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PETROLOGICAL STUDIES OF THE ROCKS OF THE HADDO HOUSE AND ARNAGE DISTRICTS, ABERDEENSHIRE.

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Thesis presented for the Degree of Doctor of Philosophy of the University of Edinburgh in the Faculty of Science.

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CONTENTS

		Page No.
I		
	(a) Introduction and Aims	1
	(b) Nomenclature	3
	(c) History of Research	5
II	A model applicable to natural rocks, based on studies in the system $CaO-MgO-Al_2O_3-SiO_2$, is outlined.	36
III	THE COUNTRY ROCKS	53
	(a) Fyvie Schists	53
	1. The distribution and petrography of the Fyvie schists	53
	2. The Geochemistry of the Fyvie schists	69
	(b) Mormond Hill quartzites	75
	(c) Ellon gneisses	78
IV	THE IGNEOUS ROCKS	80
	I Distribution and Petrography	80
	1. Haddo House	80
	(i) Olivine-hypersthene-gabbros	80
	(ii) Quartz-hypersthene-gabbros	85
	2. Arnage	92
	(i) Olivine-hypersthene-gabbros	92
	(ii) Quartz-hypersthene-gabbros	93
	II The Geochemistry of the Haddo House and Arnage Igneous rocks	95
	III The Petrogenesis of the Haddo House and Arnage Igneous rocks	98
V	THE UNHOMOGENEOUS ROCKS	112
	I Distribution and Petrography	112
	1./	

Page No.

1. Haddo House 112

Quartz-cordierite-norites and associated rocks 112

2. Arnage 119

1 Quartz-cordierite-norites and associated rocks 119
2 Arnage gneisses 121
3 Ardlethen gneisses 125
4 Kinharrachie gneisses 127

3. Xenoliths 130

II The Genesis of the Unhomogeneous rocks and their Geochemistry 141

VI SUMMARY AND CONCLUSIONS 166

ACKNOWLEDGEMENTS

REFERENCES

APPENDIX A Location of rocks analysed by the author

B 3 rock analyses

C 7 whole and partial analyses of ferromagnesian minerals.

D 1-cation percentages of all rocks analysed by the author

E Chemical analytical methods

District map (in pocket at end of thesis).

CHAPTER 1

(a) Introduction and Aims

In north-east Scotland, Younger gabbros outcrop in seven areas; two of these areas are the Haddo House and Arnage districts of Aberdeenshire. Detailed remapping of the geology of both districts was not the aim of this study, and the specimens and data required were obtained from a traverse through the region along the river Ythan, from the district of Gight (grid reference 835395) to Ellon (grid reference 956303) 16 miles north of Aberdeen. This river section, which is about 10 miles long, includes every rock type or group previously described by Read (1923a, 1935) from the Haddo House and Arnage districts. In many cases geological mapping was extended along small tributaries of the Ythan river to provide greater sampling coverage of some rock types and to examine certain critical localities mentioned by previous workers. The countryside is well cultivated, and very badly exposed apart from the river section. The geological history of these districts in relation to that of north-east Scotland as a whole will be examined in detail in section c of this chapter.

In this thesis the author intends to describe the effects of the Haddo basic intrusion on the surrounding country rocks; to reclassify the igneous rocks of the district and investigate hypotheses of their formation; and to suggest and examine a new/

new hypothesis for the origin of the xenolithic rocks associated with the gabbroic masses of Haddo House and Arnage. This new hypothesis was put forward by recent investigators working on the synthetic system $CaO-MgO-Al_2O_3-SiO_2$ at atmospheric pressure.

Chapter II of this thesis sets out to construct a model based upon these workers' suggestions and the data for the experimentally investigated synthetic system, which may be applicable to the natural rocks. The petrographic and geochemical data presented in later chapters are there considered in the light of this model.

Previous accounts of the geology of the Haddo House and Arnage districts divided the rocks into 4 distinct groups; country rocks, basic rocks of igneous intrusive origin, xenolithic rocks which appeared to be associated with the basic masses, and intrusive younger granites (Read, 1923a, 1935). The petrography and geochemistry of the rocks of these districts are described in chapters IV, V and VI respectively.

Seventy-two new whole-rock analyses and seven whole or partial mineral analyses are provided.

In chapter VII the author's conclusions are given and this chapter includes a brief account of other areas where similar rock types to those encountered in the Haddo district have been observed.

The/

The 5 appendices include: the locations of analysed rocks (A), 3 rock analyses (B), 7 whole and partial analyses of ferromagnesian minerals (C), 1-cation percentages of all rock analyses performed by the author (D), and a brief account of analytical techniques employed in analysing the rocks (E).

(b) Nomenclature

(i) Before the presentation of the history of research, a list of some rock terms and the sense in which they are used in this thesis is given. These terms will be used throughout this thesis and substituted for those originally used in the various papers described in this chapter to ensure uniformity of nomenclature.

Hypersthene-gabbro	-	a basic rock containing orthopyroxene, clinopyroxene and basic plagioclase, and generally with some biotite.
Olivine-hypersthene-gabbro	-	as above with olivine.
Quartz-hypersthene-gabbro	-	a hypersthene-gabbro as described above, but containing some interstitial quartz.
Orthonorite	-	a rock containing orthopyroxene, plagioclase of composition approximately An_{50}, and generally some/

some biotite. Read (1935) used the term 'norite' to describe a rock with this mineralogy, although Read (1923a) used the word 'norite' to denote quartz-hypersthene-gabbros, orthonorites and quartz-cordierite-norites.

Quartz-orthonorite - quartz-bearing orthonorite.

Quartz-cordierite-norite - a rock containing orthopyroxene, basic plagioclase, quartz, cordierite, and generally with some biotite.

Picrite - an ultrabasic rock containing principally olivine and interstitial basic plagioclase, and with minor amounts of clinopyroxene.

(ii) Abbreviations used in the text

Ab	albite	Fs	orthoferrosilite
An	anorthite	K-fels	potash feldspar (orthoclase)
And	andalusite		
Cdt	cordierite	Lc	leucite
Cor	corundum	Mu	mullite
Cpx	clinopyroxene	Ne	nepheline
Di	diopside	Ol	olivine
En	enstatite	Opx	orthopyroxene
Fo	forsterite	Or	orthoclase
Pl/			

Pl	plagioclase	s.s.	solid solution
Pr	protoenstatite	Sill	sillimanite
Px	pyroxene	Sp	spinel
Qz	quartz	Tr	tridymite
R.I.	refractive index		

(c) History of Research

The history of research will be presented in two parts. The first part deals with the geology of the main basic masses of north-east Scotland and their disposition; and the structural and metamorphic history of the region. The second part deals in detail with the geology of the Haddo House and Arnage areas of Aberdeenshire. A map showing the general region is presented in figure 1.

The basic masses of Insch and Huntly were described by Watt (1914) and by the Geological Survey (Read 1923b) and this memoir still provides the most complete description of the Huntly mass, although Sadashivaiah (1954), Read, Sadashivaiah and Haq (1961, 1965) and Read and Haq (1963) have revised the geology of the Insch basic suite; and Shackleton (1948) has discussed the origin of layering in the Huntly basic mass. The rock types of the Huntly body range from picrites to olivine-gabbros and hypersthene-gabbros, the most basic being those forming the western border of the mass to the west of Huntly and the least basic occuring in the east. At Insch similar rock types to these at Huntly were described but in this/

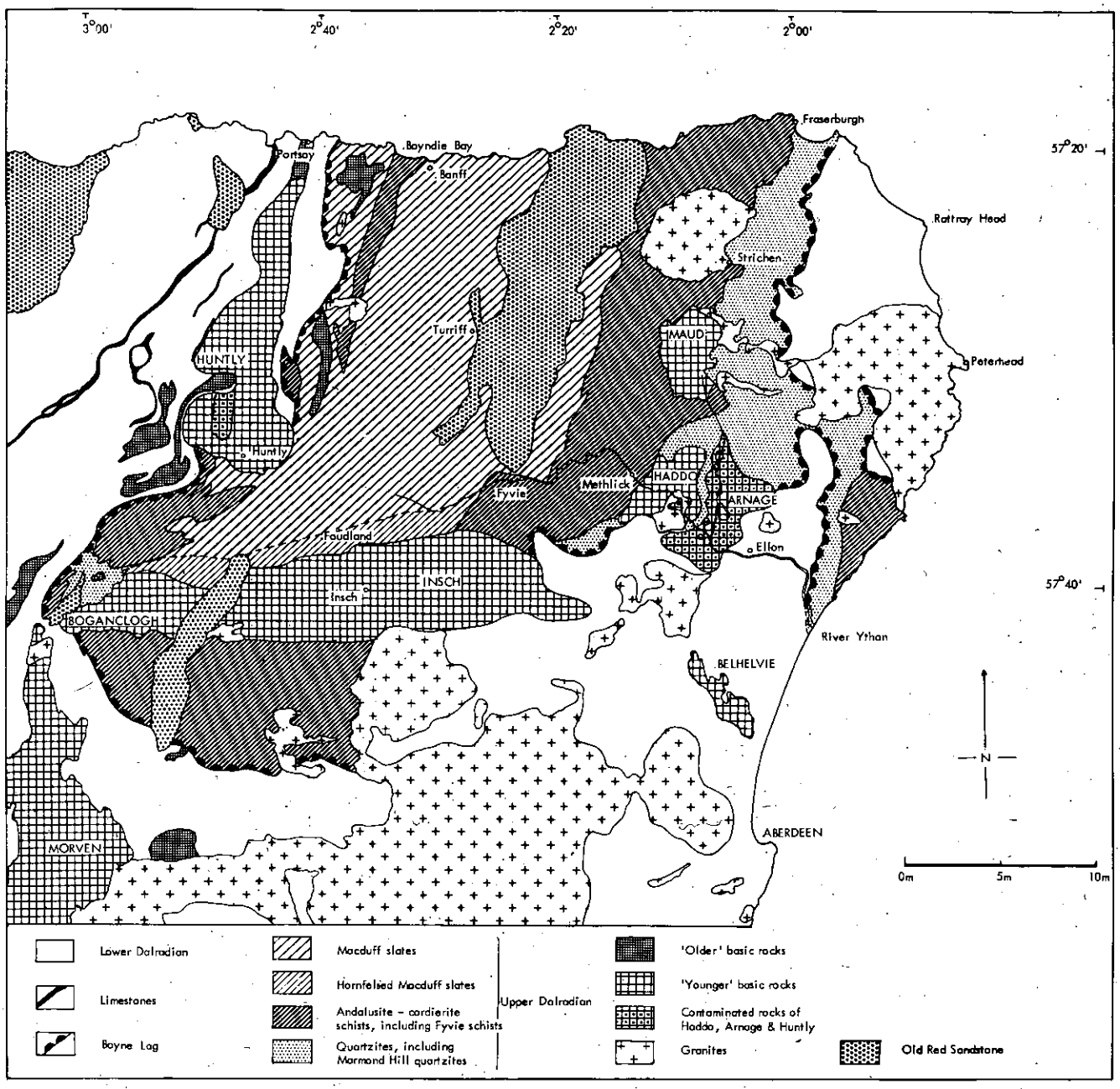


FIG. 1 GEOLOGICAL MAP OF NORTH-EAST SCOTLAND.

this area the least basic varieties include syeno-gabbros and syenites in the vicinity of the Red Rock Hills. Read et. al. (1961) revised the geology of this area and described two suites of rocks. A western suite ranging from olivine-gabbro to syenite was interpreted as demonstrating ... "the seeping of low temperature constituents towards the roof of the crystallising olivine-gabbro magma which itself may have been enriched in iron by the abstraction of a magnesia rich phase." An eastern suite termed "the Bourtie Series" ranging from dunites to troctolites, all magnesium rich, was also interpreted as a differentiated suite, and Read et. al. (1961) suggested that the western suite and the Bourtie Series together demonstrate one complete fractionated sequence from basal dunites to roof syenites. Hypersthene-gabbros also occur at Insch (Read, 1923b). The hypersthene-gabbro consists of basic plagioclase, hypersthene, augite and ore with other subsidiary minerals. Read (1923b) included these hypersthene-gabbros with the other main igneous types of Insch although he gave no indication as to the mode of origin of the hypersthene-gabbro. Read et. al. (1965) decided that the hypersthene-gabbro was a contaminated rock which did not constitute part of the normal differentiated sequence as described previously by Read et. al. (1961).

The hypothesis that the hypersthene-gabbro is a contaminated rock appears to have been reached because "/it does/ not/

not fit into the Insch Differentiated Suite - this suite is olivine-bearing as far as the syeno-gabbro stage of its development." Although the field relations of the hypersthene-gabbro with other rocks at Insch are poor, contaminated rocks containing xenoliths of sedimentary origin are often found near the hypersthene gabbro. However Read et al.(1965) stated that although it might be contaminated in its present position "contamination has played some part in the production of the magma from which this rock consolidated." Read et al.(1965) believed that the hypersthene-gabbro was formed "by contamination of a gabbro magma possibly of olivine-gabbro composition." Clarke (Ph.D. thesis, 1965) has suggested that the hypersthene-gabbros of Insch are in fact part of the normal differentiated sequence there, and occupy a place above the ultrabasic rocks and below the olivine-gabbros of Read (1923b) which Clarke has termed ferro-gabbros because they are much more iron rich than other olivine-gabbros of the north-east basic masses. Therefore, according to Clarke, all the basic igneous rocks at Insch fit into a single, reasonably complete fractionation sequence.

In parts of the Huntly area quartz-cordierite-norites, underlying the basic sheet, are noted for whose origin three hypotheses were advanced by Read (1923b). These were:-

(a) contamination of picrite by incorporation of sediments.

(b) modification of an original norite magma by incorporation of sediments.

(c)/

(c) contamination of original gabbroic magma by incorporation of sediments at its base before the ultrabasic layer had had time to accumulate.

Read (1921, 1923b) considered (c) the most attractive possibility and one which would be readily adopted ... "if one was sure that any kind of differentiation in place had occured in the Huntly Mass." If differentiation of the basic mass could be proved this would rule out hypothesis (a) because the picrite layer would have been derived by fractionation from the Huntly gabbroic magma. Although very little work has been done recently in the Huntly mass, Shackleton (1948) was convinced that a differentiated suite of rocks was displayed at Huntly, thus confirming Read's (1923b) hypothesis (c) above. Although Read (1921, 1923b) gave no reasons for rejecting hypothesis (b) which was the production of cordierite-bearing quartz norites by the incorporation of sediments into an original norite magma, there is no doubt that true orthonorites are very rare within the gabbroic suites of rocks in north-east Scotland, and, therefore, there is no encouragement to postulate a supply of orthonoritic magmas.

Contaminated rocks, similar to those found at Huntly, were observed in the Insch area by Read (1923b) and Whittle (1936) and again in the Arnage and Haddo House districts of Aberdeenshire by Read (1923a, 1935) who intended his papers on both districts to be a study of assimilation. The original gabbroic magma was envisaged as being modified by incorporation of/

of sedimentary material, thus forming contaminated rocks varying from highly contaminated but mainly igneous quartz-cordierite-norites, to mainly sedimentary material such as garnet-cordierite-potash feldspar rocks.

The Belhelvie mass was described by Stewart (1946) who showed that a mass of basic rocks ranging from dunite-serpentinites through troctolites to olivine-gabbros and hypersthene-gabbros had been intruded into country rocks consisting mainly of schists and gneisses. In the basic rocks rhythmic layering and small scale structures led to the deduction that the different types were formed by large scale differentiation through crystal settling in the basic magma, under the influence of gravity, similar to that seen in other large basic intrusions, such as the Bushveldt intrusion in South Africa (Daly 1928), the Skaergaard intrusion in Greenland (Wager and Deer 1939), and the Stillwater igneous complex in North America (Hess 1960). The layering at Belhelvie was shown to dip steeply to the east and Stewart (1946) concluded that the Belhelvie mass had been tilted after its consolidation.

The remaining two basic masses of north-east Scotland are found at Maud and Boganclogh. The basic body at Maud is very poorly exposed and the gabbroic rocks of Boganclogh were shown to be similar to the basic rocks of western Insch (Read 1923b). The petrography of the Morven-Cabrach mass was/

was described by Henry (1938) who considered that the rock-types of that basic mass were similar to the rock types of the other younger basic masses of north-east Scotland, and that therefore the Morven Cabrach mass was a 'younger' basic igneous intrusion.

Two theories concerning the disposition and nature of the basic masses of north-east Scotland were put forward.

Read (1923a) considered that these were part of one huge sill exposed at Huntly, Insch, Haddo, Arnage, Maud and Belhelvie. This sill was later than the regional folding but antedated the Middle and Upper Old Red Sandstone. Read (1923b, p.9) stated that ... "in the conglomerates of this group /the Middle Old Red Sandstone/ are found pebbles of Younger Igneous Rocks /the basic masses of north-east Scotland/."

The interpretation of Stewart (1946) and Shackleton (1948, and in discussion of Read and Farquhar 1956) was similar to that of Read except that they proposed that the basic sill had been folded during the regional folding to explain the layering at Belhelvie and Huntly; these theories will be discussed more fully on p. 17.

It is worthwhile to trace briefly the development of the main structural ideas on north-east Scotland from their initial interpretation in the Geological Survey Memoir of Read (1923b) to the present day.

Read (1923b) noted a discontinuity between the eastern members of his Keith division of the Dalradian series, the Cowhythe/

Cowhythe gneiss, and the Western members of his Banff division, the Boyne limestone. He called this discontinuity the Boyne line. Read suggested that the groups of his Banff division (see below) represented a 'cake' of rocks lying unconformably on gneisses of the Keith division, i.e. the Banff division represented the upper part of a large nappe structure.

Banff division { Macduff group
Boyndie Bay group ≡ Fyvie schists ≡ Fraserburgh beds ≡ Colliestón schists
Whitehills group ≡ Mormond Hill Quartzites
Boyne limestone

discontinuity XXXXXXXXXXXXXXXXXXXXXXXXX - Boyne line

Keith division (Cowhythe gneiss ≡ Ellon gneisses
upper group only

The Boyne limestone is only found in the west lying with discontinuity against Cowhythe gneisses (Read 1923b p. 45). The limestone was believed by Read (1923b p.50) to swing south-westwards into the Boyne line and be cut out.

Read (1955) restated his earlier theory of a large nappe structure in north-east Scotland and he called this the Banff nappe. His earlier postulated disposition of rock types was retained. The Banff division was equated with a group of Perthshire rocks and placed in the Upper Dalradian while the Keith division was equated with another group of Perthshire rocks and placed in the Lower Dalradian. The Upper and Lower Dalradian groups were separated from each other by the Boyne line dislocation which Read renamed the Boyne lag. The Lower Dalradian is in the form of a recumbent anticline closing to the south-east, the core of which is composed of migmatitic gneisses./

gneisses.

Sutton and Watson (1956) dealt with structures on the Banffshire coast and proposed the term Boyndie syncline for the great fold affecting the Dalradian in this region. Similar conclusions to these of Read (1955) were accepted, viz.:

(1) the Lower Dalradian of the western limb of the fold is steeply inclined and youngs to the east.

(2) the eastern limb of the fold is gently inclined and flexed to form the Turriff syncline.

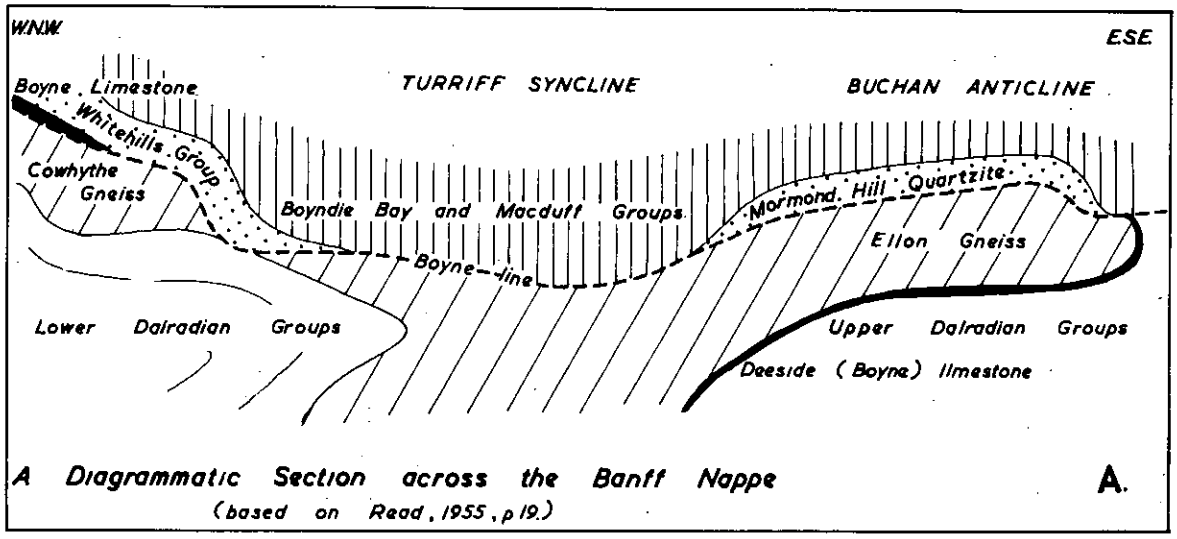
However, from detailed work on the large and small scale structures, the authors felt inclined to reject the nappe hypothesis of Read because of lack of evidence of a large discontinuity at Boyne Bay where the Boyne line of Read reaches the coast. Thus Sutton and Watson explained all structures by folding on a NNE axis, with minor differential movements between members of the succession during this folding.

Read and Farquhar (1956) upheld the views of Read (1955) on north-east crustal structures. The Banff nappe was shown to exhibit two major structures, anticlinal in the east for which structure the name 'Buchan anticline' was proposed, and synclinal in the west, the 'Turriff syncline'. The Buchan anticline consists of Upper Dalradian represented by a capping of Mormond Hill quartzites, resting on a migmatitic core of Lower Dalradian originally part of the Ellon gneisses. Read and/

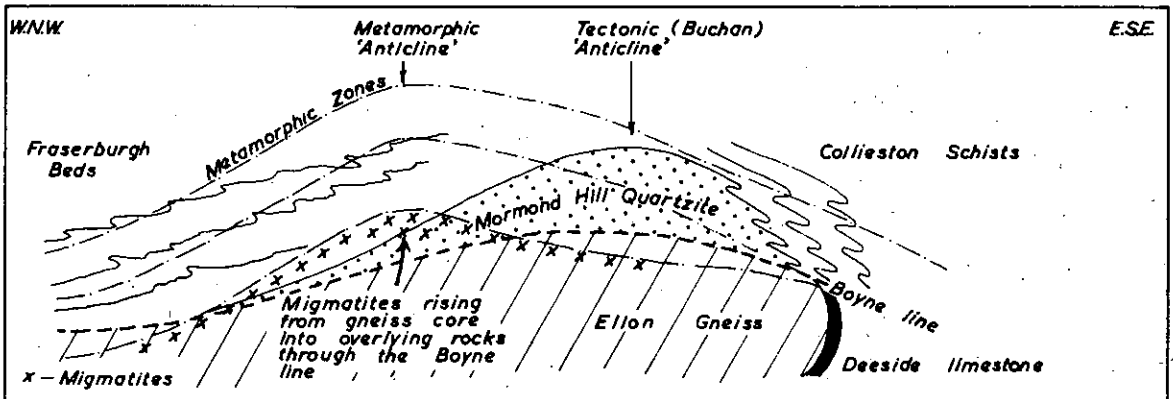
and Farquhar (1956) considered that the Collieston beds to the east of the anticline were piled up in front of this anticline, whereas to the west the Fraserburgh beds had slid down the western slope into the Turriff syncline. These sliding movements resulted from the migmatitic core of the anticline rising upwards and eastwards.

A condensed diagram from Read (1955 p.19) is given in fig. 2A.

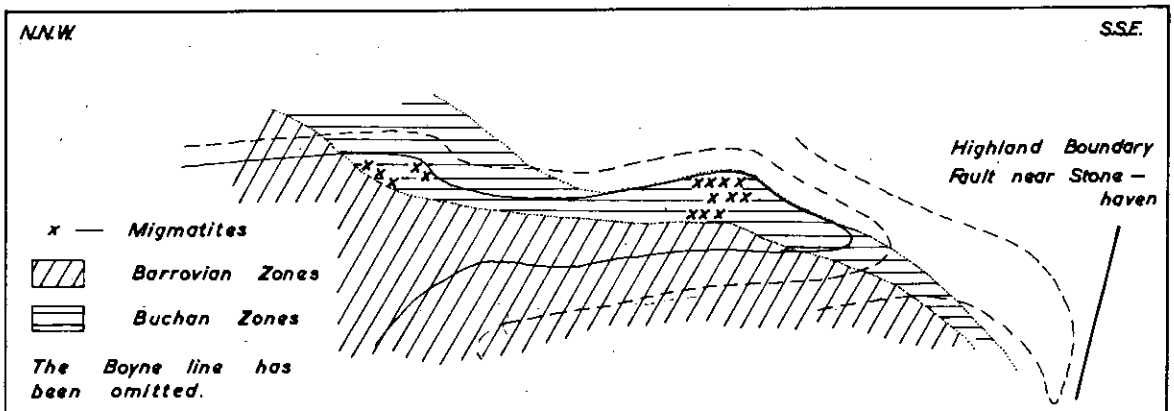
When the folding movements which formed the Buchan anticline and Turriff syncline finished, Read and Farquhar (1956) envisaged that an essentially thermal metamorphism from the migmatitic core of the Buchan anticline was imprinted on the folded series of rocks. Earlier Read (1952) had discussed the metamorphism and migmitisation of the country rocks of the Ythan Valley in Aberdeenshire. The country rocks comprise from west to east, Macduff slates and knotted slates, andalusite-cordierite schists (Fyvie schists) and sillimanite-cordierite gneisses (Ellon gneisses). According to Read (1952) these were ... "clearly the result of one metamorphic operation increasing in intensity from west to east or from above downwards." Read (1952) and Read and Farquhar (1956) were of the opinion that the permeation and migmatitic gneisses of Haddo and Arnage were a late stage of the regional metamorphic period, and if the base of a nappe exists in these areas separating Upper and Lower Dalradian rocks, then ... "/these/ /



A Diagrammatic Section across the Banff Nappe (based on Read, 1955, p 19.) **A.**



A Schematic Interpretation of the Structural and Metamorphic History of the Buchan Area (based on Read and Farquhar, 1956, p.152) **B.**



A Diagram showing the disposition of Buchan and Barrovian Zones in N. E. Scotland. (based on Johnson 1963, p.126) **C.**

FIG. 2

"/these/ migmatities swamp the boundary between Banff Division /Upper Dalradian/ and Ellon series /Lower Dalradian/." This main metamorphic period was therefore one of regional thermal metamorphism culminating in migmatisation and Read (1952) named it the "Buchan Type" of metamorphism. This metamorphism had anticlinal isograds separating the different metamorphic zones with the metamorphic grade increasing downwards towards the migmatitic core of the Buchan anticline. After this main regional metamorphism had taken place the migmatisation front rose highest into the overlying folded rocks from within the core of the anticline. Fig. 2B is reproduced from Read and Farquhar (1956, p.152).

Regional metamorphism of the Barrovian type to the south has kyanite and sillimanite as the main index minderals of metamorphic grade. Johnson (1963) stated that regional metamorphism of Barrovian type would imply higher pressures than would be required in regional metamorphism of Buchan type as there was probably no time difference between the climax of the Buchan metamorphism and the climax of the Barrovian metamorphism. In other words Barrovian metamorphism probably requires a deeper structural level than does Buchan metamorphism (see fig. 2C from Johnson 1963, p.126).

Read and Farquhar (1956) completed Read's ideas on the structural history of the north-east Scotland which may be summarised as the following sequence of postulated events.

(i)/

(i) formation of the Banff nappe with a dislocation (the Boyne lag) in the upper limb of the nappe separates the Upper Dalradian from the Lower Dalradian.

(ii) the superimposing of an anticlinal and synclinal structure on the Banff nappe; the Buchan anticline in the east and the Turriff syncline in the west.

(iii) a regional metamorphism of essentially thermal type resulting from heat from the migmatitic core of the Buchan anticline. This metamorphic 'anticline' is two miles west of the Buchan anticline, i.e. it overprints the original anticlinal structure. (see fig. 2B).

(iv) an advancing front of migmatites rising from the gneissose Lower Dalradian core of the Buchan anticline and affecting the Upper Dalradian across the Boyne lag.

Johnson and Stewart (1960) stated that the structures on the Banffshire coast were more complex than either Sutton and Watson (1955) or Read and Farquhar (1956) had previously supposed, although their divisions into early tight folds and later open folds still held.

Johnson (1962) described the relationships between folding and metamorphism in the Dalradian rocks of north-east Scotland. Four periods of folding were recognised in these rocks. Throughout their folding history low grade metamorphic conditions/

ditions prevailed, usually producing biotite growth in the rocks. A metamorphic climax occured between the second and third folding periods which led to the production of andalusite-cordierite mineral assemblages in the Dalradian rocks. This main metamorphic period is the Buchan type of metamorphism in north-east Scotland as named by Read (1952) and Read and Farquhar (1956). Johnson (1963) stated that the Buchan anticline and its complementary Boyndie syncline were formed during the third fold episode. Thus the metamorphic climax responsible for the Buchan type of metamorphism took place before the formation of the Buchan anticline. This is in complete disagreement with Read's sequence of events (p.15) as it reverses no. (ii) and (iii), and makes the position of (iv) unclear. Johnson's (1962 p.56) table of events is reproduced below in a somewhat attenuated form, to summarise the main sequence of metamorphic and fold periods recognised in the Buchan region.

Structural Episodes	Structures Formed	Metamorphic Episodes
F_1	Recumbent folds Banff nappe	Growth of biotite
F_2	Tightly appressed folds	Post kinematic growth of andalusite, cordierite, staurolite garnet.
F_3	Assymmetrical folds Boyndie syncline Buchan anticline	
F_4	Assymmetrical folds	

The/

The main theories regarding the disposition and time of intrusion of the gabbroic masses will now be examined. As has been stated previously Read (1923a) regarded the various north-east masses as the outcrops of parts of a huge sheet, intruded after the folding and metamorphic movements which affected the country rocks in the region.

Shackleton (discussion in Read and Farquhar, 1956) did not believe that the position of these masses had been clarified because the layering was very steep in some of the masses, notably Huntly in the west and Belhelvie in the east. Shackleton (1948) showed that the layering is actually overturned at Huntly, dipping steeply west and 'younging' eastwards. Shackleton (discussion in Read and Farquhar, 1956) considered that this evidence showed that the gabbroic intrusive phase was earlier than the Boyndie fold period, a view which Stewart (1946) had originally put forward. Read (in discussion after Read and Farquhar, 1956, replying to Shackleton) stated that ... "the assumption that layering of gabbro bodies was originally horizontal ... was an assumption that he /Read/ could not accept."

Stewart and Johnson (1960) re-examined the relationships of basic masses to the country rocks in the whole region including the internal structures which some of these masses exhibit and outlined the main arguments for and against deformation of the gabbroic masses.

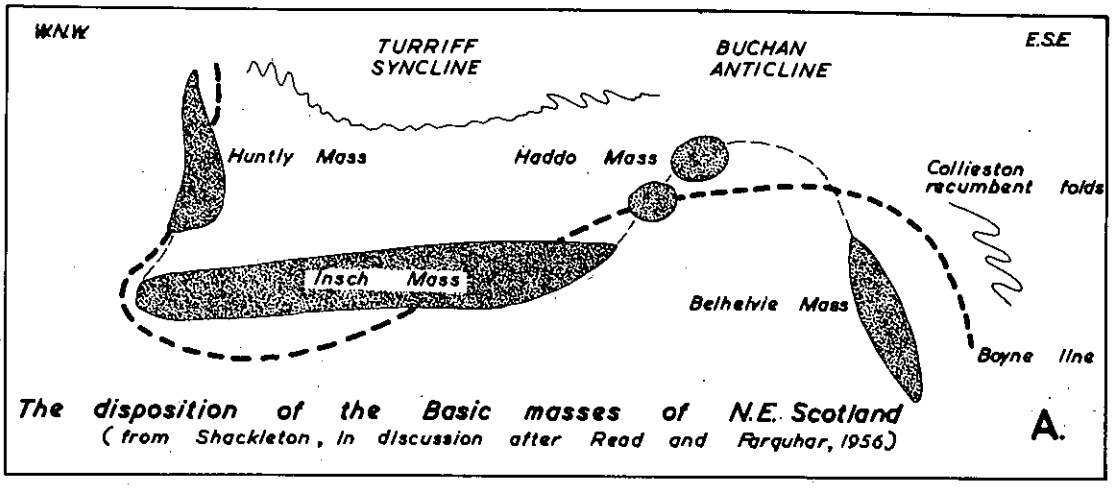
In/

In addition to Shackleton's interpretation (after Read and Farquhar, 1956), Stewart and Johnson (1960) stated that at Belhelvie small scale gradational banding dipping steeply east with occasional density gradations could be seen. This, together with the broad arrangement of rock types, showed that the basic mass had been moved after its consolidation into a nearly vertical position with its base to the west.

Geological data on the basic suites at Huntly and Insch was also examined by Stewart and Johnson (1960) who pointed out that the banding in these masses had never been mapped in detail, so that their attitude was not yet adequately known.

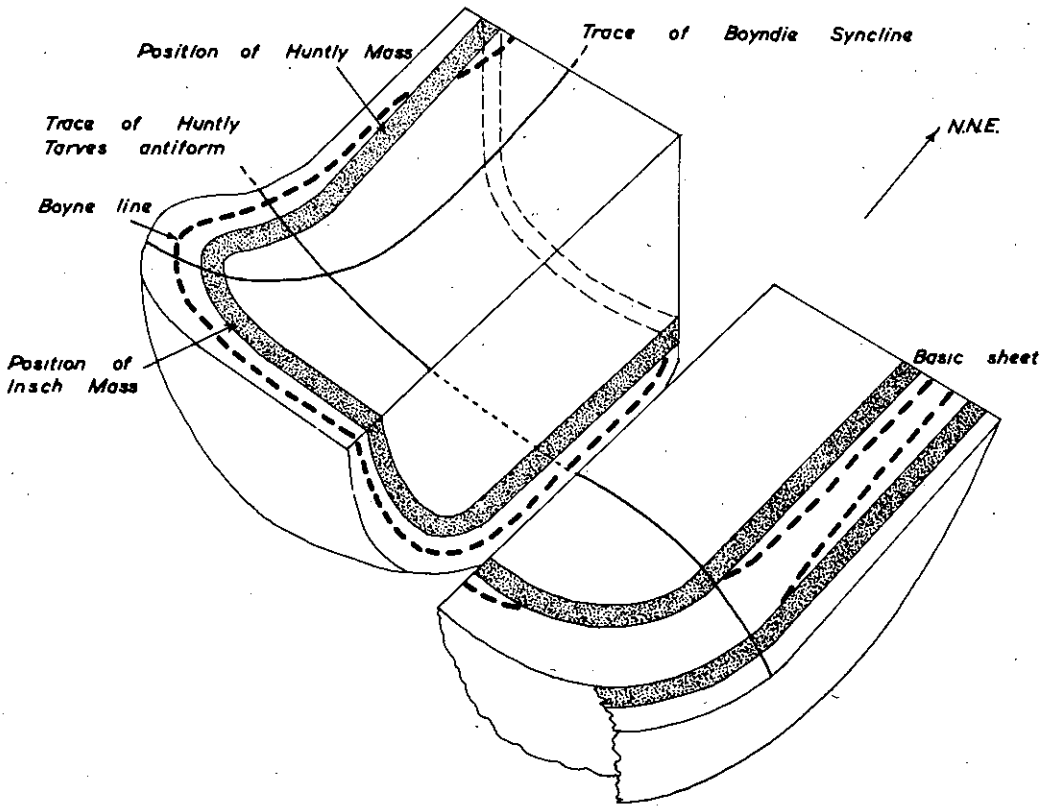
The Haddo House, Arnage and Maud bodies are so poorly exposed as to produce no detailed information. However, the large areas of contaminated rocks (quartz-cordierite-norites, etc.) at Haddo House and Arnage and ? Maud, together with the confining of olivine-hypersthene gabbro exposures to low ground led Stewart and Johnson (1960) to the conclusion that the masses were horizontal and that roof material and its associated phenomena were exposed (this was the original view of Read, 1923a). Therefore this evidence, together with the Belhelvie structures plus the views of Shackleton (in discussion after Read and Farquhar, 1956), led Stewart and Johnson (1960) to the conclusion that the basic sheet was folded after its consolidation.

