diagram of $\delta^{18}O$ versus $(^{87}Sr/^{86}Sr)$ for granite of Western Highlands, Northern England and Southern Uplands.

amount of 'inherited' zircon in the Hill of Fare granite reflects substantial assimilation of younger continental crust prior to its emplacement. The remainder of the granites in this region, all with their strong S-type characteristics plus O- and Sr-isotopic composition, require a derivation mainly from an upper crustal source.

3. Central Highlands (Fig. 2.4b; 2b in Table 2.1).

Two distinct groups occur. Firstly Cairngorm and Lochnagar centres with similar isotopic composition to other Newer last granitoids in the Grampian Highlands, and for which a lower crustal source is inferred. Secondly, the older granites of Ben Vuirich and Dunfallandy Hill and the Findhorn granite, which suggests a derivation from Lower Proterozoic continental crust.

4. Western Highlands (Fig. 2.5a; 2c in Table 2.1).

Granite plutons in, and adjacent to, the Glen Coe area (Moor of Rannoch, the Etive complex, Ballachuilish, Ben Nevis and Strath Ossian) suggest a mantle or lower crustal origin, and the Kilmelford complex with the lowest observed $^{87}Sr/^{86}Sr$ ratios and a wide range of $\delta\,^{18}O$ values suggests a deep-seated magma source, perhaps with some hydrothermal alteration. The Strathspey granite-migmatite complex shows variation in composition which suggests either an upper crustal origin or an upper crustal melt which has been contaminated by a more primitive magma derived from a deep-seated source. The Ben Nevis and Etive complexes have been shown by Nd- and Pb-isotope data to have a lower crustal component in their magmas (Hamilton *et al*. 1980; Clayburn 1981).

The Meall Ohdar and Starav granites contain the largest component of lower crustal Pb and Nd, suggesting a longer magma residence time in the lower crust prior to emplacement. The Foyers complex is not shown in Figure 2.5a, but limited data suggest that the Foyers magmas were largely products of deep-seated melting, and subsequently changed by upper crustal assimilation and fractional crystallization.

5. Northern England and Southern Uplands (Fig. 2.5b; 4 and 5 in Table 2.1).

$\delta^{18}O$ values correlate well with $^{87}Sr/^{86}Sr$ ratios and also discriminate between different intrusions. This figure shows a linear array which lies between the fields of primitive mantle or lower crust (M,LC) and the local, Lower Palaeozoic sedimentary upper crust (LPS). In addition, SiO_2 increases and Sr decreases with increasing $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ ratios.

2.3. Geographical extent of the Helmsdale granite.

The Helmsdale granite is situated on the east coast of Caithness and Sutherland about 60km south west of Wick. The outcrop area of $100km^2$ probably represents about half of the original pluton as it is bounded to the southeast by the Helmsdale Fault (Fig. 2.6).

To the west, the granite is bounded by Moine granulite and Old Red Sandstone sediments, to the south by Moine granulite; to the east and southeast by Old Red Sandstone and Jurassic sediments, and to the northeast by Old Red Sandstone sediments (see Fig.2.6).

Compositionally, the granite consists of two rock types, whose boundary appears to be transitional, with a coarser grained outer porphyrytic granite and a finer grained, inner granite with less feldspar phenocrysts. This feature is seen on the southern side of the Helmsdale River along the Eldrable Burn on the western part of the granite mass. Helmsdale granite has a sharp vertical to steeply outward dipping contact, and was intruded at a high structural level into non-migmatitic, cold Moine granulites (Read _et al_. 1925; Read 1931; Gallagher _et al_. 1971). This granite contact

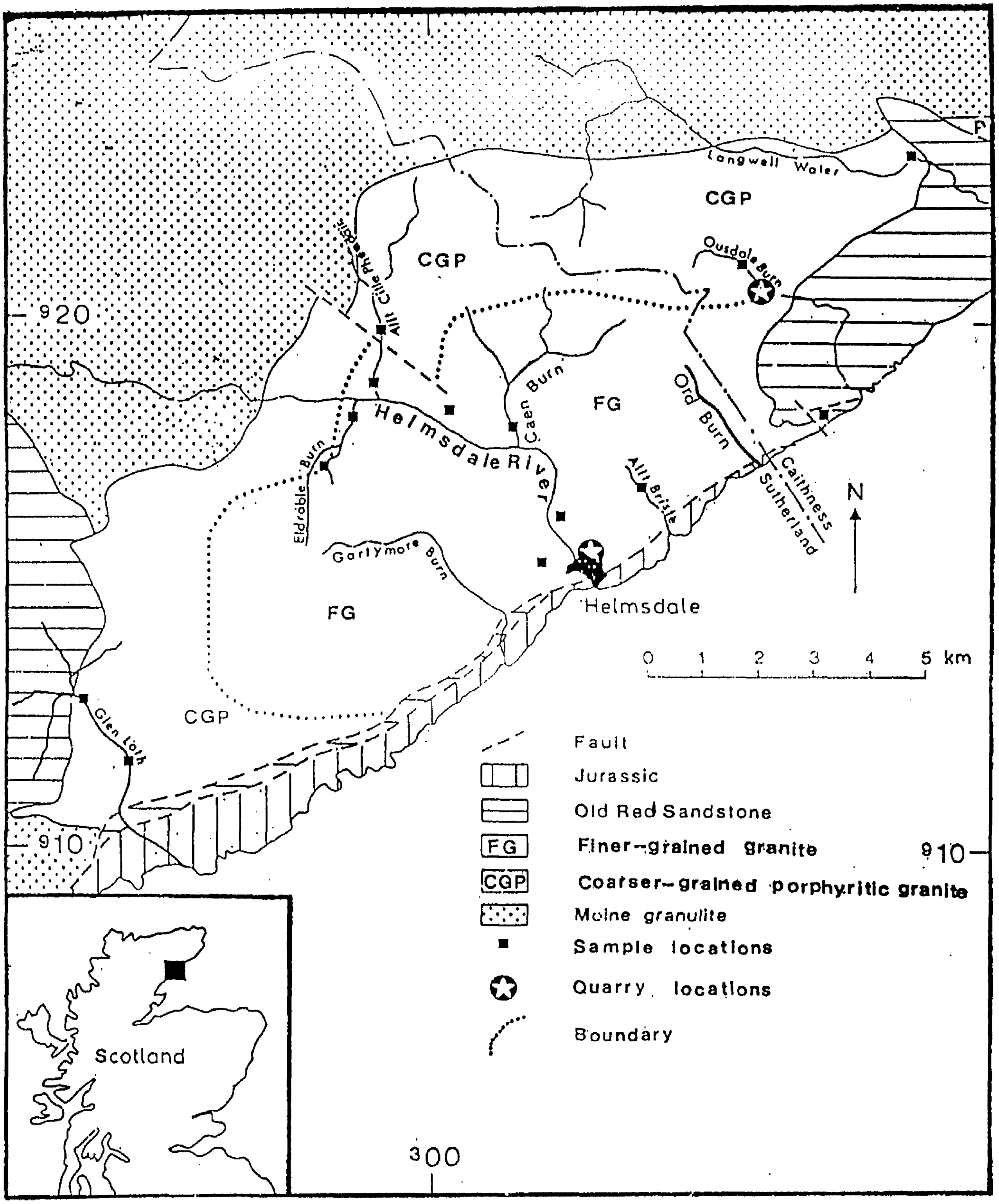


FIGURE 2.6. Geology of Helmsdale granite and surrounding rocks. Based on BGS 1 inch maps 103, 109 and 110, Gallagher et al. (1971); and the author

is exposed on the western margin at the Oulmsdale Burn, about one kilometre upstream from the junction with the Helmsdale River. There the Moine granulites are intensely broken with small fragments hardened and welded together, some of which can be seen as xenoliths in the granite.

The granite is overlain by Old Red Sandstone sediments. In Glen Sletdale 200m from the junction with Glen Loth, Old Red Sandstone lower conglomerates rest at an angle of 50° against the Helmsdale granite, showing that the granite was intruded before the deposition of this conglomerate. Furthermore, the conglomerate contains many monomineralic clasts (feldspars, etc.) and clasts which have been derived from disintegration of the granite.

The Helmsdale granite was originally mapped in 1896, but it was the detailed work of Read and Phemister (1925), which first suggested that the Helmsdale granite was contemporaneous with the other "Newer" granites of northeast Scotland, and therefore of Lower Old Red Sandstone age.

CHAPTER THREE

Petrography and Geochemistry of the Helmsdale granites

3.1. Petrography

Introduction

Petrographic descriptions of the Helsmdale granites are based on a study of 100 thin sections and rock hand specimens the location of which is shown in Figure 2.6. Thin section examination shows that, despite small mineralogical variations such as changes in the amounts of plagioclase and mafic minerals, the intrusion as a whole has a fairly uniform petrography. Two rock types coexist each with a distinctive grain size: a coarser-grained porphyritic type which was intruded into the country rock slightly earlier than a finer-grained type with scarce phenocrysts of K-feldspar.

Both rock types are pink to brown in colour and contain approximately equal proportions of quartz, K-feldspar and plagioclase. Together these minerals account for more than 90% of the rock constituents. For this reason, and also because in all the samples investigated the plagioclase composition ranges from An_0 to An_{16}, the classification and nomenclature advocated by Streckeisen (1976), have been used in the present study. Using this classification, both of the Helmsdale granites are classified as a granite (it is called an "adamellite" by other authors).

The finer-grained member contains slightly more mafic minerals and more anorthitic plagioclase and less quartz than the coarser-grained porphyritic member.

3.2. The coarser-grained porphyritic type (CGP)

The coarser-grained porphyritic type occupies a smaller area than the finer-grained type (FG), occurring as a narrow rim about 4km across, forming the outer margin of the Helmsdale granites. The CGP type has a sharp contact against the surrounding country rocks but internally grades into the FG type.

The CGP granite is coarser-grained with a hypidomorphic texture (Plate 3.1) containing K-feldspar, Na-rich plagioclase feldspar (An_{00-14}), quartz, biotite and rare hornblende. The common accessory minerals include zircon, sphene, magnetite and apatite which are usually associated with the ferro-magnesian minerals in the groundmass.

The colour is pink to reddish and the texture, including the percentage of phenocrysts, is homogeneous throughout the samples obtained from this rock type. Modal analyses of some specimens of the coarser-grained porphyritic type are given in Table 3.1. (The phenocryst minerals are not included in counting)

Phenocrysts

K-feldspar

These are large (up to 30mm long), fresh, pink in colour and perthitic: Carlsbad twinning is usually present. Unmixing and perthite development occurs over a wide range of feldspar compositions. Figure 3.1 shows perthites occurring in the range Ab_{15-20} and mesoperthites in the range Ab_{70-90}. The K-feldspar, orthoclase Ab_{0-15}, is a homogeneous phase. The perthite shows exsolution of an Na-rich phase from the K-feldspar host, the exsolved phase appearing sometimes as fine stringers or veinlets, making an angle of from 57° to 80° with the $\{010\}$ cleavage in the (011) plane. The exsolved Na-plagioclase also appears as blobs and patches (up to 0.7mm across)

PLATE 3.1. Photomicrograph of sample from Glen Loth area (CGP type) showing typical texture of normal granite. Hypidiomorphic plagioclase grains form the fundamental framework. K-feldspar (K-fel) and quartz (Q) are interstitial to the plagioclase (Pl). Some altered biotite (Bi) is present. Crossed nicols, X10.

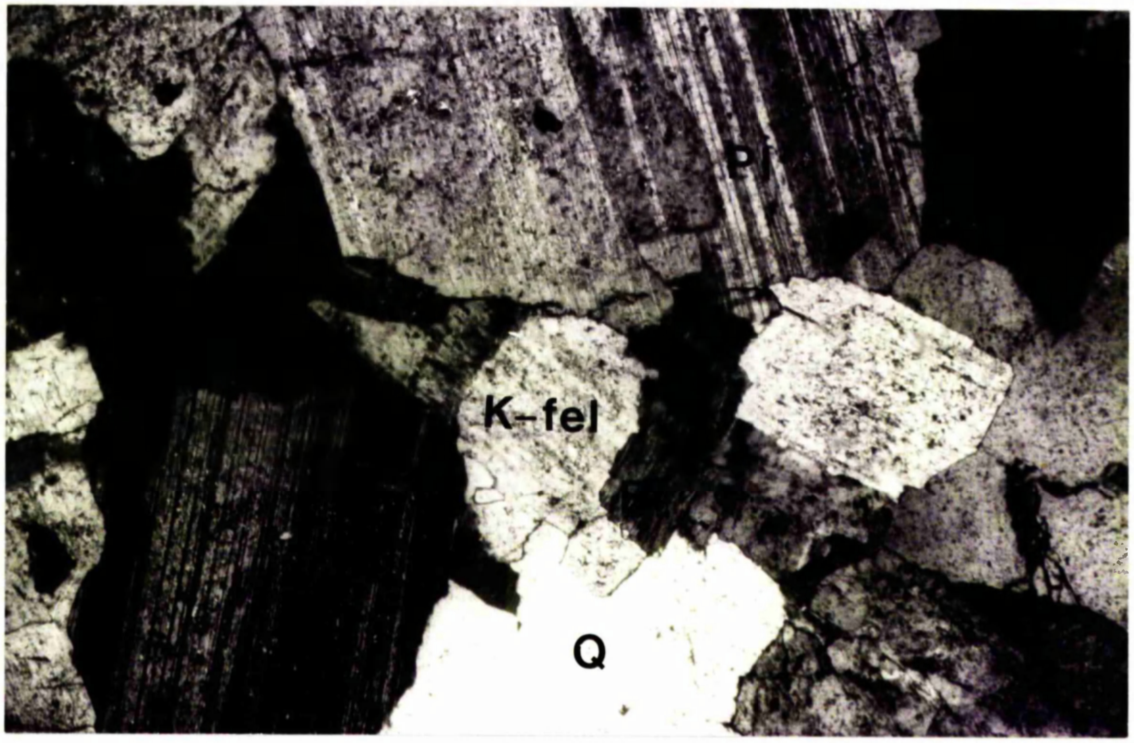

P
K-fel
Q

TABLE 3.1

Sample Location	% Plag	% K-fel	% Quartz	% Biot	% Muscov	% Access	% Opaque	Total	No. of point count	Height in Ft. from Sea Level
* EB	31.73	31.05	31.0	4.96	0.93	0.23	0.1	100	2,100	350
GL	32.3	35.2	27.84	2.80	0.25	0.61	1	100	3,500	400
LW	32	37.3	23.5	5.8	tr	tr	1.3	100	1,400	420
OB	26.8	35.6	31.8	4.25	tr	0.36	1.19	100	2,800	500
OQ	31.15	40.40	25.82	1.5	0.91	tr	0.22	100	4,900	550

TABLE 3.1 Modal analyses of the coarser-grained porphyritic type based on groundmass only.

EB = Eldrable Burn
GL = Glen Loth
OB = Ousdale Burn
OQ = Ousdale Quarry
LW - Longwell Water

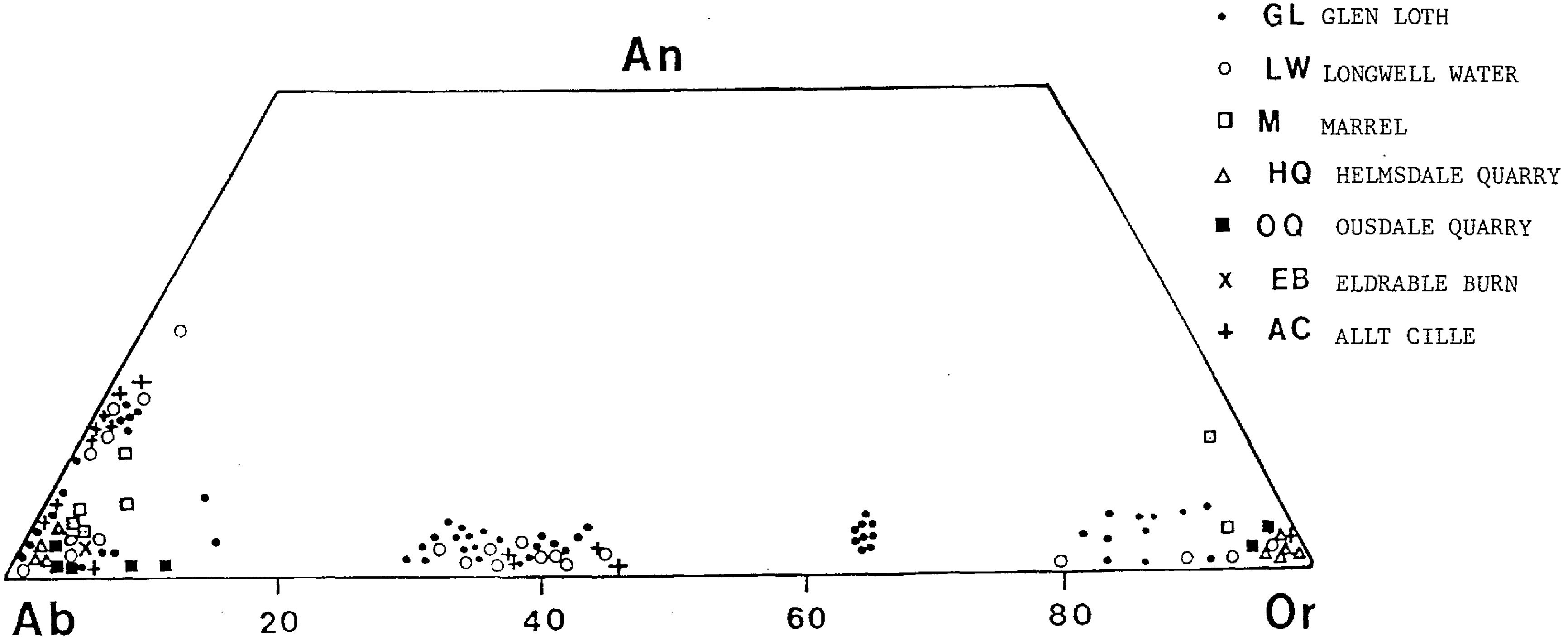


FIGURE 3.1. Classification and formation of perthite

near the K-feldspar margins. In larger phenocrysts the exsolved phase may appear as a narrow (0.2mm) continuous rim of composition An_{12} (Plate 3.2). Table 3.2 gives microprobe analyses of K-feldspar hosts and their exsolved Na-plagioclase phases. These analyses show that the host K-feldspar is homogeneous with its composition remaining unchanged throughout each crystal. The classification and formation of perthites is summarized by Smith (1974).

Analysis No.		11	12	13
		K-feldspar	Na-plagioclase	K-feldspar
SiO_2		62.22	63.60	62.38
Al_2O_3		18.43	19.14	18.75
Total FeO		0.19	0.28	0.00
CaO		0.37	0.27	0.32
Na_2O		1.52	7.20	1.32
K_2O		13.04	5.25	13.82
	(Or	81.2	31.6	84.5
Mol. %	(Ab	14.7	65.5	12.1
	(An	4.1	2.8	3.4

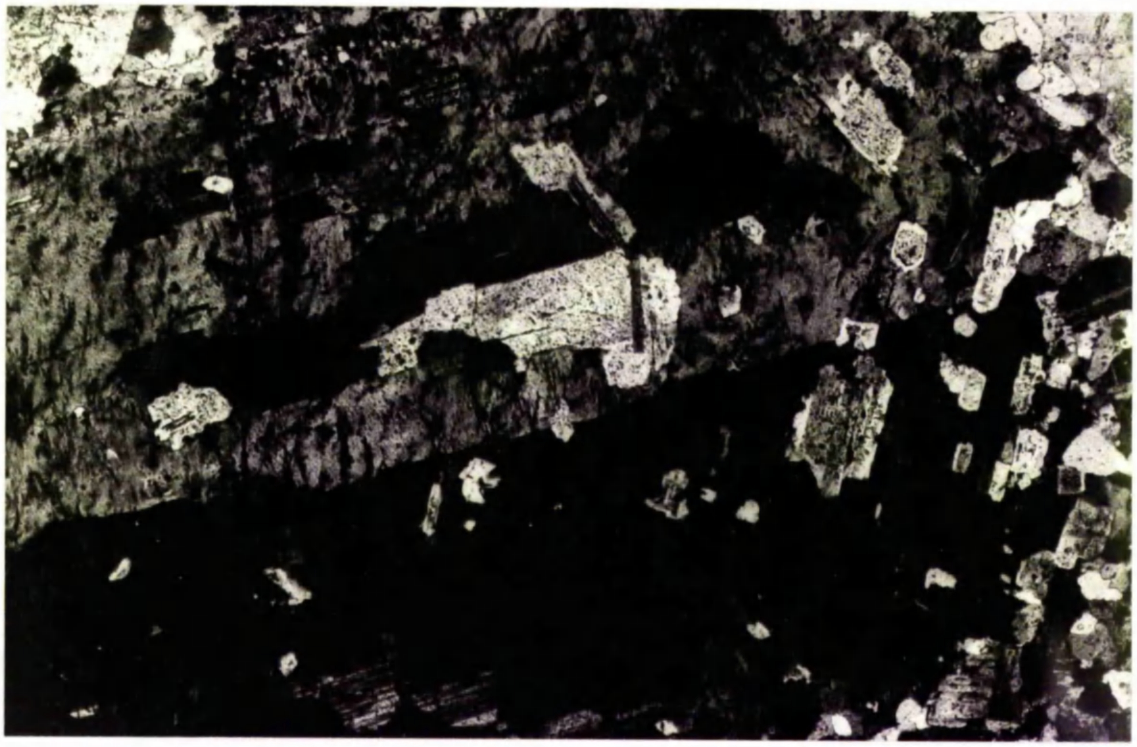
TABLE 3.2 Microprobe analyses Nos 11, 12, 13 from K-feldspar (perthite) phenocryst taken from the Glen Loth area.

The K-feldspar phenocrysts contain inclusions, usually of earlier-formed small plagioclase prismatic crystals (up to 1.5mm long), but small quartz crystals may occasionally be present (Plates 3.2, 3.3 and 3.4). Microprobe analyses of such feldspar inclusions are given in Table 3.3 (see also Fig. 3.2). These feldspar inclusions have altered cores surrounded by fresh albite rims. These altered cores are low in

PLATE 3.2. Large K-feldspar phenocryst from coarser-grained porphyritic type, showing continuous narrow rim of exsolved Na-rich phase (albite). Inclusions in phenocryst are small plagioclase crystals (up to 1.5mm long).

PLATE 3.3. Photomicrograph of another K-feldspar phenocryst from Ousdale Quarry (CGP type) showing small early formed plagioclase prismatic crystals poikilitically enclosed. The inclusions are arranged mostly along the margin of the host K-feldspar. Crossed nicols, X10.

PLATE 3.4. Photomicrograph of perthitic K-feldspar phenocrysts showing parallel orientation of enclosed plagioclase crystal with the segregated albite, from Ousdale Quarry. Crossed nicols, X10.



CaO ($\sim$0.4%) compared to the rims which have about 1.8% CaO. Either this difference is original - caused by several periods of crystallization under variable conditions of temperature and pressure giving oscillatory zoning during crystal growth, or as the result of the Ca-rich cores of the crystal breaking down with calcium being leached out and increasing in amount towards the rim. Examination of the Carlsbad twins show that the twin plane is unaffected by exsolution so that perthitic development probably post-dates the twinning and may be a late-stage feature. A microprobe traverse across such a plagioclase feldspar crystal inclusion with altered core is shown in Figure 3.2.

Quartz may also occur as phenocrysts in the coarser-grained porphyritic type (see page 41).

Groundmass

Plagioclase feldspar

Plagioclase feldspar is an important constituent in the CGP type occupying from 26.5% to 32.4% of the rock (Table 3.1).

The crystals range in size from 1mm to 4mm and alteration is common along twin planes and cleavages, with cores of crystals showing most alteration, Plate 3.5, (as was also seen in the plagioclase feldspar inclusions in the K-feldspar phenocrysts). These plagioclase feldspar crystals also have Na-rich rims which are corroded due to reaction with late liquids since these crystals are early formed.

Albite twinning is common with occasional combined Carlsbad-albite twins present, and zoning is also present. Many of the plagioclase crystals, particularly those taken from the margin of the

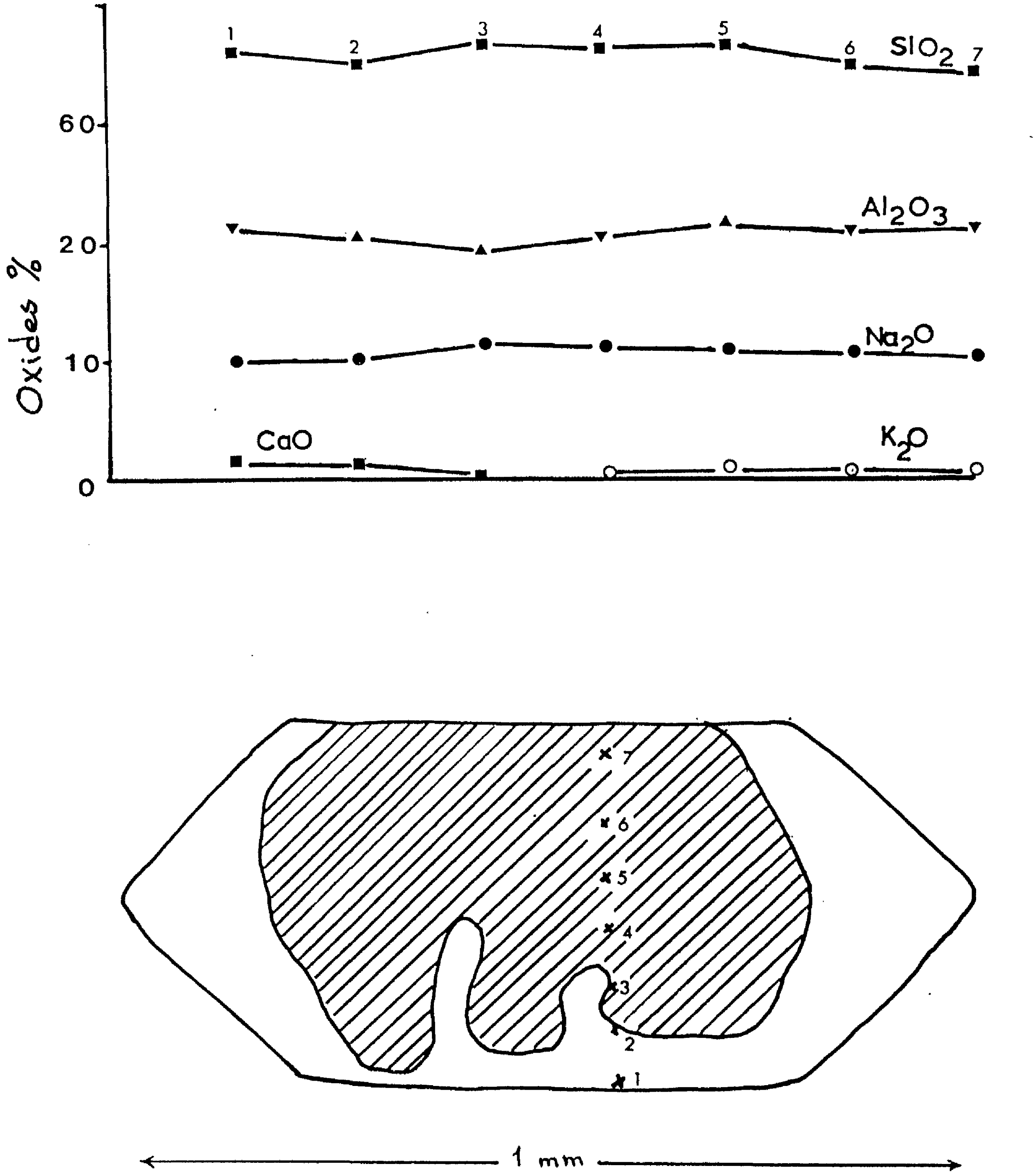


FIGURE 3.2. Microprobe traverse across a plagioclase feldspar crystal inclusion in the K-feldspar phenocrysts.

intrusion, show evidence of strain as their twin lamellae are bent, and, in some extreme cases, broken and displaced (Plate 3.6).

Analysis No	59	60	61	62	63	64
Position on Sample	1	2	3	4	5	6
SiO_2	65.81	65.02	66.43	65.85	66.04	64.23
Al_2O_3	21.51	20.75	19.13	20.37	21.23	20.93
FeO	0.27	0.00	0.13	0.00	0.43	0.29
MnO	0.14	0.00	0.00	0.21	0.00	0.00
CaO	1.76	1.47	0.00	0.45	0.30	0.40
Na_2O	10.13	10.32	11.43	11.03	10.92	10.5
K_2O	0.12	0.00	0.00	0.00	1.18	0.85
(Or	1.1	0.0	0.0	0.0	6.8	4.9
Mol % (Ab	36.6	89.5	100	96.7	91.3	92.2
(An	12.4	10.5	0.0	3.3	1.9	2.9

TABLE 3.3 Microprobe analyses of plagioclase inclusion in K-feldspar phenocryst, Glen Loth.
Analyses Nos. 59, 60, 61, 62, 63, 64 see Appendix 2.

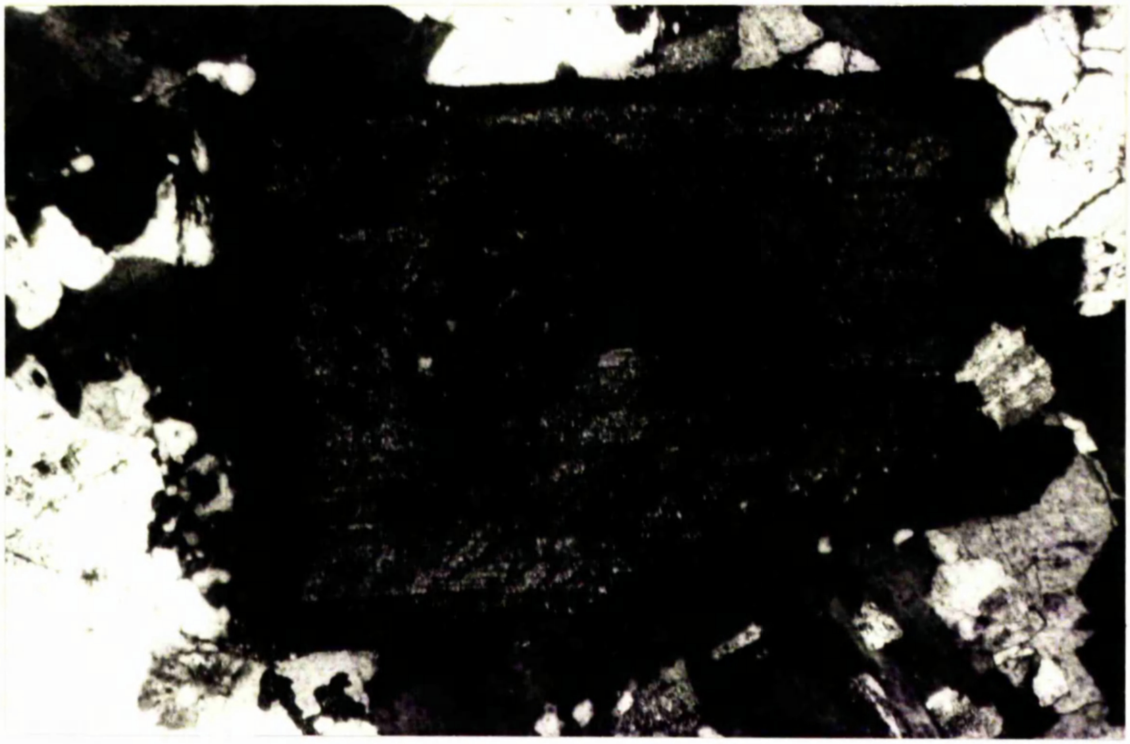
Microprobe analyses of plagioclase crystals are given in Appendix 2. The range of composition of the plagioclase crystals in the groundmass varies from An_0 to An_7. Traverses across some of these crystals are illustrated in Figure 3.3.

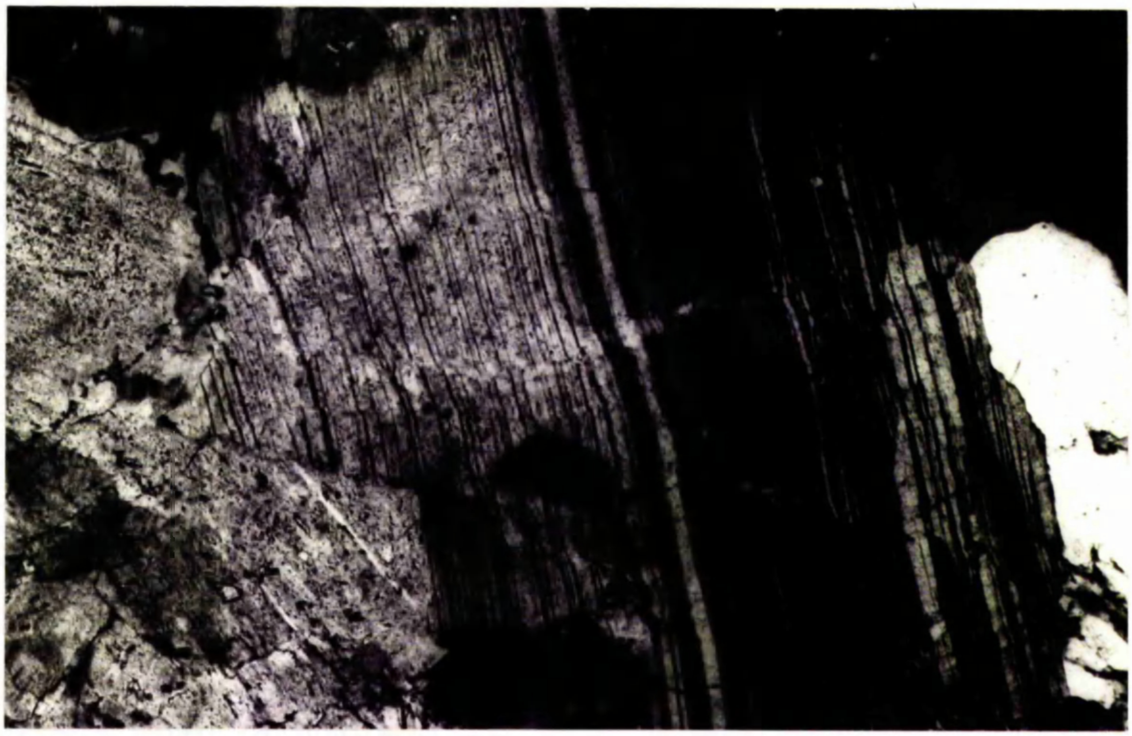
K-feldspar

Low temperature orthoclase feldspar is the K-feldspar of the groundmass, varying in size from 1 to 4mm and comprising 31% to 40.8%

PLATE 3.5. Early formed albite rim bounding plagioclase crystal with highly altered core (dark area in the centre). Note the highly irregular border due to reaction with late liquids. Crossed nicols, X12.8.

PLATE 3.6. Photomicrograph of plagioclase crystal, showing evidence of strain as the twin lamellae are bent, broken and displaced. Crossed nicols, X10





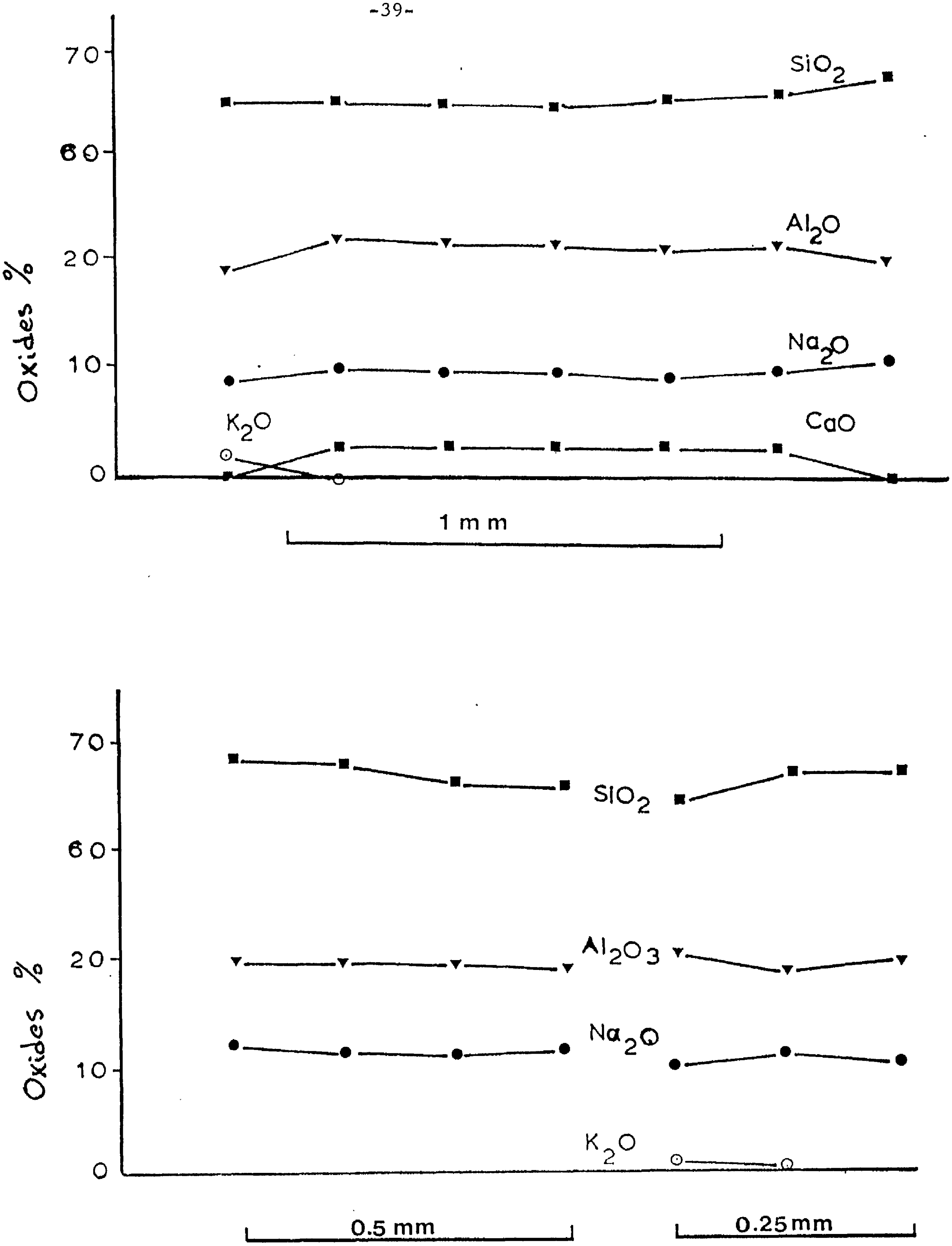


FIGURE 3.3. Microprobe traverses across plagioclase crystals in groundmass

of the volume of the rock (Table 3.1). These K-feldspars are also pink in colour and perthitic(cf the phenocrysts) with the exsolved phase occurring as stringers or veins making an angle of between 57° and 90° with the $\{010\}$ cleavage in the (001) plane. In some crystals the (Na-rich) exsolved phases are up to 0.7mm across and occur as blebs.

Microprobe analyses of some of these perthitic K-feldspar crystals are given in Table 3.4, with the complete results given in Appendix 2.

Analysis No.		105	106	107	108
Position on Sample		K-rich	Na-rich (vein)	Na-rich (bath)	Na-rich (rim)
SiO_2		62.35	64.76	67.01	68.70
Al_2O_3		18.31	18.96	19.89	20.13
FeO*		00.00	0.29	0.13	0.00
CaO		00.00	0.00	0.11	0.00
Na_2O		00.00	10.01	11.6	11.45
K_2O		16.13	1.6	0.14	0.00
Mol %	Or	100	9.5	1.1	0.0
	Ab	0.0	90.5	98.2	100
	An	0.0	0.0	0.5	0.0

TABLE 3.4 Microprobe analysis of a K-feldspar perthite from a sample taken in Ousdale Quarry.

Analyses Nos. 105, 1 6, 107, 108 (see Appendix 2)

Quartz

Quartz occurs as small interstitial, anhedral crystals in the groundmass, although some larger phenocrysts (up to 10mm long) occasionally occur (Plate 3.7). The quartz crystals are clear, with regular fractures which are particularly common in samples taken from contact zones. Internal cracks are iron-stained and often filled with clay. Quartz crystals may contain inclusions of apatite and zircon (Plate 3.9).

Myrmekite

Myrmekitic intergrowths are rare in the CGP type, but more common in the FG type which has more basic plagioclase feldspar present. The myrmekite occurs between plagioclase feldspar and K-feldspar crystals.

Mafic minerals (Biotite and Hornblende)

Biotite (~ 0.7mm across) is the commonest ferromagnesian mineral present. The early formed biotite crystals (which are richer in FeO and MgO than later formed ones) are occasionally included in K-feldspar phenocrysts, but biotite crystals are usually found in the rock in irregular 'clumps'. The biotite crystals contain inclusions of magnetite, apatite and zircon (Plate 3.8), and alteration to chlorite is very common.

The percentage of biotite varies from 15% to 5.87% in the CGP type (Table 3.1). Table 3.5 gives microprobe analyses of some biotites and secondary chlorites taken from different CGP granite specimens and the full results may be found in Appendix 2.

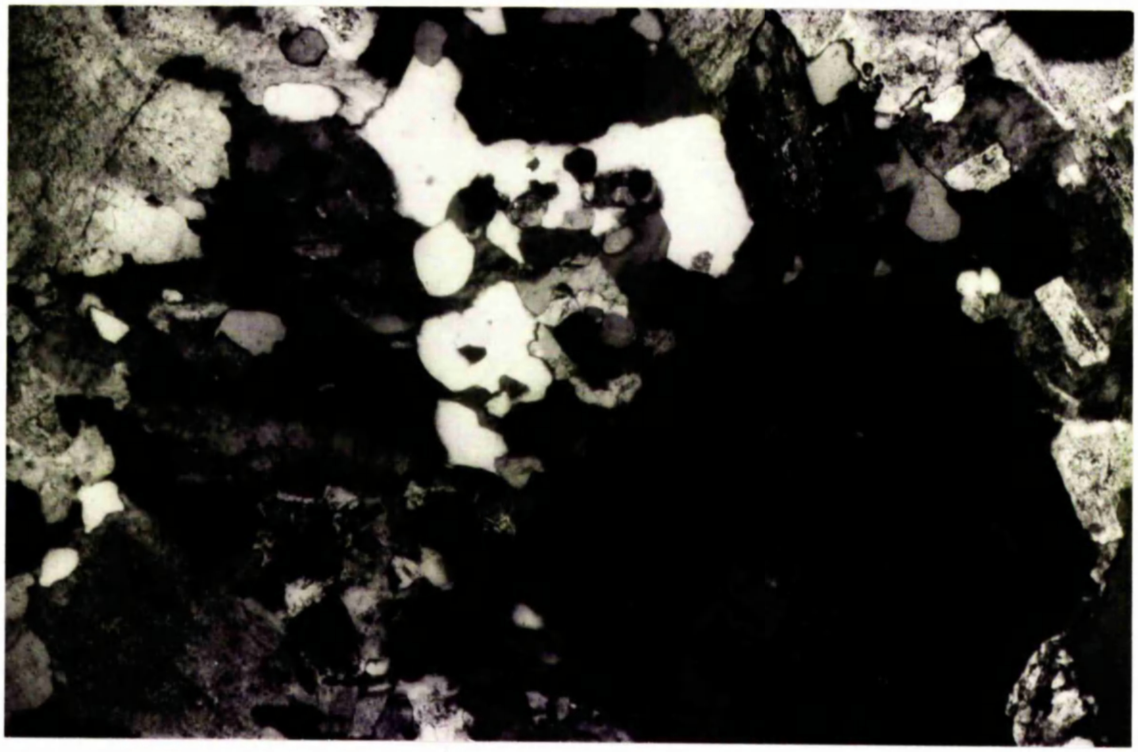
Hornblende is less common than biotite, and is found in

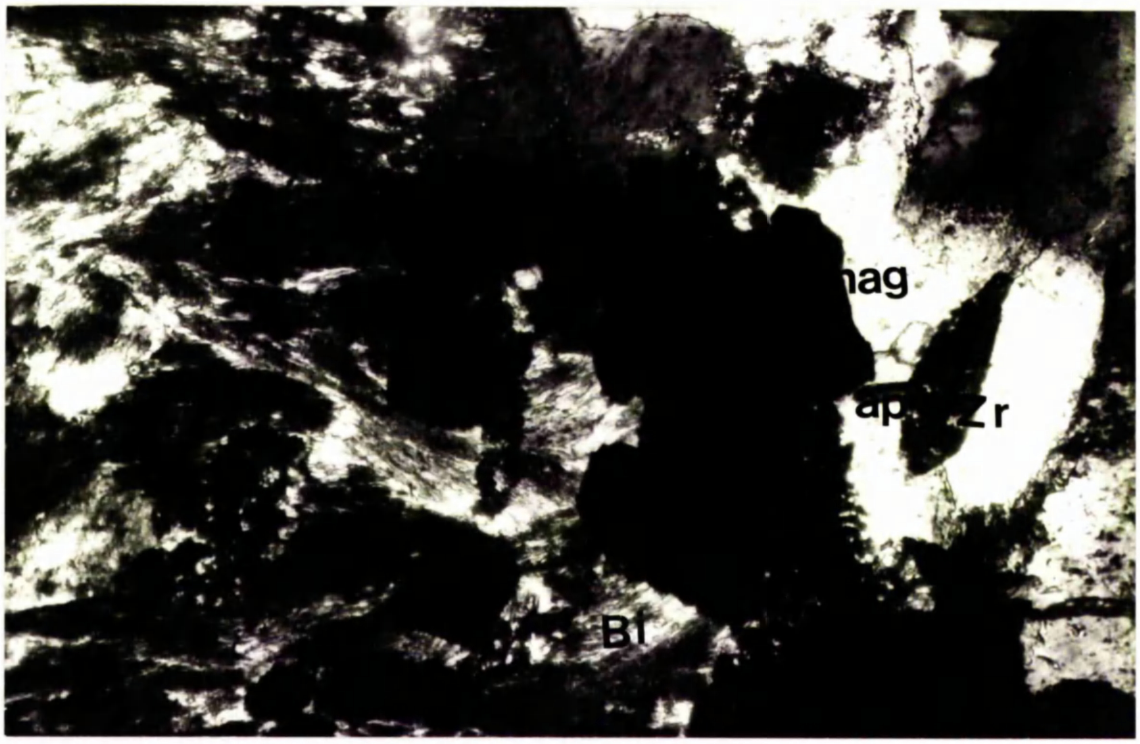
PLATE 3.7. Photomicrograph of the large quartz phenocrysts with a few intergranular and some hair-like microcracks. Note the small quartz grains are free of microcracks and they appear to be slightly orientated (mosaic texture). The small quartz grains are free of inclusions. Sample from Glen Loth area.

Crossed nicols, X10.

PLATE 3.8. Photomicrograph of the mafic minerals 'clump' containing chloritised biotite (Bi), magnetite (mag), apatite (ap), zircon (Zr). Sample from Ousdale Burn area (CGP type).

Crossed nicols, X51.2.




mag
ap
Zr
Bi

association with biotite and accessory minerals similar to that described by Cawthorn and Brown (1976). According to their study, when the SiO_2 percentage of the rock is greater than 71% and the Na/Na + K ratio is less than 0.6, crystallization of amphibole will either cease or continue to crystallize together with mica forming mafic clots.

Analysis No.	70	74	112	65	66
	Biotite (LW)	Biotite (LW)	Biotite (OQ)	Chlorite (GL)	Chlorite (GL)
SiO_2	50.36	48.22	50.94	25.28	24.32
Al_2O_3	24.87	29.95	24.14	15.72	15.49
FeO	4.83	4.09	4.73	21.81	24.36
MgO	2.33	0.94	2.23	12.25	11.96
MnO	-	-	-	0.18	0.16
CaO	-	-	-	0.36	0.24
K20	9.73	9.73	9.26	0.47	0.31

TABLE 3.5 Microprobe analysis of selected biotite and chlorite from Langwell Water (LW), Ousdale Quarry (OQ) and Glen Loth (GL).

Accessory minerals

The main accessory minerals - magnetite, apatite, zircon and sphene - usually occur with biotite and other ferromagnesian minerals within mafic clots, but are also found as inclusion in K-feldspars phenocrysts (Plate 3.9).

PLATE 3.9. Some of the accessory minerals are illustrated in this plate, enclosed in K-feldspars (K-fel); magnetite (mag), apatite (ap).
Crossed nicols, X51.2.


ap

3.3. The finer-grained type (FG)

Introduction

The finer-grained type occupies a larger area of the Helmsdale granite than the CGP type. The colour of the rock changes from pink, near the contact with the CGP type, to brownish towards the centre of the intrusion. The pink variety is very similar to the CGP type except for the grain size which is smaller (~ 1mm), and the rock may be termed a finer-grained granite with granular texture (Streckeisen 1976; see also Plates 3.10, 3.11). The constituent minerals are similar to those of the CGP type, and include K-feldspar, Na-plagioclase (An_{16}), quartz, biotite, hornblende and the accessory minerals zircon, sphene, magnetite and apatite. The volume percent of the mafic minerals present is slightly higher (4% to 8%) than in the CGP type (see Table 3.1). Modal analyses of rock hand specimens of the finer-grained granite are given in Table 3.6. (The phenocryst minerals are not included in point counting)

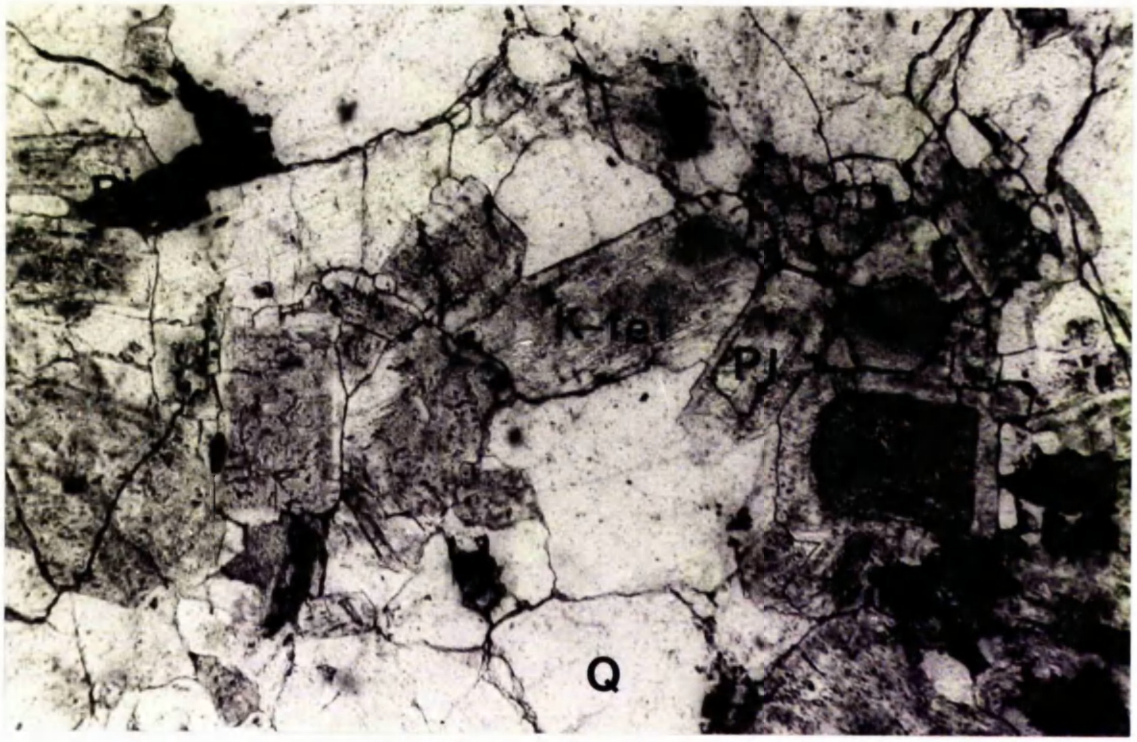
Plagioclase feldspar

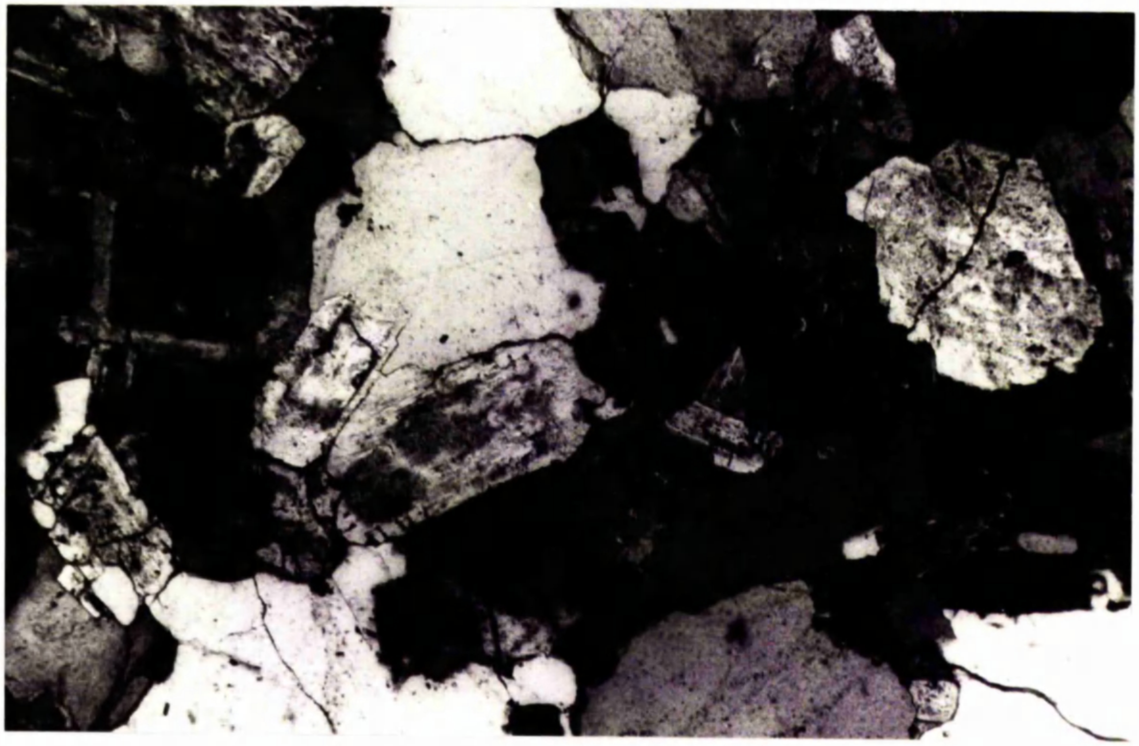
Plagioclase feldspar comprises 23% to 43% of the volume of the rock (Table 3.6) and the crystals range in size from 0.2mm to 1mm. The composition of plagioclase feldspars were determined by microprobe analysis and the results are given in Appendix 2. In general the range of composition of plagioclase crystals varies from An_0 to An_{16}. Although the plagioclase crystals commonly show albite twinning, occasional combined Carlsbad-albite twins occur and zoning is also present.

Alteration is common and is most advanced in the case of some plagioclase crystals. Microprobe traverses across some altered plagioclase crystals are shown in Figure 3.4 (see also Table 3.7).

PLATES 3.10, 3.11.

These micrographs are from the finer-grained type of granite (Eldrable Burn area). From the photographs it can be seen to consist mainly of a granular mixture of K-feldspar (K-fel), plagioclase (Pl), quartz (Q) and biotite (Bi). One of the zoned plagioclase feldspars can be seen to have a cloudy core, mantled by a more sodic rim. Plate 1 is plain light and plate 2 is crossed nicols, X10.


K-fel
Pl
Q



Samples Location*	% Plag	%K-fel	% Quartz	% Biot	% Muscov	% Access	% Opaque	Total	Number of Count	Height in Ft. from Sea level
HQ	23.2	46.5	23.80	5.14	0.84	tr	0.52	100	7,000	100
CB	43.67	32.28	19.93	4.12	tr	tr	0.60	100	2,100	100
AC	23.70	42.0	25.22	8.6	0.12	0.36	tr	100	3,500	160
EBL	25.10	42.77	25.34	5.53	0.93	0.23	0.1	100	2,100	200
M	28.04	39.0	23.02	8.12	0.98	tr	0.84	100	2,100	8000

TABLE 3.6 Modal analyses of the finer-grained type with no phenocryst minerals.

*HQ = Helmsdale Quarry

CB = Caen Burn

EBL = Eldrable Burn (lower part)

AC = Allt Cille

M = Marrel

Analysis No.		141	142	143	144
SiO_2		63.7	65.59	63.87	65.87
Al_2O_3		21.54	18.77	19.96	20.51
FeO*		1.88	0.68	0.29	0.15
MnO		-	-	-	-
CaO		0.29	-	0.09	0.34
Na_2O		5.75	9.54	10.52	11.28
K_2O		5.72	3.30	0.84	0.51
Mol %	Or	38.4	18.5	5.0	2.6
	Ab	58.5	81.5	94.2	95.8
	An	3.1	0.0	0.8	1.6

TABLE 3.7 Microprobe analyses of plagioclase feldspar with altered core from Caen Burn area (FG type).

Figure 3.4 shows while sodium and calcium increase in amount towards the centre of the crystal (point 4 in Fig. 3.4) potassium decreases in the same direction.

K-feldspar

The K-feldspar, which is usually quite fresh, is again a low temperature orthoclase feldspar comprising 32% to 46% of the volume of the rock (Table 3.6). Although the average grain size of a K-feldspar crystal in the finer-grained granite is about 1mm, larger K-feldspar phenocrysts may exist (up to 30mm in size). These K-feldspar phenocrysts are perthitic (cf. CGP type) and occasionally

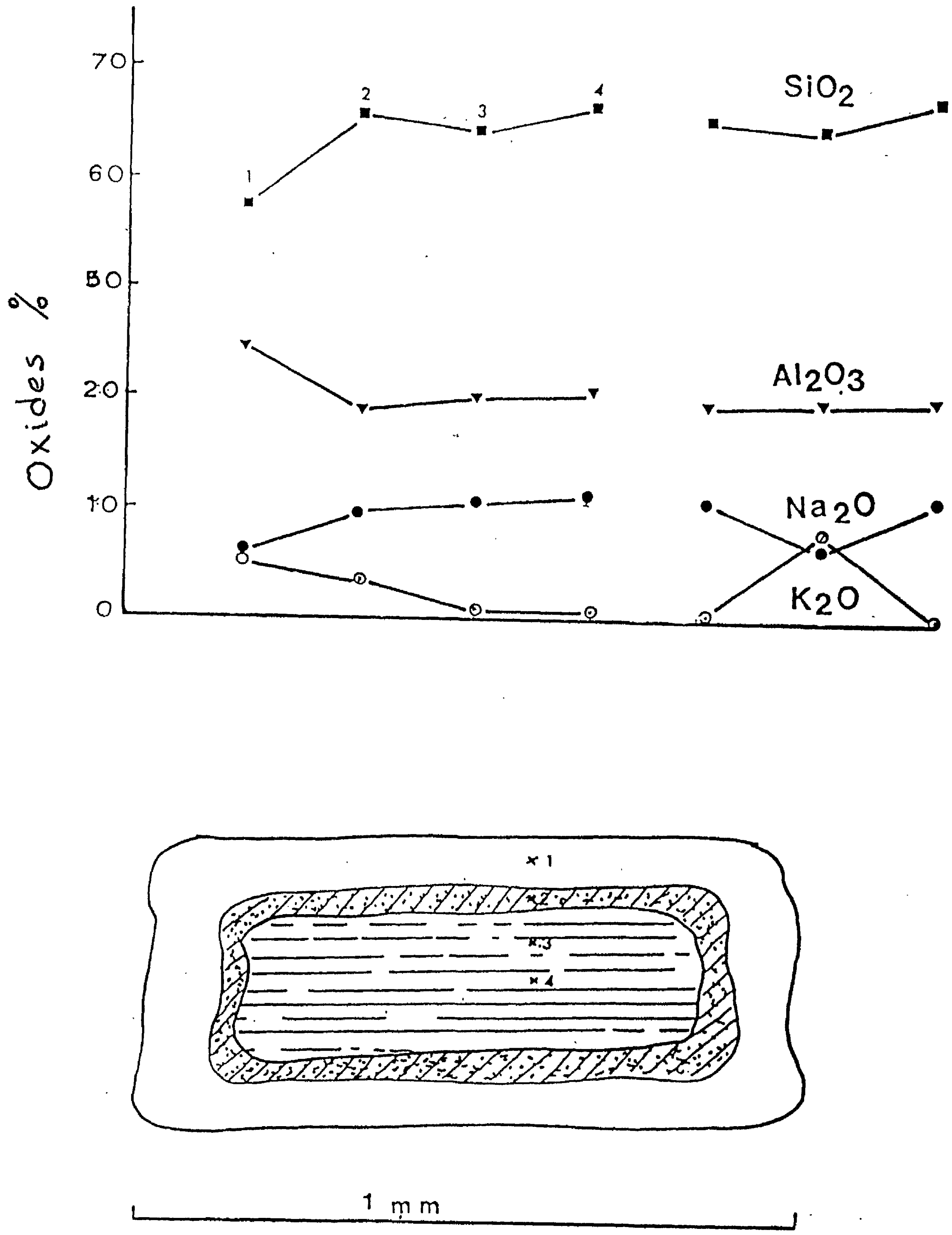


FIGURE 3.4. Microprobe traverses across some altered plagioclase crystals of FG type.

contain small elongate plagioclase crystals as inclusions. These small plagioclase crystals are not orientated and are not surrounded by albitic rims as was the case in the CGP type. Microprobe analyses of the feldspars are given in Table 3.8.

Myrmekite

Myrmekite is more common in the FG type than it is in the CGP type. In the FG type the amount of quartz (in the form of vermicules) in the myrmekitic intergrowth has increased as the host plagioclase feldspar became more basic. This caused more replacement of K-feldspar by Ca-rich plagioclase and the release of more silica to form vermicules of quartz between the plagioclase and K-feldspar crystals (Plate 3.12).

Mafic minerals

Biotite and hornblende are more common than in the CGP type, comprising 4% to 8.5% of the volume of the rock (Table 3.6). Biotite is often altered to chlorite but microprobe analyis of unaltered biotites shows that they are richer in MgO and FeO than the corresponding biotite from the CGP type (see Table 3.9).

Accessory minerals

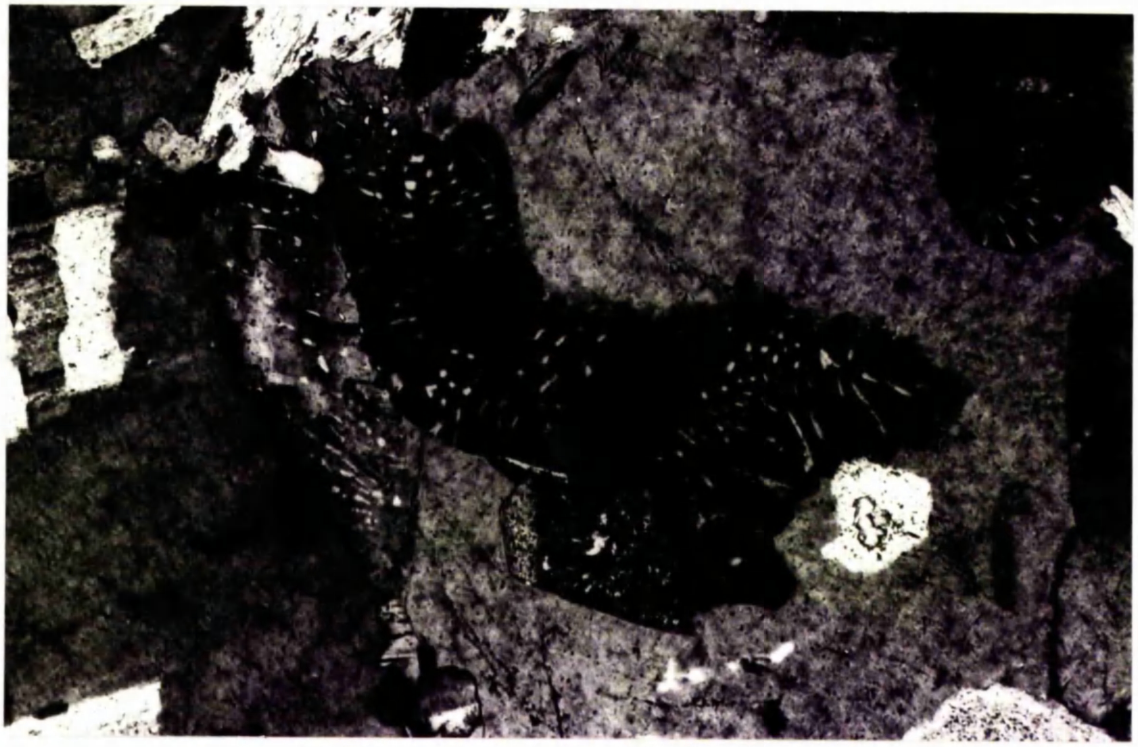
Apatite, magnetite, sphene and zircon are common, but smaller in size and less in amount than in the CGP type. They are always found in association with the mafic minerals (Plate 3.13).

PLATE 3.12. Sodic plagioclase crystal containing irregular inclusion of quartz. The intergrowth is commonly to be found at the margin of plagioclase crystals, where it penetrates a K-feldspar crystal.