Fig. 3A from Shackleton (in discussion after Read and Farquhar/



The disposition of the Basic masses of N.E. Scotland
(from Shackleton, in discussion after Read and Farquhar, 1956)

A.



A diagram showing the attitude of a transgressive basic sheet emplaced in originally flat-lying beds and then folded, firstly on NNE – SSW axes and secondly on ESE – WNW axes. *(from Stewart and Johnson 1960, p.111.)*

B.

FIG. 3

Farquhar, 1956) and Fig. 3B from Stewart and Johnson (1960) are reproduced to illustrate more clearly the alleged disposition of the basic sheet (and the individual masses) in the Buchan area.

As evidence against the gabbros being folded Read (1923b) and Blundell and Read (1958) produced three arguments and these are summarised with comments by Stewart and Johnson (1960) and by the author.

The first of Read's arguments (Read, 1923b) concerned the destruction of the cleavage in the Macduff slates at Foudland, just north of the Insch basic mass, by heat from the gabbro. The gabbro's thermal aureole in these slates at Foudland is about one and a half miles wide which suggested a gently dipping gabbroic sheet to the north under the Macduff slates. The cleavage in the Foudland slates was assumed by Read (1923b) to be due to the Boyndie fold period (its later name in Read and Farquhar, 1956), and thus earlier than the Insch gabbro. However, Stewart and Johnson (1960) pointed out that the dating of the cleavage in these slates is not at all certain. Recently Fettes (personal communication) has shown that the cleavage in the Foudland slates cuts metamorphic minerals produced in these slates by heat from the gabbro. Therefore this cleavage must be later than the intrusion of the Insch basic mass, and this point invalidates the first argument.

The/

The second argument against the gabbro masses being folded concerned the existence of delicate textures within the basic bodies and their hornfelses which should have been destroyed by later folding movements. It was pointed out by Stewart and Johnson (1960) that amphibolites from the older igneous suite on the Banffshire coast still display excellent preservation of linear structures. These structures were produced earlier than the Boyndie fold movements and hence must have been subjected to these movements. Johnson (1962) showed that these Boyndie fold movements (Johnson's F_3 fold period see table p. 16) were accompanied by only a low grade regional metamorphism which even allowed preservation of sedimentary structures in the Macduff greywacke.

Blundell and Read (1958) carried out a palaeomagnetic survey on specimens from each gabbroic body, in Aberdeenshire. In this survey, the directions of magnetism exhibited by each basic mass were shown to be essentially the same and hence the masses could not have been folded; this constituted the third and most powerful of Read's arguments against post-consolidation folding of the north-east gabbros.

The limitations of this last argument were exposed by Stewart and Johnson (1960) who showed :-

(1) the variation in the direction of magnetism within any one mass is considerable, as witness by the spread of this data when plotted on a stereogram. (Blundell and Read, 1958, p.201 fig.A). The geographical/

geographical position of each of the stereographic points were not stated. Stewart and Johnson (1960) showed that since there is a considerable variation in the dip of the banding within the Insch mass which might be due to deformation ... "it is possible that the mean direction of magnetism of the five samples studied is an average of significantly different directions." As this might also be true at Huntly, Read's presentation of the results from the data is misleading.

(2) there are limitations in the methods of sampling of the basic masses because, of the sixty samples collected from twenty-six sites in six intrusions, only twenty-one were considered to be suitable for palaeomagnetic work. Discussing the sampling of the Haddo House mass Blundell and Read (1958) stated that ... "although ten samples were collected, only one was finally considered to be in situ." Nine of the samples were rejected because ... "what looked like a good in situ outcrop is really ... a group of large boulders ... /which/ have probably not moved more than a few inches or feet from their original positions." The one specimen "in situ" is a biotite-norite in contact with the country rock at Michael Muir quarry on the east edge of the Haddo House gabbro. Since Blundell and Read (1958 p.198) rejected/

rejected a sample from Huntly for being "partly of contaminated origin" it is difficult to understand why they should use a biotite-norite from the Haddo House mass as Read (1935 p.634) stated ... "it is concluded that the norites (that is gabbros in which no clinopyroxene is present) have been produced by the assimilation of argillaceous material." In other words this biotite-norite sample is itself a contaminated rock. However, the author fails to understand why contaminated rocks should be rejected for palaeomagnetic measurement purposes, since these must have been formed at the same time as the intrusion of the gabbros. The lack of exposures generally in the inland areas of the Buchan region and the difficulty experienced in determining whether exposures are in place also undermines Read's last argument.

(3) Stewart and Johnson (1960) pointed out that in certain rocks the degree of inclination of magnetism varies with the ratio of magnetite to minerals of the Fe_2O_3 - $FeO.TiO_2$ - TiO_2 system (Balsley and Buddington, 1958), and a factor of this type must be shown not to be involved.

Thus Stewart and Johnson (1960) found that the balance of the evidence/

evidence was in favour of the north-east basic sheet being folded after its consolidation although they indicated that two other possibilities existed.

The first possibility is that of pre-intrusive gravity differentiation in another chamber and then intrusion into present positions whilst as a crystal mush. At Belhelvie this would mean that the gabbro would have to be intruded with its layering nearly vertical. This possibility was ruled out at Belhelvie because the great thickness of the mass, the lack of pronounced linear structures in the banded rocks and the lack of veining of one rock type by another weighed against it.

The second possibility is that of differentiation and deformation of the igneous bodies whilst still partly liquid or solid but above the Curie Point. Stewart and Johnson (1960) offered no evidence for or against this theory. However the existence of the upper differentiates only in the western part of Insch where the basic mass is horizontal, plus the fact that the Haddo gabbros, which are believed to lie in the upper part of the Buchan anticline, are quite basic even though the gabbroic sheet is horizontal there, seems partial evidence in favour of this theory. From Nagata (1953) the Curie-point of cooling gabbros is c.560°C. Above this point the magnetic susceptibility of the gabbros becomes apparently zero, and thus, any palaeomagnetic properties which a rock has, must have been acquired when the rock cooled from just above the Curie-point of the ferromagnetic minerals/

minerals concerned. Thus if the palaeomagnetic data presented in Blundell and Read (1958) has been correctly interpreted, there is the possibility that the gabbroic sheet might have been folded at temperatures above the Curie-point (c.560°C.) and then cooled through the Curie-point, after the folding of the partially liquid sheet had taken place. Blundell and Read (1958 p.192) stated that ... "Any subsequent metamorphism would naturally modify this magnetisation." It will be shown in Chapter IV, that from evidence presented in Johnson (1963) and Rast (in Stewart and Johnson 1963) the gabbros could have been intruded at great depth (10 Km or more) into country rocks which were themselves at relatively high temperatures, perhaps 500° - 600°C. Since Johnson (1962) showed that the Dalradian rocks of north-east Scotland were subjected to a low grade regional metamorphism with growth of biotite throughout the folding movements F_1 to F_4, the gabbroic sheet could have taken a very long time to cool down through the Curie-point of the ferromagnetic minerals. Therefore, the basic sheet could apparently be shown not to be folded after its consolidation on the palaeomagnetic evidence. This second possibility of differentiation and deformation of the basic sheet of north-east Scotland whilst still partially liquid must remain a most attractive proposition although more palaeomagnetic work must be done, or alternatively, the gabbroic sheet investigated over a wider area, either by drilling or gravity surveys.

Bell/

Bell (unpublished Ph.D. thesis 1964) outlined a possible order of events in north-east Scotland by means of age dating some of the main rock types in the region. Part of this order of events is given below, with some comments.

(1) Deposition of the Dalradian series 740 ± 40 million years (m.y.) ago. The dating of sedimentary rock is difficult because the initial Sr 87/86 ratio is unknown and inherited radiogenic Sr^{87} need not be a constant within the same stratigraphic unit. The isochron drawn by Bell (1964) from his data shows an age of deposition of 740 ± m.y. This corresponds to the age of a metamorphism which Gilletti, Moorbath and Lambert (1961) obtained from nearby Moine rocks. Bell (1964) suggested that this could indicate a metamorphic episode followed by uplift in the Moine rocks and subsequent erosion of land masses or basement, of uniform Sr isotopic composition to give the Dalradian sediments.

(2) Formation of F_1 primary recumbent fold structures (the Banff nappe of Read, 1923b, 1955) accompanied by low grade metamorphism.

(3) Intrusion of granites and pegmatities 530 m.y. ago. These are the Older Granites of north-east Scotland and include those mentioned by Read (1961). The Strichen granite, previously considered a Newer Granite/

Granite, was found to be of similar age to the Older Granites.

(4) F_2 fold movements and continued low grade metamorphism.

(5) High grade regional metamorphism with intrusion of minor microcline granites at Auchlee and Clova, and formation of the Glen Clova and Aberdeenshire migmatites 440 ± m.y. ago.
Emplacement of basic masses 440 ± 10 m.y. ago.

(6) F_3 fold movements with progressive metamorphism to the west and intrusion of granites about 400 m.y. ago. These granites are part of the Newer Granites of Scotland and were emplaced after the main folding and metamorphism of the country rocks.

From point (5) above it will be seen that Bell cannot separate the time of the climax of the Dalradian metamorphism, the formation of migmatites and the emplacement of the north-east Basic Masses. The specimens which provided ages for the metamorphism and migmatisation in north-east Scotland all gave ages in close agreement with one another. However Bell found certain anomalies in the ages obtained from some of the basic material. Although ages obtained from a hornfels within the aureole of the Belhelvie gabbro and a pegmatite which cut the Insch gabbro both approximated to 440 m.y. (450 ± 8 m.y.), the specimens of basic rocks from Insch did not. These gave ages younger than 440 m.y. One specimen gave a much younger age (393 ± 8 m.y.) using the Rubidium/Strontium method for/

for age determination than it did using the Potassium/Argon method although the latter method tends to give younger ages since Argon is usually lost through time. Bell (p.VII - 22) stated that these low ages might indicate later heating of the basic masses by the Newer Granites, but until further analytical work has been done little emphasis should be placed on this figure. This seems reasonable since Bell (p.VII - 23) stated that the figure of 440 ± 10 m.y. for the age of the north-east basic sheet represents an average Rb-Sr intersection age from the Belhelvie hornfels, the Insch pegmatite and the Insch basic mass as well as the K-Ar ages of the biotites from a few gabbro specimens from the Insch basic mass.

Thus, although Bell (1964) provides much useful information about the source areas of the Dalradian sediments the origin of the older and younger granites and the times during which the F_1, F_2 and F_3 folding took place, he was unable to separate the time of the climax of the Dalradian metamorphism in north-east Scotland from the time of intrusion of the basic masses and the formation of the migmatites, all these events apparently taking place approximately 440 m.y. ago, between F_2 and F_3.

The geological work done by Read (1923a, 1935) and Read and Farquhar (1952) on the basic bodies at the Haddo House and Arnage districts will now be discussed in more detail.

The/

The Arnage gabbro was shown to have been intruded into two major country rock groups (Read 1923a). These are :-

Upper Dalradian	Andalusite-cordierite schists and feldspathic quartzites often containing impure limestone bands occurring west, north and north-east of the gabbro (see fig. 1 and district map.) This group comprises both the pelitic and psammitic members of the Fyvie schists and also the Mormond Hill quartzites.
Lower Dalradian	Biotite-cordierite gneisses and subordinate hornblende schists occurring to the south-east of the gabbro - the whole series being termed the Ellon gneisses.

These two series provided materials for the contamination of the Arnage igneous body. The chief characteristics which Read (1923a) recognised in the contaminated rocks were:-

(a) extreme richness in xenoliths.

(b) variability of grain size and type distribution (see below).

(c) the presence of a pronounced fluxional structure.

(d) variation from gabbroic to granitic types.

(e) the presence of many alumina-rich minerals (cordierite and spinel) considered to be abnormal in igneous rocks.

Read (1923a) does not explain exactly what is meant by (b) above. "Type distribution" probably means that if the contaminated rocks are divided/

divided into different groups depending on the composition of the original introduced sedimentary material and its proportion to the original igneous magma, then these groups would not occupy areas of equal size in the Arnage district (see main divisions of Arnage rocks, below). The third characteristic given above, namely "a pronounced fluxional structure," means that the various contaminated rocks show an alignment of xenoliths or their constituent minerals exhibit banding, as Read (1923a p.460) describing a contaminated rock stated ... "these xenoliths /in the contaminated rock/ preserve a constant bedding dip to the north-west, and the dip of the fluxion in the magmatic rocks /matrix surrounding xenoliths/ is in the same direction."

Read (1923a) proposed a division of the Arnage contaminated rocks into four main groups, and this division is given below, although the author has reversed this classification (chapter V).

(1) Gabbro type — similar to the main quartz-hypersthene-gabbro but with more quartz. This group included quartz-orthonorites and quartz-cordierite-norites.

(2) Arnage type — the most widespread of the contaminated types found north of a line from Arnage station to Cookston and comprising cordierite-bearing/

bearing two-feldspar gneisses. This type is allegedly the result of modification of the initial magma by the Fyvie schists and pelitic material from the Ellon gneisses.

(3) Kinharrachie type — seen two miles west of Ellon town near the Kinharrachie farms. This type was produced by contamination of the initial magma with the hornblende schists from the Ellon series.

(4) Ardlethen type — found at Ardlethen and according to Read (1923a, p.458) was ... "the best development of the granitic end-product of contamination."

A gradual change was envisaged from quartz-hypersthene-gabbro to contaminated rock and thence to country rock. More detailed discussion on the contamination process and the development of the contaminated rocks, both from this area and from the Haddo House district, will be found in chapter V in this thesis. Read (1923a p.484) made the main purpose of his paper to establish that ... "the contamination process depends upon reciprocal reaction between the gabbroic magma and argillaceous xenoliths; the magma becomes more acid, the xenoliths more basic/

basic."

These views were amended greatly by Read and Farquhar (1952) in which they suggested that the Arnage, Kinharrachie and Ardlethen divisions of his contaminated rocks were, in actual fact, part of an older migmatitic series similar to the Cromar gneisses of Deeside, and of much earlier age than the gabbroic intrusion. The evidence for this is based on the field relations between gneiss and gabbro at a few localities summarised below (Read and Farquhar, 1952).

At two of these localities field relations were admitted to be obscure although in the Nether Mill district a quartz-cordierite-norite - a transitional type - was reported by Read (1923a p.458).

At the two remaining districts namely Gallow Hill and Waulkmill of Savoch critical evidence in support of Read's hypothesis was claimed. At the former, nearness of gabbro to gneiss without transitional types was put forward as evidence of a sharp boundary between the gabbros and the gneisses, although no actual contact was seen. Great difficulty is experienced in recognising true outcrop because the area is covered with a vast amount of loose boulders from nearbye drystone dykes.

At the latter area, the Waulkmill of Savoch railway cutting, Read and Farquhar (1952) claimed evidence in support of there being sharp gabbro/gneiss contacts. At this cutting two large outcrops/

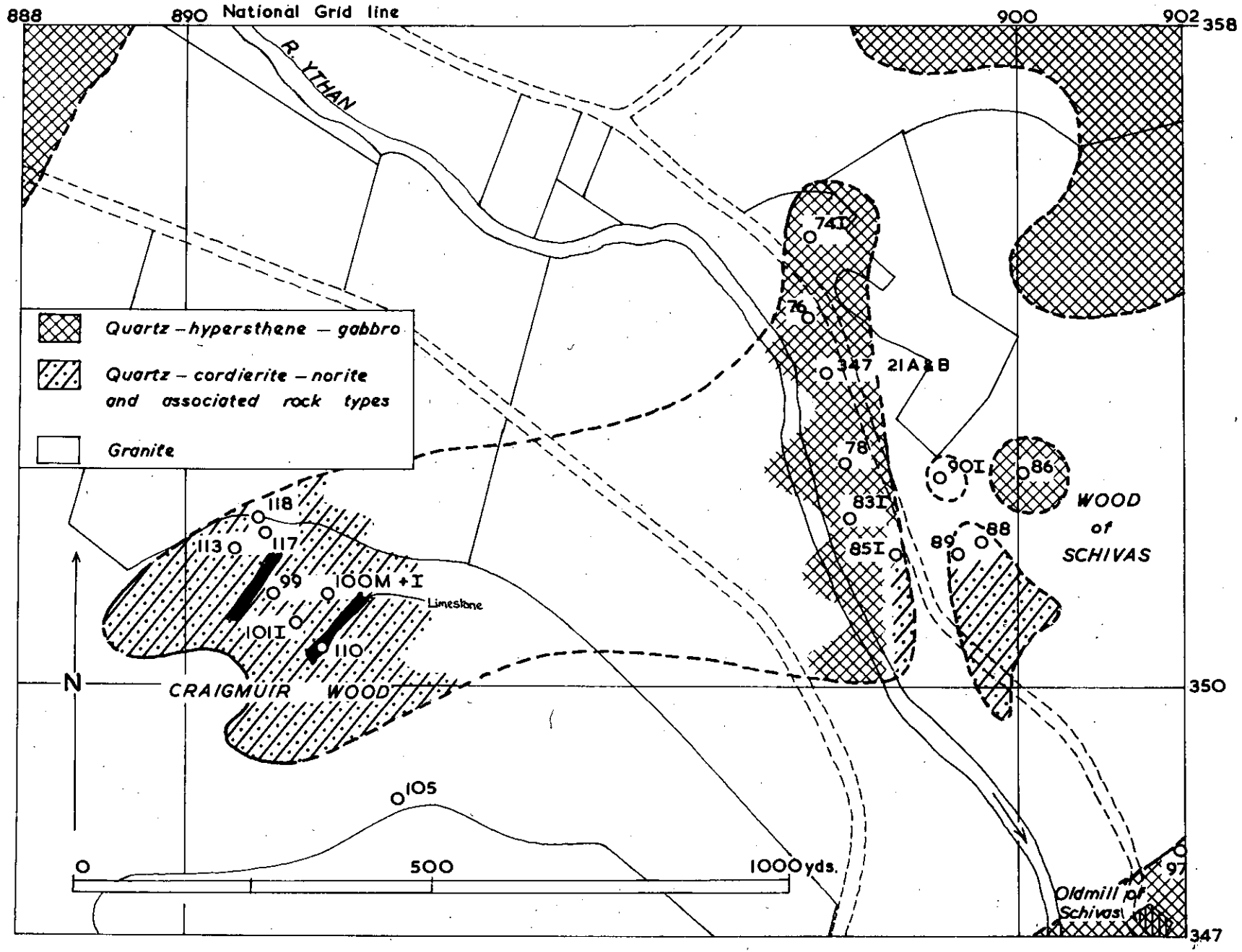
outcrops of Arnage gneisses were reported to be surrounded on all sides by gabbros; however quartz-cordierite-norites also exist there (Read 1923a p.431). A more detailed description of these areas and their rock types will be found in chapter V of this thesis which deals with the contaminated rocks of Arnage.

After Read (1923a) had written his work on Arnage he continued to write papers dealing with certain features of assimilation as exhibited by differing rock types (Read 1924, 1931). With new evidence from Bowen (1928), Read (1935) continued his work on assimilation processes further, with publication of his interpretation of the geology of the Haddo House district. This paper is still the major work on the area.

In this paper the main country rocks were again described. Gabbros were seen to have intruded these schists and a later granite, the Auchedly granite, was intruded into the gabbroic suites of rocks. This granite enclosed both the quartz-hypersthene gabbros and the quartz-cordierite norites in the Wood of Schivas and Craigmuir Wood districts (see map, fig.4).

Read described the following separate groups of rocks;-

(a) Olivine-hypersthene-gabbros, and quartz-hypersthene-gabbros and their "end-stage derivatives." By "end-stage derivatives" Read does <u>not</u> mean the final fractionated product from the differentiation of a gabbroic/



THE CRAIGMUIR WOOD and WOOD of SCHIVAS AREAS, HADDO HOUSE DISTRICT

FIG. 4

gabbroic sheet but (1935 p.604) ... "post magmatic modification" ... and (p.607) ... "epidioritization ... the result of autometamorphism or end-stage action in the ... gabbro body itself," producing (p.604) "post-magmatic amphibole associated in the last stages with chlorite, epidote and sericite." These end-stage derivatives are uralitised gabbros.

(b) Orthonorites ("norites" of Read, 1935, p.607), quartz orthonorites and their "end-stage derivatives."

(c) Quartz-cordierite-norites found at the Wood of Schivas and Craigmuir Wood, within the Auchedly granite intrusion (these were not included with the quartz-orthonorites and quartz-hypersthene-gabbros as happened with similar Arnage types in Read (1923a, p.459). These quartz-cordierite-norites comprised, two main types - quartz-cordierite-norites as the name suggested, and quartz-rich cordierite-bearing, potash feldspar rocks with occasional garnets.

In groups (b) and (c) above, xenoliths of different compositions, varying from alumina-rich to quartz-rich were observed, and these were seen to be most prolific in the quartz-cordierite-norites.

The country rocks show marked thermal effects near the gabbro contact especially in the valley of the Ythan River near/

near Methlick. These effects are discussed in chapter III of this thesis.

After all the rock types and xenoliths had been described in great detail, Read (1935) set out his ideas on the contamination process as seen in the rocks of the Haddo House district of Aberdeenshire. His main argument was that a xenolith with the composition of a pelitic member of the Fyvie schists, an andalusite-cordierite-schist, has never been observed, although all other country rock types, calcareous and quartzitic, have been seen as xenoliths. Thus Read (1935, as in 1923) postulated a gradual change in composition from andalusite-schists to alumina-rich xenoliths by incorporation of schistose material into the igneous rocks. He discussed Bowen's (1928) work on assimilation in detail, used it to substantiate his own hypothesis, and finished his discussion with a repeat of his earlier dictum ... "if there were not so many slates there would not be so many norites." By "norites" Read implies orthonorites as (1935 p.634) he states ... "norites (that is gabbros in which no clino-pyroxene is present)."

The significance of his discussion and investigation of some of the main rock types will be reviewed later in this thesis, although it is of interest to note here that there are NOT so many orthonorites in Haddo as Read envisaged. Finally from his work at Haddo, Read (1935) concluded that there/

there were two primary magmas - an olivine-hypersthene-gabbro, and a quartz-hypersthene-gabbro both of which were xenolith free. All the other rocks containing xenolithic material, were produced by varying degrees of assimilation of country rock material into the original magma. However it might be possible that the olivine-hypersthene-gabbros, and quartz-hypersthene-gabbros (which do contain alumina-rich xenoliths) are derived from the same initial magma (see petrogenesis section chapter IV).

CHAPTER II

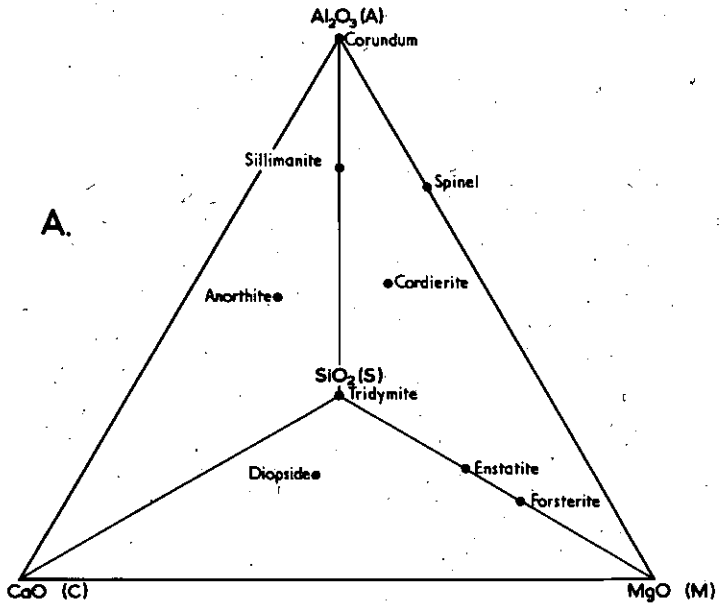
A model to help with the petrogenesis of the rocks of uncertain origin, or unhomogeneous rock group, of the Haddo House district is outlined in this chapter. This group includes xenolithic quartz-cordierite-norites and the contaminated rocks of Haddo as described by Read (1935) and also similar Arnage rocks described by Read (1923a) including the Arnage and Ardlethen gneisses.

In previous years many workers have published results dealing with liquid trends, primary phase volume equilibria, etc., in various 2, 3 or 4 - component systems. Not much work has been carried out on systems involving more than four components. Thus it is difficult to equate natural rocks, whose analyses involve 9 or more components (oxides) $\pm$ H_2O with the data from synthetic systems. However, it might be possible to equate some natural rocks with parts of experimentally determined synthetic systems if natural rock analyses can be recalculated or reduced to 4 (or less) components.

At Haddo after the mineral assemblages and chemical compositions of the unhomogeneous rock group (and other groups) had been examined by the author, it was decided that the system $CaO - MgO - Al_2O_3 - SiO_2$ (CMAS) was the most relevant to the problem of genesis which these Haddo rocks presented, see figure 5A.

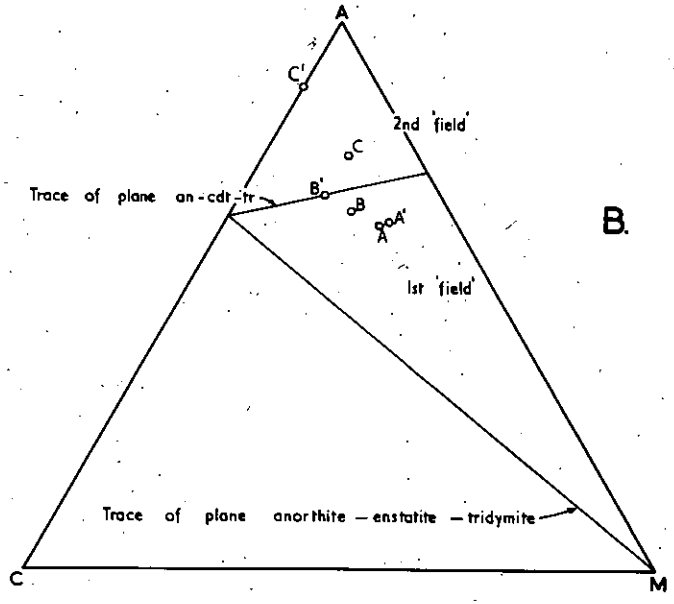
Chinner and Schairer (1962) first revealed how this system could be applied to the petrogenesis of the Haddo rocks. Their work dealt in detail with melting relations along the join $Ca_3Al_2Si_3O_{12}$ (grossular) - $Mg_3Al_2Si_3O_{12}$ (pyrope) in dry conditions at atmospheric pressure and the/

FIG. 5



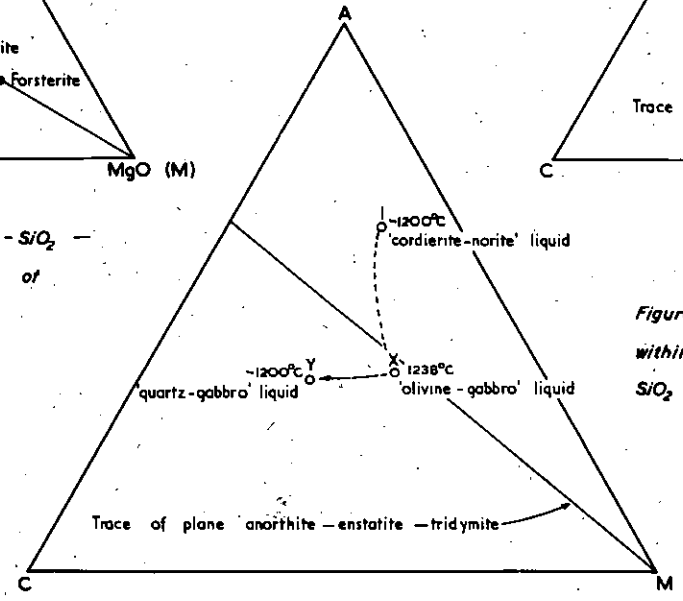
A.

A diagram of the system $CaO - MgO - Al_2O_3 - SiO_2$ — the system CMAS — showing the position of some phases present.

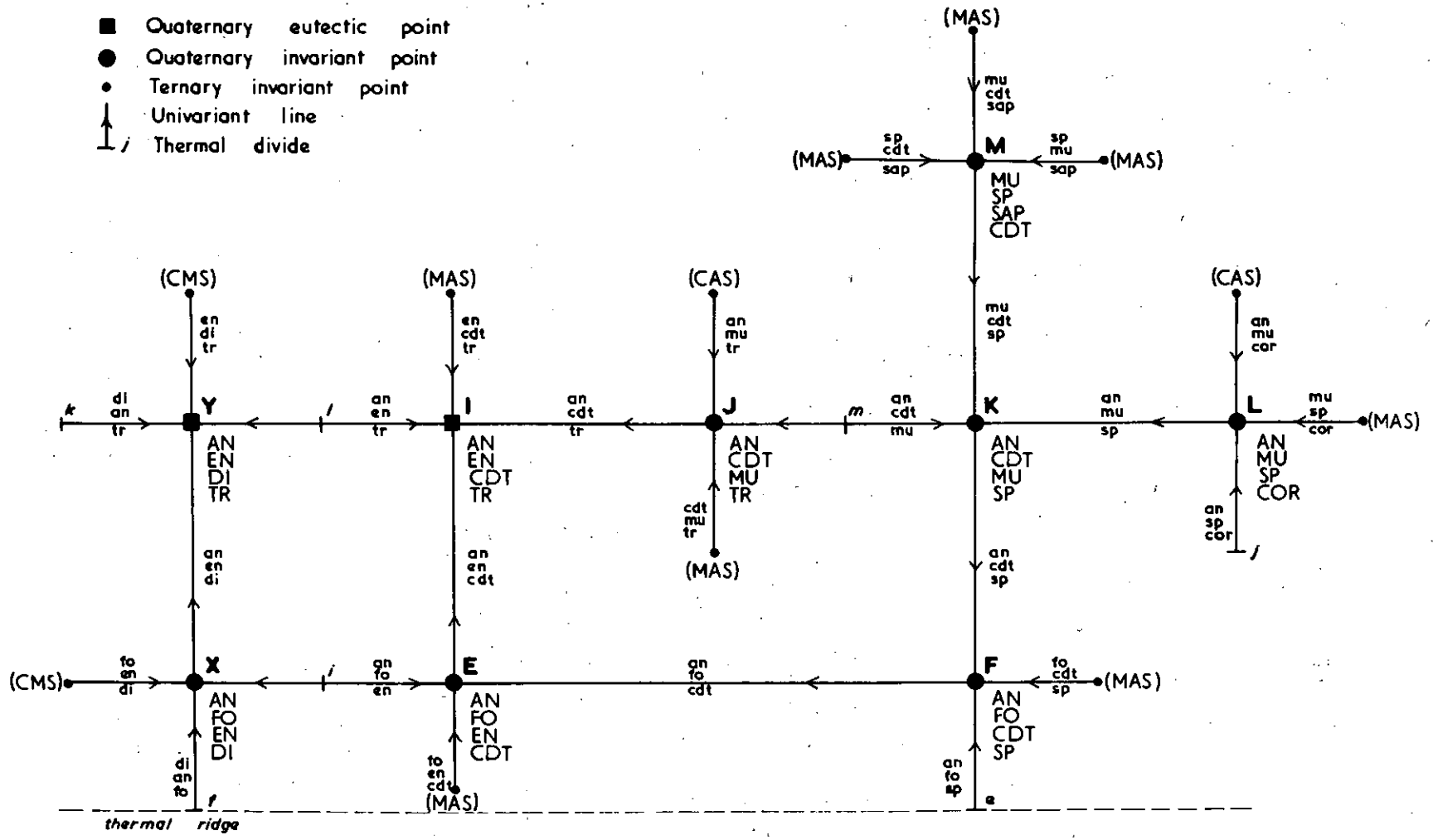


B.

Figures 5B and 5C represent the same plane within the system CMAS. A projection from SiO_2 into the plane SiO_2 = 50%



C.



A flow sheet diagram for part of the system $CaO-MgO-Al_2O_3-SiO_2$
(from Chinner and Schairer 1962)

FIG. 6

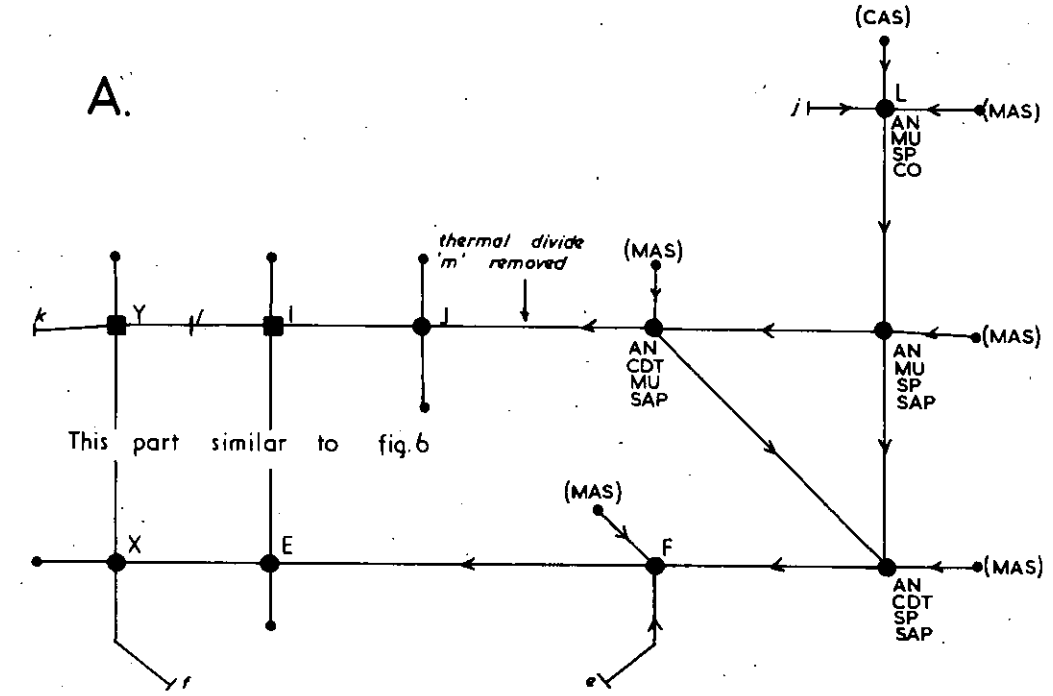
the bearing that this join had on the CMAS system. This join cuts 3 subsolidus tetrahedra and passes very close to others. The phase relations on the bounding planes of most of these subsystems were known from previous data, and from this Chinner and Schairer constructed a flow-sheet. This shows phase relationships and univariant and invariant equilibria in part of the CMAS system always under isobaric conditions.

Although a large part of the CMAS system was given in their flow sheet it is not intended to reproduce all of it and only that part which applies to the author's problem is given (fig. 6) and discussed in some detail. (Fig. 6 from Chinner and Schairer, 1962, p. 619).