Crossed nicols, X25.2.

PLATE 3.13. Some of the common accessory minerals can be seen to be associated with the mafic minerals.

Crossed nicols X25.2.



Analysis No.	87	88	131	134
	Perthite		Plagioclase	K-feldspar
	K-rich	Na-rich	(enclosed in K-fel)	(orthoclase)
SiO_2	63.14	68.55	63.68	62.27
TiO_2	-	-	-	0.15
Al_2O_3	18.42	20.07	21.03	18.13
Feo*	0.15	-	0.15	-
CaO	-	-	2.15	-
Na_2O	-	11.72	9.77	-
K_2O	16.28	0.09	0.21	16.19
(Or	100	-	1.1	100
Mol % (Ab	-	100	86.5	-
(An	-	-	12.4	-

TABLE 3.8. Microprobe analyses Nos 87, 86, from K-feldspar perthite taken from Helmsdale Quarry and analyses nos 131 and 134 from Allt Cille area, showing Ca-rich plagioclase enclosed in orthoclase analysis No.134.

Analysis No.	95	139	120	150
	Biotite	Biotite	Chlorite	Chlorite
SiO_2	37.01	34.81	29.72	28.75
TiO_2	3.07	2.19	0.26	0.14
Al_2O_3	15.13	17.5	16.22	20.76
FeO*	20.18	22.39	19.78	20.01
MgO	10.26	13.11	15.35	15.42
CaO	0.10	0.19	-	-
K_2O	10.22	5.92	1.06	0.96

TABLE 3.9. Microprobe analyses Nos 95 and 139 are biotite from Helmsdale Quarry and Allt Cille respectively. Analyses Nos 120 and 150 are chlorite from Allt Cille and Caen Burn respectively.

Summary

1). The dominant textural feature of the Helmsdale granites as a whole is hypidiomorphic granular.

2). The coarser-grained porphyritic type (CGP) has large poikilitic potash-feldspar (perthite) phenocrysts which decrease considerably in amount in the finer-grained type (FG).

3). The preferred orientation and zonal arrangement of plagioclase inclusions, particularly in the CGP type, suggests that during growth the smaller plagioclase inclusions were rotated into a position with their long axes parallel to the crystal faces (both 100 and 001) of the potash-feldspar. Very occasionally a similar arrangement occurs with the plagioclase crystals surrounding K-feldspar phenocrysts, which helps to support the hypothesis that these potassium-feldspar phenocrysts grew in a liquid medium rather than a solid one.

4). Albite rims which occur on the K-feldspar phenocrysts decrease in the finer-grained type as the amount of K-feldspar phenocrysts also decreases. The albite rims formed during the development of perthite when sodium-rich material migrated to the edge of the potassium-feldspar and crystallized there. This agrees with the views of Tuttle and Bowen (1958) and Miller (1973).

5). The petrographic study supports the view that two granite intrusions are present at Helmsdale, a coarser-grained porphyritic type (CGP) and a finer-grained type (FG). Figure 3.5 confirms the existence of the two rock types using a Q-Ab-An plot. Some variations in grain size and mineralogy occur, with the inner component of the intrusion (the FG type) having slightly more mafic minerals than the other one (the CGP type).

3.4. Geochemistry

Introduction

Rock specimens from the Helmsdale granites were analysed to investigate any variation in the chemical composition of both granite types. 95 samples were collected and analysed for major elements and 16 trace elements (Ce, La, Sr, Zr, Ba, Ga, Cu, Zn, Nb, Co, Ni, Cr, Y, Rb, Pb, Th). Major and trace element analyses were carried out by X-ray fluorescence techniques (Leake et al. 1969) using fused beads and pressed powder pellets in either a Philips PW1450 (major

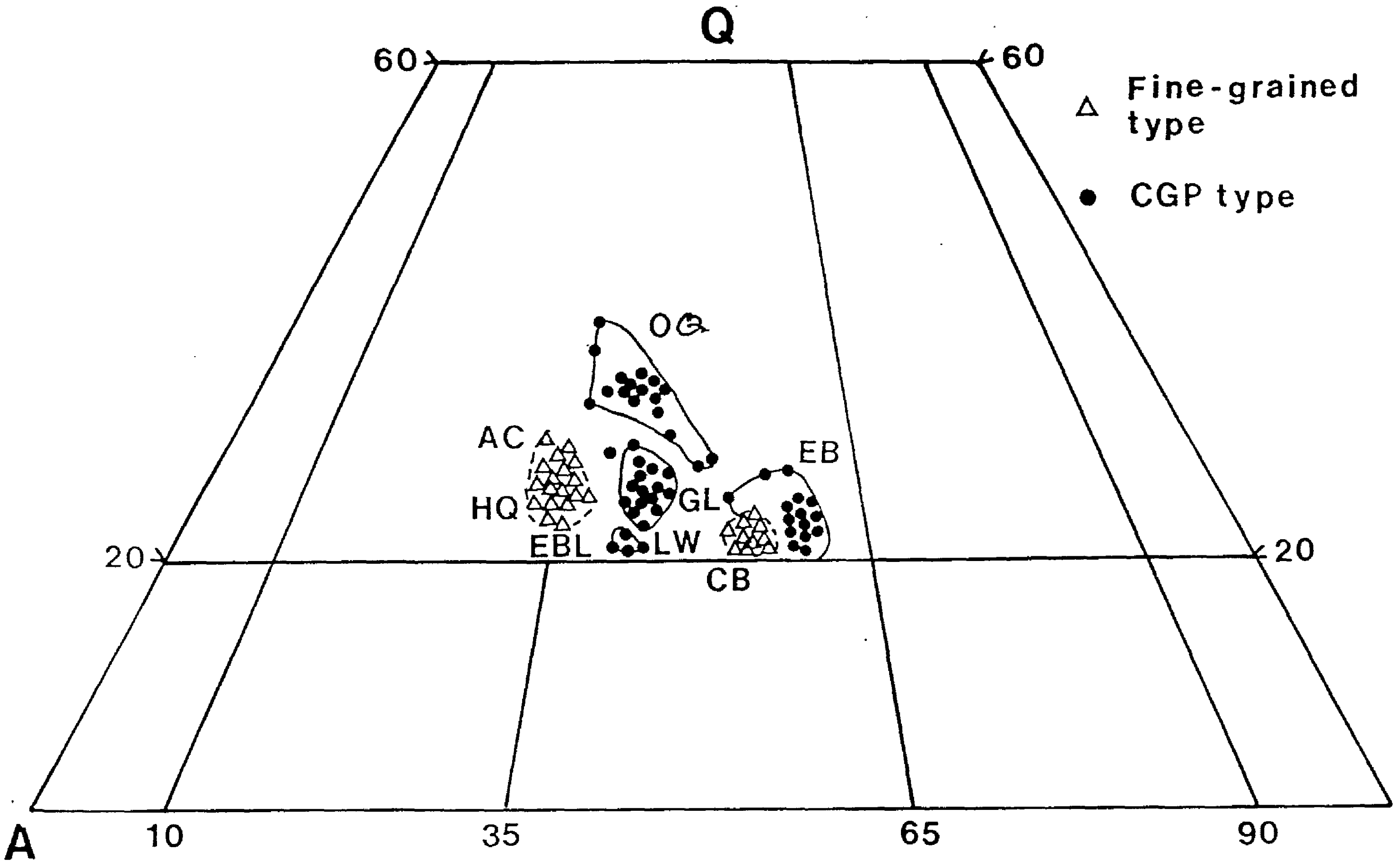


FIGURE 3.5.
Classification of the Helmsdale granites (after Streckeisen 1976). See Figure 3.1 for symbols.

elements), or a Philips PW1220 (trace elements). Results of the rock analyses carried out are given in Appendix 1. This large number of analyses permits a detailed comparison to be made between the two granite types forming the Helmsdale intrusion.

3.5. Major element variation

Major elements have been plotted against SiO_2 and other major elements (Al_2O_3, total Fe) and significant and regular trends have been revealed from both granite types. This major element distribution, the use of Niggli numbers and normative amounts may provide a means of interpreting the chemical relationship and the crystallization history of the two granites (FG and CGP types).

Silica (SiO_2)

SiO_2 contents of the Helmsdale granites change from an average of 71% in the FG type to about 74.5% in the CGP type.

Calcium Oxide (CaO) (Fig. 3.6, a-c)

The average CaO content of the Helmsdale granites decreases from 0.6% in the finer-grained (FG) type to approximately 0.3% in the coarser-grained porphyritic (CGP) type. In Figure 3.6a the CaO content decreases with increasing SiO_2. Although the trend is continuous for both granite types, they are separated on their SiO_2 contents, and also on their CaO contents although the later boundary is not so clear cut. Figures 3.6b and c show positive trends - increasing CaO with increasing Al_2O_3 and total iron respectively. The slight enrichment in CaO in the FG type probably reflects the more basic plagioclase feldspar constituent present.

Sodium Oxide (Na_2O) Fig. 3.7a)

In Figure 3.7a Na_2O against SiO_2 shows a negative trend, with the

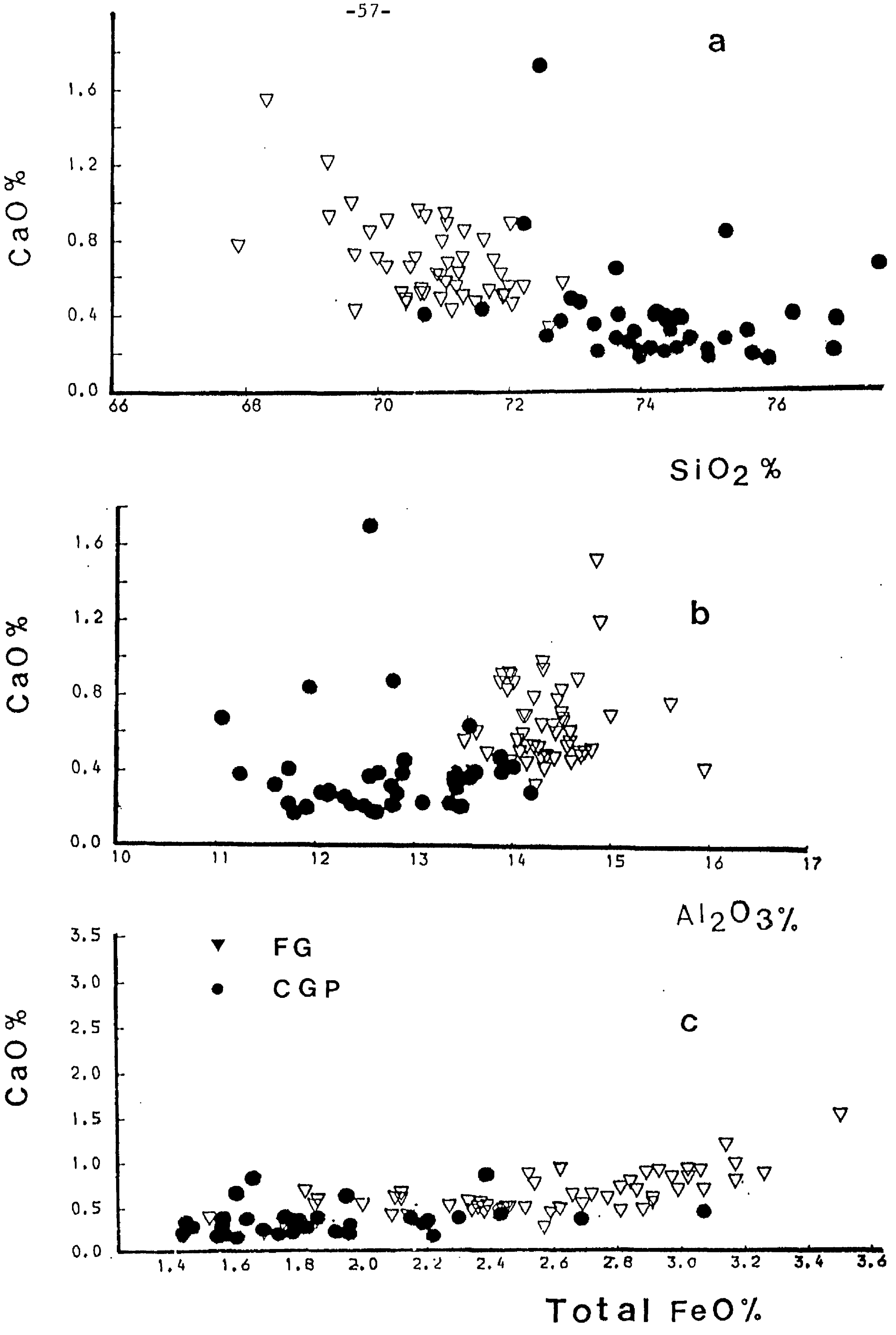


FIGURE 3.6. CaO percentage against Total FeO, Al_2O_3 and SiO_2

CGP type having slightly lower average Na_2O (4.9%) than the FG type (average 5.3%). The Na_2O individual values in the CGP type are also more scattered, because of the uneven distribution of K-feldspar phenocrysts in this granite.

The FG type has more Na-rich plagioclase than the CGP type (see Tables 3.1 & 3.6). In the FG type, microprobe analysis of plagioclase feldspars shows that the plagioclase crystals present are very sodic, ranging in composition from An_0 to An_{16}, and Figure 3.7a confirms this point with the FG type having the higher Na_2O content than the CGP type.

Potassium Oxide (K_2O)(Fig.3.7b)

K_2O is plotted against SiO_2 in Figure 3.7b, and the diagram shows that variation in K_2O is independent of SiO_2 content.

In Figure 3.7c, $K_2O + Na_2O$ has been plotted against SiO_2 and a slight negative trend results.

Aluminium Oxide (Al_2O_3)(Figs 3.6b and 3.8)

The CGP granite has an average Al_2O_3 content of 12.8%, whereas the FG granite has an average content of 14.8%. The higher alumina in the FG type corresponds with higher CaO, total Fe, MgO, TiO_2 and Na_2O. The higher CaO, Na_2O and Al_2O_3 reflect the increased amounts of plagioclase feldspar in the FG granite types, and the higher total iron, MgO and TiO_2 reflect the increased amounts of mafic minerals in the FG granite types.

Other Oxides (Figs 3.9 & 3.10)

In Figures 3.9 and 3.10 Fe_2O_3, TiO_2, MgO and total iron + MgO + MnO show negative trends when plotted against SiO_2; that is, they decrease with increasing SiO_2.

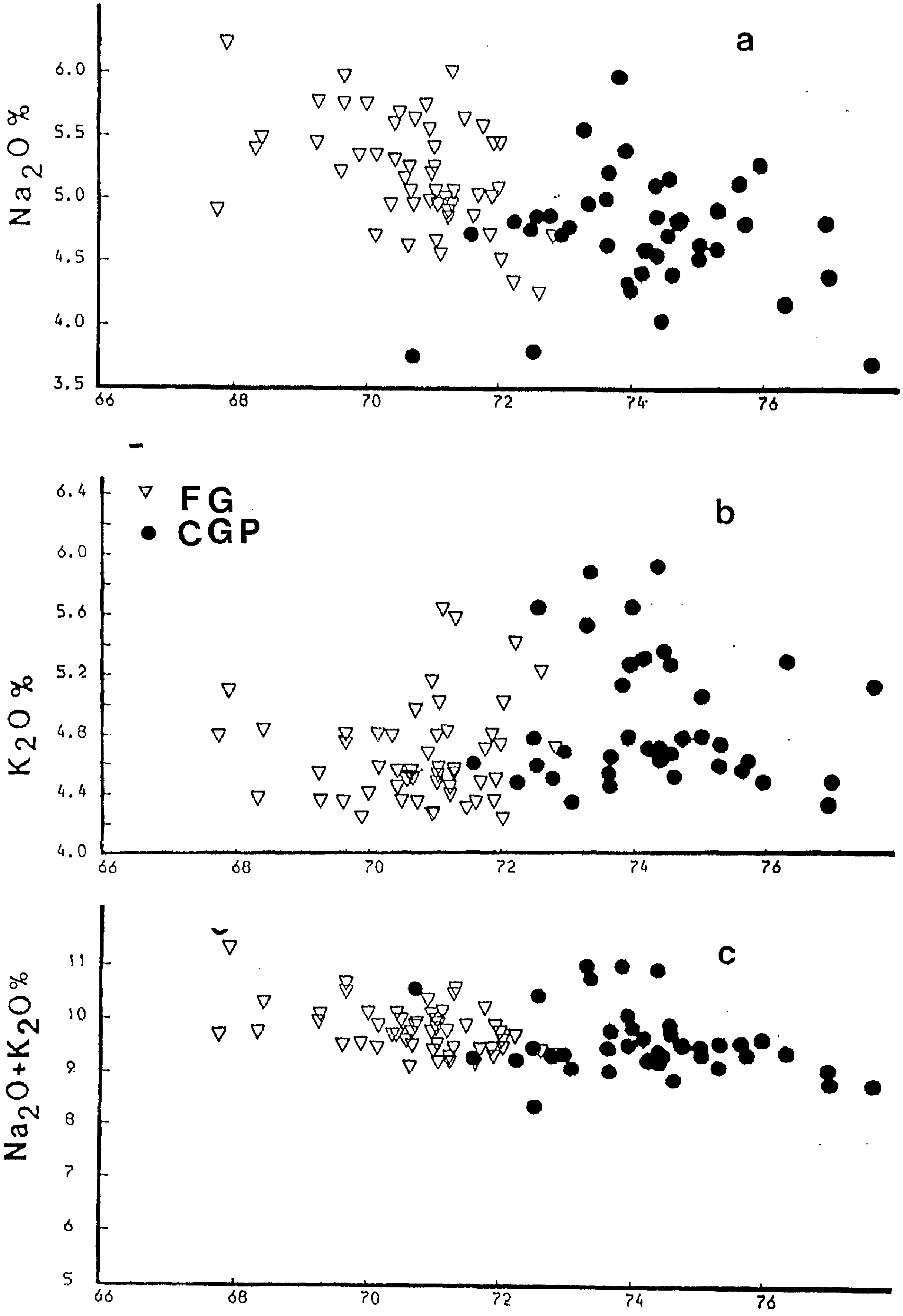


FIGURE 3.7. SiO_2 percentage against K_2O+ Na_2O, K_2O and Na_2O

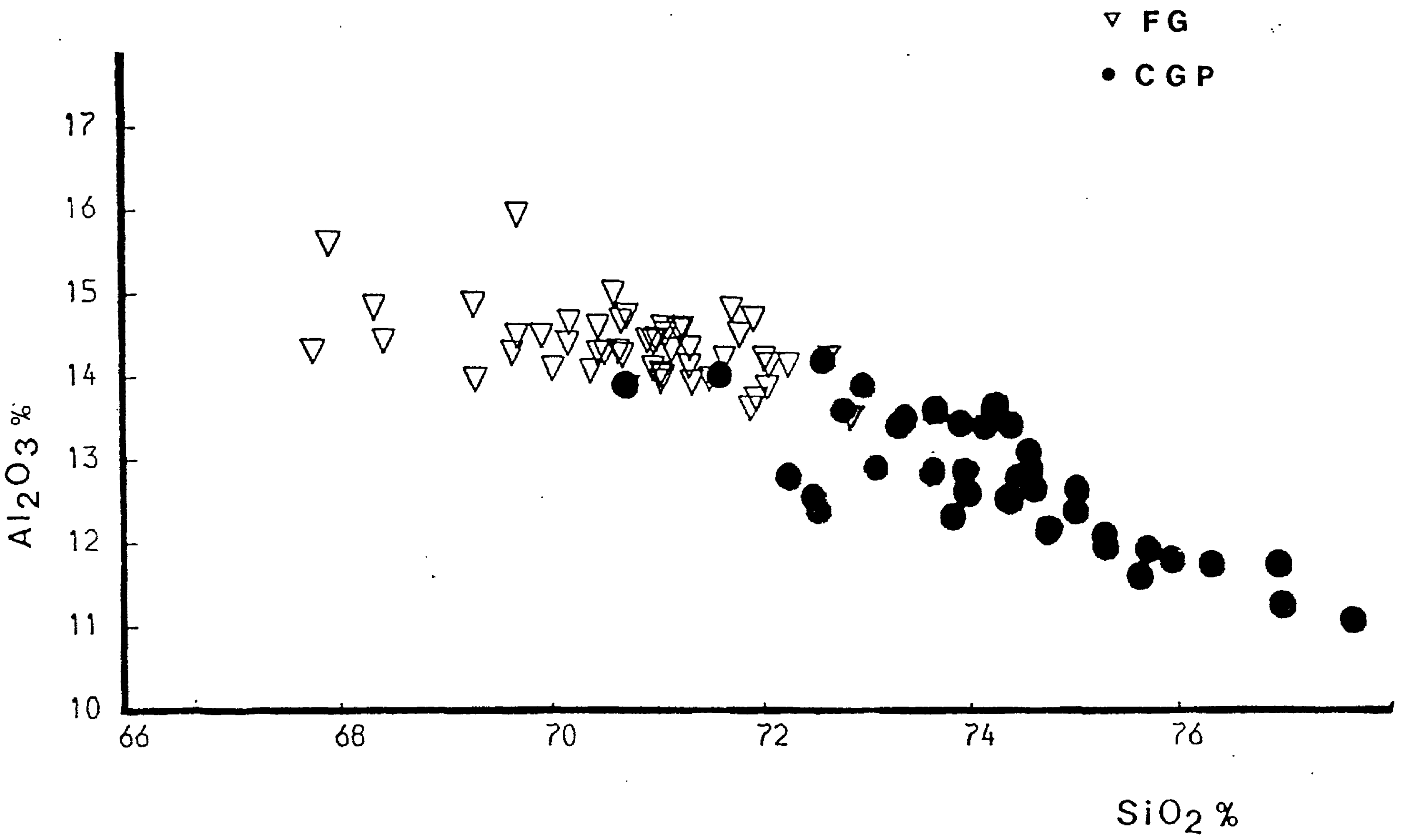


FIGURE 3.8. SiO_2 percentage against Al_2O_3.

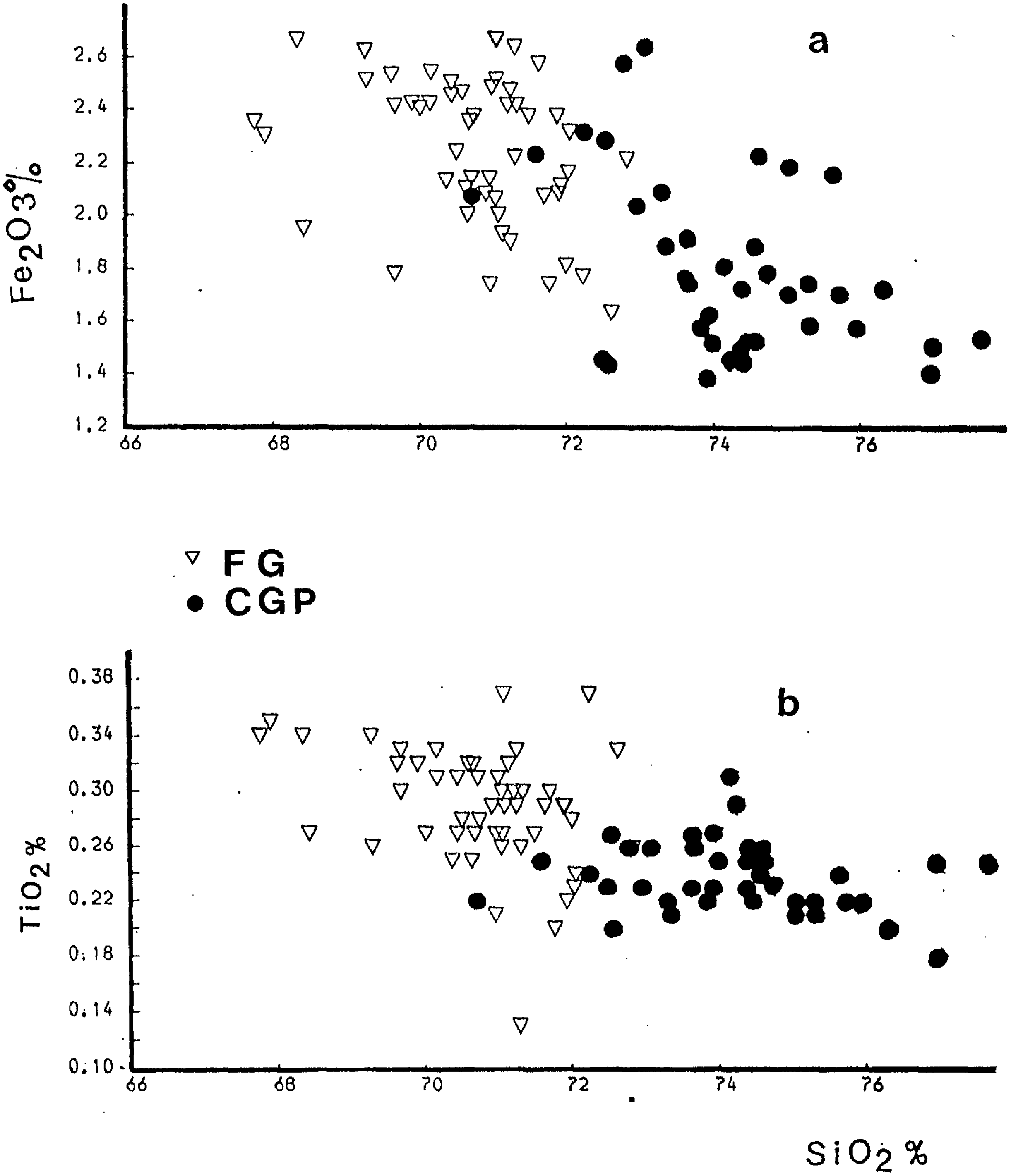


FIGURE 3.9. SiO_2 percentage against $TiO_2\%$ and $Fe_2O_3\%$

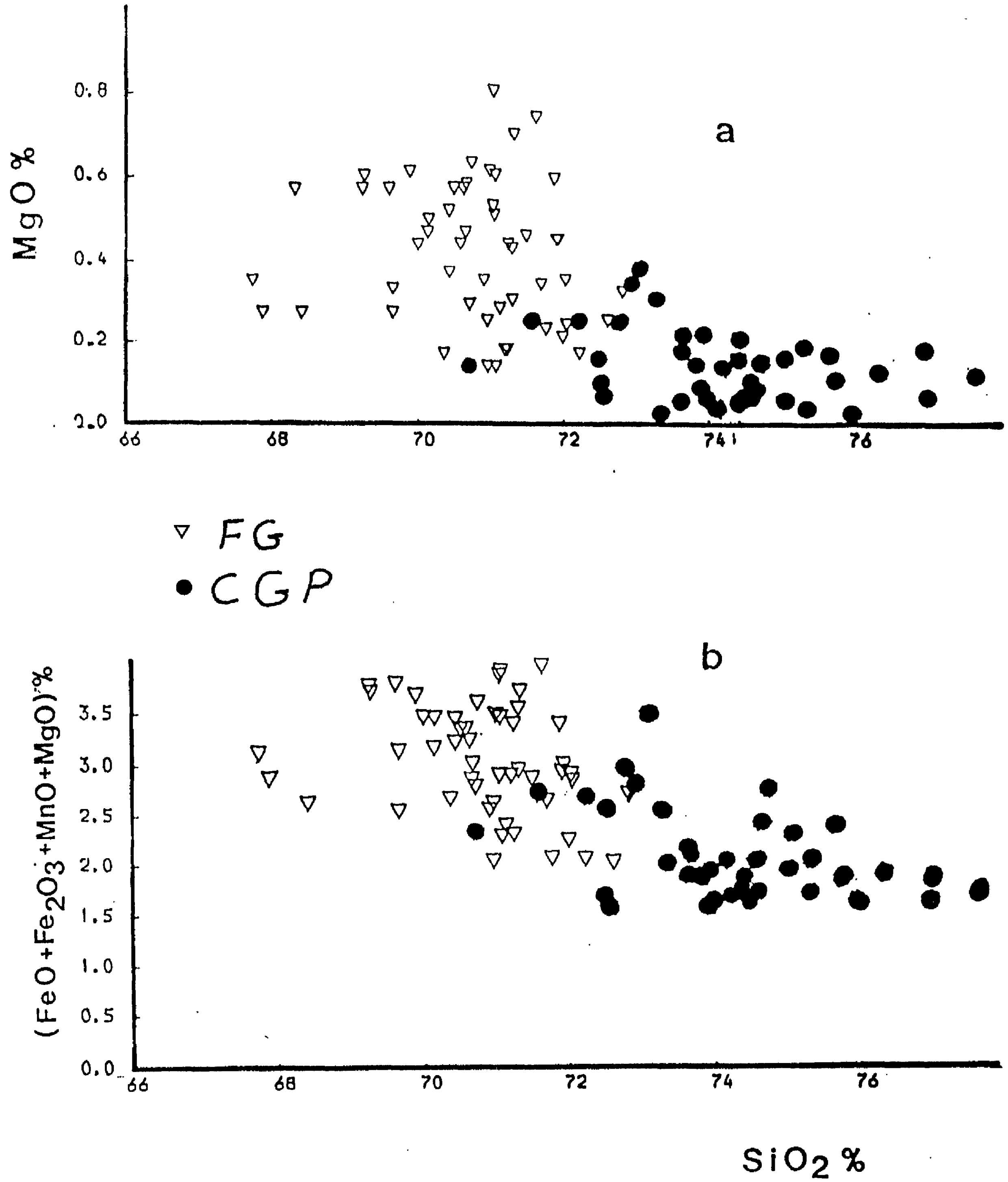


FIGURE 3.10. SiO$_2$ percentage against (FeO + Fe$_2$O$_3$ + MnO + MgO) and MgO%.

3.6. Variation in normative minerals

The geochemical data have been recalculated to normative mineral constituents, and quartz, orthoclase and albite have been plotted into the triangular diagram (Fig. 3.11). All the points occur in a small central field with the CGP types showing most scatter, with a compositional field which is elongated towards the albite apex. Figure 3.12 represents a Q-Ab-An triangle with all the points occurring in a small area along the Q-Ab side of the triangle. The 2 plots strongly suggest that albite was the main fractionating feldspar phase in the Helmsdale granites (see also Figs 3.6 to 3.10)..

3.7. Variation in Niggli values

Niggli values were also calculated from the analyses and various plots made of alk, mg, fm, al, *ti*, K, and *c* against *si*. In Figure 3.13a, al against *si* shows a positive trend in the FG type (al increases as *si* increases) but a possibly negative trend in the CGP type, although the points are more scattered and the trend is more imprecisely determined.

In Figure 3.13b both rocks show positive trends although the individual points of the CGP type are more scattered.

Niggli *si* is plotted against mg and fm values in Figures 3.14a and b respectively, and show negative trends with both mg and fm decreasing as *si* increases.

In Figures 3.15 a, b and c the plots of *si* against C, *ti* and K are inconclusive with no clear cut trends emerging.

3.8. Trace element variation

The detailed major element studies of the Helmsdale granite show that it consists of two homogeneous intrusions which are geochemically

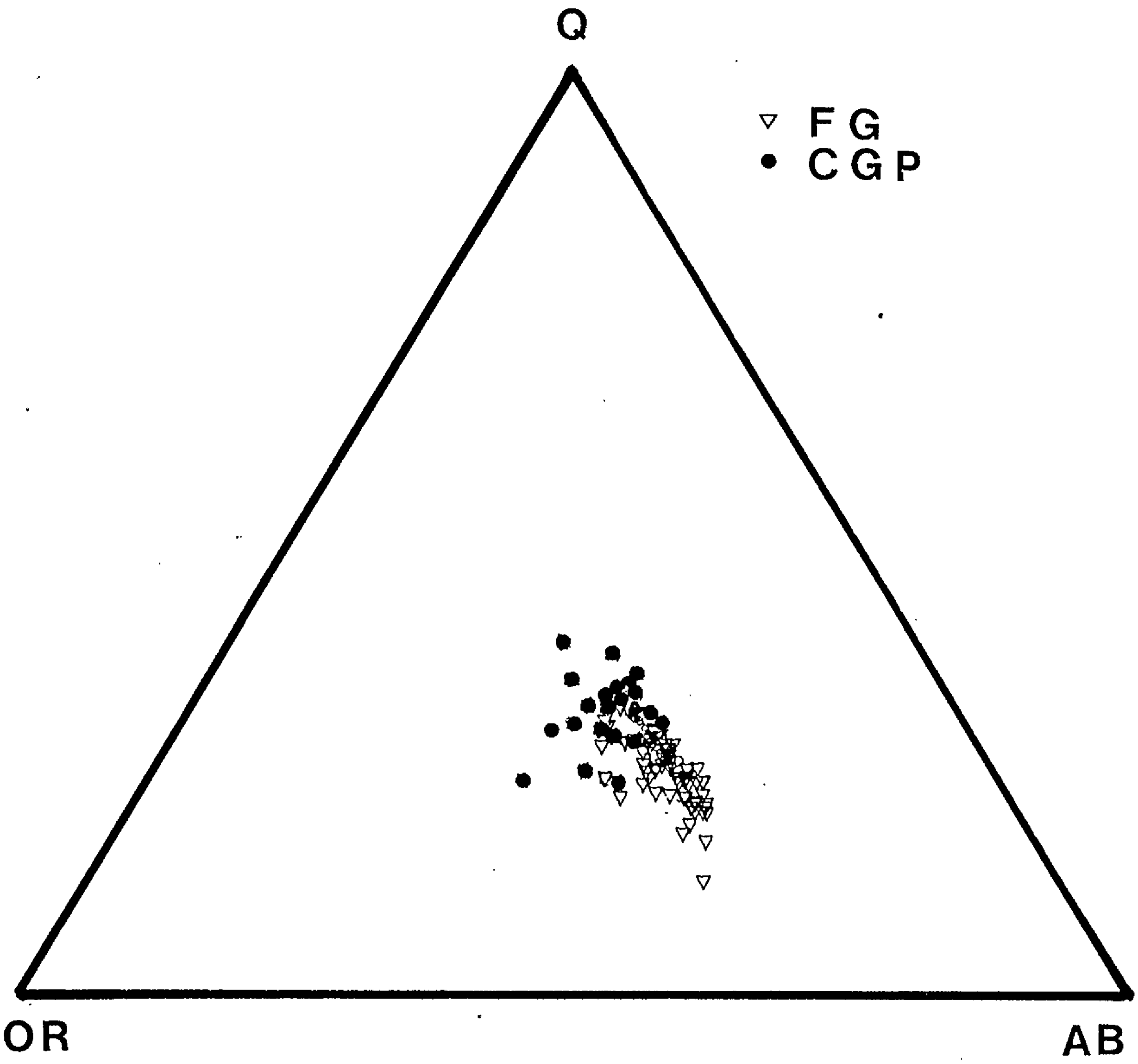


FIGURE 3.11. Silica, orthoclase, plagioclase system (projection from anorthite)

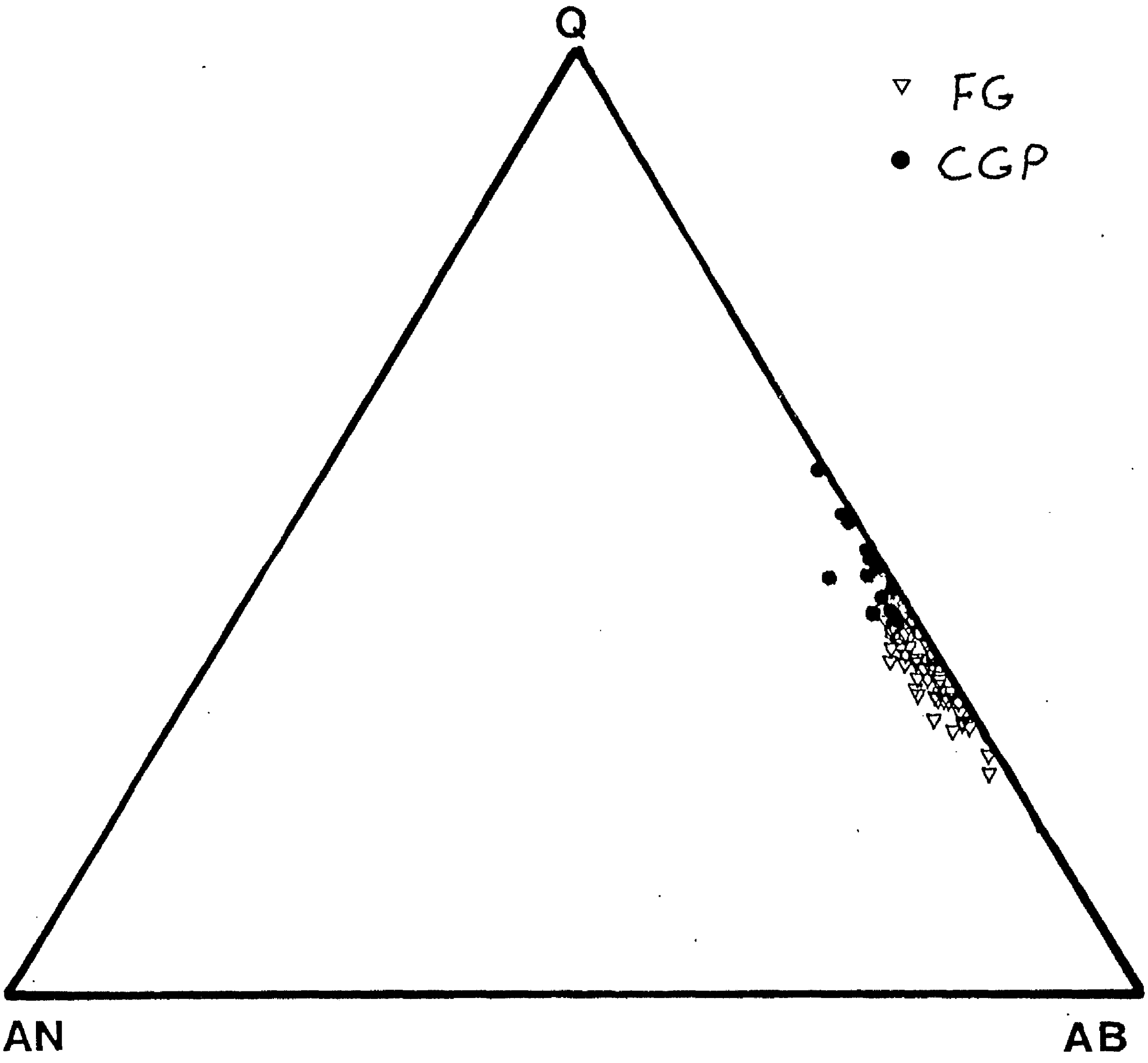


FIGURE 3.12. Silica, albite, anorthite system (projection from orthoclase)

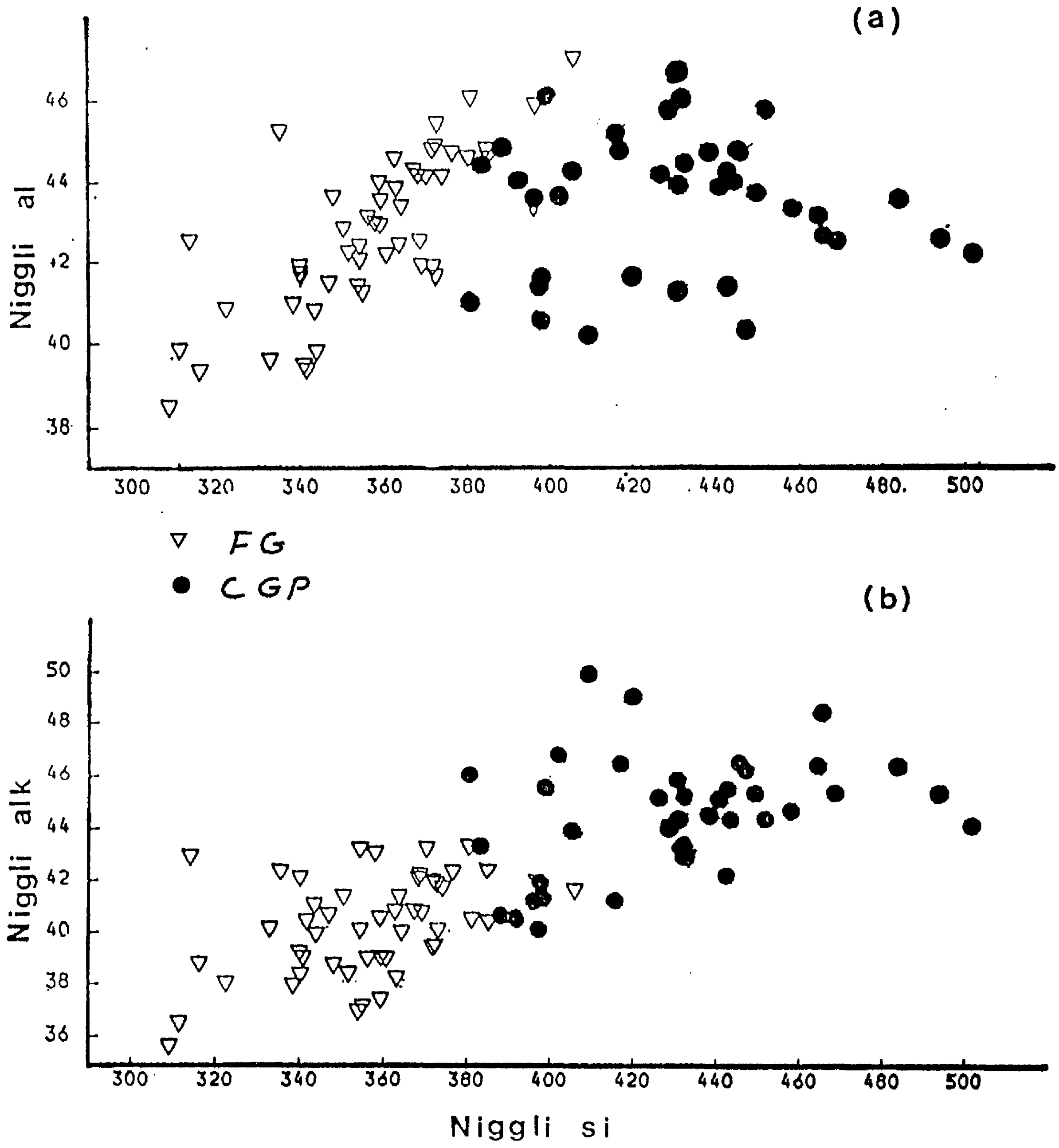


FIGURE 3.13. Niggli Si against alk and al

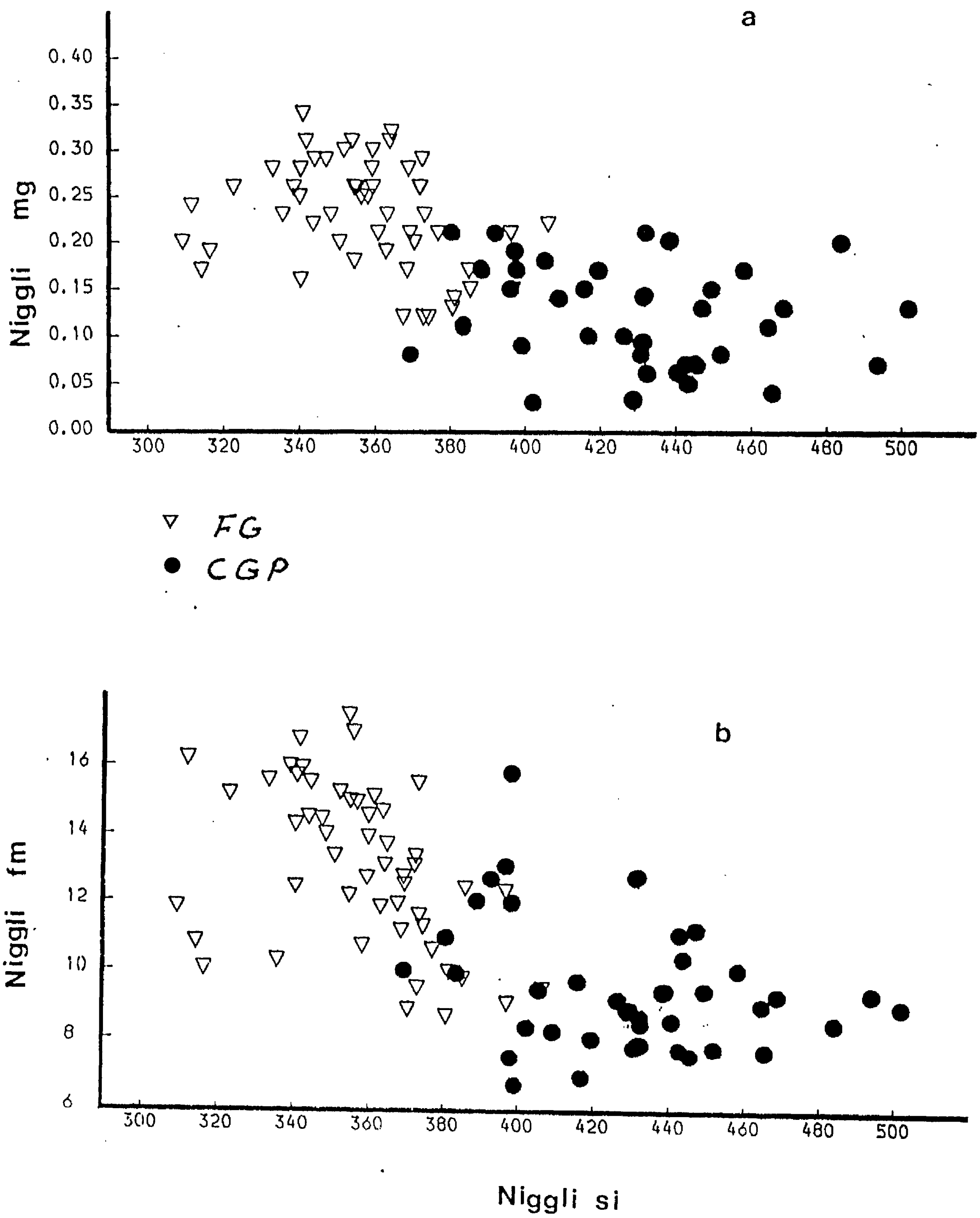


FIGURE 3.14. Niggli Si against fm and mg

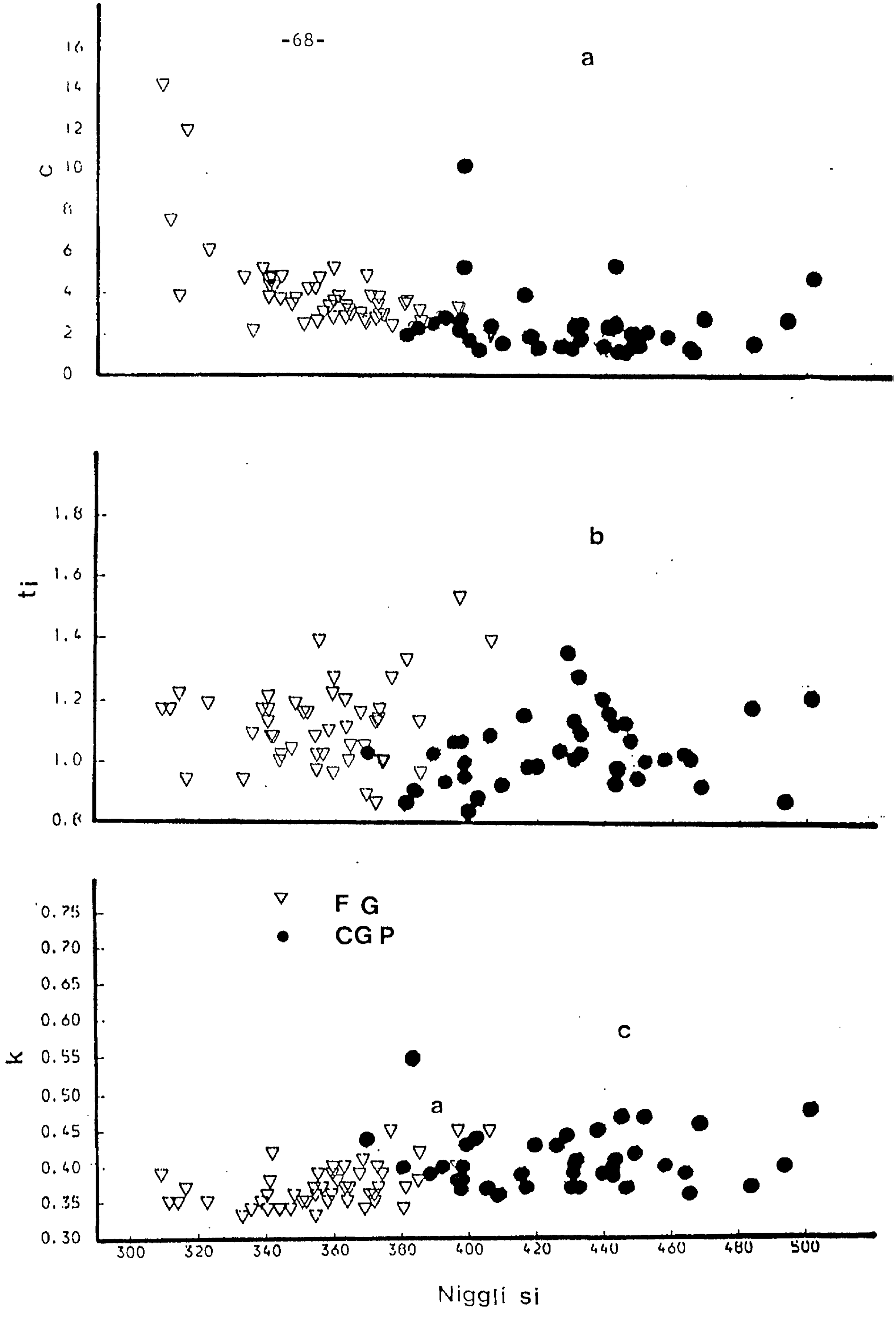


FIGURE 3.15. Niggli si against k, ti and C

dissimilar with the central intrusion - the finer-grained granite type (FG type) having less siliceous minerals and more mafic minerals than the other intrusion - the coarser-grained porphyritic granite type (CGP type). Trace element data which have been used by other workers to establish a possible genetic history of granitic intrusions (Hanson 1978; Atherton and Tarney 1979; Halliday et al. 1980), will be used here to demonstrate the amount of differentiation in the intrusion, by plotting these data against Niggli si and fm values.

Barium (Ba)

Barium decreases from the FG type (average 1400 ppm) to the CGP type (average 900 ppm). Ba^{2+} tends to occupy K^{+} sites and is removed at an early stage of differentiation. Ba^{2+} occupies 8-fold co-ordinated sites and so preferentially enters K^{+} sites in feldspars (particularly K-feldspar).

Rhodes (1969), in his study of the Ba content of 70 granitic rocks from Australia, concluded that the Ba content decreased as the whole rock composition changed from granodiorite to leucocratic granite.

In Figure 3.16, Ba values of the Helmsdale granites are plotted against Niggli si. A negative trend results and although some scattering of points exists, the trend is very clear with analyses from both granite types lying in the same trend line, with the more mafic intrusion, the FG type having the higher Ba values.

Strontium (Sr)

Sr^{2+} ion tends to occupy calcium positions in feldspars although the relationship is not a clearcut one. This may be because the Sr^{2+} ion enters both plagioclase feldspars and K-feldspars. In Figure 3.17a, data from both intrusions tend to show that a negative trend occurs in the Helmsdale granite as a whole, although the plots from

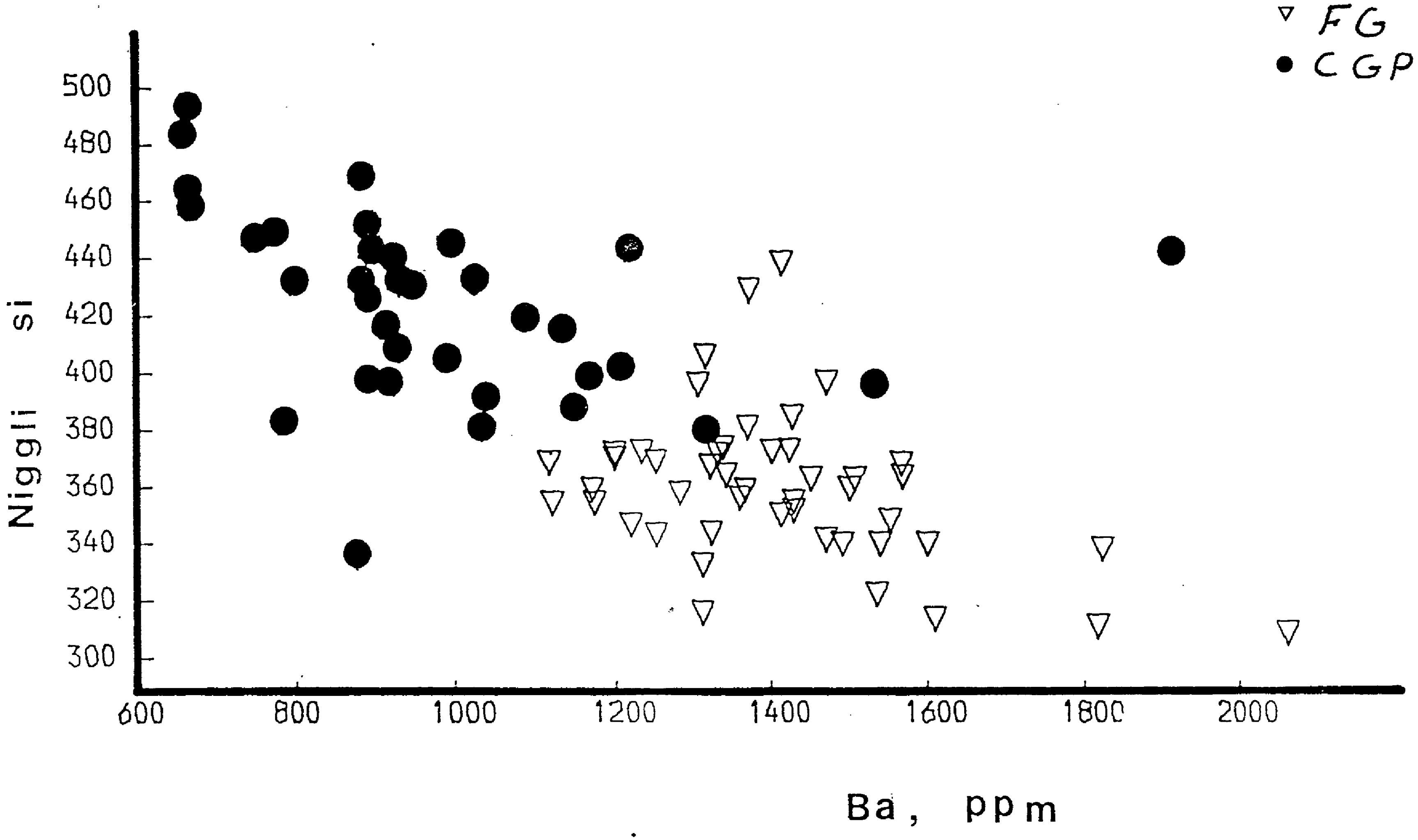


FIGURE 3.16. Ba ppm against Niggli Si.

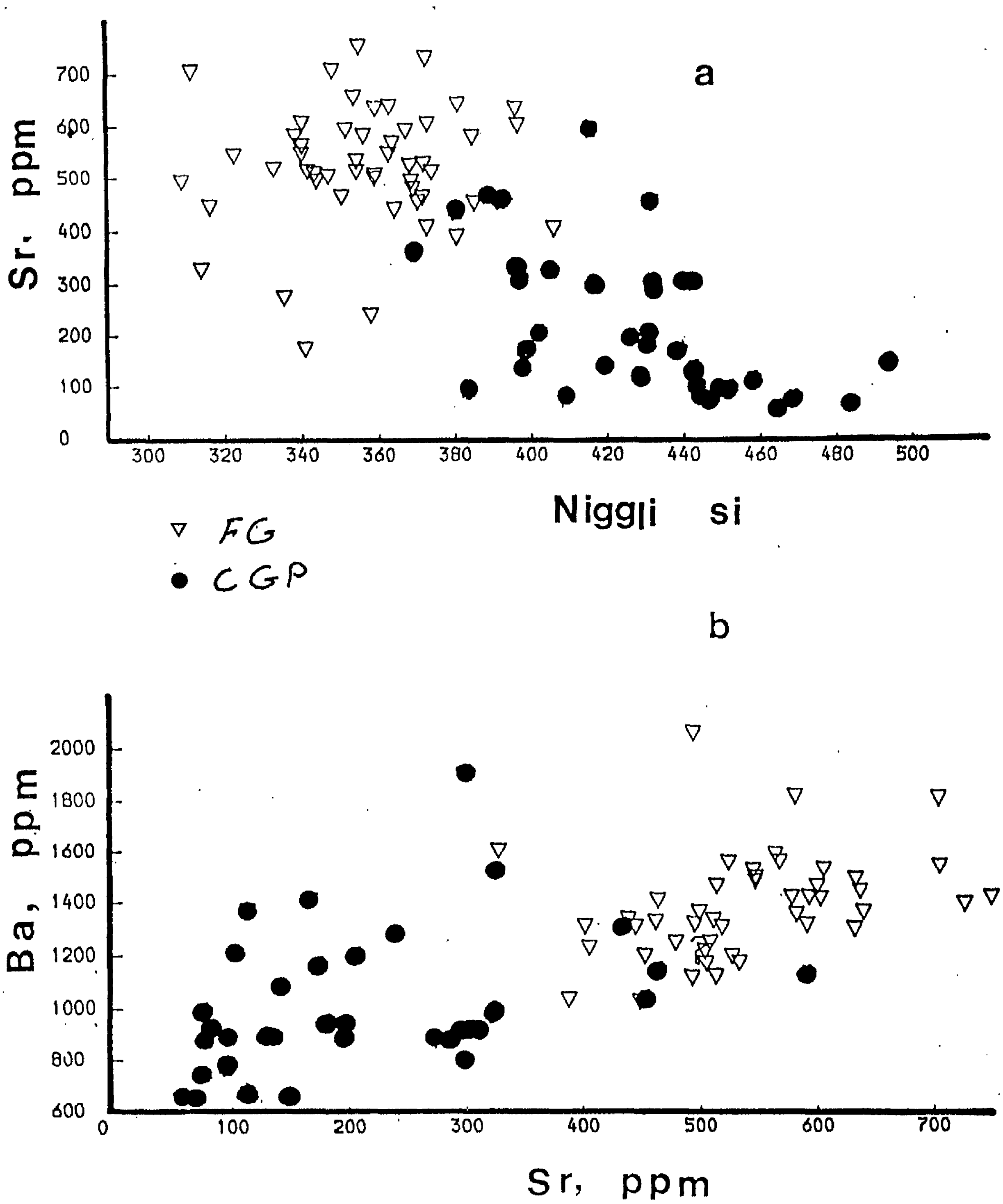


FIGURE 3.17. Sr PPm against Ba ppm and Niggli Si against Sr ppm

each intrusion do not show any clearly defined trend (especially the FG type), and a trend is only revealed when both intrusions are considered together.

The Sr^{2+} ion is larger than Ca^{2+} and during fractionationmagma should become enriched in Sr relative to Ca. However, in an acid magma, such as gives rise to granitic rocks, this pattern is reversed and Figure 3.17a shows this, with Sr decreasing as the rocks become more silica-rich (i.e. as silica increases), with the most acid members of the CGP type having least strontium. The reason for this is that preferentially the Sr will tend to enter the Ca^{2+} position in a plagioclase lattice, and since the FG type contains more plagioclase feldspar, the Sr is removed before the CGP type crystallizes. All the evidence points to a single magma source for the two granite intrusions with the FG granite being an earlier differentiate than the CGP type. The sympathetic behaviour of Ba and Sr is shown in Figure 3.17b.

Rubidium

The analyses show that the Sr/Rb ratio falls from the FG type to the CGP type which might result from a decreasing fractionation of plagioclase in this sequence. Figure 3.18 is a plot of K_2O against Rb, and Figure 3.19 shows the two trend lines plotted in another K-Rb diagram. The trend line suggests an average K/Rb ratio of 228 for the CGP granite and 205 for the FG granite. The K/Rb ratio of 228 for the CGP type of granite fits exactly the trend line for differentiated rocks of the normal calc-alkaline magmas. Since the FG type is richer in biotite, Rb^{+} will preferentially enter the K^{+} positions there, and the FG type will therefore have a lower K/Rb ratio than the more 'acid' granite - the CGP type.

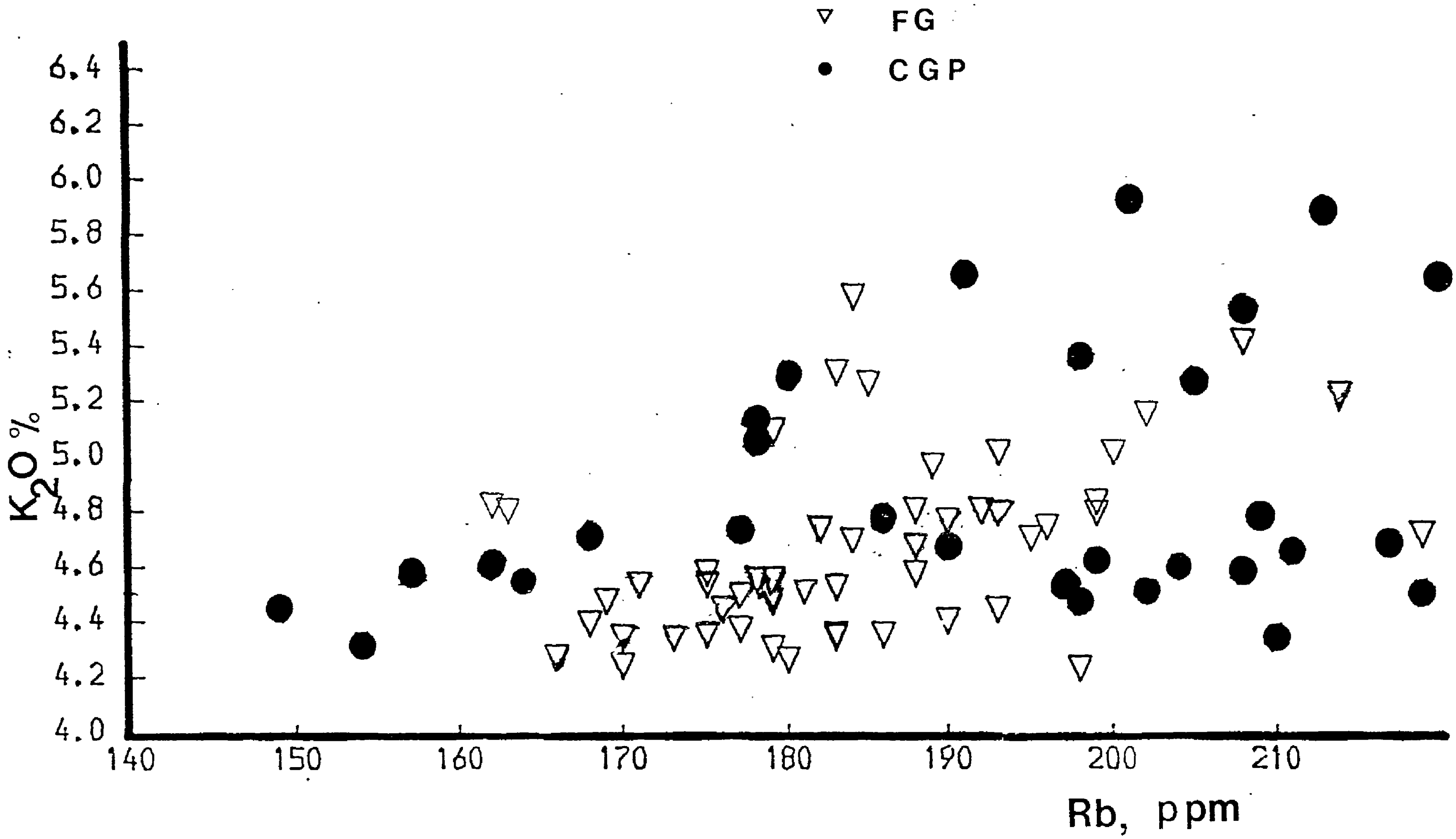
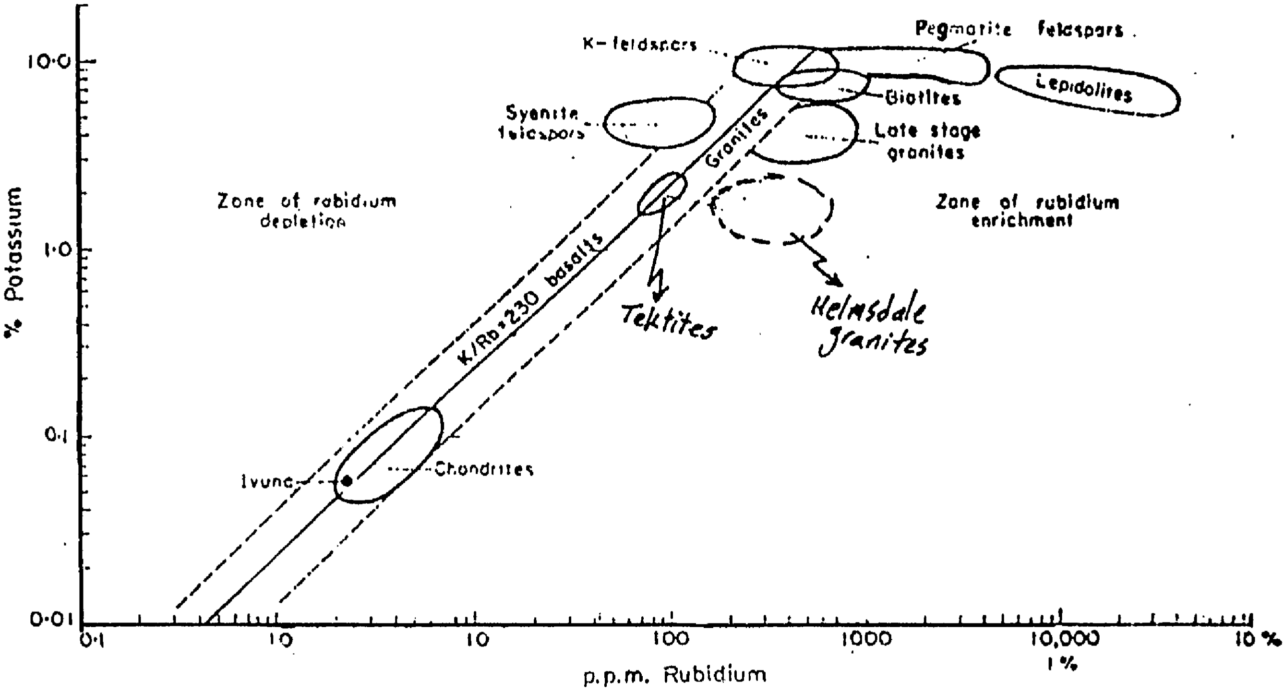


FIGURE 3.18. Rb, ppm against K_2O percentage.