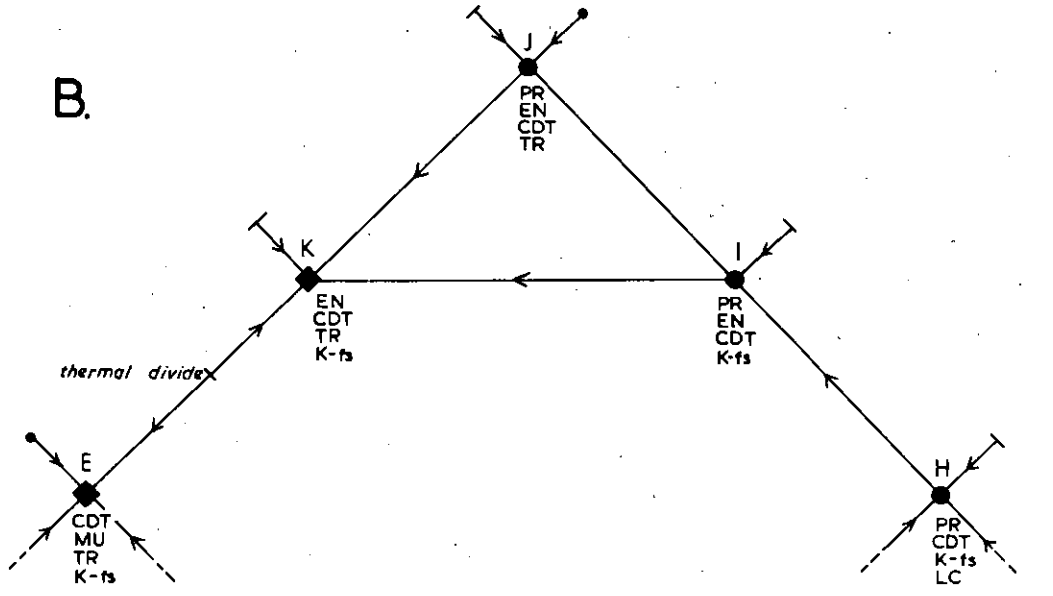
In the part of the diagram reproduced, the line e - f separates melilite-bearing assemblages from non-melilite-bearing ones, and since none of the Haddo rocks contain melilite only the part of the system in which melilite does not appear is reproduced in fig. 6. Chinner and Schairer examined the liquidus data in the subsystems An-En-Di-Tr and An-En-Cdt-Tr. The former contains the liquids appropriate to two quaternary isobaric invariant equilibria, an-en-di-fo-liquid (reaction equilibrium X) and an-en-di-tr-liquid (eutectic equilibrium Y). The latter subsystem (An-En-Cdt-Tr) was known to contain the liquids appropriate to four univariant equilibria passing through the bounding plane an-cdt-en of the tetrahedron. In addition the liquids appropriate to six more univariant lines were shown to pass into the subsystem through the other bounding planes (an-en-tr, cdt-en-tr, etc.) and thus Chinner and Schairer (1962) considered that the/

the tetrahedron An-En-Cdt-Tr contained the liquids appropriate to five quaternary invariant equilibria, of which four, 'points' EFJK on diagram fig. 6 are reaction equilibria, and one, the remaining equilibrium I, an-en-cdt-tr-liq., is a quaternary eutectic. All these liquids crystallise to a composition appropriate to that of a cordierite-norite. Invariant equilibria Y and I are 'joined' by a univariant equilibrium through the plane anorthite-enstatite-tridymite. Since this plane represents a temperature maximum on the univariant equilibrium Y-I it would be impossible to proceed down temperature from one equilibrium to the other. Both are quaternary eutectics, and if liquids corresponding to equilibria Y or I are cooled below the eutectic temperature, two solid assemblages, anorthite, enstatite, diopside, tridymite, and anorthite, enstatite, cordierite, tridymite respectively, would be produced. These synthetic assemblages correspond to a quartz-hypersthene-gabbro (eutectic Y) and a quartz-cordierite-norite (eutectic I).

O'Hara and Schairer (unpublished) revised part of the 'flow-sheet' of Chinner and Schairer (1962), the relevant part of which is shown in fig. 7A. The main revision in the part reproduced in this figure, is that reaction equilibria K and M in Chinner and Schairer's diagram have been replaced by three new isobaric invariant equilibria all lying within the tetrahedron An-En-Cdt-Tr, which thus contains 7 invariant equilibria. This proposed revision of detail is not significant in constructing a model for the Haddo rocks as each of the three new invariant equilibria like one of the old, contains sapphirine, and this mineral is not present in the Haddo rocks. However, the thermal/



Revised flow sheet diagram of part of the system $CaO - MgO - Al_2O_3 - SiO_2$ *(from O'Hara and Schairer , unpublished)*



Flow sheet diagram of part of the system $K_2O - MgO - Al_2O_3 - SiO_2$
(from Schairer 1954.)

FIG. 7

thermal divide 'm' in the flow sheet of Chinner and Schairer was removed by O'Hara and Schairer, and, as will be seen in chapter V, no divide 'm' is envisaged between points J and K for the natural rock flow sheet corresponding to the Haddo rock assemblages. It is possible that a 'point' equivalent to invariant equilibrium (K), although replaced by O'Hara and Schairer, might still apply to the natural rock system under review, as assemblages containing the phases anorthite-cordierite-sillimanite-spinel are occasionally found at Haddo.

A flow sheet such as fig. 6, is merely a diagram to help depict phase relations inside a 4-component system. The lines, points, etc. on the diagram do NOT lie in a plane and the position of points representing the invariant equilibria, length of lines representing univariant equilibria etc., are purely arbitrary. The arrows always indicate falling temperature. Ternary invariant equilibria lie at the ends of some of the univariant equilibria on a bounding plane of the system CMAS, e.g. the plane $CaO-MgO-SiO_2$. It is impossible to take a liquid composition appropriate to a univariant equilibrium in the synthetic system 'through' a thermal divide by fractional crystallisation or partial melting while keeping it in that equilibrium. Since the Haddo rocks contain no sapphirine- or forsterite-bearing xenoliths, that part of the flow-sheet relevant to assemblages with these phases (points E, F and M, fig. 6) will not be described in detail. Since this CMAS model is to be used for partial melt phenomena, interpretations of the flow-sheet are always for temperatures increasing and an original solid mixture melting/

melting, rather than a liquid cooling, although fractional crystallisation effects may be important after maximum temperatures of partial melting have been reached and the liquids formed begin to cool.

O'Hara and Schairer (unpublished) considered in great detail the application of this part of the CMAS system to natural rocks. They asked and tentatively answered a series of 'questions' concerning the problems encountered in applying a partial melt theory of origin to natural rocks.

1. Their first question investigated the mechanism of partial melting, and whether it would be possible to produce Si-rich and Al-rich xenoliths purely by the partial melting of some initial sedimentary material. O'Hara and Schairer followed Chinner and Schairer (1962) in stating that a liquid of composition appropriate to that of eutectic I could correspond to the liquid produced in natural rocks by the partial melting of rock consisting of the phases plagioclase, orthopyroxene, cordierite and quartz. In natural rocks, the intrusion of a basic magma whose composition is appropriate to that of invariant equilibrium X, fig. 6, into a series of pelitic sediments might produce a variety of quartz-orthopyroxene-plagioclase-cordierite hornfelses, due to a thermal metamorphism of these pelites. In the synthetic system a mixture of random proportions of anorthite, enstatite, tridymite and cordierite, if heated sufficiently for melting to begin, will melt initially with the production of a liquid of fixed composition appropriate to that of eutectic I. With further increase in temperature, no 4-phase crystalline aggregates remain

and/

and the liquid, whose composition must vary from place to place would exist with a variable number of crystalline phases in various sub-systems each liquid appearing in equilibrium with 1, 2 or 3 of the original 4 phases present; every liquid would lie within the composition tetrahedron An-En-Cdt-Tr.

Fig. 5B, represents a projection from SiO_2 into the 50% SiO_2 plane of the tetrahedron CMAS. In this diagram a field corresponding to pelitic compositions has been drawn and a partial melt liquid, first produced by the melting of one of these mixtures is also shown on the diagram, point A; this represents the initial liquid which appears when the initial material is partially melted and corresponds to eutectic equilibrium I. With increase in temperature the liquid produced still lies within the area of the tetrahedron An-En-Cdt-Qz and it coexists with xenoliths whose compositions depend on the composition of the original mixture undergoing melting (i,e. the proportions of CaO, MgO, Al_2O_3 and SiO_2) in the original mixture. For example a mixture corresponding to B will produce a liquid of composition A coexisting with a xenolith B', consisting of phases anorthite, cordierite (and quartz) and which lies on the line An-Cdt in the projection 5B. Thus depending on the composition of the mixture a liquid corresponding to a cordierite-norite (lying within the tetrahedron An-En-Cdt-Qz) would surround xenolithis ranging in composition from pure quartz to anorthite-enstatite-cordierite. In nature a quartz-cordierite-norite (liquid) of slightly variable composition would surround xenoliths composed of any one, two or three of/

of the four phases originally present in the sediments undergoing partial melting (e.g. the quartz-anorthite-orthopyroxene-cordierite hornfelses already mentioned). Xenoliths ranging in composition from pure quartz to plagioclase-orthopyroxene-cordierite would appear in the liquid and any restriction in the type of xenolith appearing would depend entirely on the nature of the original pelitic hornfelses which underwent partial melting - i.e. the proportion of original crystalline phases present in them, before partial melting took place.

In the synthetic system if the temperature is increased still further, a liquid could be produced which co-exists with cordierite, mullite and spinel (e.g. the liquid whose composition is appropriate to that of quaternary invariant equilibrium K). This liquid is known to lie inside the composition tetrahedron anorthite-enstatite-cordierite-tridymite, and 2 of the 3 crystalline phases mentioned (mullite and spinel) lie outside it. If all possible mixtures of the 4 phases-anorthite, enstatitite, cordierite and quartz - were available in the original material undergoing partial melting, then there must be some subsystems which lie between the liquid which co-exists with cordierite mullite and spinel and these 3 crystalline phases. In this case a mixture whose composition might lie in the 2nd field, corresponding to aluminous pelites (fig. 5B), would melt with production of a liquid whose composition still lies in the sub-system An-En-Cdt-Tr and near to point A (say A'). This liquid would still crystallise to a quartz-cordierite-norite but it would surround xenoliths containing mullite and/or spinel etc., depending upon/

upon the original composition of the mixture undergoing melting. For example mixture C would melt to give liquid A' and xenolith C' - which consists of anorthite, mullite and corundum. Thus depending on the composition of the original material, partial melting would produce a liquid always lying within the tetrahedron An-En-Cdt-Qz and surrounding highly aluminous xenoliths. In nature a quartz-cordierite-norite (the liquid whose composition has not changed greatly - it still lies within tetrahedron An-En-Cdt-Tr) would surround xenoliths which would be highly aluminous (and silica-poor). Such a process could be interpreted as a magma assimilating sedimentary material (Bowen 1928; discussion in chapter V of this thesis) although such an assimilation process cannot explain why xenoliths become enriched in constituents with which they were already enriched with respect to the magma before this process occurred. With a partial melt theory of origin for both matrix and xenolith no assimilation or metasomatic action is required.

2. The second question concerning contact phenomena is discussed in full, in chapter V where it is more relevant to the discussion.

3. Question three concerned the nature of the xenoliths that might be encountered in rocks of partial melt origin, or in intrusive igneous rocks. O'Hara and Schairer (unpublished) discussed three situations. The first envisaged a country-rock fragment in a crystallising gabbro, the second a xenolith in a partial melt country rock (a situation already discussed in the first question) and the third, the meeting of partial melt of country rock and gabbro magma with the formation of xenoliths.

In/

In the first situation a xenolith with a high temperature assemblage may be surrounded by partial melt liquid derived from the xenolith.

(i) If this liquid is removed, the remaining xenolith is not in equilibrium with the surrounding magma and hence it would tend to armour itself with a crystalline layer in equilibrium with the magmatic liquid, such as anorthite-orthopyroxene-forsterite if the xenolith is immersed in an olivine-gabbro magma crystallising these phases. Since this zone itself is not in equilibrium with the aluminous core of the xenolith another zone e.g. anorthite-orthopyroxene-cordierite, in equilibrium with the inner core, might be formed. The formation of this intermediate zone might lead to melting and disruption at the 4-phase low melting point assemblage at the contact to the outer zone which might then break-up and the xenolith would slowly 'dissolve' in the magma by a repetition of the process. In natural occurrences this situation would be reflected in a xenolith with a corundum or spinel-bearing core surrounded by a cordierite-norite zone and finally by a zone of olivine-norite between it and the enclosing gabbroic magma. This situation is discussed further in chapter IV with reference to the xenolithic quartz-hypersthene-gabbros which occur in the Haddo and Arnage districts.

(ii) If the liquid formed at the edge of the xenolith is not swept away and incorporated into the surrounding magma, then a situation analogous to the third situation envisaged by O'Hara and Schairer in this question is encountered. In this situation a liquid corresponding in composition to eutectic I is produced by the xenolith/

xenolith and this meets the crystallising gabbro magma corresponding to quaternary eutectic Y.

Fig. 5C is a projection from SiO_2 into the 50% SiO_2 plane of the CMAS tetrahedron. 'Point' Y represents a mixture corresponding to a quartz-gabbro (consisting of anorthite, enstatite, diopside and quartz) and 'point' I represents the partial melt liquid corresponding to a cordierite-norite formed by melting a mixture of composition anorthite, enstatite cordierite and quartz. The liquids Y and I would meet on the composition plane an-en-tr which is a thermal divide. Chinner and Schairer (1962) stated that because of this divide it is impossible to produce a liquid on the alumina rich side by progressive contamination of liquid Y. Such an attempt heads to the precipitation of more and more tridymite, enstatite and anorthite until the (orthonoritic) mixture froze. A solid screen would occur between the two liquids, separating these liquids, although the partial melting of mixtures on the alumina rich side of the screen would continue. Thus on crystallisation, mixtures corresponding to Y and I would occur with only a small quantity of material occurring whose composition lies on the thermal divide. In nature because of the variation in compositions of gabbroic magma and pelitic material undergoing melting, the gabbros and cordierite norites would occupy a large field on a diagram similar to 5C, but these two groups of rocks would still be separated by the plane an-en-tr. The orthonoritic screen would be expected between partially melted country rocks and a magma which was at the stage of crystallising quartz, if the thermal divide is effective.

It/

It is possible that an assimilation process of sorts does operate and O'Hara and Schairer (unpublished) examined the meeting of a liquid corresponding to equilibrium X (anorthite, enstatite, diopside, forsterite) and a liquid produced by partial melting of a mixture of composition appropriate to eutectic I. This liquid could co-exist with anorthite, cordierite and mullite (or any other 3 phases, 1 or 2 or 3 of which were phases originally present).

If a liquid whose composition is appropriate to that of invariant equilibrium X (corresponding to an olivine-gabbro liquid) meets the partial melt liquid I, see fig. 50, then the temperature of X (1238°C) is greater than that of the thermal divide an-en-tr (1222°C). If the temperature remains at 1238°C through a long period of time the liquid X will modify I towards and even through the plane an-en-tr. In this case a progressive contamination sequence will be observed with a series of mixtures from X - I in diminishing frequency of types. The geological analogue of this would be the progressive contamination of an <u>olivine</u> gabbro magma (equilibrium X) by pelitic sediments, producing a complete range of rock types from olivine gabbro ⟶ quartz-cordierite-norite, in diminishing frequency of observed rock types. If the thermal divide An-En-Tr <u>is</u> effective no progressive range of contaminated rock types will be observed, and X (olivine-gabbro ~~liquid~~) would have fractionated to give Y (quartz-gabbro ~~liquid~~) and the meeting of liquids corresponding to Y and I would produce a precipitation of a solid orthonoritic screen (see page 45).

4/

4. The fourth question posed by O'Hara and Schairer (unpublished) investigated the nature of the conditions at the time of partial melting, and is concerned with whether partial melting begins (and continues) with a water vapour phase present. If partial melting begins under a water vapour pressure then it will begin at relatively low temperatures. Winkler and Von Platten (1961) and Wyllie and Tuttle (1961), determining the composition of the liquids formed by partially melting natural materials under P_{H_2O} = 2 Kb found that the most basic melt formed was of tonalite composition, from a greywacke with a very high Na/K ratio. The effects of melting shales, etc., under dry conditions has never been discussed and the composition of the resultant melt is unknown. It is probable that if melting in shales, pelites, etc., began with a water vapour phase present, and then continued in 'dry' conditions (i.e. no P_{H_2O}) then the melt produced might be quite different from anything previously observed by workers examining the melting of sediments under wet conditions.

5. Finally O'Hara and Schairer discussed the temperatures at which various natural rocks, relevant to the above model, would melt. In the synthetic system under discussion, the temperatres of equilibria X, Y, I and the thermal divide 'l' (see fig. 6) are known, 1238°C, 1180° ± 9°C, 1190 ± °C and 1222°C respectively, but these are for melts of mixtures containing only CaO, MgO, Al_2O_3 and SiO_2 as constituents, determined at atmospheric pressure in the dry state. Melting data for the Haddo rocks are not available although attempts will be made in parts of this thesis to estimate the temperatures of the olivine-hypersthene-gabbro (X) at the time of intrusion, the temperature of the country rocks at the climax of the Buchan meta-

mosphism (probably just prior to gabbro intrusion) and the pressure under which the basic sheet was intruded.

Temperatures of reaction equilibria, etc., are known in the synthetic system but the presence of additional oxides found in natural rocks will affect these temperatures, add extra degrees of freedom, and change the phases which appear. The addition of iron oxide to MgO-bearing systems usually lowers temperatures. In the system 2 MgO SiO_2-2FeO.SiO_2 (Forsterite - Fayalite) an increase in the amount of the iron-rich molecule present in olivine will substantially lower the melting range of the olivine. Pure forsterite melts at 1850°C± and pure fayalite at 1205°C (Bowen and Schairer, 1935). Similarly, in another solid solution equilibria diagram Albite - Anorthite (Bowen, 1913), an increase in the albite molecule in the plagioclase will lower its melting temperature substantially. Anorthite melts at 1550°C and albite at ~1100°C. Although rocks contain many major oxides it is postulated that the oxides having the greatest effect on the CMAS system will be Na_2O, K_2O and FeO. H_2O was present in the partial melts and intrusive magmas at Haddo but it will be argued that the consolidation of the magmas and melt took place with no water vapour phase present. It is possible however that the initial anatexis of the country rocks adjacent to the magma took place in the presence of a water vapour pressure, thus ensuring that initial melting began at low temperatures (chapter V). It has been stated how melting temperatures of calcium and magnesium compounds can be steadily lowered if increasing amounts of sodium and iron are added to each compound respectively. Schairer (1954) did/

did describe in detail phase equilibria in part of the system K_2O-MgO-Al_2O_3-SiO_2 (KMAS) at atmospheric pressure and part of Schairer's flow sheet is reproduced in fig. 7B. This shows the existence of quaternary eutectic point K and melting of a mixture of composition appropriate to K would produce a liquid of composition, enstatitite, cordierite, quartz and K-feldspar. Thus a rock containing the phases at K (e.g. a potash-rich cordierite-biotite schist) could, on melting, produce a liquid, analogous to a quartz-cordierite-K-feldspar (-? garnet) rock. This partial melt rock would enclose xenoliths of any 1, 2 or 3 of the 4 original phases present e.g. enstatite-cordierite-tridymite, etc. With great increase in temperature in the synthetic system KMAS the liquid could have a composition appropriate to reaction equilibrium H, and leucite might appear in the xenoliths co-existing with the liquid formed. In this case the liquid appropriate in composition to reaction equilibrium H would have to lie inside the composition tetrahedron enstatite-cordierite-tridymite-K-feldspar, a situation analogous to that discussed in the CMAS system. However, since the Haddo xenoliths do not contain leucite this system obviously has limited application although mineral assemblages corresponding to eutectic K have been noted. It is important to note that eutectic K, although similar to eutectic I in the system CMAS (3 phases similar), has a temperature more than 200°C lower (960 $\pm$ 20°C and 1190° $\pm$ respectively). Yoder and Schairer (1964) carried out investigations in part of the synthetic system Na_2O-

CaO/

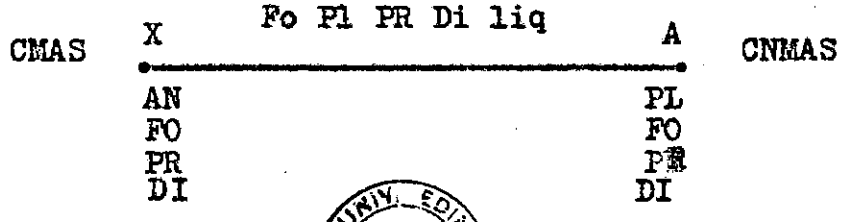
$CaO-MgO-Al_2O_3-SiO_2$, and produced some information about temperatures of divides, invariant points, etc. in the subsystem-nepheline-forsterite-larnite-silica. A flow sheet of part of the system in which assemblages relevant to alkali-basalts occurred was constructed. Two of the quaternary invariant equilibria described have the assemblages, plagioclase, diopside (s.s.), protoenstatite, forsterite -(A) and plagioclase, diopside (s.s.), protoenstatite and tridymite (B). These 2 invariant equilibria A and B (B is a eutectic) correspond to invariant equilibria X and Y in the synthetic system CMAS (fig. 6). A and B represent liquid of composition appropriate to olivine-tholeiite (or olivine-gabbro) A, and tholeiite (or quartz-gabbro) B. However the temperatures of these invariant equilibria A and B are much lower than the temperatures of the corresponding equilibria X and Y. The temperatures of A and B were not precisely given by Yoder and Schairer (1964) but A < $1098^{\circ} \pm 10^{\circ}C$ and is probably greater than the thermal divide 'c', the plane albite-forsterite-tridymite (corresponding to the thermal divide 'l', anorthite-enstatite-tridymite in the CMAS system). i.e. the temperature of A lies between $1098^{\circ}C$ and $1058 \pm 5^{\circ}$ (c) and B < $1058^{\circ}C$. The temperature of X and Y in the CMAS system were $1238^{\circ}C$ and $1180^{\circ} \pm 9^{\circ}C$ (p. 47) and the thermal divide 'l' is $1222^{\circ}C$. Thus addition of Na_2O to the system CMAS would appear to lower the various solidus temperatures by at least $150^{\circ}C$. The system Na_2O-CMAS is more comparable with natural rocks as Yoder and Tilley (1962, p. 382) found that the melting temperature of a tholeiitic basalt was about $1050^{\circ}C$ (c.f. temperature of eutectic point B,

1058°/

$< 1058^{\circ}$ in the synthetic system). It appears that additions of K_2O, Na_2O and iron would lower temperatures of melting and amend the compositions of the crystal phases which appear but not change them fundamentally. Thus the CMAS model (and flow sheet) which is to be used in interpreting the relations between the Haddo rock groups seems justified. In a ferromagnesian-rich melt at moderate to high pressure if water is present in the melt, biotite might replace K-feldspar as the main potash-bearing phase which appears. It must be emphasised that further proof of the partial melt theory of origin for rock groups can only be acquired by experimentation with the rock groups themselves. This would be attempted by carrying out a series of melting experiments at different P and T conditions on the actual rocks (powders) and examining the charges after each experiment.

N.B. It is important to remember that natural rocks contain far more than 4 components. In the flow sheet given in chapter V, fig. 16, which represents natural rock assemblages at Haddo, the 'points' do not represent invariant equilibria but represent polyvariant equilibria with 1 degree of freedom less than those represented by the lines.

In the system Na_2O-CMAS mentioned above, each invariant 'point' gives rise to a univariant line in the 5-component system thus:



If/

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If iron is also added the phases appearing would be plagioclase, olivine, orthopyroxene and clinopyroxene. In a natural rock flow sheet all this is represented by one 'point' - e.g. X', fig. 16.

CHAPTER III

The Country Rocks

The country rocks will be described under their established headings:

(a) Fyvie Schists

(b) Mormond Hill Quartzites

(c) Ellon Gneisses

(a) 1. The distribution and petrography of the Fyvie sohists.

The Fyvie schists contain both psammitic and pelitic members and are best observed in the valley of the River Ythan to the north-west and south-east of Methlick Village. Loose blocks of schist are also seen at Castlehill, 2 miles north-east of Methlick, and from there south along the western bank of the Burn of Cessnie. At North Newton, over 2 miles ENE of Methlick, Read (1935, p. 602) reported a gabbro/country rock contact visible in a road cutting. Although this contact is no longer visible a number of blocks of schist have been noted at North Newton, a few of which might be in place. East of North Newton, at Skilmafilly Wood, schists occur which were placed in the Mormond Hill quartzites (Read 1952). However these are mainly pelitic and have here been included with the Fyvie schists. About 1 mile south of Methlick an exposure of schist at Back Brainjohn is observed. The above constitute the only exposures of Fyvie schists near the edge of the Haddo House gabbros.

The remaining isolated outcrops situated along the eastern

and/

and southern borders of the Haddo House gabbro belong either to the Mormond Hill quartzites in the east or to the Ellon gneisses in the south. These southern Ellon gneisses constitute part of the 'permeation' gneisses of Haddo (Read 1952).

Apart from the outcrops along the Ythan valley, the exposures of Fyvie schists mentioned above are isolated, small and in many places perhaps not in place; thus for the purposes of their petrology and geochemistry, only the schists from the Ythan valley are described in detail, where a reasonably continuous section is available across the strike of the foliation of the schists.

Rock sampling began at Gight, about 2 miles north-west of Methlick, where the Ythan river, after wending its way in a north-easterly direction, changes direction and flows south-eastwards. It was decided to start there because:

(i) the Fyvie schists at Gight were considered far enough away from the basic mass to be unaffected by thermal effects from the gabbro, even if the gabbro sheet was dipping gently to the north-west.

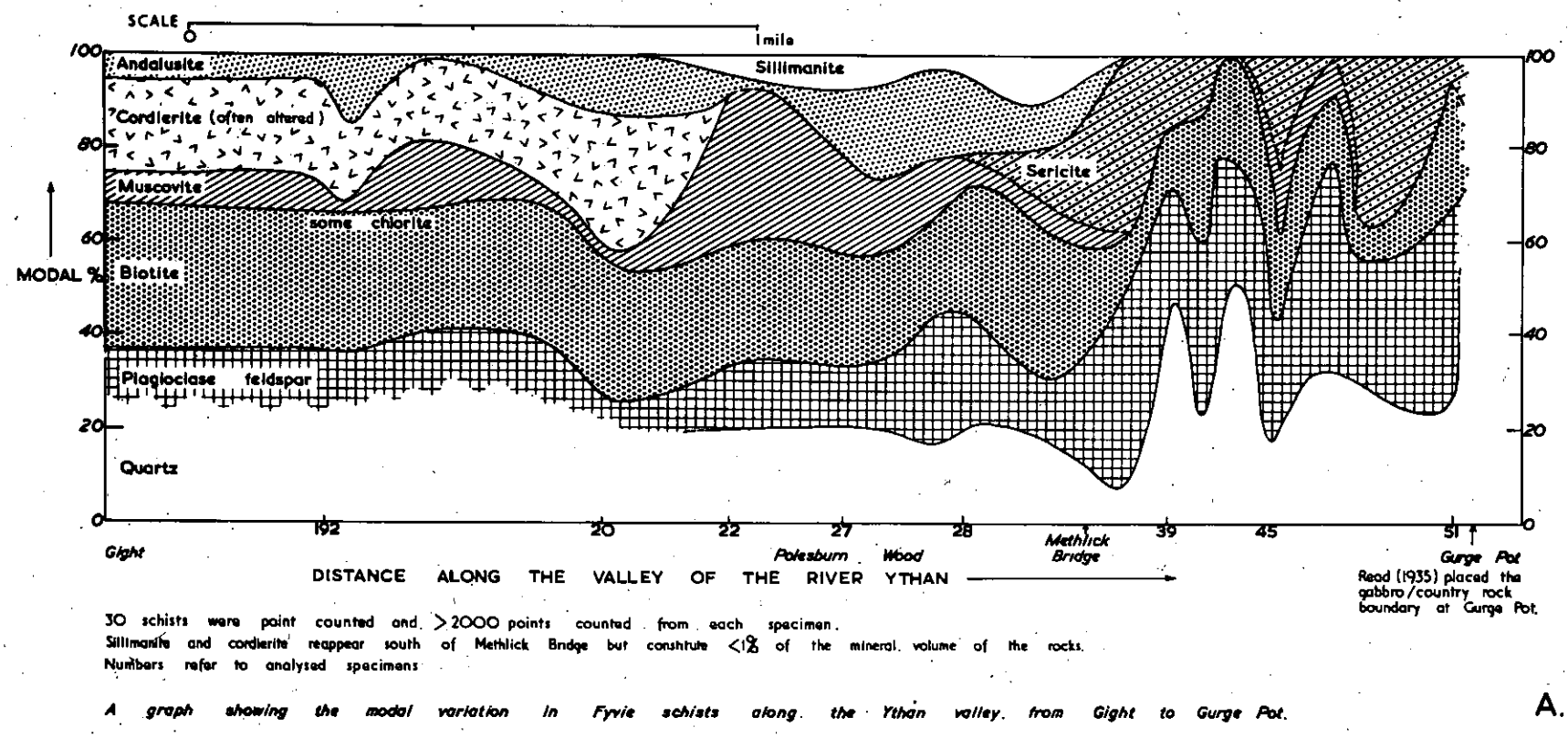
(ii) no exposures exist north-west of Gight, and to continue sampling along the Ythan river west of Gight, where outcrops of schists do occur, would mean sampling almost along the strike of the Fyvie schists, i.e. parallel to the regional metamorphic boundaries.

At Gight, the pelites in the hand specimen are dark grey, micaceous, fine grained rocks with large porphyroblasts of cordierite and andalusite up to 1 cm in length. The strike of the schists/

schists varies from north to 20°E of north, and the dip is steep, 45° or more, and to the west. In thin section a typical pelite contains prismatic andalusite and spongy cordierite porphyroblasts set in a fine grained ground mass of quartz, plagioclase feldspar of oligoclase composition (from optical measurements), and micas. A typical psammite from Gight contains, in thin section, large quartzes and plagioclase feldspars also of oligoclase composition, with minor amounts of mica, garnet and rare potash feldspar. A summary of the general mineralogical changes in the Fyvie schists along the river Ythan is given in the graph, fig. 8A, which is based on the modal percentages of minerals in the schists. In this graph, the accessory minerals occurring in the schists (ores, tourmaline, zircon and apatite) have been omitted.

Going downstream towards Methlick the strike of the schists remains constant but the dip steepens until about 1 mile north-west of Methlick, it is vertical. From the graph, fig. 8A, it is seen that sillimanite of fibrolite variety appears in the pelites in addition to andalusite and cordierite. Just south of this occurence, i.e. towards the gabbro, cordierite disappears from the pelites and seems to be replaced by large muscovite flakes and quartz.

The sillimanite might have been formed from the breakdown of cordierite. This hypothesis is rejected because sillimanite appears in the pelites together with cordierite and andalusite, north of the cordierite disappearance. South of this, the apparent increase of andalusite and sillimanite together in some pelites is probably due/


SCALE
1 mile
Andalusite
Sillimanite
?Cordierite (often altered)
Muscovite
some chlorite
Sericite
Biotite
Plagioclase feldspar
Quartz
MODAL %
100
80
60
40
20
0
192
20
22
27
28
39
45
51
Gight
Polesburn Wood
Methlick Bridge
Gurge Pot
DISTANCE ALONG THE VALLEY OF THE RIVER YTHAN
Read (1935) placed the gabbro/country rock boundary at Gurge Pot.
30 schists were point counted and > 2000 points counted from each specimen.
Sillimanite and cordierite reappear south of Methlick Bridge but constitute <1% of the mineral volume of the rocks.
Numbers refer to analysed specimens
A graph showing the modal variation in Fyvie schists along the Ythan valley, from Gight to Gurge Pot.
A.

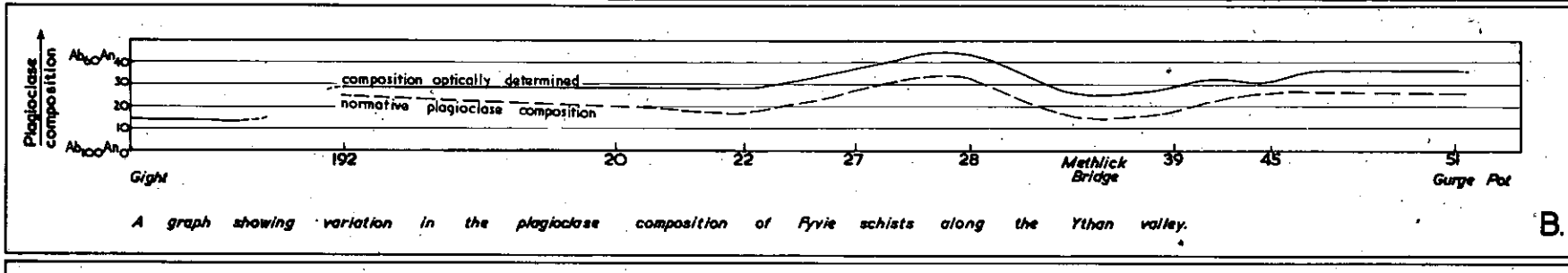

Plagioclase composition
Ab60An40
30
20
10
Ab100An0
composition optically determined
normative plagioclase composition
192
20
22
27
28
39
45
51
Gight
Methlick Bridge
Gurge Pot
A graph showing variation in the plagioclase composition of Fyvie schists along the Ythan valley.
B.

FIG. 8

due to original large alumina contents in the argillites. Chinner (1961) proposed a hypothesis for sillimanite formation which is:

Biotite + dissolved /Andalusite/ ⟶ Biotite + Sillimanite ..... (1)

The biotite acts as nucleating centres for the development of sillimanite. The sillimanite in the Fyvie schists is probably formed in a similar way.

The disappearance of cordierite in the schists about 1 mile north-west of Methlick would seem to have arisen from the hydrothermal break-down of cordierite to give quartz and muscovite as follows:

3 Cordierite + $4H_2O$ + $2K_2O$ ⟶ 4 Muscovite + 3 Quartz + 4(MgFe,O) ..(2)

The white mica was separated from this rock (specimen 22, table 1) and analysed for K_2O only. The K_2O content of the mineral was found to be 10.38% which confirms that the white mica is muscovite.

As these schists do not appear to contain any potash feldspar - a thorough microscopic examination and thin section staining with sodium cobaltinitrite confirmed this - it would seem that a certain degree of potash metasomatism is needed to complete the above reaction. The right-hand side of the above equation would imply a release of iron ore and this is observed in the thin section where knots of muscovite and quartz are often surrounded by veins of haematite.

Since there appears to be a decrease in the amount of biotite in the pelites south of the disappearance of cordierite (see the modal graph fig. 8A) it is possible that biotite could have entered into/

into the reactions. Chinner (1961) gave a possible equation for this as follows:

2 Biotite (Fe rich) $\longrightarrow$ 4 Sillimanite + 10 Quartz + $(H_8K_4O_8Mg_4Fe_5)$..(3)

i.e. $1K_4Mg_4Fe_5Al_8Si_{10}O_{40}(OH)_8 \longrightarrow 4Al_2SiO_5 + 10SiO_2 + H_8K_4O_8Mg_4Fe_5$

but unfortunately the above equation does not balance. In the paper, Chinner (1961) analysed a biotite and found that the Mg/Fe ratio was 4/5, thus the above equation should read:

$K_4(\underline{MgFe})_{10}Al_8(OH)_8Si_{10}O_{40} \longrightarrow 4Al_2SiO_5 + \underline{6}\ SiO_2 + H_8K_4(MgFe)_{10}O_{16}$ ..(3a)

In equation (3a) the Mg/Fe ratio in the biotite will be 4/5, and the equation can be written as follows:

2 Biotite (Fe/Mg = 5/4) $\longrightarrow$ 4 Sillimanite + 6 Quartz + $2K_2O + 4H_2O$ + $10(MgFe)O$ (Fe/Mg = 5/4) ..... (3b)

Alternatively, Francis (1956) put forward another possible equation for the break-down of biotite using the hypothesis of dissolved alumina silicate which Chinner (1961) used (see equation 1) although in Francis' case he envisaged the biotite breaking down and entering into the reaction as follows:

1 Biotite (Fe rich) + dissolved /Andalusite/ $\longrightarrow$ 1 Potash Feldspar + $3FeO + H_2O$ ..... (4)

5 c.c. 2.2 c.c.