Relationship between potassium and rubidium in chondritic meteorities, tektites and several common crustal rocks and minerals.

FIGURE 3.19. Rb ppm against percent K

Metallic trace elements (zinc, nickel, cobalt, copper and chromium)

As the FG type is the more basic granite with more ferromagnesian minerals present, and therefore more Fe and Mg, trace elements Ni, Co and Zn which are sympathetic with Mg or Fe, or both, should be greater in amount in the FG type which is the case. Figures 3.20a, b and c show Ni, Co and Zn plotted aginst Niggli fm. A good, positive trend can only be identified in the zinc plot since zinc correlates closely with iron unlike Ni and Co which tend to occupy Mg^{2+} sites preferentially. Furthermore, Ni and Co are very low in amount which makes any trend difficult to ascertain. Zinc (Fig.3.20c) occupies the Fe^{2+} sites and will enter biotite which is the common ferromagnesian mineral in the Helmsdale granites. Chromium and copper (Figs 3.21a, b) show no variation with Niggli fm, although there is a greater scatter of copper in the CGP type granite, perhaps due to Cu^{+} ions being disseminated with K-feldspar phenocrysts (trapped within the lattice but not occupying any specific sites), and the amount of copper is therefore related to the amount of K-feldspar phenocrysts in the rock sample.

Zirconium

Zirconium is an element that concentrates in accessory minerals particularly sphene, apatite and zircon. Zr is more or less constant in both granite types with the FG type slightly richer on average (165 ppm in FG type and 155 ppm in CGP type).

Gallium

Ga^{3+} is always sympathetic with Al^{3+}, and correlates with the Al_2O_3 content in rocks; those with most Al_2O_3 having most gallium.

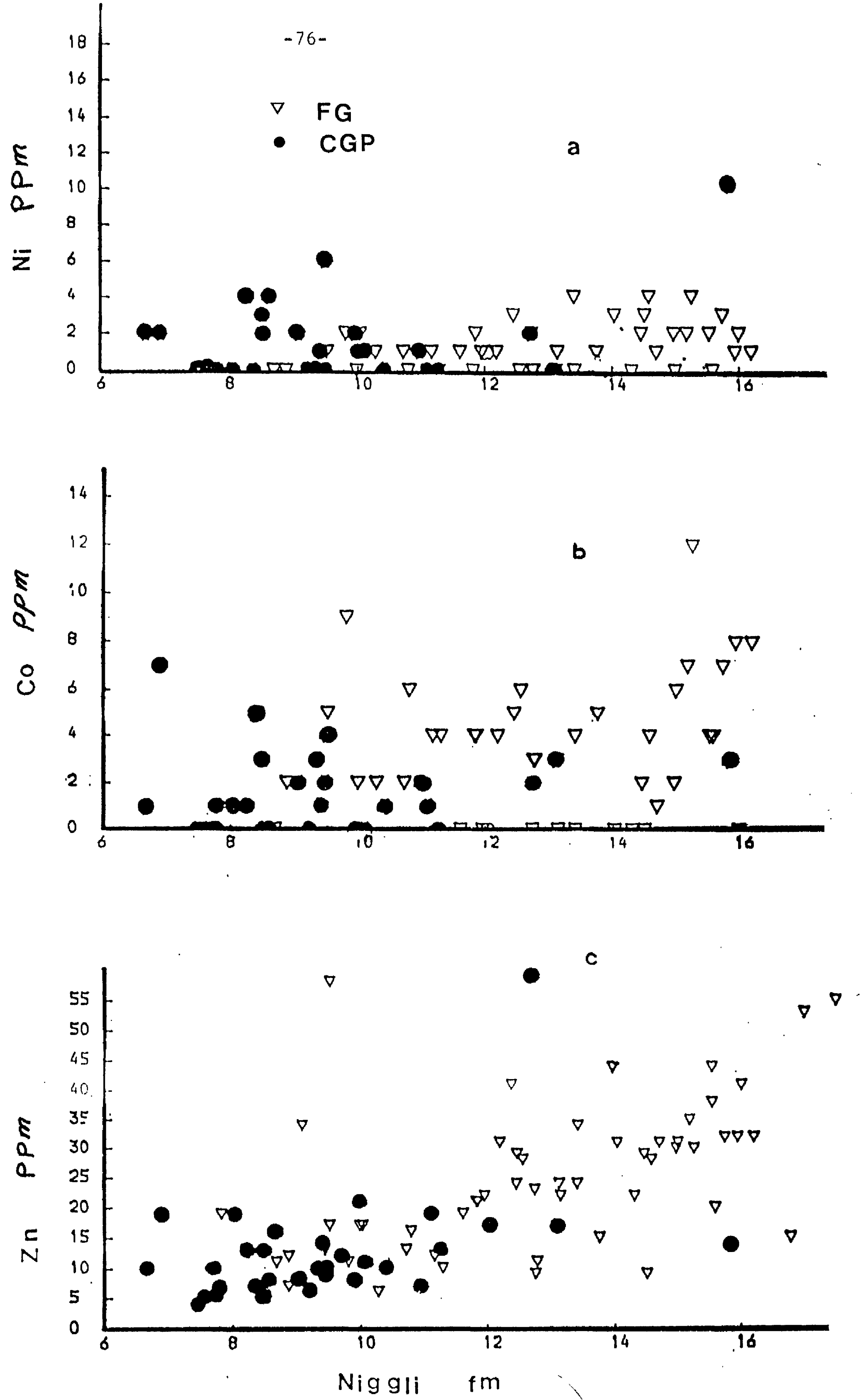


FIGURE 3.20. Niggli fm against Zn, Co, Ni ppm

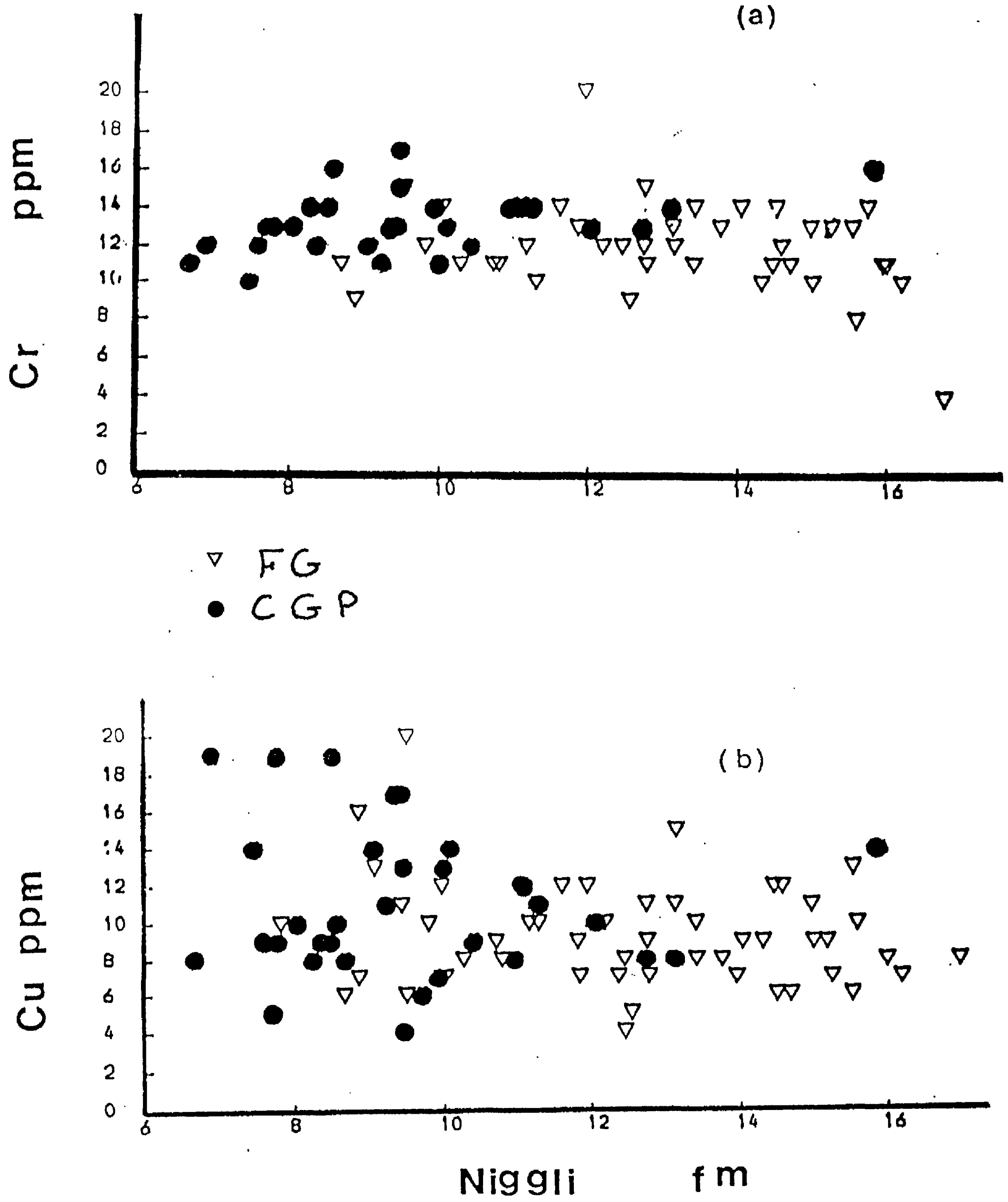


FIGURE 3.21. Niggli fm against Co and Cr ppm

Lead and Thorium

Lead is commonly held in the silicate lattices of feldspar minerals. Both granites have similar amounts of lead (average 40 ppm).

Thorium tends to be concentrated in late stage igneous rocks where it can be correlated with potassium because thorium may be remobilized in acidic conditions (Sinha 1972). The thorium content is rather similar in both granite types (average 25 ppm).

Summary

1). Some major element variation diagrams show dissimilarities between the FG type and CGP type, with the former having less silica and more mafic phases.

2). Alumina shows positive correlation with CaO and Na_2O, with the FG type having more basic plagioclase than the CGP type.

3). The low CaO and high Na_2O contents in plagioclase feldspar obtained throughout the Helmsdale granite samples confirm the feldspar is albite to oligoclase.

4). Alteration effects have tended to increase the K_2O percentage in the FG type (Tweedie 1981), and therefore the analyses cannot be used to identify primary feldspar composition, thus potassium and sodium are of limited use in this study.

5). Another important alkali element which occurs in trace amounts, is rubidium. The plots of Rb against K^+ show that the K/Rb ratio is greater in the CGP type (apart from some points with unexpectedly low Rb) than in the FG type. This variation in K/Rb may be due to the CGP type being a later fractionated product.

6). The FG type is characterized by higher iron, MgO and TiO_2 which are the main constituents of biotite, and Figures 3.7, 3.10 and 3.11 suggest possible biotite fractionation.

7). Graphs involving normative values suggest a closer relationship between the FG type and CGP type as the plotted points occupy a small field of composition. These graphs also suggest that the earlier differentiate (in the FG type) crystallized albite and biotite changing the magma composition towards the later differentiated CGP type.

8). It is clear from many of the plots discussed in this section that the Helmsdale granites should be considered as two intrusions, probably derived from a single magmatic source.

On the basis of O and Sr isotope data, Harmon and Halliday (1980) suggested that the parent magma of those late Caledonian plutons emplaced between 390 and 435my, including the Helmsdale granite, were hybrids derived from the partial melting of mantle-like material containing varying proportions of a crustal component (such as the Lewisian gneiss for these northern Scottish granites).

CHAPTER FOUR

Rock weathering and its influence upon aggregate properties of the Helmsdale granite

4.1. Introduction

Many igneous rocks have solidified at various depths in the Earth's crust at higher temperatures and pressures than exist at the surface. When these rocks are exposed to the atmosphere, under the new lower temperatures and pressures, and in the presence of air and water, they undergo a series of processes called 'weathering'. These processes cause changes in the physical, chemical and mineralogical nature of both the rock material and the rock mass. Rock weathering will continue until the state of stability is achieved once again when rocks are transformed to soil. The rock transformation is, for the most part, complete only at, and very close to, the surface, although in some jointed igneous rocks, such as granite, the weathering agents can penetrate along joints often many metres deep. For example, in parts of Australia depths of 300 metres of weathered granite have been recorded (Beavis 1985) and at up to 1500 metres in the USSR (Razumova and Kheraskor 1963).

Just as the depth of weathering may vary from place to place, patterns of weathering can also be extremely variable even in an apparently homogeneous rock mass. The nature of weathering and depth to which rocks weather are of considerable importance to all aspects of geotechnical engineering and often cause a great deal of damage if they are not fully assessed.

The weathering of granite rocks has been studied for many different natural environments. Goldich (1938) was one of the first geologists to investigate chemical changes occurring during weathering. Subsequent workers who have summarized the main trends of geochemical and mineralogical evolution towards the residual systems of weathering include Butler (1953, 1954),

Richardson and Adams (1963),Harriss and Adams (1966), Helgeson et al. (1969), Loughnan (1969), Rice (1973), Chesworth (1979), Taylor and Fryer (1982) and Baker (1985). In spite of all these publications relatively little has been considered from an engineering point of view. Consequently, in the present study, an attempt has been made to establish the type and pattern of weathering which has occurred in the Helmsdale granite, with particular emphasis on the behaviour of major and trace elements during the weathering and their effects on the engineering properties of the aggregate.

4.2.
Methods of investigation

For the purpose of the weathering study, only those samples from the two quarry faces, namely Helmsdale Quarry and Ousdale Quarry, have been used. Samples of relatively fresh rock and their weathering products were collected in a vertical profile representing the finer-grained type (FG) and coarser-grained porphyritic type (CGP) respectively. In order to ascertain the effects of homogeneity of parent rocks within each FG and CGP type a number of horizontal samples were also taken from the bottom of the quarry faces and were subjected to the same analytical techniques as those from vertical profiles.

A total of 34 samples was chosen for this part of the study of which the freshest, least altered samples were those collected from the bottom of each quarry face, whereas the more altered samples were those collected towards the upper parts of the quarry faces and near the major discontinuities.

Thin sections were made of all 34 samples from both granite types (FG and CGP) of which 6 samples (3 from each quarry face) were chosen for microprobe study. These 6 samples were chosen particularly to be representative and showed the widest observed variation in degree of mineralogical changes caused by both weathering and hydrothermal alteration processes. Rock forming minerals were identified by petrographic observation of all 34 thin sections.

Modal analysis, whole rock chemical analysis and electron microprobe analysis of minerals were performed as described in Chapter 1, the XRD method being used to identify all the primary and secondary minerals, particularly those clay minerals which are normally difficult to identify under the normal microscope.

4.3. Weathering of the Helmsdale granite

The rate of decomposition of rock forming minerals is directly controlled by the differential between physical and chemical conditions at the time of formation of the minerals, and those existing on the surface of the Earth during the weathering process.

In the present study, however, the two main types of weathering (physical and chemical) together with the hydrothermal alteration processes in the Helmsdale granite were investigated as follows.

4.3.1. Physical weathering

Physical weathering involves the breakdown of the rock into smaller pieces without considerable alteration of its minerals, by some mechanical action such as loading and unloading, thermal expansion, freezing and growth of minerals and wetting and drying. Thus, the in situ or residual soil derived from the disintegration process consists of an accumulation of minerals and rock fragments from the virtually unchanged original rock.

The breakdown of rock mass is usually controlled by discontinuities in the mass such as joints and fractures (block disintegration), whereas the mechanical breakdown of the rock material is controlled by micro-discontinuities such as micrafractures, grain boundaries and mineral cleavages (granular disintegration).

Discontinuities in the rock mass possess a number of physical and mechanical characteristics, some of which influence the degree of weathering, and this in turn influences the behaviour of the rock when placed under stress. Some of these characteristics which can be measured, include the number of discontinuities, their location and orientation; their spacing, the nature of the openings, surfaces and infillings and their persistence or continuity. In particular, their spacing is very important since this affects the degree of freedom available for displacements or fluid movements within the mass, allowing weathering action to progress downwards or inwards from the ground surface or top of the quarry face. In other words, the nearer the rock is to the ground surface or top of the quarry face, the more it will be weathered.

The joint survey of the Helmsdale granite was carried out and the results were logged systematically and can be seen in Table 4.1. According to this survey both types of granite were found to have medium to widely spaced joints (less than 1.2m). At least four main joint sets were identified in each of the two granite types using the stereographic projection and density contour peaks technique and rose diagram (Fig. 4.2). The results are shown in the orientation diagram (Fig. 4.1) where the diameters show the strikes of the joint sets, with the amount of dipping and dip direction also given.

TABLE 4.1. Joint set data; strike measurements are in degrees magnetic

A Joint set

- a) Widely spaced 1m+
- b) Open joint (narrow, between 6 to 20mm width), no water flow
- c) 350° to 010°/vertical

B Joint set

- a) Widely spaced 1.2m (in the FG type becomes medium spaced 600mm.
- b) Close joints, those joints which are not vertical/ have rather smooth surface.
- c) 050° to 090°/vertical but variable (always more than 60° SE)

C Joint set

- a) Medium spaced
- b) Close joints, smooth surface
- c) 120° to 140°/vertical but variable

C Joint set

- a) Medium spaced in FG, widely spaced in CGP type
- b) Narrow joints; filled with broken pieces and soil
- c) 020° to 040°/sub horizontal dipping maximum 20° NW

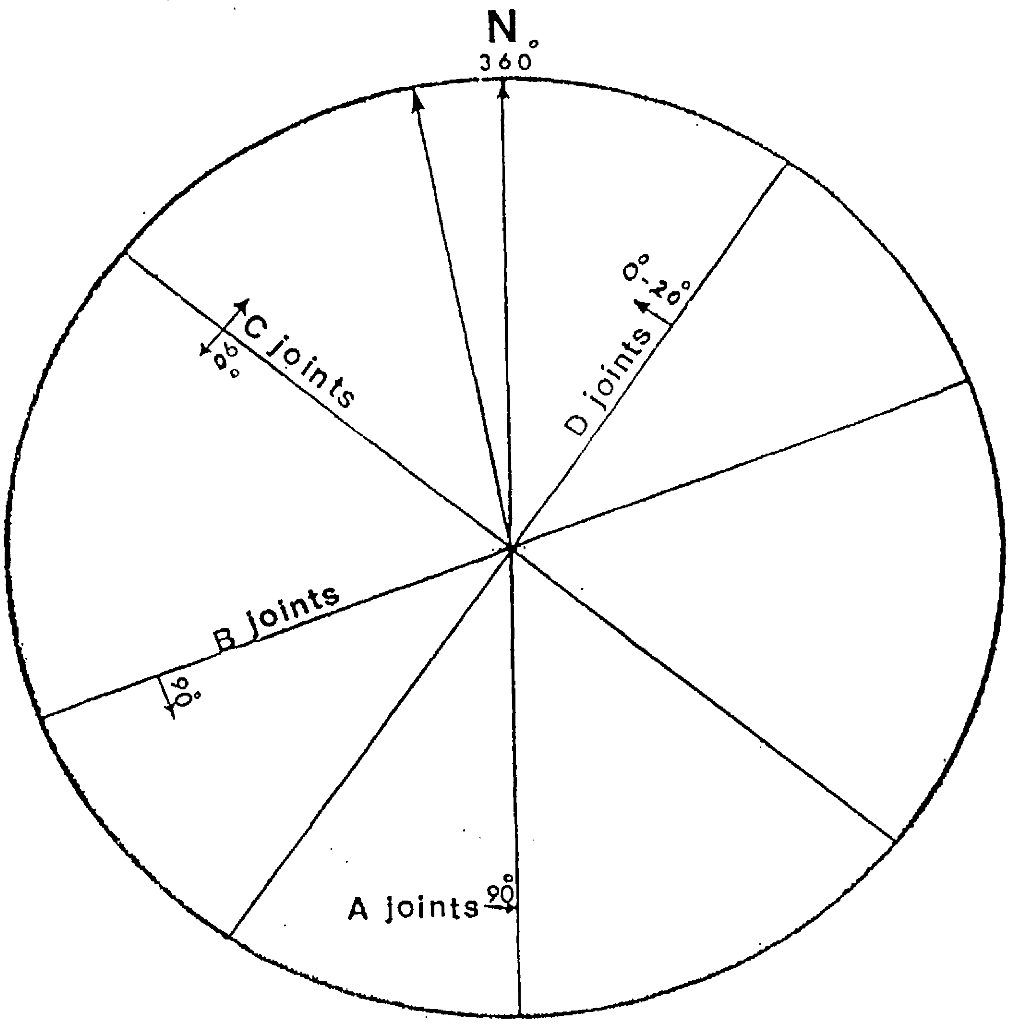


FIGURE 4.1. An orientation diagram showing the strike directions and dips of the four major joint sets.

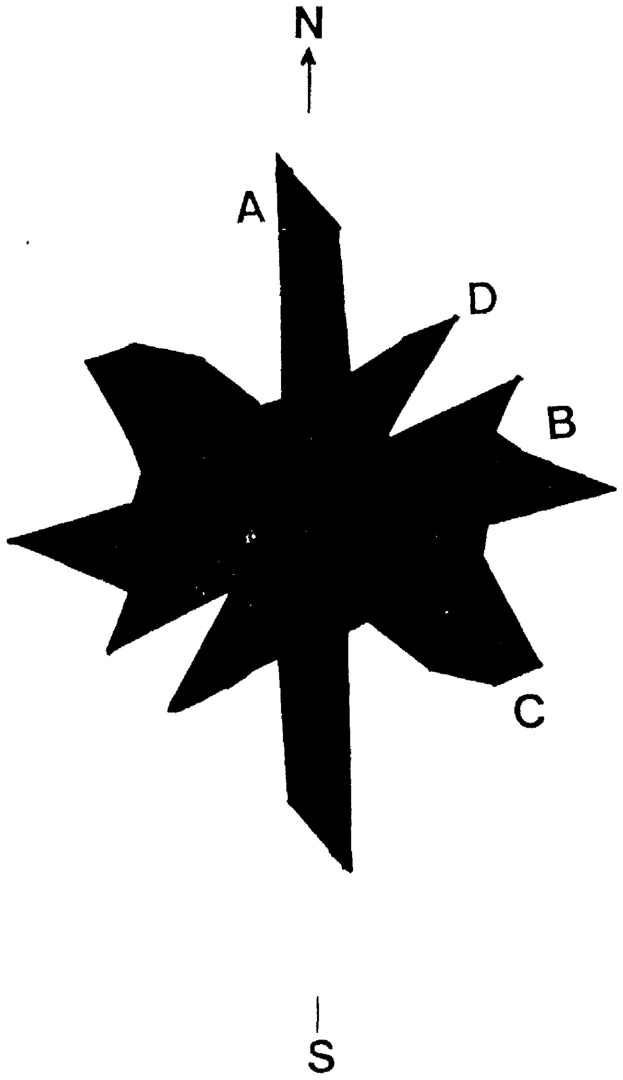


FIGURE 4.2. Rose diagram, showing the strikes of four joint sets for the Helmsdale granites.

Figures 4.1 and 4.2 also show that in general the joint sets (in both granites) are scattered in different directions and are normally vertical or within $30^{o} \pm$ of it, except the D-joint set which is a sub-horizontal type or slightly dipping towards a NW direction.

The A joint set normally occurs in sets of parallel joints about 1m apart, and are open (between 6 to 20mm) having rough joint surfaces and are commonly observed at the quarry faces as vertical long joints. The B and C joint sets are both close and vertical, or nearly vertical joints which are seen at the quarry faces striking 070 and 130 respectively, the latter being perpendicular to the Helmsdale Fault. The D joints are the sub-horizontal joints (floor or sheet joints) and are narrow, commonly filled with residual and broken pieces of rock. They normally occur as mediumly spaced joints, although in the FG type (Helmsdale Quarry face) some closely spaced ones were observed.

Careful observation of many joints (B and C sets in particular) reveals a small displacement (of only a few cm) with the development of smooth joint surfaces.

At various stages of its history, joints in the Helmsdale granite have been exploited by hydrothermal fluids from which minerals have crystallized to form a variety of mineral veins, some of which are narrow.

Other types of discontinuities commonly observed in the Helmsdale granite (in both FG and CGP types) are fractures, but their intensity is not constant over the length of the quarry faces. Both the intensity and openness of the fractures tend to increase towards the upper part of the quarry faces which may suggest that the granites were subjected to an intense degree of physical weathering (such as freezing and thawing) after their formation. The surfaces of the fractures like those of the joints exhibit slight discolouration due to the penetration of subsequent chemical weathering agents, the effects of which gradually decrease from the fracture surfaces inwards. The depth of chemical penetration, in general, is slightly higher in the CGP type compared to the FG type which may well be due to the coarser-grained porphyritic texture, and also a rather weak mineral boundary condition existing only in the CGP type;and the lack of such features in the FG type makes it less prone to the penetration of the weathering agents along the fracture surface.

Microfracture in rock materials also plays an important part upon the extent of both physical and chemical weathering. Microfracture analysis of the samples in the present study was also carried out, applying the standard point counting technique (Chayes 1956), using a petrological microscope and a Swift Automatic Point Counter machine. Microfractures, including microcracks and voids have been quantified by counting the number of microfractures along a line of traverse of 10mm long and a spacing of 0.5mm between each traverse line until all the microfractures within a total area of 100mm^2 were counted on each thin section. Then the microfracture indices (FI) for all thin sections were calculated as the number of fractures per 10mm length (based on the procedure explained by Irfan & Dearman 1978). Results of the determination of microfracture indices of all samples from the two quarry faces are given in Table 4.2.

Height from bottom of the Quarry	FI (FG) Helmsdale Quarry	FI (CGP) Ousdale Quarry
1	0.8	0.6
2	0.9	0.6
3	1.5	0.9
4	1.0	0.6
5	0.9	0.4
6	1.0	0.4
7	1.2	1.0
8	1.1	0.8
9	1.1	0.9
10	1.3	0.12
11	2.0	1.4
12	2.5	1.7
13	2.7	2.1
14	2.9	
15	2.9	

TABLE 4.2. Microfracture indices for Helmsdale granite from two quarry faces.

No attempt was made to differentiate between microfractures according to their type and amount of infilling materials, since most of the microfractures in the present study are either iron-stained or filled with some weathering products. But attention has been paid to the thin section making procedure, since some of the open microcracks and open grain boundaries observed in thin sections are caused by high speed diamond cutting. Therefore, the cutting process was carried out under minimum force and lower speed.

4.3.2. Origin of discontinuities

Discontinuities including joints, fractures and microfractures represent failure of rock mass or rock materials under conditions of stress. Such applied stress can have a number of origins, some of which can be identified in the field by simple field observation techniques (Fookes et al. 1971; Attwell and Farmer 1976; Hawkes 1982 and Heath 1985). The study of the Helmsdale granites, however, revealed that the major cause of fracture formation in this area was partly stress originated as a result of post-crystallization cooling stress of the granites. Relief of such stress following erosion of the overlying rocks could be responsible for the formation of the sub-horizontal joints (the D joint sets) in the Helmsdale granites (see Fig. 4.1). This type of discontinuity, referred to by some workers as "floor or sheet joints" (Heath 1985), are usually tight below the weathering zone, but here due to excavation or erosional unloading they tend to be open, and sometimes infilled with material produced during weathering processes. This process, however, continues up through the weathering zone, reaching to its maximum width at the surface as was shown by the D joint sets in the case of the Helmsdale granites, and also by those sub-horizontal joints in the study of Carnmenellis granite in Cornwall (Heath 1985).

The possible source for the second group of joint sets in the Helmsdale granites appears to be tectonic, related to later activity along the Helmsdale Fault at various times since the emplacement and cooling of the granites (Gallagher et al. 1971; Tweedie 1981). The build-up of tension as a result of such activity appears to have had some control over the orientation of the second group of joint sets (the B and C joint sets) in the Helmsdale granites, particularly in the FG type and along the Helmsdale Fault.

These joint sets (B and C) are both vertical or nearly vertical (more than 60^o).

The third group of joints in the Helmsdale granite is the A joint set which probably resulted from the pressure produced by the confinement of aqueous fluids which were found to be responsible for a small area of crystallization zone near the Helmsdale Fault. Heath (1985) in the fracture study of the Carnmenelis granite in Cornwall has demonstrated that the existence of this type of joint is often accompanied by brecciation as he found fragments of broken granite in a tourmaline vein filled joint system. Although such association of brecciated country rocks within mineralized veins have not yet been reported for the Helmsdale granite, Tweedie (1979) reported the existence of a zone of chalcopyrite, molybdenite, pyrite and quartz, occurring as narrow veins and joint coating in an outcrop of brecciated finer-grained granite (central granite phase) in the valley of the Ord Burn (see Fig. 2.1 for location). The A joint sets commonly occur as vertical and open joints (between 6 to 20mm wide) with a rather rough surface.

4.3.3. Chemical weathering (decomposition)

This is generally a destructive process which weakens the rock due to change of the mineral composition into new compounds by the action of chemical agents such as acid in the air, in rain and in river water. However the decomposition process can sometimes strengthen the rock substances rather than weaken them due to silicification and calcification.

Chemical weathering affects almost all minerals and only a few, among them quartz, may remain unaffected. The greater the percentage of weatherable minerals, particularly the ferromagnesian minerals, in the original rock the more advanced are the chemical changes. The chemical processes involved in decomposition are; oxidation, reduction, hydration, hydrolysis, carbonation, solution and leaching.

The great majority of igneous rocks in Britain are weathered to some extent, including the Helmsdale granite and other granitic rocks on the east coast of Scotland (i.e. Peterhead and Strichen; see Fitzpatrick 1963).

At the north of the Helmsdale river (Allt Cille, see Fig.2.1), the presence of deeply weathered rock of the CGP type (at least 35 metres deep) has been reported by the Institute of Geological Sciences (Gallagher et al. 1971). Based on this report and further study by Tweedie (1979), it has been demonstrated that the Helmsdale granite was unroofed for the last time during the Tertiary period, allowing the formation of deeply weathered mantle to cover the Helmsdale granite. But as a result of Pleistocene ice advances, most of the existing residual soil and weathered rocks had been removed, leaving behind fairly fresh rocks generally containing only slightly weathered to partly stained rock. If this is true then the presence of deeply weathered rock in the north east of Scotland, including that in some parts of the Helmsdale granite, must be regarded as a result of weathering processes of pre-glacial age as was suggested by Fitzpatrick (1961). Moore (1979) also concluded a pre-glacial age for weathering of the Peterhead granite, based on the existence of fragments of weathered granite in the overlying boulder clay.

It is also true that the Helmsdale granites have been subjected to hydrothermal alteration some time before weathering took place, since a high concentration of U, associated with deep weathering of the granites, was demonstrated by Tweedie (1979) as the result of subsequent weathering and redistribution of U in deeply weathered material. (see alteration section following).

4.3.4. Hydrothermal alteration of the Helmsdale granites

For engineering purposes, chemical decomposition can be divided into two processes described by the following terms:

a) Chemical weathering, which is decomposition caused by surface agencies such as air and water,

and

b) Chemical alteration, which is decomposition caused by water and gases of plutonic or volcanic origin - known as hydrothermal agencies.

The resulting substances of chemical alteration are called "alteration products" which can be distinguished from chemical "weathering products" on the basis of the extent, distribution and type of material resulting from each process. Weathering products are generally found within 100 metres of the ground surface (except for some rare conditions in which the weathered material could be found at much greater depths), the effects dying out with depth. In the case of alteration products however, these can be encountered at any depth below the surface and also differ in type of mineralogical change.

Simpson et al. (1976, 1979) in their study of several Caledonian granites from northern Scotland reported that the Helmsdale granites have an anomalously high uranium content (between 1-18 PPm) compared to other granites (between 2-8PPm). This enrichment of uranium is believed to be the result of a general weak, low to medium temperature (in the range of 100-400^{o}C) hydrothermal event. But in some areas, mainly within the finer-grained type (FG) where the alteration is intense, the uranium content increases to up to 70PPm (see Fig. 4.3). This latest local high concentration of U is probably due to redistribution of uranium by secondary action such as weathering processes. This point however, would suggest that the main hydrothermal event must have taken place sometime before the weathering processes started, and before the unroofing of the intrusion in Lower Devonian times (Tweedie 1979).

The source of hydrothermal fluids responsible for the alteration of the Helmsdale granite is not yet quite clear. Based on a study of similar alteration processes by Sheppard (1977), it was suggested by Tweedie (1979, 1981) that the hydrothermal fluids were derived from water circulating at various times in fractures and faults related to tension and movement on the Helmsdale Fault, which set up a convection system driven by a heat source at depth in the intrusion. There are two ways in which such heat necessary to generate the convection system could be produced: a) a hot interior of the presently exposed finer-grained granite type (FG), and b) as the result of a later intrusion phase as suggested by G.C. Brown, based on aeromagnetic evidence and further supported by Watson and Plant (1979) who suggested that a younger intrusion may be present at depth, beneath the Helmsdale granite which could have supplied heat, uranium or other mineralization. This idea is also supported by a similar conclusion based on the study of hydrothermal alteration events by Gavrilan and co-workers (1967).

The chemical and mineralogical changes due to hydrothermal alteration in the Helmsdale granite were studied in the present work.

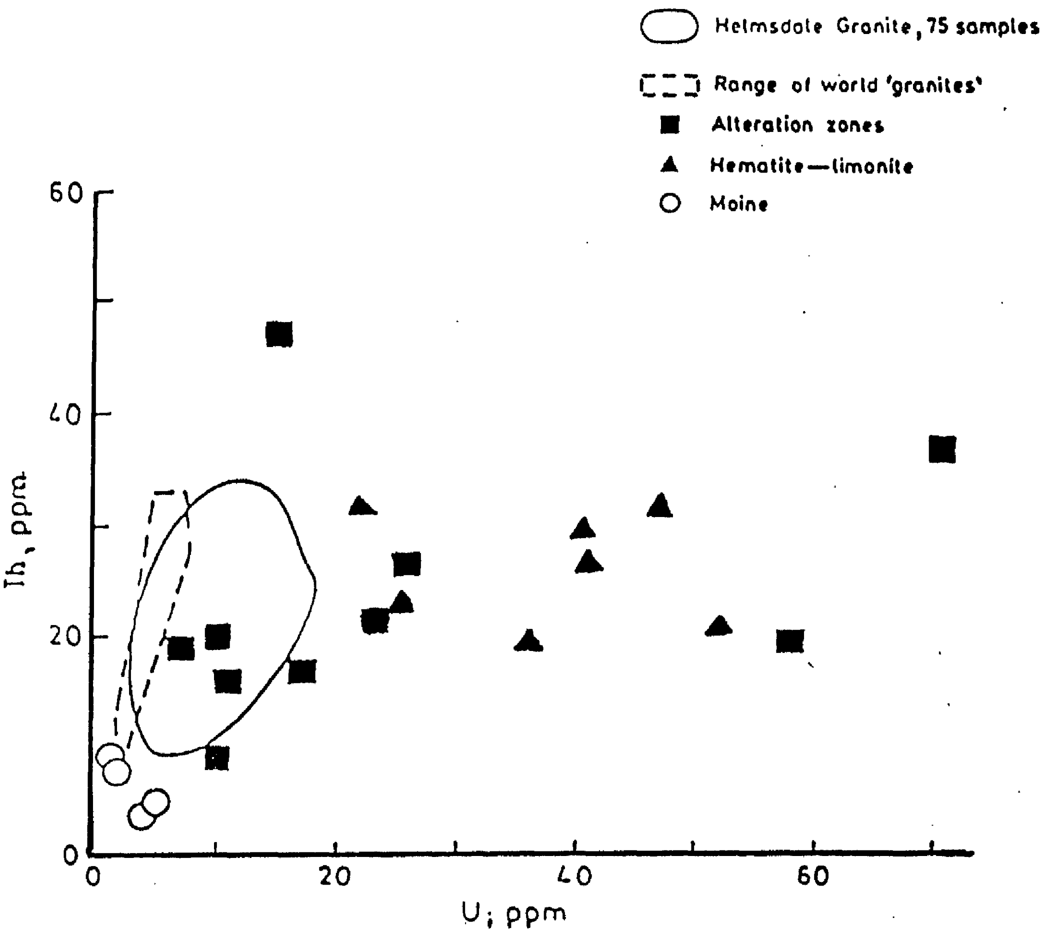


FIGURE 4.3. Th vs U for whole-rock samples from Helmsdale Granite and adjacent Moine granulite showing two main U anomaly types (after Tweedie 1979).

During the sampling collection from Ousdale Quarry, which is a coarser-grained porphyritic type, a zone of highly altered granite, about 5 metres wide, was observed on the left-hand side of the quarry. Two samples (58 and 59) were selected for analysis from this hydrothermally altered zone together with more samples from the adjacent, apparently unaltered granite, of which two - one from each side of the altered zone (57 and 60) - were also analysed for reference. Thin section study of the samples 58 and 59 (altered once) has revealed intense alteration, with complete sericitization of plagioclase and complete transformation of biotite to muscovite and release of iron-oxide as a result of alteration processes. K-feldspar also appears to be affected and shows cloudiness under the microscope, particularly along the cleavage. Although quartz is not affected by alteration, its size has been reduced to small rounded crystals.

Four whole rock major, and trace element analyses of the samples for potassic alteration zone are presented in Table 4.3. The analyses of the two sericitized samples show a gain in K, total Fe, Mg, Al and water, accompanied by loss of Si, and Na, while other elements remain more or less constant. The increase of K_2O and F (fluorine) up to 3 times in the zone of intense petassic alteration has also been reported by several works as the result of a hydrothermal event (Gallagher et al. 1971; Tweedie 1979, 1981). The high potash values in the zones of intense alteration reflect the amount of sericitic alteration in these zones. The effect of sericitization on the alkaline elements is best shown by the "igneous spectrum" of Hughes (1972), where the altered samples are displaced out of the normal range of granite values into the K-enrichment field (Fig.4.4, Plot a). The effects of sericitization on the position of the samples in the

TABLE 4.3.

	57	58	59	60
SIO2	74.37	73.65	72.10	74.46
TIO2	0.23	0.27	0.26	0.22
AL2O3	12.50	13.26	13.32	12.77
FE2O3	1.49	1.84	2.46	1.52
FEO	0.08	0.12	0.12	0.04
MNO	0.03	0.03	0.03	0.03
MGO	0.16	0.57	0.57	0.07
CAO	0.21	0.20	0.40	0.32
NA2O	5.08	1.58	1.49	4.03
K2O	5.92	7.54	9.24	5.36
P2O5	0.11	0.12	0.12	0.10
H2O	0.52	1.38	0.58	0.32
CO2	0.00	0.00	0.00	0.10
TOTAL	100.70	100.56	100.69	99.34
AL'	41.57	46.78	42.62	45.68
FM'	8.05	13.97	15.21	7.78
C'	1.27	1.28	2.33	2.08
ALK'	49.11	37.96	39.84	44.46
SI'	419.70	440.88	391.45	451.91
K'	0.43	0.76	0.80	0.47
TI'	0.98	1.22	1.06	1.00
MG'	0.17	0.36	0.30	0.08
W'	0.94	0.93	0.95	0.97
AB	31.33	13.37	12.60	34.09
OR	34.99	44.56	54.61	31.68
Q	26.84	34.66	26.70	30.27
AN	0.00	0.21	1.20	0.30
AP	0.26	0.28	0.28	0.23
IL	0.17	0.25	0.25	0.08
AC	4.31	0.00	0.00	0.00
MT	0.00	0.00	0.00	0.00
HM	0.00	1.34	2.46	1.52
HYEN	0.40	1.42	1.42	0.17
HYFS	0.00	0.00	0.00	0.00
TOTAL	98.30	96.59	99.52	98.34
BA	1086.00	963.00	1068.00	889.00
SR	142.00	185.00	269.00	98.00
RB	201.00	467.00	461.00	198.00
ZR	151.00	162.00	161.00	153.00
CE	52.00	66.00	73.00	60.00
LA	23.00	38.00	48.00	32.00
PB	8.00	26.00	40.00	22.00
TH	25.00	27.00	29.00	24.00
GA	24.00	25.00	25.00	17.00
NB	19.00	17.00	18.00	20.00
CR	13.00	17.00	13.00	13.00
CU	10.00	12.00	8.00	19.00
ZN	19.00	34.00	23.00	6.00
CO	1.00	8.00	0.00	0.00
NI	0.00	8.00	11.00	0.00
Y	3.00	8.00	8.00	3.00

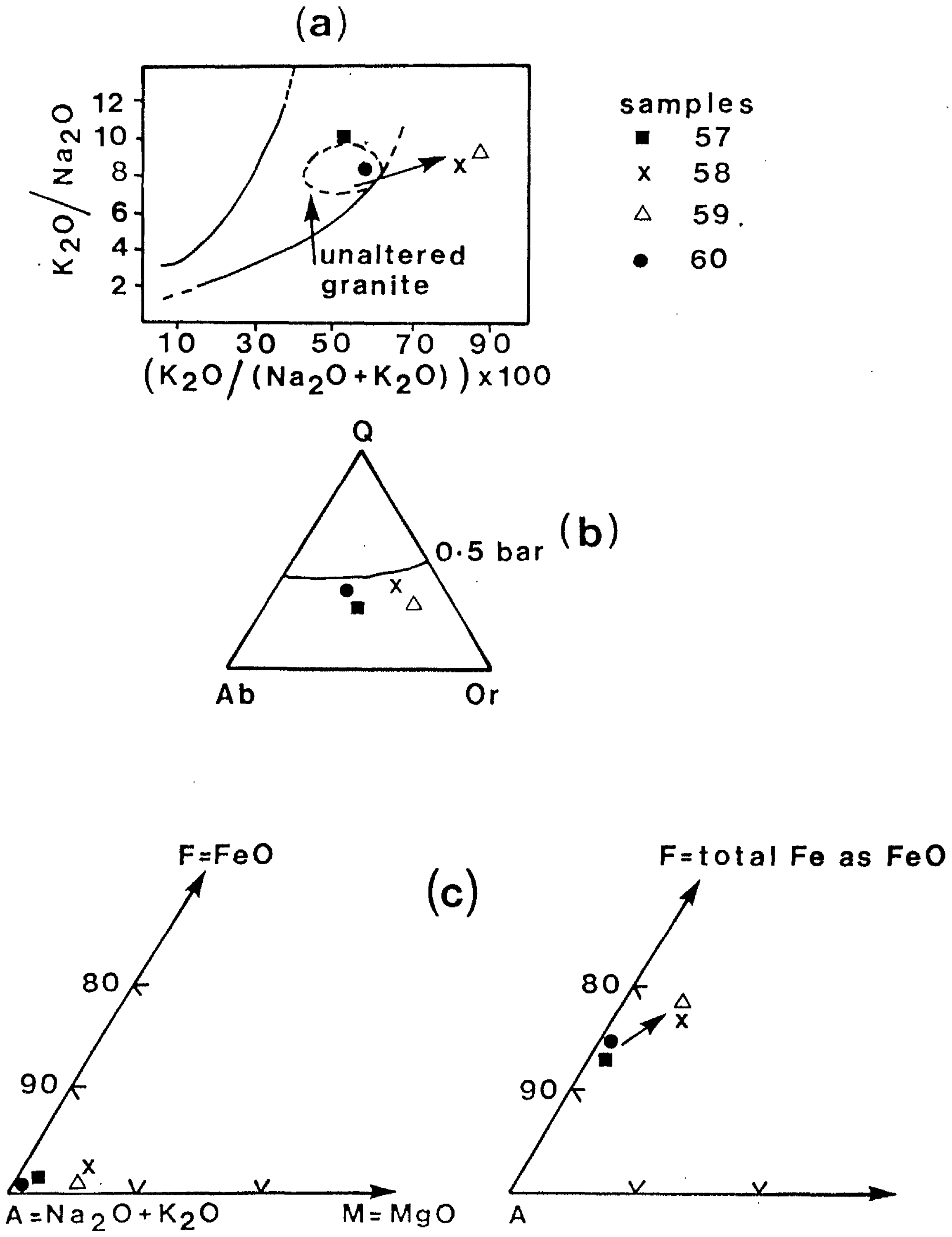


FIGURE 4.4. $K_2O + Na_2O$ percent against $K_2O/(Na_2O + K_2O$ x 100 silica, plagioclase, orthoclase projection and AFM projection.

Q-Ab-Or diagram of Tuttle and Bowen (1958) are equally pronounced (Fig. 4.4, Plot b) displacing the altered samples to Q-Or join due to an increase of K and reduction of Na and Ca contents as a result of the alteration of plagioclase and biotite to K-mica. Furthermore, in an AFM plot (Fig. 4.4, Plot C) the altered samples are slightly displaced towards the MgO corner if measured FeO is used, but if the total iron is used as FeO the increase of Fe_2O_3 content (limonite and hematite) of altered samples, as a result of oxidation of Fe^{2+} to Fe^{3+} in the biotite, drives the altered samples towards the F corner.

4.3.5. Petrography of the weathered granites

Based on visual assessment of the quarry faces combined with a close examination of handspecimens obtained from them, it appears that the Helmsdale graniteshave been affected by weathering processes in the following sequence:

1). Formation of discontinuities such as joints and fractures as a result of physical weathering.

2). Opening of discontinuities and breakdown of rock mass (block disintegration) as a result of alternative actions of freezing and thawing. Steps 1 and 2 become more advanced towards the upper part of the quarry faces.

3). Discolouration of discontinuity surfaces from brown to pale brown (the FG type) and reddish brown (the CGP type) as a result of chemical alteration processes, and penetration of discolouration into the rock accompanied by partial decomposition of some minerals (i.e. biotite and feldspar) to their secondary mineral products (dominated by illite and small amounts of kaolinite.

4). Increase in the amount of discolouration and decomposition of some minerals to clay minerals (dominated by kaolinite), accompanied by a small increase in the percentage of microfractures.

Thin section description

Thin sections were used to characterize optically the composition of the parent rocks and their secondary products together with different stages of mineral breakdown. The relatively fresh samples from the lower part of the quarry faces (samples 37 and 54) showed that assemblages of primary and secondary minerals were as follows: K-feldspar (orthoclase and occasionally microcline perthite), plagioclase (albite and lower oligoclase), quartz, biotite and hornblende (this mineral was observed mainly in the FG type), plus muscovite and chlorite as secondary minerals. Although the mineral constituents examined in handspecimens showed no sign of alteration, under the microscope, feldspars showed cloudiness due to numerous small inclusions of secondary minerals (muscovite flakes) as a result of hydrothermal alteration - "sericitization".

The "sericitization" process is characterized in the Helmsdale granite by the partial breakdown of both types of feldspar to muscovite (or its finer-grained form "sericite"). Practically all plagioclase feldspar grains in samples from both granite types are altered and the altered minerals usually have very irregular outlines. In contrast to plagioclase feldspar, K-feldspar appears to be less affected by "sericitization". The volume of any particular K-feldspar crystal altered to secondary muscovite (usually found along the fracture) is very small at less than 10%, compared to plagioclase which is usually more than 20% in the same thin section. During this early stage of alteration biotite crystals also appeared to have been altered to secondary chlorite. Optical examination of thin sections shows clearly that alteration begins around the margin and along the cleavage planes of biotite and gradually proceeds inwards, resulting in the formation of a green chlorite. The The proportion of biotite that is altered varies from less than 5% to over 90%.

Quartz is fresh and unaffected by alteration in samples from the lower part of the quarry faces. There are, however, a few short and tight intergranular microcracks mainly confined within the quartz crystals. Plates 4.1 and 4.2 show samples representative of this early stage of alteration.

The next stage of alteration can be recognised among the samples taken from the middle part of the quarry faces (samples 31, 49) which show further development of fractures, characterized by the appearance of longer, transgranular and stained microcracks on some minerals such as plagioclase feldspar and quartz grains (Plate 4.3). Plagioclase feldspar appears to be more cloudy and more sericitized as the rock becomes more weathered. Alteration of plagioclase feldspar is mainly confined along the central part of the minerals and the cleavage and twinning planes. Sometimes small opaque areas are formed in some plagioclase (samples from the FG type in particular) as a result of extreme alteration and intense iron oxide staining. Most plagioclase grain boundaries, especially those between plagioclase feldspar and quartz in samples from the CGP type granite, are fractured by tight to slightly open but stained grain boundary type cracks.

PLATES 4.1., 4.2.

Photomicrographs of relatively fresh granite showing cloudy and slightly sericitized plagioclase (Pl), cloudy but fresh K-feldspar (K-fel), large quartz with no cracks, and partially chloritized biotite. Grain boundaries are tight. Microcracks are few, intergranular and mainly in plagioclase and quartz. Plate 4.1. is from Helmsdale Quarry (FG type) and Plate 4.2. is from Ousdale Quarry (CGP type).


Bi
Q
K fel

Biotite also appears to be more weathered. Pleochroism of the biotite is lost to some degree, and marked colour changes from dark-brown to golden-yellow are very common. At the same time the decomposition of biotite was found to be accompanied by iron seggregation along cleavage planes and sometimes by loss of iron, preceded by the oxidation of ferrous to ferric oxides and loss of magnesium, potassium, sodium and a gain in water (see also Mineral Chemistry section). K-feldspar, now more weathered, appeared to be more cloudy (up to 25%) and some of them had developed microcracks. Quartz still showed no sign of alteration, but had developed more microcracks.

The final stage of weathering process was observed in samples from the upper part of the two quarry faces (samples nos. 27, 44). This stage is characterized by a high proportion of microcracks which vary in shape from a simple to branched transgranular type. Tight microcracks are normally iron-stained but iron-oxide has been removed from the open cracks which are now filled with secondary minerals formed during weathering. Alteration of biotite which started from the rims and cleavage planes long before this stage is now complete, covering all of the biotite crystals. This process is commonly followed by the liberation of iron-oxides, particularly among the samples from the Helmsdale Quarry granite (FG type). Although some of the released iron-oxides fill the microcracks and grain boundary cracks, most of them appear to form euhedral grains (magnetite) which are normally associated with the altered biotite and other mafic minerals. This phenomenon is particularly much more common in the FG type than in the CGP type of granite due to the existence of more mafic minerals in the FG type. Another possible explanation for this could be because the iron which has segregated in the CGP type is leached out through the open grain boundaries.

Most of the plagioclase feldspars were now partially or wholly replaced by secondary minerals (kaolinite) in all samples. Where the replacement is incomplete, the alteration was observed to be concentrated either adjacent to grain boundaries (i.e. mainly in the CGP type) or in the centre of the plagioclase grain surrounded by a clear albite rim. Pores were occasionally observed in some plagioclase feldspar as a result of the removal of alteration products by solution and could be seen to be deposited along the joints and open cracks. K-feldspar appeared more cloudy than before, but alteration is incomplete, covering up to 40% of its volume percent. In some samples a nearly opaque area has been formed in some of the K-feldspar grains. Quartz has also been intensely fractured by tight to open microcracks (Plate 4.4).

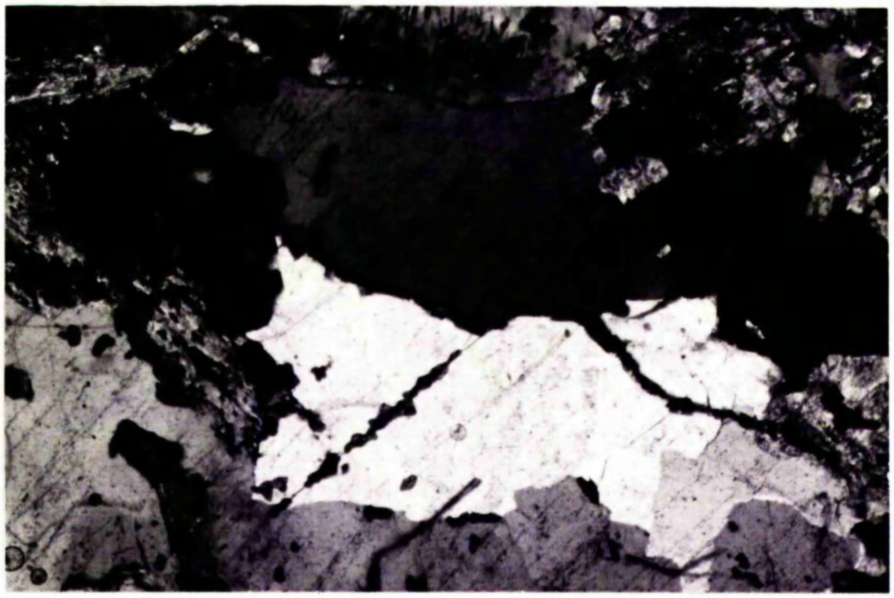
Based on thin section study of weathered rock of the Helmsdale granites, the sequence and nature of weathering processes has been revealed as far as the primary minerals are concerned, as follows: hydrothermal alteration, including sericitic and chloritic alteration, followed by physical and chemical weathering. Both biotite and feldspar have undergone some mineralogical changes which can be attributed to either hydrothermal alteration or weathering.

4.3.6. Mineralogical composition

The bulk mineralogy of the samples, as revealed by the X-ray diffraction traces (XRD) in Figures 4.5, 4.6 is further evidence accompanying the thin section study and can be related to the major changes in mineral composition of the samples explained in the thin

PLATE 4.3. Photomicrograph of sample illustrating higher degree of alteration with further development of fractures. Microcracks are transgranular and stained. Grain boundaries are also stained, but tight, except for plagioclase which are open and filled with iron-oxides.

PLATE 4.4. This plate shows more advanced alteration process, having most of the plagioclase partially or wholly replaced by secondary minerals (kaolinite), assuming an opaque appearance under Plain light. The rock fabric is highly microfractured by tight to open, stained microcracks.



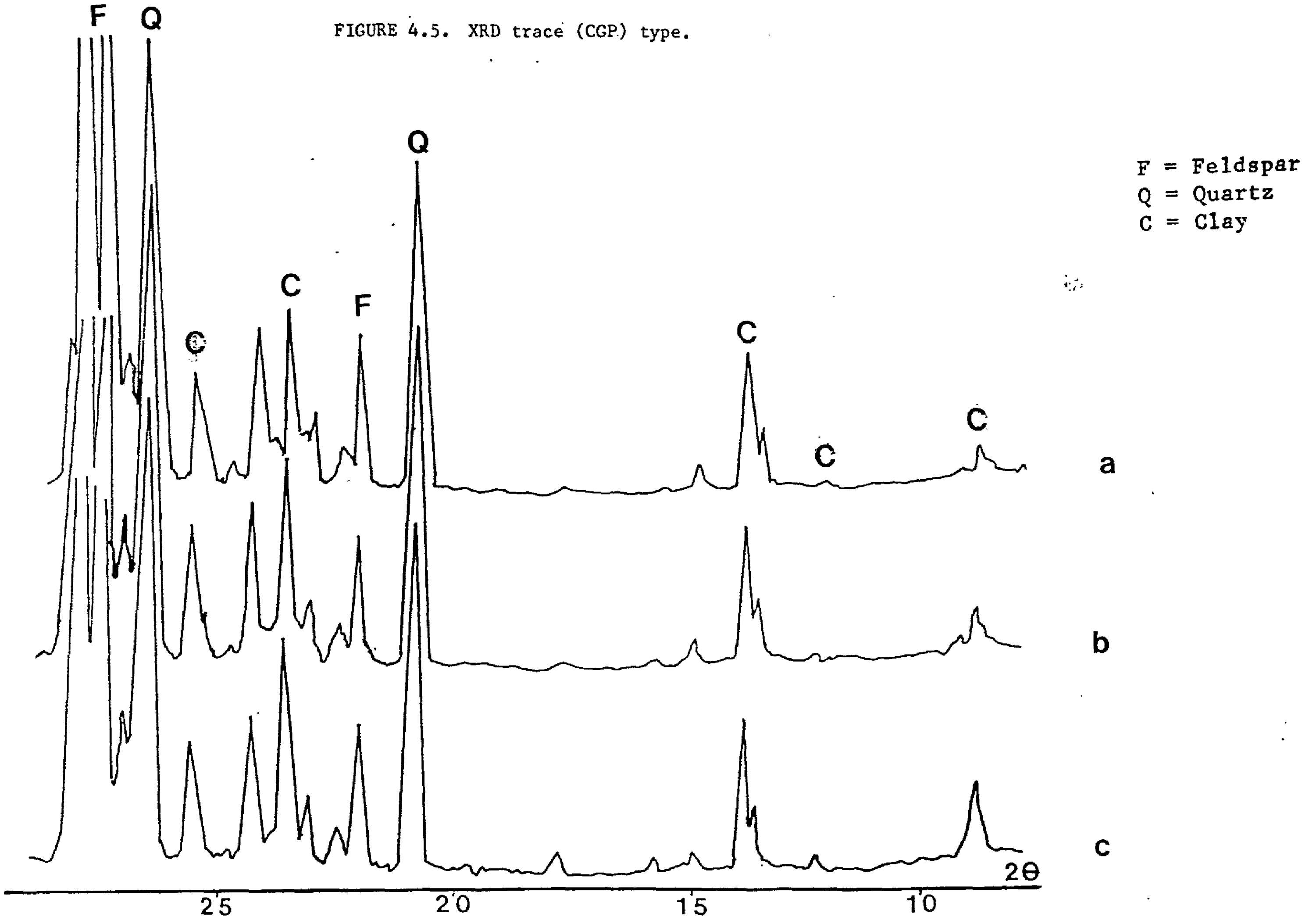


FIGURE 4.5. XRD trace (CGP) type.

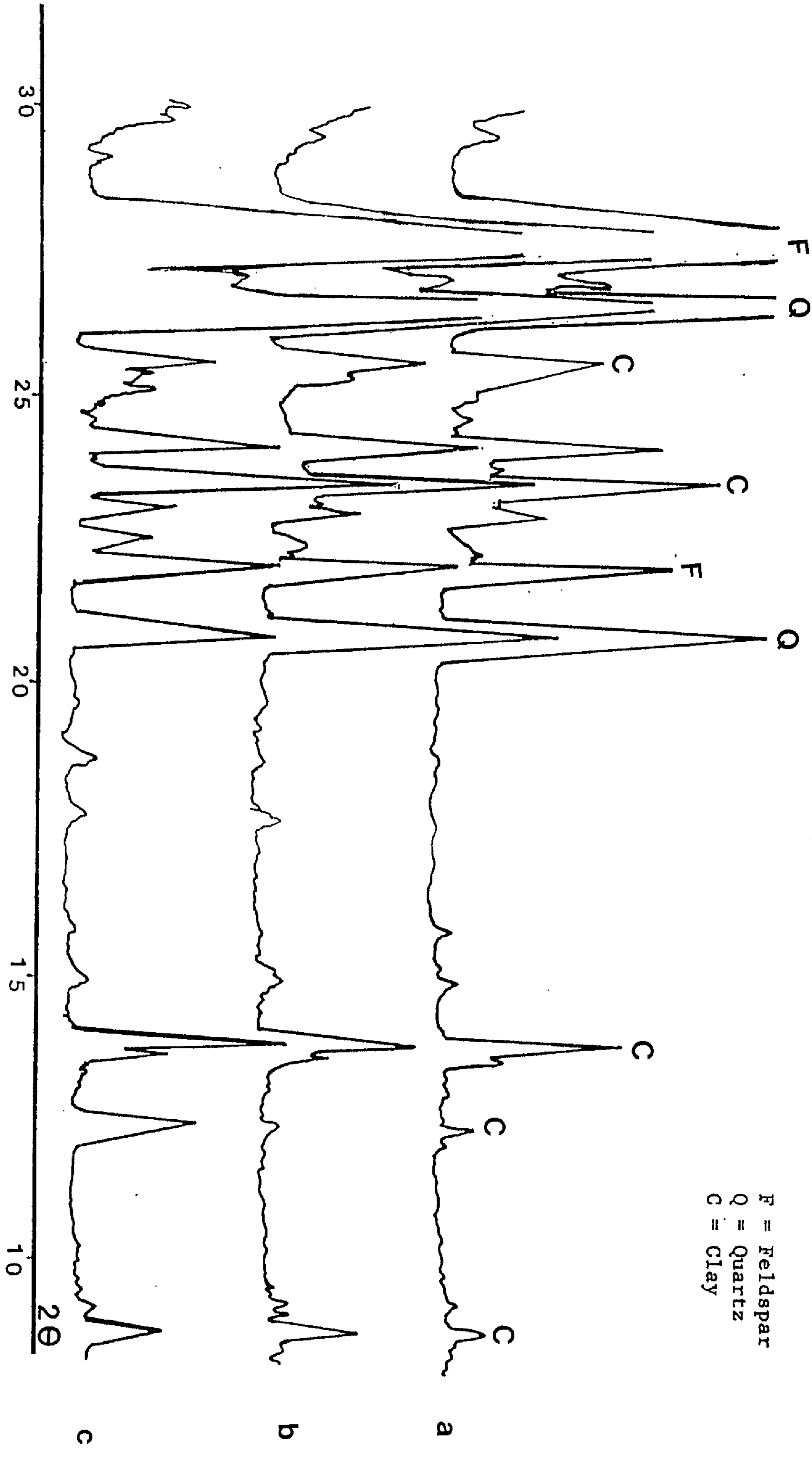


FIGURE 4.6. XRD trace (FG) type

section study. The diffraction trace of relatively fresh samples from the lower part of the Ousdale Quarry face (CGP type) is shown in Figure 4.5, trace a, which contains many high peaks due to a high percentage of both quartz and feldspars (Q and F peaks respectively) and a few very small peaks due to clay minerals (C). The traces b and c for slightly more weathered samples from the upper part of the quarry face, also contain many high peaks of quartz and feldspars like those shown in trace a, but have more clay (C). The amounts of feldspar have also been reduced upwards accompanied by slightly increased amounts of quartz.

The diffraction races of the samples from Helmsdale Quarry (FG type) are shown in Figure 4.6. All the traces (a, b and c) contain some high peaks similar to traces from Ousdale Quarry (CGP type, see also Fig. 4.5) due to high contents of quartz and feldspar (Q and F peaks) and a few moderate to small peaks due to clay minerals. The only difference between the traces of these FG type samples and those obtained from the CGP type is the appearance of a new 14.10 A^o peak (001 chlorite) and it's second order (002) which appears as a strong 7 A^o peak (002 chlorite) in the trace from more weathered samples (Fig. 4.6, trace c).

4.3.7. Microprobe analyses of selected minerals and their mineral chemistry

Microprobe analyses were used to study the chemical or mineral elements which were active during weathering processes (Menier and Velde 1979). Assemblages of primary and secondary minerals and their modes, both for the FG type granite (samples from Helmsdale Quarry) and the CGP type granite (samples from Ousdale Quarry) are presented in Tables 4.4 and 4.5 respectively. A selected number of microprobe analyses of minerals from each sample are given in Tables 4.6, 4.7 and 4.8.

K-feldspar

K-feldspar in samples from both granite types were examined and appeared to be less affected during hydrothermal and subsequent weathering alteration. The clear, primary K-feldspar occurs in all the samples and has a composition of An_{00} to $An_{4.1}$ and Or_{80} to Or_{100}. However, only some of the clear K-feldspars have been replaced by cloudy, secondary K-feldspar and this is a common feature among most of the samples. Although the replacement in most samples is partial and commonly occurs along the cleavage planes and transgranular cracks, in some other samples it is complete.

Unlike analysed clear K-feldspar which shows a closer range of composition in any one sample, the altered one exhibits a wider range in composition from orthoclase fledspar (Or_{100}) to pure albite (Ab_{100}). The altered K-feldspar grain is commonly perthite, consisting of a K-rich part which is altered and cloudy in thin section and Na-rich which is clean and unaltered, formed during exsolution process at low temperature from an original homogeneous feldspar solid solution. (see Chapter 2 for more detail).

Plagioclase feldspar

Unlike K-feldspar which showed little mineralogical change during weathering, the plagioclase feldspar exhibited much more alteration effect which the microprobe analyses revealed as a loss of some chemical constituents, most commonly Ca and Na. Nevertheless, the clear (unaltered), primary plagioclase feldspar occurs in all the samples, but it's volume percentage decreases from samples numbers 37 to 24 and 55 to 43 within each FG and CGP type respectively. (See Tables 4.5 and 4.6).