From the modal graph it is seen that an average percentage of biotite in/

in the pelites north of the cordierite disappearance is 30% whereas south of this the average percentage is 25% , i.e. there is a decrease of 5% in the biotite volume in the rock. From equation (4) it is seen that 5 c.c. of biotite produce 2.2 c.c. of K-feldspar on breaking down, which contains enough K_2O to form about 3.5 c.c. of muscovite. Thus although 5 c.c. of biotite on breaking down produces enough K_2O for about $3\frac{1}{2}$ c.c. muscovite this is not nearly enough as the muscovite content of the schists increases from 10% north of the cordierite disappearance to about 30% when cordierite is gone. Thus equation (2) appears the most important reaction in this case.

It could be argued that because of the lack of exposures along the river Ythan, it is impossible to provide evidence that the original rock from which cordierite disappears could have had much more biotite than any other schist examined i.e. $>$ 30%, and the decrease in biotite amount would be much greater than 5%. On breaking down, enough K_2O would be released to produce a large amount of muscovite. However, if this is so, it would entail a large release of iron from the biotite break-down and this is <u>not</u> apparent from either thin section examination or the analysis of this pelite (no. 22 table1) which shows no large difference in total iron content from the other schists of the Ythan valley.

In many of the andalusite schists along the Ythan valley, from Gight to where there is no cordierite, the porphyroblasts of cordierite are often seen altering to chloritic minerals probably in/

in the manner suggested by Schreyer and Yoder (1964) as follows:

$$2 \text{ Cordierite} + 6H_2O \longrightarrow 1 \text{ Chlorite} + 2 \text{ Pyrophyllite} \quad \ldots\ldots (5)$$

Although this is a low temperature reaction at pressures of less than 5Kb(P_{H_2O}), cordierite can break down at high pressure (P_{H_2O} = 10Kb) and high temperatures to give chlorite and metastable quartz and corundum (the metastable quartz and corundum together give sillimanite). However, as the amount of chlorite is rather small in most of the pelites in the vicinity of Methlick village; and since the schists could not have been at 10Kb pressure as they contain andalusite (at 10Kb kyanite would have replaced andalusite as the main alumino-silicate phase present), this possible source of sillimanite is discounted. Thus to summarise what has been written:

(1) Although part of the sillimanite could be derived from a break-down of biotite with release of potash feldspar, the majority of the sillimanite must have formed at the expense of andalusite as in equation (1).

(2) Although part of the potash required to form muscovite when corierite disappears could be derived from break-down of biotite, giving K-feldspar and iron ore, an examination of the amounts of biotite present in pelites, with and without cordierite present, show that insufficient k-feldspar could be produced by this means to form enough muscovite. The amount of iron ore present in the rocks after cordierite has completely gone would indicate that only a small amount of biotite has broken down.

There could be some potash feldspar present in unexposed

.../

pelites, as the outcrops along the Ythan which were examined, only constitute a minute percentage of the area of the country underlain by the Fyvie schists. However this is impossible to prove and the available evidence seems to point to there being some potash metasomatism in the pelites, accompanying a hydrothermal action which led to the substitution of quartz and muscovite for the cordierite (see equation 2).

About 1 mile north-west of Methlick the grain size in the pelites is first seen to increase and the feldspar gets more calcic, increasing to An_{25+} from approximately An_{10} at Gight. Over ½ mile north-west of Methlick at Polesburn Wood the plagioclase is zoned to An_{40}(core). A graph of plagioclase composition plotted against distance along the river Ythan from Gight is given in fig. 8B. The plagioclase composition becomes more calcic towards the village of Methlick i.e. towards the gabbro contact. This increase from oligoclase to andesine seems due to relative increases in the CaO/Na_2O ratio in the pelites between Gight and Methlick (see analyses table). These changes in plagioclase compositions (determined optically) are also reflected in the normative plagioclase composition, see also fig. 8B. The psammites show similar changes in their plagioclase compositions along the Ythan river section.

At Methlick the pelites are medium grained and remain so up to the gabbro contact. The strike of the foliation is the same as at Gight (i.e. east of north) and the dip either extremely steep to the west, or vertical, but difficult to measure as the foliation is not well developed.

Large prismatic crystals of sillimanite are noted enclosed and developing within large broken porphyroblasts of andalusite. It was observed that these two alumino-silicate minerals had their c crystallographic axes directions parallel. In this instance the equation proposed by Chinner (1961) for sillimanite formation given previously in this chapter as:

Biotite + dissolved /Andalusite/ ⟶ Biotite + Sillimanite

did not seem to hold true as there appeared to be no biotite present. However, the andalusite porphyroblasts almost always contain small flakes of biotite and these could act as nucleating centres for the growth of the large sillimanite crystals. Cordierite re-appears at Methlick but it is as small clear crystals with pleochroic haloes and rare inclusions - quite different from the very large spongy porphyroblasts of cordierite in the schists at Gight. Plate 1a gives a detailed view of the schists at Methlick bridge showing their foliation which is not as well developed at Methlick as at Gight (see plate 1b).

South of Methlick bridge the foliation of the pelites becomes much more irregular. In thin section the quartz grains are strained and develop irregular contact boundaries, or sutures, with each other. The andalusite and sillimanite crystals no longer have a prismatic outline but are broken up, although the small crystals so formed may still remain in optical continuity. Many of the minerals have been altered to micaceous products and some of this alteration could be/

be due to hydrothermal action at the time of the emplacement of the 'Newer Granites', as the Auchedly granite within the main Haddo House gabbro and many small granitic or felsitic intrusions are seen to occur in the area. These are post-gabbro intrusions (Read 1935, p. 634). At this point about ¼ mile south-east of Methlick bridge no further exposures exist for more than ½ mile. Although many blocks of country rock are seen in this area, none of these are demonstrably in place.

Just over ½ mile south-east of Methlick, about 400 yards from the Ythan river and well above it, outcrops of country rocks again occur. The area here is heathland and the outcrops appear as isolated rocky knolls surrounded by many loose boulders, see plate 2a. In hand specimen the rocks appear gneissose in character and lenses and pods of micaceous material can be seen squeezed and drawn out between more competent bands of quartzo-feldspathic material (plates 2b and 3a). In thin section the replacement of minerals by alteration products especially feldspars and micas (biotites) is seen to have increased and more than half the mineral constituents of some of the incompetent bands is sericite and other alteration products.

The presence of ferrous iron in biotite facilitates alteration by H_2S to yield pyrite and other sulphides (Schwartz, 1958; Kullerud and Yoder, 1964) and pyrite commonly occurs within these 'mobile' micaceous bands. Oligoclase/andesine feldspar grains are sometimes seen in streaked out bands of micaceous alteration products but these/

these feldspar crystals are usually small and altering at the edges. Wherever found, quartz crystals show undulose extinction. If the quartzo-feldspathic bands are thin the feldspar and micas are completely altered, whereas if these bands are broad, the feldspars and micas are less altered and some plagioclase crystals exhibit undulose extinction. Usually the fine albite twin lamellae are gently curved. All the alumino-silicate minerals in the rocks have disappeared and the gneissose country rocks consist of competent and incompetent bands which behave in an irregular fashion as in plate 2b. In these country rocks apart from the undulose extinction of the quartz grains which might be caused by very small pressure differences there is very little sign of directed pressure effects in these gneisses. There is only a vague foliation noticeable as can be seen from the previous plates. The incompetent bands rarely show alignment, the structure and banding in these rocks appearing rather randomly orientated. In the same area, at Gurge Pot on the river Ythan, occurs a small country rock outcrop which is mainly quartzitic and resembles that seen in plate 2b.

Finally, about $\frac{8}{5}$ miles south-east of Methlick, west of the Bellmuir area, a few small isolated outcrops occur. The rocks are seen to be xenolithic gneisses with xenoliths of quartzitic and micaceous pelitic material, often subangular and completely enclosed in a quartzo-feldspathic matrix material, see plate 3b. No. b. exposures occur further to the south-east, in the Bellmuir district.

In thin section a specimen of this xenolithic gneiss shows large crystals of subhedral andesine with quartz, both granular and interstitial/

interstitial, often completely surrounding feldspar crystals. Biotite laths are also present but are frequently altered along cleavages to chlorite. There minerals form a matrix which surrounds the inclusions. The xenoliths in this gneiss are almost always intensely altered to sericite and chlorite with release of iron, which forms numerous ore grains within them. Most of the xenoliths are similar in composition to those incompetent bands already described from the nearby gneissose rocks, although the feldspar is more basic, occasionally zoned to An_{50}. One small much altered xenolith shows development of a pleochroic amphibole (α pale yellow, β , γ green) which could be secondary after some ferromagnesian mineral. Another xenolith which contains epidote was observed, and this may represent further retrograde alteration of the ferromagnesian minerals originally in the xenolith. The Haddo House gabbros in this area, which are on the periphery of the gabbroic suite, are extensively uralitised and show "the production of a post-magmatic amphibole, associated in the last stages with chlorite, epidote and sericite" (Read, 1935, p. 604); and these xenolithic gneisses, close to the gabbro/country rock boundary, exhibit similar hydrothermal alteration of minerals. The highly altered nature of the xenoliths makes it difficult to determine whether their mineral assemblages could have higher melting points, than the mineral assemblage of the surrounding matrix. However, the xenoliths contain quite basic plagioclase (An_{40} to An_{50}), and ferromagnesian minerals (hornblende, epidote) which may be alteration products from other minerals (? pyroxenes). Thus it

is/

is probable that the mineral assemblages of the xenoliths represent higher temperature assemblages than the mineral assemblages of the surrounding matrices. These gneisses are similar to the Haddo permeation gneisses of Read (1952) which will be described in section c of this chapter. Thus the Ythan valley shows a transition from Fyvie schists at Gight into migmatitic and xenolith-bearing gneisses south of Methlick, near the gabbroic suite of Haddo.

Two further outcrops of country rock occur within the area occupied by the Haddo House gabbro suite of Read (1935). At Forester's Bridge, 1½ miles south of Methlick, a group of rocks occur which are undoubtedly country rocks, although original mapping showed these as gabbroic (Read 1935, p. 594, outcrop marked with a cross just north of North lodge, on the south bank of the Ythan river). Also at Gillha Wood in the Haddo House policies, ½ mile north of Haddo House, there is a large outcrop of impure quartzite.

Three possibilities to explain these two occurences can be put forward; they may be:

(i) rafts of original country rock caught up in the roof of the gabbro mass.

(ii) part of an irregular roof of country rocks.

(iii) alternatively the gabbro boundary, which is mapped in Read (1935) as running from Gurgedyke east to Bellmuir and SSW to Brainjohn, is wrong, and Gillha Wood and Forester's Bridge lie on the country rock side of the boundary (see district map).

However/

However, in 1935 many more gabbro outcrops must have been present, as witness the large number of outcrops marked in the Bellmuir district by Read (1935, p. 594) although these can no longer be found. Therefore theory (i) or (ii) is probably correct although any of the three hypotheses could be correct on the available evidence.

The hornfelsed country rocks at Forester's Bridge have bands which contain large poikilitic, highly pleochroic (pink to blue-green) hypersthenes, unobserved elsewhere in the Fyvie schists. Cordierite is common, occuring as small, relatively unaltered crystals with no inclusions. Andesine plagioclase and quartz also appear.

The Ythan section has shown evidence of a quartz, andalusite, cordierite, albite/oligoclase feldspar assemblage changing to a quartz, sillimanite, andesine feldspar assemblage at Methlick (the disappearance of cordierite from these schists is discussed fully on pp.56-60). These metamorphic assemblages belong to the hornblende hornfels facies (Fyfe, Turner and Verhoogen, 1958, p. 205) and demonstrate essentially thermal metamorphic assemblages occuring on a regional scale. Johnson (1962, 1963) demonstrated, with his work on the pelites of the Banffshire coast equivalent in age to the Fyvie schists, that these metamorphic assemblages were produced on a regional scale <u>before</u> the intrusion of the gabbroic sheet. It is important to record that all the different stages of progressive metamorphism seen in the Fyvie schists - andalusite-cordierite-schists, sillimanite-schists and migmatitic gneisses - were placed by Fyfe et al. (1958) in the hornblende hornfels facies and perhaps, at the highest grades, transitional to the almandine amphibolite facies. The migmatitic gneisses/

gneisses above, mentioned by Fyfe et al. (1958) are the Arnage gneisses of Read (1923a) and not the gneisses south of Methlick bridge which Read (1952, p. 267) mapped as part of the normal andalusite-cordierite Fyvie schists. However, the occurence at Forester's Bridge of a quartz-hypersthene-cordierite-andesine assemblage, in spite of the fact that this rock is of a different bulk composition to the 'normal' pelitic schists of the Ythan valley, would indicate that its metamorphic assemblage is of pyroxene-hornfels facies. This is very near the gabbro contact. Proof of the high temperatures attained within the gabbro's aureole is provided by large prismatic sillimanite crystals developing within the andalusite crystals at Methlick (see page 61). This sillimanite is analogous to that produced in the country rocks within the thermal aureole of the Ross of Mull granite (Bosworth, 1910). The re-appearance at Methlick of fresh cordierite after the regional cordierite had disappeared from the pelitic mineral assemblages about ½ mile north of Methlick (see p. 56) is also proof of high temperatures attained within the aureole. The presence of these minerals at Methlick, ½ mile from the country rock/gabbro boundary of Read (1935), would imply that even higher temperatures would be attained between Methlick and the gabbro contact. It has been stated how the schists gradually lost their regular foliation as the gabbro was approached and became more gneissose in character, with bands of pelitic material squeezed and drawn out between competent bands of quartzo-feldspathic material; and with finally a xenolithic gneiss appearing closest to the gabbro/country rock/

rock boundary (pp.62-65, Plates 2a-3b). It is therefore possible that, in the Ythan section immediately south of Methlick, temperatures high enough to mobilise the country rocks could have been reached and the available field evidence would agree with this hypothesis, this mobilisation being directly due to heat from the gabbro.

The disappearance of cordierite from the schists 1 mile north-west of Methlick was fully discussed earlier in this chapter. The available evidence seemed to point to a hydrothermal break down of cordierite in the schists, accompanied by a potash metasomatism, producing knots of quartz and muscovite. It is possible that heat from the gabbro could have been directly responsible for these events by producing:

(a) a dehydration effect in the country rocks nearest the gabbro with water being driven outwards into country rocks further away from the basic body

(b) an alkali diffusion from the rocks nearest the gabbro outwards from the gabbro

(a) and (b) above will be discussed in the part of this chapter dealing with the geochemistry of the schists (p. 73). The presence of sillimanite indicative of inner zones of thermal aureoles at Methlick, 1 mile north of the gabbro boundary, would suggest that the gabbro/country rock contact is not steep, but in fact dips very shallowly to the west and north-west. Some of the hydrous solutions released in the country rocks surrounding the gabbro could also have been 'soaked up' by the basic mass itself, producing the uralitisation of pyroxenes which is most common in the peripheral gabbro.

(a)/

TABLE 1

Rock type	Fyvie schists (pelites)						
	Gight	1 mile North of Methlick			Methlick		near Gabbro
	841392	845386	847383	852379	859374	864371	864367
Rock No.	192	20	22	28	39	45	51
SiO_2	60.36	56.76	53.16	55.32	55.46	51.45	67.15
TiO_2	1.18	1.26	1.08	0.94	1.05	0.98	0.69
Al_2O_3	19.18	20.51	21.63	22.09	22.39	22.69	15.30
Fe_2O_3	1.25	1.57	2.36	1.45	1.25	2.00	1220
FeO	5.72	6.98	6.36	6.36	5.49	5.82	3.92
MnO	0.12	0.11	0.078	0.14	0.12	0.12	0.08
MgO	2.51	3.37	3.52	2.79	2.97	3.05	1.91
CaO	1.54	1.22	0.88	1.21	1.49	2.85	1.45
Na_2O	2.41	2.20	1.92	1.58	3.94	2.87	2.46
K_2O	3.08	3.88	4.94	3.66	2.51	3.56	2.92
H_2O+	2.31	1.83	3.50	2.90	2.16	3.04	1.80
P_2O_5	0.16	0.16	0.26	0.10	0.14	1.02	0.12
TOTAL	99.89	99.85	99.86	98.55*	98.97*	99.45	99.00

All analyses carried out by author on material dried at 110°C for 2 hrs. *(28 & 39) both contain sulphur and carbon in addition to above.

Trace elements							
Cr	145	153	171	122	160	158	111
Ba	915	1210	1340	1225	550	770	1000
Rb	108	102	165	140	78	120	81
Sr	255	176	132	165	255	239	171
Oxidation Ratios (see p.74)	16.4	16.8	25.0	17.0	16.5	23.6	21.6

Eskola Norms (based on 1-cation percentages, see appendix D)							
Orthoclase	18.95	23.00	30.55	22.90	15.20	21.85	18.10
Albite	22.50	19.80	18.00	15.05	36.30	26.75	23.15
Anorthite	6.95	5.20	2.90	5.75	6.75	8.45	6.80
Orthopyroxene	13.08	16.36	15.88	15.30	14.04	14.00	9.28
Quartz	23.95	19.56	13.27	21.59	12.07	9.94	33.11
Corundum	10.71	11.81	13.83	15.67	12.07	12.62	6.55
Magnetite	1.82	2.20	3.44	2.14	1.80	2.88	1.76
Ilmenite	1.72	1.76	1.58	1.40	1.50	1.42	1.00
Apatite	0.33	0.30	0.55	0.20	0.28	2.08	0.25

TABLE 1 contd.

Rock types	Fyvie schists		Macduff Slates		Mormond Hill	Ellon	gneiss
	Psammites		Banff	Foudland	Quartzite	Pelite	Psammite
Rock no.	16 842391	27 851381	(1)	(2)	280 915329	164 946308	340 947306
SiO_2	79.78	72.30	58.47	56.50	81.38	57.75	75.51
TiO_2	0.54	0.59	1.30	nd.	0.79	0.99	0.51
Al_2O_3	9.57	13.62	18.27	23.14	7.80	19.55	11.84
Fe_2O_3	0.46	0.58	1.66	nd.	0.89	1.53	0.78
FeO	2.03	3.08	6.49	10.37	1.78	5.97	2.38
MnO	0.051	0.061	0.25	nd.	0.023	0.077	0.049
MgO	1.10	1.59	2.64	1.33	0.44	3.21	1.33
CaO	1.01	1.95	0.78	0.45	0.29	1.57	1.60
Na_2O	3.48	3.54	2.46	1.17	0.79	2.97	2.61
K_2O	1.06	0.98	2.84	2.38	4.47	4.95	1.71
H_2O+	0.38	0.74	3.37	3.92(inc.H_2O-)	0.64	1.83	0.97
P_2O_5	0.086	0.052	0.15	0.18	0.043	0.068	0.041
TOTAL	99.55	99.08	98.68	99.44	99.33	100.47	99.33

All analyses carried out by author on material dried at 110°C for 2 hrs. Analyses (1) and (2) above from Read (1923b, p.64 noX; 1935, p.595, no. 3)

Trace elements

Cr	102	127	-	-	83	126	105
Ba	310	550	-	-	725	2210	380
Rb	33	32	-	-	88	121	61
Sr	187	331	-	-	123	226	175
Oxidation Ratios	16.9	14.5					

Eskola Norms

Orthoclase	6.45	6.00			28.05	29.70	10.55
Albite	32.30	32.85			7.55	27.05	24.45
Anorthite	4.65	9.70			1.25	7.45	8.00
Orthopyroxene	5.04	7.08			1.76	14.96	5.88
Quartz	48.78	38.07			57.37	9.79	45.87
Corundum	1.19	3.71			1.43	7.34	3.29
Magnetite	0.66	0.84			1.32	2.16	1.14
Ilmenite	0.78	0.86			1.18	1.40	0.74
Apatite	0.18	0.10			0.10	0.15	0.10

(a) 2. The Geochemistry of the Fyvie schists.

Silica as SiO_2

There is a random variation in SiO_2 content in the pelites of the Ythan valley (table 1) which is probably due to these pelites containing varying amounts of interbedded psammitic material.

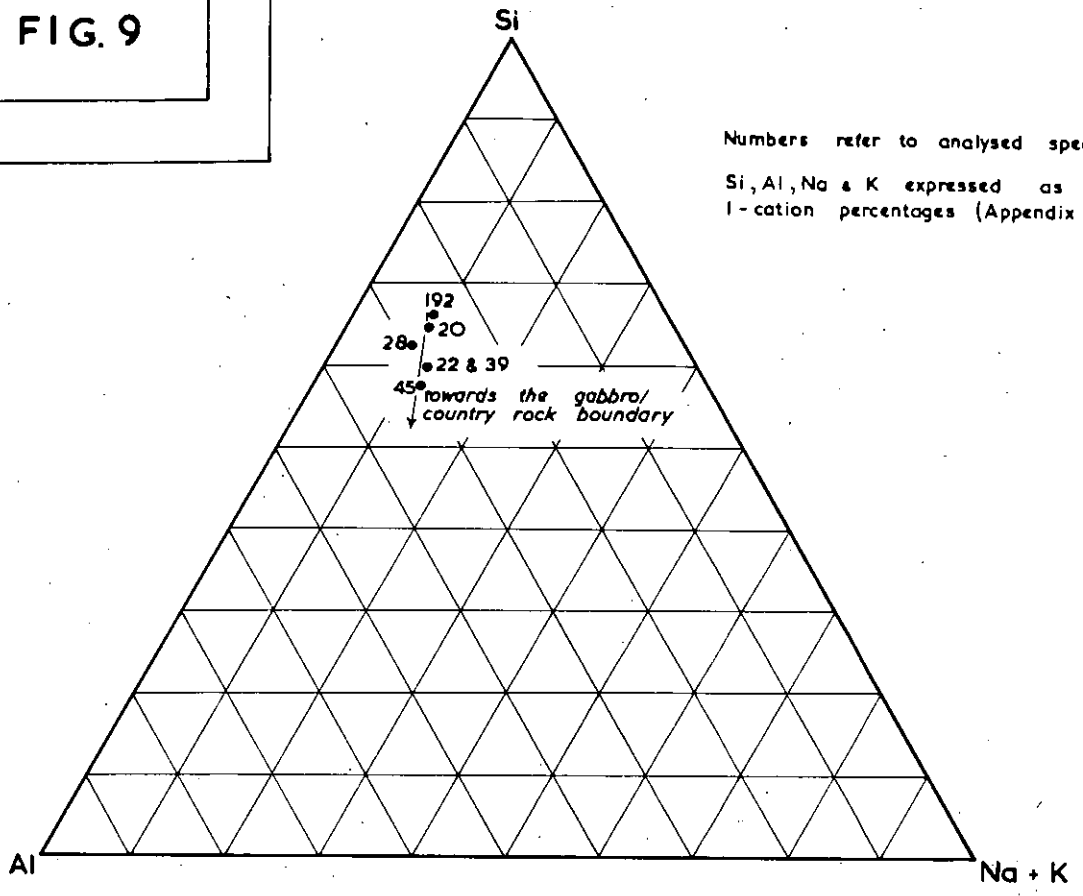
Aluminium as Al_2O_3

The pelites might show an increase in Al_2O_3 content as the gabbro/country rock boundary is approached. The available analyses of pelites were re-calculated to one-cation percentages, so that H_2O+ could be removed from each rock, and incidentally, so that Eskola norms could be calculated. A complete list of 1-cation percentages is found in appendix D at the end of this thesis. The Si, Al and Na + K, have been plotted against each other in triangular diagram fig. 9A. This shows that although there appears to be a slight increase in the aluminium content of a pelite with respect to Si and Na + K towards the gabbro, the increase is so slight that real proof of this (increase) would require many more analyses of pelitic material from the Ythan valley. It is interesting to note that the hornfelsed Macduff slates (table 1, Macduff slate analysis No. 2) actually found within the thermal aureole of the Insch gabbro shows an increase in alumina compared to the average Al_2O_3 content of a Macduff slate (analysis 1, table 1).

Iron, Magnesium (Manganese, and Chromium) as FeO, MgO, MnO and Cr.

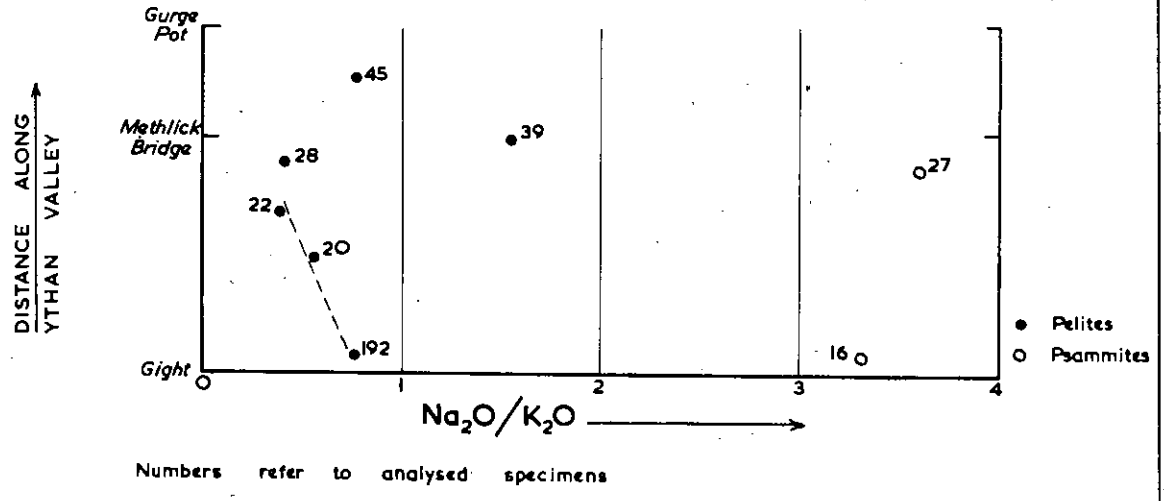
FeO and MgO vary greatly in the schists although the FeO/FeO + MgO ratio for all the pelites in the Ythan valley remains between .69 and/

FIG. 9



A triangular diagram showing an apparent slight increase of Al in pelites towards the gabbro/country rock boundary.

A.



Variation in the ratio Na_2O/K_2O in the Fyvie schists of the Ythan valley

B.

and .64 showing that a schist with a high iron content will also have a correspondingly high magnesium content. This could imply that the iron and magnesium were carried in a single phase of the argillite such as a chlorite. Occasional lenses rich in biotite and garnet are observed in the schists at Gight thus implying that specific bands within the pelites can be far richer in iron and magnesium than any of the pelites analysed in table 1. Chromium (and manganese) show little variation although chromium is greatest in these pelites with greatest amounts of MgO.

Titanium as TiO_2

The schists show little variation in titanium.

Phosphorus as P_2O_5

The schists show minor variations in P_2O_5 content except for analysis 45 table 1 which contains over 1% P_2O_5. This large phosphorus amount is perhaps due to a large local amount of apatite in the sediments before metamorphism took place, and is reflected in the mineralogy of the pelite which contains much apatite.

Calcium as CaO

A little variation is displayed in the schists, the relative amount of CaO with respect to Na_2O increases towards Methlick bridge, and this could be due to compositional differences in the original argillities.

Alkalis (Sodium and Potassium)

There is a great difference between the Na_2O/K_2O ratios for pelites and psammites with this ratio also varying in the pelites themselves/

themselves, north and south of Methlick village. As is shown in fig. 9B the ratios decrease in the pelites from Na_2O/K_2O about 0.8 at Gight to a 'low' value about 1 mile north of Methlick where the value is about 0.4, that is the pelites have more than twice as much K_2O as Na_2O. Between Methlick and the gabbro/country rock contact the ratio rises to roughly the same as at Gight. Specimen 39, which has a very high Na_2O/K_2O ratio is quite quartzose and could be grouped with specimens 16 and 27 (psammites) as well as with the pelitic ones. The ratio of soda to potash in the two psammites is represented in fig. 9B and shows a very high Na_2O/K_2O ratio (more than three times more soda than potash).

The increase in amount of soda in the country rocks analysed south of Methlick would agree with these rocks being mobilised gneisses (p. 65) with both psammitic and pelitic members of the Fyvie schists contributing to their composition.

Strontium as Sr

The strontium content in the Fyvie schists varies greatly, and although it appears unrelated to either the calcium, sodium or potassium contents of the schists it might be related to the plagioclase composition. From the norms, table 1, it can be seen that the schists with the most calcic normative plagioclase, and lowest amount of normative orthoclase have the highest Sr contents (e.g. 192, 39, 27).

Barium and Rubidium as Ba and Rb

Barium and rubidium increase in amount with increasing potash content. Thus pelite no. 22 which has the greatest amount of K_2O also/

also has the greatest amounts of Ba and Rb. The psammites are quite low in Ba and very low in Rb. Ba and Rb would appear to be held in the mica structures especially muscovite as the psammities are low in muscovite. Barium is greater in amount in the Fyvie schists (0.1%) than in usual pelites (0.05%), and the pelitic Ellon gneisses contain even greater amounts of barium, 0.22%, (analysis 164, table 1).

Water as H_2O+

The pelites are reasonably rich in combined water although the pelites and gneisses at Methlick have less H_2O+ than the pelites north of Methlick, with the pelite in which the regional cordierite was replaced by muscovite and quartz having most water of all. (analysis no. 22 table 1).

From the geochemical data the following points have emerged:

(i) the schists (and gneisses) south of Methlick i.e. going towards the gabbro, are lower in water and potash than any of the other pelites.

(ii) the pelite in which muscovite and quartz replaces the regional cordierite (no. 22 in the analyses table) is richer in water and potash than any of the other pelites.

(iii) the alkali content of the gneisses south of Methlick is consistent with their being formed by a mobilisation of both the pelitic and psammitic members of the Fyvie schists.

(iv) there might be an increase in alumina content in the pelite towards the gabbro.

The above points would confirm many of the hypotheses regarding the/

the thermal effects of the gabbro on the country rock that were put forward after an examination of the Fyvie schist petrography (pp. 67-68). The heat from the gabbro produced a dehydration in the country rocks nearest the basic mass, with the outgoing hydrous solutions producing the alteration of the cordierite discussed in this chapter.

It is also possible that these hydrous solutions carried some alkalis (particularly potash) producing the potash enrichment seen in rock 22, or alternatively there was some alkali diffusion in the schists.

However such an alkali diffusion is impossible to prove in this area because:

(a) not enough rocks were analysed,

(b) insufficient exposures of country rocks are available,

(c) the proportion of pelitic members to psammitic members in the Fyvie schists is not known,

(d) the chemical variations in the original sedimentary rocks is also unknown.

The observations of Pitcher and Sinha (1957) describing the petrochemistry of the Ardara aureole in Northern Ireland are worth recalling here. In an area with good rock exposures, a granodiorite could be seen intruded into pelitic rocks with other subordinate members. A series of sample traverses were taken in these schists, outwards from the pluton at regular intervals, and their petrological and geochemical data investigated.

Pitcher and Sinha reported that as the pluton was approached sillimanite replaced biotite, and then muscovite replaced both sillimanite/

sillimanite and biotite. There was also a steady decrease in the H_2O content of the country rocks.

They concluded that although the replacement of biotite and sillimanite by muscovite suggested that there is an increase in potassium towards the contact ... "the role of this element is far from simple ..." Because it was impossible to detect limited migration of material during thermal metamorphism and metasomatism, Pitcher and Sinha (1957) stated that contact metamorphism involved a dehydration but was otherwise isochemical. They further stated that it was essential to possess knowledge of the original sedimentary chemical variation of rocks before a petrochemical study of their metamorphic derivatives could be undertaken.

Finally it will be seen from table 1 that the oxidation ratios from the analysed Fyvie schists have been calculated.

This oxidation ratio was given by Chinner (1960) as equal to:

$$\text{mol} \quad \frac{2Fe_2O_3}{2Fe_2O_3 + FeO} \quad x \quad \frac{100}{1}$$

Chinner (1960) showed that during regional metamorphism rocks appear to behave as narrowly defined units closed to oxygen, the oxygen partial pressure in each unit being determined by the mineral assemblage rather than being externally imposed. Within any area of metamorphic rocks individual rock layers which have widely differing oxidation ratios can be found intimately interbedded. In Glen Clova, Chinner/

Chinner (1960) showed that regional metamorphic rocks had oxidation ratios varying from 6 to 75. Chinner showed that a thermal metamorphic environment is generally open to oxygen, due partly to greater mobility of water within the aureole.

The oxidation ratios in the pelites of the Ythan valley cover a very narrow range (between 16 and 25) and these values would only appear to demonstrate that the pelites of the Ythan valley are quite similar mineralogically and chemically.

(b) Mormond Hill Quartzites.

These occur in the eastern border of the Haddo House mass as isolated outcrops at Quarrybrae of Auchedly and Shallowplough, to the south and north of the River Ythan, about half way between Methlick and Ellon town. The Mormond Hill Quartzites occupy a narrow strip of land running north-south between the Haddo gabbros and the gneisses of the Arnage group which Read (1952, p. 270) described as "a narrow tongue /of country rock/ in a hornfelsed condition."

In hand specimen the quartzites are seen to be rather impure and contain many pelitic layers. Limestones appear within the quartzite group occuring as small bands which have often been quarried in the past.

In thin section the quartzites are medium to fine grained and consist of large grains of quartz and potash feldspar, up to 2 mm. long, with subsidiary oligoclase feldspar, biotite (chloritised), muscovite, iron ore and rare garnets. The more pelitic quartzites contain/

contain cordierite presumably because they occur within the aureole of the Haddo gabbro. Read (1923a p. 449) described a quartzite from the type locality i.e. Mormond Hill far from the basic masses, which does not contain any cordierite or garnet.

The mineralogy of these quartzites reflects their chemical composition sample no. 280, table 1. It is of interest to note that the Mormond Hill quartzite contains about 5 times more potash than soda. This is quite different from the psammitic members of the Fyvie schists (samples 16 and 27, table 1) which had more than three times more soda than potash.

At Auchreddie, 1 mile north of Shallowplough, a quartzite outcrop occurs. In hand specimen large garnets are seen to have developed. In thin section this rock contains plagioclase of andesine composition usually zoned from An_{30} (edge) to An_{40} (core), quartz grains and with occasional large poikilitic garnets developed. Certain bands show development of clear sector-twinned cordierite and large muscovite laths. Prisms of sillimanite can be seen developing within large pleochroic crystals of andalusite. The pleochroism of the andalusite is α pale rose-red, β , γ almost colourless. The development of sillimanite here resembles its development in the schists at Methlick bridge (p. 61) and hence the rock must be of a similar metamorphic grade as the schists at Methlick.

Two of the limestone bands found in the quartzites which occur at Shallowplough are easily recognised in the field as two deep gouges in a hillside - the remains of previous limestone workings.