TABLE 4.4. Primary and secondary minerals plus AI_f and AI_m (FG)

Sample No.	Helmsdale Quarry (FG type)						
	24	25	29	32	34	36	37
Primary minerals							
Quartz	25.18	25.92	27.41	24.02	26.00	25.10	25.75
Clear K-feldspar	18.52	32.12	29.01	33.12	32.73	36.42	33.90
Clear plagioclase	8.12	10.49	10.14	15.22	16.43	14.16	17.30
Biotite	0.15	0.82	1.00	2.12	2.53	3.71	3.92
Magnetite	0.19	0.14	0.17	0.10	0.11	0.20	0.10
Accessory	tr	tr	tr	0.39	tr	tr	tr
Secondary minerals							
Cloudy K-feldspar	17.94	10.12	7.59	6.37	5.14	5.75	4.18
Cloudy plagioclase	24.51	15.84	21.13	14.81	4.01	11.41	10.6
Chlorite	0.15	0.40	1.10	1.90	1.41	2.00	2.75
Muscovite	0.41	0.30	0.55	1.00	1.05	1.25	1.50
Clay minerals	4.00	3.50	1.45	0.65	0.59	0.00	0.00
Iron oxide	0.85	0.35	0.45	0.30	0.00	tr	0.00
Total feldspar	69.09	68.57	67.87	69.52	58.31	67.74	65.98
Total altered feldspar	42.45	25.96	28.72	21.18	9.15	17.16	14.78
AI_f	0.61	0.38	0.42	0.30	0.16	0.25	0.22
Total mafic minerals	4.30	4.72	3.55	4.67	4.53	5.71	6.67
Total secondary mafic	4.15	3.90	2.55	2.55	2.00	2.00	2.75
AI_m	0.96	0.83	0.72	0.55	0.44	0.35	0.41

TABLE 4.5. Primary and secondary minerals plus AI_f and AI_m (CGP)

	Ousdale Quarry (CGP type						
Sample No.	43	44	46	48	53	54	55
Primary minerals							
Quartz	28.15	29.47	31.72	27.95	26.70	29.25	25.5
Clear K-feldspar	28.55	29.32	35.17	40.0	32.85	35.98	30.52
Clear plagioclase	2.35	4.15	17.00	9.25	8.10	5.34	10.14
Biotite	1.22	0.90	2.25	2.10	2.45	3.15	2.82
Magnetite	tr	tr	tr	tr	tr	tr	tr
Accessory	tr	tr	tr	tr	tr	tr	tr
Secondary minerals							
Cloudy K-feldspar	11.5	8.85	4.45	4.90	5.14	4.05	5.66
Cloudy plagioclase	24.68	23.93	7.11	13.85	22.52	17.09	23.32
Chlorite	0.45	0.13	0.25	0.34	0.33	0.55	0.90
Muscovite	tr	0.35	tr	0.46	0.99	1.25	1.09
Clay minerals	2.22	2.21	1.38	0.90	0.92	0.05	0.05
Iron oxide	0.98	0.69	0.72	0.25	0.00	0.05	0.00
Total feldspar	67.08	66.25	63.73	68.0	68.61	62.46	69.64
Total cloudy feldspar	36.18	32.78	11.56	18.75	27.66	21.14	28.98
AI_f	0.54	0.49	0.18	0.27	0.40	0.34	0.42
Total mafic minerals	3.69	3.24	3.73	3.34	3.70	3.75	3.77
Total secondary mafic	2.47	2.34	1.48	1.24	1.25	0.60	0.95
AI_m	0.67	0.72	0.40	0.37	0.34	0.16	0.25

This decrease in volume percentage of clear plagioclase in samples from the upper part of the quarry faces is accompanied by a progressive increase in weathering intensity as was shown by XRD traces (Figs 4.5 and 4.6).

While clear (fresh) plagioclase in general, has average composition - Or_{00} Ab_{97} An_{3}, the altered plagioclase exhibits more chemical variation. The altered plagioclase in samples from the FG type granite shows a gradual decrease in Ab content from the rim with almost pure albite to the core with the composition of Ab_{88}. The An content of the altered plagioclase also decreases, but in a closer range from An_{7} to An_{5} in the same direction. But the Or content in the same altered plagioclase also shows a wider range from Or_{00} to Or_{6} from rim to core respectively. The chemical composition of the altered plagioclase in samples from the CGP type granite on the other hand, shows a different trend, with margins of the mineral containing higher concentrations of Ab and Or and lower concentrations of An than the core. Such analysed altered plagioclase from the CGP type shows an average composition of Or_{1} Ab_{88} An_{11} and $Or_{2.6}$ $Ab_{95.4}$ An_{2} at core and rim respectively.

Quartz, opaque and accessory minerals

All samples contain a significant amount of quartz and several analyses confirm that it is practically pure SiO_{2} and shows no sign of alteration.

Magnetite occurs in most of the samples, especially those samples from the FG granite type. Most of the magnetites occur as euhedral minerals associated mostly with biotite and other mafic minerals. Microprobe analyses show that magnetite in samples from the FG type is relatively homogeneous in composition and almost pure iron-oxide (Fe_3O_4) with no Ti and Mn. Because of its texture of fine granules, needles or plates within other mafic minerals and secondary chlorite, and also because of its chemical composition, the origin of this magnetite could be related to a secondary formation. Analysed magnetite from the FG type also shows a small amount of Al_2O_3 and SiO_2 which probably represents impurities, although small amounts of Al substitute for Fe^{3+} can occur.

Analysed opaque (magnetite) minerals from the CGP type on the other hand, show that in most samples they are relatively less homogeneous in composition than those of the FG type. Here analysed magnetite shows a lower percentage of iron-oxide (Fe_2O_3, FeO) content accompanied by a richer Al content, which replaces Fe^{3+} and also has a small amount of Ca which may partially replace the Fe^{2+}. Ti is also present in small amounts in all magnetites analysed in samples from the CGP type. The chemical composition shows however, that most of the magnetites are close to a magnetite-ulvospinel solid solution (Deere et al. 1966). The differences in magnetite composition existing within each granite, as well as between the two granite types are probably caused by partial conversion of primary titaniferous magnetite to a Ti-poor one during hydrothermal alteration and/or weathering processes.

Biotite

Analysed biotites in samples from FG type granite are distinctive in their high MgO content and low total FeO. Although the composition of biotite is nearly constant within any specimen, it varies from one specimen to another. Nevertheless, analysed biotite in samples from the lower part of the quarry face show lower MgO and higher K_2O, TiO_2 than those analysed from the upper part. This point also suggests that samples from the lower part of the quarry face are less altered. Furthermore, analysed biotites from relatively fresh samples show alteration to secondary green chlorite accompanied by magnetite as its main by-products. This partial chloritization of biotite is commonly accompanied by similar alteration of feldspar (sericitization) in the same relatively fresh samples which again can be related to hydrothermal alteration.

Samples from the CGP type were also chosen for microprobe analyses for biotite (Table 4.6) for which the results appear to be slightly different from those obtained for the FG type. Here biotite is characterized by lower MgO and higher total FeO content. Furthermore, the alteration product is mainly clay and only a small volume percentage of it has altered to chlorite.

	FG 32 Oxygen			CGP 23 Oxygen		
	129	124	121	165	166	167
SiO_2	31.41	31.94	37.61	34.95	31.85	24.90
TiO_2	0.61	0.99	2.15	3.90	3.43	0.00
Al_2O_3	15.26	14.21	13.54	12.77	14.30	19.20
T FeO	18.95	19.81	17.23	28.88	30.74	36.00
MnO	0.38	0.49	0.34	0.34	0.45	0.40
MgO	16.52	16.66	14.59	3.69	5.54	4.93
CaO	0.00	0.10	0.00	0.00	0.00	0.00
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	2.09	3.52	8.86	8.88	4.70	0.65
Total	85.22	87.71	94.32	93.21	90.89	860.8
K	0.64	1.07	2.50	1.94	1.03	0.16
Na	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.00	0.03	0.00	0.00	0.00	0.00
Fe	3.82	3.94	3.19	4.14	4.50	5.72
Mg	5.93	5.90	4.81	0.94	1.42	1.35
Mn	0.08	0.10	0.06	0.05	0.07	0.06
Ti	0.11	0.18	0.36	0.51	0.45	0.00
Al	4.33	3.98	3.54	2.58	2.96	4.27
Si	7.56	7.59	8.33	6	5.57	4.70

TABLE 4.6. Microprobe analysis of biotite – chlorite mixtures.

Chlorite

Chlorite occurs in all samples from both granite types, and it shows a restricted range in composition. Chlorite composition in all samples except sample $82_{(b)}$ is characterized by its low total FeO and high MgO content (see Table 4.7). A small amount of TiO_2 (less than 1%) was found only in chlorite analysed in samples from the FG type, whereas those samples from the CGP type show no TiO_2 in their chlorite composition. Another difference between the two granite types is in their Al content which is slightly higher in specimens from the FG type. Chlorite, in general, occurs either as a direct replacement of biotite or along the edge and cleavage plans of biotite and other mafic minerals, with no obvious textural relation to any primary mafic minerals.

Muscovite

Muscovite occurs in a small amount only as a secondary mineral in all samples. It is usually restricted to samples containing more altered plagioclase feldspar and principally occurs as very small flakes, replacing the interior of plagioclase feldspar. Because of its small grain size, only a few satisfactory analyses of muscovite from the CGP type were obtained (see Table 4.8).

Table 4.8 also shows the chemical composition of analysed illite in samples from both granite types.

CHLORITE

	FG			CGP		
	149	150	82(b)	163	65	66
SiO_2	25.84	28.75	47.13	29.04	25.28	24.32
TiO_2	0.15	0.14	0.58	0.00	0.00	0.00
Al_2O_3	20.57	20.76	15.62	18.56	15.72	15.49
T FeO	21.43	20.00	20.68	17.55	21.80	24.35
MnO	0.60	0.35	0.00	0.47	0.17	0.16
MgO	16.52	15.42	0.74	18.89	12.25	11.97
CaO	0.00	0.00	0.76	0.00	0.36	0.24
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	0.18	0.96	0.94	0.61	0.47	0.31
Total	85.25	86.34	86.43	85.10	76.05	76.82
Ca	0.00	0.00	0.18	0.00	0.10	0.07
K	0.06	0.29	0.27	0.19	0.16	0.11
Na	0.00	0.00	0.00	0.00	0.00	0.00
Fe	4.36	3.96	3.88	3.49	5.04	5.67
Mg	5.99	5.45	0.25	6.69	5.04	4.97
Mn	0.125	0.07	0.00	0.09	0.04	0.04
Ti	0.03	0.02	0.09	0.00	0.00	0.00
Al	5.90	5.79	4.13	5.20	5.12	5.09
Si	6.29	6.81	10.57	6.90	6.99	6.77

TABLE 4.7. Microprobe analysis of chlorite.

	(Illite) FG			(Illite) CGP			Muscovite CGP
	78	96a	96b	71	74	75	73
SiO_2	45.87	49.16	49.23	50.64	48.22	48.99	46.98
TiO_2	0.00	0.00	0.15	0.00	0.00	0.00	0.19
Al_2O_3	24.96	26.12	26.25	25.06	29.95	30.14	20.61
T FeO	7.01	4.91	4.77	4.31	4.09	3.02	14.32
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	1.54	1.84	1.93	0.00	0.93	1.32	2.61
CaO	0.11	0.00	0.00	0.00	0.00	0.00	0.14
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	8.85	9.75	9.36	10.23	9.73	10.19	8.42
Total	88.33	91.78	91.69	93.10	92.92	93.66	93.27
Ca	0.02	0.00	0.00	0.00	0.00	0.00	0.03
K	2.41	2.53	2.42	2.61	2.48	2.56	2.26
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	1.25	0.83	0.81	0.72	0.68	0.49	2.52
Mg	0.49	0.56	0.58	0.85	0.28	0.39	0.82
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.02	0.00	0.00	0.00	0.03
Al	6.28	6.25	6.27	5.91	7.04	7.00	5.11
Si	9.79	9.98	9.97	10.13	9.62	9.66	9.88

TABLE 4.8. Microprobe analysis of illite.

4.3.8. Chemical changes on weathering and hydrothermal alteration

A geochemical study was carried out of all 28 samples taken from the two quarry faces (analyses numbers 25 to 39 from Helmsdale Quarry and 43 to 55 from Ousdale Quarry). The detailed geochemical results, including major and trace elements are given in Table Appendix 1. Chemical analysis was carried out in order to follow the chemical changes involved in the mineralogical transformation and formation of secondary minerals during weathering.

From the petrography study it has been revealed that the degree of weathering has decreased gradually from the top of the quarry faces downwards, characterized by a higher content of clay minerals like kaolinite in samples from the upper part of the quarry faces (see Figs 4.5, 4.6). Further evidence has been provided by microprobe analyses of primary and secondary minerals which has shown that the volume percentage of altered feldspars and altered biotite also decreased downwards (see page 110).

Study of the geochemical data indicates that small chemical changes have occurred during weathering for some of the major elements and lesser changes for the trace elements, related to such mineralogical changes during weathering and hydrothermal alteration.

In most studies, the interpretation of geochemical data from weathered rocks is commonly based on a comparison of element concentration in soil (the final weathering product) to those in parent rock (fresh rock). It is also possible to estimate the amounts of element removal based on camparisons with an element (usually Al or Ti) assumed to be immobile during weathering processes (Harris and Adams 1966). However, the assumption of immobility for such elements (Al and Ti) is not always warranted (Gardner et al. 1978; Dumon and Vigneaux 1979), as was found in the present study. Therefore, the chemical variation was studied by plotting all chemical data obtained against the related heights of the samples on the quarry faces.

Major element variation

Since the leaching of SiO_2, Na_2O, CaO and MgO with the advancement of weathering in granite rocks is more considerable compared to that of Al_2O_3 and K_2O, the ratios Na_2O/K_2O, $Al_2O_3/(SiO_2 + Al_2O_3)$ and $(Na_2O + K_2O + CaO + MgO)/Al_2O_3$ may be used as the indices of chemical weathering. Furthermore, the ratio of Fe_2O_3/FeO which was found to be a useful index for chemical weathering (Moore 1979), plus microfracture index (FI) after Irfan and Dearman (1978), is also applied in the present study to identify different stages of chemical and physical weathering of the two granite types (FG and CGP). The results are given in Table 4.9 and Figures 4.7 and 4.8 for the CGP and FG types respectively.

Figure 4.7 shows that in spite of the increased microfracture index (FI), due to increased physical weathering towards the upper part of the quarry face, no considerable leaching of SiO_2, Na_2O, K_2O and MgO occurred on the chemical side. The Fe_2O_3/FeO ratio, however, shows considerable increases towards the top of the quarry, except for the last four samples at the top. The same unusually lower Na_2O/K_2O ratio also exists in samples from the top of the quarry, which may suggest a strong leaching of Na_2O due to breakdown of plagioclase feldspar accompanied by a increase in Fe_2O_3/FeO ratios because of the breakdown of biotite (Fe^{2+}) and the formation of Fe_2O_3 which has been carried away from more weathered rocks at the top. The original mineralogical variation might also be partly responsible for this

FG TYPE

Samples	24	25	26	27	28	29	30	31	32	33	34	35	36	37
Na_2O/K_2O	1.15	0.99	1.1	1.3	1.18	1.28	1.29	1.22	1.13	1.19	1.3	1.12	1.3	1.32
$Al_2O_3/(SiO_2+Al_2O_3)$	0.17	0.17	0.17	0.16	0.17	0.16	0.16	0.17	0.17	0.17	0.16	0.17	0.17	0.17
$(Na_2O+K_2O+CaO+MgO)/Al_2O_3$	0.73	0.73	0.73	0.75	0.77	0.78	0.83	0.79	0.9	0.75	0.77	0.75	0.8	0.83
Fe_2O_3/Feo	5.5	6.7	6.3	14.5	21.7	6.0	4.2	5.2	5.4	5.7	23.7	58.7	4.1	4.6

CGP TYPE

Samples	43	44	45	46	47	48	49	50	51	52	53	54	55
Na_2O/K_2O	1	0.84	0.75	0.98	1.1	1.04	0.99	1.09	1.04	1.1	1.09	1.09	0.86
$Al_2O_3/(SiO_2+Al_2O_3)$	0.14	0.15	0.14	0.13	0.13	0.13	0.15	0.15	0.14	0.16	0.15	0.15	0.16
$(Na_2O+K_2O+CaO+MgO)/Al_2O_3$	0.82	0.82	0.81	0.83	0.81	0.81	0.86	0.77	0.79	0.77	0.77	0.8	0.76
Fe_2O_3/FeO	2.21	23.5	37.7	5.36	35	42.5	36.2	44	21.5	14.5	5.9	12.6	35

TABLE 4.9. Weathering index results

FIGURE 4.7. Weathering indices against heights on Ousdale Quarry face

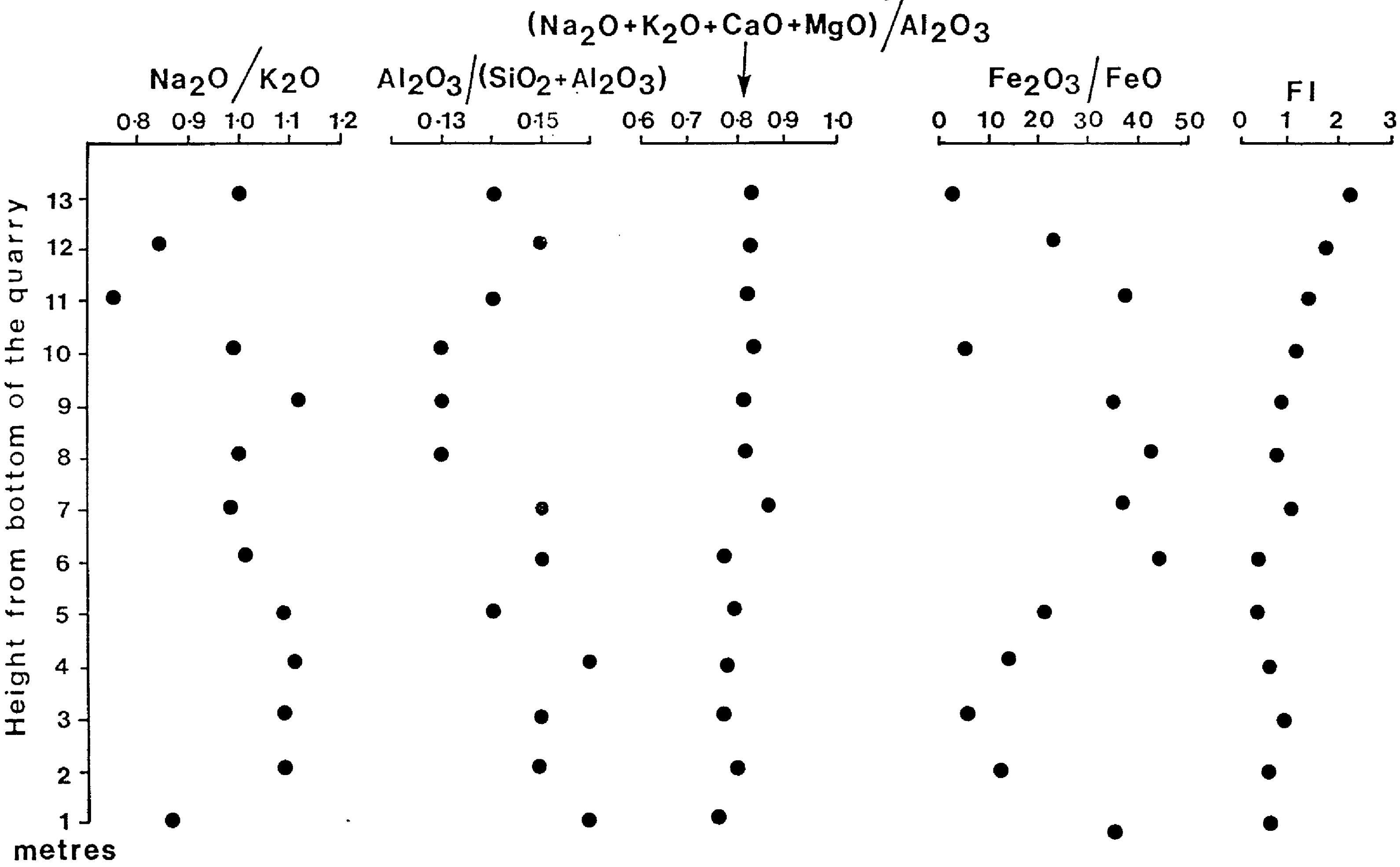
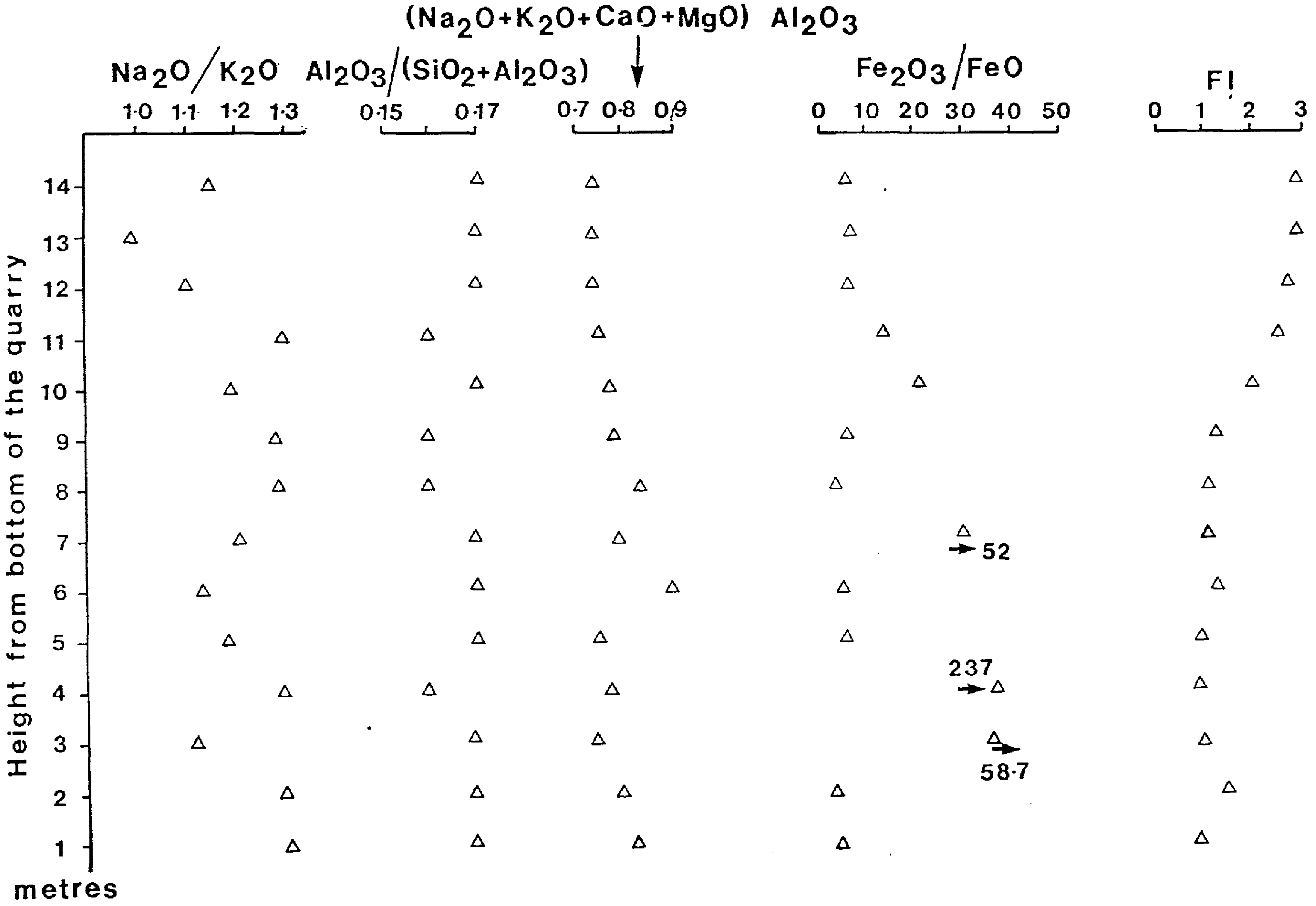


FIGURE 4.8. Weathering indices against heights on Helmsdale Quarry face.



behaviour since one sample at the bottom of the quarry face shows a similar result.

Figure 4.8 also shows no variation on the chemical or physical side except for samples at the top of the quarry. The Fe_2O_3/FeO ratio however, shows a very high value in some samples, due to leaching out of the Fe^{3+} at the top and its accumulation along the grain boundaries (iron stained boundary) as was observed in the thin section study.

In order to find out the composition and amounts of important minerals, such as feldspar (plagioclase feldspar in particular) and their behaviour during the weathering process, the major element analyses of all the samples from the two quarry faces were recalculated to CIPW norms so that the results could be compared between different rock types as well as different samples within each granite type. In Figures 4.9 and 4.10 normative albite, quartz, orthoclase, albite plus anorthite (plagioclase) and orthoclase plus plagioclase (total feldspar) have been plotted against the height of each sample from the CGP type and FG type respectively.

Samples from the CGP type (fig. 4.9) show that the amounts of albite, orthoclase, plagioclase (Ab and An) and total feldspar (Ab + Or + An) increase at the expense of quartz, which decreases. In particular, plagioclase (Ab + An) appears to be slightly more susceptible to breakdown as a result of chemical weathering than orthoclase feldspar. Samples from the top of the quarry face, however, show rather different proportions in their orthoclase and quartz amounts than the rest of the samples, i.e. a very high amount of orthoclase is accompanied by very low quartz, while plagioclase shows normal behaviour as do the remainder of the samples.

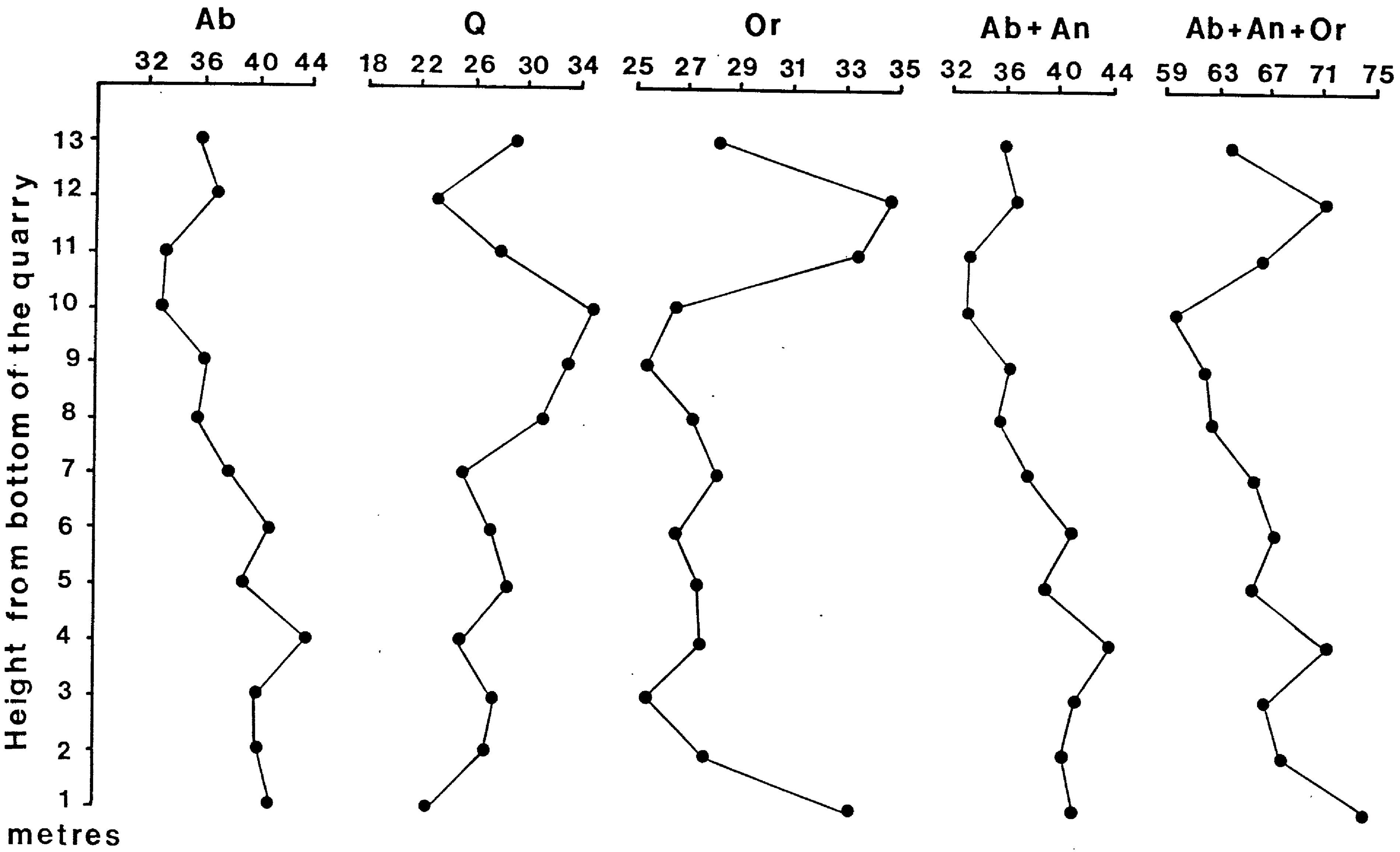


FIGURE 4.9. Normative values against heights (CGP type).

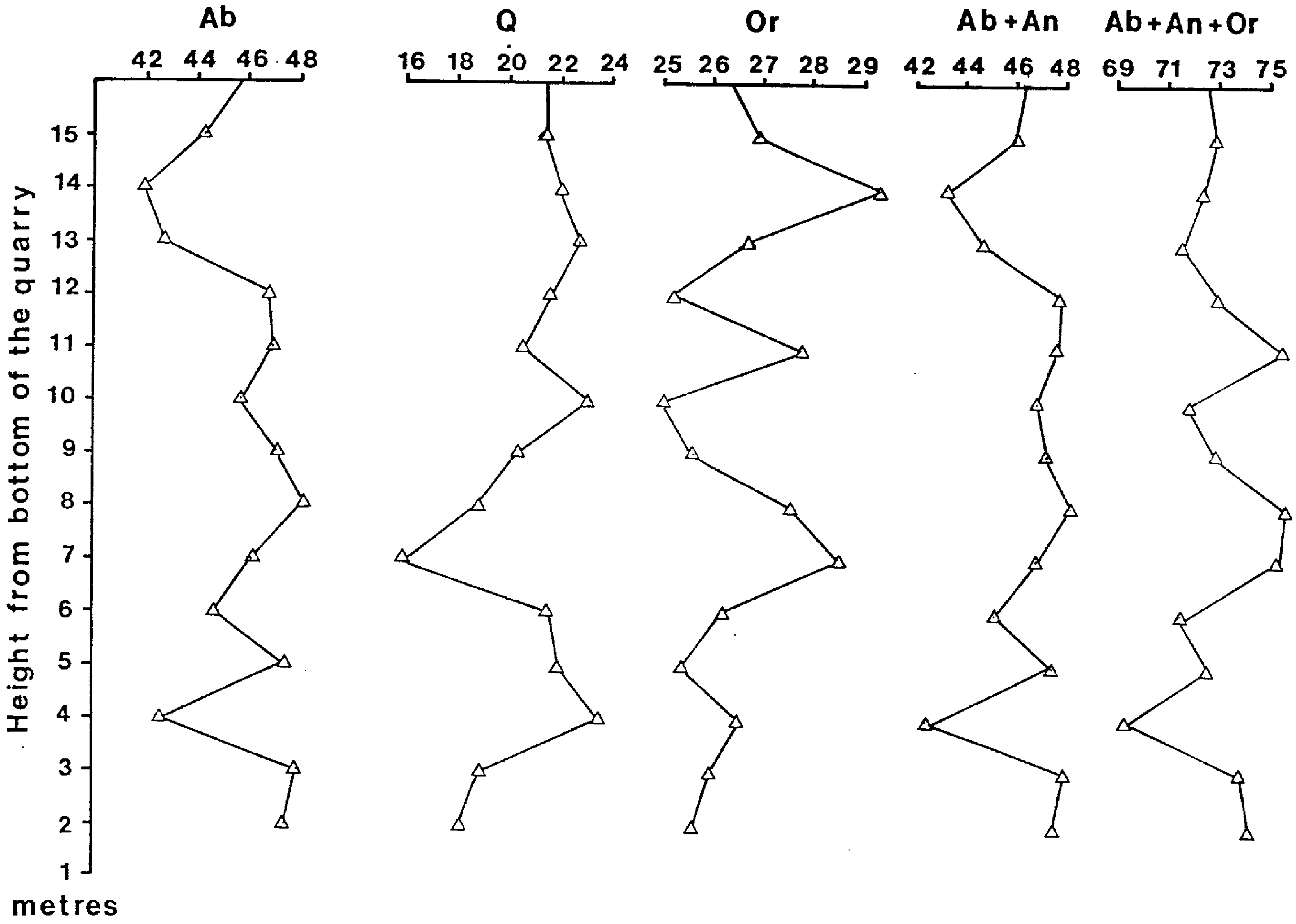


FIGURE 4.10. Normative values against heights (FG type).

This is partly due to the original variation in mineral composition, since the CGP type samples contain large orthoclase phenocrysts. The same explanation is true for the sample from the bottom of the quarry face, with almost the same high amount of orthoclase and low quartz.

Samples from the FG type (Fig. 4.10) on the other hand, show a different trend than was observed in samples from the CGP type. Here the figure tends to support the view that a decrease in the plagioclase is followed by an increase in the orthoclase as well as quartz, due to the effect of weathering and breakdown of plagioclase (less Ab + An). Variation in sample 32 (6 metres high) however, is again related to the original mineralogical variation since the high amount of orthoclase is followed by very low quartz, while the plagioclase shows normal behaviour. This rather different mineralogical behaviour during the weathering process between samples from the two quarry faces is better illustrated in Figure 4.11, where normative plagioclase Ab + An) in samples from both granite types are plotted against normative quartz (Plot a), and normative orthoclase against normative quartz (Plot b). Furthermore, Figure 4.12 shows a plot of normative plagioclase (Ab + An) against orthoclase which suggests that while the decrease in plagioclase in the FG type is directly related to an increase in normative amounts of orthoclase, the variation of plagioclase in the CGP type is completely unrelated to orthoclase feldspar.

Distribution of trace elements during weathering process

The behaviour of trace elements and their relative changes during the weathering along the two quarry faces is shown in Figures 4.13 and 4.14.

These figures show, in general, the absence of significant

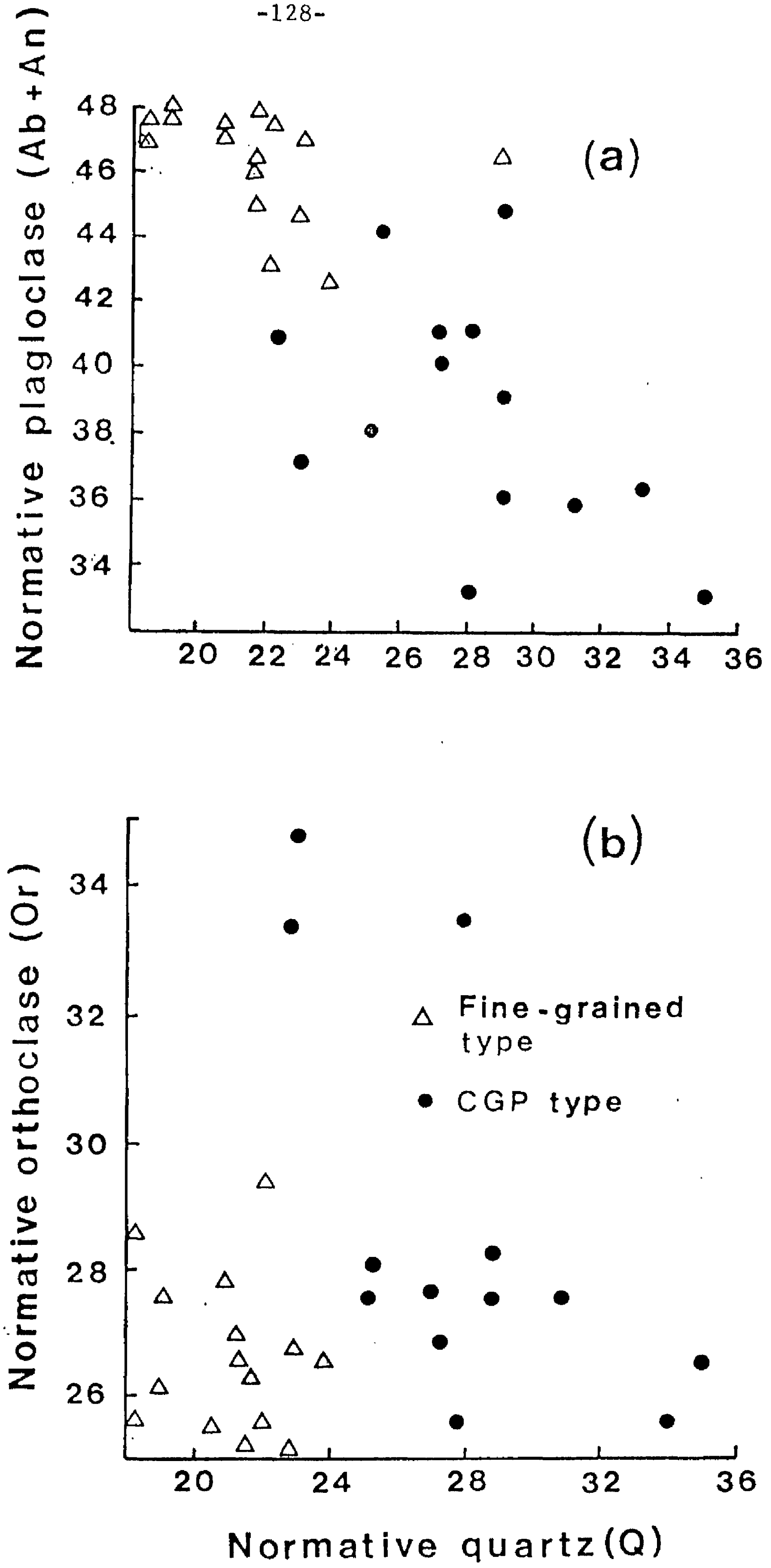


FIGURE 4.11. Normative quartz against normative plagioclase and orthoclase.

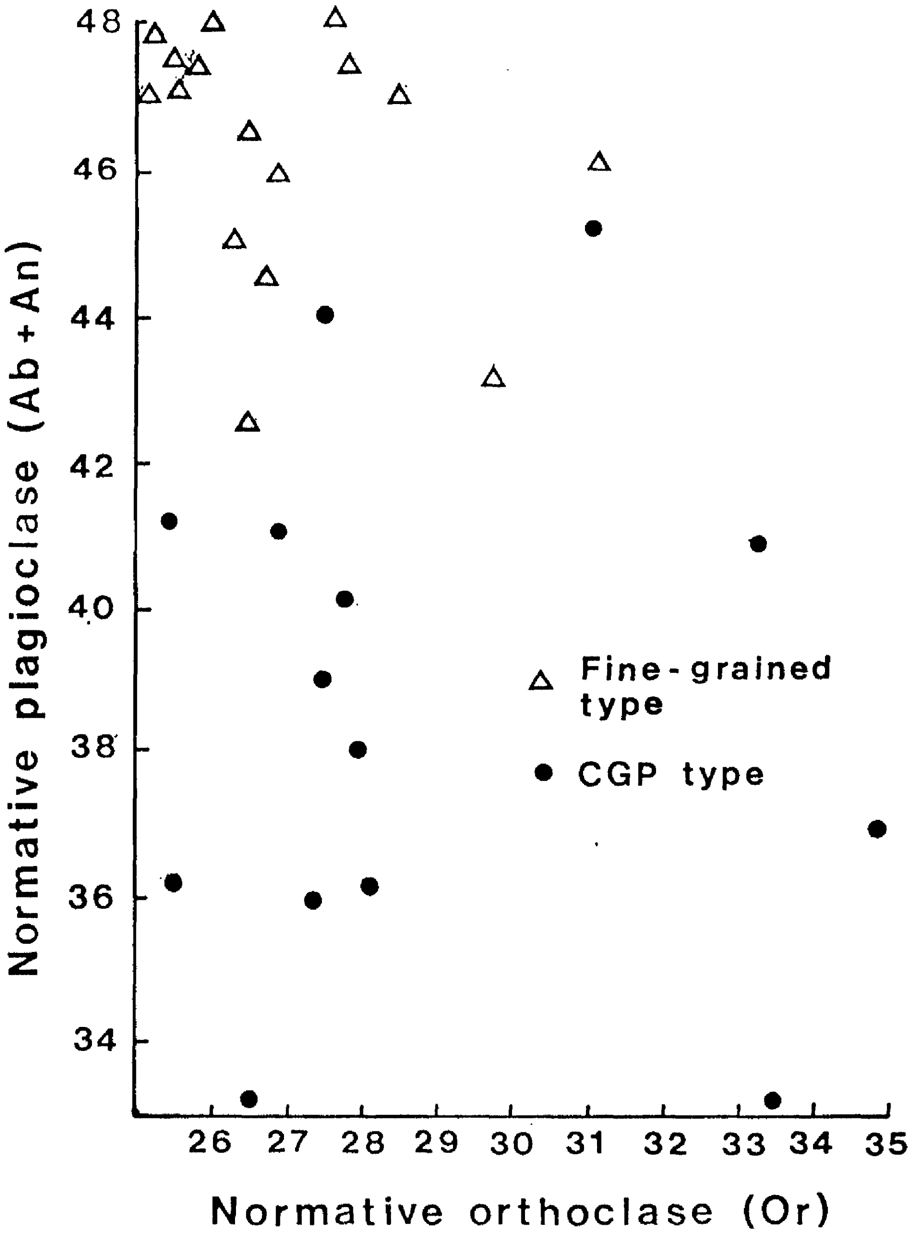


FIGURE 4.12. Normative orthoclase against normative plagioclase.

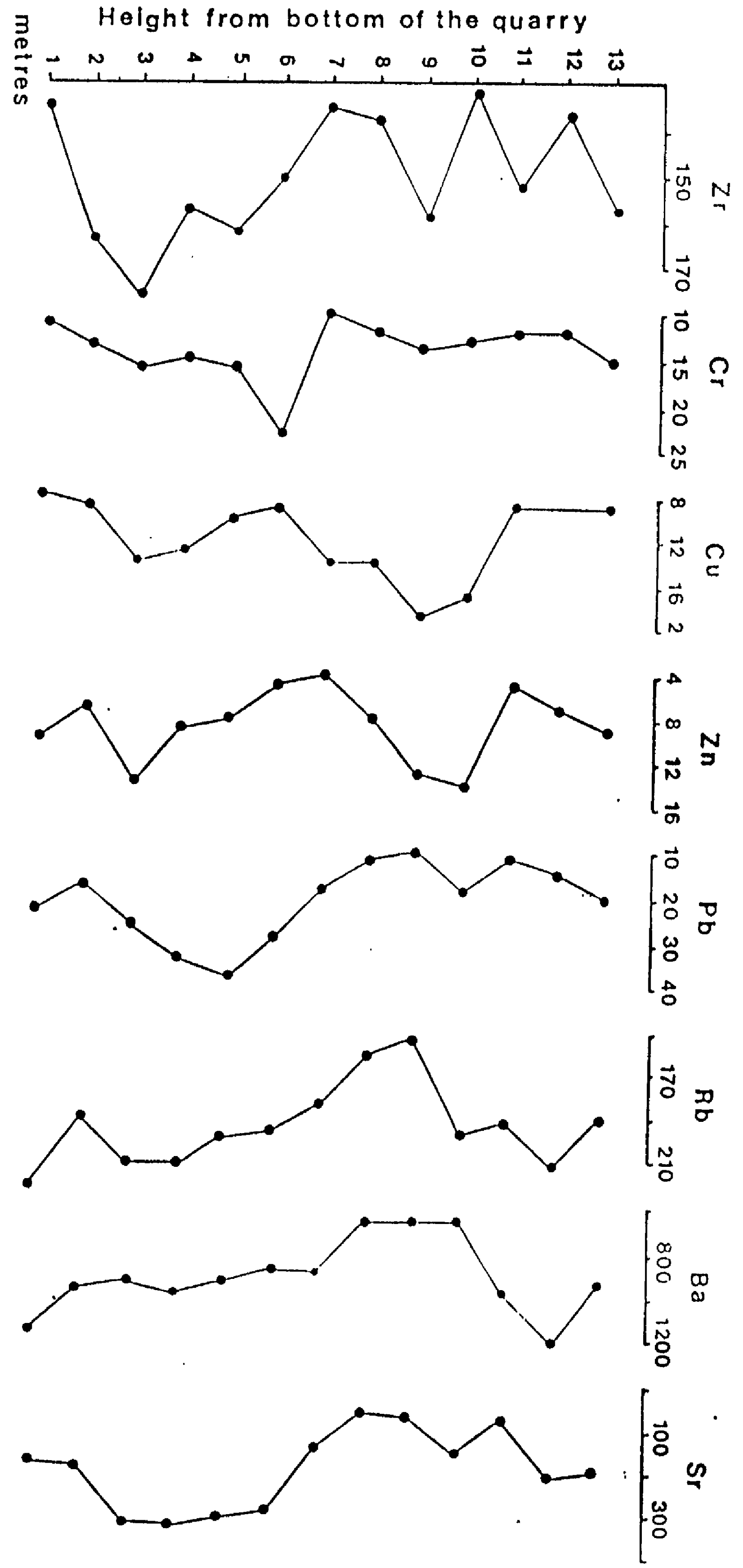


FIGURE 4.13. Trace elements against heights on Ousdale Quarry face (CGP type).

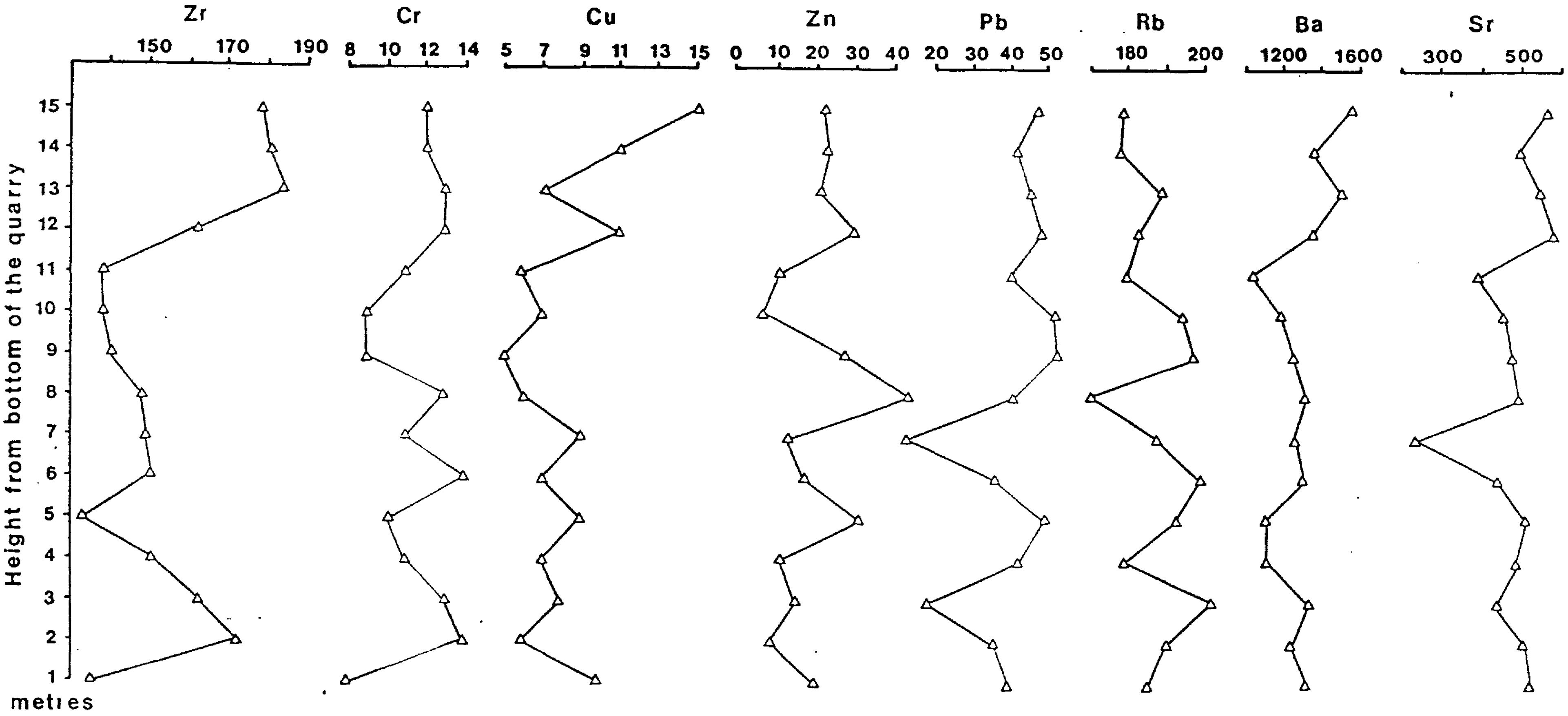


FIGURE 4.14. trace elements against heights on Helmsdale Quarry face (FG type)

changes for the majority of the trace elements in samples from both quarry faces, which is rather consistent with major element study. A small enrichment of Zr in samples from the upper part of the quarry faces can be attributed to the accumulation of zircon in samples with more advanced weathering.

Observations in the field, together with chemical and mineralogical studies indicate that the tops of the two quarry faces (maximum three metres) are the most chemically altered parts, whereas the effect of physical weathering (shown by FI: see Figs 4.7, 4.8) is extended deeper into the quarry faces.

The following series of relatively stable major primary minerals during weathering has been established; Biotite plagioclase feldspar (albite) K-feldspar (orthoclase) quartz, in order of increasing stability. The chloritization of biotite and sericitization of feldspar which occur in the parent rocks continues during weathering. Small chemical changes occur mainly in a ratio of Fe_2O_3/FeO, Ca and Na, whereas among the trace elements only small enrichment of Zr ocurred in more weathered samples.

4.4. The clay mineral study of the weathered Helmsdale granite

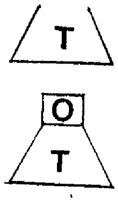
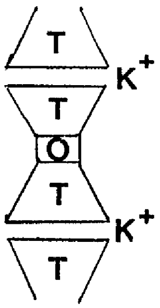
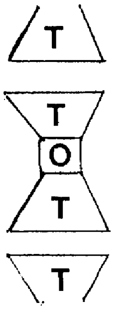
The clay minerals are a group of secondary minerals formed at, or near, the earth's surface by weathering or hydrothermal alteration of feldspar and other aluminous silicates.

The clay minerals are built up of two basic structural units, the first comprising silicon-oxygen sheets, each formed by the linking together of tetrahedral SiO_4-group, which is generally referred to as a "tetrahedral" layer, and the second unit, called "octahedral" layers, comprising a metal ion, such as aluminium or magnesium, lies within a group of six hydroxyls arranged at the corners of an octahedron. Adjoining octahedrals are linked by sharing hydroxyls (see Grim 1962; Brindley and Brown 1980 for more detail).

Different arrangements of the above layers built up the units of which the clay minerals are composed. Some clay minerals have two-layer units (e.g. kaolinite), and others have three-layer units (e.g. montmorillonite), in which an octahedral layer lies between two tetrahedral layers. Figure 4.15 shows the structure and properties of principal clay minerals.

Although the atomic structure and cyrstal form of clay minerals is similar to that of mica, individual clay crystals are normally much too small to be identified using an ordinary microscope. Therefore the clay size fractions of four samples from the Helmsdale granites were examined by X-ray diffraction method to determine: a) what type of clay mineral exists in each granie type, b) the nature of the alteration processes (weathering or hydrothermal alteration, and c) the intensity of alteration along the quarry faces.

Preparation of samples for XRD testing was carried out, starting with disaggregation of more weathered samples, from the upper part of the quarry faces, using a gentle grinding method under water, and then less weathered samples were crushed to small pieces using the mechanical jaw crusher. Since such mechanical crushing processes tend to disorder the crystalline structure of some clay minerals, the size of fresh samples was reduced to 10mm long aggregate using a jaw crusher after which they were subjected to a physical dispersion procedure such as being vigorously shaken in water for 48 hours. Finally, two size fractions 2μm and 0.5μm were separated by standard

Mineral	Structure*	Cation exchange capacity in Millieg uivs per 100 grams	Layer charge	Basal spacing
Kaolinite	1:1 	10	0	7 A°
Illite	2:1 	10-40	1.5 – 2	10 A°
Mont-morillonite	2:1 	80-150	0.5-1.0	Variable depending on relative humidity

* O = $Mg(OH)_2$ or $Al(OH)_3$, Octahedral Unit

T = SiO_4, Tetrahedral Unit

FIGURE 4.15 Showing some of the clay mineral properties useful for engineering purposes.

sedimentation procedure. There are considerable limitations to analyses based on the basal spacing and intensities of each clay mineral (Brindley and Brown 1980) and frequently a large number of minerals are present, which leads to overlapping reflections and few observable reflections from less abundant components. It is usual, therefore, to examine clay specimens before and after various treatments such as ethylene glycol, to aid the identification of smectites, and various heat treatments that collapse swelling minerals by dehydrating the interlayer material and destroy or transform minerals such as kaolinite and hydroxides. These various treatments were exercised for all the samples in the present study.

The X-ray diffraction (XRD) traces are shown in Figures 4.16, 4.17, 4.18 and 4.19 for samples 25, 35, 43 and 54 respectively. The X-ray diffraction patterns for sample 25 (from the upper part of the Helmsdale Quarry, FG type granite) showed the presence of the following clay minerals:

Chlorite

The presence of this mineral in this relatively weathered sample, as revealed by X-ray trace (d) in Figure 4.16 (based on the clay fraction 2 m), is identifiable by a strong 14.10 A^{o} Peak (001), accompanied by very weak second-order 4.7 A^{o} Peak (002). Grim et al. (1961) and Brown and Bradley (1980) and others have pointed out that only those chlorites in which the proportion of octahedral positions occupied by Fe ions is not greater than about 30 per cent have such strong intensities for their first-order basal reflection. This point is also shown by both microprobe analyses of the chlorite (see Table 4.7) and present XRD trace.

The trace (c), based on 0.5μm fraction, shows only a small reduction in the amount of chlorite present, whereas the trace (b)

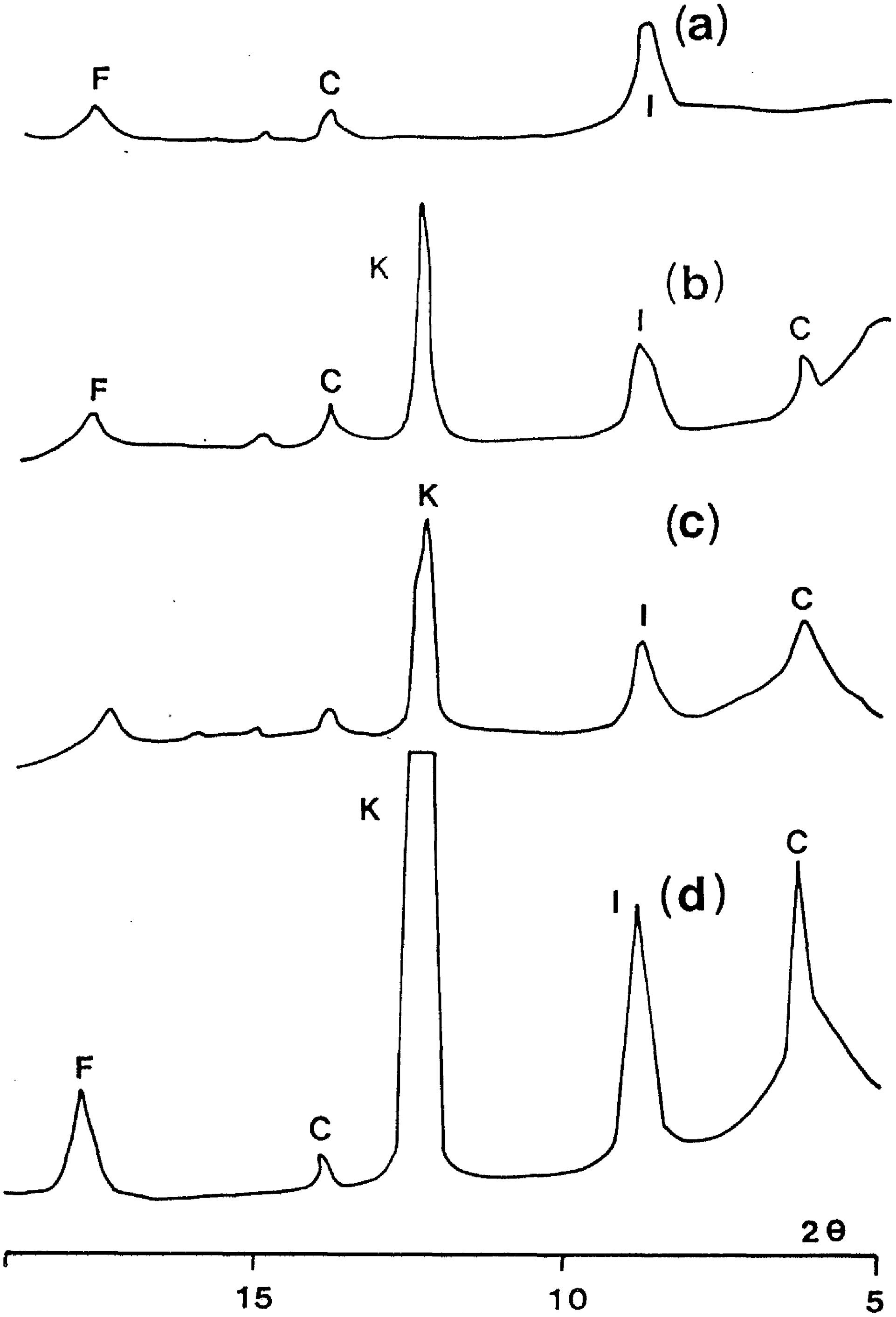


FIGURE 4.16. The X-ray diffraction trace for sample 25 (FG type).
(a) heated to 550°, (b) after treatment with ethylene glycol vapour, (c) trace for 0.5 μm fraction, and (d) trace for 2 μm fraction.
I = Illite, C = Chlorite, K = Kaolinite, F = Feldspar.

showed no sign of displacement on peaks position when the trace was run after treatment with ethylene glycol vapour. After the heating treatment to 550° (trace a in Fig. 4.16), an increase in the intensity of the (011) reflection of chlorite and a decrease in the intensities of the (002), (003), and (004) reflections would normally be expected, but as trace (a) shows the (001) reflection has totally gone and other basal reflections show almost no changes (the 003 and 004 orders are not included in the trace in Fig. 4.16).

Illite

This is also present in quantity, displayed by 9.9A° peak which has not been affected by any subsequent treatment (glycol and 550°C heating), although it is known that illite starts to lose its water from 200°C to about 600° and eventually its structure is destroyed above 850°C. Grim et al. (1951); Walker (1950); MacEwan (1947) have pointed out that the position of the (006) reflection and the intensity of the second-order basal reflection can generally be used to distinguish between dioctahedral and trioctahedral forms. Accordingly, and because of the absence of second-order reflection, it can be concluded that the form of illite in sample HQ 25 is a trioctahedral type. This point is further supported by microprobe analysis of illite which shows very low Ti^{4+}, and the mica (illite) is mainly ferriferous in octahedral positions (Table 4.8).

Kaolinite

The X-ray diffraction trace (d) in Figure 4.16 shows two very strong 7.13 A° (001) and 3.57 A° (002) peaks which are adequate for identification of kaolinite. Furthermore, on heating up to 550°C, kaolinite peaks totally disappeared due to loss of its crystalline character. Based on the ratio of the intensity of reflections, Hinckley (1965) showed that a strong and sharp reflection indicated the degree of high crystallinity of kaolinite. It is also true that the kaolinite in sample 25 is highly crystallized due to its very sharp X-ray diffraction peaks (see Fig. 4.16). This figure also shows that in sample 25 from the upper part of the Helmsdale Quarry face, kaolinite is the most abundant clay mineral present, accompanied by lesser amounts of chlorite and trioctahedral illite.

The X-ray diffraction patterns for sample 35 (from the lower part of the Helmsdale Quarry, FG type granite) is shown in Figure 4.17, which contains the same clay minerals as present in the X-ray diffraction trace of sample 25. The only difference is that here the amount of clay minerals is much less than the slightly more weathered sample 25, from the upper part of the same quarry face. Illite in particular has been reduced greatly in comparison to that in sample 25.

In contrast, in samples 43 and 54 from the upper and lower part of the Ousdale Quarry face respectively (CGP type granite), illite is the most abundant clay mineral present in both samples. The X-ray diffraction traces (figs. 4.18 and 4.19) contain very sharp and strong 9.91 A^o (001) reflections followed by very weak 4.9 A^o (002) reflections and a very much stronger 3.33 A^o peak (003) reflection. Furthermore, illite in CGP type granite like that in the FG type appears to be trioctahedral and its amount decreases from sample 54 (lower part of the quarry face, less weathered) to sample 43 (from the upper part of the quarry face, more weathered). Kaolinite and chlorite on the other hand, are less abundant clay minerals present in CGP samples, particularly in sample 54 (see Fig. 4.18).

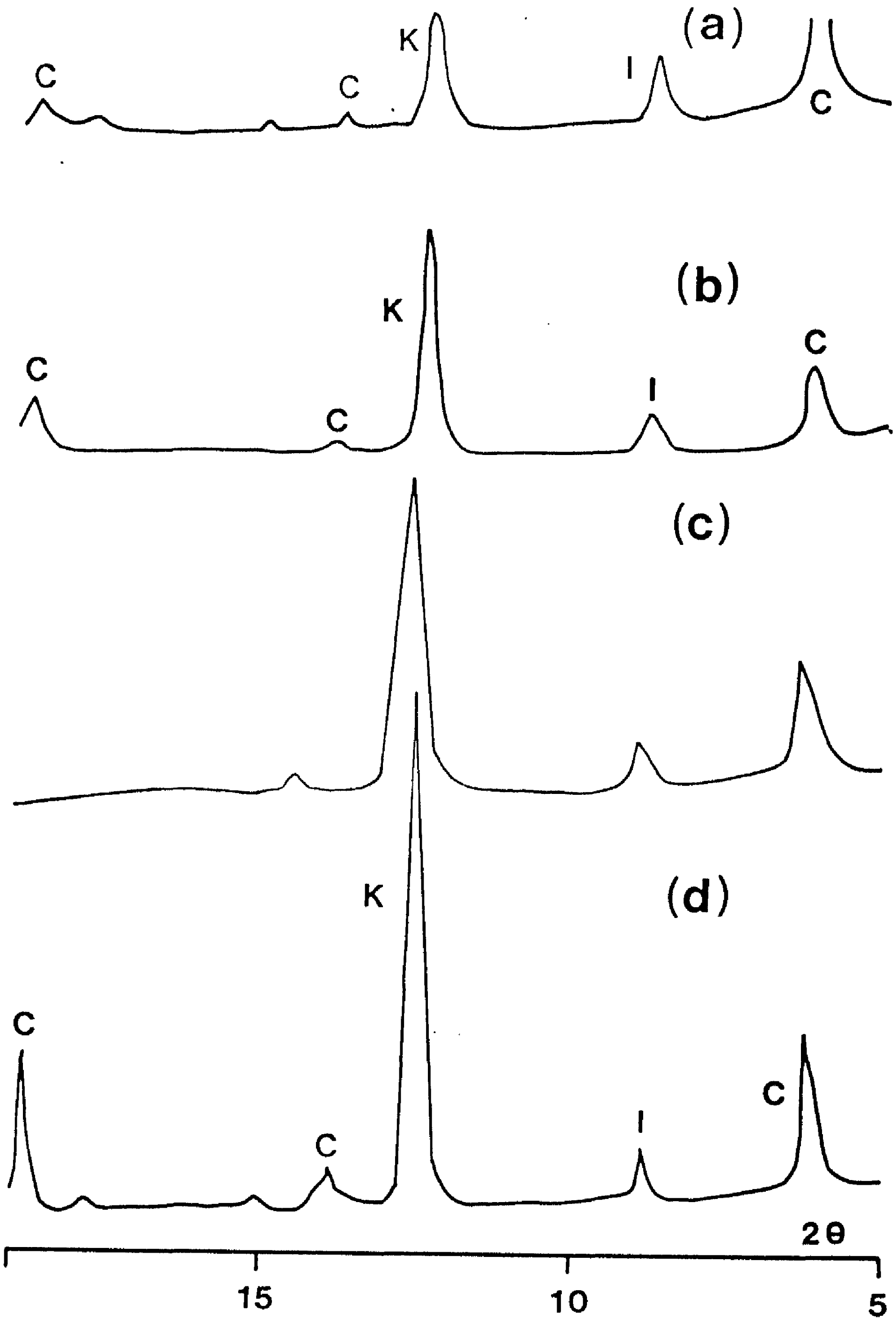


FIGURE 4.17. The X-ray diffraction trace for sample 35 (FG type) See Figure 4.16 for symbols.

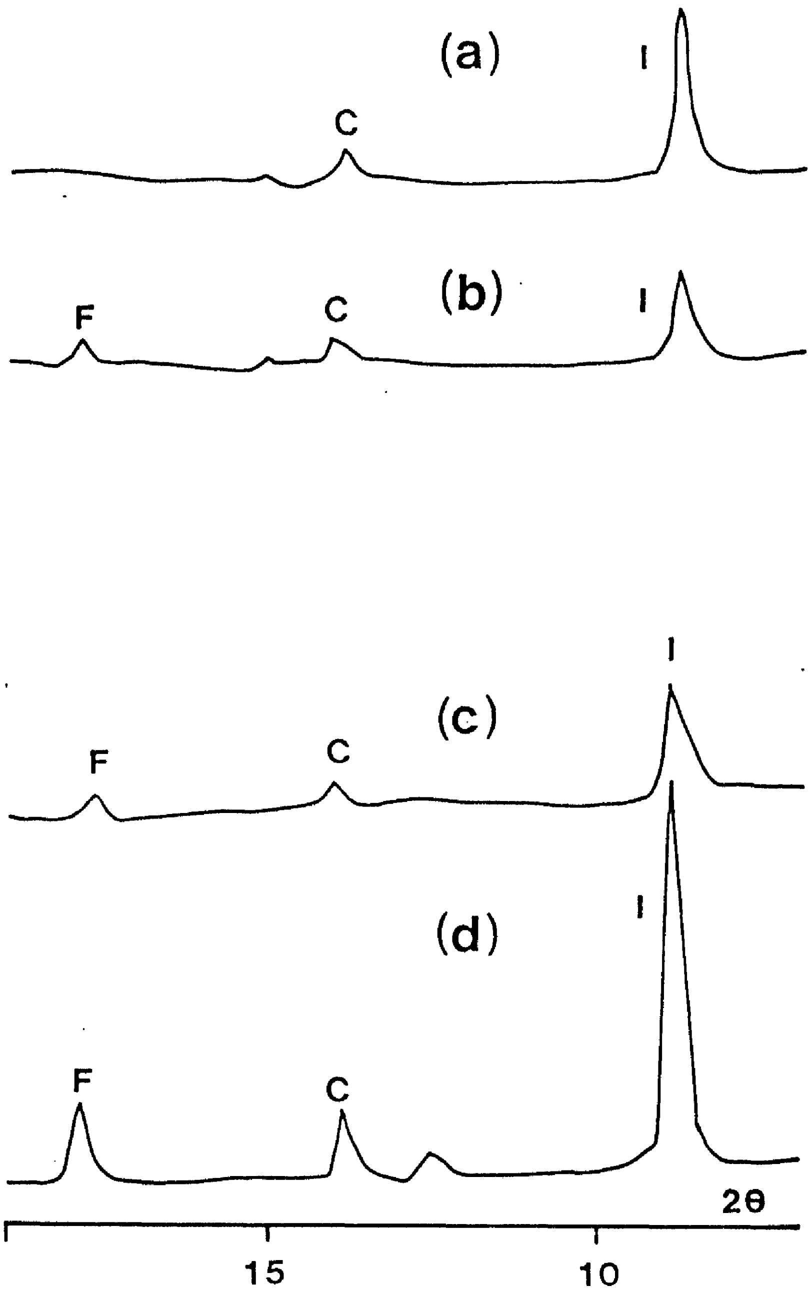


FIGURE 4.18. The X-ray diffraction trace for sample 54 (CGP type) See Figure 4.16 for symbols.

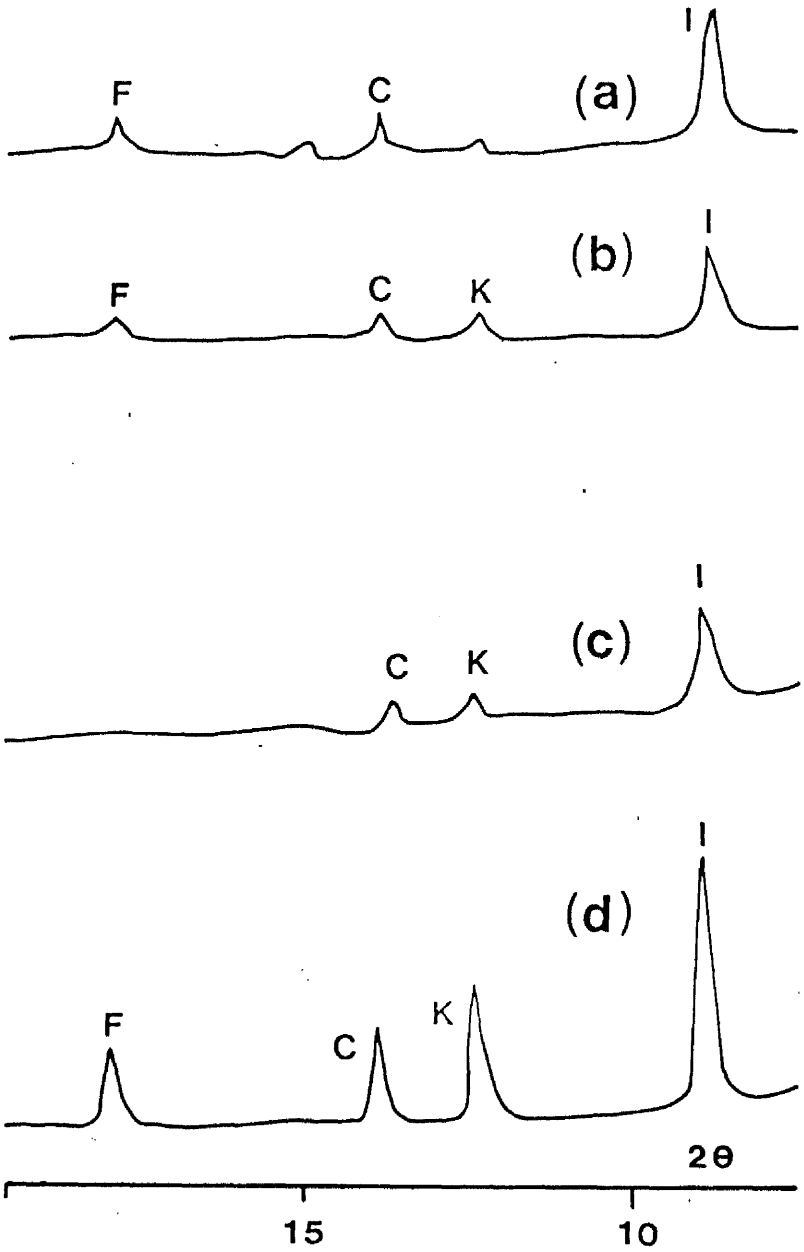


FIGURE 4.19. The X-ray diffraction trace for sample 43 (CGP type) See Figure 4.16 for symbols.

CHAPTER FIVE

Aggregate and its engineering properties

5.1. Introduction

The term 'aggregate' is used to identify any crushed rock or sand and gravel used for a variety of engineering purposes, of which the two main ones are roadstone and concrete. Aggregate normally comprises between 60 to 80 per cent of the volume of Portland cement concrete and bitumen mixes (Fig. 5.1). Therefore they should be hard, durable, clean and free from harmful materials such as clay or dust, iron pyrites, coal, mica, shale or similar laminated material, or flaky or elongated particles, in such a form or in sufficient quantities to affect adversely the strength or durability of the concrete or bitumen mixes (BS 882: 1983). However, the cost of rejecting an aggregate because it is of marginal soundness or contains a small amount of some unwanted material, can sometimes be very high, especially in areas where sound and clean supplies are scarce (Fookes 1980).

The suitability of the Helmsdale granite as an aggregate for use in different engineering purposes is determined by evaluating the material in terms of its physical and chemical properties. Various British standard engineering laboratory tests are employed to assess the suitability of these aggregates for use in structural purposes, including roadstone and concrete making. And finally, the influence of mineralogical and geochemical changes, as a result of weathering processes, upon aggregate engineering properties have been investigated.

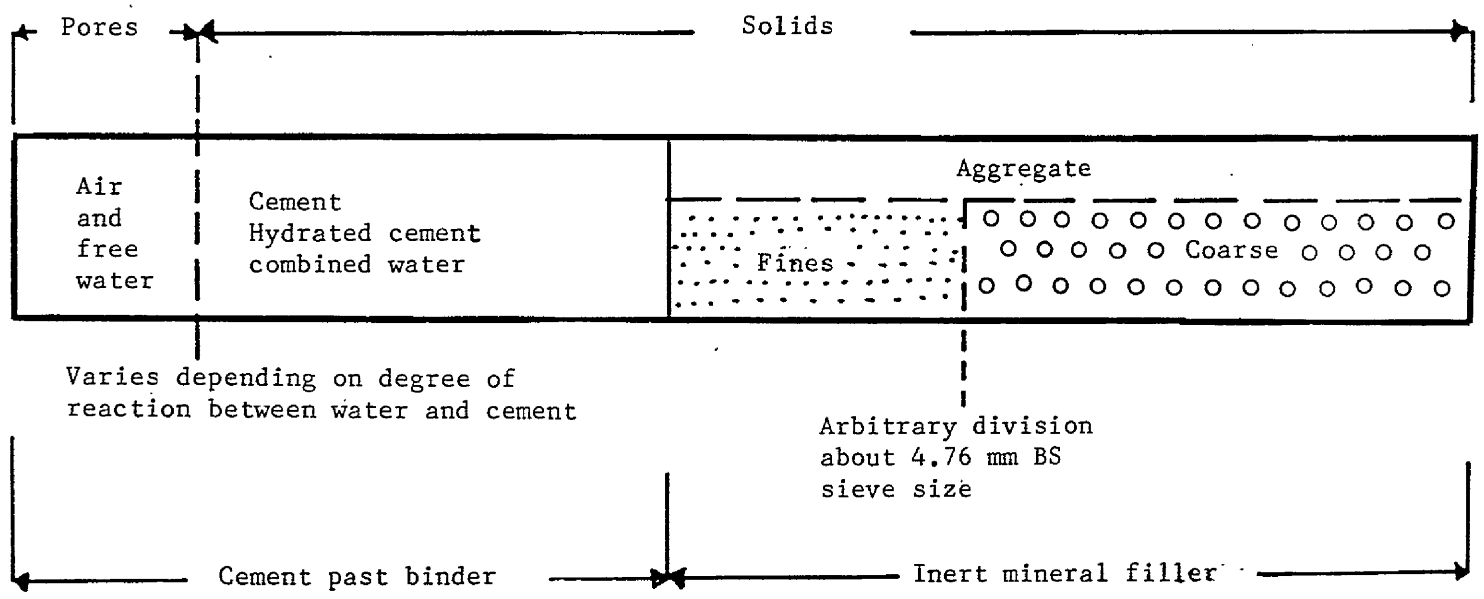


FIGURE 5.1. Range of proportion of materials used in the construction of typical Portland cement concretes. (Fookes 1980).

5.2. Geological factors affecting aggregate properties

The assessment of quality of aggregate is achieved through a set of physical tests (BS 812 : 1975). Based on the results obtained by these tests, it is common to find that the physical performances of crushed rock aggregates from different sources are not comparable, even if the parent rocks are the same (i.e. the Helmsdale granites). This lack of similarity in aggregate performance is mainly due to certain geological factors such as petrography and weathering processes to which the parent rocks may have been subjected after they had formed (Woods _et al_. 1960; Hosking 1968, 1976; Hartley 1968, 1974; Ramsay _et al_. 1974; Lee _et al_. 1975; Irfan _et al_. 1978; Kazi _et al_. 1980). The difference in aggregate performances is particularly more pronounced when there are differences in their grain sizes, porosity and degree of alteration. This point however, has been investigated in the present study of the two distinct grain size varieties of granite rocks of the Helmsdale area.

5.2.1. Petrography

This depends upon a) rock type and b) rock texture. Properties such as porosity, grain size, proportion of soft minerals and the development of foliation depend upon the process of crystallization in igneous rocks. In their unweathered state, most igneous rocks possess low porosity and are relatively hard due to the nature of the silicate minerals and the crystalline texture, and give high strength aggregates (Hartley 1974).

Rock texture has already been described as another important factor affecting the performances and properties of aggregates. In particular:

1). The orientation and arrangement of minerals in a rock, and
2). the occurrence and distribution of fossils or metallic ores within the rock.

Rocks such as quartzite which is almost entirely composed of quartz are brittle, but have a high resistance to abrasion (see page 172) even although they tend to have rather low crushing or impact strengths. Matthews (1961) demonstrated that aggregates with high silica contents (such as acidic igneous rocks), show higher resistance to abrasion and poorer adhesion to bituminous binders in the presence of water than more basic igneous rocks which contain less free silica and have a much higher ferromagnesian content. Coarse-grained rocks tend to be weaker in strength than medium to fine-grained rocks (see Figs for AIV, ACV, 10% fines). Aggregate which possesses a rough surface, due to the type of its mineral constituents, will exhibit a greater surface energy (Hughes et al. 1959) and thus forms a stronger bond between bitumen and aggregate.

Any 'inclusions' in rocks such as fossils or metallic ores, will have an effect upon the aggregate properties, and the extent of any effect depends upon the size, proportion and distribution of these inclusions within the rock.

5.2.2. Chemical alteration

Chemical alteration and the manner in which it develops can strongly influence aggregate properties. Alteration may proceed on the periphery, within a crystal, (kernel alteration), or throughout the whole crystal. Of the two types of granite in the present study, the coarser-grained porphyritic type (CGP) has been more affected by peripheral weathering than the finer-grained type

(FG). Peripheral weathering may reduce the bonding strength between grains so that their minerals are easily pulled out as was shown by some samples of the CGP type (e.g. samples 75 and 92).

Knill (1960) and Hartley (1968) showed that a small amount of alteration materials within a rock can improve its resistance to polishing since an assemblage of hard and soft minerals may increase the degree of roughness of stone surface (see PSV test results in this chapter).

In the U.K. however, chemical weathering is usually a long term process and is not therefore considered important in relation to the relatively short period that an aggregate is in service. In other countries and particularly those with tropical and sub-tropical climates, weathering can present a major problem to engineers with the stability of structures as was shown by several workers (Weinert 1968; Fookes _et al_. 1971; Dearman _et al_. 1978).

5.3. _Aggregate shape and surface texture_

A property perhaps even more important than strength is particle shape. Angular aggregate characteristics give a better interlocking property which increases the stability of all types of mixes. Thin and elongated aggregate pieces on the other hand, besides being subjected to size segregation in the mixing process, tend to be of low strength.

The importance of shape and surface texture characteristics were studied by Maupin (1970) who discussed the fatigue life of asphalt mixes, and concluded that a significantly shorter life occurs in mixtures containing "slabby" shaped aggregate. In concrete production, smooth and rounded aggregate particles are often more common (from gravel deposits, etc.), but due to their weaker bond with cement paste, the concrete produced has a lower strength than one made with angular particles which bond better with the cement.

The shape and surface texture of an aggregate particle derived by crushing depends in part on the presence of cleavage in some minerals, so that angular particles are produced by crushing, whereas the existence of crystals such as quartz, which has no cleavage, usually produces equidimensional particles. Many mineral crystals such as feldspar possess two cleavages which can cause rectangular shaped particles, which are even less desirable.

If weathered rocks are used to produce aggregate, the presence of cleavage and its effect on the shape of the particle becomes stronger. For example, in the present study, due to a high proportion of K-feldspar and quartz, the coarser-grained porphyritic type (CGP), in particular, has produced angular- to rectangular-shaped particles whereas the finer-grained type (FG) with a high percentage of mica (see petrography section) and finer-grained minerals has produced more elongate-shaped particles. Details in particle size and shape analyses can be found in BS 812: 1975.

5.4. Specific gravity, relative density and water absorption

Specific gravity of an aggregate is the ratio of its weight to the weight of an equal volume of water. Although this value is used in certain computations for mix design, it is not generally used as a measure of the aggregate quality. Specific gravity determinations reported for most aggregates in common use show that values varying between 2.4 and 2.9 appear to be strongly dependent upon contents of iron and magnesium-rich minerals in igneous and metamorphic rocks and the accumulation of such minerals in sedimentary rocks.

Bhatia and Hammond (1970) have shown that specific gravity values may be useful in the identification and classification of laterite rocks and related aggregates for construction purposes. Based on specific gravity test results on such laterite rocks De Graft-Johnson et al. (1972) demonstrated that a linear correlation exists between specific gravity and aggregate impact and abrasion values. They showed for example, that high specific gravity values are associated with aggregate having lower AIV and AAV. An attempt was made to establish the existence of such a relationship between specific gravity results and the engineering properties of aggregate for weathered granite rocks of the Helmsdale types. The results obtained showed that the finer-grained type, in general, has a slightly higher specific gravity accompanied by higher aggregate strength (AIV, ACV, 10% fines) than the coarser-grained type. This study also shows that variation in aggregate physical properties within each granite type has no significant correlation with specific gravity test results.

Water absorption tests on the other hand, have produced more reliable results in the present study. Water absorption value is expressed as a percentage of the ratio of mass of the water absorbed by the sample to mass of the oven-dried aggregate in air.

In Figures 5.2. and 5.3. water absorption values are plotted against aggregate impact and abrasion values. These figures show that between the two types of Helmsdale granite the finer-grained type (FG) possesses slightly higher water absorption values than coarser-grained porphyritic (CGD) granite. These plots also show that the

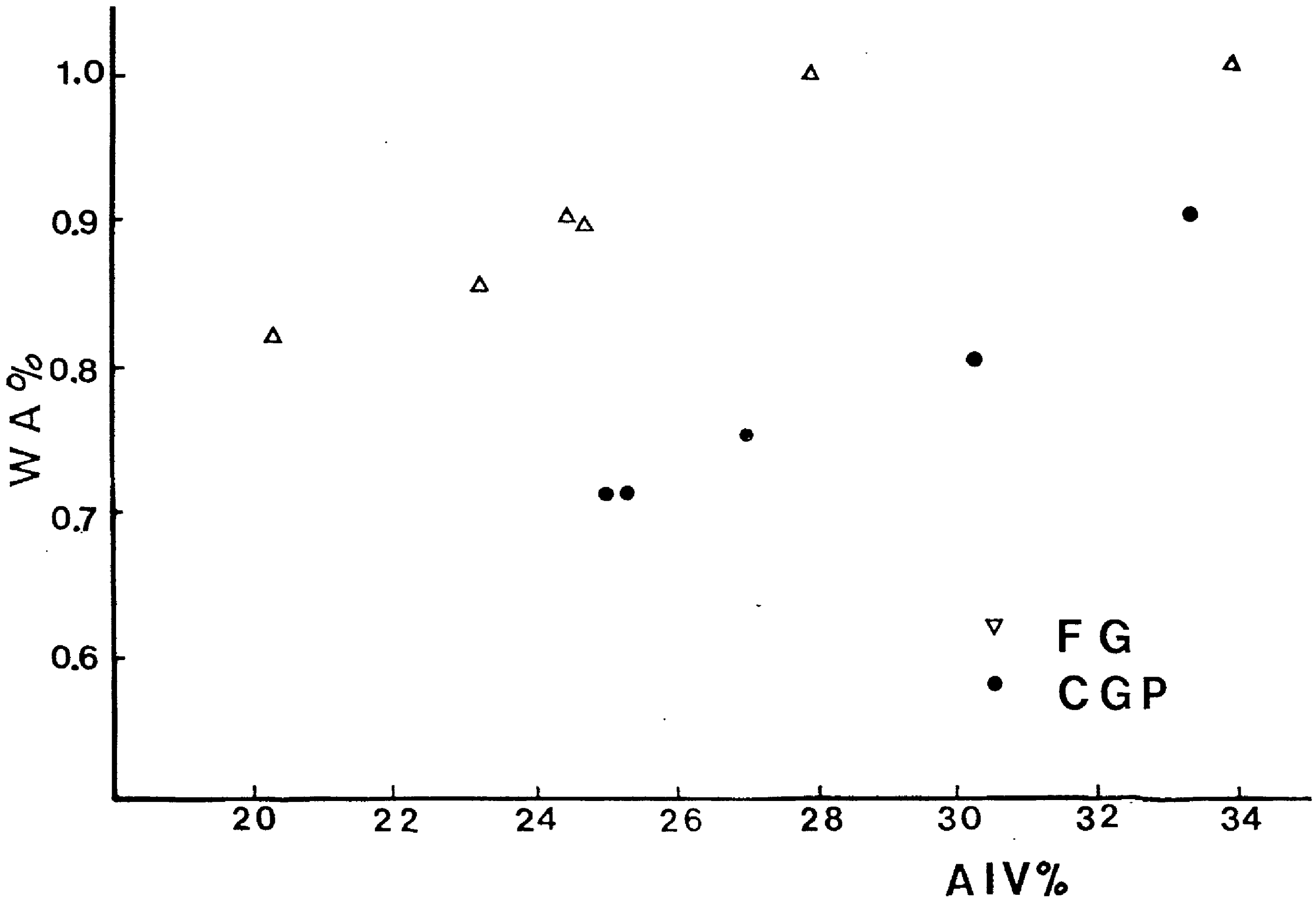


FIGURE 5.2. AIV values against water absorption.

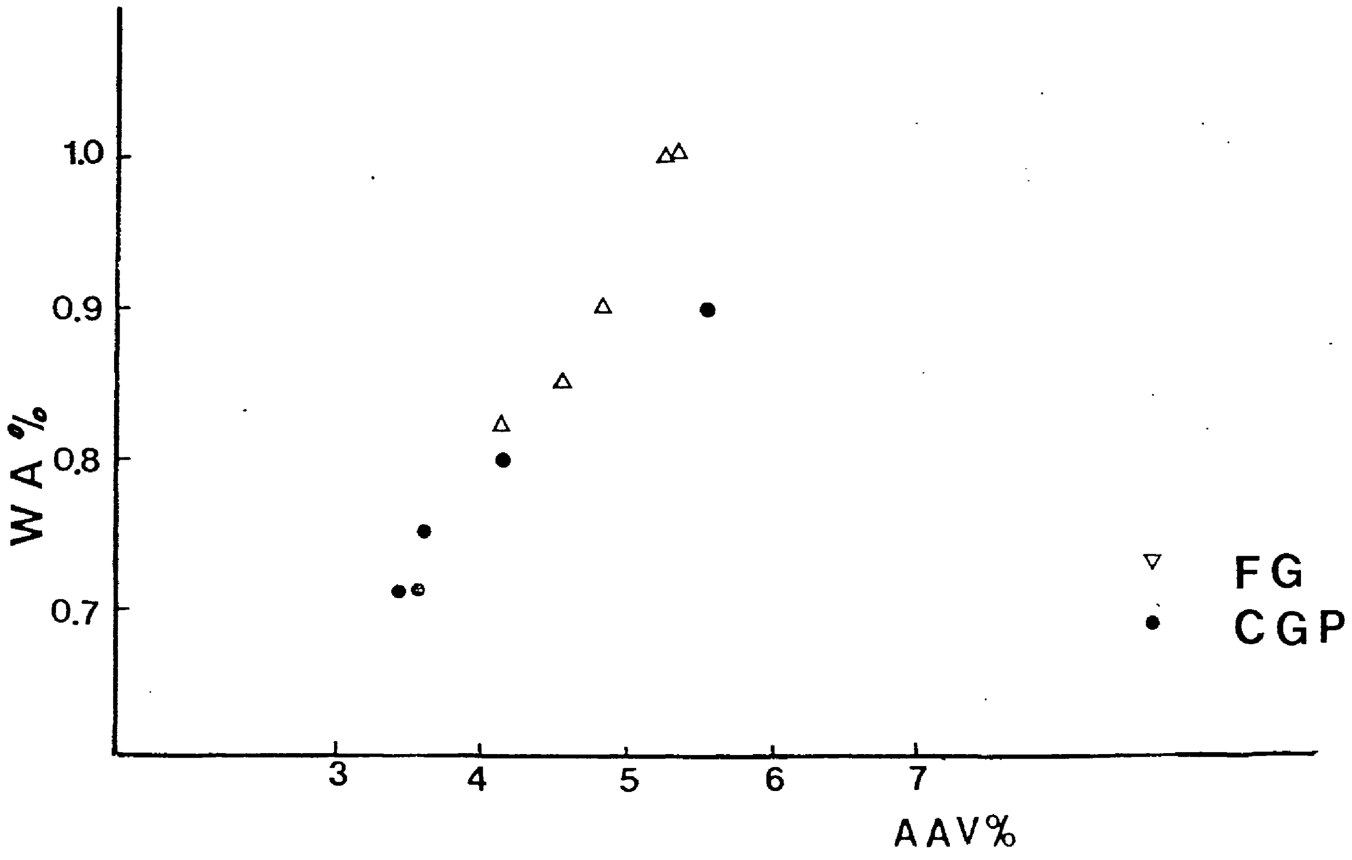


FIGURE 5.3. AAV values against water absorption.

water absorption values obtained for both granite types correlate well with mechanical properties such as aggregate impact, abrasion, crushing and 10% fines values, and may be useful in the evaluation of weathered rocks and aggregates for engineering purposes.

Although no specification exists for the maximum water absorption values allowed in aggregate, values for igneous and metamorphic rocks are usually less than 1% and for sedimentary rocks are usually less than 5% if these rocks are going to be successfully employed for engineering purposes. The water absorption values for the two granite types are different (see Appendix 3). The coarser-grained porphyritic type (CGP) has water absorption value of about 0.09% whereas in the finer-grained type (FG) this value reaches up to 1% and both values are acceptable for most engineering purposes.

In Figure 5.4. water absorption values are plotted against 10% fines values. If the water absorption values can be regarded as an indication of the degree of weathering, then Figure 5.4. shows that for any given water absorption, the required force necessary to get 10% fines values, for the finer-grained type, is higher than for the coarser-grained porphyritic type. In other words, for the same type of weathering process affecting both granites the FG type with a water absorption value of, say, 0.9% required a 10% fines - about 160 kN, which is higher than the CGP type granite with the same water absorption (0.9%), which required a much lower force - 125kN.

Determination of relative densities was carried out to assess the variation in degree of the weathering between the two granite types. The method of testing adopted for the present study was that explained by BS 812 (1975) for aggregate 10mm nominal size and smaller. The

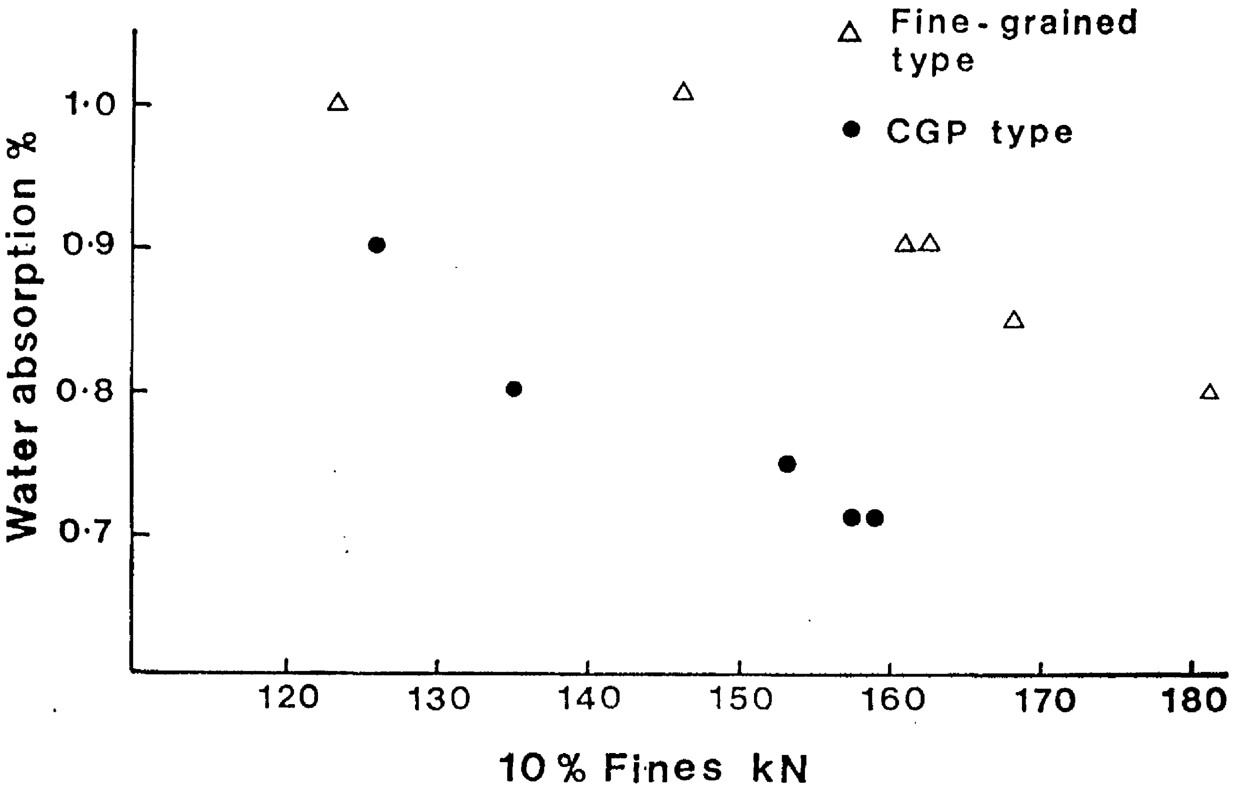


FIGURE 5.4. 10% fines value against water absorption.

results (see Appendix 3) are based on three different conditions, as follows: a) Oven dry basis, b) saturate and surface dry basis and c) air dry basis (the apparent density).

5.5. Aggregate strength

In general, the strength of an aggregate depends on its mineral composition, texture and structure. Thus, a low strength specimen may be due to weakness of its constituent mineral grains if they are weathered.

Several engineering tests were employed to determine aggregate strength as follows:

5.5.1. Aggregate Impact Value (AIV)

This test measures the resistance to sudden shock or impact by subjecting a prepared test sample in a cylindrical steel cup, having an internal diameter of 102mm and an internal depth of 50mm, to a total of 15 blows from a 13.5kg to 14kg hammer, falling freely from a height of 380 ± 5mm. The percentage of the ratio of mass of fines passing a 2.36mm BS sieve to total sample mass is known as the aggregate impact value. The stronger the aggregate the lower are the aggregate impact values.

This test, combined with the aggregate crushing value test (see page 165), are two standard tests recommended by the British Standards Institute (BS 812, 1975) to assess the strength of road aggregates under different conditions of loading, namely repeated impact loading or continuous loading (static) in the AIV and ACV tests respectively.

Typical aggregate impact values obtained for the roadstone from different rock groups are given in Table 5.1. (from R.R.L. 1963). According to this table, the average aggregate impact value obtained for granite is 19%, which is very good compared with values of more than 30% obtained from weathered rocks. The former value, however, is regarded by engineers as an unsatisfactory value for hard wearing road surface purposes, and should be avoided.

Ramsay (1965) in the investigation of the aggregate strength tests demonstrated that within specific rock groups (i.e. granite), aggregate impact value is dependent on aggregate particle shape, and in particular the aggregate flaky index (If). He also argued that the choice of fines passing the 2.36mm sieve as the critical size to assess the strength of roadstone aggregate is an arbitrary value and does not take into account the percentage of original size range aggregate retained on a 10mm sieve after the impact test, which he called 'aggregate impact value residue (AIVR). Ramsay (1965) introduced this value for the first time as a more sensitive way to assess the quality of roadstone aggregate and the "in service" performance of such aggregate than the aggregate impact value. This AIVR test, however, has its limitations like some other aggregate tests currently used. The main condition for this test was that the samples under investigation belonged to groups of fresh, fine-grained igneous rock aggregates having a high flaky index (I_f). In a situation where the aggregate used is weathered or has a low flaky index, the shape of aggregate particles becomes less significant and instead the petrographic-petrological characteristics of the rock dominate. As a result, more studies were needed to investigate the behaviour of different rock groups with different strengths and grain sizes when subjected to impact and crushing tests,

Group classification B.S. 812:1960		Aggregate crushing value*	Aggregate impact value*	Aggregate abrasion value*	Water absorption (per cent)	Specific gravity	Ten per cent fines aggregate crushing value	Polished stone coefficient
Artificial	Mean	28	22	8·3	0·7	2·68	—	**0·59**
	Range	(15–39)	(17–33)	(3–15)	(0·2–1·8)	(2·8–2·6)		**(0·35–0·74)**
	No. of samples	55	21	18	18	18		**33**
Basalt	Mean	14	15	6·1	1·1	2·80		**0·62**
	Range	(7–25)	(7–25)	(2–12)	(0·0–2·3)	(3·0–2·6)	—	**(0·45–0·81)**
	No. of samples	123	79	65	68	68		**70**
Flint	Mean	18	23	1·1	1·0	2·54	—	**0·39**
	Range	(7–25)	(19–27)	(1–2)	(0·3–2·4)	(2·6–2·4)		**(0·30–0·53)**
	No. of samples	63	32	45	24	24		**7**
Granite	Mean	20	19	4·8	0·4	2·69	—	**0·59**
	Range	(9–35)	(9–35)	(3–9)	(0·2–0·9)	(3·0–2·6)		**(0·40–0·70)**
	No. of samples	41	32	28	16	16		**23**
Gritstone	Mean	17	19	7·0	0·6	2·69	—	**0·72**
	Range	(7–29)	(9–35)	(2–16)	(0·1–1·6)	(2·9–2·6)		**(0·60–0·82)**
	No. of samples	81	45	31	33	33		**32**
Hornfels	Mean	13	12	2·2	0·4	2·82	—	**0·45**
	Range	(5–15)	(9–17)	(1–4)	(0·2–0·8)	(3·0–2·7)		**(0·40–0·50)**
	No. of samples	28	24	13	15	15		**4**
Limestone	Mean	24	23	13·7	1·0	2·66		**0·43**
	Range	(11–37)	(17–33)	(7–26)	(0·2–2·9)	(2·8–2·5)	—	**(0·30–0·75)**
	No. of samples	164	61	34	42	42		**51**
Porphyry	Mean	14	14	3·7	0·6	2·73	—	**0·56**
	Range	(9–29)	(9–23)	(2–9)	(0·4–1·1)	(2·9–2·6)		**(0·43–0·71)**
	No. of samples	62	29	23	30	30		**23**
Quartzite	Mean	16	21	3·0	0·7	2·62	—	**0·58**
	Range	(9–25)	(11–33)	(2–6)	(0·3–1·3)	(2·7–2·6)		**(0·45–0·67)**
	No. of samples	57	37	29	21	21		**20**
All groups†	Mean	19	19	5·7	0·7	2·68	17	**0·58**
	Range	(5–39)	(7–35)	(1–26)	(0·0–3·7)	(3·0–2·3)	(1–37)	**(0·30–0·83)**
	No. of samples	724	370	311	312	312	69	**292**

TABLE 5.1: Groups of aggregate and their properties

as well as the relative residue tests (AIVR and ACVR).

Only recently, research was carried out in Glasgow University to investigate the influence of the mineralogy of weathered granite upon aggregate impact and crushing values. (Moore and Gribble 1980), who demonstrated that aggregate impact and crushing values increased (lower strength aggregate), as the amount of feldspar (plagioclase in particular), decreased due to breakdown of feldspar during weathering processes.

In the present study, however, the aggregate impact test was carried out to investigate the following points: a) To assess the strength of the Helmsdale granites aggregate (both FG and CGP types), and b) check the validity of the AIV and AIVR test result for weathered and low-strength aggregates from both the finer and coarser grained Helmsdale granites.

The Helmsdale granites were particularly suitable for this investigation since there are two types, the CGP type (outer part) and FG type (inner part). Both granites were derived from a single magma (see Chapter 3) and were subjected to the same weathering processes (see Chapter 4), thus a comparison of the influence of grain sizes and degree of weathering upon aggregate impact and residue values can be made between the two granite types.

The aggregate impact test was carried out in accordance with BS 812: 1975, whereas impact residue testing was carried out using procedures introduced by Ramsay (1965). The AIVR was determined by measuring the amount of aggregate retained on 10mm sieve after the aggregate impact test; expressed as a percentage of the original sample by weight.

Because of the nature of the rocks under investigation, sample

Sample No.	AIV	AIVR
	%	
1	20.82	22.12
2	23.00	18.01
3	21.09	20.91
7	20.84	22.19
11	18.65	26.25
14	17.35	28.14
15	21.04	25.10
17	19.30	30.32
18	20.44	22.53
21	29.17	10.10
24	19.55	31.11
25	20.62	23.14
29	20.1	21.19
30	19.08	29.80
32	17.26	27.47
34	18.28	20.81
37	17.21	30.01
41	22.01	20.71
43	26.22	15.28
44	24.31	16.00
45	25.08	15.97
49	26.35	15.90
53	24.51	16.72
54	24.00	16.50
70	27.84	15.73
71	24.09	17.00
73	28.78	16.13
75	32.84	9.13
86	25.25	16.5
90	26.14	21.15
92	22.97	20.15
94	25.96	15.45
95	23.45	21.20
96	27.82	12.52
97	23.14	17.79
98	25.81	-
99	30.83	10.9
100	29.79	12.5

TABLE 5.2. Aggregate impact and impact residue values.

preparation was probably the most important part, since weathered minerals such as feldspar and biotite are prone to breakdown during grading and sieving procedure and reduce to finer fractions which will, in turn, reduce aggregate impact value and increase aggregate impact value residue values. Therefore sampling procedure was carried out in accordance with BS 812 (1975) with some additional care so as to reduce the effect of the 'grading factor' upon the aggregate properties. In particular:

1. Grading of samples was carried out in a shorter period by widening the jaw gap in the mechanical crusher.
2. Sieve procedure was carried out by hand and for a shorter time, rather than using a mechanical shaker.
3. No attempt was made to wash the samples. Since this procedure would cause further reduction in particle size and the loss of more fine fractions as a result.

In Table 5.2. the aggregate impact values and related impact value residue values are given for both finer-grained (FG) and coarser-grained porpyritic (CGP) type granites.

In Figure 5.5. aggregate impact values (AIV) are plotted against related aggregate impact value residue (AIVR). This figure shows that the relationship between AIV and AIVR is a linear one and those samples with higher impact values produced a lower AIVR. Figure 5.5. also shows that although both granites were subjected to the same weathering processes, the finer-grained type (FG) gave lower impact values and higher impact value residue than the CGP type. This suggests that among weathered rocks, the most important factors affecting AIV and AIVR are the grain size, proportion and

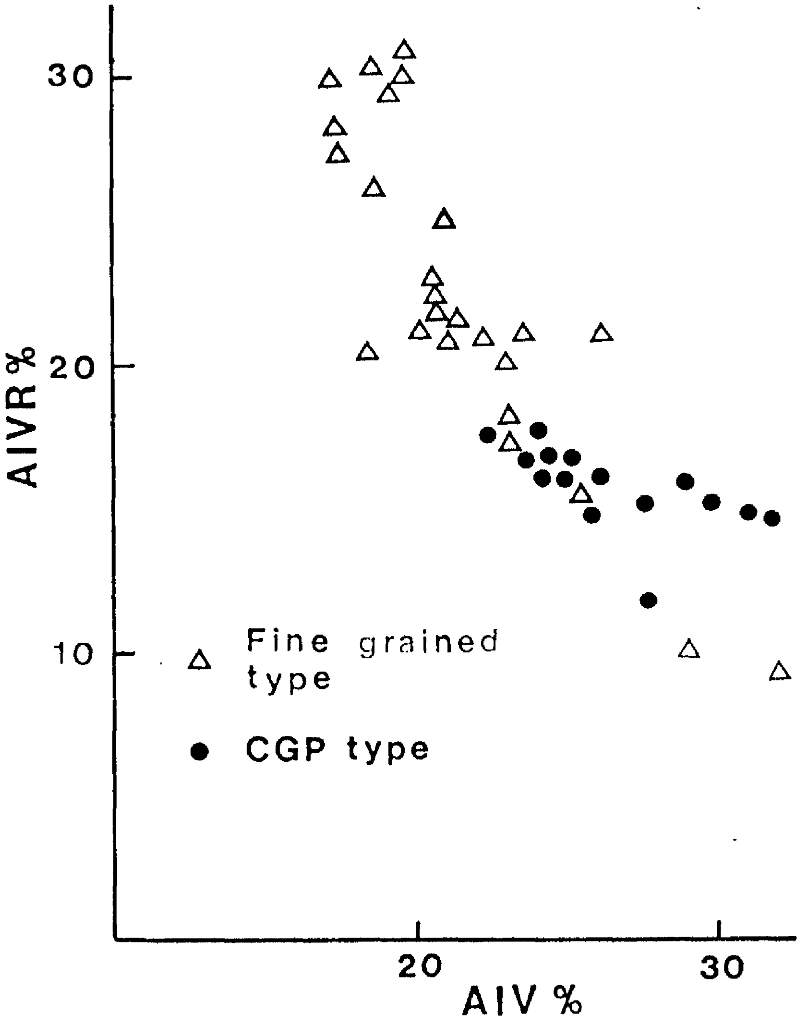


FIGURE 5.5. AIV against AIVR

nature of microcracks (caused by physical weathering), and grain boundary conditions. Thus, the existence of two different AIV and AIVR values for the two granite types of the Helmsdale granite can be explained as follows: - When CGP type samples were subjected to the AIV test, the constituent minerals started to break down. This breakdown may develop along the grain boundaries as well as through the weathered minerals, such as biotite and plagioclase, leaving other minerals, mainly quartz and K-feldspar, to their original sizes. The situation is rather different where FG type samples were subjected to the same AIV test procedure. In this case, because of finer-grain size, the weak"grain boundary effects"no longer exist and mineral constituents of finer-grained type samples were starting to break through the weathered minerals only. Thus, the FG type samples have shown lower AIV than the CGP type samples (see Fig. 5.5).

These different AIV test results obtained for the two granite types from Helmsdale can be further explained by more AIVR test results which tend to support the behaviour of samples under the impact test. For example, as was expected AIVR test results from FG type samples show a linear relationship with AIV results, i.e. the more weathered samples, having higher AIV produced lower AIVR values, whereas in the case of the CGP type, in those samples with AIV values higher than 27% the AIVR has its lowest value and remains almost the same as the AIV value increases (see Fig. 5.5). This result suggests that in the case of weathered CGP type samples with AIV higher than 27% the AIVR test loses its sensitivity and remains unchanged with the increase of AIV.

Normative amounts of each rock specimen from both granite types were used to find out which mineral had an influence over engineering properties of aggregate and also to investigate the effect of mineralogical changes, as a result of chemical weathering, over such aggregate properties. In Figures 5.6, 5.7 and 5.8 the aggregate impact values are plotted against normative plagioclase (Ab + An), normative quartz (Q), and total feldspar (Ab + An + Or). These figures show that overall, the quality of aggregate gradually declines (higher AIV) from finer-grain type granite towards the coarser-grained porphyritic type as the amounts of feldspars decrease, accompanied by an increase in normative quartz in the same direction. Moore (1978) has demonstrated that aggregate properties of Peterhead granite from the north-east of Scotland have declined due to alteration of feldspar; particularly the plagioclase feldspar. Although the highly weathered samples in the present study (AIV higher than 27%) show markedly a reduction in plagioclase content, in the case of the rest of the samples the AIV results for both granite types show a positive linear trend with normative quartz content (Fig. 5.7) rather than plagioclase feldspars (Fig. 5.6). The FG type samples with lower quartz content have produced aggregates with lower AIV, whereas the CGP type, with higher quartz, appears to be lower in strength (higher AIV).

Further support for the above explanation is better illustrated by Figure 5.8, which also shows that the CGP type with higher AIV values has nearly the same amounts of total feldspars as the FG type with lower AIV. There are, however, those points representative of highly weathered samples which show rather unclear trends, except in Figure 5.8 which suggests a further loss of feldspar as a result of alteration process. These results support the conclusion that of the relatively fresh samples, those containing a higher quartz content and coarser grain size, tend to give higher AIV results, than the rock

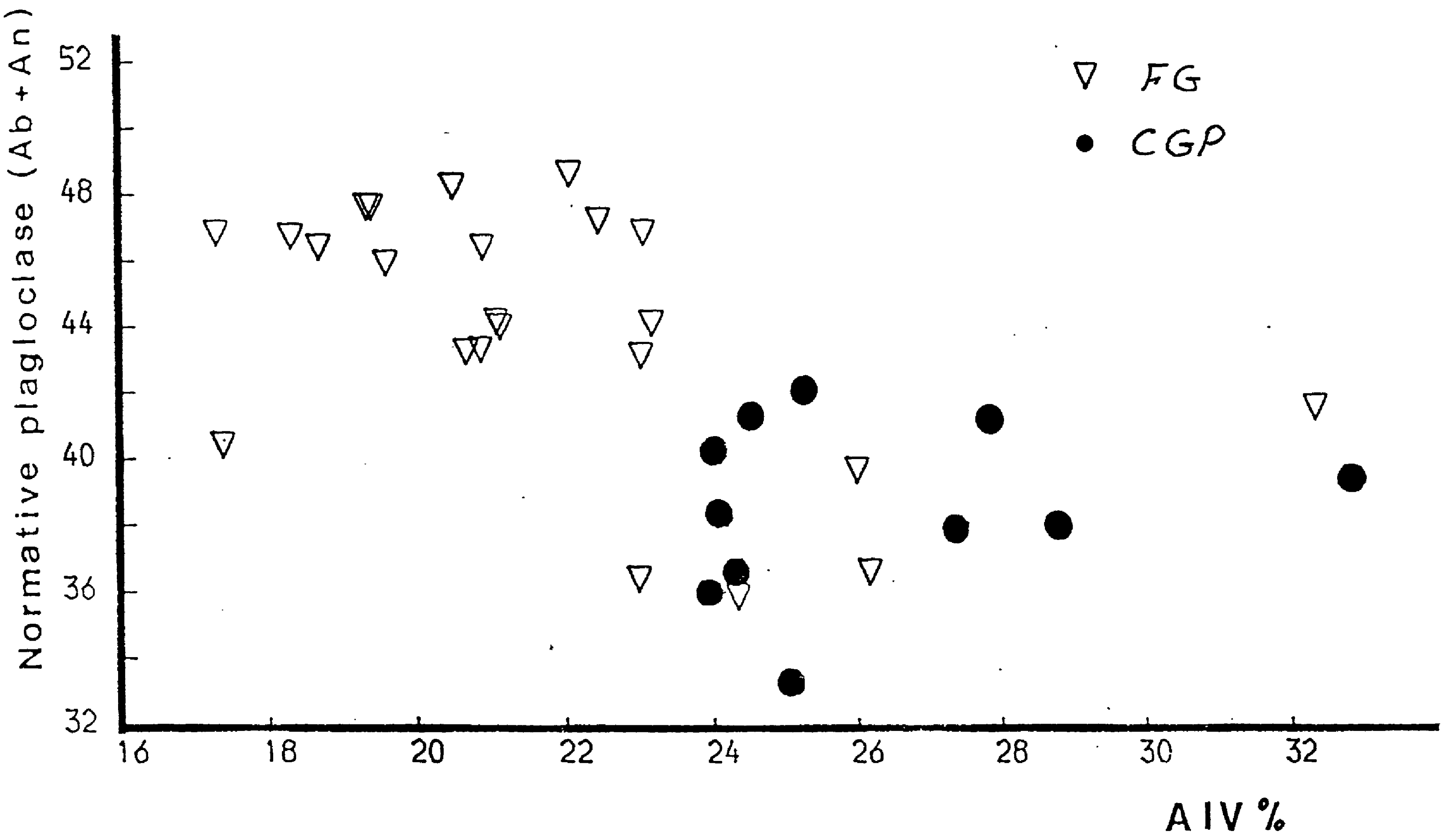


FIGURE 5.6. AIV against normative plagioclase.

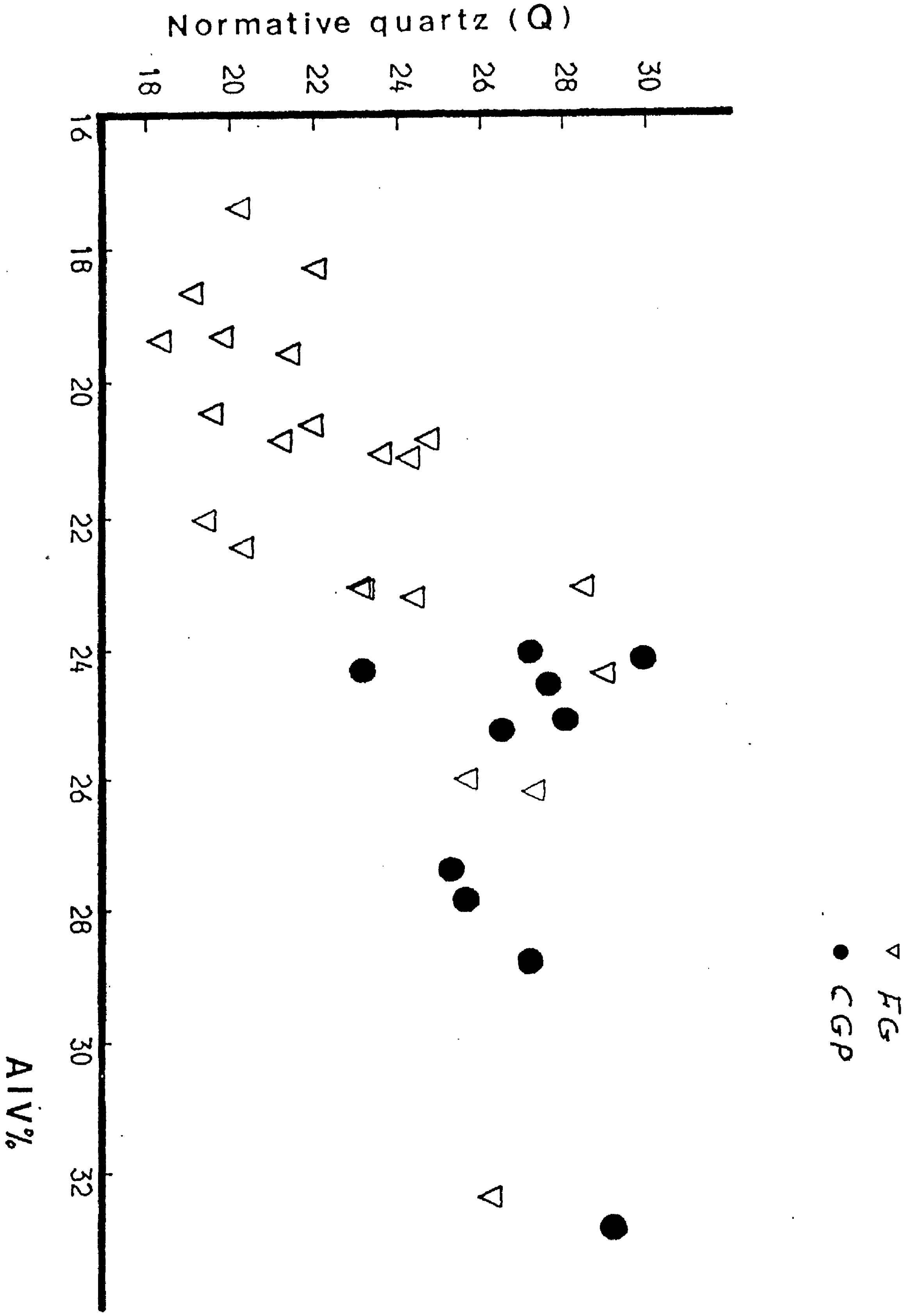


FIGURE 5.7. AIV against normative quartz.

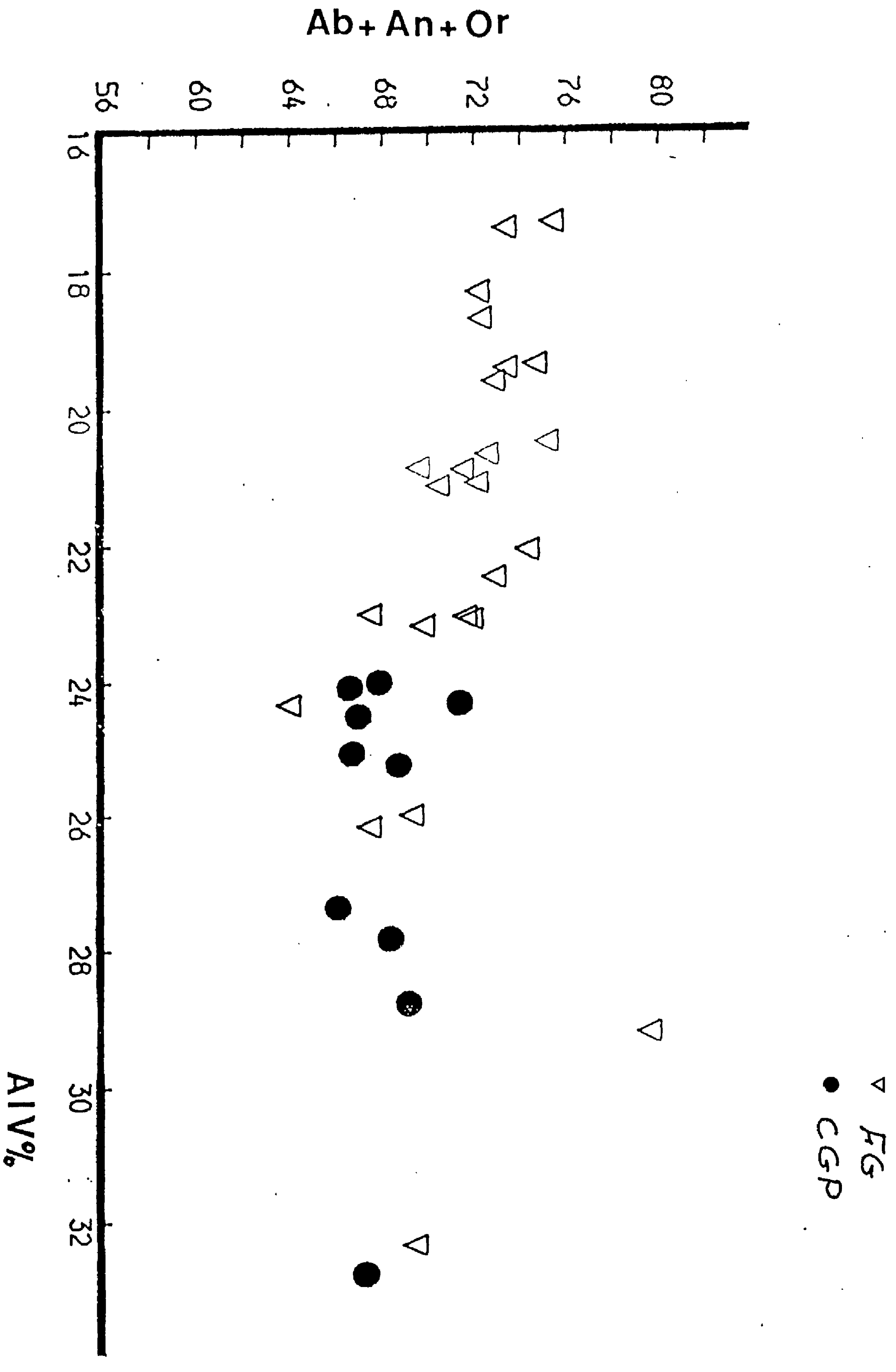


FIGURE 5.8. AIV against normative feldspar

samples which have a lower quartz content and finer grain size (Lees and Kennedy 1975). This is due to the brittleness of the quartz associated with weaker grain boundaries nature of the rock-forming minerals existing in the CGP type samples and the lack of such properties in the FG type.

5.5.2. Aggregate crushing value (ACV)

In this test, a 150mm diameter open-ended steel cylinder is filled in three stages, at equal depths, by 10mm aggregates. The cylinder is then compressed at up to 400kN within 10 minutes at a constant rate. The crushing value is expressed as a percentage of the ratio of mass of fines passing a 2.36mm sieve to mass of the original sample.

Aggregate crushing value (ACV) gives a relative measure of resistance of an aggregate to a static load. Any value below 10% indicates a very strong aggregate and those aggregates with crushing values greater than 35% would be regarded as too weak for any engineering use.

Dhir *et al.* (1971), in the study of the aggregate crushing value of some igneous and metamorphic rocks (such as dolerite, porphyrite, basalt, andesite, dacite and felsite), showed that aggregate crushing values (ACV) for all rock types tested are related in a linear fashion to petrography and flakiness index like those explained for aggregate impact values (see page 154). With increasing flakiness index the aggregate crushing values increased linearly. They also demonstrated that the modified aggregate crushing value residue (ACVR) is more sensitive and more reliable than the standard aggregate crushing value (ACV) test.

Two types of the Helmsdale granites (FG and CGP)were once again used to assess the reliability of this test for weathered aggregate. It appears from Figure 5.9 that the crushing test loses its sensitivity for weaker rocks (AIV $>$27% for the coarser-grained porphyritic type). The aggregate crushing value residue test was not conducted for any samples in the present study. Based on study by Dhir et al. (1971), the same linear relationship was assumed to exist between ACV and ACVR for all samples except those with ACV higher than 27%, which test results are prone to distortion, as was demonstrated by the ACV test results.

5.5.3. 10% fines value

Aggregate with high crushing value results (ACV greater than 35%) frequently give distorted results because of increased degradation during the ACV test. Therefore, another test, the 10% fines test (Shergold and Hosking 1959) can be employed, which is more appropriate for weathered or weak aggregates.

The 10% fines value is obtained by measuring the percentage of fines passing a 2.36mm BS sieve for several loading values; these are graphed against the percentage of fines and the 10% value obtained in kN. This test was carried out for the present study in accordance with the procedure outlines in British Standard 812: 1975. The results are given in Appendix 3.

In Figures 5.10, 5.11, 5.12 and 5.13 the 10% fines values are plotted against normative quartz, albite (as the main constituent of plagioclase feldspar), orthoclase, and total feldspar (Ab + An + Or) respectively. These graphs show that the strength of the aggregate is higher (higher 10% fines value) in the FG type than in the CGP

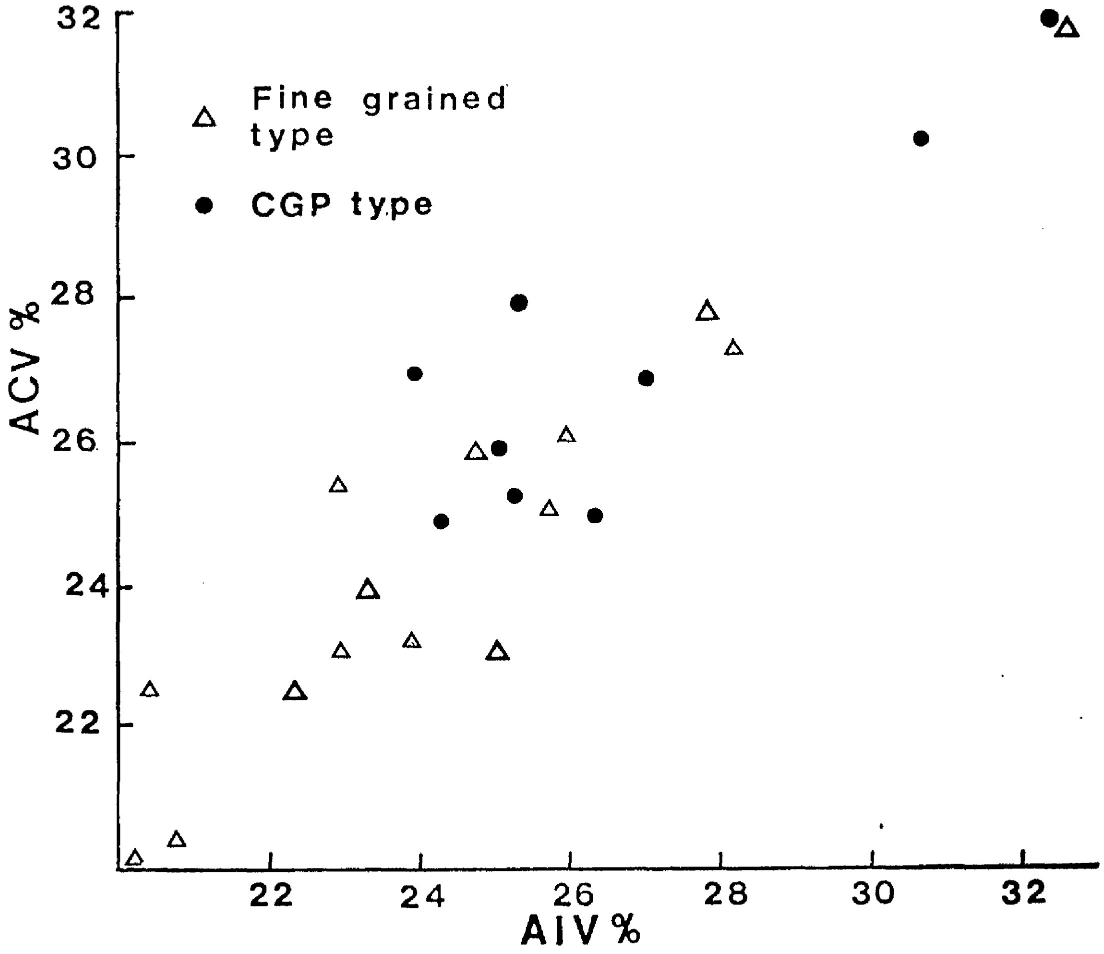


FIGURE 5.9. AIV against ACV.

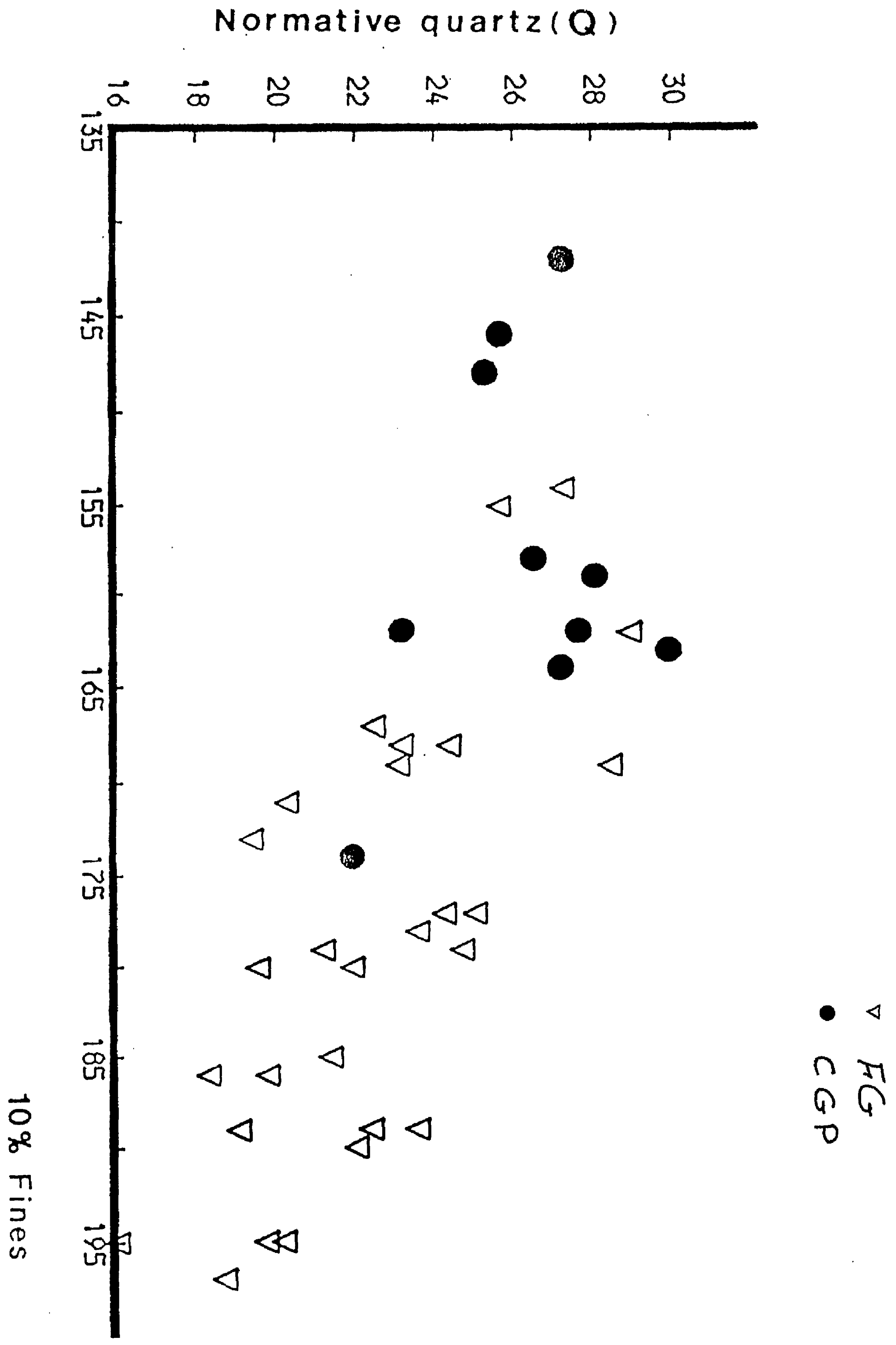


FIGURE 5.10. 10% fines against normative quartz.