Read (1923a) examined one of these limestones from a location west/

west of Auchnagatt station and found it contained large grains of calcite with subordinate quartz, alkali feldspar, pyroxene, and some apatite and magnetite. This is an indication of the regional metamorphic grade in the Mormond Hill Quartzites. Bowen (1940) drew up a series of 13 reactions for the progressive metamorphism of siliceous dolomites and limestones. The reaction:

$$16CaCo_3 + 7SiO_2 \quad = \quad 7CaSiO_3 + 9CaCO_3 + 7CO_2$$

Calcite Wollastonite

corresponds to step 6 in Bowen's series. This relation may be expressed graphically by a pressure - temperature curve:

$$CaCO_3 + SiO_2 \quad = \quad CaSiO_3 + CO_2$$

This curve corresponds to the high temperature boundary of the hornblende hornfels facies (Turner and Verhoogen, 1960) and this curve represents the maximum temperature and pressure, at which quartz - calcite assemblages can exist. Since the Fyvie schists of the Ythan valley were shown to be of hornblende hornfels facies, the Mormond Hill quartzites must also be of the same metamorphic grade. In slice the limestone bands from Shallowplough vary from fine to medium grain and have diopside as the primary mineral in the rock. Because of the impure nature of the original limestone (Read, 1923a, described it as "an impure sandy limestone.") other minerals are present. The grossular variety of garnet and basic plagioclase feldspar are seen; quartz, pale-brown pleochroic mica (? phlogopite/

(? phlogopite) and sericitic products probably from altered feldspar crystals also occur. The limestone bands lie close to the Haddo gabbro and thus have been thermally metamorphosed, with the mineral assemblage representing a high thermal metamorphic grade (pyroxene-hornfels facies; Turner and Verhoogen, 1960).

(c) Ellon gneisses.

The country rocks which border the gabbros of the Haddo House district in the south are the Ellon gneisses. Similar gneisses, often with subordinate hornblende-schists also border the xenolith-bearing Arnage rocks to their south and east. The usual Ellon gneiss is a brownish, micaceous rock in hand specimen with large crystals of quartz and plagioclase feldspar visible. In thin section the the main constituents are oligoclase feldspar, biotite, quartz and cordierite with either plagioclase (and biotite), or quartz, dominant depending on whether the gneiss is pelitic (no. 164, table 1) or psammitic (no. 340, table 1). Both the analysed Ellon gneisses, 164 and 340 come from outcrops near the town of Ellon - the type locality of the Ellon gneiss.

To the south of the Haddo district the Ellon gneisses are best exposed near Keithfield Lodge, and in Raxton Wood. In Raxton Wood scarce outcrops are found along the banks of Raxton burn (see district map). These outcrops usually show typical quartz-biotite-cordierite gneisses with occasional porphyroblasts of garnet visible. In thin section sillimanite is seen to be present, increasing in amount as the gabbroic rocks are approached to the north. About ½ mile from/

from the gabbro/country rock boundary (Read, 1935, p. 594), the last outcrop of country rock is seen, a coarse-grained gneiss with bands of micaceous (pelitic material) squeezed, and drawn out between more competent bands of quartzo-feldspathic material. These gneisses closely resemble the gneissose Fyvie schists, south of Methlick near the river Ythan. Read (1952, p. 272) described gneisses near the southern gabbro/country rock boundary as ... "a group of gneisses that ... have been produced by feldspathisation of normal /country/ rocks ...", and designated these the Haddo 'permeation gneisses.' Read (1952) also stated that gradual transitions from normal country rock into permeation gneiss could be observed and finally an enclave-bearing gneiss appeared which he had described in an earlier paper as ... "rocks ... belonging to the Ellon series show a structure that can be intepreted only as xenolithic". (Read, 1935, p. 598) Although these outcrops were not found by the author, there would appear to be some similarity close to the gabbro between the Ellon gneisses to the south of the Haddo basic mass, and the Fyvie schists to the west of the mass. In both areas typical members of each country rock group pass into gneissose rocks, with incompetent material 'squeezed' between competent, quartzo-feldspathic bands, and finally xenolithic gneisses appear close to the gabbro/country rock boundary.

Chemically the typical Ellon gneisses (164 and 340) resemble the pelitic and psammitic members of the Fyvie schists. The pelites are potash rich and the more psammitic types (340) soda rich. It is interesting to note the large amount of barium in the pelitic Ellon gneisses (0.22%, no. 164).

Table 2

READ 1923a	GRIBBLE 1965	READ 1935
ARNAGE	HADDO & ARNAGE	HADDO
Norite	Olivine – hypersthene – gabbro	Olivine – gabbro
	Quartz-hypersthene-gabbro (including uralitised quartz-hypersthene-gabbro)	Quartz – gabbro (including 'end-stage' derivatives)
		Quartz – biotite – norite (including 'end-stage' derivatives)
Gabbro type	Quartz-cordierite-norite ± K-feldspar ± garnet	Cordierite – norite and Cordierite – garnet – feldspar – rocks
Arnage gneiss	Arnage gneiss	
Ardlethen gneiss (includes Glencroft granite)	Ardlethen gneiss (excludes Glencroft granite)	

Main differences in the classification of the Haddo and Arnage rocks between the author and Read (1923a and 1935).

CHAPTER IV

The Igneous Rocks of the Haddo House and Arnage Districts

I. Distribution and Petrography

1. Haddo House

(i) The Olivine-Hypersthene-Gabbros

(a) Field Occurrence

The olivine-hypersthene-gabbro is best observed in the north-east part of the Haddo House policies, south of the River Ythan, at the south-west corner of the Lower Lake. There it forms extremely large blocks which are probably not in place. Other loose blocks of olivine-hypersthene-gabbro occur along the south-side of the road between North Lodge and Mill of Kelly and are also found in the wood between the Lower Lake and the road. About 300 yards north-east of Haddo House another outcrop occurs which is probably in place. Blundell and Read (1958) used a specimen from this exposure when they gathered palaeomagnetic data from the north-east gabbros. Read (1935, p. 598) described the area of olivine-hypersthene-gabbro which stretches from Mains of Schivas, north-eastwards to the crofts between Airdlin and Quilquox. There are no longer any rock outcrops to be seen in this area although some scattered blocks of olivine-hypersthene-gabbro appear in a small stream to the west of Airdlin. In the south-east of the Haddo area about ¼ mile south-west of the bridge at Michael Muir an outcrop of olivine-hypersthene-gabbro is found near the eastern boundary of the Auchedly granite, although

Read (1935) placed this outcrop in his 'norite' group.

(b) Petrography

The olivine-hypersthene-gabbro shows some mineralogical variation, and modal analyses of 4 olivine-hypersthene-gabbros (nos. 57, 61, 62, 123) given in the table ~~overleaf~~ below demonstrates this. No xenoliths were found in this group (c.f. Read, 1935)

Modal Compositions

Mineral	HADDO				ARNAGE		
	57*	61	62	123	276 A*	235	282
Plagioclase	52.5	52.9	53.1	62.6	55.4	61.7	45.1
Orthopyroxene	18.8	20.2	26.4	14.4	25.8	28.4	27.7
Clinopyroxene	4.1	5.2	2.2	0.6	6.1	1.8	4.4
Olivine	11.9	4.7	11.5	16.3	4.2	4.6	14.6
Amphibole	11.8	9.9	2.4	2.0	1.5	1.5	6.4
Biotite	0.5	2.2	4.1	1.5	6.4	2.0	1.5
Ores & Accessories	tr.	4.9	0.3	2.5	0.6	tr.	tr.

* see also analysis table.

$>$ 2000 points counted from each specimen.
For location of specimens see appendix.

In the hand specimen the rock is fresh, dark grey-blue in colour and medium grained. From the modal compositions above, plagioclase feldspar is seen to be the dominant constituent, always greater than 50%. Olivine, orthopyroxene and clinopyroxene are present in varying/

varying amounts and clinopyroxene is always subordinate to orthopyroxene. Thus it would be in order to term these rocks olivine-norites rather than olivine-hypersthene-gabbros (Hatch and Wells, 1961 p. 308). However, as this would have meant changing almost every rock term used by Read (1935) it was decided to continue to use the term gabbro as before, but to amend olivine-gabbro to olivine-hypersthene-gabbro (and quartz-gabbro to quartz-hypersthene-gabbro). These terms have also been applied to similar igneous rocks in the Armagh district.

Texturally the rocks consist of subhedral olivine crystals up to 2 mm. long, and basic plagioclase feldspar, forming subhedral elongated plates also about 2 mm. long. The plagioclase plates are rarely poikilitic and their edges are truncated by olivine crystals. Clinopyroxenes, up to 6 mm. x 4 mm. in extent, orthopyroxene and biotite, both 3 mm. x 3 mm. in area, appear as large, poikilitic crystals which enclose both olivine and plagioclase. Amphibole appears both as large poikilitic crystals, 3 mm. x 3 mm. in size, enclosing olivine, plagioclase and pyroxene, and as reaction rims around pyroxenes. Ore minerals constitute the main accessories although apatite and rare zircon also occur.

The <u>olivine</u> in the olivine-hypersthene-gabbro is usually colourless and altered slightly along cracks to serpentine. In the six specimens examined the olivine had $2V_{\alpha}$ in the range 82° to 84° corresponding to a composition of Fa_{27} to Fa_{30} (Emmons, 1943; Henriques, 1958). An analysis (appendix C) of the olivine from specimen/

specimen 57 gave a composition $Fo_{73}Fa_{27}$ (molecular proportions; all Fe_2O_3 being taken as FeO). Zoning was not observed.

The clinopyroxene is colourless or pale greenish in thin section, non-pleochroic and slightly zoned. It often has a fibrous appearance due to exsolved lamellae of orthopyroxene. Some clinopyroxenes show one set of lamellae parallel to the (100) plane. At high temperatures a magma will crystallise a magnesian augite, which upon cooling, will exsolve orthopyroxene, the plane of this exsolution being (100), (Hess, 1960). $2V_\gamma$ was found to vary between 43° (core) and 48° (margin). The clinopyroxene (from No. 57) was separated and analysed (appendix C) yielding a composition $Ca_{32}Mg_{52}Fe_{16}$. The clinopyroxene is an augite (? sub-calcic) with a higher Ca and lower Mg and Fe than the formula given would imply, due to the presence of some olivine contamination.

The orthopyroxene is colourless and non-pleochroic. It contains very fine exsolution lamellae (ore ?) parallel to the (001) plane and could be called "orthopyroxene of the Bushveldt type" (Hess and Phillips, 1940). Hess (1960) stated that the temperature of the inversion orthopyroxene $\longrightarrow$ pigeonite is approximately 1100°C. Yoder and Tilley (1962) and Y oder, Tilley and Schairer (1964) gave an account of the inversion relations between orthopyroxene and clinopyroxenes crystallising from a magma, and stated that "the writers do not believe that magma temperatures can be estimated from observation of the orthopyroxene-clinopyroxene inversion", because the temperature of this inversion would appear to be difficult to determine experimentally. Measurement of $2V_\alpha$ on several specimens gave/

gave results in the range 69° to 73° and this corresponds with a range of compositions from Fs_{23} to Fs_{26} (hypersthene; data in Hess, 1960). An analysis of the orthopyroxene from specimen 57 yielded a composition En_{74} Fs_{24} (molecular proportions; appendix C) agreeing well with the data from optical measurements.

The plagioclase is frequently zoned. The centres of the crystals are An_{78} and the margins are as sodic as An_{64} although most compositions occur in the range An_{76-72}.

The biotite is pleochroic with α - pale yellow, β , γ dark red-brown. It is rarely altered and occasionally encloses large irregular crystals of iron ore.

The amphibole which occurs as large poikilitic crystals, is pleochroic with α pale yellow/brown, β brown, γ pale brown. It is rarely altered and can be found enclosing all other ferromagnesian minerals, unlike the pyroxene and biotite which are only seen enclosing olivine and plagioclase. Occasionally very thin rims of secondary amphibole can be seen developing from pyroxene in the rock.

Unfortunately not enough time was available to investigate the amphiboles of the igneous gabbroic rocks of Haddo and Arnage but it seems possible that in the olivine-hypersthene-gabbro the (poikilitic) amphibole is primary; its pleochroism and textural characters are quite unlike those of the secondary green amphibole which occurs in the uralitised quartz-hypersthene-gabbros found on the periphery of the Haddo igneous suite.

Apatite is a common accessory mineral and its grains are usually small/

small (.5 mm in length) with good prismatic outline. Ore minerals (magnetite and ilmenite) occur, often within the biotite.

(ii) The Quartz-Hypersthene-Gabbros

(a) Field Occurrence

The quartz-hypersthene-gabbros occupy the largest area of the Haddo House igneous rocks, if infrequent rock exposures can be taken as representing areas of continuous underlying rock types. The main western occurrence of these infrequent rock exposures is in the woods south of the River Ythan, between Gurge Dyke and North Lodge, and at the north-west end of the Lower Lake in the Haddo House estate. The quartz-hypersthene-gabbros there are always uralitised and often contain quartzitic inclusions. Similar amphibolitised quartz-hypersthene-gabbros occur as isolated outcrops to the east of the Burn of Cessnie between Castlehill and Cessnie. Read (1935, p. 594) draws the western boundary of the Haddo gabbros along this Burn presumably because blocks of country rock are seen to the west of the Burn of Cessnie, although none of these are demonstrably 'in situ'. Other outcrops of uralitised quartz-hypersthene-gabbros occur between Airdlin and Skilmafilly in the north and at Michael Muir in the south-east. There are not as many quartz-hypersthene-gabbros exposures in the district as there were in 1935, probably because of farmers clearing rocks from their fields in order to make the land suitable for cultivation. However in the Wood of Schivas, 3 miles south-east of Methlick outcrops of gabbroic rocks appear within the Auchedly granite intrusion. Some of these are cordierite-bearing/

bearing quartz-norites and will be discussed in chapter V of this thesis, but many of the outcrops are quartz-hypersthene-gabbros. Some of these are quite fresh with very little uralitisation, although some specimens (no. 86 modal analysis table) contain secondary amphibole as the dominant ferromagnesian mineral.

(b) Petrography

Read (1935) divided the igneous rocks (excluding the olivine-hypersthene-gabbros) into two major types. These were xenolith-free quartz-gabbros (and uralitised quartz gabbros) in the west, and xenolith-bearing norites in the east. Read (1935), p. 634) defined a norite as a gabbro ("in which no clinopyroxene is present". However many of the uralitised gabbros near Gurge Dyke contain quartzitic xenoliths and some of the xenoliths in rocks from the Wood of Schivas area are enclosed in a matrix which contains clinopyroxene. Outcrops at Shallowplough in the district of Michael Muir were mapped by Read (1935, p. 594) as part of the xenolith-rich norite group. Rocks from this area reveal traces of clinopyroxene in thin section. Thus there would appear to be no real reason to continue using the divisions proposed by Read (1935). Therefore the two main igneous groups of Read - the quartz-gabbros (including uralitised quartz-gabbros) and the norites have been combined under one heading - the quartz-hypersthene-gabbros. This grouping will also be applied to the Arnage quartz-bearing gabbroic rocks. There is no doubt that clinopyroxene IS scarce in the quartz-hypersthene-gabbros of the Haddo (and Arnage) districts. Examination of the modal percentages shows that few of the specimens examined/

examined contain much clinopyroxene, and even the olivine-hypersthene-gabbros contain very little clinopyroxene (table p.81 specimens 62, 123 have orthopyroxene/clinopyroxene $>$ 10/1). Specimens of gabbro which appear to contain little or no clinopyroxene in the mode always show clinopyroxene present as a normative mineral (see Eskola norms, table 3).

The modal analyses of 5 quartz-hypersthene-gabbros from Haddo are given in the table below of which two are uralitised quartz-hypersthene-gabbros. These analyses show the range of mineralogical variation in this igneous group.

Modal Compositions

Mineral	HADDO					ARNAGE			
	76*	78*	86*	87	R1	245*	248	345-3	345-14*
Plagioclase	59.3	68.0	46.7	52.9	46.1	43.3	59.4	54.3	55.3
Orthopyroxene	19.1	17.1	6.4	13.2	-	32.8	22.5	24.0	15.7
Clinopyroxene	4.1	2.7	altered	4.9	-	tr.	4.7	1.8	3.5
Amphibole	3.0	0.4	20.8	4.2	33.4	5.5	2.1	9.8	3.5
Biotite	7.3	8.3	7.2	7.7	12.8	6.5	9.8	6.2	11.9
Quartz	7.0	3.1	8.1	16.2	7.7	10.2	1.0	3.1	-
Sericite	-	-	9.8	-	nd.	-	-	-	-
Accessories including Ores	tr.	0.4	1.0	0.9	nd.	1.2	o.6	0.8	1.2

R1 from Read (1935, p. 606)

* see also Analyses (table 3)

$>$ 2000 points from each specimen counted.
For specimen location see appendix.

In/

In the hand specimen the typical quartz-hypersthene-gabbro is a fine to medium grained, greyish rock with visible biotite laths. From the modal compositions given, plagioclase feldspar is seen to constitute usually about 50% of the rocks volume. Varying amounts of orthopyroxene and clinopyroxene are present in the fresh quartz-hypersthene-gabbros (76, 78 and 87) but orthopyroxene is always much greater in amount than clinopyroxene.

Texturally the quartz-hypersthene-gabbros in thin section consist of subhedral plates of basic plagioclase, usually about 1 mm x 1 mm, although large crystals can reach 3 mm. in length (|| c axis) and subhedral prismatic orthopyroxene, from 0.3 to 2 mm. long. The orthopyroxene crystals often enclose small crystals of basic plagioclase. Clinopyroxene, although rare, is found as large poikilitic crystals, about 3 x 3 mm. in size, which enclose smaller crystals of plagioclase and orthopyroxene. Biotite occurs as large plates or aggregates of smaller laths, in either case occupying an area of about 2 mm x 2 mm. The biotites are poikilitic enclosing plagioclase feldspar, both pyroxenes and sometimes secondary amphibole after pyroxene. Occasional fine intergrowths of biotite and quartz are seen, but these are rare and quartz is usually interstitial. In the uralitised gabbros the orthopyroxene and clinopyroxene have been replaced by a secondary amphibole and in the most altered gabbros epidote and chlorite also appear. The most altered gabbros contain no pyroxenes and the ferromagnesian minerals present are mainly amphibole and biotite. The late stage hydrothermal action which led to the development of amphibole from pyroxene also produced sericitisation/

sericitisation of plagioclase feldspar crystals. Ore minerals (mainly magnetite and ilmenite) and apatite comprise the most common accessory minerals.

The clinopyroxene is colourless or pale greenish, non-pleochroic, and never zoned. It exhibits one set of exsolution lamellae parallel to the (100) plane. (for an explanation see page 83) An analysed clinopyroxene from this rock group gave a formula $Ca_{27}Mg_{54}Fe_{19}$ (molecular proportions) which is that of a sub-calcic augite. The separated mineral contained many exsolution lamellae of orthopyroxene which were not removed. The formation of sub-calcic augite is thought to be restricted to environments of rapid cooling at high temperature (Kuno, 1955), although high pressure appears to favour the formation of stable sub-calcic pyroxenes (Green and Ringwood, 1964). Tilley and Yoder (1964) showed that sub-calcic pyroxenes are unstable at low pressures.

The orthopyroxene is pale coloured and usually faintly pleochroic with α pale pink, β , γ pale green. This agrees with the pleochroic scheme given in Read (1923b, p. 454) for hypersthenes from the 'quartz-norites' of the Arnage district. It usually contains fine exsolution lamellae of clinopyroxene parallel to the (100) plane as did the orthopyroxenes in the olivine-hypersthene-gabbro. In the quartz-hypersthene-gabbros, measurement of $2V_\alpha$ in many orthopyroxenes gave results in the range 61° to 50° and a γ RI measured gave a value of $1.705 \pm .002$. These measurements would imply compositions from Fs_{32} to Fs_{42} (Hess, 1960). The value of $2V_\alpha$ obtained agrees with a value of 55° obtained by Read (1935, p.608) for an orthopyroxene from a quartz-biotite-norite. An analysis of the/

the orthopyroxene from specimen No. 76 gave a composition $En_{67}Fs_{33}$ (molecular proportions), which would agree with the compositions obtained by optical methods.

The plagioclase feldspar is always zoned. The zoning is not continuous but the centres of crystals are always more calcium rich than the edges. The cores were as calcic as An_{70} although the edges were often as sodic as An_{55}. In the uralitised gabbro, the plagioclase was usually partly altered to sericite.

The biotite of the quartz-hypersthene-gabbro is similar to that of the olivine-hypersthene-gabbro, and possesses a similar pleochroic scheme. In the uralitised rocks biotite is often a paler colour and can be seen altering to chlorite.

Secondary amphibole after pyroxenes is seen in the uralitised gabbros where it constitutes the main ferromagnesian mineral present (up to 33% of the modal composition can be amphibole, and chlorite) see R1 in modal analyses table. This amphibole, perhaps hornblende as suggested by Read (1935), is pleochroic with α pale yellow, β , γ , clear green, which is quite different from the pleochroism exhibited by the hornblende in the olivine-hypersthene-gabbros (p. 84). This secondary hornblende can replace the pyroxenes, according to Subramaniam (1956), as follows:

1 Anorthite + 1 Diopside + 3 Enstatite + H_2O $\longrightarrow$ 1 Hornblende

Stewart (1946) quoted Henry (1936) on the uralitisation of gabbros due to hydrothermal action. As Henry's thesis (unpublished) was not obtainable, the chemical reactions leading to the production of hornblende from orthopyroxene are given in detail below (from Stewart/

Stewart, 1946, p.483):

$$7(MgO, FeO)SiO_3 + H_2O + SiO_2 \longrightarrow H_2(MgFe)_7 Si_8O_{24}$$

Hypersthene → Cummingtonite

1 Cummingtonite + 1 Anorthite → 1 Hornblende + Silica

Firstly the hypersthene reacts with water in presence of silica to form cummingtonite, with the silica being derived from the simultaneous reaction of clinopyroxene with feldspar to produce green hornblende. The cummingtonite then reacts with the anorthite molecule of plagioclase to form a green aluminous hornblende. Perhaps some soda from the albite molecule also enters into the reaction to account for the bluish green colour which is often observed in the hornblende. No analytical work has been carried out on the amphiboles so it is impossible to predict what their precise composition is.

Epidote occurs in highly uralitised quartz-hypersthene-gabbro. Pale yellow in colour and with a high birefringence, it is found associated with chlorite and may have formed as an alteration product from pyroxenes and plagioclase in the manner suggested by Fyfe et al. (1958).

$$4 \text{ Anorthite} + 5 \text{ Enstatite} + 5H_2O \longrightarrow 2 \text{ Epidote} + 1 \text{ Chlorite} + 4 \text{ Quartz}$$

Quartz appears as interstitial patches in the quartz-hypersthene-gabbros and normally between 5% and 10% of a quartz-hypersthene-gabbro is composed of quartz.

Apatite, iron ores (usually magnetitic) and rare zircon constitute the usual accessory minerals present.

Read (1935, p. 602) describes specimens from this group which have more clinopyroxene than orthopyroxene. These are probably similar to two specimens examined by the author which also show clinopyroxene greater in amount than orthopyroxene. However the textures of the rocks examined were considered to be those of hypabyssal intrusive rocks; the textures are ophitic with random arrangement of euhedral plagioclase crystals. An analysis and norm of one of these (no. 97) is given in Appendix B at the end of this thesis. These rocks are probably intrusive quartz dolerites which have suffered some degree of alteration after their intrusion. Similar rocks have been reported from the Insch basic suite (Read et al. 1961; 1965).

2. Arnage

(i) Olivine-hypersthene-gabbro

(a) Field Occurrence.

Read (1923a, p. 456) described an olivine-norite from Glencroft, and other occurrences of olivine-bearing types have been found by the author at Braik's Belt. An occurrence was noted north-west of Inverebrie Croft, but this might not be in place.

(b) Petrography.

Texturally and mineralogically these are similar to the olivine-hypersthene-gabbros of Haddo. The modal compositions of 3 of these Arnage rocks are given on p. 81 (276A, 235, 282) and these are seen to be essentially of similar mineralogical constitution to equivalent Haddo rocks (same page). The Arnage olivine-hypersthene-gabbro/

gabbro is not quite so basic as the Haddo one. A comparison of the chemical analyses of no. 57 (Haddo) and no. 276A (Arnage), table 3, demonstrates this. This chemical difference is reflected in the mineral compositions, and the main mineralogical differences between the olivine-hypersthene-gabbros of Haddo and Arnage are listed in summary form, to avoid a repetition of petrographic detail.

	Haddo	Arnage
Mineral	Composition	
Olivine	Fa_{27} to Fa_{30}	$Fa_{33/34}$
Hypersthene	Fs_{23} to Fs_{26}	Fs_{24} to Fs_{28}
Plagioclase	An_{78} to An_{72} edges can be as sodic as An_{64}.	An_{70} to An_{60} occasional plagioclase crystals with cores of composition An_{78} are noted.

(ii) Quartz-hypersthene-gabbros

(a) Field Occurrence.

These are usually found near the olivine-hypersthene-gabbro outcrops although the relation between the two types is never apparent in the field. No transition from one type to the other is ever seen. Most of the igneous rock locations given in Read (1923a, p. 453) as forming part of his "norite group" belong to the quartz-hypersthene-gabbros. These are at Inkhorn, just north of Towie Wood, Waulkmill of/

of Savoch and Arnage, north of Gallowhill, all of which lie on the Ebrie Burn which flows south to meet the Ythan River at Ebrie Bridge, about 2 miles north-west of Ellon. Exposures in these localities can be found in railway cuttings, as the route of the Aberdeen to Fraserburgh railway line is alongside the Ebrie Burn in this area. About 1 mile south of Gallowhill the last of the gabbroic 'kernäls' mentioned by Read (1923a) occurs, and this 'kernel' is also exposed in railway cuttings.

(b) Petrography.

Since the quartz-hypersthene-gabbros of Arnage are found to be texturally and mineralogically similar to those of Haddo, it is not proposed to discuss their petrography in detail and the main differences in mineralogical composition between the quartz bearing gabbros of Haddo and those of Arnage are given in summary form:

	Haddo	Arnage
Mineral	Composition	
Hypersthene	Fs_{32} to Fs_{42}	Fs_{32} to Fs_{45}
Plagioclase	An_{70} to An_{55}	An_{65} to An_{50}

There would appear to be no overlap in the hypersthene compositions above with those from the olivine-hypersthene-gabbros. This is probably because there are so few igneous exposures (especially of olivine-bearing types) that a true compositional range of hypersthene cannot be given for the igneous groups, and the range given/

District	HADDO	ARNAGE	HADDO					ARNAGE	
Rock type	Olivine-hypersthene-gabbro		Quartz-hypersthene-gabbro						
Rock no.	57	276A	76	78	63	59	86	245	345-14
SiO_2	47.09	48.34	53.63	53.72	53.38	51.86	51.09	63.61	52.54
TiO_2	0.65	0.68	0.86	0.82	1.25	1.11	2.58	0.86	0.80
Al_2O_3	17.90	17.97	17.38	17.22	16.11	17.91	16.54	14.73	18.27
Fe_2O_3	1.36	1.63	1.54	1.52	0.91	1.65	2.01	1.00	1.36
FeO	6.78	7.73	5.52	6.86	8.01	7.26	7.28	7.10	5.66
MnO	0.13	0.15	0.14	0.18	0.16	0.17	0.16	0.15	0.14
MgO	12.95	10.19	8.20	7.51	7.21	6.63	5.46	11.36	8.33
CaO	9.75	9.03	8.62	7.76	7.71	8.64	9.08	7.98	8.50
Na_2O	1.74	2.24	2.20	2.00	2.74	2.31	2.34	0.81	2.17
K_2O	0.38	0.56	0.88	0.85	1.35	1.07	1.04	0.81	0.81
H_2O+	0.74	0.77	0.90	0.91	0.50	1.00	1.12	0.81	0.50
P_2O_5	0.066	0.092	0.085	0.094	0.18	0.13	0.26	0.079	0.081
Total	99.54	99.38	99.96	99.44	99.51	99.74	99.08	99.30	99.16
Trace element amounts in ppm.	Analysis carried out by author on powder dried at 110°C for 2 hrs.								
Cr	348	213	325	238	195	188	196	404	313
Ba	115	125	225	390	450	340	340	225	175
Rb	4	9	20	25	36	27.5	15	34	24
Sr	271	213	237	238	250	287	275	167	245
ESKOLA NORMS									
	57	276A	76	78	63	59	86	245	345-14
Orthoclase	2.25	3.30	5.25	5.10	8.05	6.40	6.35	4.85	4.80
Albite	15.45	20.15	19.80	18.25	24.80	21.05	21.75	7.35	19.60
Anorthite	39.48	37.38	35.10	36.10	27.93	35.90	32.70	34.62	37.95
Hypersthene	14.20	17.72	25.26	27.86	25.98	23.62	15.98	38.52	27.54
Diopside	6.36	5.56	5.80	2.00	7.68	5.52	9.92	4.04	3.20
Olivine	19.35	12.51	-	-	-	-	-	-	-
Quartz	-	-	5.26	7.20	2.17	3.36	6.13	7.85	3.74
Magnetite	1.88	2.28	2.16	2.14	1.28	2.34	2.90	1.40	1.90
Ilmenite	0.90	0.94	1.20	1.16	1.76	1.56	3.72	1.22	1.12
Apatite	0.13	0.17	0.18	0.18	0.35	0.25	0.54	0.15	0.15

TABLE 3

District	HADDO							ARNAGE
Rock Type	Uralitised quartz-hypersthene-gabbro					Xenolithic quartz-hypersthene-gabbro		
Rock no.	124	126	145	168	171	64M	347-21B	345-4M
SiO_2	49.37	55.13	51.12	54.05	45.29	52.68	53.01	55.29
TiO_2	2.45	1.50	2.64	2.66	4.73	1.23	1.20	1.88
Al_2O_3	18.36	17.17	15.07	15.25	15.46	19.65	19.09	16.21
Fe_2O_3	2.56	1.69	2.95	3.02	4.47	1.71	1.89	2.35
FeO	8.70	7.50	8.35	7.88	9.46	7.43	7.35	7.45
MnO	0.18	0.17	0.19	0.17	0.20	0.15	0.17	0.15
MgO	4.70	4.85	4.96	3.09	6.30	5.83	5.33	4.53
CaO	8.39	5.60	8.03	6.59	9.83	7.03	7.35	4.18
Na_2O	2.61	2.81	2.78	3.54	2.23	2.69	2.08	2.60
K_2O	0.57	2.08	1.23	1.86	0.62	0.98	1.09	3.28
H_2O+	0.66	0.85	1.44	1.24	1.45	0.80	1.14	1.72
P_2O_5	0.20	0.48	0.29	0.35	0.049	0.037	0.083	0.087
Total	98.75	100.42	99.05	99.70	100.09	100.22	99.78	99.73
Trace elements in ppm.	Analyses carried out by author on powder dried at 110°C for 2 hours							
Cr	112	130	43	32	59	157	180	146
Ba	225	850	490	710	140	360	500	1205
Rb	27.5	62	45	58	10	29	41	206
Sr	314	352	333	306	288	312	282	93
ESKOLA NORMS								
	124	126	145	168	171	64M	347-21B	345-4M
Orthoclase	3.50	12.55	7.60	11.40	3.80	5.85	6.60	20.00
Albite	24.30	25.70	26.05	32.90	20.90	24.35	19.10	24.15
Anorthite	38.02	25.35	26.10	20.95	31.60	35.00	36.85	20.95
Hypersthene	18.90	21.22	14.52	9.24	12.80	23.94	22.60	19.04
Diopside	3.16	-	10.96	8.64	15.16	-	-	-
Quartz	4.48	8.34	6.06	7.96	2.27	5.09	8.82	8.54
Corundum	-	1.31	-	-	-	1.58	1.46	1.08
Magnetite	3.70	2.40	4.28	4.36	6.50	2.40	2.70	3.38
Ilmenite	3.54	2.14	3.84	3.84	6.86	1.72	1.70	2.70
Apatite	0.40	0.98	0.60	0.70	0.10	0.07	0.17	0.17

TABLE 3 (contd.)

given in this chapter is the most complete that was obtained. There is an overlap in the compositions of the normative hypersthenes between the two groups.

The differences in modal compositions between the quartz-hypersthene-gabbros of Haddo and Arnage can be seen on p.87 (excluding the uralitised rocks of Haddo, nos. R1 and 86). The main difference between Haddo and Arnage quartz-hypersthene-gabbros is that the latter are richer in orthopyroxene (and poorer in clinopyroxene) than the former.

II. The Geochemistry of the Haddo House and Arnage Igneous Rocks.

Two analyses of olivine-hypersthene-gabbros from Haddo and Arnage are given in table 3. Several analyses of quartz-hypersthene-gabbros from both areas are shown in table 3. Specimens 76, 78, 63, 245 and 345-14 are unaltered quartz-hypersthene-gabbros, but 59 and 86 show some alteration, mainly amphibole replacing pyroxenes. 124, 126, 145, 168 and 171 are highly uralitised rocks from the periphery of the Haddo House gabbros. The three specimens 64M, 347-21B and 345-4M on table 3, are xenolith-bearing quartz-hypersthene-gabbros from which the xenoliths were removed before they were analysed. However, since many of the xenoliths are small, these might not all have been removed, and it is doubtful if the 3 analyses truly represent quartz-hypersthene-gabbros. Xenoliths are usually rich in SiO_2, Al_2O_3 or FeO depending on their original composition; thus a rock containing xenoliths would tend to be richer in SiO_2, Al_2O_3 or FeO and poorer in CaO and MgO than a rock without xenoliths.

Specimens/

Specimens 64M and 347-21B are richer in Al_2O_3 and poorer in MgO, and CaO than the corresponding quartz-gabbros in table 3. Values of 4 trace elements are shown in addition to the usual 12 major elements. Eskola norms based on 1-cation percentages have been calculated, and the normative constituents of each analysed rock are given under each chemical analysis.

Silica as SiO_2

This is higher than the SiO_2 content of gabbros with similar Mg/Mg + Fe ratios from other parts of north-east Scotland (Read et al., 1961; Stewart, 1946)

Aluminium as Al_2O_3

Alumina is high in the gabbros and is reflected in the large amount of normative (and modal) plagioclase feldspar in the rocks (50% - 65%). The alumina content is higher than that of similar basic rocks from Insch but similar to that of some of the Huntly and Belhelvie rocks (Read, 1923b; Stewart, 1946).

Iron and Magnesium (and Manganese) as FeO MgO and MnO

The quartz-hypersthene-gabbros of Haddo and Arnage are rather basic rocks with Fe/Fe + Mg ratios (Fe = total iron) and varying from .40 in the olivine-hypersthene-gabbros to .65 in the quartz-hypersthene-gabbros. The uralitised gabbros are noticeably lower in MgO than the unaltered gabbros, and this might be due to the hydrothermal alteration suffered by these gabbros.

Sodium and Potassium as Na_2O and K_2O

Soda/

Soda does not vary much in the various igneous rocks and has lowest values in the olivine-hypersthene-gabbros and highest values in the uralitised quartz-hypersthene-gabbros. Specimen 245, table 3 is deficient in Na_2O but this is a feldspar-poor, quartz-hypersthene-gabbro, (see modal compositions p. 87). Potash increases from about .5% (or less) in the olivine-hypersthene-gabbro to well over 1% in the quartz-hypersthene-gabbro. Basic rocks with similar orthopyroxene compositions from the Belhelvie and Insch masses of north-east Scotland have much lower amounts of K_2O (.16 to .6%). In the Haddo igneous rocks K_2O is probably held in the biotite structures (biotite appears as a primary phase in the Haddo and Arnage igneous rocks, but not in the basic rocks of Insch); the basic gabbros of Insch are lower in K_2O than the Haddo gabbros, and are part of a fractionated series - quite unlike the Haddo gabbros (see petrogenesis section of this chapter).