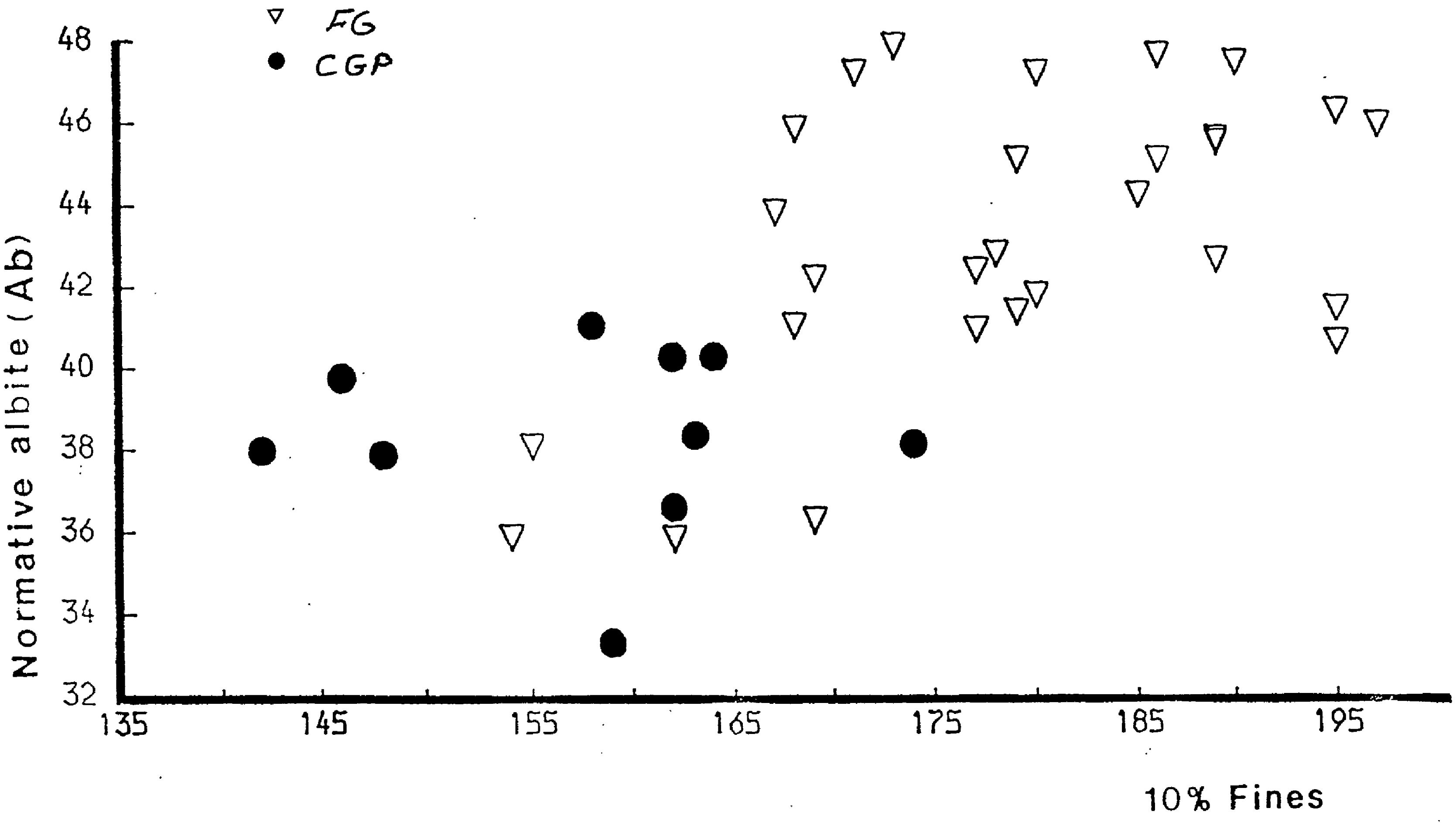


FIGURE 5.11. 10% fines against normative albite.

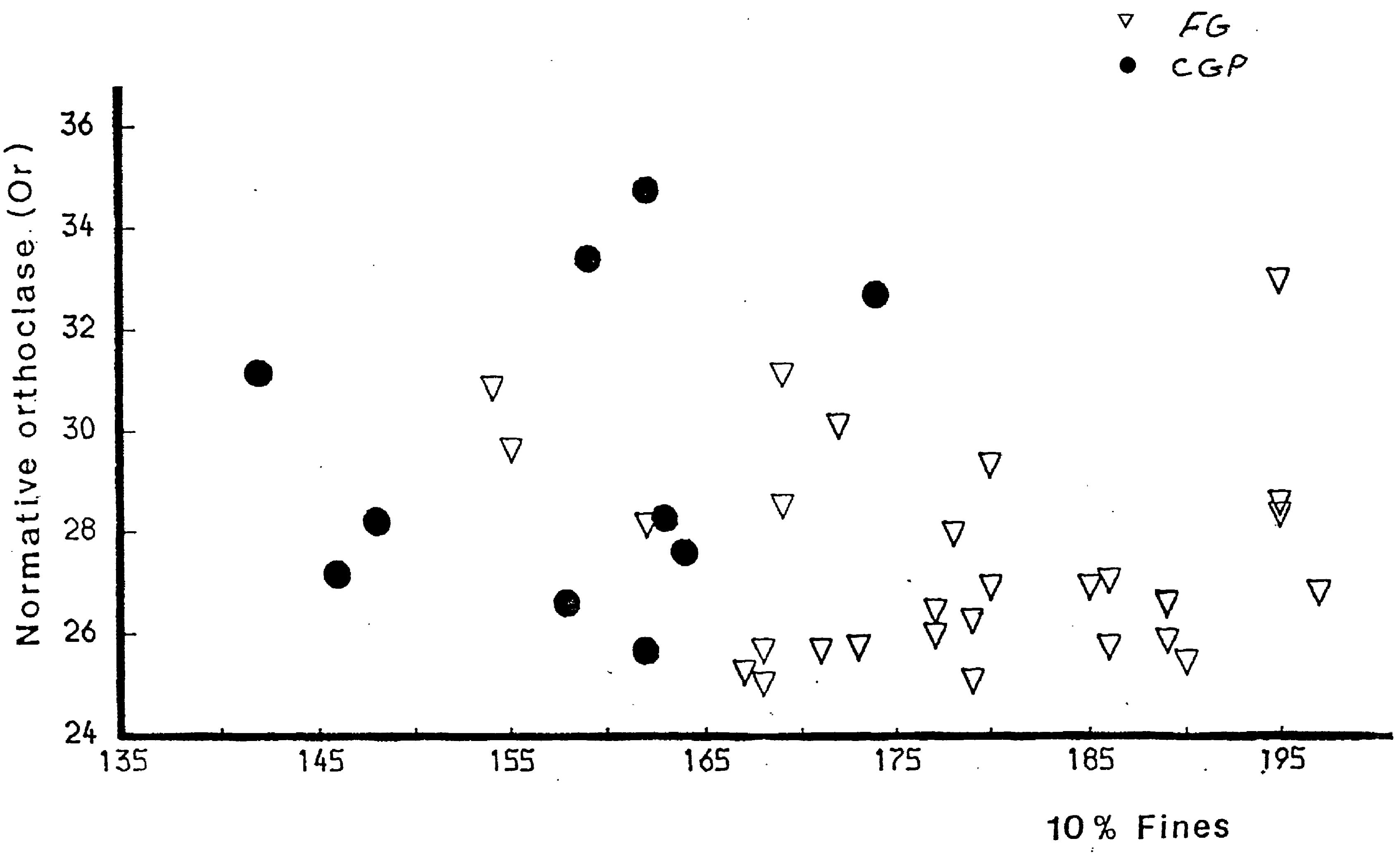


FIGURE 5.12. 10% fines against normative orthoclase.

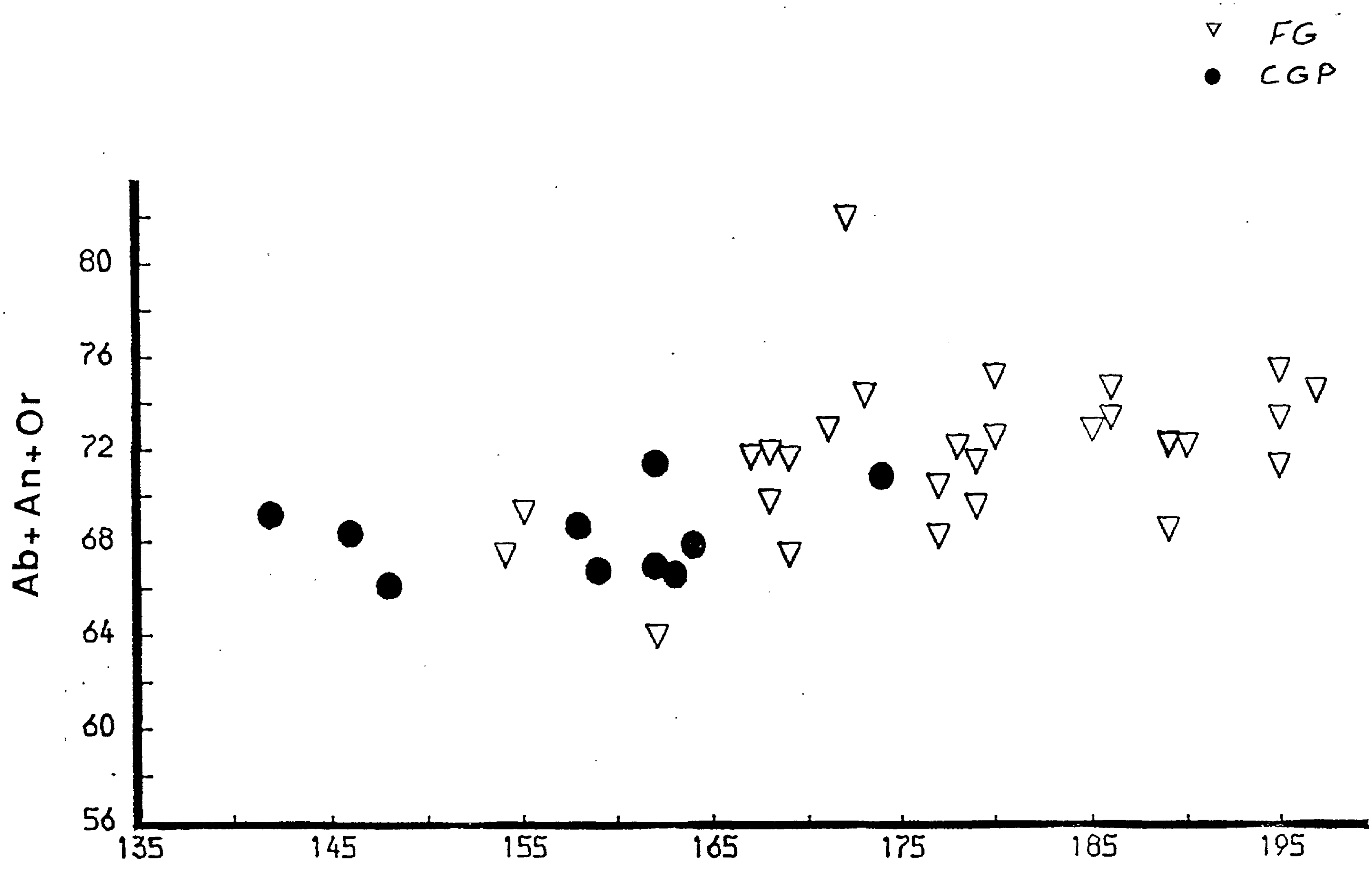


FIGURE 5.13. 10% fines against normative plagioclase plus orthoclase.

type. Furthermore, the amount of orthoclase does not seem to influence the 10% fines values for either granite type. Plagioclase and quartz contents do influence the strength of aggregate, particularly when the rocks are also weathered. Aggregates of both granite types subjected to 10% fines test have shown the same behaviour as explained in AIV test results.

5.6. Special aggregate tests for roadstone

The quality of roadstone aggregate is of great importance in determining the uses to which it can be put. The relevant tests are as follows:

5.6.1. Aggregate abrasion value (AAV)

The term "abrasion" means surface wear by means of attrition and the AAV gives a measure of the resistance of aggregate to such surface wear. The abrasion characteristic of the aggregate used in heavily trafficked road surfacing is a major factor in determining its resistance to wear. The AAV is expressed as the percentage loss of weight of aggregate particles mounted on a flat plate which is subjected to abrasion by a standard quartz sand (Leighton Buzzard silica sand) in a Dory abrasion machine consisting essentially, of a machined flat circular steel grinding lap. The lower the abrasion value, the better the aggregate quality will be. The range of values varies from 1% for hard, resistant rocks (i.e. quartzite, flints) to more than 14% for softer, easily eroded rocks (i.e. limestones, weak sandstones).

Weathered aggregates usually give very high abrasion values, due to chemical decomposition, which can destroy the intergranular bond between the mineral grains, particularly in siliceous sedimentary rocks like sandstones, where the resistance is almost entirely dependent upon the nature of such intergranular bonds.

Among igneous rocks however, those acidic types with a high silicate and free silica content tend to be more resistant to abrasion (lower AAV) than basic varieties, with a high ferromagnesian, low silicate and no free silica (Hartley 1974). For example, fresh granites generally have abrasion values of about 3 - 4% whereas gabbros and dolerites have abrasion values of about 5%. Vesicular and amygdoloidal texture may also affect the AAV result depending on the nature of the mineral infilling, but in general they lower the resistance of the aggregate to abrasion. Hartley (1974) and Kasi (1980) also pointed out that the main factors causing a reduction in aggregate abrasion resistance are an increase in grain size and the proportion of soft minerals as a result of chemical alteration (see Chapter 4).

The influence of mineralogy on aggregate abrasion value is demonstrated in Figure 5.14, which suggests that the aggregate abrasion value increases with decreasing normative quartz and increasing albite (plagioclase). In each case of finer-grained and coarser-grained type, there is a similar relationship between AAV and normative quartz and albite (plagioclase), although such relationship appears to be better illustrated in the case of coarser-grained porphyritic (CGP) than the finer-grained (FG). Further examination of Figure 5.14, shows that between two coarser-grained and finer-grained granites, the former has lower AAV value. This can be explained as follows:

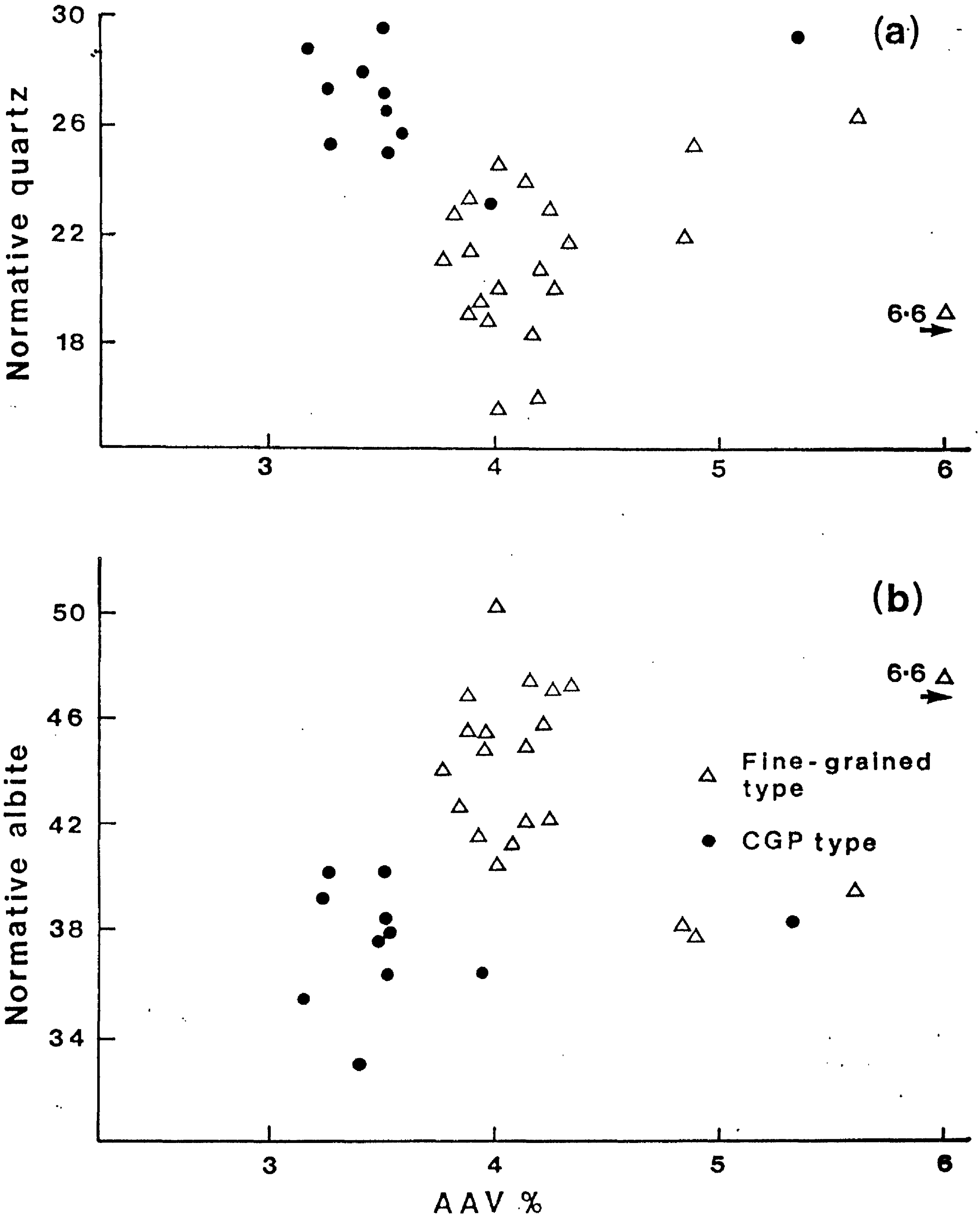


FIGURE 5.14. AAV against normative albite and quartz.

a). Petrographical and geochemical studies detailed in previous chapters showed that coarser-grained porphyritic type (CGP) contains higher SiO_2 and free silica (quartz) than the finer-grained type (FT). It appears (see Fig. 5.14(a)) that this higher free silica percentage in the CGP type has increased aggregate abrasion resistance (lower AAV) because of the hardness and lack of cleavage in the quartz crystals.

b). Chemical alteration, plus orientation and distribution of cleaved minerals such as biotite and feldspars in the finer-grained type produced a higher proportion of soft minerals when altered (chlorite), which caused a reduction in abrasion resistance (higher AAV) compared to the CGP type, which has less biotite and feldspar. This point has also been demonstrated by Figure 5.3, page 150

The adverse effect of alteration of plagioclase upon AAV is shown in plot (b) of Figure 5.14, where normative albite content (as plagioclase) is plotted against AAV. It can be seen that finer-grained type granite with higher albite (as plagioclase) produced a higher AAV than the coarser-grained porphyritic type with less plagioclase. There are, however, a few samples which do not support these explanations, particularly within the finer-grained type.

The petrography study of fresh and weathered granite (Chapters 3 and 4) showed that these samples are highly weathered and most of the biotite and plagioclase feldspar is altered to chlorite and sericite respectively. Nevertheless, based on aggregate abrasion tests conducted on the Helmsdale granites, the proportion of hard, uncleaved minerals such as quartz was found to be the most important factor influencing the aggregate abrasion resistance of relatively fresh samples. Whereas in the case of weathered samples the above factor, combined with further adverse effects provided by the formation of the soft secondary minerals, are the real cause for further reduction in aggregate abrasion values. However in the Helmsdale granite the coarser-grained porphyritic type (CGP) is found to be more resistant to abrasion tests than the finer-grained type (FG), although aggregate abrasion values (AAV) obtained from samples of both granite types are very low (between 3 and 7) and acceptable for most engineering purposes.

5.6.2. Aggregate polished stone value (PSV)

Perhaps the most obvious road surface characteristic is skid resistance which represents the tendency of aggregate used for road surface dressing to be polished by traffic. The polished stone value or PSV gives a measure of resistance of roadstone aggregate to such road surface wearing action. This is one of the major determinants of road-user safety, since a proper level of skid resistance will ensure safe driving conditions.

Many factors affect the PSV, and in particular the microtexture and macrotexture of the road surface. Microtexture or microroughness is related to the surface texture of the aggregate and varies from harsh to polished. Macrotexture or macroroughness on the other hand, is defined by the surface relief of the pavement and is related to the gradation of wearing course mixes and to surface treatments (see Road Transport Research 1984). The macrotexture is described as being rough or smooth. A classification of micro- and macrotexture is given in Figure 5.15.

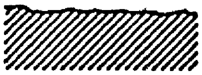
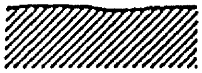
Surface		Scale of texture	
		Macro	Micro
A		rough	harsh
B		rough	polished
C		smooth	harsh
D		smooth	polished

FIGURE 5.15. Illustration of term used for describing road surface texture (RTR 1984).

The microtexture of the Helmsdale granite aggregates was evaluated from the polished stone value (PSV). This value was obtained on a standard test sample (four samples for each rock specimen) containing aggregates which were mounted in a special curved metal mould with a polyester resin. Then the samples were subjected to the PSV test which consists of two parts; the first part involving the use of a pneumatic tyre and fine abrasive (corn emery and emery flour) which will artificially polish the specimens, and the second part which tests the polished aggregate mould in a friction tester to measure the coefficient of friction between the specimen surface and a pendulum-mounted rubber slider. The mean of the PSV values of the four specimens were calculated and are shown in Table 5.3. This test was carried out in accordance with BS 812 (1975) where the test procedure is given in detail.

It was not possible to carry out the PSV test on all the samples obtained for the Helmsdale granite because the PSV test required a large quantity of material and also because the variation in the test results obtained for each type of granite was not significantly high. Thus it was decided to reduce the number of PSV tests to one sample for each location (with four specimens prepared for each test), except for the two quarry faces where the number of samples was increased to six, chosen from different heights on each quarry face. Sample numbers for which the PSV tests were carried out together with their normative amounts of albite and quartz are given in Table 5.3.

In Figure 5.16 PSV values have been plotted against the normative albite (as the main constituent of plagioclase) and normative quartz. Figure 5.16 (a & b) shows that for each granite type the relationship between PSV values and amounts of normative quartz and albite are

Sample No.	Albite	Quartz	PSV
2	42.21	23.07	54
21	50.33	15.87	49
25	41.79	21.93	53
30	47.22	20.28	50
32	46.27	16.02	50
37	47.63	18.3	51
43	35.83	28.96	52
44	36.59	23.17	54
45	33.29	28.07	53
49	37.88	25.29	57
53	40.27	27.67	55
54	40.24	27.21	56
71	38.34	29.94	59
75	38.32	29.24	57
78	39.63	26.23	56
86	40.61	26.03	56
92	36.29	28.46	58
95	38.41	22.21	55

TABLE 5.3. PSV results for selected samples from the Helmsdale granites and their normative amounts of albite and quartz.

linear and that higher PSV values are associated with higher normative quartz accompanied by lower normative albite content in rock samples, except in the case of the three samples of the CGP type (43, 44 and 45) which have anomalously lower normative albite due to the high state of chemical weathering (see Chapter 4).

Aggregate polishing characteristic behaviour shown by the two Helmsdale granites can be explained as follows: In the case of relatively fresh rock samples consisting mainly of minerals of comparable hardness such as plagioclase feldspar, K-feldspar and quartz and which tend to accept a high polish, the tendency towards a highly polished state (lower PSV) goes higher as the amount of free silica (quartz) decreases followed by the increase of cleavable minerals such as feldspar and mica. This point has been highlighted by fresh samples from the FG type (Fig.5.16). But in the case of weathered samples the proportion of hard mineral (quartz) increases at the expense of other minerals such as feldspar (plagioclase in particular), and mafic minerals which decrease due to the chemical alteration which generally results in the formation of a softer, altered product. This process transforms the existing comparable-hardness rock-forming minerals into a rock consisting of mineral components with different hardness values which provides fresh texture during the PSV test which tends to increase the resistance to polishing. Samples of the CGP type granite (fig. 5.15) show this point by having higher PSV values.

However, the polished stone value (PSV) test has been regarded by some workers as either not being reproducible (Hingley 1971), or not showing the true behaviour of aggregate in actual traffic polishing conditions (Hosking 1969; Hartley 1974).

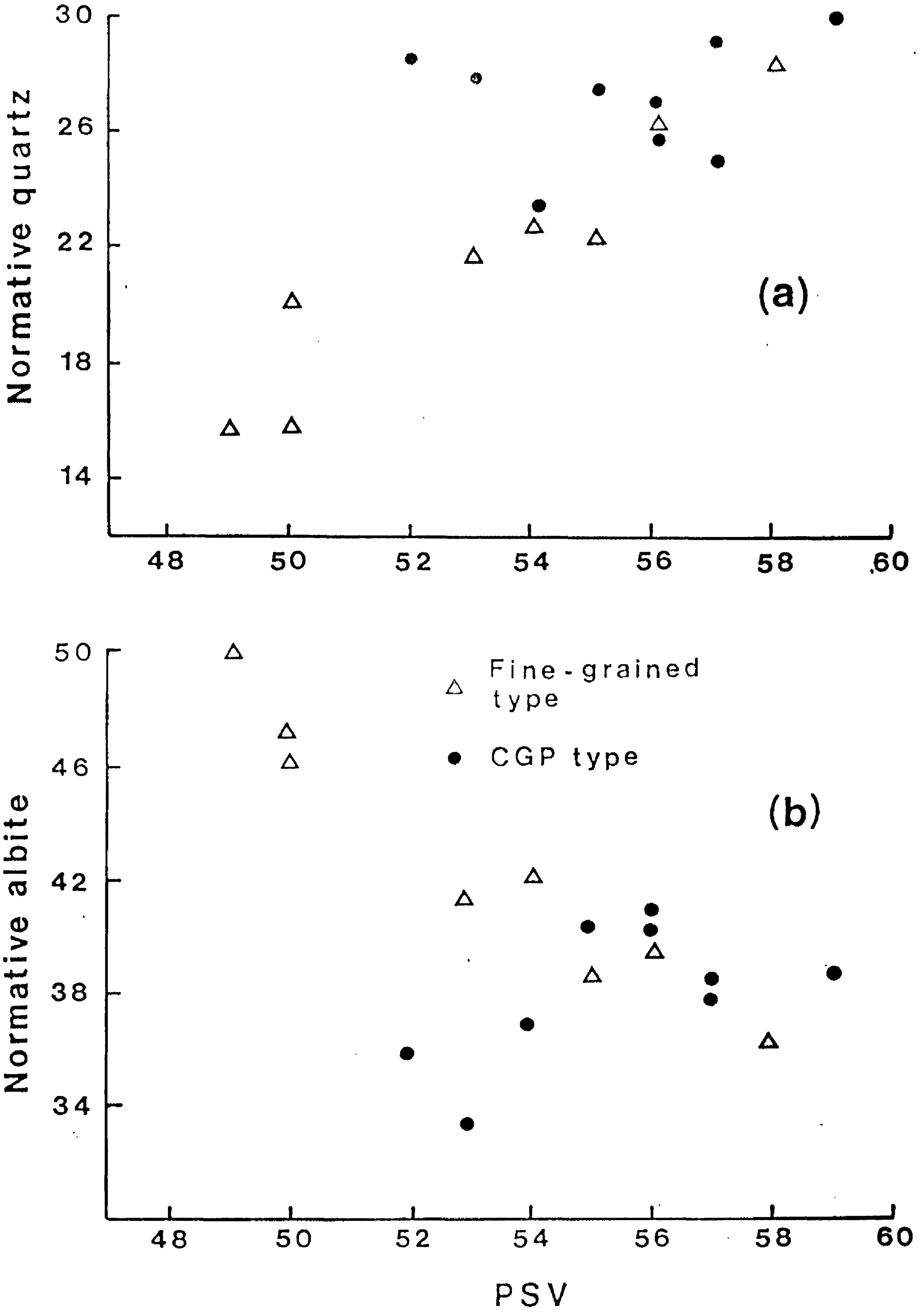


FIGURE 5.16. PSV against normative albite and quartz.

The requirements for aggregate PSV in the surfacing of new motorway and trunk roads are given in detail by Harris (1977). According to this, the PSV values of between 48 and 59 which obtained for Helmsdale granites (FG and CGP) suggest that these rocks are only suitable for the B and C sites wearing course. These sites include generally straight sections and large radius curves on motorways, trunk and principal roads, other roads carrying more than 250 commercial vehicles per lane per day, and finally those roads where wet skidding accidents are unlikely to be a problem.

5.6.3. Bitumen binding characteristics

Since aggregates make up about 80 percent by volume of bituminous mixes, their influence on the properties and performance of mix is great. Thus the ideal aggregate should have the following properties:

1). Suitable particle size and gradation

2). Strength and toughness

3). Correct particle shape

4). Low porosity (low bitumen absorption)

5). Resistance to stripping (surface texture and cleanliness.

Factors 1, 2 and 3 are primarily for stability reasons, whereas factors 4 and 5 are important to aggregate and bitumen interaction. Depending upon the use or purpose of the mix, a wide variety of sizes and gradations of aggregate may be used. For example, aggregate used for the surface of heavily travelled roads generally should contain densely graded aggregate (i.e. materials that are well graded from coarse to fine; see Specification for Road and Bridge Work 1980). In the case of strength and toughness properties of the aggregate: because aggregate in a bituminous mixture supplies most of the mechanical stability, it must have a certain amount of strength and toughness to prevent breakdown under traffic and subsequent loss of stability. Unfortunately, there is no truly satisfactory test for measuring the the effective strength and toughness of an aggregate, hence when making a choice between different aggregates, one would certainly choose the toughest and strongest available, as indicated by the tests such as aggregate abrasion, impact, crushing, and 10% fines test. Particle shape is another important property - perhaps even more important than factors 1 and 2. Angular aggregates in a mix result in higher strength compared with a similar mix made from rounded ones. Thin and elongated aggregates are also not quite suitable for a bituminous mixture; besides being subject to size segregation in the mixing process, they also tend to be of low strength.

Porosity strongly affects the economics of mix, the higher the porosity the more bitumen will be absorbed into the aggregate thus causing a higher percentage of bitumen to be required in the mix design. However, this high porosity and higher percentage of bitumen required as a result, generally do not affect the quality of a mix. The surface texture and cleanliness of an aggregate, on the other hand, play an important role upon adhesion between aggregate and bitumen. A smooth glossy aggregate is easy to coat with a bituminous film but offers little adhesion to hold the film in place. Thus, the rougher the surface texture generally the higher the stability and durability of the bituminous mixture.

Many aggregates have surface coatings (clay, silt, calcium carbonate, iron oxides, opal, gypsum) which are the most common cause of stripping when surface dressing materials are affected by traffic

(Tompkins 1972). The surface chemistry of an aggregate also plays an important role in the design of bituminous mixtures (Rice 1958). In igneous rocks, more basic rock aggregates generally adhere better with binders than do acid rocks.

5.6.4. Frost heave test

The resistance of aggregates to attack by frost is related to porosity, water absorption, pore structure and the quality of the bond between bitumen and aggregate.

The performance of roadstone aggregates exposed to frost can be assessed either from their past performance in roads or by using the frost heave test. In this test a cylinder of rock aggregate, 150mm high and 100mm in diameter, is subjected to freezing conditions for 250 hours (Croney and Jacobs 1968). The maximum expansion (or heave) allowed by the specimen must be less than 12mm. This test was omitted for the present study because the test results obtained elsewhere are generally unsatisfactory when compared with actual service records shown by the same aggregates (Fookes 1980). This test was also used for soils and road material by RRL (1968) and the general conclusion was that the results obtained were not realistic in terms of 'in service' performance. It was suggested by TRRL (1968), that crushed granites with 10 percent or less of particles passing the 75 μm BS test sieve can be regarded as non frost-susceptible. According to this, both granite types (CGP and FG) of the Helmsdale granites which produced average values of 9.6% for the coarser-grained porphyritic type and 7.92% for finer-grained type, will be acceptable as non frost-susceptible aggregates. (Croney *et al*. 1968; RRL Report LR90).

5.7. Special aggregate tests for concrete

Concrete is a material which consists essentially of aggregates held in a cement paste (the binder or matrix). The cement paste is a mixture of water and cement and comprises 20% to 40% of the total volume of concrete (see Fig. 5.1.). Aggregate used in concrete consists of sand, which is fine grained (less than 4mm in size) and coarser grained aggregate (up to 30mm or more in size). The coarse aggregate and sand can comprise more than 80% of the total volume of the concrete and significantly affect the strength, durability and appearance of the concrete, therefore its selection must be carefully controlled. Sometimes the presence of an undesirable mineral (for example, iron pyrites) in a particular rock may be a source of weakness and may give rise to aggressive chemical reactions with the cement paste.

However, in properly made concrete, each particle of aggregate is completely coated and surrounded by cement paste which also fills all of the pore spaces. Therefore, the quality of concrete is dependent upon the quality of the bond between the aggregate and the cement paste; the stronger the bond the stronger the concrete. Consequently the formation of the bond depends upon several factors (Teychenne 1978; Teychenne et al. 1975), such as:

1). The surface texture of the aggregate and its cleanliness. An aggregate with a rougher surface will have a better bond with the cement paste and the concrete made with it will be stronger (see also Page 183)

2). The type of cement

3). The water/cement ratio

4). The curing method

Aggregate used in concrete is also subjected to testing (BS 882, 1973; BRS 1968; BRE 1982). The main tests are as follows:

5.7.1. The drying shrinkage test

The drying shrinkage refers to the difference in length between the original wet measurement and the dry measurement of a concrete prism or cylinder, expressed as a percentage of the dry length (BRS Digest 35, 1968). Hobbs (1974) has shown that the shrinkage of concrete depends primarily on two parameters, a) aggregate shrinkage and b) paste shrinkage. Normally cement shrinkage causes most of the shrinkage in concrete, but some aggregates such as weathered basic igneous rocks and mica-rich rocks, which contain chlorite and other sheet silicates, exhibit rather high volume changes and, hence, will increase the shrinkage value of concrete mix. Other materials to be avoided include an excessive amount of clay in the aggregate, or admixtures of calcium chlorite which can be used as an agent to accelerate the drying-out procedure. The presence of gypsum (calcium sulphate) is particularly deleterious in concrete.

Certain factors, however, such as a change in the concrete mix proportions by the addition of cement or increase in the maximum particle size of the aggregate may help to reduce the amount of shrinkage of such shrinkable aggregate. Although the survey of crushed rock aggregates in Scotland, carried out by the Building Research Station (1968 and 1970), has shown that some of the rock types (i.e. fresh granite included) are not shrinkable (shrinkage value 0.04%), the drying shrinkage test was carried out on concrete prisms made with coarse aggregate (size between 4.76-10mm from the Helmsdale granites and natural sand as fine-aggregate (Zone 2 according to BS 882, 1973), based on procedures described in BRS Digest 35, 1968). The sand was from one particular source (Hyndford sand) which is low in shrinkage and therefore has no effect upon the shrinkage value of the coarse aggregate from the Helmsdale granites. The samples from which the aggregates were used for this test, and their related shrinkage values, are given in Table 5.4.

	FG TYPE						CGP TYPE			
Sample No	2	21	32	78	92	95	49	71	75	86
Shrinkage %	0.036	0.033	0.032	0.029	0.030	0.032	0.031	0.036	0.046	0.026

TABLE 5.4. The drying shrinkage values of selected samples from two types of Helmsdale granite.

From Table 5.4. it can be seen that the initial drying shrinkage varied from 0.026 percent to 0.046 percent. The shrinkage values obtained show that fresh amples from both granite types have similar low shrinkage values (less than 0.036%), except sample 75 (CGP type) which has slightly higher shrinkage value (0.046%). This is mainly due to chemical alteration of its mineral constituents such as biotite and feldspar, as was demonstrated by Moore (1980): that formation of hydrous clay minerals, especially illite formed by breakdown of biotite - first to vermiculite and then to illite - was in fact the cause of higher shrinkage values in the more weathered rocks.

5.7.2. Compressive strength of concrete.

Strength of a concrete is probably the most important parameter in concrete construction, since it is the one generally used to define the quality of concrete and to specify the quality required by an engineer (BS 8328: 1976).

Although strength of concrete increases with time, for test purposes the strength of concrete is specified after 28 days curing in water. The test can be carried out on either a) Four cubes of 100mm edge, or b) Four cylinders 150mm diameter and 300mm high, or c) two beams 100mm x 100mm x 500mm long.

Cubes were used in this study and after 28 days curing in the storage tanks they were loaded at an approximate rate of 15 N/mm^2/min until total failure was reached (see BRE 1975 and BS 5328: 1976 for method of mix design and test procedure).

The compressive strength of concrete depends on many factors such as the water/cement ratio, the type of cement and its amount in the mix, rock type, degree of alteration and proportion of secondary minerals in the aggregate, and the grading and shape of the aggregate particles. Some external factors also affect the behaviour of the concrete, such as temperature and environmental conditions under which the concrete is to be used. Thus, in order to make a comparison between the performance of concrete made with aggregate from two different rock types (FG and CGP) with different aggregate properties, all the factors in the mix design were kept constant for all the samples. The particular mix design used for the present study is given in Table 5.5, based on BRE (1975).

The compressive strengths of cubes made with selected aggregates from both granite types are given in Table 5.6. These values were derived from an average of four mixes (cubes) at the end of a 28 day period.

TABLE 5.5. Concrete mix design used for present study.

Concrete mix design form

Stage	Item		Reference or calculation (see TRRL 1975)	Values
1	1.1	Characteristic strength	Specified	Compressive 50 N/mm² at 28 days Proportion defective 1 per cent
	1.2	Standard deviation	Fig 3	5.0 N/mm² or no data - N/mm²
	1.3	Margin	C1	(k = 2.33) 2.33 × 5 = 11.6 N/mm²
	1.4	Target mean strength	C2	50 + 11.6 = 62 N/mm²
	1.5	Cement type	Specified	OPC/SRPC/RHPC
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed ~~Uncrushed~~
	1.7	Free-water/cement ratio	Table 2, Fig 4	0.40 — Use the lower value
	1.8	*Maximum free-water/cement ratio*	*Specified*	-
2	2.1	Slump or V-B	Specified	Slump 30-60 mm or V-B - s
	2.2	Maximum aggregate size	Specified	10 mm
	2.3	Free-water content	Table 3	230 kg/m³
3	3.1	Cement content	C3	230 ÷ 0.4 = 575 kg/m³
	3.2	*Maximum cement content*	*Specified*	____ kg/m³
	3.3	*Minimum cement content*	*Specified*	1 kg/m³ — Use if greater than Item 3.1 and calculate Item 3.4
	3.4	Modified free-water/cement ratio		1
4	4.1	Relative density of aggregate (SSD)		2.6 known/assumed
	4.2	Concrete density	Fig 5	2300 kg/m³
	4.3	Total aggregate content	C4	____ - ____ - ____ = 1505 kg/m³
5	5.1	Grading of fine aggregate	BS 882	Zone 2
	5.2	Proportion of fine aggregate	Fig 6	145 per cent
	5.3	Fine aggregate content	C5	1505 × 0.45 = 677.25 kg/m³
	5.4	Coarse aggregate content	C5	1505 - 677.25 = 827.75 kg/m³

Quantities	Cement (kg)	Water (kg or l)	Fine aggregate (kg)	Coarse aggregate (kg)
per m³ (to nearest 5 kg)				
per trial mix of ____ m³				

Items in italics are optional limiting values that may be specified.

1 N/mm² = 1 MN/m² = 1 MPa.

OPC = ordinary Portland cement; SRPC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement.

Relative density = specific gravity.

SSD = based on a saturated surface-dry basis.

	FG TYPE						CGP TYPE					
Sample No	3	15	32	78	92	95	43	45	54	71	86	75
Compressive strengths N/mm^2	69.9	71.15	71.1	62	66.5	66.5	65.4	68.8	69.9	67.9	64	62

TABLE 5.6. The compressive strengths of selected samples from Helmsdale

Since in Table 5.5., the mean deviation of the results of concrete block tests is 5MPa, the values of compressive strengths of concrete blocks in Table 5.6 occur more or less within this margin of error and therefore the compressive strength of concrete cubes using Helmsdale granites as aggregates can be given as 67.1 (mean value) ± 5MPa (or MN/m^2).

The relationship between some of the physical characteristics of the aggregates and the compressive strength of concrete made of the same aggregate is shown in Figure 5.17. This figure shows that aggregates with higher 10% fines and lower water absorption values produced concrete cubes with higher strengths. Although the above explanation is true for samples of both granite types, the samples of CGP type in general made slightly lower strength concrete cubes than samples of the FG type. This is again because of the grain size differences between the two granite types and weaker grain boundary characteristic of the CGP type, which caused the concrete cubes to fail under lower load than the stronger and interlocked samples of the FG type.

In the case of weathered samples, however, because of the unclean condition of the surface of aggregate due to clay and other alteration products, the cement-aggregate bond is greatly reduced

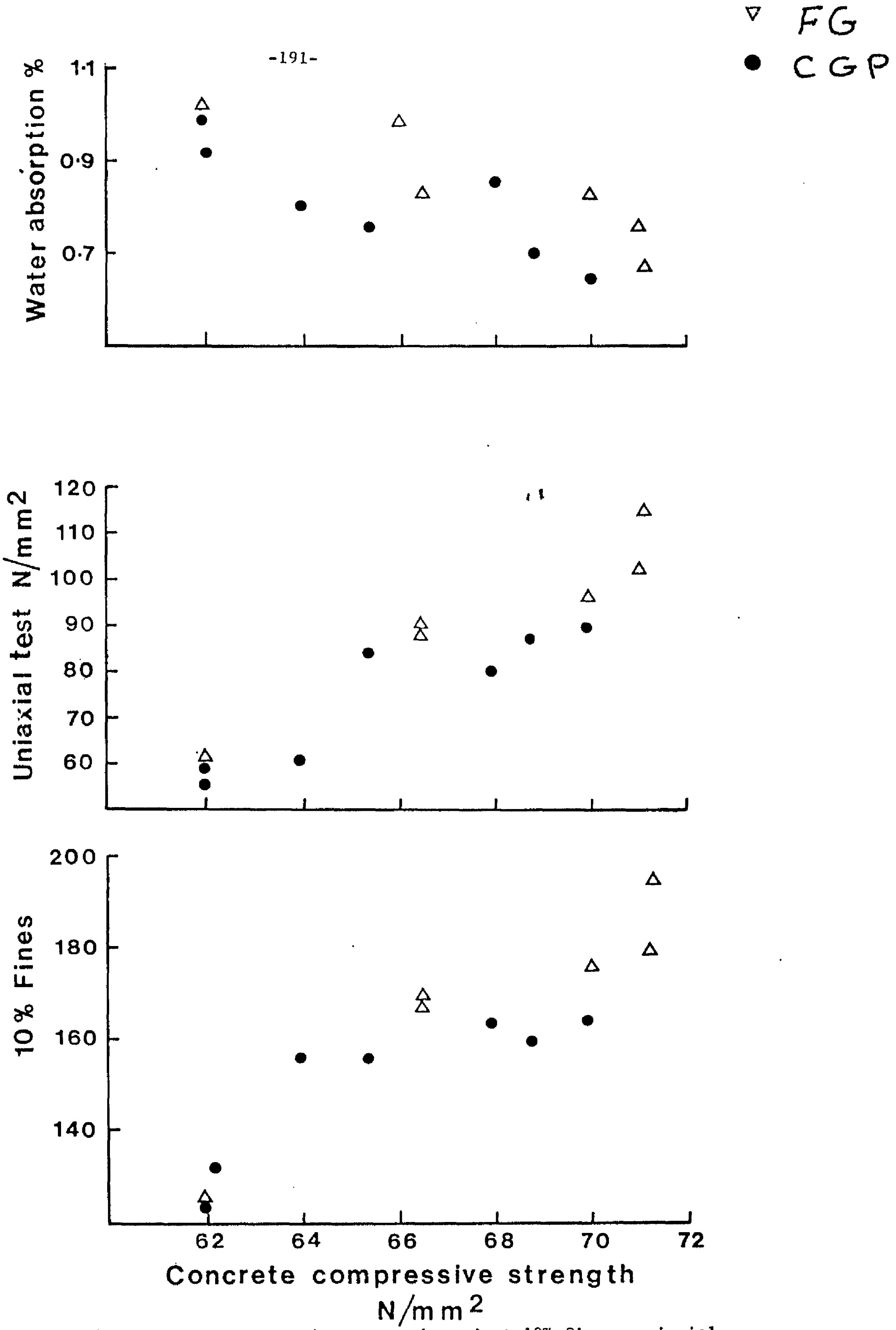


FIGURE 5.17. Concrete compressive strength against 10% fines, uniaxial strength and water absorption.

which in turn caused a reduction in the strength of the concrete.

Although compressive strengths of concrete in the present study have shown a linear relationship with aggregate physical properties, Teychenne (1978), in a similar study but one based on several different rock groups, had demonstrated that except for the water absorption and particle shape, other aggregate physical properties had no effect on concrete compressive strength test results. This may be because when different rock groups are involved in concrete tests, the influence of factors affecting the strength of a concrete is different, depending upon the type of rocks (sedimentary, igneous or metamorphic) and grain sizes.

5.7.3. Alkali reactivity

Under normal conditions, ordinary or rapid-hardening Portland cement and chemically non-reactive aggregates will be adequate against weathering and chemical attacks.

However, there have been many instances of concrete structures deteriorating in a distressingly short time becase of decomposition of the concrete due to some sort of chemical reaction between unsound aggregate and cement paste. The commonest form of chemical reaction is alkali aggregate reaction. The amount of reactive ingredient necessary to cause damage is very small - often as low as 0.5% of the total aggregate content. The alkalis involved in these chemical reactions are usually derived from the cement paste, whereas the other ingredients (such as certain carbonates or silicates) needed in the chemical reaction come from the aggragate.

Two types of reaction occur: a) an alkali-silica reaction, and b) an alkali-carbonate reaction. A typical alkali reaction starts if the alkalinity produced by the lime (from the cement) induces the minerals comprising the aggregate to release their silica and associated alumina, and form new minerals within the alkali-silica gel that develops as reaction rims around the unstable aggregate (Fig. 5.18.). This alkali-silica gel then absorbs water from its immediate surroundings and swells, creating internal pressures that can exceed the strength of concrete and will eventually destroy its structure.

The alkali reaction, therefore, can easily take place if release of silica occurs in an alkaline environment. Amorphous silica minerals, such as opal, appear to be reactive and rocks containing opal or other similar minerals such as chalcadony, chert and volcanic glass, have all been shown to be reactive (Vivian 1975; Dolar-Mantuani 1975; French and Poole 1976).

Acid reaction is commonplace in some special environments, such as the formation of an organic acid by the decomposition of an organic material (plants, etc.), or by oxidation of certain minerals (e.g. pyrites). These acids are effective on all calcareous cements and protection must be provided against such reactions. Table 5.7. lists the various types of protection required for concrete exposed to such acid attack.

Sulphate reactions are less common, but any sulphates needed for this type of reaction may be provided by the presence of minerals such as pyrites, gypsum, or by external sources such as continuous saturation of concrete by seawater, or groundwater containing magnesium or sodium sulphate. The possible protection against such reaction is to use special Portland cements, low in tricalcium aluminate (necessary for this reaction).

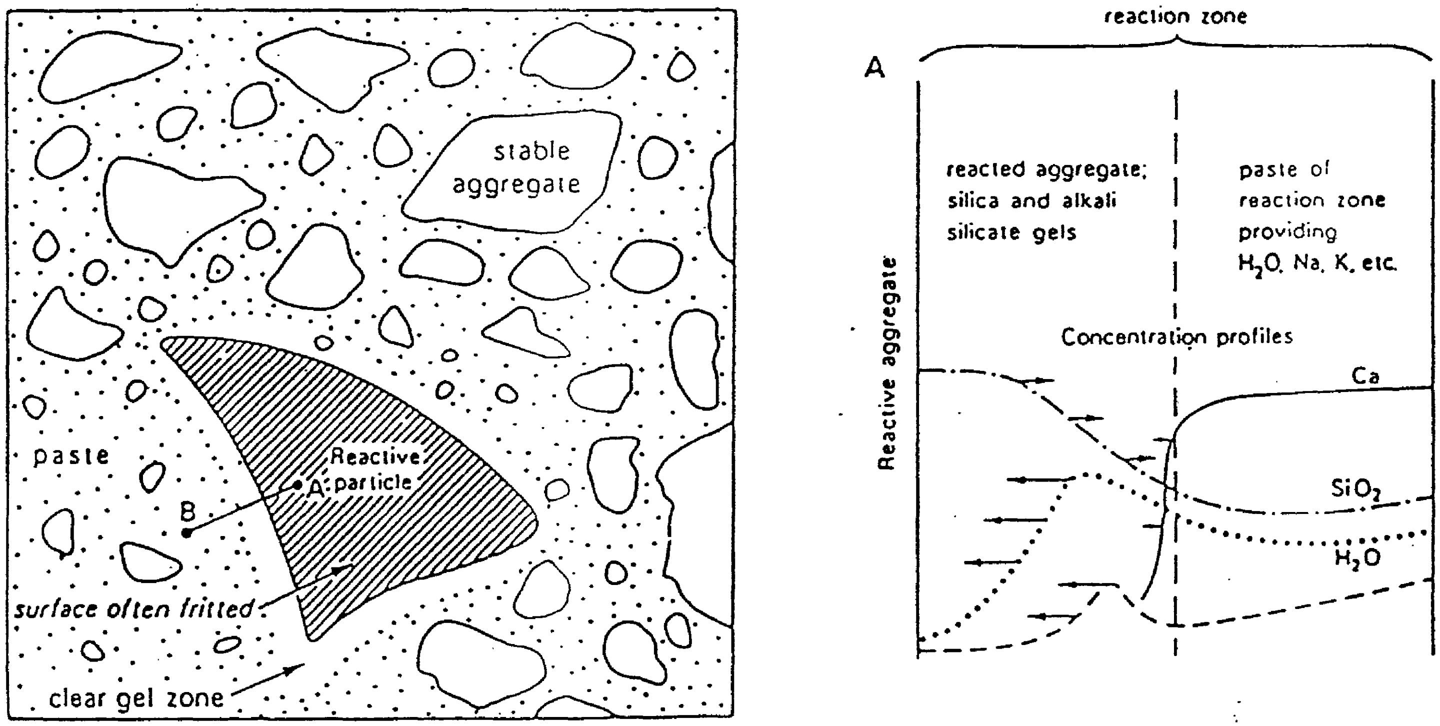
There are several tests to diagnose the presence of a reactive

FIGURE 5.18. Concrete viewed in thin section, showing a piece of reactive aggregate bound in cement, is surrounded by healthy aggregate. The margins of the reactive particles are often fritted and gel often penetrates into the particle. Radial microcracks develop around the fragment at an early stage.

A-B represents the line of section for the graph (right) illustrates the relative concentration of constituents (concentration increases upwards) and their movement during reaction (Reaction boundary details from French, 1980).

The arrows represent the sense of movement of the components with Si and Ca showing little or no movement.

REACTIONS BETWEEN AGGREGATES AND CEMENT PASTE



ingredient in aggragate, such as the gel-pat test (Jones and Tarleton 1958), the rock sylinder test (ASTM C586: 1977), and the rock prism test, which may also be used as rapid test (French 1980). As a generalization the in-service performance of old concrete provides the best information for selection of non-reactive aggregates.

PH value of groundwater	Type of protection required
5 - 7	No special protection required.
3.5 - 7	Increased cement content, use of special cement, use of limestone aggregate.
less than 3.5	In the case of excessive groundwater movement, a protective coating should be applied, such as polythene or hard bitumen.

TABLE 5.7. Type of protection required for buried concrete exposed to acid attack.

5.8. Pavement constructions and their engineering properties

The suitability of an aggregate for roadstone aggregate depends on its usage related to its function and position in a particular road structure.

There are two types of pavement where crushed rock aggregates are used; namely:

1). Flexible pavements
2). Rigid or concrete pavements

Each pavement consists of several layers of varying thickness, which also vary, depending upon other factors including traffic density, life expectancy of road and size and weight of vehicles. In general, each pavement consists of four layers (see Fig. 5.19 (a)) as follows:

a) Subgrade

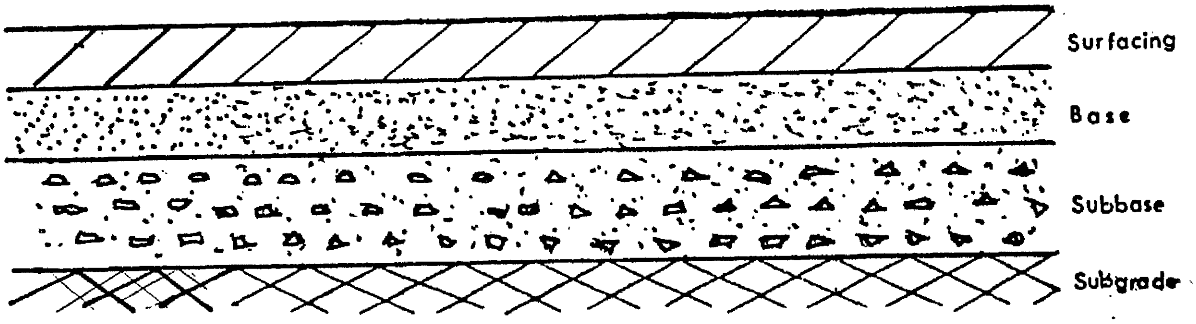
The term 'subgrade' refers to the completed earthworks below the structural layers of a road foundation - b) and c). It may be *in situ* material, or imported and placed as fill and will be compacted to give it strength, which is a principal factor in determining the thickness of the pavement and it can be assessed from the California Bearing Ratio test. The CBR test must be carried out on subgrade material compacted to density specified for the road construction and at the wettest moisture content which is likely to occur during the life of the pavement (see BS 1377: 1967 for more detailed information about the CBR test procedure).

Once the subgrade CBR and the expected total traffic flow (cumulative number of standard axles) have been determined, the thickness of other layers (b), c) and d)) can be found from the pavement thickness design chart for roads (see Fig.5.19 (b)) published by the Transport and Road Research Laboratory (TRRL 1970).

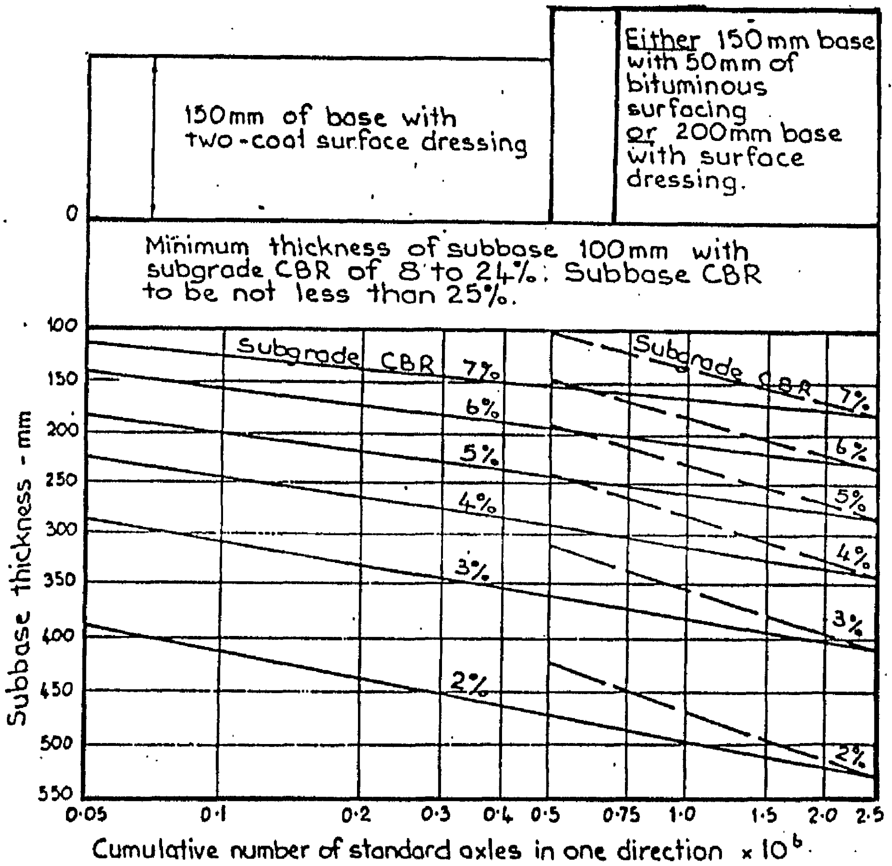
b) Subbase

This is the layer foundation immediately above the subgrade d) and below the road-base c) and which supports it. The quality of the materials used for this layer need not be as high as for the overlying layers c) and d), and the material for the subbase can usually be obtained from a site near the road under construction.

The thickness of the subbase depends upon the cumulative number of standard axles and the subgrade CBR. For example, it can be seen from the Figure 5.19 that the subbase thickness will be 100mm for a



FLEXIBLE PAVEMENT CONSTRUCTION



b

Pavement thickness design chart for Road Note 31 method.

FIGURE 5.19. Pavement thickness design chart for roads.

subgrade CBR values of between 8 and 24. The thickness of subbase will be more than 100mm for CBR of less than 8, and such subbase will not be required where the subgrade CBR exceeds 24.

c) Roadbase

This is the top layer of the foundation of the road, and the main load-spreading layer of it. It is usually constructed from high quality selected materials consisting of one of the following:

1). Natural gravel or crushed gravel
2). Crushed rock
3). Cement or lime stabilised soil
4). Bitumen stabilised sand

The quality of the aggregate used in the roadbase, and its thickness, depends upon the traffic conditions for which the road has been designed. One of the most economical forms of road construction up to 0.5 million standard axles, is a 150mm thick base layer with surface dressing and a variable thickness of subbase to accommodate variations in subgrade strength and traffic flow (see Fig. 5.19.(b)). This base thickness for roads carrying more than 0.5 million standard axles, changes to either a 150mm base with 50mm of bituminous surfacing, or a 200mm base with a double layer of surface dressing. Other requirements for crushed stone base materials are its strength (ACV $<$ 35%) and susceptibility to the a tion of frost, by which the rock must not be affected.

d) Wearing course

This is the uppermost layer (surface dressing), which is composed of selected crushed rock aggregate with a bitumen binder. The type of materials used and their thicknesses depend on several factors including traffic density, the type of roadbase material used and thickness of the other layers of the pavement.

Although the wearing course of a road uses only a small amount of aggregate in comparison with the rest of the layers, the wearing course is very important, and a high proportion of the total cost of roadmaking can usually be allocated to it. Therefore, typical properties which may be specified for roadstone for bituminous surfacing courses are as follows:

1). Durability and resistance to abrasion. Maximum AAV for chippings ranges from 10% to 14% depending on traffic flow (Harris 1977).

2). Impermeability, or low water absorption (less than 5%).

3). Resistance to frost action, swelling and softening.

4). Must be strong enough to resist failure during emplacement and service (ACV less than 25%).

5). Should be of low tractive resistance and yet not liable to cause skidding. Minimum PSV values for materials used in highway construction varies, depending upon traffic density and type of highway layouts, from 45 (site C) to 75 for site A (Harris 1977), having traffic density of more than 1,750 commercial vehicles per lane per day.

The wearing course, however, has to be laid in two stages (layers), except where the cumulative traffic (total traffic flow) is less than 0.5 million standard axles (see Fig. 5.19.(b)).

It is not always possible to find an aggregate which gives excellent results for all standard tests. Therefore, the term 'durability' has been suggested by Hosking (1969) and Hartley (1974) to apply to roadstone aggregate behaviour in terms of its life-expectancy when used in any road construction.

A road may fail if the aggregate fails, and this can be assessed using the following criteria (from examination of the aggregate). The aggregate may show: -

a). disintegration and alteration due to either mechanical crushing or chemical weathering

b). stripped away from the binding medium, due to lack of adhesion

c). rapidly worn away (abraded) by the action of traffic

d). reaches a state of polish so that skidding may occur

5.9. Aggregate properties required for different types of pavement

In general, an aggregate used for pavements is required to contain some or all of the following qualities:

5.9.1. General properties (bound or unbound aggregates)

a) Hardness and toughness. To resist repeated load without breakdown, aggregate must have a certain amount of strength and toughness. They can be assessed by mechanical tests such as AIV, ACV, AAV and 10% fines values (see aggregate test in this Chapter). Two of the common factors affecting strength and toughness of an aggregate are particle shape and surface texture (see page 185 for more details).

b) Low water absorption (resistance to frost action, swelling and softening). Aggregate particles containing very small, interconnected voids are capable of attaining and retaining a high degree of saturation and may be susceptible to disruption if repeated freezing occurs.

c) Ability to provide a permanently non-skid surface.

A skid-resistant surface is one which is able to retain a high degree of roughness whilst in service. It should be noted, however, that the requirement for aggregate properties in surfacing of new motorways and trunk roads is strictly specified to match skid-resistance with various highway layouts and traffic flows. Minimum PSV and AAV values for materials used in highway running surfaces are fully given in tables by Harris (1977).

5.9.2. Special properties related to bitumen/tar bounded aggregates

There are many types of bituminous mixtures, but it is possible to formulate a concept of an ideal aggregate for most uses. The ideal aggregate would have: a) Low bitumen/tar absorption in order to prevent pseudo 'burning' and loss of cohesion (Lees and Kennedy 1975). This factor is closely related to porosity and nature of the aggregate surface and an adequate coverage of aggregate, without the use of excessive bitumen/tar, may be difficult for highly porous aggregate or, with adequate coverage an excessive amount of volatiles in the mix may be absorbed by the aggregate. A lack of proper adhesion may also occur with smooth aggregate surfaces of very low porosity.

b) Stripping is another important surface reaction, which commonly occurs where the aggregate is of a type that wets easily with water which results in aggregate-bitumen separation, known as 'stripping'. Thus, aggregate must be adequately resistant to stripping and be able to adhere well to any bituminous binder with which it may be used.

5.9.3. Special properties related to cement bounded aggregates

Aggregate properties important to Portland cement concrete are, in many cases, very different from those important to bituminous mixes. In Portland cement concrete construction, aggregate should be chemically stable, that is, to be free from components which will perhaps cause chemical reactions with other constituents of mix, particularly cement (see alkali reactivity in concrete, page 192). Aggregate thermal properties are also very important in the design of Portland cement concrete structures. Ideally, thermal coefficients of expansion of aggregate, should be similar to that of cement paste in order to reduce bond cracking which may develop during fluctuation in temperature. Thermal expansion characteristics of some more common rock types are shown in Table 5.8. However, the range of coefficient values for any particular rock may vary widely with aggregates from different sources.

Aggregate Types	Coefficient of expansion ($X10^{-6}$ per ^{o}F)
Quartz	6.6
Sandstone	6.5
Gravel	6.0
Granite	5.3
Basalt	4.8
Limestone	3.8

TABLE 5.8. After Fookes 1980

5.10. Comparison of the aggregate properties of the Helmsdale granites with other igneous rocks in the United Kingdom

In the present study, the engineering properties of the Helmsdale granites and the assessment of their qualities as aggregate have been investigated, using various physical and chemical tests (see aggregate tests in this Chapter). For this part of the study, because the spread of values for different tests, both within and between the two granite types, are so large that considerable overlap exists between samples, it was decided to use the mean values of the test results obtained for each location instead, and these are shown in Table 5.9. Furthermore, aggregate properties of different igneous rocks from selected quarries in the United Kingdom (including some of the igneous rocks of Scotland) are also chosen (Table 5.10, data from Harris 1977) for comparison between them and the results obtained in the present study.

Variation in the aggregate test results of samples from the Helmsdale granite and those from selected quarries are shown in Figure 5.20, which shows that both granite types from Helmsdale have similar specific gravities (SG about 2.60), which is lower than the rest of the samples from elsewhere.

Since the specific gravity is related to porosity, the lower value obtained in the present study may well be due to the fact that samples from the Helmsdale granite are slightly weathered. This is particularly very important for concrete mix, since an aggregate with higher porosity (lower SG) can absorb more water from mix, which in turn reduces aggregate resistance towards freezing and thawing conditions. This point is highlighted by the water absorption plot, which again is higher (about 0.9%) in the Helmsdale granite, compared

TABLE 5.9. Summary of means and range of values for aggregate tests in each location (Helmsdale granite).
(FG) = Finer-grained (CGP) = Coarser-grained

Sample Location		ACV	10% Fines value kN	AAV	AIV	PSV	SG	Water absorption
Helmsdale Quarry	Mean (FG)	22.66	181	4.2	20.3	54.5	2.61	0.82
	Range	20.1-27.4	168-189	3.8-6.6	17.3-23.0	49-58	2.58-2.65	0.54-1.39
	No.of samples	17	17	17	17	6	17	17
Caen Burn	Mean (FG)	26.00	161	4.8	24.6	56	2.61	0.90
	Range	25-27	155-167	4.8-4.8	23.4-26	-	2.60-2.62	0.82-0.99
	No.of samples	2	2	2	2	1	2	2
Allt Cille	Mean (FG)	23.1	161.5	-	24.5	56	2.6	0.9
	Range	22.1-24.1	154-169	-	23-26.1	-	2.6	0.84-1.36
	No.of samples	2	2	-	2	1	2	2
Marral	Mean (FG)	24.0	168	4.5	23	58	2.61	0.85
	Range	-	-	-	-	-	-	-
	No.of samples	1	1	1	1	1	1	1
	Mean (FG)	28.00	146	5.2	27.8	53	2.58	1.01
	Range	-	-	-	-	-	-	-
	No.of samples	1	1	1	1	1	1	1
Eldrable Burn	Mean (FG)	32.0	123	5.3	30.8	50	2.55	1.00
	Range	30-34	120-125	-	32-28.3	-	2.5-2.61	0.98-1.1
	No.of samples	3	3	1	3	1		
Ousdale Quarry	Mean (CGP)	27.9	159	3.4	25	55	2.6	0.71
	Range	26.12-29.59	148-164	3.2-3.9	24.3-27.3	52-61	2.6-2.6	0.5-0.9
	No.of samples	6	6	6	6	6	6	6

Sample Location		ACV	10% Fines value kN	AAV	AIV	PSV	SG	Water absorption
Ousdale Burn	Mean (CGP)	26.92	153.3	3.4	26.9	54	2.61	0.75
	Range	24.19-29.33	142-163	3.2-3.5	24-28.8	-	2.6-2.62	0.6-1.05
	No.of samples	3	3	3	3	1	3	3
Eldrable Burn	Mean (CGP)	32.0	126	5.6	32.35	52	2.61	0.9
	Range	30.1-32.8	125.127	-	31.1-32.9	-	2.6-2.63	0.6-0.9
	No.of samples	3	3	1	3	1	3	3
Longwall Water	Mean (CGP)	38.06	135	4.2	30.31	62.1	2.62	0.8
	Range	30.3-45.8	132-137	2.7-4.6	29.8-30.8	-	2.62-2.63	0.7-0.9
	No.of samples	2	2	2	2	1	2	2
Glen Loth	Mean (CGP)	27.95	158	3.5	25.2	68	2.6	0.71
	Range	25.25-30.6	152-164	-	24.5-26	-	2.6-2.61	0.70-0.72
	No.of samples	2	2	1	2	1	2	

TABLE 5.9 continued

TABLE 5.10. Properties of aggregates from selected quarries in the United Kingdom

Rock type (Quarry)	ACV	10% Fines value kN	AAV	AIV	PSV	SG	Water absorption
Granite (Castle-an-Dinas)	17	283	5.4	16	56	2.62	0.65
Coedana Granite (Gwalchmal)	19	-	4	19	58	2.73	0.33
Peterhead Granite (Stirlinghill)	27	130	3.4	27	49	2.63	0.37
Moine/Granite (Banavie)	21	230	3.2	21	51	2.70	0.7
Gabbro (Dean Quarry)	18	189	4.1	13	62	2.75	0.30
Porphyry (Arenig)	12	340	3	14	51	2.67	0.23
Biotite/Porphyrite (Furance)	12.6	270	2.5	14.3	52	2.64	0.9
Dolerite (Minffordd)	11	-	7	10	64	2.9	0.003
Dolerite (Devon & Cornwall)	14.6	299	5.9	10.6	59.8	2.84	0.54
Dolerite (Whin Sill)	11.4	373	4.2	9.8	57	2.9	0.61
Metamorphosed Dolerite (Penlee)	12	369	2	12	43	2.72	0.64
Andesite (Moon Hill)	16	259	5.2	12.7	59	2.68	0.88
Volcanics (Whitwick)	16	279	3.8	14	60	2.80	0.19

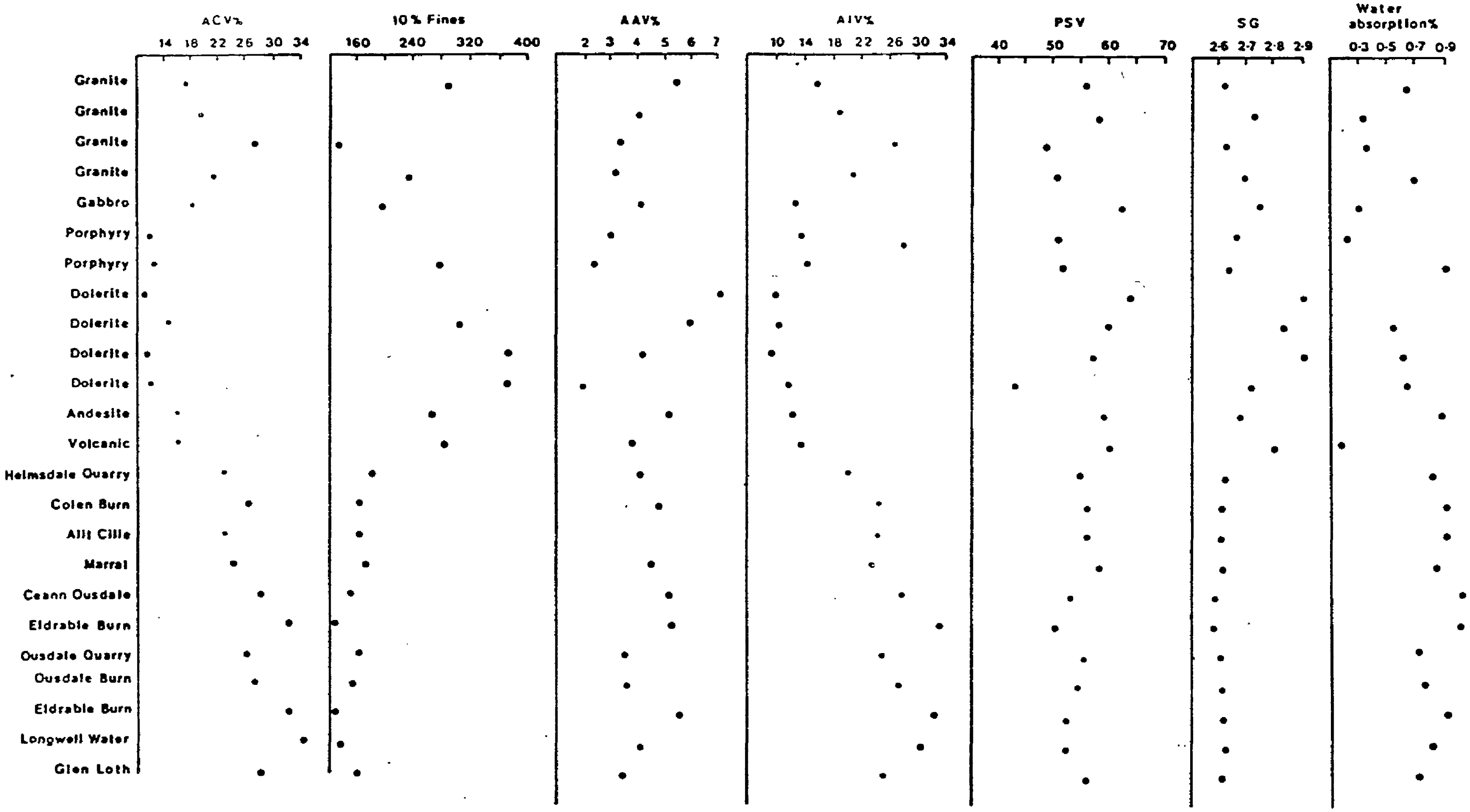


FIGURE 5.20. Correlation between aggregate properties from the Helmsdale granites and those from selected quarries in the U.K.

with the rest of the samples. The strength of aggregates was compared, based on AIV, AAV, ACV and 10% fines values.

Samples from the Helmsdale granites show, in general, lower strength than the rest of the samples from other quarries (higher ACV, AIV and lower 10% fines). The AAV and PSV results, however, are more encouraging. The PSV values, in particular, are within the granite range and even higher than the sample from the Peterhead granite.

Based on the aggregate test results in this study and those from Table 5.10, the following conclusions can be drawn:

1). More basic igneous rocks have better PSV, AIV, ACV and 10% fines, and poorer AAV and drying shrinkage values (the shrinkage values are not given in Tables 5.9, 5.10).

2). Finer-grained igneous rocks have better AIV, 10% fines and ACV, and poorer AAV and drying shrinkage values.

3). Between two granite types of the Helmsdale granites, samples of the CGP type generally have lower strength and slightly better AAV and PSV values than the samples of the FG type.

5.11. Suitability of the Helmsdale granite aggregates for engineering purposes

Although some of the samples from the Helmsdale granite (i.e. Eldrable Burn area), have produced a poor quality aggregate due to a high degree of alteration, engineering test results (Table

5.9) have revealed that aggregate from the Helmsdale granite is comparable in quality to that of the Peterhead granite, which is one of the granites mentioned in the Verney Report as a possible site for a large coastal quarry, and is currently used as a suitable aggregate for local industrial developments.

However, the quality of the samples tested as aggregates from different locations in the Helmsdale granite can be assessed as follows:

5.11.1. As roadstone aggregate

As was pointed out in a previous section (page 146), aggregate properties such as strength and surface texture, are regarded as the most important factors required for aggregates for road-making purposes. Among the samples tested in the present study, those samples from Eldrable Burn and Longell Water areas have particularly high ACV and AIV values. Apart from these badly weathered samples, the rest of the samples from the Helmsdale granites show the same ACV and AIV results as were obtained from Peterhead granite, and slightly higher ACV and AIV than was obtained from other granitic rocks (Fig.5.20). As was expected, a strong inverse relationship in 10% fines values relative to ACV and AIV was noted in each of the samples. A combination of high ACV and AIV values plus lower 10% fines values for both granite types of the Helmsdale intrusion suggests that all samples are low strength aggregates. As in the case of AAV values, while samples from Ousdale area (CGP type) are particularly very good (AAV $<$ 4%), the rest of the samples also make acceptable aggregate for most highway and trunk road running surfaces. The PSV results, on the other hand, show that except for samples from

Eldrable Burn (PSV~50%), all remaining samples have similar PSV values of between 54 and 62%, which is in the range of most of the granite rocks and better than the value obtained for Peterhead granite.

Based on the specification for road and bridge works by the Department of Transport for British Standards, minimum PSV values of between 75 and 45, and maximum AAV values between 16 to 10 depending on traffic densities and type of site (Harris 1977), aggregate from Helmsdale granite can be used for site C, with satisfactory performance.

5.11.2. As concrete mix aggregate.

In concrete construction the most important properties are hardness, durability and cleanliness. The shrinkage of aggregate is also very critical in most cases, and aggregate with high shrinkage values should not be used unless its shrinkage value is studied in detail.

Based on concrete compressive strength (Fig. 5.17), aggregate strength studies (Table 5.9), and those limited aggregate AIV and 10% fines values required for different types of concrete (Table 5.11, based on BS 882: 1983), samples of the Helmsdale granites have shown that satisfactory performances will be achieved. There are, however, a few limitations where the use of the Helmsdale granites as an aggregate are not recommended:

1) Badly weathered samples, particularly those from Eldrable, have shown unsatisfactory strength results, due to the high degree of alteration which makes these rocks unsuitable for most engineering purposes, except for low strength concrete.

2) The Helmsdale granites, in general, are not suitable for the purposes of heavy duty concrete floors which require high

Type of Concrete	10% fines (not less than)	AIV (not exceeding)
	kN	%
Heavy duty concrete floor finishes	150	25
Pavement wearing surface	100	30
Others	50	45

TABLE 5.11. Limiting values on AIV and 10% fines for different types of concrete (after BS 882: 1983).

10% fines (>150 Kn) and low AIV (<25%), except those relatively fresh samples from the FG type granites which may be used with great care.

CHAPTER SIX

CORRELATION

6.1. Introduction

Aggregates are used for a variety of purposes, the two main ones being for roadstone and concrete. They normally comprise up to 80% of the volume of concrete mixes used in engineering constructions and it is not surprising that the quality of aggregates is of considerable importance in determining their suitability for any specific engineering purposes. Thus, the suitability of aggregates for use in a given type of construction is normally determined by evaluating their physical and chemical properties.

Throughout preceding chapters references have been made to the effects that each geological factor (such as mineralogy, petrography, geochemistry, weathering and hydrothermal alteration) and environmental factors (climate, in particular) have upon the quality and durability of aggregate. Therefore it is quite common to find the physical performance of the same type of crushed aggregate (i.e. granite) from two different sources is not comparable, particularly when there are differences in their grain size and degree of alteration (Hosking 1968, 1976; Hartley 1968, 1974; Ramsey et al. 1974; Lees & Kennedy 1975). Weinert (1964), in the study of crushed rocks for roads in South Africa, concluded that existing test procedures for suitability of an aggregate only indicate its present physical condition, which may change while in service possibly due to chemical weathering. As a result, attempts have been made in recent years to reach a better understanding of the in situ behaviour of aggregates, particularly in some areas where due to growing demand for aggregates the use of slightly weathered aggregate (e.g. aggregate for weathering Grade II has successfully been used by Fookes 1980), is quite common. Moore (1978) has shown that based on comparison of some oxides (Na_2O and CaO), along with the Fe_2O_3/FeO ratio between fresh and weathered rocks, the suitability of weathered rock for use as aggregate can be evaluated from geochemical parameters.

This chapter, however, is a general analysis and correlation between the results obtained from a series of mineralogical, petrographical, geochemical and aggregate engineering tests performed on samples from two granite types (FG and CGP), distinguished by different degrees of alteration.

6.2. The correlation results

The study of the relationships between different aggregate engineering test results has been carried out on all the samples from two quarry faces, plus a selection of samples from other locations in the Helmsdale granites. The results are shown in Figure 6.1. where the test results obtained from 10% fines, PSV, AAV, shrinkage, water absorption (WA), and specific gravity (SG), are plotted against AIV. Plot (a) shows that a perfect linear relationship exists between 10% fines and AIV values for both fresh and weathered samples.of the two granite types. Plot (b) on the other hand, shows that the relationship between PSV and AIV values is different for the two granite types. In the case of the FG type, the PSV value improves (higher PSV) as the samples show small sign of alteration and then drops again to a very low value for more altered samples, whereas in the case of the CGP type; the relationship is almost the same for all samples: overall the CGP type samples appear to have higher PSV values than the finer-grained type. Knill (1960) has also shown that igneous rocks containing a small proportion of soft minerals due to the alteration processes, or containing fractured grains, tend to have reasonably high polish resistance. It was also concluded in his study that the grain size has little effect upon PSV values, i.e. the finer-grained rock with minerals of comparable hardness tends to accept a higher polish (lower PSV) than the coarser-grained rock with the same mineral composition.

The present correlation study also agrees with the conclusion made by Hingley (1971) that the PSV test, in general, is not very reliable, although this is the only test at the present time for assessing the skid-resistance of road surfacing aggregate.

The AAV test results (Plot c) show a different trend to that observed in plot (a). Here the FG type, with less quartz and a higher amount of mafic minerals (which showed higher strength - higher 10% fines and lower AIV) has higher AAV than the CGP type. This plot supports the conclusion made by Hartley (1974) that those igneous rocks containing a higher silica (e.g. the CGP) tend to resist abrasion better than the rocks with less silica and more ferromagnesium content (e.g. the FG type).

The drying shrinkage results (Plot d), while not showing any particular trends for the FG type granite, show only a small increase in the CGP type as the rock becomes more altered. Figure 6.1. (e) shows the relationship between water absorption and aggregate impact value test results. It can be seen that water absorption value increases with increasing AIV. The behaviour of the two granite types (FG and CGP) is fairly similar. The specific gravity resultd, however, do not show any variation in relation to AIV (Plot f) and remain constant around 2.6 for both granite types.

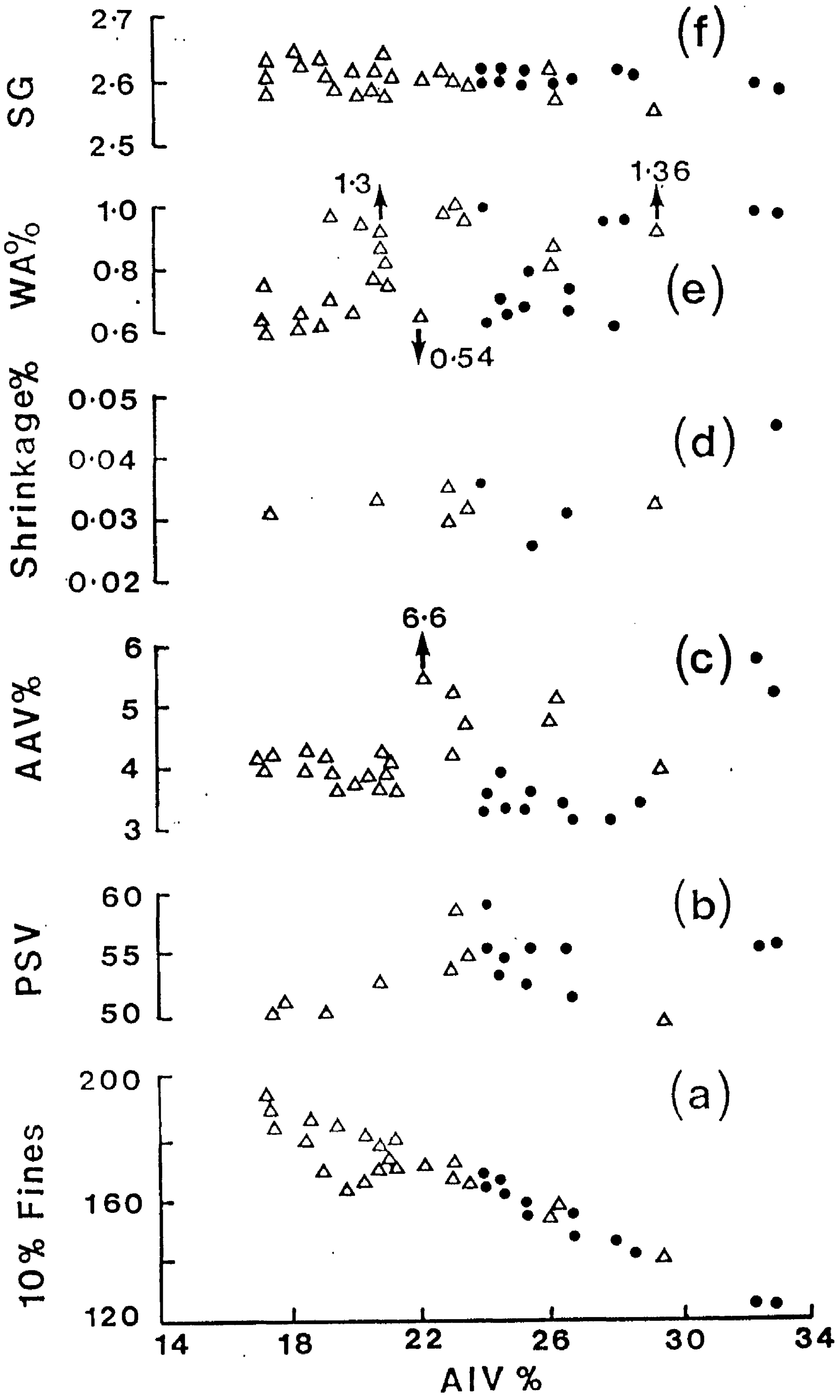


FIGURE 6.1. AIV against 10% fines, PSV, AAV, shrinkage value, water absorption value.

△ FG

● CGP

The behaviour of aggregate engineering properties (Fig. 6.1.) can be discussed in more detail, using some of the more important oxides representative of the most common mineral constituents of the Helmsdale granites. Figure 6.2.(g) shows the relationship between AIV and MgO as a main constituent of mafic mineral (i.e. biotite). This plot shows that aggregate impact value increased with decreasing MgO. Figure 6.2.(h) also shows this point very well when CaO content, as a main constituent of plagioclase is used. The CaO in the FG type is much higher accompanied by lower AIV values (higher strength), while the CGP type samples with lower CaO show no relationship with the variation in AIV values. The behaviour of Na_2O (Plot i) also as a main constituent of plagioclase, is the same as MgO and CaO oxides, i.e. lower percentage of Na_2O related to higher AIV in the CGP type. In Figure 6.2. (j & k) AIV increases as K_2O and SiO_2 increase.

The chemical analyses of the rocks were converted to normative amounts so that the relative composition of important minerals such as feldspars (plagioclase, in particular) and quartz could be compared between the two granite types as a result of weathering process.

In Figure 6.3., the normative amounts of quartz have been plotted against normative albite and albite plus anorthite, as representative of plagioclase: this figure shows a steady decrease in the percentage of plagioclase is accompanied by increase in the amount of quartz. Figure 6.4. on the other hand, shows no variation in amount of quartz when normative orthoclase (K-feldspar) is used instead of plagioclase. This figure tends to suggest that the K-feldspar is more stable during the early stage of weathering, whereas plagioclase is more susceptible to breakdown (Rice 1973; Moore and Gribble 1980).

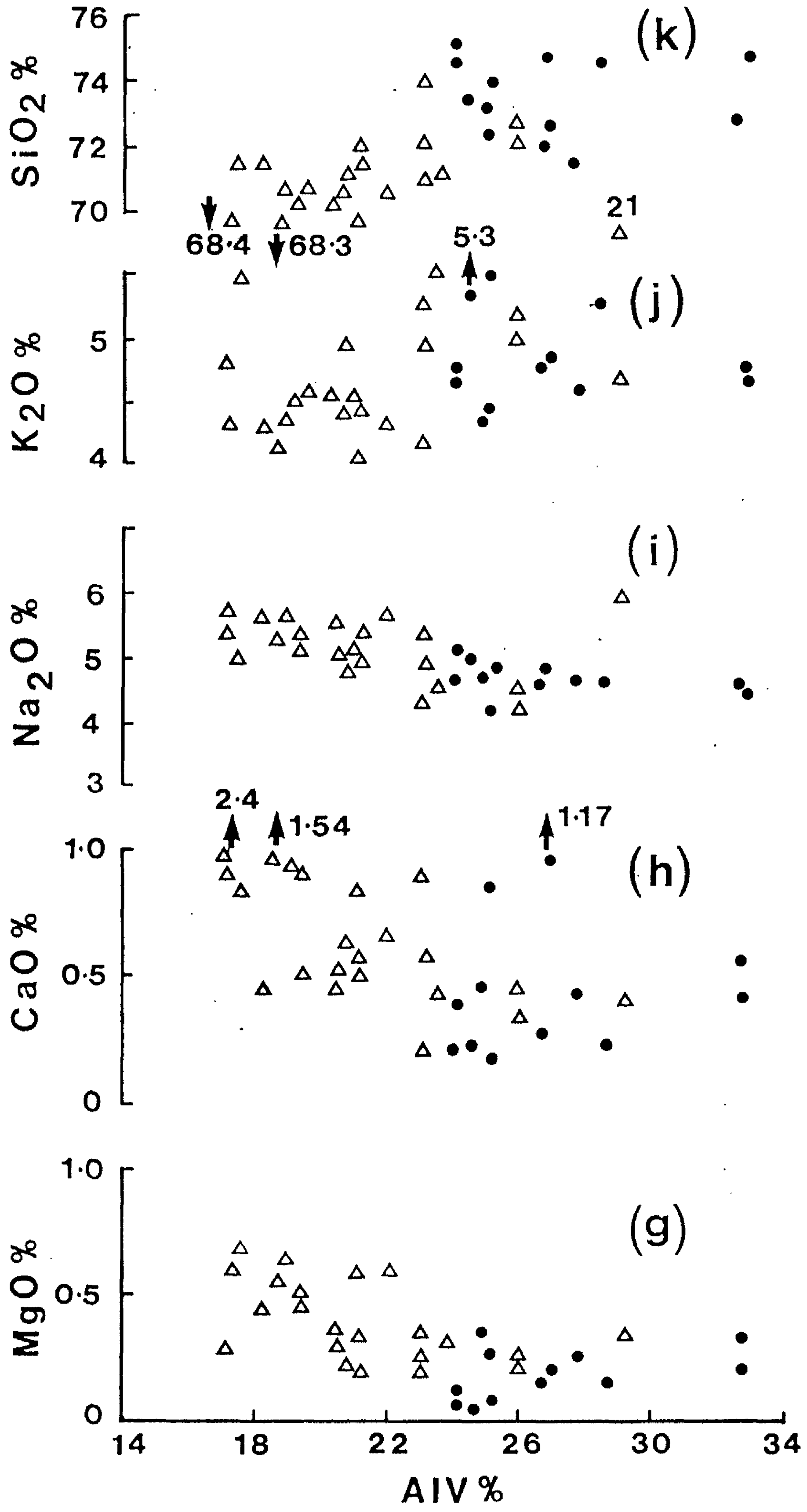


FIGURE 6.2. AIV against percentage MgO, CaO, Na_2O, K_2O and SiO_2.

△ FG

● CGP

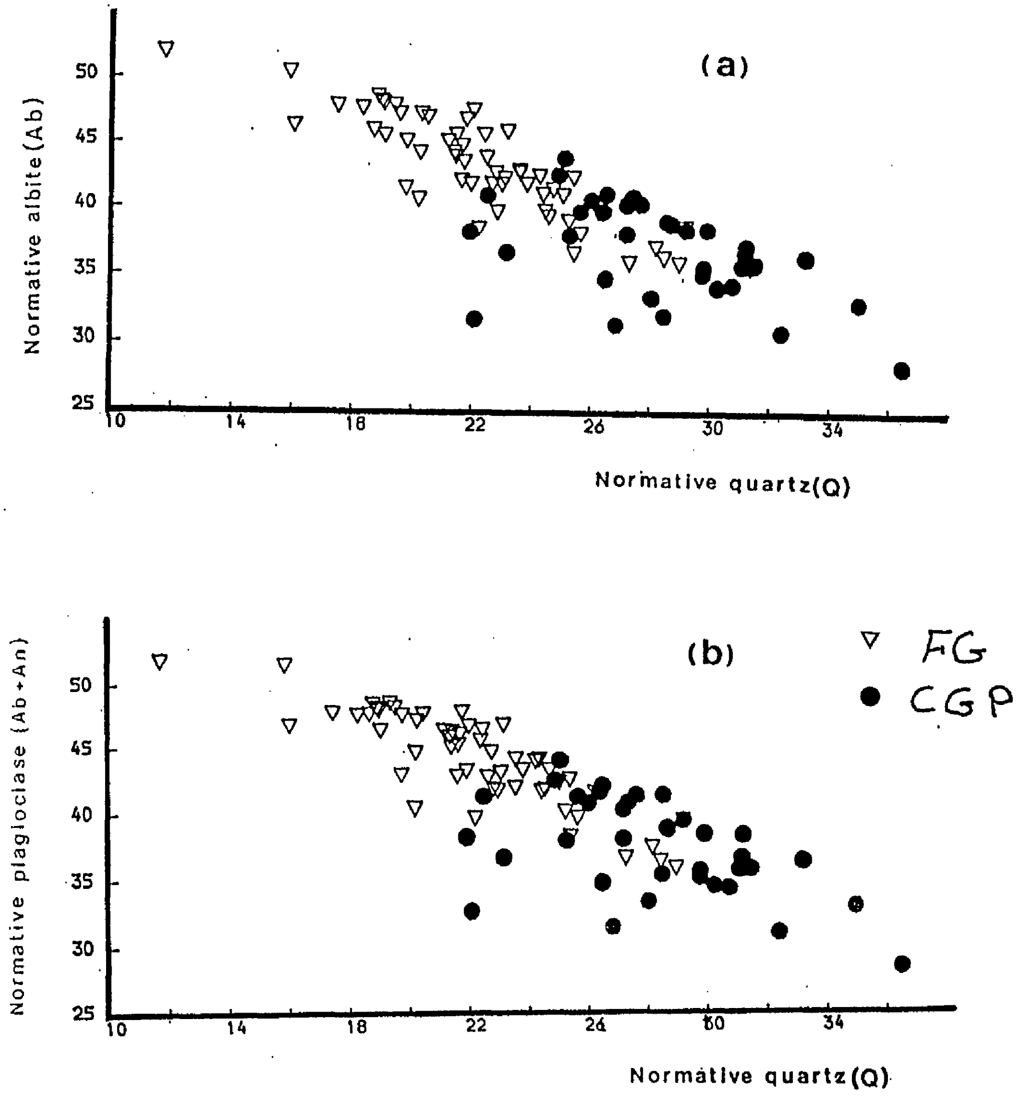


FIGURE 6.3. Plot (a) Normative quartz against normative albite
Plot (b) Normative quartz against normative plagioclase.

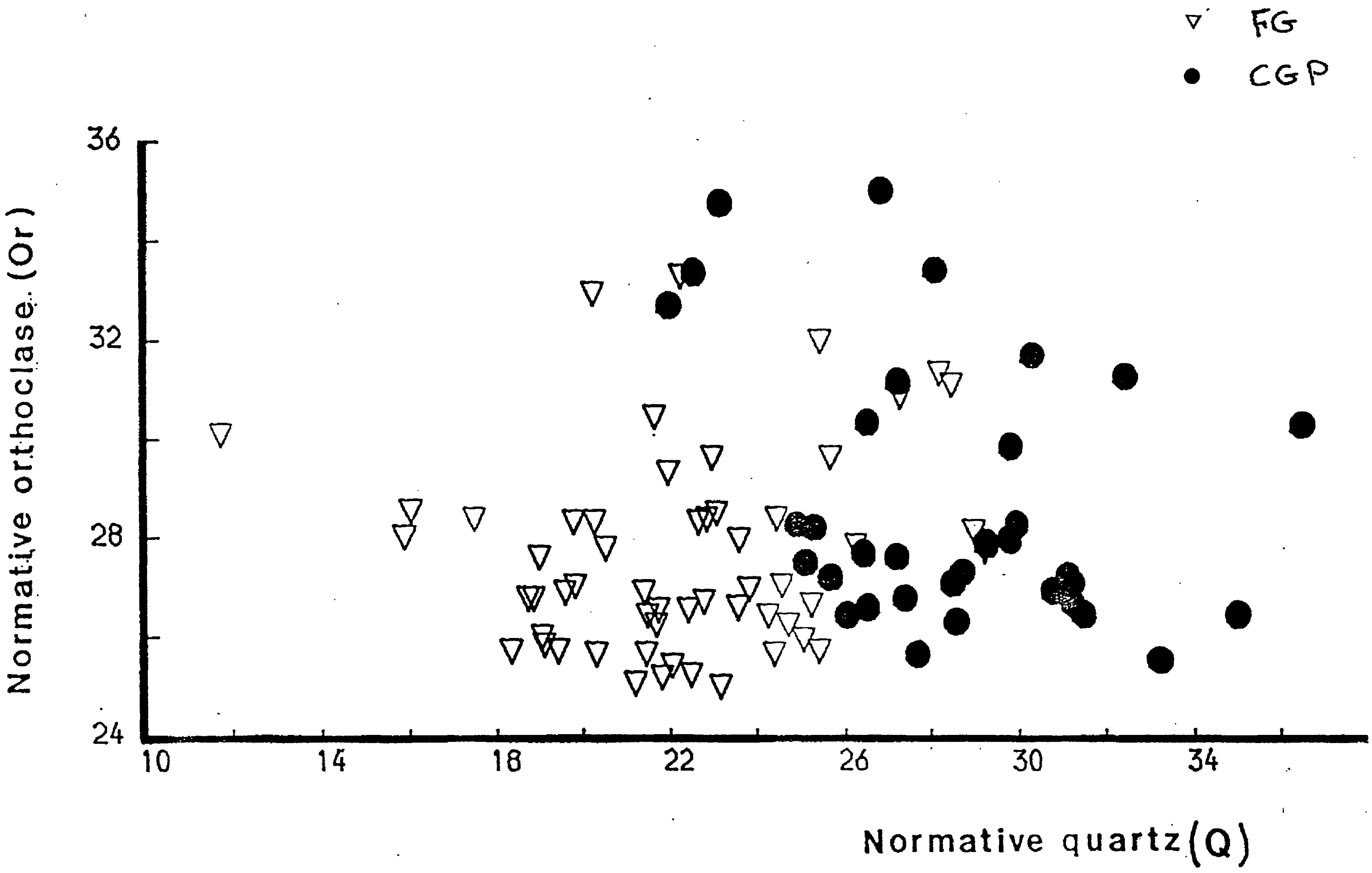


FIGURE 6.4. Normative quartz against normative orthoclase.

Finally, the analysis of the relationships between the values of aggregate engineering properties and the alteration degree FI, AI_f, AI_m and Fe_2O_3/FeO) can be used to explain the behaviour of both the fresh and the altered aggregate further. The alteration parameters are defined as follows:

1) FI is a microfracture index and were determined on thin sections as the number of microfractures in $10mm^2$ (after Irfan and Dearman 1978).
2) AI_f is an alteration index of feldspar and were determined again on thin sections as the ratio amount of altered feldspars to total feldspar.
3) AI_m is an alteration index of mafic minerals (biotite, in particular) and were also determined on thin sections as the ratio amount of altered mafic minerals to the total mafic minerals.
4) Fe_2O_3/FeO is the ratio of Fe^{3+} to Fe^{2+} as oxidation ratio determined by geochemical analysis.

In Figure 6.5., all the alteration indices are plotted against aggregate impact value results. This figure tends to suggest that the degree of alteration, oxidation and microfracturing increases as AIV increases. Furthermore, the CGP type appears to be more affected by very high degree of oxidation (higher Fe_2O_3/FeO ratio) than the FG type. The alteration indices, however, show different behaviour for the two granite types in that while the CGP type shows that feldspars are the most affected altered minerals during weathering processes, in the case of the FG type mica is the first mineral to be affected.

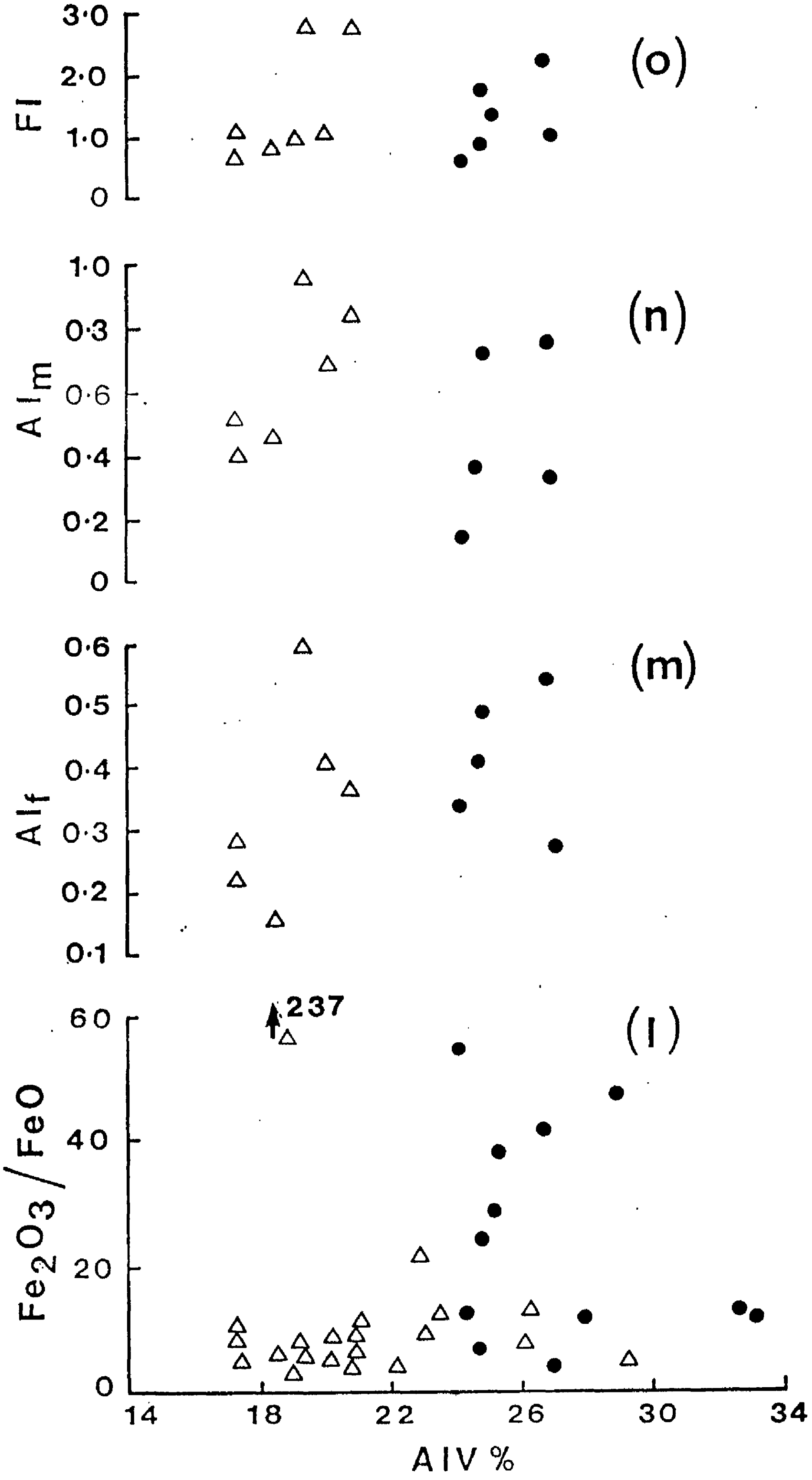


FIGURE 6.5. AIV against Fe_2O_3/FeO, AI_f, AI_m and FI.

△ FG

● CGP

CHAPTER 7

CONCLUSIONS

A study of the literature indicates that the application of standard geotechnical and engineering test procedures for the identification and evaluation of the properties of crushed rock aggregates has sometimes proved misleading. The results are even worse where the aggregates used are altered due either to weathering or hydrothermal alteration processes. It has been reported that weathered aggregate, and even fresh rock aggregate which passed all standard tests at the time of usage, failed well before its life expectancy, because the materials had deteriorated badly through further chemical weathering under field conditions.

The Helmsdale granite, therefore, has been chosen for this study because of its unique geological environment to satisfy the following objectives:

1). Petrochemical study of both the fresh and weathered rooks from the Helmsdale intrusions.

2). The study of the aggregate properties of the granites and the effects of both weathering processes and different grain sizes upon them.

3). Correlation between petrochemistry and aggregate engineering properties to establish any common factor upon which the likely behaviour of one property can be anticipated by a study of the other.

4). Finally, whether any criteria can be established upon which both the present and in-service behaviour of an aggregate can be known.

The following conclusions pertain specifically to the Helmsdale granites studied in the present investigagion:

1). Petrographic and field observations indicate that the Helmsdale intrusion consists of two granites; the outer, coarser-grained porphyritic pink granite (CGP type) and the inner, finer-grained type (FG) which shows a transitional relationship with the CGP type. Mineralogically, the FG type has slightly more biotite and plagioclase minerals than the CGP type.

2). Chemical analyses showed that the Helmsdale granites should be considered as two intrusions, probably derived from a single magmatic source, such as partial melting of mantle-like material containing some crustal component (Lewisian gneiss). Graphs involving normative values also suggest a closer relationship between the FG and CGP types and plagioclase (albite) and biotite fractionation appear to be the only minerals changing the magma composition towards the later, differentiated CGP type. Further evidence for this is illustrated by the Plots of Rb against K^+, which suggest higher K/Rb ratios for the CGP type due to later fractionation product. The FG type is characterized by higher iron, MgO and TiO_2 content which are the main constituents of the biotite which are being fractionated.

3). Based on the petrographic study of the weathered samples from the Helmsdale granites, the sequence and nature of the alteration processes has been revealed as far as the primary minerals are concerned, as follows:

Hydrothermal alteration, including sericitic and chloritic alteration, followed by physical and chemical weathering. Both biotite and feldspar have undergone some mineralogical changes which can be attributed to either hydrothermal alteration or weathering.

Geochemical study of weathered samples showed that both plagioclase and biotite are the first minerals to be affected by alteration. Kaolinite and illite are the common alteration products, which are less abundant in samples from the lower parts of the quarry faces. This point suggests a high leaching environment, since in a mild leaching environment either illite or montmorillonite, or both, would be expected. Therefore, hydrolysis and oxidation processes appear to be the main cause of the chemical weathering and this is highlighted by loss of Ca^{2+}, Mg^{2+} and Na^{+} from the solution, accompanied by a proportional increase in the amount of Al^{3+} and, occasionally, Fe^{3+} in the early stage of the process.

4). Various engineering tests were applied to assess the aggregate quality of both fresh and weathered samples, which suggested that the Helmsdale granite as a whole is suitable for most engineering purposes, except for those requiring high-strength aggregate. Between the two types of granite existing in Helmsdale, the FG type is much stronger than the CGP type, although the latter type shows better PSV and AAV values. Among the rock forming minerals quartz and plagioclase appear to be the related factor between aggregate engineering and petrochemical properties, that is, the higher the percentage of quartz in rock composition the better the aggregate (lower

AAV and higher PSV), whereas rocks with higher mafic minerals are more prone to weathering processes. Aggregate impact and 10% fines values appear to be the cheapest and quickest tests for assessing the aggregate strength and show a very good relationship with both fresh and altered samples. These aggregate tests, plus more petrographic indices (FI, AI_f and AI_m), and geochemical analyses (major oxides in particular) can provide enough information about both present and future behaviour of aggregate in use.

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APPENDIX 1

Geochemistry results

TABLE A1: Sample locations, geochemical analyses data and engineering test results. (+) data available; (..) data not available.

Sample Locations	Sample Number	Major Element	Trace Element	Niggli values	CIPW values	Relative density	Specific Gravity	Water absorption	AIV	AIVR	ACV	AAV	PSV	10% fines	shrinkage	Concrete compressive	Uniaxial compressive
Helmsdale Quarry	1	+	+	+	+	+	+	+	+	+	..	+	..	+	..	..	..
"	2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	..	..
"	3	+	+	+	+	+	+	+	+	+	..	+	..	+	..	+	+
"	4	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	5	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	6	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	7	+	+	+	+	+	+	+	+	+	..	+	..	+	..	..	..
"	8	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	9	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	10	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	11	+	+	+	+	+	+	+	+	+	..	+	..	+	..	..	..
"	12	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	13	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	14	+	+	+	+	+	+	+	+	+	..	+	..	+	..	..	..
"	15	+	+	+	+	+	+	+	+	+	..	+	..	+	..	+	+
"	16	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	17	+	+	+	+	+	+	+	+	+	..	+	..	+	..	..	..
"	18	+	+	+	+	+	+	+	+	+	+	+	..	+	..	..	..
"	19	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..

Sample Locations	Sample Number	Major Element	Trace Element	Niggli values	CIPW values	Relative density	Specific Gravity	Water absorption	AIV	AIVR	ACV	AAV	PSV	10% fines	shrinkage	Concrete compressive	Uniaxial compressive
Helmsdale Quarry	20	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	21	+	+	+	+	+	+	+	+	+		+	+	+	+	:	:
"	22	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	23	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	24	+	+	+	+	+	+	+	+	+	:	+	:	+	:	:	:
"	25	+	+	+	+	:	+	+	+	+	+	+	+	+	+	:	:
"	26	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	27	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	28	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	29	+	+	+	+	+	+	+	+	+	:	+	:	+	:	:	:
"	30	+	+	+	+	+	+	+	+	+	+	+	+	+	:	:	:
"	31	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	32	+	+	+	+	+	+	+	+	+		+	+	+	+	+	+
"	33	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	34	+	+	+	+	+	+	+	+	+	:	+	:	+	:	:	:
"	35	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	36	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	37	+	+	+	+	+	+	+	+	+	:	+	+	+	:	:	:
"	38	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:

Sample Locations	Sample Number	Major Element	Trace Element	Niggli values	CIPW values	Relative density	Specific Gravity	Water absorption	AIV	AIVR	ACV	AAV	PSV	10% fines	shrinkage	Concrete compressive	Uniaxial compressive
Helmsdale Quarry	39	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	40	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	41	+	+	+	+	+	+	+	+	+	:	+	:	+	:	:	:
"	42	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
Ousdale Quarry	43	+	+	+	+	+	+	+	+	+	:	+	+	+	+	:	+
"	44	+	+	+	+	+	+	+	+	+	+	+	+	+	:	:	:
"	45	+	+	+	+	+	+	+	+	+	:	+	+	+	:	+	+
"	46	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	47	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	48	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	49	+	+	+	+	+	+	+	+	+	+	+	+	+	+	:	:
"	50	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	51	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	52	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	53	+	+	+	+	+	+	+	+	+	:	+	+	+	:	:	:
"	54	+	+	+	+	+	+	+	+	+	:	+	+	+	:	+	+
"	55	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	56	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:
"	57	+	+	+	+	:	:	:	:	:	:	:	:	:	:	:	:

Sample Locations	Sample Number	Major Element	Trace Element	Niggli values	CIPW values	Relative density	Specific Gravity	Water absorption	AIV	AIVR	ACV	AAV	PSV	10% fines	Shrinkage	Concrete compressive	Uniaxial compressive
Ousdale Quarry	58	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	59	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	60	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	61	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	62	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	63	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	64	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	65	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	66	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	67	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	68	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
Ousdale Burn	69	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	70	+	+	+	+	+	+	+	+	+	..	+	..	+	..	..	..
"	71	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
"	72	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	73	+	+	+	+	+	+	+	+	+	..	+	..	+	..	..	..
"	74	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
Eldrable Burn	75	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Sample Locations	Sample Number	Major Element	Trace Element	Niggli values	CIPW values	Relative density	Specific Gravity	Water absorption	AIV	AIVR	ACV	AAV	PSV	10% fines	Shrinkage	Concrete compressive	Uniaxial compressive
Eldrable Burn	76	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	77	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	78	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
"	79	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	80	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	81	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
Glen Loth	82	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	83	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	84	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	85	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	86	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Allt Cille	87	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	88	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	89	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	90	+	+	+	+	+	+	+	+	+	..	+	..	+	..	..	..
"	91	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..
"	92	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
"	93	+	+	+	+	..	..	..	..	..	..	..	..	..	..	..	..

Sample Locations	Caen Burn	"	**Ceann Ousdale**	Marrel	FD	Longwell Water	"
Sample Number	94	95	96	97	98	99	100
Major Element	+	+	+	:	:	:	:
Trace Element	+	+	+	:	:	:	:
Niggli values	+	+	+	:	:	:	:
CIPW values	+	+	+	:	:	:	:
Relative density	+	+	+	+	+	+	+
Specific Gravity	+	+	+	+	+	+	+
Water absorption	+	+	+	+	+	+	+
AIV	+	+	+	+	+	+	+
AIVR	+	+	+	+	+	+	+
ACV	+	:	+	+	+	+	:
AAV	+	+	+	+	+	+	+
PSV	:	+	:	:	:	:	:
10% fines	+	+	+	+	+	+	+
Shrinkage	:	+	:	:	:	:	:
Concrete compressive	:	+	:	:	:	:	:
Uniaxial compressive	:	+	:	:	:	+	:

MAJOR ELEMENT

	1	2	3	4	5	6	7	8	9	10
SIO2	71.23	71.19	71.69	70.98	70.57	71.23	69.88	69.65	67.88	69.60
TIO2	0.33	0.30	0.30	0.31	0.32	0.29	0.32	0.33	0.35	0.32
AL2O3	14.58	14.55	14.80	14.45	14.99	14.58	14.49	14.49	15.59	14.29
FE2O3	1.90	2.41	2.07	2.48	2.46	2.47	2.42	2.41	2.30	2.53
FEO	0.20	0.28	0.20	0.36	0.40	0.44	0.60	0.40	0.24	0.64
MNO	0.03	0.03	0.04	0.03	0.04	0.04	0.04	0.05	0.06	0.04
MGO	0.18	0.18	0.34	0.61	0.44	0.44	0.61	0.27	0.27	0.57
CAO	0.62	0.54	0.52	0.79	0.70	0.61	0.84	0.72	0.77	0.99
NA2O	4.89	4.99	5.01	5.18	5.14	4.84	5.33	5.73	6.22	5.19
K2O	4.44	4.82	4.47	4.27	4.49	4.39	4.24	4.80	5.09	4.34
P2O5	0.14	0.13	0.13	0.14	0.13	0.11	0.12	0.13	0.14	0.13
H2O	0.87	1.15	0.73	0.47	0.78	0.90	1.12	1.02	0.52	0.81
CO2	0.04	0.15	0.02	0.06	0.00	0.15	0.33	0.26	0.27	0.45
TOTAL	99.45	100.72	100.32	100.13	100.46	100.49	100.34	100.26	99.70	99.90

NIGGLI VALUES

	1	2	3	4	5	6	7	8	9	10
AL'	45.96	44.24	45.38	42.19	43.58	43.79	41.57	41.70	42.49	40.94
FM'	9.98	11.95	11.61	15.24	14.02	14.09	15.73	12.45	10.79	15.99
C'	3.55	2.99	2.90	4.19	3.70	[illegible]	4.38	3.77	3.82	5.16
ALK'	40.51	40.82	40.11	38.37	38.71	38.19	38.32	42.03	42.90	37.92
SI'	381.00	367.30	373.00	351.65	348.09	365.02	340.15	340.11	313.91	338.33
K'	0.37	0.39	0.37	0.35	0.36	0.37	0.34	0.36	0.35	0.35
TI'	1.33	1.16	1.17	1.16	1.19	1.11	1.17	1.21	1.22	1.17
MG'	0.14	0.12	0.23	0.30	0.23	0.23	0.28	0.16	0.17	0.26
W'	0.90	0.89	0.90	0.86	0.85	0.83	0.78	0.84	0.90	0.78

TABLE A2. Major element and Niggli values of the analysed samples of the Helmsdale Granites.

MAJOR ELEMENT

	11	12	13	14	15	16	17	18	19	20
SIO2	68.32	67.74	69.24	71.31	71.99	70.95	70.14	70.42	71.06	71.89
TIO2	0.34	0.34	0.34	0.30	0.28	0.27	0.31	0.31	0.29	0.29
AL2O3	14.83	14.31	14.87	13.93	14.21	14.42	14.65	14.59	14.51	14.69
FE2O3	2.66	2.35	2.62	2.41	1.81	2.14	2.54	2.50	2.00	2.08
FEO	0.84	0.36	0.52	0.56	0.19	0.20	0.35	0.31	0.12	0.36
MNO	0.05	0.05	0.05	0.04	0.04	0.04	0.06	0.03	0.03	0.04
MGO	0.57	0.35	0.57	0.70	0.21	0.25	0.50	0.37	0.14	0.45
CAO	1.54	2.89	1.21	0.84	0.54	0.48	0.90	0.46	0.67	0.49
NA2O	5.38	4.90	5.43	5.04	5.06	4.97	5.33	5.58	4.94	5.00
K2O	4.37	4.79	4.53	5.57	4.73	5.15	4.57	4.55	5.01	4.35
P2O5	0.14	0.13	0.14	0.12	0.11	0.12	0.13	0.13	0.12	0.13
H2O	0.74	0.58	0.73	0.78	0.71	0.86	0.34	0.69	0.79	0.70
CO2	0.92	1.90	0.52	0.57	0.10	0.13	0.16	0.06	0.41	0.21
TOTAL	100.70	100.69	100.77	102.17	99.98	99.98	99.98	100.00	100.09	100.68

NIGGLI VALUES

	11	12	13	14	15	16	17	18	19	20
AL'	39.82	38.46	40.82	39.33	44.76	44.11	41.85	42.79	44.85	44.76
FM'	16.19	11.82	15.17	15.93	9.80	11.16	14.30	13.40	9.51	13.12
C'	7.52	14.12	6.04	4.31	3.09	2.67	4.67	2.45	3.76	2.71
ALK'	36.47	35.60	37.98	40.43	42.35	42.06	39.18	41.36	41.88	39.41
SI'	311.29	308.93	322.49	341.62	384.76	368.25	339.99	350.42	372.65	371.68
K'	0.35	0.39	0.35	0.42	0.38	0.41	0.36	0.35	0.40	0.36
TI'	1.17	1.17	1.19	1.08	1.13	1.05	1.13	1.16	1.14	1.13
MG'	0.24	0.20	0.26	0.31	0.17	0.17	0.25	0.20	0.12	0.26
W'	0.74	0.85	0.82	0.79	0.90	0.91	0.87	0.83	0.94	0.84

TABLE A2 continued

MAJOR ELEMENT

	21	22	23	24	25	26	27	28	29	30
SIO2	69.65	70.35	71.02	70.64	70.70	71.04	70.95	71.76	72.02	70.73
TIO2	0.30	0.25	0.26	0.32	0.31	0.27	0.21	0.20	0.23	0.28
AL2O3	15.94	14.07	14.04	14.67	14.73	14.58	14.10	14.50	13.86	13.88
FE2O3	1.78	2.13	2.06	2.00	2.14	2.51	1.74	1.74	2.16	2.37
FEO	0.36	0.32	0.27	0.36	0.32	0.40	0.12	0.08	0.36	0.56
MNO	0.08	0.05	0.04	0.03	0.04	0.04	0.04	0.02	0.04	0.04
MGO	0.33	0.17	0.53	0.47	0.29	0.51	0.14	0.23	0.35	0.63
CAO	0.42	0.51	0.57	0.51	0.51	0.56	0.60	0.69	0.88	0.92
NA2O	5.95	4.94	5.39	5.23	4.94	5.04	5.53	5.55	5.42	5.61
K2O	4.74	4.79	4.47	4.55	4.96	4.52	4.26	4.70	4.23	4.34
P2O5	0.13	0.11	0.11	0.13	0.14	0.11	0.08	0.09	0.08	0.12
H2O	0.98	1.06	0.99	0.81	1.17	0.86	0.99	0.49	0.84	1.21
CO2	0.00	0.14	0.22	0.00	0.03	0.00	0.21	0.09	0.31	0.36
TOTAL	100.66	98.89	99.97	99.72	100.28	100.44	98.97	100.14	100.78	101.05

NIGGLI VALUES

	21	22	23	24	25	26	27	28	29	30
AL'	45.23	44.09	42.37	43.95	44.54	43.08	44.56	44.09	41.86	39.76
FM'	10.27	11.29	13.14	12.74	11.85	14.96	8.62	8.37	12.55	15.52
C'	2.17	2.91	3.13	2.78	2.80	3.01	3.45	3.31	4.83	4.79
ALK'	42.33	41.71	41.36	40.53	40.80	38.95	43.32	43.23	40.76	39.91
SI'	335.36	374.06	363.68	359.09	362.73	356.16	380.43	370.22	369.10	343.95
K'	0.34	0.39	0.35	0.36	0.40	0.37	0.34	0.36	0.34	0.34
TI'	1.09	1.00	1.00	1.22	1.20	1.02	0.85	0.78	0.89	1.02
MG'	0.23	0.12	0.31	0.28	0.19	0.25	0.13	0.20	0.21	0.29
W'	0.82	0.86	0.87	0.83	0.86	0.85	0.93	0.95	0.84	0.79

TABLE A2 continued

MAJOR ELEMENT

	31	32	33	34	35	36	37	38	39	40
SIO2	70.89	68.41	70.42	71.48	70.66	69.99	69.26	70.62	71.92	61.72
TIO2	0.29	0.27	0.27	0.27	0.27	0.27	0.26	0.25	0.22	0.26
AL2O3	14.43	14.43	14.28	13.97	14.26	14.10	13.97	14.30	13.73	24.00
FE2O3	2.08	1.95	2.45	2.37	2.35	2.40	2.51	2.10	2.11	2.08
FEO	0.04	0.36	0.43	0.01	0.04	0.59	0.55	0.52	0.40	0.53
MNO	0.09	0.05	0.04	0.03	0.04	0.03	0.04	0.04	0.04	0.03
MGO	0.35	0.27	0.52	0.46	0.58	0.44	0.60	0.57	0.45	1.99
CAO	0.61	2.41	0.48	0.46	0.53	0.70	0.92	0.95	0.50	0.78
NA2O	5.72	5.47	5.29	5.61	5.04	5.73	5.75	4.61	5.42	4.24
K2O	4.67	4.83	4.44	4.30	4.50	4.40	4.35	4.51	4.49	3.69
P2O5	0.11	0.11	0.11	0.11	0.11	0.13	0.11	0.10	0.09	0.09
H2O	0.46	0.95	1.08	0.35	0.36	0.98	1.23	0.90	0.79	0.58
CO2	0.14	0.63	0.18	0.92	0.98	0.23	0.46	0.47	0.16	0.00
TOTAL	99.88	100.14	99.99	100.34	99.72	99.99	100.01	99.94	100.32	99.99

NIGGLI VALUES

	31	32	33	34	35	36	37	38	39	40
AL'	42.94	39.30	42.36	42.47	43.33	40.78	39.56	42.87	41.84	53.54
FM'	10.71	10.03	14.99	12.78	13.75	14.50	15.53	14.57	13.41	18.83
C'	3.30	11.93	2.59	2.54	2.93	3.68	4.74	5.13	2.77	3.16
ALK'	43.05	32.74	40.07	42.21	39.99	41.04	40.12	37.37	41.98	24.47
SI'	357.98	316.10	354.41	368.73	364.32	343.47	332.80	359.27	371.88	233.62
K'	0.35	0.37	0.36	0.34	0.37	0.34	0.33	0.39	0.35	0.36
TI'	1.10	0.94	1.02	1.05	1.05	1.00	0.94	0.96	0.86	0.74
MG'	0.25	0.19	0.26	0.22	0.32	0.22	0.28	0.30	0.26	0.60
W'	0.98	0.83	0.84	1.00	0.98	0.79	0.80	0.78	0.83	0.78

TABLE A2 continued

MAJOR ELEMENT

	41	42	43	44	45	46	47	48	49	50
SIO2	70.49	71.29	74.74	73.36	73.99	77.00	76.96	75.73	72.50	73.63
TIO2	0.28	0.26	0.23	0.21	0.25	0.18	0.25	0.22	0.23	0.23
AL2O3	14.29	14.34	12.12	13.48	12.59	11.24	11.73	11.92	12.53	12.83
FE2O3	2.24	2.22	1.77	1.88	1.51	1.50	1.40	1.70	1.45	1.76
FEO	0.48	0.40	0.80	0.08	0.04	0.28	0.04	0.04	0.04	0.04
MNO	0.05	0.03	0.04	0.02	0.03	0.03	0.04	0.02	0.03	0.03
MGO	0.57	0.30	0.14	0.03	0.06	0.07	0.18	0.11	0.16	0.06
CAO	0.65	0.49	0.27	0.21	0.18	0.38	0.22	0.20	1.71	0.28
NA2O	5.66	5.98	4.80	4.94	4.26	4.37	4.79	4.79	4.74	4.98
K2O	4.35	4.53	4.76	5.88	5.65	4.47	4.32	4.61	4.77	4.53
P2O5	0.12	0.10	0.10	0.09	0.10	0.07	0.12	0.10	0.11	0.10
H2O	0.00	0.64	0.55	0.34	0.30	0.42	0.26	0.12	0.42	0.60
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00
TOTAL	99.18	100.58	100.32	100.52	98.96	100.01	100.31	99.56	98.71	99.07

NIGGLI VALUES

AL'	41.45	42.01	41.21	43.56	44.68	42.50	43.47	43.10	40.53	44.41
FM'	14.45	12.19	12.75	8.37	7.56	9.41	8.52	9.06	7.48	8.50
C'	3.43	2.61	1.67	1.23	1.16	2.61	1.48	1.31	10.06	1.76
ALK'	40.67	43.19	44.37	46.33	46.57	45.48	46.53	46.53	41.93	45.33
SI'	346.95	354.40	431.23	402.28	445.56	494.00	483.91	464.58	397.96	432.44
K'	0.34	0.33	0.39	0.44	0.47	0.40	0.37	0.39	0.40	0.37
TI'	1.04	0.97	1.00	0.87	1.13	0.87	1.18	1.02	0.95	1.02
MG'	0.29	0.13	0.09	0.03	0.07	0.07	0.20	0.11	0.17	0.06
W'	0.81	0.83	0.67	0.95	0.97	0.83	0.97	0.97	0.97	0.98

TABLE A2 continued

MAJOR ELEMENT

	51	52	53	54	55✓	56	57	58	59	60
SIO2	74.39	73.67	73.08	74.58	72.58	75.30	74.37	73.65	72.10	74.46
TIO2	0.26	0.26	0.26	0.26	0.20	0.22	0.23	0.27	0.26	0.22
AL2O3	12.55	13.62	12.90	12.88	14.19	12.07	12.50	13.26	13.32	12.77
FE2O3	1.72	1.74	2.63	1.52	1.43	1.74	1.49	1.84	2.46	1.52
FEO	0.08	0.12	0.44	0.12	0.04	0.08	0.08	0.12	0.12	0.04
MNO	0.03	0.03	0.04	0.03	0.03	0.04	0.03	0.03	0.03	0.03
MGO	0.06	0.21	0.38	0.07	0.07	0.19	0.16	0.57	0.57	0.07
CAO	0.37	0.40	0.46	0.39	0.29	0.28	0.21	0.20	0.40	0.32
NA2O	4.84	5.18	4.76	5.13	4.84	4.58	5.08	1.58	1.49	4.03
K2O	4.62	4.65	4.34	4.67	5.64	4.58	5.92	7.54	9.24	5.36
P2O5	0.11	0.10	0.12	0.10	0.10	0.11	0.11	0.12	0.12	0.10
H2O	0.02	0.12	0.52	0.36	0.76	0.34	0.52	1.38	0.58	0.32
CO2	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.10
TOTAL	99.05	100.10	99.93	100.13	100.19	99.53	100.70	100.56	100.69	99.34

NIGGLI VALUES

	51	52	53	54	55✓	56	57	58	59	60
AL'	43.81	44.19	41.34	43.85	46.01	43.28	41.57	46.73	42.62	45.68
FM'	8.59	9.45	15.84	7.79	6.68	10.10	8.05	13.97	15.21	7.78
C'	2.35	2.36	2.68	2.41	1.71	1.83	1.27	1.28	2.33	2.08
ALK'	45.25	43.97	40.14	45.94	45.61	44.79	49.11	37.96	39.84	44.46
SI'	440.62	405.53	397.34	430.85	399.28	458.17	419.70	440.88	391.45	451.91
K'	0.39	0.37	0.37	0.37	0.43	0.40	0.43	0.76	0.80	0.47
TI'	1.16	1.08	1.06	1.13	0.83	1.01	0.98	1.22	1.06	1.00
MG'	0.06	0.18	0.19	0.08	0.09	0.17	0.17	0.36	0.30	0.08
W'	0.95	0.93	0.84	0.92	0.97	0.95	0.94	0.93	0.95	0.97

TABLE A2 continued

MAJOR ELEMENT

	61	62	63	64	65	66	67	68	69	70
SIO2	76.33	73.92	75.64	73.83	75.32	75.03	75.96	73.88	70.71	71.59
TIO2	0.20	0.23	0.24	0.22	0.21	0.21	0.22	0.21	0.22	0.25
AL2O3	11.73	13.44	11.59	12.30	11.94	12.37	11.79	12.73	13.89	14.01
FE2O3	1.72	1.38	2.15	1.57	1.58	1.70	1.57	2.04	2.07	2.23
FEO	0.04	0.08	0.04	0.12	0.08	0.08	0.04	0.12	0.08	0.20
MNO	0.03	0.04	0.03	0.04	0.04	0.03	0.03	0.03	0.04	0.04
MGO	0.13	0.08	0.17	0.14	0.04	0.16	0.03	0.42	0.14	0.25
CAO	0.41	0.31	0.32	0.26	0.84	0.22	0.17	0.14	0.40	0.43
NA2O	4.16	5.36	5.09	5.93	4.89	4.50	5.23	1.31	3.74	4.70
K2O	5.29	4.78	4.55	5.13	4.73	5.05	4.47	8.34	6.85	4.60
P2O5	0.10	0.10	0.11	0.11	0.10	0.11	0.09	0.09	0.10	0.11
H2O	0.36	0.29	0.42	0.47	0.46	0.36	0.46	1.02	0.70	0.60
CO2	0.02	0.08	0.00	0.02	0.00	0.00	0.04	0.04	0.02	0.00
TOTAL	100.52	100.09	100.35	100.14	100.23	99.82	100.10	100.37	98.96	99.01

NIGGLI VALUES

	61	62	63	64	65	66	67	68	69	70
AL'	42.46	44.69	40.38	40.18	41.37	43.67	42.60	45.46	44.38	44.81
FM'	9.35	6.91	11.26	8.26	7.73	9.49	7.72	13.70	9.94	12.04
C'	2.70	1.87	2.03	1.54	5.29	1.41	1.12	0.91	2.32	2.50
ALK'	45.50	46.52	46.33	50.01	45.61	45.43	48.56	39.93	43.35	40.65
SI'	468.81	417.08	447.17	409.26	442.78	449.42	465.67	447.65	333.39	388.52
K'	0.46	0.37	0.37	0.36	0.39	0.42	0.36	0.81	0.55	0.39
TI'	0.92	0.98	1.07	0.92	0.93	0.95	1.01	0.96	0.90	1.02
MG'	0.13	0.10	0.13	0.14	0.05	0.15	0.04	0.23	0.11	0.17
W'	0.97	0.94	0.98	0.92	0.95	0.95	0.97	0.94	0.96	0.91

TABLE A2 continued

MAJOR ELEMENT

	71	72	73	74	75	76	77	78	79	80
SIO2	75.04	73.30	74.56	77.66	74.40	73.65	74.23	72.82	71.29	72.22
TIO2	0.22	0.22	0.24	0.25	0.25	0.27	0.29	0.26	0.13	0.37
AL2O3	12.63	13.40	13.09	11.06	13.41	13.56	13.59	13.50	14.13	14.14
FE2O3	2.18	2.08	1.88	1.53	1.44	1.91	1.44	2.21	2.63	1.77
FEO	0.04	0.12	0.04	0.08	0.12	0.04	0.08	0.16	0.44	0.08
MNO	0.03	0.04	0.03	0.03	0.02	0.04	0.03	0.03	0.04	0.04
MGO	0.06	0.30	0.11	0.12	0.21	0.17	0.13	0.32	0.43	0.17
CAO	0.18	0.35	0.23	0.67	0.39	0.64	0.40	0.56	0.70	0.54
NA2O	4.61	5.52	4.69	3.69	4.53	4.61	4.56	4.69	4.94	4.32
K2O	4.78	5.53	5.27	5.12	4.71	4.45	4.69	4.71	4.56	5.41
P2O5	0.10	0.10	0.09	0.10	0.13	0.10	0.10	0.10	0.13	0.15
H2O	0.34	0.54	0.36	0.78	0.38	0.34	0.66	0.40	0.73	0.40
CO2	0.00	0.02	0.00	0.00	0.00	0.04	0.08	0.04	0.18	0.00
TOTAL	100.21	101.52	100.59	101.09	99.99	99.82	100.28	99.80	100.33	99.61

NIGGLI VALUES

	71	72	73	74	75	76	77	78	79	80
AL'	44.00	40.99	44.13	42.12	45.91	45.13	46.58	43.28	42.14	45.78
FM'	10.42	10.97	9.22	9.03	8.70	9.74	7.82	12.37	15.12	9.08
C'	1.14	1.95	1.41	4.64	2.43	3.87	2.49	3.26	3.80	3.18
ALK'	44.44	46.09	45.24	44.22	42.97	41.27	43.11	41.08	38.95	41.97
SI'	443.54	380.50	426.50	501.78	432.20	415.88	431.70	396.16	360.71	396.74
K'	0.41	0.40	0.43	0.46	0.41	0.39	0.40	0.40	0.38	0.45
TI'	0.98	0.86	1.03	1.21	1.09	1.15	1.27	1.06	0.49	1.53
MG'	0.05	0.21	0.10	0.13	0.21	0.15	0.14	0.21	0.21	0.15
W'	0.98	0.94	0.98	0.95	0.92	0.98	0.94	0.93	0.84	0.95

TABLE A2 continued

MAJOR ELEMENT

	81	82	83	84	85	86	87	88	89	90
SIO2	70.13	72.96	74.62	72.54	72.79	72.25	71.87	71.03	71.05	72.61
TIO2	0.33	0.23	0.25	0.27	0.26	0.24	0.29	0.30	0.37	0.33
AL2O3	14.40	13.88	12.64	12.39	13.56	12.78	13.62	13.95	14.00	14.23
FE2O3	2.42	2.03	2.22	2.28	2.57	2.31	2.37	2.66	2.66	1.63
FEO	0.24	0.40	0.08	0.12	0.12	0.08	0.40	0.36	0.60	0.12
MNO	0.03	0.03	0.03	0.06	0.02	0.04	0.03	0.04	0.04	0.03
MGO	0.47	0.34	0.09	0.10	0.25	0.25	0.59	0.80	0.60	0.25
CAO	0.65	0.48	0.39	3.53	0.37	0.88	0.61	0.93	0.88	0.33
NA2O	4.69	4.70	4.38	3.78	4.85	4.80	4.70	5.23	4.65	4.24
K2O	4.80	4.68	4.51	4.58	4.50	4.47	4.80	4.79	4.57	5.22
P2O5	0.16	0.09	0.11	0.09	0.12	0.11	0.10	0.13	0.14	0.14
H2O	0.71	0.68	0.67	0.25	0.73	0.40	0.52	0.28	0.61	0.63
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.05	0.16	0.00
TOTAL	99.03	100.50	99.99	99.99	100.14	98.61	99.96	100.55	100.33	99.76

NIGGLI VALUES

	81	82	83	84	85	86	87	88	89	90
AL'	43.49	43.97	44.18	37.19	43.51	41.48	41.60	39.45	41.22	46.90
FM'	13.95	12.73	11.10	10.01	13.10	11.99	15.53	16.77	16.98	9.51
C'	3.57	2.76	2.48	19.26	2.16	5.19	3.39	4.78	4.71	1.96
ALK'	38.99	40.54	42.24	33.54	41.23	41.33	39.48	38.99	37.09	41.61
SI'	359.38	392.14	442.53	369.42	396.29	397.90	372.45	340.85	354.98	406.09
K'	0.40	0.40	0.40	0.44	0.38	0.38	0.40	0.38	0.39	0.45
TI'	1.27	0.93	1.12	1.03	1.06	0.99	1.13	1.08	1.39	1.39
MG'	0.26	0.21	0.07	0.08	0.15	0.17	0.29	0.34	0.26	0.22
W'	0.90	0.82	0.96	0.94	0.95	0.96	0.84	0.87	0.80	0.92

TABLE A2 continued

MAJOR ELEMENT

	91	92	93	94	95
SIO2	74.15	73.93	71.62	72.04	71.12
TIO2	0.31	0.27	0.29	0.24	0.32
AL2O3	13.39	12.78	14.21	14.14	14.32
FE2O3	1.80	1.61	2.57	2.31	1.93
FEO	0.16	0.08	0.60	0.28	0.16
MNO	0.04	0.04	0.04	0.02	0.03
MGO	0.03	0.21	0.74	0.24	0.28
CAO	0.22	0.21	0.80	0.45	0.42
NA2O	4.38	4.29	4.85	4.50	4.54
K2O	5.30	5.26	4.34	5.01	5.63
P2O5	0.11	0.12	0.12	0.10	0.13
H2O	0.10	0.00	0.08	0.57	0.63
CO2	0.00	0.00	0.02	0.00	0.00
TOTAL	99.99	98.80	100.28	99.90	99.51

NIGGLI VALUES

	91	92	93	94	95
AL'	45.65	44.67	41.37	44.55	44.69
FM'	8.87	9.44	17.48	12.46	10.61
C'	1.36	1.33	4.23	2.58	2.38
ALK'	44.12	44.56	36.91	40.41	42.32
SI'	428.92	438.42	353.83	385.15	376.58
K'	0.44	0.45	0.37	0.42	0.45
TI'	1.35	1.20	1.08	0.96	1.27
MG'	0.03	0.20	0.31	0.15	0.21
W'	0.91	0.95	0.79	0.88	0.92

TABLE A2 continued

TRACE ELEMENTS

	1	2	3	4	5	6	7	8	9	10
BA	1368.00	1319.00	1422.00	1428.00	1551.00	1450.00	1538.00	1599.00	1609.00	1822.00
SR	640.00	591.00	603.00	593.00	706.00	637.00	606.00	564.00	328.00	581.00
RB	176.00	162.00	169.00	166.00	179.00	168.00	170.00	163.00	179.00	173.00
ZR	191.00	188.00	181.00	175.00	180.00	169.00	189.00	191.00	212.00	216.00
CE	106.00	111.00	105.00	100.00	102.00	87.00	96.00	92.00	106.00	90.00
LA	143.00	378.00	157.00	62.00	66.00	75.00	79.00	79.00	63.00	51.00
PB	53.00	56.00	51.00	38.00	47.00	38.00	41.00	32.00	46.00	40.00
TH	19.00	25.00	23.00	23.00	18.00	28.00	19.00	23.00	24.00	20.00
GA	22.00	23.00	24.00	22.00	20.00	18.00	20.00	21.00	18.00	22.00
NB	21.00	18.00	17.00	16.00	16.00	15.00	16.00	16.00	17.00	16.00
CR	35.00	20.00	14.00	13.00	14.00	11.00	14.00	12.00	11.00	11.00
CU	12.00	12.00	12.00	7.00	9.00	6.00	41.00	3.00	8.00	8.00
ZN	17.00	22.00	19.00	30.00	31.00	31.00	32.00	24.00	16.00	41.00
CC	2.00	0.00	0.00	12.00	0.00	1.00	7.00	5.00	6.00	0.00
NI	0.00	1.00	1.00	4.00	3.00	1.00	3.00	3.00	0.00	2.00
Y	10.00	24.00	12.00	5.00	3.00	4.00	3.00	1.00	5.00	3.00

TRACE ELEMENTS

	11	12	13	14	15	16	17	18	19	20
BA	1217.00	2062.00	1534.00	1470.00	1426.00	1565.00	1490.00	1412.00	1231.00	1329.00
SR	705.00	494.00	545.00	514.00	578.00	524.00	547.00	464.00	406.00	462.00
RB	177.00	193.00	171.00	184.00	182.00	202.00	175.00	179.00	200.00	175.00
ZR	217.00	208.00	212.00	192.00	187.00	169.00	179.00	176.00	173.00	179.00
CE	94.00	104.00	97.00	84.00	94.00	79.00	94.00	108.00	95.00	86.00
LA	56.00	58.00	53.00	50.00	62.00	53.00	59.00	52.00	51.00	32.00
PB	47.00	39.00	42.00	35.00	39.00	42.00	36.00	43.00	59.00	35.00
TH	16.00	29.00	21.00	52.00	23.00	24.00	25.00	26.00	26.00	24.00
GA	24.00	23.00	21.00	22.00	23.00	18.00	19.00	18.00	22.00	22.00
NB	16.00	15.00	16.00	15.00	13.00	14.00	16.00	17.00	14.00	13.00
CR	10.00	34.00	30.00	11.00	12.00	12.00	10.00	11.00	15.00	13.00
CU	7.00	9.00	9.00	22.00	10.00	10.00	9.00	10.00	6.00	11.00
ZN	32.00	21.00	35.00	32.00	11.00	12.00	22.00	24.00	58.00	24.00
CC	8.00	4.00	7.00	8.00	9.00	4.00	0.00	4.00	5.00	3.00
NI	1.00	0.00	2.00	1.00	2.00	1.00	0.00	4.00	1.00	0.00
Y	6.00	6.00	4.00	2.00	4.00	[illegible]	6.00	1.00	6.00	3.00

TABLE A3 Trace element content of the Helmsdale Granites.