Titanium as TiO_2

TiO_2 varies greatly in the igneous rocks. It is greatest in amount in the uralitised quartz-hypersthene-gabbros. In the other gabbros titanium is probably incorporated in the Y group of the pyroxene or amphibole (the analysed olivine from specimen 57 contained almost no TiO_2, see appendix C). In the uralitised gabbros, the pyroxenes (and primary amphibole?) have broken down and many of the amphibolitised gabbros show local increases in magnetite and ilmenite. This is reflected in the analyses of the uralitised gabbros table 3, which show that those rocks with a high TiO_2 value have also got high/

high FeO and Fe_2O_3. values.

Chromium as Cr

Chromium appears to increase with increasing Mg/Mg + Fe ratios and is greatest in amount in the most basic (MgO rich) rocks.

Strontium as Sr

Strontium shows little variation in the igneous rocks, and the Sr content of the Haddo gabbros would appear to compare well with the Sr content of the more basic differentiated rocks from Insch (Read and Haq, 1963).

Barium and Rubidium as Ba and Rb

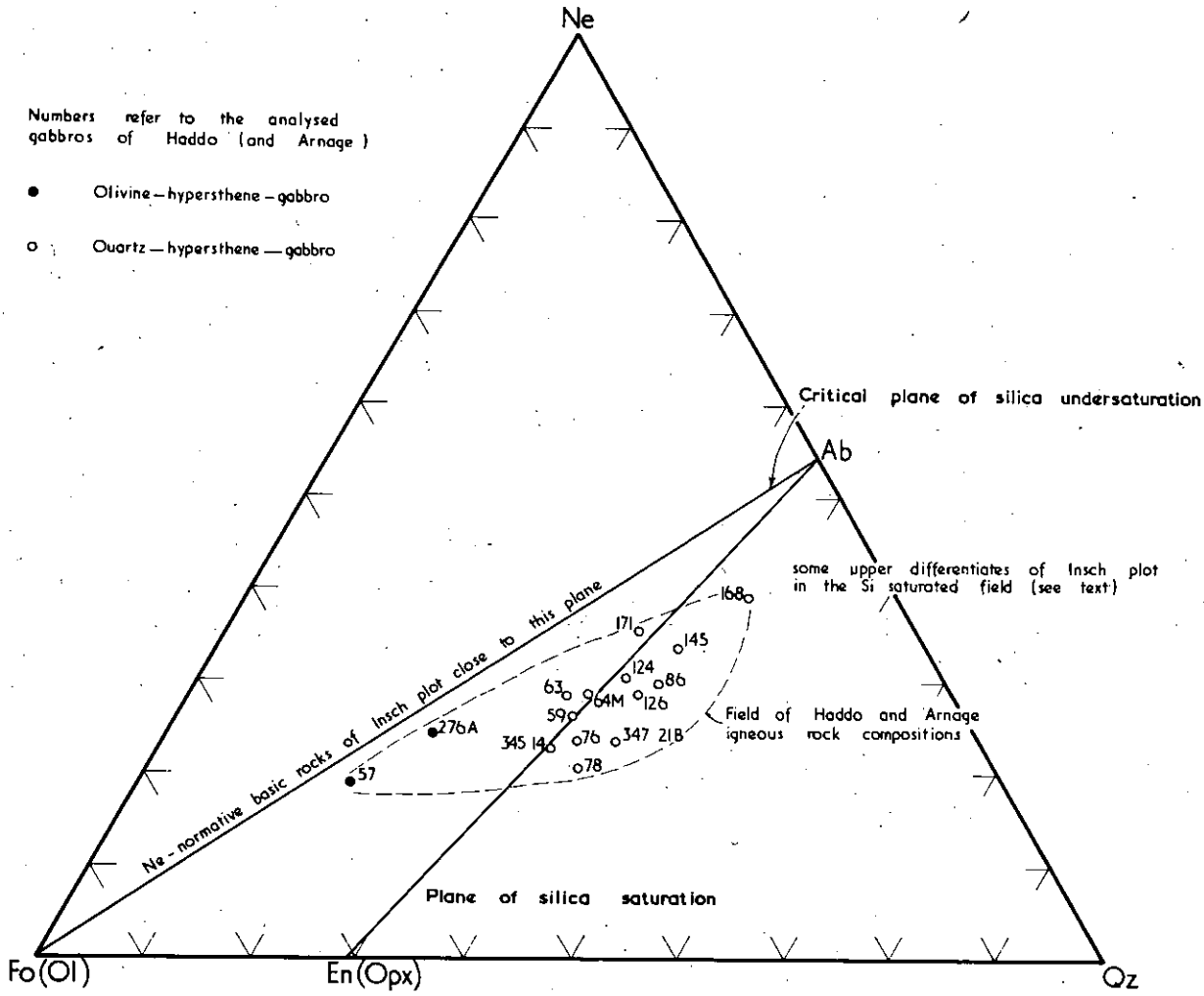
Both Ba and Rb increase with increasing K_2O. Barium values vary up to 450 ppm in the unaltered quartz-hypersthene-gabbros (850 ppm in some uralitised gabbros), although no large values were found. The basic series at Insch shows high Ba values in the upper differentiates (1.8%, Read and Haq, 1963) and it is possible that the original basic magma must have been rich in Barium. However the country rocks are rich in Barium, the Fyvie schists having up to 0.13% and the Ellon gneisses 0.22% (table 1). Whether the basic magma was originally rich in Ba, or its large Ba content was due to an introduction of Ba from the surrounding rocks or during its intrusion is difficult to say.

III. The Petrogenesis of the Haddo House and Arnage Igneous Rocks

From the table of analyses it can be seen that the olivine-hypersthene/

hypersthene-gabbro of Haddo is more basic than the corresponding Arnage rock (i.e. it has a lower Fe/Fe + Mg ratio). Unfortunately a detailed comparison between the gabbroic group of Haddo and Arnage with the basic rocks of other parts of north-east Soctland is not possible. The only mass in which extensive chemical studies have been published is Insch (Read et al. 1961, 1965; Read and Haq, 1963) although the chemistry of the major rock types of the Belhelvie mass has also been examined (Stewart 1946). The various rock types from the Insch (and Belhelvie) districts have been shown to represent cumulative fractions which have formed by differentiation from an initial magma (Clarke, 1965; also Stewart, 1946, p. 488). Passages between different rock types have been described and chemical relations between the various groups have been shown on variation diagrams (Read et al. 1961, 1965). Many of the basic rocks from Insch contain normative nepheline (data from Read et al. 1961, 1965). If the normative minerals, quartz, nepheline, forsterite, diopside are plotted into a tetrahedron with these mineral phases as its apices then many of the basic gabbroic rocks of Insch plot near the critical plane of silica undersaturation in the area Ne-Fo-Ab (see fig. 10, tetrahedron data from Yoder and Tilley, 1962). Only a few of the upper differentiates of Insch contain normative quartz, and appear in the silica saturated field of the tetrahedron (i.e. the area Di-En-Ab-Qz). Many of these upper differentiates, syenites and syenogabbros of the Red Rock Hills, could have suffered much ground water percolation, with subsequent leaching-out of alkalis, thus increasing their relative proportions/

FIG. 10



Ne = normative Ne + Ne from Ab.

Fo(Ol) = normative Ol + Ol from Opx.

Di = normative Di.

Qz = normative Qz + Qz from Ab and Opx.

A projection from diopside on to the plane nepheline – forsterite (olivine) – quartz in the system nepheline – forsterite (olivine) – quartz – diopside.

proportionsof SiO_2 (Clarke, personal communication). This would appear to place this group in the silica saturated field of the tetrahedron. This leaching of the syenites, etc., by ground water was also put forward by Bell (1964) to account for anomalous ages from the Insch gabbros obtained by the Rb-Sr technique. Some syenites at Insch do show normative nepheline and there is little doubt that these rocks are undersaturated in SiO_2. The basic rocks from the Belhelvie mass contain neither modal nor normative quartz and plot in the hypersthene-normative field of the tetrahedron.

The Haddo and Arnage rocks do not show this undersaturation in SiO_2. They never oontain normative nepheline and even rocks as 'basic' as the quartz-hypersthene-gabbros contain both modal and normative quartz. The olivine-hypersthene-gabbros plot in the hypersthene-normative part of the tetrahedron (the area Di-Fo-En-Ab) and the quartz-hypersthene-gabbros appear in both the hypersthene- and quartz-normative fields. The reason for this is discussed below. Certain interesting facts emerge when comparing the modal compositions of the Haddo and Arnage gabbroio rocks with rocks of similar mineralogical composition in the Buchan region; e.g. the hypersthene gabbros of Belhelvie and Insch. The Haddo and Arnage olivine-hypersthene-gabbros contain substantial amounts of biotite and hornblende which appear to have crystallised as primary phases (up to 6% and 12% respectively). The quartz-hypersthene-gabbros appear to contain no primary amphibole (usually the amphibole is secondary after pyroxenes, due to late-stage hydrothermal action), but the quartz-hypersthene-gabbros can contain up to 12% of biotite as a primary phase. The Insch and Belhelvie gabbros contain

virtually/

virtually no biotite and very little primary amphibole.

Bowen (1928) discussed the increase in the amount of quartz in a liquid (magma) arising from fractional crystallisation of a basaltic magma. He showed that early crystallisation (and removal) of olivine from silica-saturated basic magma produces an increase of SiO_2 in the residual liquid (olivine is a mineral undersaturated in silica). There would also be an increase in alkali feldspar due to basic plagioclase settling and therefore the residuum would be rich in alkali feldspar and quartz. Accompanying this, or occurring independently of it, there may be a reaction between alkali feldspar and ferromagnesian minerals in the rocks in the presence of H_2O (volatiles), resulting in biotite formation and a setting free of quartz. This biotite formation and increase in quartz would be a late-stage process; it is worthwhile noting that the late-stage differentiates at Insch, syenites, etc., have modal biotite, and are quite rich in SiO_2 (Read 1923b, Read et al. 1961). Bowen (1928) stated that a third process which would increase the amount of silica available in a crystallising magma might be the formation of hornblende at intermediate stages of fractionation. He showed that a sequence of rocks at Stavsjö where noritic gabbros grade into hornblende diorites and thence to quartz diorites, actually represented a fractionated sequence. An early removal of basic material containing hornblende in the early stage of fractionation would give rise to the observed late-stage products. Bowen used mineral phases present in the rocks themselves (i.e. modal minerals) rather than normative minerals in determining the fractionation/

fractionation trends. Bowen (1928) stated that "a hornblende sequence /must be/ formed by magmas richer in volatile components although a difference in content of normal oxide constituents would probably be needed as well."

Yoder and Tilley (1962) discussing the origin of basalt magmas agreed with Bowen on many points. They stated (p. 398) that "at low water pressures a potash-rich magma may trend towards silica." However, on consideration of the crystallising of basalts within the tetrahedron Fo-Ab-An-Di under equilibrium conditions, they stated (p. 401) that "under equilibrium conditions no one liquid can produce both nepheline-bearing products and silica-bearing products if only the major phases are considered /i.e./ a single basalt magma cannot produce both a tholeiitic trend and an alkali basalt trend purely by fractionation in the early stages". Yoder and Tilley considered certain mechanisms for crossing the equilibrium thermal divide between critically undersaturated and undersaturated magma types (the divide Fo-Di-Ab in the tetrahedron Ne-Fo-Qz-Di).

One condition which could lead to differing liquid trends from the same initial magma is oxidation. From studies in the system MgO-FeO-Fe_2O_3-SiO_2, Osborn (1959) suggested that an olivine tholeiite may, on differentiation, give rise to an iron enrichment trend if the oxygen content is constant, or give rise to a silica-enrichment trend if the oxygen content is variable. This difference in trends could be attributed to differences in water content of magmas.

So far it has been stated how Bowen (1928) believed that different/

different fractionation trends would produce different end products. For example, the crystallisation of olivine in the early stages of fractionation, or the formation of either hornblende in the middle stages or biotite in the late stages would all lead to an eventual increase of SiO_2 in the liquid. The hypothesis of Osborn (1959) was accepted by Yoder and Tilley (1962) who said that it might be possible to get both a nepheline-normative and a hypersthene- or quartz-normative series from the same initial magma if there were differences in its water content.

Discussing the origin of basalts O'Hara (1965) envisaged how a liquid produced at the high pressures could give rise to different basaltic magmas depending on the rate of movement to the surface (the pressure and duration of fractionation) and whether the fractionation of the liquid took place in dry or in water-saturated conditions. O'Hara (1965) also noted that the presence of water would change fractionation trends of magmas, irrespective of any oxidation effects. The 'invariant' point in the system Ca Tschermatite (+ Ne) - Ol - Qz - Cpx towards which the magmatic liquid is trending lies near the equilibrium divide Ol-Cpx-Pl for an alkali basalt fractionating in the dry state. Under water saturated conditions and moderate pressures (P_{H_2O} = 10 Kb) this invariant point is moved into the silica oversaturated field, (the area Cpx-Opx-Pl-Qz) and a magmatic liquid differentiating under water saturated conditions would be notably enriched in normative quartz, although the same phases (olivine, plagioclase, and two pyroxenes) were precipitating.

The/

The rock sequence at Insch ranges from ultrabasic and basic gabbroic rocks (many of which are nepheline-normative) to syeno-gabbros and syenites. Thus the initial magmatic liquid at Insch, in spite of producing much hypersthene-bearing cumulates might itself be silica-undersaturated. Yet the same initial magma has produced both a silica undersaturated trend (Insch) and a silica saturated or oversaturated trend (Haddo and Arnage).

Regarding the question of the water content of the Haddo magma at the time of crystallisation, it is thought worthwhile to digress and consider the depth of burial of the gabbros at Haddo and Arnage at the time of their intrusion. Johnson (1963) estimated that the climax of Buchan metamorphism produced temperatures of c. 550°C for the formation of a cordierite-andalusite assemblage. This would be in agreement with Turner and Verhoogen (1960) who gave temperatures of 550°C to 700°C for a hornblende hornfels facies assemblage (which is where Fyfe, Turner and Verhoogen (1958) placed the Fyvie schist assemblages). The pressure range for the hornblende hornfels facies is P_{H_2O} = 1 Kb to 3 Kb (Turner and Verhoogen, 1960). Johnson (1963) postulated a high geothermal gradient (160° C/Km) using known thicknesses of Upper Dalradian rocks (3.3Km) which overlie the upper limit of the andalusite-cordierite zone. Later sediments are always found resting unconformably on Upper Dalradian rocks (in Arran, Arenig rocks rest unconformably on Upper Dalradian grits, and those grits are not present in NE Scotland), thus the thickness of the Upper Dalradian series is not known. Wyllie and Tuttle (1960) stated that a high geothermal gradient in rocks, at the present day, is 50°/60° C per Km, and/

and therefore the depth of Upper Dalradian cover to the upper limit of the cordierite-andalusite (-sillimanite) zone, using this geothermal gradient would be $\frac{550^{\circ} \text{ to } 600^{\circ}}{50^{\circ}/60^{\circ}}$ Km = 10 Km (approx.). Since 1 Km is approximately equal to 300 bars pressure, then 10 Km = 3000 bars or 3 Kilobars. The Haddo and Arnage gabbros might have been intruded into the country rocks at the time of the climax of the regional metamorphism, as Bell (1964) could not separate the time of the intrusion of the gabbros from the climax of Buchan metamorphism. The basic sheet in the Haddo and Arnage districts might well have been intruded under 3 Kb load pressure.

Howie (1963) stated that orthopyroxenes from granulite facies metamorphic rocks (i.e. high P and T conditions) have an ... "increasing ability ... to accept greater amounts of alien ions." Boyd and England (1960) found that orthopyroxenes from high Al_2O_3 environments, under high P and T conditions, contained the greatest amounts of Al_2O_3. Examining garnet peridotites in Norway, which contained orthopyroxenes low in Al_2O_3, O'Hara and Mercy (1963) came to the conclusion that under conditions of high pressure and temperature, provided that the orthopyroxene was in an environment which was free from clinopyroxene, the orthopyroxene would be able to accept large amounts of Al_2O_3 into its structure. The quartz-cordierite-norites of Haddo, and the hornfelses of Sparcraigs, Belhelvie (both clinopyroxene-free) contain orthopyroxenes which contain 4.3% and 7.2% of Al_2O_3 respectively. Thus the orthopyroxenes from clinopyroxene-free rocks at Haddo and Belhelvie have probably crystallised under high P and T conditions. Therefore the available evidence from rocks associated/

associated with the gabbros in north-east Scotland would appear to support the hypothesis that the regional basic sheet was intruded at depth, with load pressures of $P_{total} \simeq 3$ Kb in operation. Since the Haddo and Arnage gabbros appear near the roof of the basic sheet of north-east Scotland (Stewart and Johnson, 1960; also chapter I, p 18) the load pressure due to the thickness of the basic sheet (perhaps > 1 Kb) is not added to the 3Kb.

The points raised concerning the gabbros of Haddo and Arnage may now be tabulated as follows:

(1) The Haddo and Arnage gabbros, because of their chemical compositions, their Fe/Fe + Mg ratios and their mineralogical compositions, could, perhaps, be expected to occupy a position in the differentiated series of rocks of the basic sheet of north-east Scotland above the level of the hypersthene-gabbros of Belhelvie, and below the hypersthene-gabbros of Insch).

(2) The Haddo and Arnage gabbros contain modal biotite and hornblende as primary phases (up to 15+%) whereas the Insch and Belhelvie rocks contain these minerals only in minor quantities. The quartz-hypersthene-gabbros of Haddo and Arnage contain modal quartz, whereas modal quartz is never found in comparable rocks at Belhelvie or Insch.

(3) The Haddo and Arnage rocks are very much richer in SiO_2 (and K_2O) than the corresponding 'basic' rocks from the Insch and Belhelvie basic masses..

(4) There must have been some water present in the basic magma at Haddo and Arnage to account for the formation of biotite and amphibole in/

in the gabbroic rocks.

(5) The presence of water in a magma can change the fractionation trend of the magma, and a basalt magma can produce both nepheline-normative, and hypersthene- or quartz- normative trends because of differences in its water content.

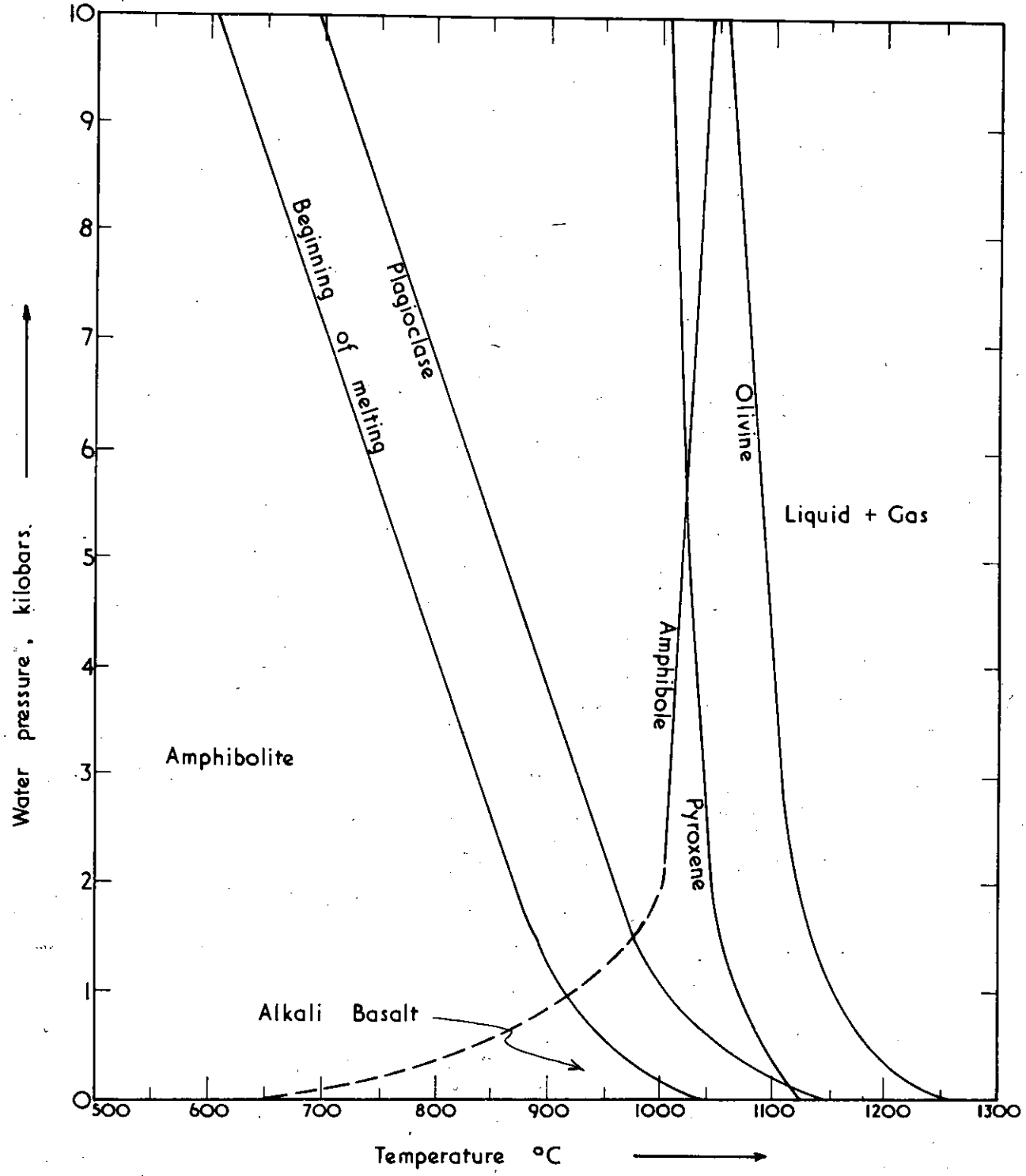
(6) The Haddo and Arnage basic rocks are always hypersthene- or quartz-normative whereas the Insch basic rocks are in many cases nepheline-normative.

(7) The gabbros could have been intruded under a load pressure of P_{total} = 3 Kb.

Points 4, 5 and 6 above would indicate that there must have been some introduction of water into the basic sheet in the Haddo region to account for the basic rock sequence displayed there.

If this is so, did the magmas at Haddo fractionate in water saturated conditions? (i.e. was P_{H_2O} = 3 Kb). Yoder and Tilley (1962) showed the melting relations of some natural basalts at various water pressures. One diagram is reproduced (fig. 11) showing the melting relations for an alkali basalt (data from Yoder and Tilley, 1962, p. 452).

It is seen that high water pressures tend to change the order of crystallisation of magmas (pyroxene replaces plagioclase as the second phase to crystallise at very small P_{H_2O}). The order of crystallisation in the gabbroic rocks at Haddo and Arnage was olivine, plagioclase and pyroxene, and this is the normal fractionation sequence in alkali basalts crystallising in the dry state, see fig. 11. Furthermore the absence of open pores or cavities in the Haddo igneous/



Projection of the natural alkali basalt — water system.
(from Yoder and Tilley 1962, p 452.)

FIG. 11

igneous rocks, together with the lack of evidence of pressure-solution effects would also agree with the postulate that the Haddo gabbro crystallised in the absence of a vapour phase. If there had been a small partial pressure of water, so that $P_{H_2O} + P_? = P_{total}$ (3Kb), then there must have been some other component of the gas phase present ($P_?$) and this seems most unlikely. Therefore it seems likely that the gabbros at Haddo were intruded and fractionated under a load pressure of 3 Kb, and water was introduced into the basic magma at Haddo to account for the different fractionation trends displayed by the same basic sheet at Insch and Haddo.

This amount of water must have been small (no vapour phase, and modal percentages of biotite and amphibole are quite small in the igneous rocks at Haddo and Arnage) and it is possible that the H_2O introduced into the liquid also carried some SiO_2 (and alkalis?) which would further tend to 'push' the liquid towards a silica enrichment trend. Kennedy, et al. (1960) showed that SiO_2 is quite mobile in water (steam) under pressure, and SiO_2 can comprise about 10% (by weight) of the vapour at about 3 Kb pressure. This SiO_2 carriage into the magmatic liquid might be important when considering point (3), p. 106.

The most attractive proposal concerning the deformation of the Buchan basic sheet was that it was folded whilst still partially liquid (Stewart and Johnson, 1960; see chapter I, p. 23). The Buchan anticline which was 'rising' between the period F_2 to F_3 (Johnson, 1962, 1963; Read and Farquhar, 1956), would fold the basic sheet during its consolidation, and produce a thinning of the basic/

basic sheet across the anticline. The heat from the gabbros could release H_2O from the breakdown of hydrous minerals in the country rocks, this vapour then being dissolved in the basic liquid (with the H_2O perhaps carrying some SiO_2 etc.) Such a mechanism might explain the silica saturated and oversaturated trends which exist at Haddo and Arnage.

Quartz-hypersthene-gabbros occur elsewhere along the axis of the Buchan anticline, at Maud (Blundell and Read, 1958) and Inzie Head (uralitised quartz-gabbros collected by Professor Stewart and examined by the author). These occurrences were to be expected if the above hypothesis was true.

The trend towards quartz-normative gabbro displayed by the basic rocks at Haddo and Arnage is thought to be a result mainly of the process outlined above. However many of the quartz-hypersthene-gabbros of Haddo and Arnage are xenolithic. The xenoliths vary from quartzitic to highly aluminous in character. Assimilation of some material from the xenoliths may have occurred, especially in those igneous rocks very close to the country rock/gabbro boundary where the proportion of xenoliths in the magma would have been greatest. The effects of a basic magma on xenolithic material enclosed by the magma were discussed in chapter II, of this thesis, and the main points raised in that discussion are restated below.

If a pelitic xenolith partially melts and the surrounding magma (quartz-gabbro) does not incorporate the liquid formed at the margin into the magma, a quartz-orthonorite 'screen' would be formed between the xenolith and the magma.

If/

If the liquid formed by partial melting of the xenolith is swept away and incorporated into the magma, the xenolith which remains would not be in equilibrium with the enclosing magma. A zone of solid phases in equilibrium with the magma would form. The core of the xenolith would meanwhile attain equilibrium with the outer zone by forming a middle zone in equilibrium with both core and outer zone. The formation of this middle zone might, however, disrupt the outer zone, more liquid would be produced, and the xenolith would slowly 'dissolve' into the magmatic liquid.

With reference to natural rocks, a pelitic xenolith in a quartz-gabbro magma would yield a partial melt of cordierite-norite composition (chapter II). This melt might be incorporated into the enclosing magma if no thermal divide was operative between that magma and the partial melt. This would occur if the enclosing magma was a 'potential' quartz-gabbro magma which at the time of xenolith incorporation was still in equilibrium with olivine. The temperature of the magma might therefore be higher than the thermal divide. The partial melt of cordierite-norite composition would have the potential phases, orthopyroxene, plagioclase, cordierite and quartz occult in the liquid, and its potential cordierite combines with the potential clinopyroxene (diopside) in the norm calculation as follows:

$$Mg_2Al_4Si_5O_{18} + 2CaMgSi_2O_6 \longrightarrow 4MgSiO_3 + 2CaAl_2Si_2O_8 + SiO_2$$

i.e. 1 Cordierite + 2 Diopside $\longrightarrow$ 4 Enstatite + 2 Anorthite + 1 Quartz

thus enriching the magma still further in orthopyroxene, plagioclase and quartz. Bowen (1928) proposed similar reactions for the assimilation/

assimilation of refractory material by a basic magma. Thus the most xenolithic gabbros would tend to be quartz-bearing and 'orthonoritic' in character (low amount of clinopyroxene and (opx $\gg$ cpx).

In chapter II it was stated that a magma crystallising olivine (olivine-gabbro) could, if its temperature remained high enough, modify its composition by continued assimilation of sedimentary material until a completelsequence of rocks from olivine-gabbro to quartz-cordierite-norite appeared. However this sequence of rock types is <u>not</u> observed at Haddo, and the magma containing xenoliths was probably already trending towards a quartz-gabbro composition (previously discussed in this chapter).

Thus the assimilation of material from the xenoliths by the magma at Haddo and Arnage would probably have the effect of accelerating the fractionating magma along a quartz-normative trend, and decreasing the amount of clinopyroxene in the igneous rocks which crystallised from this magma. This would have the effect of producing an orthopyroxene-rich xenolithic quartz-gabbro closest to the country rock/gabbro boundary.

CHAPTER V

I The Unhomogeneous Rocks and Xenoliths of the Haddo House and Arnage Districts.

1. Haddo

Quartz-cordierite-norites

(a) Field Occurrence

The cordierite-bearing rocks are found in a small area of country, about 3 miles south-east of Methlick, mainly within the Auchedly granite intrusion. In the Wood of Schivas a few isolated outcrops of quartz-cordierite-norites occur (see district map, and fig. 4), but field relations between them and the quartz-hypersthene-gabbros, which also appear in the Wood of Schivas, are obscured, due to lack of exposures. On the south side of the Ythan river, at Craigmuir Wood, cordierite-bearing rocks which also contain potash feldspar and garnet appaar (hypersthene is rarely present). Quartzose rocks and two limestone bands are also found in Craigmuir Wood. In this locality, the xenoliths present in the rocks show a poor north-south alignment which is approximately parallel to the general strike of the country rocks in the Ythan river section, north-west of Methlick. At Tangland Bridge, on the north bank of the River Ythan (outwith the Auchedly granite), many outcrops of different rock types are found together, although no transitions between different types can be seen. At Tangland Bridge every rock type found in the Haddo district is exposed, but these outcropsare probably not in place/

place. Some cordierite-bearing specimens from this location were analysed because of the difficulty experienced in obtaining fresh material elsewhere in the district.

(b) Petrography

The cordierite-bearing rocks comprise two main groups. These are the quartz-cordierite-norites and quartz-cordierite±orthopyroxene±garnet±K-feldspar rocks. The rocks show enormous variation in the proportions of mineral constituents present and although modal compositions are not representative of the group in general one was determined by the author, and Read (1935, pp.612-614) gave 3 more. These 4 analyses are given below:-

Modal Percentages (4 Haddo rocks)

	Quartz-cordierite-norites		Quartz-cordierite±orthopyroxene±K-feldspar±garnet rocks	
Mineral	68 M[x]	1	2	3
Quartz	40.1	28.9	19.5	10.1
Plagioclase	30.5	39.6	31.2	36.1
Cordierite	19.2	12.0	25.9	33.7
Orthoclase	-	-	5.8	6.6
Hypersthene	5.6	5.6	7.0	-
Biotite	4.2	13.3	9.2	1.7
Garnet	-	-	-	9.4
Ores	tr.	0.6	1.4	2.5

[x]see also analyses table

1,2,3 from Read, 1935; p.613 middle (right); p.612 and p.614.

From/

From these modes it can be seen that plagioclase is usually dominant, Generally the xenolithic rocks from Craigmuir Wood have a high proportion of potash feldspar (orthoclase) in the matrix which surrounds the xenoliths. Cordierite is common in the matrix but it is present in greater amounts in the aluminous xenoliths. Orthopyroxene, where present, constitutes only about 6% by volume of these rocks and garnet is only present in the rocks of Craigmuir Wood.

The quartz-cordierite-norites of Haddo are medium grained and consist of small prismatic hypersthenes up to 1½ X 1 mm in size, and platy plagioclase feldspar crystals, sometimes as large as 3 X 2 mm, but usually smaller and similar in size to the orthopyroxene crystals. Both the plagioclase and orthopyroxene crystals occasionally enclose grains of ore minerals. Biotite can appear as large poikilitic crystals, 3 mm by 3 mm in area, enclosing both plagioclase and orthopyroxene crystals, but usually forms small laths, 1½ X 1 mm in extent. Cordierite is seen as small irregular crystals about 0.3 X 1 mm in size, but larger crystals can appear, up to 1 X 2 mm. The cordierite is fresh although slightly altered at its edges, and this, together with its high relief and irregular twinning, distinguishes it from plagioclase.

In addition to the above minerals, the rocks at Craigmuir Wood usually contain orthoclase and garnet (and often have no orthopyroxene). Orthoclase, usually forms large crystals (4 X 3mm) containing/

containing many small inclusions of plagioclase and cordierite. Garnets vary in size from small pieces about 1 mm by 1 mm, to very large crystals (up to 1½ cm across) which exhibit dodecahedral faces. The garnets are usually broken and cracked and contain infrequent inclusions of plagioclase. Quartz is present interstitially.

The orthopyroxene is strongly pleochroic with α pink, β pink to greenish/brown and γ green. It is never zoned. Although the orthopyroxene only constitutes a small percentage of the minerals present in the rock ($< 6\%$), $2V_\alpha$ measurements were obtained from the hypersthenes of 10 quartz-cordierite-norites from Haddo, 6 different hypersthene grains being examined in each thin section. Measurements of $2V_\alpha$ on these hypersthenes gave results in the range 60° to 68°, corresponding to compositions of Fs_{66} to Fs_{73} (hypersthene; Emmons, 1940; Hess, 1960). Although 2 hypersthene compositions can be obtained from each $2V_\alpha$ value because of the shape of curve of 2V against composition, the iron-rich character of the orthopyroxene was verified by separating and analysing the orthopyroxene from a quartz-cordierite-norite (68M). The composition obtained was $En_{38.5}Fs_{61.5}$ (molecular proportions). Its composition from optical data ($2V_\alpha = 60^\circ$) was Fs_{66}, and thus the optical data appeared to give high orthoferrosilite values using the 2V/composition curve in Hess (1960, p.27). However this curve of composition against 2V might be inaccurate/

inaccurate for iron-rich hypersthenes (Fs_{45} to Fs_{100}). Only 2 points were shown and the original paper of Hess (1952) from which this curve was reproduced showed that the two iron-rich pyroxenes plotted were low in Al_2O_3 (0.38% and 0.27%). The orthopyroxene analysed from the Haddo quartz-cordierite-norite contained 4.21% Al_2O_3 (7.06% Al^{IV} in Z group) and high Al_2O_3 might make a difference to the position of the 2V curve at the orthoferrosilite end. Kuno (1954) drew a curve plotting 2V against composition for orthopyroxenes from volcanic rocks. This curve is different from the 'Hess' curve (for plutonic orthopyroxenes) between compositions Fs_{20} to Fs_{80}, with maximum differences at Fs_{50}. Using the 'Kuno' curve, $2V_\alpha$ measurements of 60° to 68° were found to correspond to a compositional range of Fs_{63} to Fs_{68}. These values were in closer agreement with the analytical data on orthopyroxenes. The γ RI of the analysed orthopyroxene was determined and also the γ RI value from orthopyroxenes in other quartz-cordierite-norites whose optical properties ($2V_\alpha$ values) were similar to those of the analysed one. These all gave values of $\gamma = 1.741 \pm .002$ which corresponds to a value of $Fs_{63\pm2}$ (Hess, 1960), and this is in good agreement with the chemical composition of the hypersthene.

The orthopyroxene exhibits a schiller effect due to fine (ore) lamellae parallel to (100).

The plagioclase feldspar is always zoned. Generally centres of/

of crystals had compositions of An_{55} although some crystal cores were zoned to An_{60}. The margins of crystals were usually more sodic (An_{45}). A plagioclase composition given in Read (1935, p.612) of $Ab_{48}An_{52}$ from the cordierite-norite group agrees with plagioclase compositions in the rocks of this group determined by the author. Normative plagioclase feldspar compositions are $An_{52/54}$. The orthoclase- and garnet-bearing rocks of Craigmuir Wood usually contain a slightly more sodic plagioclase than the quartz-cordierite-norites of Schivas (about An_{45} to An_{50}). Some alteration of the feldspar to sericite is seen but it is never extensive.

The biotite is fresh and has a similar pleochroic scheme to the biotite found in the gabbroic rocks of Haddo; intergrowths of biotite and quartz are noted.