TRACE ELEMENTS

	21	22	23	24	25	26	27	28	29	30
BA	877.00	1336.00	1567.00	1366.00	1505.00	1359.00	1032.00	1198.00	1249.00	1321.00
SR	274.00	511.00	568.00	499.00	547.00	582.00	388.00	453.00	479.00	495.00
RB	196.00	199.00	179.00	178.00	189.00	183.00	180.00	195.00	198.00	170.00
ZR	188.00	184.00	179.00	180.00	184.00	161.00	138.00	138.00	140.00	148.00
CE	130.00	33.00	88.00	99.00	98.00	83.00	61.00	66.00	66.00	73.00
LA	60.00	38.00	39.00	69.00	54.00	41.00	37.00	36.00	32.00	40.00
PB	23.00	50.00	47.00	41.00	45.00	48.00	40.00	51.00	52.00	41.00
TH	24.00	21.00	18.00	18.00	21.00	21.00	21.00	22.00	23.00	23.00
GA	21.00	18.00	19.00	20.00	23.00	24.00	24.00	24.00	24.00	26.00
NB	14.00	16.00	17.00	19.00	19.00	15.00	14.00	14.00	16.00	15.00
CR	11.00	10.00	12.00	12.00	13.00	13.00	11.00	9.00	9.00	13.00
CU	8.00	10.00	15.00	11.00	7.00	11.00	6.00	7.00	5.00	6.00
ZN	6.00	10.00	22.00	23.00	21.00	30.00	11.00	7.00	28.00	44.00
CO	2.00	4.00	0.00	0.00	4.00	2.00	0.00	2.00	6.00	4.00
NI	1.00	0.00	1.00	2.00	2.00	2.00	0.00	0.00	0.00	2.00
Y	6.00	0.00	0.00	1.00	4.00	1.00	4.00	3.00	5.00	4.00

TRACE ELEMENTS

	31	32	33	34	35	36	37	38	39	40
BA	1280.00	1310.00	1120.00	1115.00	1340.00	1250.00	1310.00	1170.00	1198.00	1200.00
SR	240.00	445.00	513.00	493.00	439.00	508.00	518.00	505.00	527.00	499.00
RB	188.00	199.00	193.00	179.00	202.00	190.00	186.00	181.00	177.00	180.00
ZR	149.00	150.00	132.00	150.00	162.00	172.00	135.00	158.00	130.00	141.00
CE	52.00	30.00	49.00	62.00	65.00	75.00	39.00	82.00	84.00	40.00
LA	116.00	50.00	168.00	55.00	44.00	45.00	43.00	39.00	41.00	31.00
PB	13.00	36.00	49.00	43.00	19.00	36.00	40.00	43.00	42.00	38.00
TH	25.00	36.00	21.00	16.00	22.00	20.00	26.00	38.00	31.00	22.00
GA	19.00	21.00	22.00	20.00	23.00	19.00	17.00	22.00	20.00	24.00
NB	17.00	15.00	16.00	20.00	18.00	13.00	17.00	19.00	15.00	18.00
CR	11.00	14.00	10.00	11.00	13.00	14.00	8.00	12.00	14.00	13.00
CU	9.00	7.00	9.00	7.00	8.00	6.00	10.00	12.00	8.00	11.00
ZN	13.00	17.00	31.00	11.00	15.00	9.00	20.00	28.00	34.00	30.00
CO	2.00	0.00	6.00	3.00	5.00	0.00	4.00	4.00	0.00	0.00
NI	1.00	2.00	0.00	0.00	1.00	3.00	0.00	4.00	0.00	1.00
Y	15.00	6.00	8.00	2.00	5.00	4.00	6.00	3.00	1.00	6.00

TRACE ELEMENTS

	41	42	43 ✓	44	45	46	47	48	49	50
BA	1218.00	1173.00	930.00	1205.00	993.00	662.00	655.00	661.00	891.00	881.00
SR	504.00	533.00	197.00	207.00	77.00	149.00	69.00	59.00	137.00	288.00
RB	183.00	175.00	190.00	213.00	191.00	198.00	154.00	162.00	186.00	197.00
ZR	150.00	147.00	157.00	137.00	153.00	131.00	159.00	138.00	135.00	150.00
CE	35.00	46.00	30.00	30.00	67.00	70.00	75.00	40.00	31.00	58.00
LA	40.00	38.00	15.00	15.00	35.00	38.00	33.00	22.00	17.00	35.00
PB	42.00	57.00	20.00	15.00	11.00	19.00	10.00	11.00	18.00	29.00
TH	25.00	27.00	28.00	25.00	26.00	38.00	29.00	25.00	20.00	29.00
GA	20.00	22.00	16.00	17.00	13.00	17.00	17.00	16.00	20.00	22.00
NB	14.00	13.00	22.00	20.00	18.00	15.00	17.00	14.00	18.00	21.00
CR	11.00	12.00	15.00	12.00	12.00	13.00	14.00	12.00	10.00	23.00
CU	12.00	10.00	9.00	9.00	9.00	17.00	19.00	14.00	14.00	9.00
ZN	29.00	31.00	9.00	7.00	5.00	14.00	13.00	8.00	4.00	5.00
CO	2.00	4.00	3.00	5.00	0.00	1.00	0.00	2.00	0.00	3.00
NI	2.00	1.00	0.00	0.00	0.00	1.00	2.00	2.00	0.00	3.00
Y	8.00	3.00	1.00	0.00	4.00	3.00	3.00	3.00	2.00	3.00

TRACE ELEMENTS

	51	52	53	54	55 ✓	56	57	58	59	60
BA	921.00	988.00	917.00	946.00	1166.00	665.00	1086.00	963.00	1068.00	235.00
SR	304.00	325.00	311.00	182.00	175.00	115.00	142.00	135.00	269.00	98.00
RB	199.00	211.00	210.00	190.00	220.00	157.00	201.00	467.00	461.00	198.00
ZR	162.00	157.00	177.00	164.00	134.00	153.00	151.00	162.00	161.00	153.00
CE	123.00	102.00	75.00	24.00	201.00	54.00	52.00	66.00	73.00	60.00
LA	72.00	61.00	43.00	12.00	118.00	24.00	23.00	38.00	48.00	32.00
PB	38.00	34.00	27.00	18.00	23.00	11.00	8.00	26.00	40.00	22.00
TH	29.00	33.00	37.00	24.00	27.00	29.00	25.00	27.00	29.00	24.00
GA	21.00	22.00	24.00	19.00	19.00	23.00	24.00	25.00	25.00	17.00
NB	22.00	18.00	18.00	21.00	17.00	19.00	19.00	17.00	18.00	20.00
CR	16.00	15.00	16.00	13.00	11.00	13.00	13.00	17.00	13.00	13.00
CU	10.00	13.00	14.00	9.00	8.00	14.00	10.00	12.00	8.00	19.00
ZN	8.00	9.00	14.00	7.00	10.00	11.00	19.00	34.00	23.00	6.00
CO	0.00	2.00	3.00	1.00	1.00	0.00	1.00	8.00	0.00	0.00
NI	4.00	6.00	10.00	0.00	2.00	1.00	0.00	8.00	11.00	0.00
Y	5.00	7.00	7.00	0.00	13.00	1.00	3.00	8.00	8.00	3.00

TRACE ELEMENTS

	61	62	63	64	65	66	67	68	69	70
BA	881.00	913.00	747.00	927.00	894.00	771.00	N.D.	906.00	784.00	1146.00
SR	78.00	299.00	76.00	83.00	134.00	96.00	N.D.	224.00	98.00	465.00
RB	180.00	209.00	164.00	178.00	177.00	178.00	N.D.	412.00	254.00	204.00
ZR	140.00	143.00	130.00	147.00	135.00	147.00	N.D.	152.00	157.00	161.00
CE	65.00	52.00	73.00	56.00	42.00	83.00	N.D.	50.00	88.00	60.00
LA	33.00	25.00	43.00	31.00	17.00	41.00	N.D.	29.00	56.00	34.00
PB	15.00	36.00	8.00	8.00	16.00	16.00	N.D.	28.00	9.00	64.00
TH	24.00	29.00	30.00	27.00	30.00	30.00	N.D.	31.00	31.00	29.00
GA	15.00	21.00	16.00	17.00	21.00	21.00	N.D.	25.00	23.00	23.00
NB	19.00	18.00	21.00	20.00	14.00	20.00	N.D.	16.00	21.00	20.00
CR	13.00	12.00	14.00	14.00	13.00	17.00	N.D.	10.00	14.00	13.00
CU	17.00	19.00	11.00	8.00	5.00	4.00	N.D.	2.00	7.00	10.00
ZN	10.00	19.00	13.00	13.00	10.00	10.00	N.D.	22.00	8.00	17.00
CO	3.00	7.00	0.00	1.00	0.00	4.00	N.D.	5.00	0.00	0.00
NI	0.00	2.00	0.00	4.00	0.00	0.00	N.D.	0.00	2.00	1.00
Y	5.00	8.00	6.00	4.00	2.00	0.00	N.D.	3.00	10.00	6.00

TRACE ELEMENTS

	71	72	73	74	75	76	77	73	79	80
BA	1215.00	1314.00	890.00	N.D.	798.00	1132.00	1022.00	1303.00	N.D.	1470.00
SR	104.00	435.00	197.00	N.D.	299.00	592.00	449.00	632.00	N.D.	600.00
RB	186.00	208.00	205.00	N.D.	168.00	149.00	184.00	219.00	N.D.	208.00
ZR	160.00	158.00	176.00	N.D.	172.00	168.00	165.00	164.00	N.D.	180.00
CE	70.00	68.00	44.00	N.D.	65.00	98.00	77.00	61.00	N.D.	70.00
LA	16.00	35.00	21.00	N.D.	23.00	16.00	14.00	11.00	N.D.	68.00
PB	21.00	34.00	15.00	N.D.	21.00	52.00	34.00	63.00	N.D.	62.00
TH	36.00	27.00	26.00	N.D.	33.00	29.00	28.00	26.00	N.D.	27.00
GA	18.00	20.00	20.00	N.D.	18.00	17.00	18.00	19.00	N.D.	24.00
NB	21.00	19.00	20.00	N.D.	20.00	13.00	17.00	12.00	N.D.	13.00
CR	12.00	14.00	11.00	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
CU	9.00	8.00	11.00	N.D.	8.00	6.00	10.00	7.00	N.D.	13.00
ZN	10.00	7.00	6.00	N.D.	16.00	12.00	19.00	41.00	N.D.	34.00
CO	1.00	2.00	0.00	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
NI	0.00	1.00	0.00	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Y	4.00	3.00	5.00	N.D.	6.00	5.00	4.00	0.00	N.D.	8.00

TRACE ELEMENTS

	81	82	83	84	85	86	87	88	89	90
BA	1499.00	1036.00	1910.00	2714.00	1530.00	N.D.	1400.00	23.00	1428.00	1312.00
SR	633.00	454.00	302.00	360.00	327.00	N.D.	727.00	174.00	750.00	402.00
RB	188.00	217.00	202.00	208.00	219.00	N.D.	192.00	69.00	188.00	214.00
ZR	199.00	153.00	169.00	156.00	180.00	N.D.	142.00	1355.00	185.00	185.00
CE	71.00	80.00	95.00	52.00	90.00	N.D.	83.00	49.00	88.00	126.00
LA	26.00	52.00	49.00	21.00	41.00	N.D.	34.00	707.00	40.00	17.00
PB	39.00	111.00	25.00	28.00	39.00	N.D.	53.00	21.00	59.00	37.00
TH	27.00	27.00	34.00	13.00	31.00	N.D.	44.00	N.D.	23.00	29.00
GA	21.00	23.00	18.00	21.00	26.00	N.D.	22.00	10.00	21.00	21.00
NB	11.00	16.00	16.00	13.00	16.00	N.D.	12.00	N.D.	14.00	14.00
CR	N.D.	13.00	14.00	11.00	14.00	N.D.	N.D.	4.00	N.D.	N.D.
CU	7.00	8.00	12.00	13.00	8.00	N.D.	13.00	43.00	8.00	20.00
ZN	44.00	59.00	19.00	21.00	17.00	N.D.	38.00	15.00	53.00	17.00
CO	N.D.	2.00	1.00	0.00	3.00	N.D.	N.D.	N.D.	N.D.	N.D.
NI	N.D.	2.00	0.00	1.00	0.00	N.D.	N.D.	N.D.	N.D.	N.D.
Y	2.00	5.00	5.00	8.00	4.00	N.D.	0.00	208.00	1.00	0.00

TRACE ELEMENTS

	91	92	93	94	95
BA	1370.00	1411.00	N.D.	N.D.	N.D.
SR	114.00	167.00	655.00	450.00	N.D.
RB	183.00	185.00	183.00	193.00	N.D.
ZR	180.00	183.00	N.D.	N.D.	N.D.
CE	90.00	84.00	N.D.	N.D.	N.D.
LA	29.00	4.00	61.00	25.00	N.D.
PB	16.00	28.00	56.00	64.00	N.D.
TH	24.00	23.00	22.00	29.00	N.D.
GA	15.00	15.00	20.00	22.00	N.D.
NB	14.00	15.00	N.D.	12.00	N.D.
CR	N.D.	N.D.	N.D.	N.D.	N.D.
CU	16.00	11.00	8.00	4.00	N.D.
ZN	12.00	13.00	55.00	29.00	N.D.
CO	N.D.	N.D.	N.D.	N.D.	N.D.
NI	N.D.	N.D.	N.D.	N.D.	N.D.
Y	4.00	0.00	6.00	0.00	N.D.

C I P W

	1	2	3	4	5	6	7	8	9	10
AB	41.37	42.21	42.38	43.82	43.48	40.94	45.09	47.80	51.84	43.90
OR	26.24	28.49	26.42	25.23	26.53	25.94	25.06	28.37	30.08	25.65
Q	24.70	23.07	24.24	22.46	21.70	25.03	21.18	17.47	11.73	21.42
AN	1.91	0.88	1.60	2.63	2.62	1.36	1.30	0.00	0.00	1.22
AP	0.33	0.30	0.30	0.33	0.30	0.26	0.28	0.30	0.33	0.30
IL	0.42	0.57	0.42	0.59	0.61	0.55	0.61	0.63	0.51	0.61
AC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.69	0.00
MT	0.00	0.03	0.00	0.26	0.36	0.58	1.01	0.33	0.00	1.14
HM	1.90	2.39	2.07	2.30	2.21	2.07	1.73	1.97	2.06	1.75
HYEN	0.45	0.45	0.85	1.52	1.10	1.10	1.52	0.28	0.34	1.42
HYFS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	97.32	98.39	98.28	99.14	98.91	97.83	97.78	97.75	97.58	97.41

C I P W

	11	12	13	14	15	16	17	18	19	20
AB	45.51	41.45	45.94	40.63	42.81	42.04	45.09	47.20	41.79	42.30
OR	25.83	28.31	26.77	32.92	27.95	30.44	27.01	26.39	29.61	25.71
Q	19.06	19.74	18.69	20.18	23.57	21.62	19.79	19.54	22.96	25.38
AN	0.91	1.48	1.80	-0.22	1.33	-0.78	2.55	1.05	-0.05	0.25
AP	0.33	0.30	0.33	0.28	0.26	0.28	0.30	0.30	0.28	0.30
IL	0.65	0.65	0.65	0.57	0.40	0.42	0.59	0.59	0.25	0.55
AC	0.00	0.00	0.00	1.77	0.00	0.00	0.00	0.00	0.00	0.00
MT	1.72	0.17	0.69	0.94	0.00	0.00	0.23	0.10	0.00	0.32
HM	1.47	2.23	2.14	1.15	1.81	2.14	2.38	2.43	2.00	1.86
HYEN	1.42	0.87	1.42	1.74	0.52	0.62	1.23	0.92	0.35	1.12
HYFS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	96.90	95.20	98.43	99.96	98.65	98.34	99.17	99.02	97.19	97.79

TABLE A4. CIPW norms of the Helmsdale Granites.

C I P W

	21	22	23	24	25	26	27	28	29	30
AB	50.33	41.79	45.60	44.24	41.79	42.64	46.78	46.95	45.85	47.22
OR	28.01	28.31	26.42	26.89	29.31	26.71	25.18	27.78	25.00	25.65
Q	15.87	22.63	21.46	21.38	21.93	22.77	21.79	20.49	23.16	20.28
AN	1.23	0.93	0.72	1.68	1.43	2.06	1.07	0.77	1.00	0.00
AP	0.30	0.26	0.26	0.30	0.33	0.26	0.19	0.21	0.19	0.28
IL	0.57	0.47	0.49	0.61	0.59	0.51	0.25	0.17	0.44	0.53
AC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21
MT	0.29	0.31	0.12	0.23	0.13	0.51	0.00	0.00	0.49	0.99
HM	1.58	1.92	1.98	1.84	2.05	2.16	1.74	1.74	1.82	1.61
HYEN	0.82	0.42	1.32	1.17	0.72	1.27	0.35	0.17	0.55	1.03
HYFS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	99.00	97.04	98.37	98.34	98.28	98.89	97.35	98.28	98.50	97.80

C I P W

	31	32	33	34	35	36	37	38	39	40
AB	48.21	46.27	44.75	47.46	42.64	48.02	47.63	39.00	45.61	35.87
OR	27.60	28.54	26.24	25.41	26.59	26.00	25.71	26.65	26.53	21.81
Q	18.95	16.02	21.65	22.01	23.56	19.01	18.30	25.22	22.40	18.55
AN	0.00	0.56	0.52	-0.72	-0.72	0.00	0.00	1.09	0.00	3.28
AP	0.26	0.26	0.26	0.26	0.26	0.30	0.26	0.23	0.21	0.21
IL	0.08	0.51	0.51	0.02	0.08	0.51	0.49	0.47	0.42	0.49
AC	0.16	0.00	0.00	0.00	0.00	0.40	0.89	0.00	0.21	0.00
MT	0.00	0.33	0.60	0.00	0.00	1.12	1.02	0.95	0.65	0.95
HM	2.03	1.69	2.03	2.37	2.35	1.49	1.50	1.44	1.59	1.42
HYEN	0.67	0.00	1.29	1.15	1.44	0.67	1.16	1.42	0.80	4.96
HYFS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	97.96	94.23	97.85	97.96	96.20	97.52	96.96	96.47	98.42	87.54

TABLE A4 continued

C I P W

	41	42	43	44	45	46	47	48	49	50
AB	47.88	48.53	35.83	36.59	33.29	32.92	36.28	35.64	37.88	40.76
OR	25.71	26.77	28.13	34.75	33.39	26.42	25.53	27.24	28.19	26.77
Q	19.38	18.81	28.96	23.17	28.07	34.99	33.20	31.10	25.29	27.39
AN	0.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AP	0.28	0.23	0.23	0.21	0.23	0.16	0.28	0.23	0.26	0.23
IL	0.53	0.49	0.44	0.17	0.08	0.34	0.08	0.08	0.08	0.08
AC	0.00	1.82	4.21	4.58	2.42	3.57	3.74	4.30	1.95	1.20
MT	0.74	0.54	0.46	0.00	0.00	0.38	0.00	0.00	0.00	0.00
HM	1.73	1.22	0.00	0.30	0.67	0.00	0.11	0.21	0.78	1.34
HYEN	0.81	0.11	0.26	0.06	0.15	0.00	0.45	0.27	0.00	0.12
HYFS	0.00	0.00	0.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	97.80	98.52	99.14	99.83	98.30	98.78	99.67	99.07	94.43	97.89

C I P W

	51	52	53	54	55	56	57	58	59	60
AB	38.82	43.82	40.27	40.24	40.94	36.58	31.33	13.37	12.60	34.09
OR	27.30	27.48	25.65	27.60	33.33	27.07	34.99	44.56	54.61	31.68
Q	28.71	25.10	27.67	27.21	22.52	31.20	26.84	34.66	26.70	30.27
AN	0.00	0.18	1.02	0.00	0.34	0.00	0.00	0.21	1.20	0.30
AP	0.26	0.23	0.28	0.23	0.23	0.26	0.26	0.28	0.28	0.23
IL	0.17	0.25	0.49	0.25	0.03	0.17	0.17	0.25	0.25	0.08
AC	1.87	0.00	0.00	2.78	0.00	1.91	4.31	0.00	0.00	0.00
MT	0.00	0.00	0.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HM	1.07	1.74	2.17	0.56	1.43	1.08	0.00	1.34	2.46	1.52
HYEN	0.00	0.27	0.77	0.00	0.17	0.40	0.40	1.42	1.42	0.17
HYFS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	98.20	99.07	98.98	98.87	99.04	98.67	98.30	96.59	99.52	98.34

TABLE A4 continued

C I P W

	61	62	63	64	65	66	67	68	69	70
AB	30.88	42.51	34.28	34.70	35.07	35.50	35.75	11.08	31.64	39.76
OR	31.26	28.25	26.89	30.32	27.95	29.84	26.42	49.29	40.48	27.18
Q	32.41	24.89	30.78	26.49	29.78	29.79	31.48	33.78	22.08	25.66
AN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.15	0.88	1.41
AP	0.23	0.23	0.26	0.26	0.23	0.26	0.21	0.21	0.23	0.26
IL	0.08	0.17	0.08	0.25	0.17	0.17	0.08	0.25	0.17	0.42
AC	3.80	2.50	6.22	4.54	4.57	2.26	4.54	0.00	0.00	0.00
MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HM	0.41	0.52	0.00	0.00	0.00	0.92	0.00	2.04	2.07	2.23
HYEN	0.07	0.20	0.36	0.30	0.00	0.40	0.07	1.05	0.35	0.62
HYFS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	99.14	99.27	98.87	96.86	97.77	99.14	98.55	97.55	97.90	97.54

C I P W

	71	72	73	74	75	76	77	78	79	80
AB	38.34	38.13	37.98	28.38	38.32	39.00	38.53	39.63	41.79	36.55
OR	26.25	32.68	31.14	30.26	27.83	26.30	27.72	27.33	26.95	31.97
Q	29.94	21.93	27.21	36.49	29.24	28.57	29.20	26.23	23.82	25.40
AN	0.00	0.00	0.00	0.00	1.09	2.27	0.83	1.37	1.49	1.70
AP	0.23	0.23	0.21	0.23	0.30	0.23	0.23	0.23	0.30	0.35
IL	0.08	0.25	0.08	0.17	0.25	0.08	0.17	0.34	0.25	0.17
AC	0.58	6.02	1.49	2.50	0.00	0.00	0.00	0.00	0.00	0.00
MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.04	0.00
HM	1.98	0.00	1.36	0.67	1.44	1.91	1.44	2.21	1.91	1.77
HYEN	0.15	0.51	0.27	0.00	0.52	0.42	0.32	0.80	1.07	0.42
HYFS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	99.55	99.75	99.74	98.70	98.99	98.78	98.49	99.19	98.62	98.33

TABLE A4 continued

C I P W

	81	82	83	84	85	86	87	88	89	90
AB	39.68	39.76	37.05	31.98	41.03	40.61	39.76	44.24	39.34	35.87
OR	28.37	27.66	26.65	27.07	26.59	26.42	28.37	28.31	27.01	30.85
Q	22.83	26.43	31.22	28.50	26.53	26.03	24.44	20.24	24.56	27.28
AN	2.18	1.79	1.22	3.31	1.05	0.12	1.89	0.44	2.44	0.72
AP	0.37	0.21	0.26	0.21	0.28	0.26	0.23	0.30	0.33	0.33
IL	0.51	0.44	0.17	0.25	0.25	0.17	0.55	0.57	0.70	0.25
AC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MT	0.00	0.62	0.00	0.00	0.00	0.00	0.45	0.29	0.86	0.00
HM	2.42	1.60	2.22	2.28	2.57	2.31	2.06	2.46	2.07	1.63
HYEN	1.17	0.85	0.22	0.00	0.62	0.00	1.43	0.91	1.49	0.62
HYFS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	97.53	99.36	99.01	93.60	98.92	95.92	99.18	97.76	98.80	97.55

C I P W

	91	92	93	94	95
AB	37.05	36.29	41.03	38.07	38.41
OR	31.32	31.39	25.65	29.61	33.27
Q	28.18	28.46	24.37	25.65	22.21
AN	0.37	0.08	3.06	1.53	1.23
AP	0.26	0.28	0.28	0.23	0.30
IL	0.34	0.17	0.55	0.46	0.34
AC	0.00	0.00	0.00	0.00	0.00
MT	0.00	0.00	1.09	0.21	0.00
HM	1.80	1.61	1.82	2.17	1.93
HYEN	0.07	0.52	1.84	0.60	0.70
HYFS	0.00	0.00	0.00	0.00	0.00
TOTAL	99.39	98.50	99.69	98.58	98.39

TABLE A4 continued

APPENDIX 2

MICROPROBE ANALYSES RESULTS

GLEN LOTH PLAGIOCLASE

Analysis No	18	19	21	22	24	47	48	50
SiO_2	65.30	66.07	66.67	68.11	68.45	67.23	68.16	64.75
TiO_2	-	-	-	-	-	0.00	0.00	0.00
Al_2O_3	19.50	19.87	19.68	19.89	19.72	19.58	19.87	19.54
T FeO	0.27	0.00	0.20	0.23	0.00	0.00	0.00	0.17
MnO	-	-	-	-	-	0.14	0.00	0.00
MgO	-	-	-	-	-	0.00	0.00	0.00
CaO	0.42	0.21	0.34	0.00	0.00	0.00	0.00	0.36
Na_2O	10.80	11.32	11.13	10.68	11.18	11.80	11.55	9.27
K_2O	0.23	0.00	0.14	0.37	0.00	0.00	0.00	2.29
TOTAL	96.52	97.47	98.16	99.28	99.35	98.75	99.58	96.38

Ca	0.08	0.04	0.06	0.00	0.00	0.00	0.00	0.07
K	0.05	0.00	0.03	0.08	0.00	0.00	0.00	0.53
Na	3.79	3.93	3.84	3.63	3.79	4.05	3.92	3.28
Fe	0.04	0.00	0.03	0.03	0.00	0.00	0.00	0.02
Mg	-	-	-	-	-	0.00	0.00	0.00
Mn	-	-	-	-	-	0.02	0.00	0.00
Ti	-	-	-	-	-	0.00	0.00	0.00
Al	4.17	4.20	4.13	4.11	4.07	4.08	4.10	4.21
Si	11.84	11.84	11.88	11.96	11.99	11.90	11.94	11.88

Analysis No.	51	52	53	54	55	56	59	60
SiO_2	65.05	64.54	64.50	64.68	65.25	66.87	65.81	65.02
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	22.42	21.86	22.01	21.39	22.13	20.09	21.51	20.74
T FeO	0.24	0.00	0.22	0.17	0.26	0.00	0.27	0.00
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	2.85	2.76	2.63	2.79	2.61	0.28	1.76	1.47
Na_2O	10.36	9.48	10.18	9.46	9.82	10.87	10.12	10.32
K_2O	0.22	0.22	0.28	0.31	0.28	0.00	0.12	0.00
TOTAL	101.14	98.86	99.82	98.80	100.35	98.11	99.73	97.55

Ca	0.53	0.52	0.49	0.53	0.49	0.05	0.33	0.28
K	0.05	0.05	0.06	0.07	0.06	0.00	0.02	0.00
Na	3.51	3.26	3.49	3.26	3.34	3.74	3.45	3.59
Fe	0.03	0.00	0.03	0.02	0.03	0.00	0.04	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	4.61	4.58	4.58	4.49	4.57	4.20	4.46	4.38
Si	11.36	11.47	11.40	11.51	11.49	11.87	11.58	11.66

Analysis No.	61	62	63	64	67	68	69
SiO_2	66.43	65.84	66.04	64.23	65.39	65.36	66.70
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	19.13	20.37	21.23	20.93	20.19	20.59	20.01
T FeO	0.13	0.00	0.43	0.29	0.15	0.28	0.00
MnO	0.00	0.20	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.00	0.45	0.30	0.40	1.33	0.14	0.30
Na_2O	11.42	11.03	10.91	10.50	10.86	10.76	11.28
K_2O	0.00	0.00	1.17	0.84	0.19	0.80	0.11
TOTAL	97.11	97.89	100.18	97.29	98.11	97.93	98.70
Ca	0.00	0.08	0.05	0.07	0.25	0.02	0.05
K	0.00	0.00	0.26	0.19	0.04	0.18	0.02
Na	3.98	3.82	3.72	3.68	3.77	3.74	3.88
Fe	0.02	0.00	0.06	0.44	0.02	0.04	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.03	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	4.05	4.29	4.40	4.46	4.26	4.35	4.19
Si	11.95	11.76	11.63	11.62	11.70	11.71	11.85

LONGWELL WATER PLAGIOCLASE

Analysis No.	25	27	28	29	30	31	35	36
SiO_2	65.46	66.59	67.65	67.72	64.01	66.28	65.11	68.6
TiO_2	-	-	-	-	-	-	-	-
Al_2O_3	21.55	20.49	19.91	19.91	21.99	21.06	19.99	19.9
T FeO	0.18	0.00	0.13	0.00	0.15	0.17	0.00	0.00
MnO	-	-	-	-	-	-	-	0.00
MgO	-	-	-	-	-	-	-	0.00
CaO	2.28	1.55	0.27	0.00	2.86	1.67	1.36	0.18
Na_2O	9.75	10.30	10.81	11.73	9.26	10.22	9.86	11.23
K_2O	0.46	0.16	0.24	0.00	0.44	0.17	0.14	0.45
TOTAL	99.78	99.09	99.01	99.36	98.71	99.57	96.46	100.4

Ca	0.43	0.29	0.05	0.00	0.54	0.31	0.26	0.03
K	0.10	0.03	0.05	0.00	0.10	0.03	0.03	0.10
Na	3.33	3.52	3.69	4.00	3.20	3.48	3.46	3.79
Fe	0.02	0.00	0.02	0.00	0.02	0.02	0.00	0.00
Mg	-	-	-	-	-	-	-	0.00
Mn	-	-	-	-	-	-	-	0.00
Ti	-	-	-	-	-	-	-	0.00
Al	4.48	4.26	4.13	4.12	4.62	4.37	4.26	4.08
Si	11.54	11.76	11.92	11.90	11.41	11.66	11.79	11.9

HELMSDALE QUARRY PLAGIOCLASE

Analysis No.	79	80	81	82	83	84
SiO_2	69.01	68.81	67.73	68.61	67.51	67.16
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	20.11	20.30	19.69	19.38	20.10	19.78
T FeO	0.00	0.00	0.00	0.45	0.00	0.00
MnO	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.25	0.00	0.00	0.00	0.00	0.00
CaO	0.00	0.00	0.00	0.00	0.27	0.00
Na_2O	11.57	11.27	11.12	11.57	11.07	11.62
K_2O	0.00	0.08	0.00	0.10	0.12	0.00
TOTAL	100.94	100.46	98.54	100.11	99.07	98.56

Ca	0.00	0.00	0.00	0.00	0.05	0.00
K	0.00	0.02	0.00	0.02	0.02	0.00
Na	3.87	3.79	3.81	3.92	3.78	3.98
Fe	0.00	0.00	0.00	0.06	0.00	0.00
Mg	0.06	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Al	4.09	4.15	4.10	3.99	4.17	4.13
Si	11.92	11.93	11.97	11.98	11.89	11.89

Analysis No.	85	86	88	89	93	94
SiO_2	68.72	67.58	68.55	68.17	68.23	68.41
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	19.67	19.74	20.07	20.48	20.94	19.97
T FeO	0.00	0.00	0.00	0.00	0.14	0.00
MnO	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.00	0.10	0.00	0.00	0.42	0.00
Na_2O	11.28	11.75	11.72	11.13	11.21	11.46
K_2O	0.00	0.00	0.09	0.12	0.18	0.00
TOTAL	99.67	99.17	100.43	99.90	101.12	99.84

Ca	0.00	0.02	0.00	0.00	0.07	0.00
K	0.00	0.00	0.02	0.02	0.04	0.00
Na	3.82	4.01	3.95	3.76	3.75	3.87
Fe	0.00	0.00	0.00	0.00	0.02	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Al	4.05	4.10	4.11	4.21	4.27	4.11
Si	12.0	11.91	11.92	11.89	11.79	11.94

OUSDALE QUARRY PLAGIOCLASE

Analysis No.	99	100	101	102	108	109	110	111
SiO_2	68.59	68.21	66.62	66.32	68.69	65.48	68.16	68.15
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	19.86	19.70	19.47	19.52	20.13	21.29	19.57	20.01
T FeO	0.00	0.00	0.00	0.23	0.00	0.42	0.00	0.00
MnO	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00
Na_2O	11.97	11.87	11.32	11.86	11.44	10.41	11.44	10.81
K_2O	0.00	0.00	0.14	0.24	0.00	1.36	0.09	0.00
TOTAL	100.42	99.78	97.69	98.26	100.26	98.96	99.26	99.17

Ca	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
K	0.00	0.00	0.03	0.05	0.00	0.31	0.02	0.00
Na	4.04	4.02	3.92	4.10	3.85	3.59	3.89	3.67
Fe	0.00	0.00	0.00	0.03	0.00	0.06	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	4.07	4.06	4.10	4.11	4.12	4.46	4.05	4.14
Si	11.93	11.94	11.91	11.84	11.94	11.64	11.97	11.95

ELDRABLE BURN PLAGIOCLASE

Analysis No.	115	116	117	118
SiO_2	66.68	67.01	68.75	67.22
TiO_2	0.00	0.00	0.00	0.00
Al_2O_3	20.32	20.60	20.03	19.87
T FeO	0.00	0.00	0.00	0.00
MnO	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00
CaO	0.69	0.34	0.00	0.36
Na_2O	10.82	11.36	11.19	11.43
K_2O	0.18	0.16	0.10	0.10
TOTAL	98.69	99.47	100.07	98.98

Ca	0.13	0.06	0.00	0.07
K	0.04	0.03	0.02	0.02
Na	3.71	3.87	3.77	3.91
Fe	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00
Al	4.24	4.27	4.11	4.13
Si	11.81	11.78	11.96	11.87

ALLT CILLE PLAGIOCLASE

Analysis No.	122	123	126	127	128	131
SiO_2	64.51	67.60	65.69	68.21	64.35	63.67
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	20.19	19.58	19.27	20.01	22.10	21.02
T FeO	0.00	0.00	0.00	0.00	0.00	0.14
MnO	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00
CaO	1.04	0.00	0.00	0.11	2.74	2.51
Na_2O	11.01	11.31	11.95	11.52	9.23	9.76
K_2O	0.10	0.00	0.00	0.00	0.62	0.21
TOTAL	96.85	98.49	96.91	99.85	99.04	97.31

Ca	0.20	0.00	0.00	0.02	0.52	0.48
K	0.02	0.00	0.00	0.00	0.14	0.04
Na	3.86	3.88	4.18	3.90	3.18	3.42
Fe	0.00	0.00	0.00	0.00	0.00	0.02
Mg	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Al	4.31	4.08	4.10	4.12	4.63	4.48
Si	11.68	11.96	11.87	11.92	11.43	11.51

Analysis No.	132	133	136	137	138
SiO_2	65.22	63.48	64.66	65.51	64.66
TiO_2	0.00	0.00	0.00	0.00	0.00
Al_2O_3	20.81	21.73	21.31	21.19	21.19
T FeO	0.20	0.18	0.00	0.00	0.00
MnO	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00
CaO	1.58	2.60	2.05	2.27	2.11
Na_2O	9.94	10.17	10.23	10.17	10.41
K_2O	0.20	0.17	0.21	0.24	0.42
TOTAL	97.95	98.33	98.56	99.38	98.79

Ca	0.30	0.50	0.39	0.43	0.40
K	0.04	0.03	0.04	0.05	0.09
Na	3.44	3.53	3.54	3.48	3.60
Fe	0.03	0.02	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00
Al	4.38	4.59	4.48	4.41	4.45
Si	11.66	11.39	11.54	11.58	11.53

CAEN BURN PLAGIOCLASE

Analysis No.	140	141	142	143	144	145
SiO_2	64.92	63.70	65.58	63.87	65.86	64.95
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	20.30	21.53	18.77	19.96	20.51	19.50
T FeO	0.00	1.88	0.68	0.29	0.15	0.00
MnO	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.81	0.00	0.00	0.00	0.00
CaO	1.23	0.28	0.00	0.09	0.34	1.05
Na_2O	10.24	5.74	9.53	10.52	11.27	10.59
K_2O	0.21	5.71	3.30	0.84	0.50	0.17
TOTAL	96.90	99.65	97.86	95.57	98.63	96.26

Ca	0.23	0.05	0.00	0.01	0.06	0.20
K	0.05	1.36	0.76	0.19	0.11	0.04
Na	3.58	2.08	3.35	3.74	3.89	3.73
Fe	0.00	0.29	0.10	0.04	0.02	0.00
Mg	0.00	0.22	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Al	4.32	4.50	4.01	4.32	4.30	4.18
Si	11.72	11.39	11.90	11.73	11.72	11.81

Analysis No.	147	148	151	152	156	157
SiO_2	66.31	66.10	64.43	67.46	59.4	67.16
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	19.89	19.50	20.93	19.71	18.77	20.73
T FeO	0.35	0.00	0.00	0.35	0.36	0.00
MnO	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.18	0.00	1.58	0.18	1.43	0.29
Na_2O	10.70	11.52	10.31	11.40	9.96	12.06
K_2O	0.41	0.11	0.19	0.18	0.33	0.12
TOTAL	97.84	97.23	97.44	99.28	90.25	100.36

Ca	0.03	0.00	0.30	0.03	0.30	0.05
K	0.09	0.02	0.04	0.04	0.08	0.02
Na	3.70	4.01	3.60	3.89	3.77	4.08
Fe	0.05	0.00	0.00	0.05	0.05	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Al	4.19	4.13	4.44	4.09	4.32	4.27
Si	11.85	11.88	11.60	11.89	11.61	11.73

K FELDSPAR FROM GLEN LOTH (CGP TYPE)

Analysis No.	2	3	4	6	7	8	9	10	11
SiO_2	62.96	62.16	63.41	66.29	61.78	62.48	63.13	62.63	62.22
TiO_2	-	-	-	-	-	-	-	-	-
Al_2O_3	18.44	18.40	19.23	19.62	19.12	19.09	18.91	18.33	18.43
T FeO	0.00	0.00	0.00	0.00	0.21	0.00	0.21	0.19	0.19
MnO	-	-	-	-	-	-	-	-	-
MgO	-	-	-	-	-	-	-	-	-
CaO	0.13	0.29	0.26	0.17	0.32	0.30	0.32	0.25	0.37
Na_2O	0.82	1.37	4.20	10.92	1.46	1.88	3.52	1.76	1.52
K_2O	14.31	14.00	9.53	0.00	13.43	13.31	10.27	13.45	13.03
TOTAL	96.66	96.22	96.63	97.00	96.32	97.06	96.36	96.61	95.76

Ca	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
K	0.86	0.85	0.56	0.00	0.81	0.80	0.61	0.81	0.79
Na	0.07	0.12	0.38	0.95	0.13	0.17	0.32	0.16	0.14
Fe	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01
Mg	-	-	-	-	-	-	-	-	-
Mn	-	-	-	-	-	-	-	-	-
Ti	-	-	-	-	-	-	-	-	-
Al	1.03	1.03	1.05	1.04	1.07	1.06	1.04	1.02	1.03
Si	2.93	2.96	2.95	2.97	2.93	2.94	2.96	2.97	2.97

Analysis No.	12	13	14	15	16	17	20	23
SiO_2	63.60	62.38	62.54	61.76	62.70	63.10	63.05	64.57
TiO_2	-	-	-	-	-	-	-	-
Al_2O_3	19.14	18.75	19.09	18.46	18.81	18.47	18.53	18.81
T FeO	0.27	0.00	0.21	0.25	0.00	0.00	0.00	0.24
MnO	-	-	-	-	-	-	-	-
MgO	-	-	-	-	-	-	-	-
CaO	0.27	0.32	0.32	0.39	0.37	0.28	0.00	0.00
Na_2O	7.20	1.30	1.00	0.73	1.25	1.25	1.56	0.99
K_2O	5.24	13.82	13.94	14.51	14.66	14.20	14.11	14.96
TOTAL	95.72	96.57	97.10	96.10	97.79	97.30	97.25	99.57
Ca	0.05	0.06	0.06	0.08	0.07	0.05	0.00	0.00
K	1.24	3.34	3.36	3.54	3.06	3.42	3.40	3.52
Na	2.59	0.47	0.20	0.27	0.46	0.45	0.57	0.35
Fe	0.04	0.00	0.03	0.04	0.00	0.00	0.00	0.03
Mg	-	-	-	-	-	-	-	-
Mn	-	-	-	-	-	-	-	-
Ti	-	-	-	-	-	-	-	-
Al	4.20	4.19	4.26	4.17	4.21	4.11	4.12	4.09
Si	11.83	11.83	11.83	11.83	11.90	11.90	11.91	11.93

					MARREL K-FELDSPAR	
Analysis No.	46	47	57	58	39	40
SiO_2	67.76	65.51	64.80	64.79	64.03	64.13
TiO_2	0.00	0.00	0.29	0.13	0.35	0.40
Al_2O_3	19.66	19.65	19.40	19.39	18.80	18.93
T FeO	0.18	0.20	0.20	0.35	0.17	0.00
MnO	0.00	0.00	0.29	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.30	0.00	0.00	0.66	0.16	0.20
Na_2O	6.51	6.99	1.88	9.43	1.15	1.04
K_2O	6.87	7.57	14.03	2.01	14.44	15.43
TOTAL	101.28	99.92	100.89	96.76	99.10	100.13
Ca	0.05	0.00	0.00	0.13	0.03	0.04
K	1.54	1.74	3.26	0.46	3.41	3.63
Na	2.22	2.44	0.66	3.33	0.41	0.37
Fe	0.02	0.03	0.03	0.05	0.02	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.04	0.00	0.00	0.00
Ti	0.00	0.00	0.04	0.01	0.04	0.05
Al	4.08	4.17	4.17	4.16	4.11	4.11
Si	11.94	11.80	11.82	11.81	11.87	11.83

LONGWELL WATER AREA K-FELDSPAR

Analysis No.	26	32	33	34	76	77
SiO_2	64.87	66.29	64.01	64.20	64.32	66.57
TiO_2	-	-	-	-	0.00	0.00
Al_2O_3	18.93	19.45	18.46	19.0	18.52	18.88
T FeO	0.00	0.00	0.18	0.00	0.00	0.00
MnO	-	-	-	-	0.00	0.00
MgO	-	-	-	-	0.00	0.00
CaO	0.00	0.35	0.00	0.12	0.00	0.00
Na_2O	2.02	7.68	0.39	1.12	0.81	7.24
K_2O	12.78	5.52	15.58	14.79	15.31	6.54
TOTAL	98.60	99.29	98.62	100.23	98.96	99.23

Ca	0.00	0.06	0.00	0.02	0.00	0.00
K	3.00	1.26	3.71	3.49	3.63	1.50
Na	0.72	2.66	0.14	0.40	0.29	2.52
Fe	0.00	0.00	0.02	0.00	0.00	0.00
Mg	-	-	-	-	0.00	0.00
Mn	-	-	-	-	0.00	0.00
Ti	-	-	-	-	0.00	0.00
Al	4.11	4.10	4.06	4.14	4.06	4.00
Si	11.95	11.87	11.95	11.87	11.96	11.98

HELMSDALE QUARRY K-FELDSPAR

Analysis No.	87	90	91	92	97	98
SiO_2	63.14	64.72	64.67	64.21	64.36	63.72
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	18.42	18.84	18.71	18.33	18.59	18.68
T FeO	0.15	0.31	0.00	0.00	0.22	0.00
MnO	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	.00	0.00
CaO	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	0.00	0.00	0.50	0.00	0.46	0.00
K_2O	16.28	16.63	16.41	16.46	16.69	16.36
TOTAL	98.99	100.50	100.29	99.00	100.32	98.76

Ca	0.00	0.00	0.00	0.00	0.00	0.00
K	3.92	3.91	3.86	3.92	3.93	3.90
Na	0.00		0.18	0.00	0.16	0.00
Fe	0.02	0.04	0.00	0.00	0.03	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Al	4.10	4.09	4.07	4.03	4.04	4.12
Si	11.92	11.92	11.93	11.99	11.88	11.92

K-FELDSPAR

	OUSDALE QUARRY			EB	AC	
Analysis No.	104	105	106	119	130	134
SiO_2	63.35	62.35	64.76	63.51	63.61	62.27
TiO_2	0.00	0.00	0.00	0.26	0.18	0.15
Al_2O_3	18.01	18.31	18.96	18.74	18.36	18.12
T FeO	0.00	0.00	0.29	0.00	0.16	0.00
MnO	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.24	0.00	0.00	0.00	0.00	0.00
Na_2O	0.00	0.00	10.01	0.58	0.57	0.00
K_2O	16.01	16.12	1.60	15.62	15.67	16.18
TOTAL	97.61	96.78	95.62	98.71	98.55	96.72

Ca	0.05	0.00	0.00	0.00	0.00	0.00
K	3.86	3.93	0.37	3.72	3.75	3.95
Na	0.00	0.00	3.57	0.21	0.20	0.00
Fe	0.00	0.00	0.04	0.00	0.02	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.03	0.02	0.02
Al	4.02	4.12	4.11	4.13	4.05	4.09
Si	11.99	11.92	11.90	11.87	11.92	11.92

CEAN BURN K-FELDSPAR

Analysis No	146	153	154	155	158	159
SiO_2	63.91	63.14	63.76	64.27	64.12	63.88
TiO_2	0.00	0.00	0.00	0.00	0.13	0.00
Al_2O_3	19.66	18.44	19.16	18.56	18.52	18.47
T FeO	0.54	0.21	0.00	0.00	0.59	0.14
MnO	0.00	0.00	0.00	0.19	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	6.13	1.17	1.11	0.47	6.21	0.00
K_2O	8.05	14.83	15.15	16.01	8.09	16.65
TOTAL	98.29	97.79	99.18	99.50	97.66	99.14

Ca	0.00	0.00	0.00	0.00	0.00	0.00
K	1.89	3.56	3.59	3.79	1.91	3.97
Na	2.18	0.42	0.40	0.17	2.23	0.00
Fe	0.08	0.03		0.00	0.09	0.02
Mg	0.00	0.00		0.00	0.00	0.00
Mn	0.00	0.00		0.03	0.00	0.00
Ti	0.00	0.00		0.00	0.01	0.00
Al	4.25	4.10	4.19	4.06	4.04	4.07
Si	11.74	11.90	11.85	11.94	11.86	11.94

BIOTITE

	MORREL	LW		H.Q.	O.Q.	EB	
Analysis No.	42	70	74	95	112	113	114
SiO_2	25.42	50.36	48.22	51.12	50.93	33.73	40.44
TiO_2	11.20	0.00	0.00	0.14	0.00	0.21	0.20
Al_2O_3	15.05	24.86	29.95	26.62	24.14	20.97	32.71
T FeO	18.67	4.82	4.09	4.54	4.73	14.43	5.72
MnO	0.51	0.00	0.00	0.00	0.00	0.00	0.00
MgO	16.29	2.32	0.93	2.35	2.23	5.98	3.54
CaO	0.14	0.00	0.00	0.00	0.16	0.19	0.17
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	0.49	9.73	9.73	10.21	9.26	2.29	0.43
TOTAL	87.79	92.11	92.92	94.98	91.45	77.80	83.21

Ca	0.03	0.00	0.00	0.00	0.03	0.05	0.04
K	0.14	2.50	2.47	2.55	2.39	0.37	0.11
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	3.69	0.81	0.68	0.74	0.80	3.02	1.02
Mg	5.74	0.70	0.27	0.68	0.67	2.24	1.13
Mn	0.10	0.00	0.00	0.00	0.00	0.00	0.00
Ti	1.99	0.00	0.00	0.02	0.00	0.04	0.03
Al	4.20	5.92	7.04	6.14	5.76	6.20	8.25
Si	6.02	10.17	9.61	10.01	10.32	8.46	8.65

BIOTITE

	AC				CGP		
Analysis No	121	124	129	139	165	166	167
SiO_2	37.61	31.94	31.41	36.66	34.9	31.8	24.9
TiO_2	2.15	0.98	0.61	2.07	3.9	3.4	0.00
Al_2O_3	13.54	14.21	15.26	14.18	12.7	14.3	19.2
T FeO	17.23	19.81	18.95	15.11	28.8	30.7	36.0
MnO	0.34	0.49	0.38	0.40	0.34	0.45	0.4
MgO	14.59	16.66	16.52	13.26	3.69	5.54	4.93
CaO	0.00	0.10	0.00	0.21	0.00	0.00	0.00
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	8.86	3.52	2.09	5.76	8.88	4.7	0.65
TOTAL	94.32	87.71	85.22	87.65	93.21	90.89	
Ca	0.00	0.02	0.00	0.05	0.00	0.00	0.00
K	2.50	1.06	0.64	1.70	1.94	1.03	0.16
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	3.19	3.93	3.81	2.92	4.1	4.5	5.72
Mg	4.81	5.90	5.93	4.57	0.9	1.42	1.35
Mn	0.06	0.09	0.07	0.08	0.05	0.07	0.06
Ti	0.35	0.17	0.11	0.36	0.5	0.45	0.00
Al	3.53	3.98	4.33	3.87	2.58	2.96	4.27
Si	8.32	7.58	7.56	8.48	6.0	5.5	4.7

CHLORITE

	GL		H.Q.	AC	CB		GL
Analysis No.	65	66	82b	120	149	150	163
SiO_2	25.28	24.32	47.13	29.71	25.84	28.74	29.03
TiO_2	0.00	0.00	0.58	0.26	0.14	0.13	0.00
Al_2O_3	15.72	15.49	15.61	16.22	20.56	20.75	18.55
T FeO	21.80	24.35	20.67	19.77	21.43	20.00	17.55
MnO	0.17	0.15	0.00	0.17	0.60	0.34	0.47
MgO	12.25	11.96	0.74	15.35	16.51	15.42	18.89
CaO	0.36	0.24	0.76	0.00	0.00	0.00	0.00
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	0.47	0.31	0.94	1.06	0.17	0.96	0.61
TOTAL	76.05	76.82	86.43	82.54	85.25	86.34	85.10
Ca	0.10	0.07	0.18	0.00	0.00	0.00	0.00
K	0.16	0.11	0.27	0.33	0.05	0.29	0.18
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	5.04	5.67	3.88	4.11	4.36	3.96	3.49
Mg	5.04	4.97	0.24	5.68	5.99	5.44	6.69
Mn	0.04	0.03	0.00	0.03	0.12	0.07	0.09
Ti	0.00	0.00	0.09	0.04	0.02	0.02	0.00
Al	5.12	5.08	4.13	4.75	5.90	5.79	5.20
Si	6.99	4.77	10.57	7.38	6.29	6.81	6.90

ILLITE

	LW			H.Q.	
Analysis No.	71	75	78	96a	96b
SiO_2	50.64	48.99	45.87	49.16	49.23
TiO_2	0.00	0.00	0.00	0.00	0.15
Al_2O_3	25.06	30.14	24.95	26.12	26.25
T FeO	4.31	3.02	7.01	4.91	4.77
MnO	0.00	0.00	0.00	0.00	0.00
MgO	2.86	1.32	1.54	1.84	1.93
CaO	0.00	0.00	0.11	0.00	0.00
Na_2O	0.00	0.00	0.00	0.00	0.00
K_2O	10.23	10.19	8.85	9.75	9.36
TOTAL	93.10	93.66	88.33	91.78	91.69

CaO	0.00	0.00	0.02	0.00	0.00
K	2.61	2.56	2.41	2.52	2.40
Na	0.00	0.00	0.00	0.00	0.00
Fe	0.72	0.49	1.25	0.83	0.80
Mg	0.85	0.38	0.49	0.55	0.58
Mn	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.02
Al	5.90	7.00	6.28	6.25	6.27
Si	10.12	9.66	9.79	9.98	9.97

APPENDIX 3

AGGREGATE ENGINEERING TEST RESULTS

R.D. (OD) = Relative Density (oven dry)

R.D. (SD) = Relative Density (surface dry)

SG = Specific Gravity

WA % = Water absorption

AIV % = Aggregate Impact Value

AIVR% = Aggregate Impact Value Residue

AAV % = Aggregate Abrasion Value

ACV % = Aggregate Crushing Value

PSV = Polishing stone value

CCS = Concrete Compressive Strength (cubes)

D.Sh = Shrinkage %

UCS = Uniaxial compression strength

Sample No.	R.D. (OD)	R.D. (SD)	SG	WA %	AIV %	AIVR%	AAV %	ACV %	PSV	10% fines value	CCS	D.Sh %	UCS
1	2.54	2.58	2.63	1.35	20.82	22.12	4.03	-	-	179	-	-	-
2	2.56	2.59	2.63	1.08	23.0	18.01	4.2	25.40	54	169	-	0.036	-
3	2.56	2.58	2.62	0.83	21.09	20.91	4.10	-	-	177	69.9	-	96
7	2.59	2.61	2.65	0.86	20.84	22.19	4.14	-	-	179	-	-	-
11	2.59	2.61	2.63	0.66	18.65	26.25	3.92	-	-	189	-	-	-
14	2.58	2.6	2.63	0.76	17.35	28.14	3.99	-	-	195	-	-	-
15	2.51	2.55	2.59	1.39	21.04	25.1	3.85	-	-	178	71.15	-	102
17	2.54	2.57	2.61	0.99	19.3	30.32	3.91	-	-	186	-	-	-
18	2.52	2.55	2.58	0.96	20.44	22.53	3.86	20.5	-	180	-	-	-
21	2.44	2.49	2.56	1.87	29.17	10.1	3.99	-	49	140	-	0.033	-
24	2.56	2.57	2.60	0.70	19.55	31.11	3.76	-	-	165	-	-	-
25	2.53	2.55	2.58	0.75	20.62	23.14	3.90	22.6	53	172	-	-	-
29	2.59	2.6	2.63	0.57	20.1	21.19	3.80	-	-	168	-	-	-
30	2.59	2.61	2.63	0.54	19.08	29.8	4.25	20.1	50	171	-	-	-
32	2.55	2.57	2.6	0.66	17.26	27.47	4.17	-	50	195	71.1	0.032	115
34	2.59	2.61	2.64	0.74	18.28	20.8	4.30	-	-	190	-	-	-
37	2.58	2.6	2.62	0.62	17.21	30.0	4.15	-	51	186	-	-	-
41	2.57	2.59	2.61	0.54	22.01	20.71	-	-	-	173	-	-	-
43	2.55	2.56	2.6	0.75	26.32	28.0	3.16	-	52	155	65.4	-	84
44	2.56	2.58	2.6	0.72	24.31	16.0	3.95	24.96	54	162	-	-	-
45	2.54	2.56	2.6	0.95	25.08	15.97	3.39	-	53	159	68.8	-	87

Sample No.	R.D. (OD)	R.D. (SD)	SG	WA %	AIV %	AIVR%	AAV %	ACV %	PSV	10% fines value	CCS	D.Sh %	UCS
49	2.55	2.57	2.6	0.67	26.35	15.9	3.5	24.92	57	148	-	0.031	-
53	2.58	2.59	2.61	0.65	24.51	16.72	3.24	-	55	162	-	-	-
54	2.55	2.57	2.6	0.65	24.0	16.5	3.5	-	56	164	69.9	-	90
70	2.58	2.59	2.62	0.93	27.84	15.73	3.24	-	-	146	-	-	-
71	2.53	2.56	2.6	1.05	24.09	17.0	3.50	26.92	59	163	67.9	0.036	79
73	2.55	2.57	2.61	0.98	28.78	16.13	3.5	-	-	142	-	-	-
75	2.53	2.55	2.59	1.00	32.84	9.13	5.3	32.0	57	123	62	0.046	55
78	2.56	2.58	2.6	1.09	32.35	-	5.58	32.0	56	125	62	0.029	62
86	2.58	2.59	2.61	0.80	25.2	16.5	3.55	25.2	56	158	64	0.026	60
90	2.55	2.57	2.6	0.84	26.14	21.15	5.10	-	-	154	-	-	-
92	2.51	2.55	2.6	1.36	22.97	20.15	5.32	23.1	58	169	66.5	0.030	90
94	2.57	2.59	2.62	0.82	25.96	15.45	4.86	26	-	155	-	-	-
95	2.54	2.56	2.6	0.99	23.45	21.2	4.80	-	55	167	66.5	0.032	89
96	2.51	2.54	2.58	1.01	27.82	12.2	4.25	28	-	146	-	-	-
97	2.56	2.58	2.61	0.65	23.14	17.79	4.53	24	-	168	-	-	-
98	2.57	2.58	2.61	0.65	25.81	-	4.18	25	-	155	-	-	-
99	2.57	2.59	2.63	0.91	30.83	10.90	4.63	31	-	132	-	-	58
100	2.57	2.59	2.62	0.69	29.79	12.5	3.7	-	-	137	-	-	-