Cordierite is common. It is usually colourless when fresh, but marginal alteration is common and sometimes cordierite crystals have been completely altered to a pale yellow material (pinite). Pale-yellow pleochroic haloes are seen surrounding small zircon crystals and sometimes the cordierite exhibits perfect sector twinning (although this is best seen in cordierite-rich xenoliths). No cordierites were analysed but a discussion of possible compositions of cordierite and garnet in these rocks is given below. The cordierite-bearing rocks of Craigmuir Wood contain large spongy plates of orthoclase in which many small inclusions of plagioclase/

plagioclase and cordierite can be seen. The orthoclase is rarely altered and its low RI makes it easily identifiable. Orthoclase crystals can sometimes be seen in the oordierite-bearing rocks of Schivas Wood.

Deep red/brown garnet (pink coloured in thin section) is also present in rocks at Craigmuir Wood. The iron-rich character of these rocks (analysis 100M, table 4) and the colour of the garnet would suggest that the garnet is a variety of almandine. Chinner (1962) discussed the stability of garnet in thermal aureoles and examined the conditions whereby cordierite and garnet can co-exist. At low pressures garnet appears limited to rocks with $MgO+MnO+FeO/Al_2O_3 > 1$, and within that range the rocks must have a high FeO+MnO/MgO ratio. This condition is obviously not relevant to the rocks of Craigmuir Wood e.g. 100M. Increasing pressure tends to move the stability field, garnet-cordierite-biotite, to the Mg-rich side of an AFM diagram, tending to increase the range of rock Mg/Fe ratios from which garnet will form. At high pressure garnet is stable over a complete range of FeO/MgO ratios (and high P_{H_2O} suppresses cordierite preferentially to garnet). High temperature decreases the limiting Fe/Mg ratio of cordierite and the limiting Mg/Fe ratio of garnet, and the garnet-cordierite field contracts. A change in distribution ratio of Fe and Mg between cordierite and garnet is involved and though difficult to estimate, Chinner (1962) proposed that at moderate pressure and temperature a garnet ($Almandine_{75}$ Pyrope/

Pyrope$_{25}$) would co-exist with a cordierite (Mg-member$_{60}$ Fe-member$_{40}$). Thus the rocks of Craigmuir Wood, formed under moderate pressure (3 Kb, Chapter IV) and moderate temperature (discussion this chapter), probably contain Almandine-rich garnet and a Mg-rich cordierite. Chinner (1962) states that high MnO/feO+MgO would extend the garnet-bearing field. This could have been effective in the Craigmuir Wood rocks (MnO = 0.19 in analysis of 100M), and the garnets may contain the Spessartite molecule.

Quartz is always present in the cordierite-norite and is interstitial.

Apatite, iron ores and zircon are present as accessories.

2. Arnage

Similar divisions of the Arnage rocks to those originally proposed by Read (1923a) will be used in this section. However, parts of Read's 'Gabbro type' and 'Arnage gneiss' have been placed in the quartz-cordierite-norite group in this thesis. The main differences in rock classification at Haddo and Arnage between the author and Read (1923a, 1935) have been summarised in a table 2. It should also be noted that part of Read's 'Gabbro type' has already been included in the quartz-hypersthene-gabbros.

1) Quartz-cordierite-norites

(a) Field Occurrence

Quartz-cordierite-norites, comparable with those found in the/

the Wood of Schivas at Haddo, are rare in the Arnage district. However they do occur at Towie Wood, 5 miles north of Ellon, appearing as small isolated exposures near outcrops of quartz-hypersthene-gabbros. Field relations between the two types cannot be established (Read and Farquhar, 1952). Quartz-cordierite-norites are exposed just north of Gallow Hill, on the south bank of the Ebrie burn, about 3 miles NNW of Ellon. It is possible that these exposures are not in place. On the south bank of the river Ythan, north of Braik's Belt, cordierite-bearing rocks occur, in which hypersthene, garnet and orthoclase may be present. These rocks closely resemble the garnetiferous, K-feldspar rocks of Craigmuir Wood, in the Haddo district. Read (1923a, p.458) mapped these as, "Roof cakes of quartzite veined by cordierite-bearing contaminated rocks." It is possible that other occurrences of quartz-cordierite±orthopyroxene±K-feldspar rocks do appear in the Arnage district but only the exposures mentioned, were observed by the author, in the area studied and mapped.

(b) Petrography

The Arnage quartz-cordierite-norites, including the orthoclase- and/or garnet-bearing varieties resemble, both in hand specimen and in thin section, the corresponding Haddo types (of Schivas and Craigmuir Wood). The Arnage types are usually richer in quartz and contain plagioclase similar to that found in the rocks of Craigmuir Wood. Orthopyroxene is rare but some $2V_{\alpha}$ measurements were obtained from pyroxenes in/

in the rocks of Braik's Belt region. These gave an average value of 65° which corresponds to a composition of either Fs_{67} or Fs_{30} (Kuno, 1954). Since no analyses were performed it is impossible to say which composition is correct, but because these rocks are similar chemically and mineralogically to the rocks of Craigmuir Wood in the Haddo House district (p.117), it is probable that the hypersthene composition Fs_{67} is the correct one. This corresponds with the normative hypersthene compositions from analysis of rocks in the Braik's Bslt area, e.g. 231M, table 4.

2) Arnage Gneiss

(a) Field Occurrence and Observations

This rock, a medium grained quartz-biotite-oligoclase-cordierite gneiss containing xenoliths, is the most widespread type found in the Arnage district. The area mapped by the author between Michael Muir and Ebrie bridge, north and south of the Ythan river, contains many exposures of Arnage gneiss. Arnage gneisses were also examined near the Boat of Ardlethen and at several localities on the Ebrie burn.

If the original Ellon gneiss/Mormond Hill quartzite boundary occurred as Read (1923a, p.452) postulated, then Arnage gneisses occur on both sides of this boundary. In many of the areas examined by the author, there would appear to be transitions between the Arnage gneisses and the quartz-cordierite-norites, especially near Braik's Belt. Read and Farquhar (1952/

(1952, p.424) described the Arnage gneiss as "occasionally hypersthene-bearing". However, when the cordierite-bearing Arnage gneiss contains hypersthene, the plagioclase is more calcic (up to An_{50}) and the rock can be termed a quartz-cordierite-norite and placed in that group. At Braik's Belt many varieties can be seen including quartz-cordierite-norites, quartz-cordierite±K-feldspar±garnet rocks and 'typical' Arnage gneiss, all of which appear to be closely related to one another. Differences in bulk compositions would appear to be responsible for differences in mineralogy. There would appear to be no real 'dividing line' between the Arnage gneisses and quartz-cordierite-norites. However, in this study, the term Arnage gneiss will refer to a quartz-biotite-oligoclase-cordierite gneiss±garnet which contains xenoliths. It never contains hypersthene or orthoclase in the matrix, but can contain hypersthene as a constituent of xenoliths. In many parts of the Arnage district, xenolithic Arnage gneisses occur which are similar to the xenolithic gneisses found near the river Ythan, just south of Methlick described in chapter III.

(b) Petrography

Read (1923a, p.463) stated that ... "the relative proportion of the chief constituents /of the Arnage gneiss/ is extraordinarily variable. Any of the four main components (quartz, cordierite /plagioclase/ feldspar, and biotite) may dominate." This variation in mineral constituents together with the gneiss's xenolithic/

xenolithic character makes modal analysis of dubious significance, and none have been determined. The main minerals are briefly described.

Plagioclase feldspar is usually andesine (An_{30} to An_{34}) and slightly zoned. It is usually found as small platy crystals 1 mm to 2 mm long although larger ones are seen. (Read, 1923a, noted crystals up to 1 cm long).

The cordierite forms irregular crystals up to 5 mm long. Sector twinning of a patchy nature, alterations and pleochroic haloes have all been observed.

Biotite plates, about 2 X 2 mm, are common and these exhibit the usual pleochroic scheme (yellow to red/brown). Slight alteration to chlorite is occasionally seen.

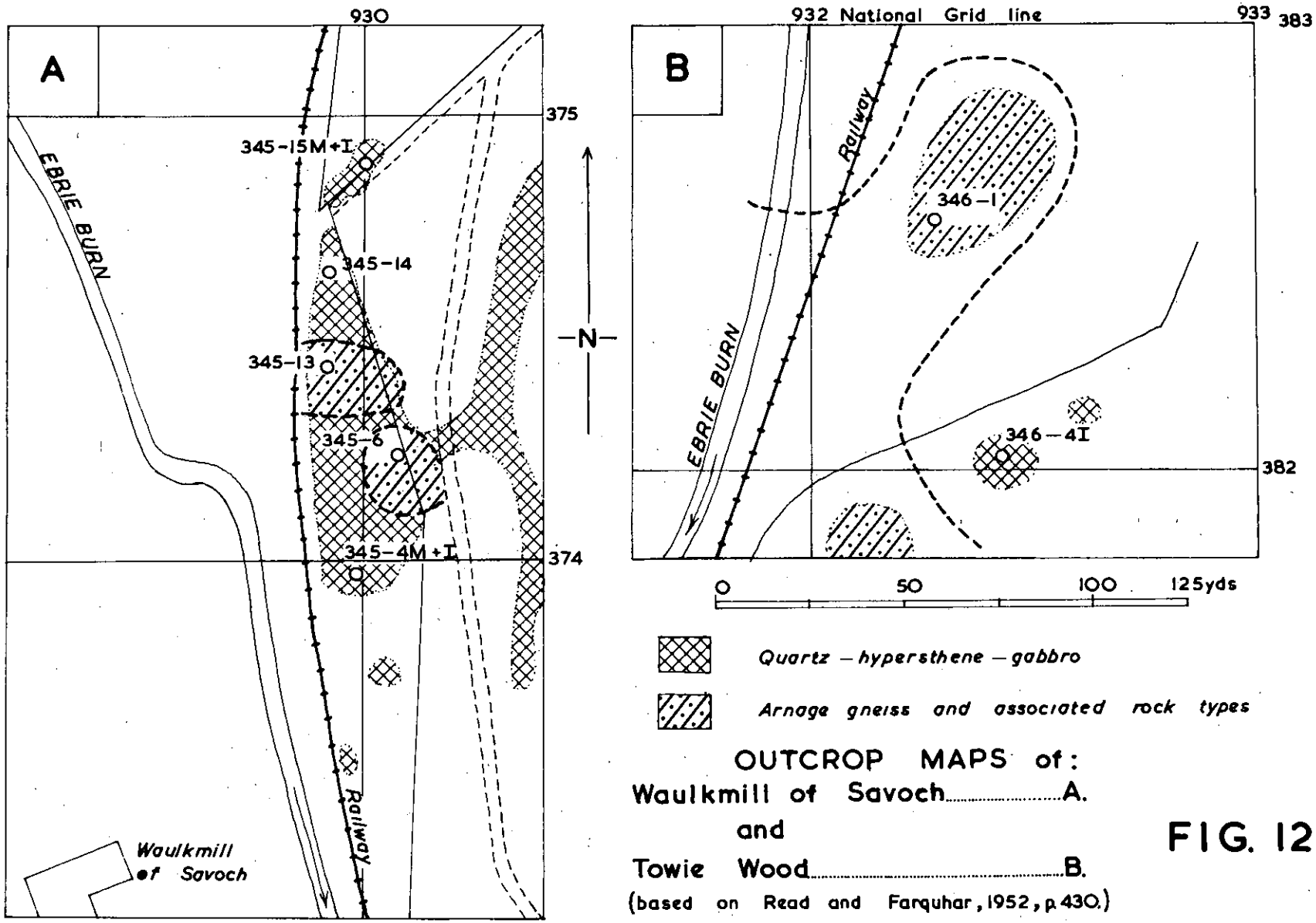
Quartz is interstitial and appears as irregular interlocking crystals with sutured boundaries. Strain effects are often present.

In addition to these major minerals garnet appears occasionally and apatite, zircon and iron ore are the normal accessories.

Because of paucity of exposures in the district field relations between the Arnage gneisses and the gabbros are difficult to determine. Read and Farquhar (1952, p.429) described Arnage gneiss/gabbro field relations from a few localities along the Ebrie burn. At Towie Wood and Gallow Hill, they concluded that "from /these/ localities ... no more than suggestions concerning the relations of gabbros and Arnage Type can be made." However/

However east of Waulkmill of Savoch, two small areas of xenolithic Arnage gneiss appear in a railway cutting which is dominantly composed of gabbroic rocks. A larger scale mappof this locality (including Towie Wood) is given, in this thesis, figs. 12A and B. Read and Farquhar (1952, p.431) suggested "that the more northerly of these /areas of Arnage gneiss/ ... consists mostly of norite /orthonorite ??/ with bands or large xenoliths of cordierite-free Arnage Type rock which itself holds enclaves of the chief country rocks." However this was only a suggestion as they had previously stated that ... "the relations between the rock types ... cannot be firmly established without detailed slicing on the spot." South of this occurrence the remaining area of Arnage gneiss in the railway cutting is "clearly ... enclosed within the /quartz-hypersthene-gabbro/."

These statements on the gabbro/Arnage gneiss relationshipps must be regarded as hypothetical because the Arnage gneiss areas at Savoch are never seen to be surrounded on all sides by gabbroic rocks, and their relations in depth are unknown. It is possible that the Arnage gneiss outcrops could be part of an irregular roof of country rocks. Another hypothesis is that these could be small rafts of country rock caught up in the roof of the gabbro. A similar theory was proposed earlier in this thesis to explain country rocks apparently outcropping within the main body of the Haddo House gabbro (chapter III, p. 65). If this is so, then Read and Farquhar's statement (p.431) "the enclave/



OUTCROP MAPS of:
Waulkmill of Savoch.....A.
and
Towie Wood.....B.
(based on Read and Farquhar, 1952, p. 430.)

FIG. 12

enclave-bearing Arnage Type rock /Arnage gneiss/ occurs as a xenolith within the norite /quartz-hypersthene-gabbro/" could be correct. Their conclusion, which allegedly follows from this, namely ... "that the gabbro intrusion is later than the formation of rocks of the Arnage Type" need not, however, be correct, and another hypothesis will be put forward in the petrogenetic section; namely that the Arnage gneiss was formed at the same time as the gabbros were intruded. It is worthwhile mentioning briefly the mineralogy of the Arnage gneisses in the railway cutting. The more northerly of the two areas is not noritic as Read and Farquhar (1952) suggested, but a quartz-biotite-plagioclase feldspar-gneiss which surrounds xenoliths containing hypersthene and calcic plagioclase (cordierite may also be present but only as knots of alteration products). In the other area of gneiss, a matrix of quartz-biotite-(feldspar)-cordierite-gneiss with or without garnet contains occasional aluminous xenoliths of cordierite and spinel.

3) Ardlethen gneiss

(a and b) Field Occurrences and Petrography

The diagnostic feature of this gneiss, from the type area of Read (1923a) south-east of Ardlethen, seems to be the occasional presence of large crystals of orthoclase feldspar. Otherwise this Ardlethen gneiss closely resembles the Arnage gneiss. Mineralogically/

Mineralogically and texturally it is similar to the Arnage gneisses, and even chemically there would appear to be no real differences between the two groups. In table 4 nos. 322M and 296 are analyses of Ardlethen gneisses from the type area of Read (1923a) and these are very similar to analyses of Arnage gneisses (same table). The Ardlethen gneiss is usually xenolithic and the xenoliths which it contains are mineralogically similar to xenoliths found in the Arnage gneiss. Read and Farquhar (1952, p.435) stated that the Ardlethen gneiss was ... " 'granitic' in character and dominantly composed of quartz, oligoclase, potash feldspars and biotite." An analysis of Ardlethen gneiss given by Read (1923a, and re-quoted in Read and Farquhar, 1952) is also reproduced in table 4 (analysis VIII). From its location, "340 yards SSE of Ardlethen," this is an analysis of a pink, foliated granite similar to the Glencroft granite which occurs in a few isolated outcrops near Upper Ardlethen Farm. Read (1923a) first mappped the Glencroft granite as an intrusive body, but subsequent mapping lead Read to believe that it was xenolithic in character and passed to the north, into Arnage gneiss. It is usually homogeneous and only occasionally are mica-rich pods found within it. Its constituents are quartz, oligoclase, orthoclase, biotite and rare muscovite and accessory minerals such as apatite and ores. Northwards from Glencroft quarry, relations between this granite and the Arnage gneisses are obscured/

obscured due to poor exposure but east of Glencroft, about 50 yards north of the main road, a sharp contact between Arnage gneiss and Ardlethen granite is exposed. Contact effects are not noted in the gneisses outcropping near this boundary but this is not surprising as their xenolithic character would probably tend to conceal any contact effects. From analysis VIII (table 4; from Read, 1923b) which incidentally appears too low in H_2O+, the Glencroft rock type resembles a biotite-granite (adamellite), and both mineralogically and chemically it is similar to intrusive granites described from other parts of north-east Scotland by Read (1923b). He described the Aberchirder granite at Huntly as a "gneissose" granite (actually a granite with "fluxional-structures") which contains quartz, orthoclase, oligoclase, microcline and biotite. Unfortunately, this granite was not analysed but another intrusive granite from the Huntly district (analysed in Read, 1923b, p.115, analysis VII) is chemically similar to the Glencroft granite. It would appear that the Glencroft granite is an intrusive "Newer" granite, unrelated to the Ardlethen gneiss.

4) Kinharrachie gneiss

(a) Field Occurrence

This dioritic gneiss is most common in the southern part of the Arnage district. Its type locality is in the area near West/

West Kinharrachie farm, especially at Craighorn Wood on the east bank of the Ythan river, where the gneiss forms large, blocky crags. At the Boat of Ardlethen, 2 miles west of Ellon, the Kinharrachie gneiss appears as a small tongue of amphibole-bearing rock surrounded to the north, south and west by Arnage gneisses. Although mapping was not continued further north than the main Methlick to Ellon road, the area occupied by these amphibole-bearing gneisses would appear to be smaller than that proposed by Read (1923a) since its eastern boundary is quite well marked. This boundary must lie to the west of two quarries (see district map), both of which expose quartz-biotite-bearing Arnage gneisses. The other main locality for this type is in an area about 1½ miles NW of Ellon, where it is exposed in railway cuttings (Read, 1923a, p.465). This latter area was not examined by the author.

(b) Petrography

Mineralogically the Kinharrachie gneiss constitutes a completely different rock type from the cordierite-bearing types, so far described in this chapter. In the hand specimen the rock is medium to coarse grained, containing large clusters of green amphibole crystals and occasional brown biotites, set in a cream coloured feldspathic matrix. The rock is xenolithic and both quartzose and iron (and magnesium)-rich inclusions are present.

The/

The rock has a granular texture in thin section with large prismatic amphibole crystals, 3 X 2 mm in size, and smaller, platy plagioclase feldspar crystals (1 X 1½ mm in area) dominating. The feldspars are sometimes enclosed in the amphibole. Plates of biotite, 2 mm by 2 mm in area, are also noted, and quartz is interstitial.

Read (1923a) reported that this group contained quartz, biotite, plagioclase, hornblende, pyroxene and iron oxide. Pyroxene is a rare mineral in the matrix but it is present in some xenoliths. Read also noted the presence of orthoclase and garnet in the dioritic gneisses, from the locality north-west of Ellon, but these minerals have not been observed in the gneiss at Kinharrachie. The main minerals are as follows:-

The amphibole is pleochroic with α pale yellow, β olive green/brown and γ blue-green. 2V is large (-ve) and $\gamma \wedge c$ is 17°. This mineral is probably hornblende as Read (1923b) suggested, but no analytical work was carried out.

The plagioclase feldspar is slightly zoned and of andesine composition, An_{40}. It often shows cloudy alteration.

Orthopyroxene is very rare but one specimen contained a few grains which were pleochroic in thin section in pink and greens. $2V_{\alpha}$ is 49°. Because of its scarcity it was impossible to separate and determine the γ RI of hypersthene and therefore there are two possible compositions for this mineral. The shape of the curve of 2V against composition for hypersthenes makes/

makes the composition either Fs_{43} or Fs_{54} (normative mineral compositions would suggest Fs_{43}).

Brown pleochroic biotite forms large poikilitic plates enclosing feldspars and ores, and quartz is interstitial.

In his account of the Kinharrachie gneiss Read (1923a) stated that it would be possible to assume that this rock was igneous in origin from an examination of hand specimens, but field evidence refuted this hypothesis. Examples of garnetiferous and orthoclase-bearing types were given. Many examples of transitions from Arnage gneisses to Kinharrachie gneisses were described and details of their association on a small scale. Read (1923a) then concluded that the Kinharrachie gneiss was derived from the hornblende schist group which is a subordinate member of the Ellon gneisses.

N.B. Descriptions of the main Arnage rock types in this section of the thesis have constituted no more than a summary of the main mineralogical data. Field occurrences generally refer to that part of the Arnage district mapped by the author (usually the valley of the river Ythan between Michael Muir and Ellon). A more detailed, excellent account of the distribution and petrography of the gneisses of the Arnage district can be found in Read (1923a, pp.457-473).

3. The Xenoliths

(a) Field Occurrence

Xenoliths are found in all the rocks of doubtful origin described/

described in this chapter from both the Haddo and Arnage districts and also occur in the quartz-hypersthene-gabbros.

(b) Petrography

The xenoliths found in the Haddo and Arnage districts display great mineralogical variety. The broad classification of xenoliths proposed by Read (1935; based on Tilley, 1924) is by far the best and easiest to use: Read proposed that "a classification /of the xenoliths/ based on easily recognised rock types of geological significance /namely argillaceous, siliceous and calcareous/ be employed."

Read (1935) included another type termed "greenstone xenoliths" calcium-rich pyroxene-bearing xenoliths which were probably derived from the hornblende schists of the Ellon series. Many such xenoliths are associated with the Kinharrachie gneiss and probably belong to class 6 table facing (Tilley, 1924).

Argillaceous xenoliths are among the most frequently observed and their mineralogy is variable. They can contain varying proportions of minerals such as corundum, spinel, sillimanite, cordierite and plagioclase. Hypersthene occurs and actually dominates in a few inclusions (64I, and 68I, table 5). Mineral assemblages similar to the above have been observed in pelites from other areas which have been thermally metamorphosed (Tilley, 1924; Leake and Skirrow, 1960; Barker/

Hornfels Mineral Assemblages of the Inner Contact Zone of the Carn Chois Diorite.

Shale - Calcic Group		Non - Calcic Hornfelses	
Free - silica	Silica - poor	Free - silica	Silica - poor
1* Andalusite, Cordierite	1a Andalusite, cordierite corundum 1b Cordierite, corundum 1c Cordierite, corundum spinel	1 Mg i. Cordierite	1 Mg ii. Cordierite Hypersthene
2 Andalusite, cordierite plagioclase	1d /Corundum, spinel/* 1e /Corundum, spinel, andalusite/ 1f /Spinel, andalusite/ 1g Spinel, andalusite, cordierite		
3 Cordierite plagioclase	3c Cordierite, spinel plagioclase 3b Spinel plagioclase		
4 Cordierite, plagioclase hypersthene	4a Cordierite, spinel plagioclase, hypersthene 4b Spinel, plagioclase hypersthene		
5 Plagioclase, hypersthene			
6 Hypersthene, plagioclase diopside			

/ /* Assemblage predicted by Tilley but not observed

1, etc. Assemblage number in classification

All the above assemblages may contain biotite, and orthoclase as additional minerals.

Reproduced from Tilley, 1924, p.58.

Barker, 1964). In these other areas, basic bodies had been intruded into pelitic country rocks. The hornfelsed pelites within the aureole of the basic masses contain minerals similar to those seen in the argillaceous xenoliths from the rocks of Haddo and Arnage.

Tilley (1924) described mineral assemblages observed in thermally altered country rocks at Comrie, Perthshire. Each mineral assemblage was assigned to different classes depending on whether these were calcium-bearing or calcium-deficient with further divisions if the assemblage contained free silica or was silica-poor. Some of these divisions are given on the facing page.

Assemblages similar to those of Tilley (1924) were given by Turner and Verhoogen (1960) as present in rocks from high grade facies of contact metamorphism. Mineral assemblages were presented on ACF (and AMS) diagrams.

Read (1935) listed the various silica-poor assemblages at Haddo as follows:-

(Tilley's class number is given).

Cordierite-corundum-spinel-(plagioclase)	Class 1c
Corundum-spinel	1d
Spinel-sillimanite-cordierite-(plagioclase)	1g
Cordierite-spinel-plagioclase	3a
Spinel-plagioclase	3b
Cordierite-spinel-plagioclase-hypersthene	4a

The author has also observed the following types of assemblage in xenoliths from the Haddo and Arnage districts:-

Sillimanite-/

Sillimanite-(? cordierite)	)	Class 1) or either
Sillimanite-(? cordierite) -plagioclase	)	2) 1 or 2.
Cordierite-plagioclase-(?)	)	3 (or 4 ?)
Plagioclase-hypersthene	)	5
Cordierite-hypersthene	)	1 Mg. ii.

Silica-saturated assemblages (not 1 Mg. ii.)

All the above assemblages also occur containing biotite as an additional mineral phase present. Mineral assemblages similar to many of the above have been described by Stewart (1946) from the hornfelses in the Sparcraigs area of the Belhelvie district. There, most of the hornfelses contain garnet whereas garnet is rarely present in the Haddo and Arnage xenoliths. Garnet, however, is an important constituent in the cordierite-bearing rocks of Craigmuir Wood and Braik's Belt, where it appears as a constituent of the matrix which surrounds silica-poor xenoliths.

In the hand specimen the 'argillaceous' xenoliths are usually bluish, greasy looking hornfelses of variable, but usually small grain size. Spinel crystals are small, about 0.3 mm across, but occasionally larger aggregates occur. Hypersthene crystals also are small, often less than 0.5 mm in length, and occur as small subhedral prisms. Cordierite appears as small grains about 0.6 X 0.6 mm in area, but in the corundum-bearing xenoliths euhedral cordierites appear which are slightly larger (1 mm across). Corundum is present as small subhedral, broken crystals (0.6 X 0.6 mm in size), often prismatic and enclosed in biotite or plagioclase. Small, thin, prismatic crystals of sillimanite up to 2 mm long by 0.03 mm broad, can be observed. Biotite varies in size

probably/

probably depending on orientation from plates 1½ mm X 1½ mm in area, to very thin (0.06 mm) laths which might also be quite large in area (i.e. || to the (001) plane). Plagioclase varies in size but in most cordierite-spinel-plagioclase xenoliths, if the cordierite is small the plagioclase also is small. In the corundum-spinel xenoliths (class 1c) the plagioclase usually occurs as large square prisms up to 2 mm X 2 mm in extent.

A brief note on the main minerals present in the argillaceous xenolith group is given.

The corundum is usually colourless, but may be faintly pleochroic in pinks and blues. It was high relief, low birefringence and exhibits a rough cleavage or parting.

Cordierite is colourless with good pleochroic haloes. It is fresh with only slight alteration at the crystal edges. In some xenoliths cordierite shows good hexagonal (pseudo-hexagonal) form. Sector twinning is common.

Spinel is deep green (? pleonaste).

Some inclusions have orthopyroxene dominant. Only three xenoliths of this type were found and each of these contained an orthopyroxene more Mg rich than the orthopyroxene of the surrounding matrix. Specimen 68I contained an orthopyroxene of composition En_{41} Fs_{59} (molecular proportions) as against an orthopyroxene of composition $En_{38.5}$ $Fs_{61.5}$ from the surrounding matrix (both compositions obtained from analyses). A true separation of xenolith from matrix is essential if ortho-

pyroxene/

pyroxene compositions are required. Orthopyroxenes from both xenolith and matrix were examined from another quartz-cordierite-norite. RI γ measurements were obtained and these showed that orthopyroxene of the matrix had an RI γ = 1.741±.002 corresponding to a composition of Fs_{62}, whereas the orthopyroxene of the xenolith had RI γ = 1.738±.002 giving a composition of Fs_{58} (Hess 1960). A small xenolith extremely rich in hypersthene (64I) was separated from its surrounding quartz-hypersthene-gabbro matrix (64M). $2V\alpha$ readings were obtained for the orthopyroxene from both matrix and xenolith. The matrix orthopyroxene had $2V\alpha = 51^{o}$ corresponding to a composition Fs_{41}, and the xenolith orthopyroxene had $2V\alpha = 54^{o}$ corresponding to a composition of Fs_{37}. It is interesting to note that the normative orthopyroxene in 64I is much more Mg rich than the normative orthopyroxene in 64M (data from analysis, table 4).

Sillimanite occurs as small colourless prisms, elongated parallel to the c axis. Some xenoliths containing sillimanite (and quartz) often have the other constituent minerals (? cordierite, ? mica) completely altered to micaceous products. What these products are it is difficult to say but specimen no. 85I (table 5) contains 6.67%H_2O+ and it is possible that the alteration product is a member of the chlorite family.

The Plagioclase feldspar composition is rather difficult to identify. However in some xenoliths especially the corundum-spinel-cordierite types, where plagioclase is present as/

as large crystals, it is zoned with calcic plagioclase cores.

Biotite is a common mineral in the xenoliths, and quartz also can appear in the free-silica assemblages. Stewart (1946) also noted these minerals in some of the hornfelses at Sparcraigs. Other minerals occur as minor constituents, excluding the alteration products which appear in most xenoliths. In xenolith 74I from a quartz-hypersthene-gabbro, minerals not reported by Read (1935) have been seen and it is considered worthwhile to record these here. Identification was solely by optical methods.

Lazulite is a mineral of moderate relief, and pleochroic with α colourless, β , γ azure blue. 2V is (-ve) but was difficult to estimate. Lazulite, an aluminium-hydroxy-phosphate, is very scarce in the rock (only 3 grains were apparent in 2 thin sections). The P_2O_5 content of the rock is low, although the whole rock analysis is perhaps suspect because of the difficulty experienced in getting this rock into solution. The aluminous xenoliths proved extremely difficult to analyse. Normally rocks were crushed to 100 mesh powder before analysis commenced. This powder was treated with hydrofluoric acid to decompose the sample and subsequently taken up in other acids e.g. HCl, H_2SO_4, before the amount of each oxide present in the rock could be determined (excluding SiO_2, H_2O, see brief account of analytical techniques in appendix E). However hydrofluoric acid/

acid does not decompose certain minerals, e.g. spinel, corundum, sillimanite, lazulite, etc., and the alumina-rich minerals have to be decomposed by fusion with potassium dihydrogen sulphate, sodium carbonate or sodium peroxide before dissolution in the other acids is possible. Even with repeated fusions many xenoliths still showed insoluble residues, with the result that a few analyses of xenoliths have low totals of the analysed oxides (74I, 273I, etc.); probably Al_2O_3 although in 74I other elements might be 'low' P_2O_5, TiO_2, etc.

Sphene is present as small yellow/brown crystals with good crystal shape. Its strong dispersion and high relief make it easy to identify. It appears associated with biotite and is often enclosed in large biotite laths.

Minute prisms are present which exhibit extremely high relief, weak pleochroism in pale shades of brown and extreme dispersion. These might be brookite (TiO_2) but no good estimate of 2V was obtained although it might be (+ve) ? biaxial.

In the xenoliths zircon is sometimes present, and ores are often observed (magnetite and ilmenite).

Read (1923b) noted garnet and alkali feldspars present in some xenoliths but, as has been stated before, these minerals probably occur in the enclosing matrix. For example, xenolith 101I contains no orthoclase (only cordierite,/

cordierite, spinel and sillimanite±plagioclase) and yet the K_2O content of the analysed material is high. This is because the xenoliths are small fine-grained inclusions surrounded by a matrix containing garnet, orthoclase and cordierite. This matrix is extremely difficult to separate completely from the xenolith and therefore many xenoliths from rocks of the Haddo and Arnage districts appear to be quite rich in K_2O. Some analysed xenoliths do show the low K_2O content their mineral assemblage suggests, and analyses of silica-poor xenoliths in Read (1935, p.619) confirm this low K_2O content.

Some xenoliths are zoned, especially those from the quartz-hypersthene-gabbros. These have a core of spinel and corundum (and plagioclase) which grades into a spinel-cordierite (-plagioclase) zone. The contact between xenolith and surrounding matrix is often marked by a 'rim' of biotite with or without feldspar. These minerals are commonly altered to chlorite and sericite. Read (1935, p.620) described these zoned xenoliths and stated that the 'reaction rim' between them and the surrounding rock consisted entirely of basic plagioclase in some cases, and micaceous products in others Specimen 347-21A is a feldspathic (+ biotite + orthopyroxene) xenolith in a quartz-hypersthene-gabbro (347-21B, table 3). The orthopyroxene is highly altered and only cores of these crystals remain. As the xenoliths contain no cordierite or orthopyroxene it could be termed an orthonorite and this is one of the/

the very rare examples of a plagioclase-hypersthene (-quartz-biotite) assemblage found in the Haddo and Arnage areas.

Quartz is the dominant constituent in the siliceous xenoliths, appearing as large grains surrounded by what Read (1935) termed "a scanty reconstructed matrix." The matrix composition varies, depending on the composition of the original quartzite or psammite. Sometimes more calcic varieties tend to show amphibole or pyroxene crystals, or a large amount of plagioclase, in the matrix surrounding the quartz grains. Biotite is common and one siliceous xenolith contains large crystals of epidote in addition to quartz.

Argillaceous and quartzitic xenoliths are both extremely common. Read (1935) stated that the argillaceous xenoliths were most abundant and this would certainly appear to be true judging by the numbers of 'pelitic' xenoliths analysed in table 5. However the mineral assemblages of the silica-saturated and silica-poor hornfelses, and their conspicuous appearance in the hand specimen could be a reason for these being collected in preference to others. Certainly, the author found he had collected far more spinel- and cordierite-bearing xenoliths than any dher type even although some gabbroic rocks in the Haddo policies for example in Gillha Wood contain abundant siliceous xenoliths.

Only one true derivative from a calcium-rich schist was collected and anlysed, (345-15I). In thin section it contained amphibole/

amphibole (tremolite), plagioclase and orthopyroxene. A xenolith derived from a calc-silicate rock would probably have an analysis similar to no.110, appendix B, which is an analysis of a calc-silicate band found in the quartizitic rocks of Craigmuir Wood. Read (1935) found some calcareous xenoliths and these contained wollastonite, tremolite and diopside which could be accompanied by small quantities of quartz, plagioclase, sphene and rare biotite.

In each xenolith-bearing rock examined the xenolith is quite separate from the material which surrounds it. A reaction rim of alteration products usually separates matrix and xenolith and the xenolith grain size is often much smaller than the grain size of the matrix.

Two interesting facts emerge regarding the xenoliths of Haddo and Arnage. Rarely does one find large xenoliths, the largest recorded, a siliceous one, measured 2 ft. by 6 inches. The large xenoliths are invariably quartzitic and the argillaceous xenoliths are almost always small averaging about 2 inches in length. Silica-poor xenoliths from Craigmuir Wood never contain corundum, and spinel is scarce, whereas the silica-poor xenoliths from the quartz-hypersthene-gabbros often contain corundum. In fact corundum-bearing xenoliths are only found in the quartz-hypersthene-gabbros, never in the quartz-cordierite-norites and associated rocks.

District	HADDO									ARNAGE
Rock Type	Quartz-cordierite-norite				Quartz-cordierite-norite					±garnet ± Kfs
Rock no.	68M	69	88	89	99	100M	113	117	118	345-15M
SiO_2	58.06	58.33	55.27	56.54	73.77	57.88	63.38	73.15	80.23	62.37
TiO_2	1.65	1.53	1.60	1.52	0.72	0.73	1.29	0.83	0.59	1.12
Al_2O_3	17.56*	18.35	21.13	18.19	13.66	19.40	16.22	12.88	9.47	15.25
Fe_2O_3	1.37	1.80	2.73	2.65	0.96	1.46	1.66	0.90	0.71	1.67
FeO	7.17	7.69	6.98	8.15	3.63	7.67	5.33	3.74	2.77	4.83
MnO	0.13	0.15	0.16	0.17	0.089	0.19	0.11	0.075	0.068	0.11
MgO	2.74	3.25	3.02	3.02	1.19	1.29	2.00	1.33	0.87	3.68
CaO	4.68	3.84	4.05	4.35	2.39	0.64	3.09	1.93	1.19	4.37
Na_2O	2.36	1.76	1.80	2.17	1.42	1.18	2.16	1.30	1.02	2.50
K_2O	1.22	1.20	0.94	1.06	0.69	7.24	2.80	1.61	1.13	1.97
H_2O+	1.41	1.26	1.31	1.25	0.76	1.72	1.97	1.23	1.07	1.50
P_2O_5	0.12	0.084	0.22	0.095	0.067	0.25	0.18	0.070	0.077	0.068
Total	98.47	99.24	99.21	100.07	99.35	99.65	100.19	99.05	99.20	99.44
Trace elements in p.p.m.	*probably low		All analyses carried out by author on powder dried at 110°C for 2 hrs.							
Gr	100	125	141	142	84	96	74	119	73	172
Ba	480	595	360	400	475	1420	1035	835	675	625
Sr	298	275	257	255	219	218	247	150	125	250
Rb	15	32	22	32	18	183	82	65	37	65
ESKOLA NORMS										
	68M	69	88	89	99	100M	113	117	118	345-15M
Orthoclase	7.60	7.45	5.80	6.55	4.30	44.70	17.25	10.15	7.15	12.05
Albite	22.35	16.55	16.90	20.45	13.45	11.10	20.25	12.40	9.80	23.25
Anorthite	23.70	19.45	19.70	22.05	12.10	1.80	14.95	9.75	5.75	22.00
Orthopyroxene	15.46	17.28	14.02	16.18	7.08	13.28	10.26	7.64	5.34	14.46
Quartz	21.48	25.82	25.08	21.85	53.12	15.18	27.65	50.78	64.45	22.67
Corundum	4.73	8.42	11.73	6.62	7.35	10.26	5.00	6.56	5.40	1.40
Magnetite	2.02	2.62	3.98	3.88	1.40	2.12	2.42	1.34	1.06	2.40
Ilmenite	2.42	2.22	2.32	2.22	1.06	1.06	1.88	1.24	0.88	1.62
Apatite	0.25	0.18	0.45	0.20	0.13	0.50	0.35	0.15	0.18	0.15

TABLE 4

District	ARNAGE											
Rock Type	Arnage Gneiss								Ardlethen Gneiss			Kinharrachie Gneiss
Rock no.	231M	236M	250M	256M	273M	345-6	345-13	346-1	296	322M	VIII *	309M
SiO_2	60.37	60.58	75.24	62.61	65.76	68.31	59.24	65.46	70.24	63.31	69.84	60.48
TiO_2	1.54	1.02	0.78	1.30	0.83	0.66	1.04	0.93	0.84	0.85	0.60	0.92
Al_2O_3	17.54	18.93	11.60	17.80	17.02	14.75	16.20	17.27	14.22	17.17	13.16	14.34
Fe_2O_3	1.50	1.77	0.76	1.44	1.08	1.22	1.86	1.70	0.84	1.49	1.45	2.87
FeO	7.40	6.11	2.95	6.60	4.89	4.36	5.67	5.42	4.31	5.03	2.37	5.52
MnO	0.12	0.092	0.061	0.12	0.11	0.14	0.16	0.13	0.10	0.084	0.15	0.11
MgO	2.46	2.52	1.06	2.20	2.25	1.89	4.10	1.60	1.99	2.55	1.06	4.42
CaO	1.21	1.65	0.85	2.81	1.85	2.95	4.20	1.55	1.55	2.11	2.13	5.84
Na_2O	2.14	2.00	2.07	2.34	2.57	1.98	2.31	1.53	2.08	2.94	3.07	3.12
K_2O	2.96	3.00	2.47	1.68	2.46	1.55	2.23	2.53	2.99	2.31	5.68	1.32
H_2O+	2.11	2.35	1.08	1.44	1.65	1.65	2.21	1.17	1.00	1.92	0.06	1.00
P_2O_5	0.096	0.095	0.079	0.25	0.11	0.10	0.13	0.074	0.073	0.095	0.14	0.055
Total	99.45	100.12	99.00	100.57	100.57	99.56	99.35	99.36	100.23	99.86	99.71	100.00
Trace elements in p.p.m.	All analyses carried out by author on rock boulder dried at 110°C for 2 hours + Analysis from Read (1923b, p. 464); analyst E.G. Radley.											
Cr	137	155	124	74	137	132	166	134	114	144	n.d.	153
Ba	1225	870	950	455	725	385	400	1355	1565	650	1100	435
Sr	194	181	135	190	224	235	259	185	194	229	n.d.	218
Rb	75	105	75	78	53	50	74	59	96	56	n.d.	34
ESKOLA NORMS												
	231M	236M	250M	256M	273M	345-6	345-13	346-1	296	322M	VIII+	309M
Orthoclase	18.40	18.50	15.40	10.25	14.95	9.60	13.75	15.70	18.25	14.10	34.10	7.95
Albite	20.20	18.70	19.60	21.70	23.70	18.70	21.65	14.45	19.30	27.30	28.05	28.65
Anorthite	5.75	7.95	4.00	12.90	8.80	14.80	21.00	7.60	7.50	10.20	5.40	21.72
Orthopyroxene	14.94	13.24	5.72	13.10	11.62	10.08	17.02	9.80	10.34	12.10	2.24	12.96
Quartz	25.91	26.42	48.08	29.05	30.11	38.54	19.12	37.69	36.52	25.69	23.37	17.12
Corundum	10.13	10.94	4.76	8.54	7.86	5.33	2.98	10.75	5.53	7.03	-	-
Magnetite	2.20	2.58	1.12	2.08	1.54	1.78	2.70	2.50	1.20	2.16	2.06	4.08
Ilmenite	2.26	1.48	1.16	1.88	1.20	0.96	1.52	1.36	1.20	1.22	0.84	1.32
Apatite	0.20	0.20	0.15	0.50	0.22	0.20	0.25	0.15	0.15	0.20	0.27	0.12
										CPX	3.64	6.08

* Norm calculated by author

TABLE 4 (contd.)

District	HADDO								
Surrounding Matrix	Quartz-hypersthene-gabbros				Quartz-cordierite-norite (and related rocks)				
Xenolith no.	64I	74I	85I	347-21A	68I	83I	90I	100I	101I
SiO_2	51.16	42.21	43.94	56.00	51.01	73.85	71.92	49.10	50.80
TiO_2	0.45	0.98	1.76	1.10	0.80	0.18	0.65	1.17	1.40
Al_2O_3	10.30	32.23	29.75	23.97	12.87	13.07	12.13	26.67	27.52
Fe_2O_3	2.00	3.51	4.47	0.78	1.53	0.72	0.79	3.46	2.35
FeO	14.98	2.46	7.47	2.66	19.29	0.67	3.17	8.10	7.44
MnO	0.35	0.20	0.15	0.047	0.35	0.019	0.085	0.055	0.13
MgO	15.20	2.15	2.64	1.51	7.72	0.38	2.73	1.11	1.92
CaO	4.04	9.55	0.51	8.73	3.30	1.52	4.79	0.52	0.56
Na_2O	0.84	2.91	0.71	2.94	1.61	2.87	1.23	1.48	1.12
K_2O	0.30	1.21	1.19	0.89	0.43	5.28	0.74	7.13	5.98
H_2O	0.54	1.10	6.67	1.14	0.61	0.46	0.95	0.75	0.63
P_2O_5	0.071	0.076	0.049	0.069	0.053	0.055	0.21	0.16	0.22
TOTAL	100.23	98.59	99.31	99.84	99.57	99.08	99.40	99.71	100.07

All analyses carried out by the author on material dried at 110°C for 2 hrs.

Trace elements in p.p.m.

	Cr	97	196	205	139	86	13	122	156	129
	Ba	30	1015	390	370	0	3250	525	2180	1225
1	Sr	129	400	81	410	186	267	315	212	155
	Rb	13	34	44	32	8	104	12	178	138

ESKOLA NORMS

	64I	74I	85I	347-21A	68I	83I	90I	100I	101I
Orthoclase	1.80	7.25	7.80	5.35	2.65	32.05	4.60	43.25	36.05
Albite	7.60	23.40	7.05	26.80	15.10	26.50	11.60	13.65	10.25
Anorthite	19.75	47.60	2.50	43.50	16.85	7.35	23.65	1.55	1.50
Orthopyroxene	62.90	-	11.54	5.82	50.80	1.12	11.12	9.54	12.04
Quartz	2.82	-	29.39	13.01	6.68	31.70	45.27	7.16	13.60
Corundum	1.56	9.88	32.00	2.71	4.42	0.02	1.22	17.90	20.79
Magnetite	2.80	2.48	6.90	1.10	2.24	0.72	1.16	4.94	3.34
Ilmenite	0.62	1.38	2.72	1.56	1.16	0.26	0.94	1.66	1.98
Apatite	0.15	0.15	0.10	0.15	0.10	0.13	0.45	0.35	0.45
Olivine	-	4.74	-	-	-	-	-	-	-
Nepheline	-	1.86	-	-	-	-	-	-	-
Haematite	-	1.24	-	-	-	0.15	-	-	-

TABLE 5

District	ARNAGE									
Surrounding Matrix	Quartz-cordierite norites, Arnage gneisses, Ardlethen gneisses.								Kinharrachie Gneiss	
Xenolith no.	231I	250I	255I.	273I	322I	346-4I	345-15I	345-4I	301I	309I
SiO_2	53.61	47.66	55.57	77.60	44.56	47.61	50.79	46.26	57.83	46.94
TiO_2	1.05	1.28	1.05	0.29	1.66	1.23	1.58	1.09	0.76	1.62
Al_2O_3	24.34	28.71	26.18	9.98	26.63	25.89	15.52	27.03	13.13	15.49
Fe_2O_3	1.44	2.63	1.81	0.91	2.25	2.21	2.26	3.44	2.16	4.64
FeO	3.70	4.19	2.58	1.64	7.52	6.47	8.46	4.90	5.34	9.13
MnO	0.053	0.11	0.029	0.082	0.15	0.13	0.18	0.12	0.13	0.20
MgO	2.26	1.86	1.04	1.38	3.95	2.53	8.15	2.15	5.15	7.71
CaO	1.61	1.71	0.69	4.10	2.29	2.72	10.53	5.38	11.89	9.29
Na_2O	2.72	2.57	1.76	0.84	2.63	2.98	1.09	3.98	1.45	2.95
K_2O	5.80	5.93	7.81	0.71	3.99	4.47	0.25	3.34	0.31	0.96
H_2O	2.94	2.94	1.02	1.46	3.06	2.75	0.54	1.24	0.62	1.08
P_2O_5	0.21	0.19	0.16	0.078	0.34	0.24	0.14	0.070	0.092	0.07
TOTAL	99.73	99.78	99.70	99.07	99.03	99.23	99.49	99.00	99.75*	100.09

All analysis carried out by author on powder dried at 110°C for 2 hrs.

Trace elements in p.p.m.

Cr	127	182	158	58	164	133	172	140	281	195
Ba	2180	2710	1260	340	1450	1570	625	1105	145	175
Sr	316	182	196	242	177	276	250	314	305	217
Rb	103	171	180	23	130	83	65	59	13	9

ESKOLA NORMS

	231I	250I	255I	273I	322I	346-4I	345-15I	345-4I	301I	309I
Orthoclase	35.15	35.90	46.75	4.50	24.45	27.25	1.50	19.95	1.90	5.75
Albite	25.05	23.65	16.00	8.10	24.50	27.65	10.05	29.10	13.55	26.95
Anorthite	6.90	7.60	2.55	21.30	9.65	12.45	37.70	26.60	29.58	26.62
Orthopyroxene	8.80	6.50	2.94	5.16	17.96	12.82	25.28	-	6.88	4.52
Quartz	7.66	3.22	12.01	58.36	0.58	1.18	7.58	-	18.71	-
Corundum	12.46	17.17	15.39	0.64	16.49	13.21	-	7.99	-	-
Magnetite	2.06	3.76	2.56	1.36	3.26	3.18	3.24	4.86	3.12	6.58
Ilmenite	1.50	1.82	1.48	0.42	2.40	1.76	2.26	1.54	1.10	2.30
Apatite	0.43	0.37	0.30	0.17	0.70	0.50	0.27	0.13	0.20	0.15
Olivine	-	-	-	-	-	-	-	5.61	-	11.25
Nepheline	-	-	-	-	-	-	-	4.23	-	-
Clinopyroxene	-	-	-	-	-	-	12.12	-	24.96	15.88

* total includes 0.89% CO_2

TABLE 5 cont.

II The Genesis of the Rocks of Uncertain Origin, or Unhomogeneous Rock Group, and their Geochemistry

Certain differences in major oxides appear if xenolith and surrounding matrix are compared in the Haddo rocks of uncertain origin or unhomogeneous rock group as it is proposed to call them. This is a collective name for the rock groups described in the first part of this chapter.

At Haddo, the unhomogeneous rocks of the Wood of Schivas are mainly quartz-cordierite-norites, which appear to be rich in Al_2O_3, but some of this Al_2O_3 may arise from included xenoliths. Specimens 68M, 69 and 89 (table 4) are reasonably free from xenoliths however and they are richer in Al_2O_3 than similar rocks from Craigmuir Wood (the quartz-cordierite± garnet±K-feldspar rocks) nos. 99, 113 and 117 (specimen 100M is excluded because of unremoved aluminous xenoliths). The Schivas rocks are also richer in FeO, MgO and CaO and lower in SiO_2 than the Craigmuir rocks, and consequently show larger amounts of normative anorthite and orthopyroxene. The argillaceous xenoliths which these rocks contain are usually alumina-rich and low in silica, lime and alkalis. (analyses 85I, 100I, 101I table 5). Xenoliths from the Schivas area (enclosed in quartz-cordierite-norite) are richer in spinel and/or sillimanite than argillaceous xenoliths found in the rocks at Craigmuir Wood; thus the Schivas xenoliths tend to have/

have higher amounts of Al_2O_3 than Craigmuir xenoliths. Xenolith 851 is very rich in normative corundum.

Reviewing the petrography and chemistry of the xenoliths Read (1935, p.624) remarked that "not a single xenolith has been observed that has the composition of the most widespread country rock, the andalusite-cordierite-schist." He argued that pelitic country rocks picked up by the intruding magma were transformed into silica-poor xenoliths by the magma abstracting silica, lime and alkalis from the xenoliths; this abstraction produced an enrichment of alumina, iron and magnesium in the inclusion. Lime, iron and alumina could also be added to the xenolith in some cases.

Read (1935) then argued that the xenolithic rocks of Haddo were formed by the basic magma assimilating country rocks at the time of intrusion. Bowen (1928) had previously explored the mechanism of assimilation from a chemical viewpoint and a brief summary of Bowen's work and its application to the Haddo unhomogeneous rocks will now be given.

A magma is seldom in a state of chemical equilibrium with the (country) rocks into which it is intruded. There is a tendency to regain a state of equilibrium by reaction between magma and the surrounding rock thus modifying the magma composition.

Bowen/

Bowen (1928) outlined general principles which determine the way the assimilation process works.

A considerable amount of heat is necessary to melt most rocks, and, as this heat must be supplied by the magma, the magma will cool as assimilation proceeds. Wholesale assimilation by melting would require the magma to be superheated, i.e. at a temperature above its liquidus, and this is unlikely if the magma is either of partial melt origin itself (at depth), or fractionating from an original liquid as it probably was at Haddo (chapter IV).

Most igneous minerals belong to a reaction series and in a crystallising magma there can be more than one such series. If one such reaction series consists of a sequence of crystalline phases A, B, C, etc. (with falling temperature) then phase A will separate from a magma at a given temperature but will be unstable at a lower temperature and will react with the remaining liquid to give the next phase B, and so on. The magma might incorporate sediments which contain members of reaction series already crystallising from the magma. If the magma, which is crystallising an early formed, high temperature member of a reaction series (e.g. B), has a subsequent member of the same series (C, D, etc.) added to it, equilibrium will be restored by the liquid reacting with the added members and incorporating them into the liquid fraction.

More/

More of the early member B will separate out to supply the latent heat needed for this reaction and to maintain equilibrium. If, on the other hand, the magma has crystals added which are earlier members of the reaction series (e.g. A), then the magma, which is already supersaturated with respect to the earlier members (A) of the reaction series, cannot convert these added crystals to liquid. It can however react with them in a complex reaction involving crystals A, crystals B and liquid, and crystals A are converted to B. Assimilation is, therefore, a reciprocal reaction between magmatic liquid and original country rock, involving these processes briefly described above. As reaction proceeds, the magma cools and crystallises giving rise to a contaminated rock, which owes its origin both to the country rock and also to the magma. There is no sharp boundary between country rocks and magmas, as metasomatic processes at the contact produce a very diffuse zone.

Bowen described in detail how a basic magma could assimilate sedimentary material, (including aluminous pelitic material). If the basic magma is considered to be crystallising olivine, or olivine, calcic plagioclase and pyroxene, then most of the minerals present in sedimentary rocks, sodic feldspars, micas, etc., are usually late members of various igneous reaction series (i.e. forming at low temperatures). Since the magma is already crystallising early-formed (high temperature) members of these same reaction series, many of the minerals from the sedimentary/

sedimentary rocks will react and be incorporated into the liquid. Addition of quartz and potash feldspar has unknown effects, but Bowen argued that since a basaltic magma of tholeiitic composition is capable of differentiating towards a 'granitic end-point' then it should be capable of dissolving material of granitic composition (i.e. rich in SiO_2, K_2O). Since lime, silica and alumina are major constituents of basaltic magmas a basalt magma should be able to dissolve additions of these. Bowen stated that if the magmatic liquid's rate of cooling is such that the sediment cannot be entirely dissolved then the 'low-melting fraction' of granitic composition will first be produced as a liquid and incorporated into the magma, and the recrystallised residue will contain large amounts of silica, lime or alumina, depending on whether the incorporated sediment was quartzitic, calcareous or pelitic.

The highly aluminous xenoliths (60% Al_2O_3 by weight) with their mineral assemblages of spinel, corundum, cordierite, etc., were believed by Bowen to represent the residue of the original sediment (pelite) after the granitic liquid was sweated out. Bowen suggested that this Al-rich residue could react with the magma as follows:-

$$Al_2SiO_5 \quad + \quad CaMgSi_2O_6 \quad \overset{?}{\longrightarrow} \quad CaAl_2Si_2O_8 \quad + \quad MgSiO_3$$

Xenolith Magmatic phase

thus increasing the anorthite and orthopyroxene contents of the contaminated liquid when crystallised. If enough time is available/

available for all xenoliths to react, the resultant magma would crystallise as a norite (orthonorite) or a spinel-cordierite-bearing norite. Siliceous xenoliths react in much the same way, a granitic melt being 'sweated out' leaving a quartz-rich core. Since quartz is a refractory mineral these quartz-rich xenoliths will remain, although Bowen suggested that even quartz can be incorporated by reaction with the magma, producing either orthopyroxene, or orthopyroxene and anorthite, as before.

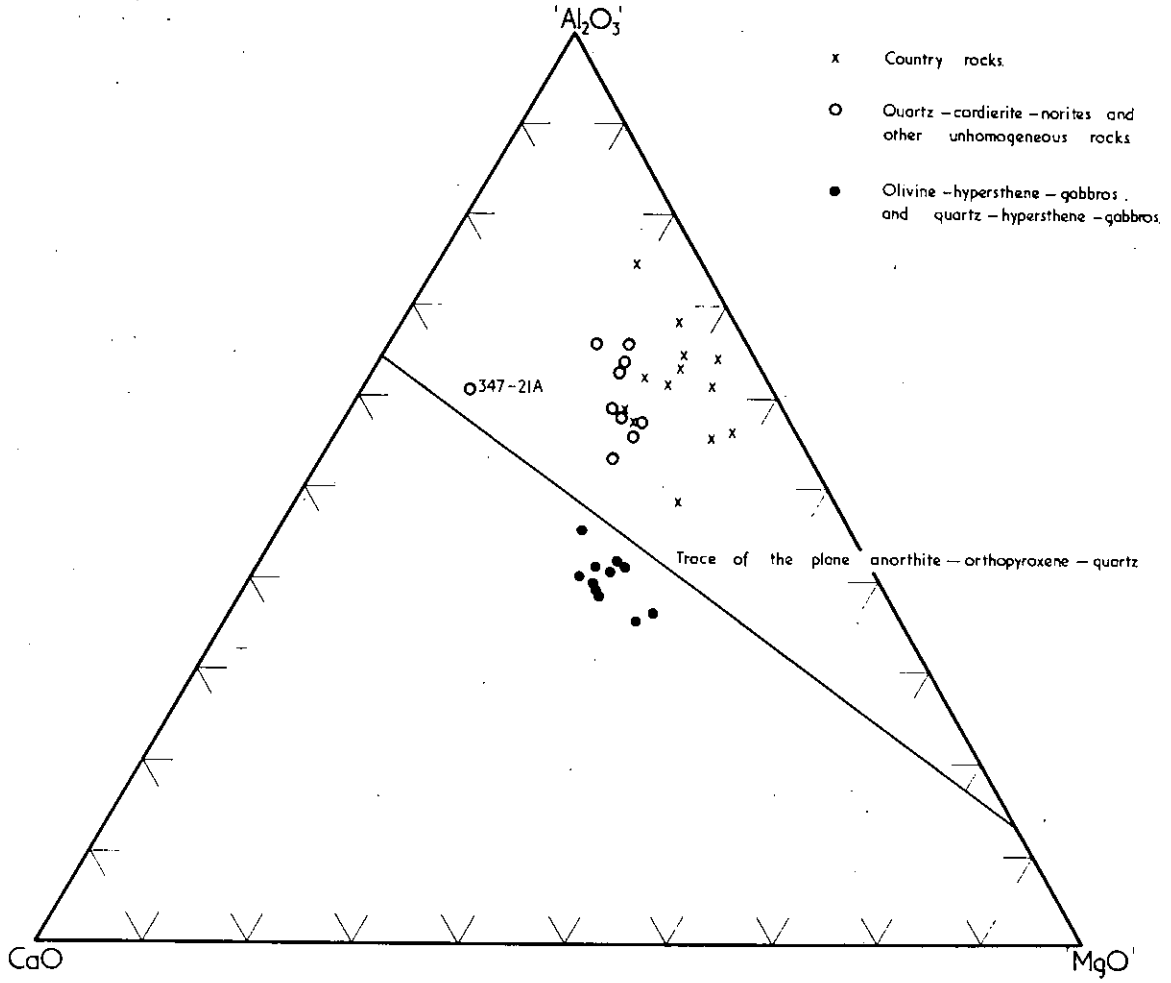
It is obvious that the hypothesis of Bowen could be applied to the unhomogeneous rocks of Haddo. The xenolithic quartz-cordierite-norites etc., would represent evidence of the validity of his proposals. Read (1935) using Bowen's hypothesis, stated that the most widespread xenolithic rock at Haddo is an orthonorite and the large amount of orthopyroxene is due to the magmatic liquid reacting with the Al-rich xenoliths. Bowen's theory anticipated an increase in the anorthite molecule of plagioclase. The lack of any noticeable increase in calcium content of the plagioclase in the orthonorites ('norites' in Read, 1935) was because the 'granitic' liquid, formed by being sweated out of the sediment at the first stage of the assimilation process, contains albite and this combines with the anorthite produced after the xenolith and magma react at a later stage (Read, 1935, p.629). Xenoliths rich in orthopyroxene were considered by Read to "illustrate the last episode/

episode in the production of the noritic rocks," i.e. a complete reaction of magma and xenolith and its incorporation into the magma.

Chapter II in this thesis was devoted to a report on the recent investigations in the system $CaO-MgO-Al_2O_3-SiO_2$ (CMAS) and how these investigations resulted in new theories being proposed for the formation of certain rock types. Of especial interest regarding the genesis of the unhomogeneous rock group of Haddo was a proposal by Chinner and Schairer (1962), that xenolithic quartz-cordierite-norites might not be the end product of a reaction between gabbro magma and pelitic country rock with the excess alumina being stored up in aluminous xenoliths. Instead, Chinner and Schairer proposed that the presence of a thermal divide, the join anorthite-enstatite-tridymite in the system CMAS which separates liquids in equilibrium with anorthite, diopside, enstatite and tridymite, and anorthite, enstatite, cordierite and tridymite from each other, might make it impossible to proceed from one liquid to the other (the two liquids correspond to 2 quaternary invariant eutectic equilibria in the CMAS system) by any process of continuous down-temperature evolution. These liquids are analogous to quartz-hypersthene-gabbro and quartz-cordierite-norite respectively (see fig. 5C). Chinner and Schairer (1962) concluded that "cordierite- and garnet-bearing norites at igneous contacts may not be so much the end products of the gabbro-/

gabbro-norite contamination sequence /Bowen's theory/ as the result of the formation of a liquid correspondong to the low temperature eutectic I /a quartz-cordierite-norite/ ... by partial fusion of the country rock xenoliths." Thus, allowing sufficient heat, many argillaceous rocks would yield quite large quantities of liquid of quartz-cordierite-norite composition, with the infusible components contained in residual xenoliths.

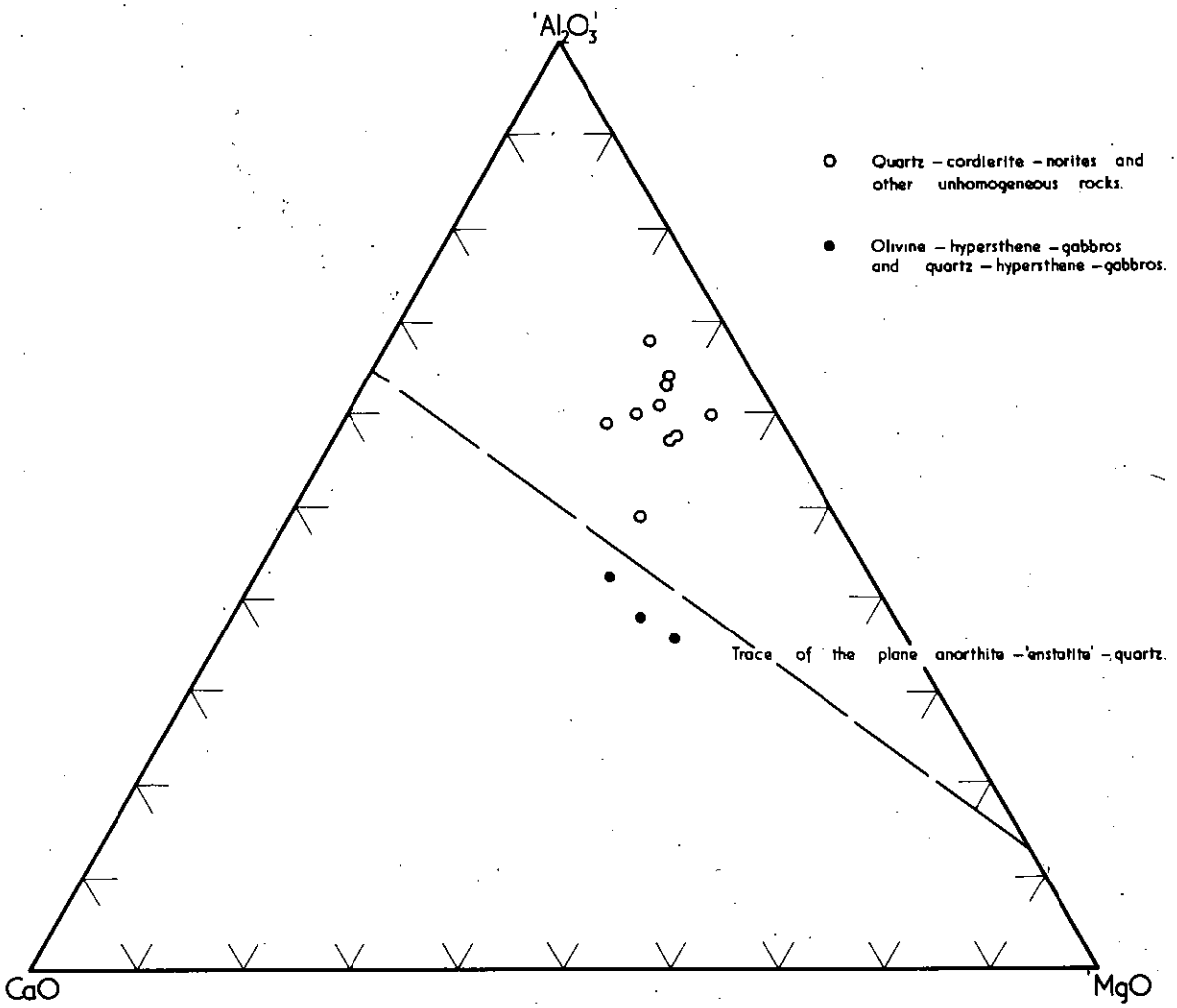
Since it was decided in chapter II that studies in the system $CaO-MgO-Al_2O_3-SiO_2$ were most relevant to the problem of the genesis of the Haddo unhomogeneous rock group, the chemical analysis of every rock from Haddo, analysed by the author, was recalculated to 4 major constituents equivalent to the CaO, MgO, Al_2O_3 and SiO_2 of the system CMAS. In major oxide redistribution FeO and MnO were recalculated as MgO, and Fe_2O_3 as Al_2O_3. Na_2O and K_2O were removed by forming albite and potash feldspar and the equivalent amounts of Al_2O_3 and SiO_2 removed to make up these feldspar molecules. CaO remained as CaO, and TiO_2, P_2O_5 and H_2O were neglected. The 4 constituents CaO, 'MgO', 'Al_2O_3' and 'SiO_2' (as weight percentages) were recalculated to 100% and plotted into the CMAS tetrahedron. Fig. 13 shows the Haddo analyses projected into the 50% SiO_2 plane of the CMAS tetrahedron. Quartz-hypersthene-gabbros 347-21B and 64M have not been plotted because they contain unremoved xenoliths (chapter V, p. 96). The/



A projection from quartz into the 50% SiO_2 plane of the CMAS tetrahedron

The Haddo rock analyses plotted within the CMAS tetrahedron showing a division into two groups of rocks at either side of the plane anorthite – orthopyroxene – quartz.

FIG. 13



A projection from quartz into the 50% SiO_2 plane of the CMAS tetrahedron

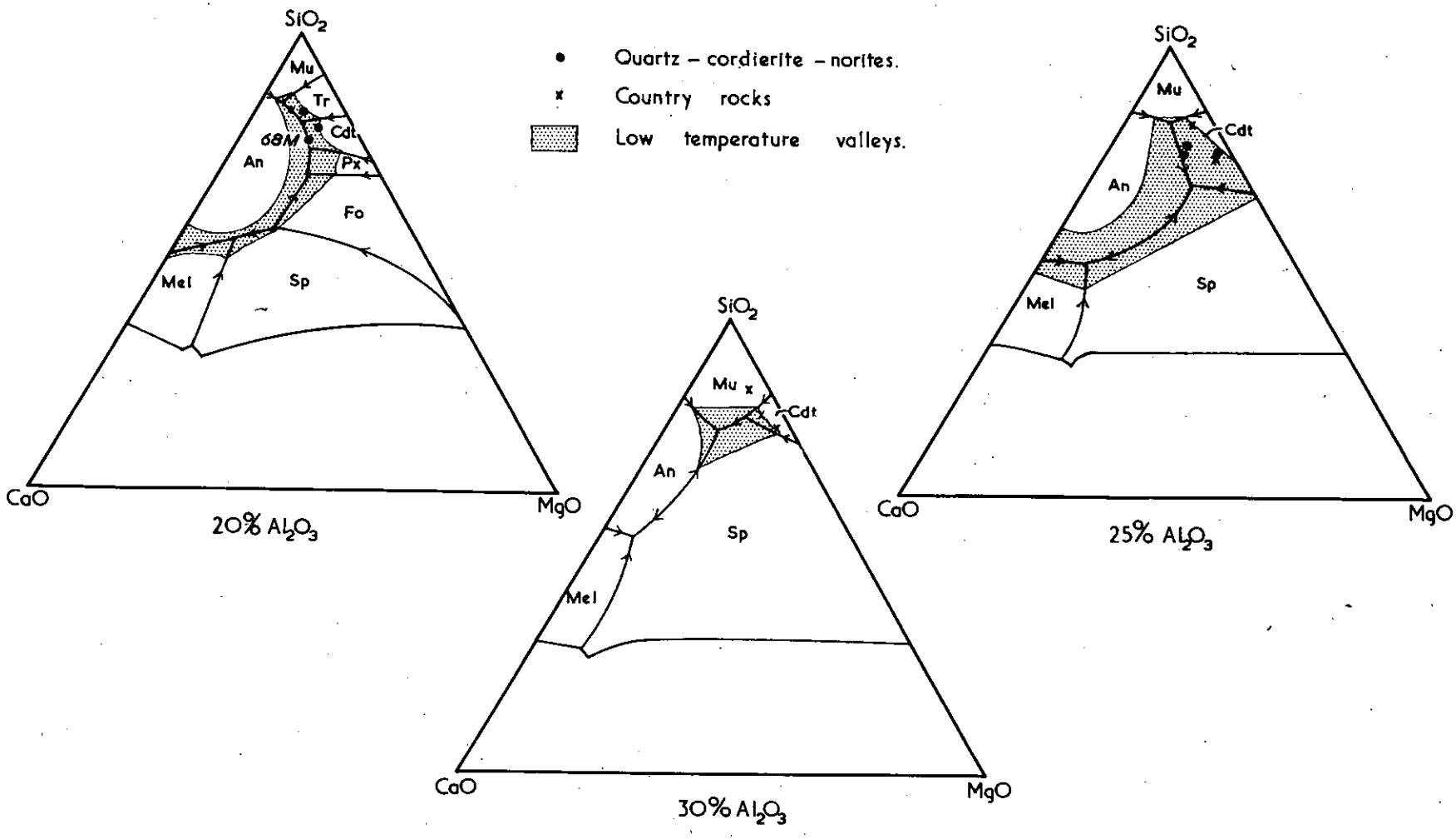
The Arnage rock analyses plotted within the CMAS tetrahedron showing a division into two groups of rocks at either side of the plane anorthite – 'enstatite' – quartz.

FIG. 14

The xenoliths also have not been plotted, and will be shown on a separate diagram (fig. 18). The Haddo rocks show an excellent division into two groups in fig. 13, with the gabbroic rocks plotting on the alumina-poor side of the plane anorthite-enstatite-quartz (shown as a line on the projection into the 50% SiO_2 plane of the CMAS tetrahedron), and the quartz-cordierite-norites and associated rocks plotting on the alumina-rich side of the plane anorthite-enstatite-quartz. There is no transition from one group to another, across the plane anorthite-enstatite-quartz.

The Arnage rocks have been plotted on a similar diagram, fig. 14. Analysis 345-15M has not been plotted as it contains unremoved xenoliths. 345-15I would tend to 'move' the analysis 345-15M towards the anorthite-quartz plane. The unhomogeneous rocks and igneous rocks of Arnage also plot at either side of the plane anorthite-enstatite-quartz.

In fig. 13 the country rocks have been plotted, and the plane anorthite-enstatite-quartz has been repositioned on the basis of the analysis of an orthopyroxene from a quartz-cordierite-norite (68M). The orthopyroxene from 68M (analysis 68M, Opx, Appendix C), contains a large amount of Al_2O_3 (4.25%) which tends to displace the plane An-En-Qz towards the alumina component in the CMAS tetrahedron. The new position of the plane anorthite-orthopyroxene-quartz (for/



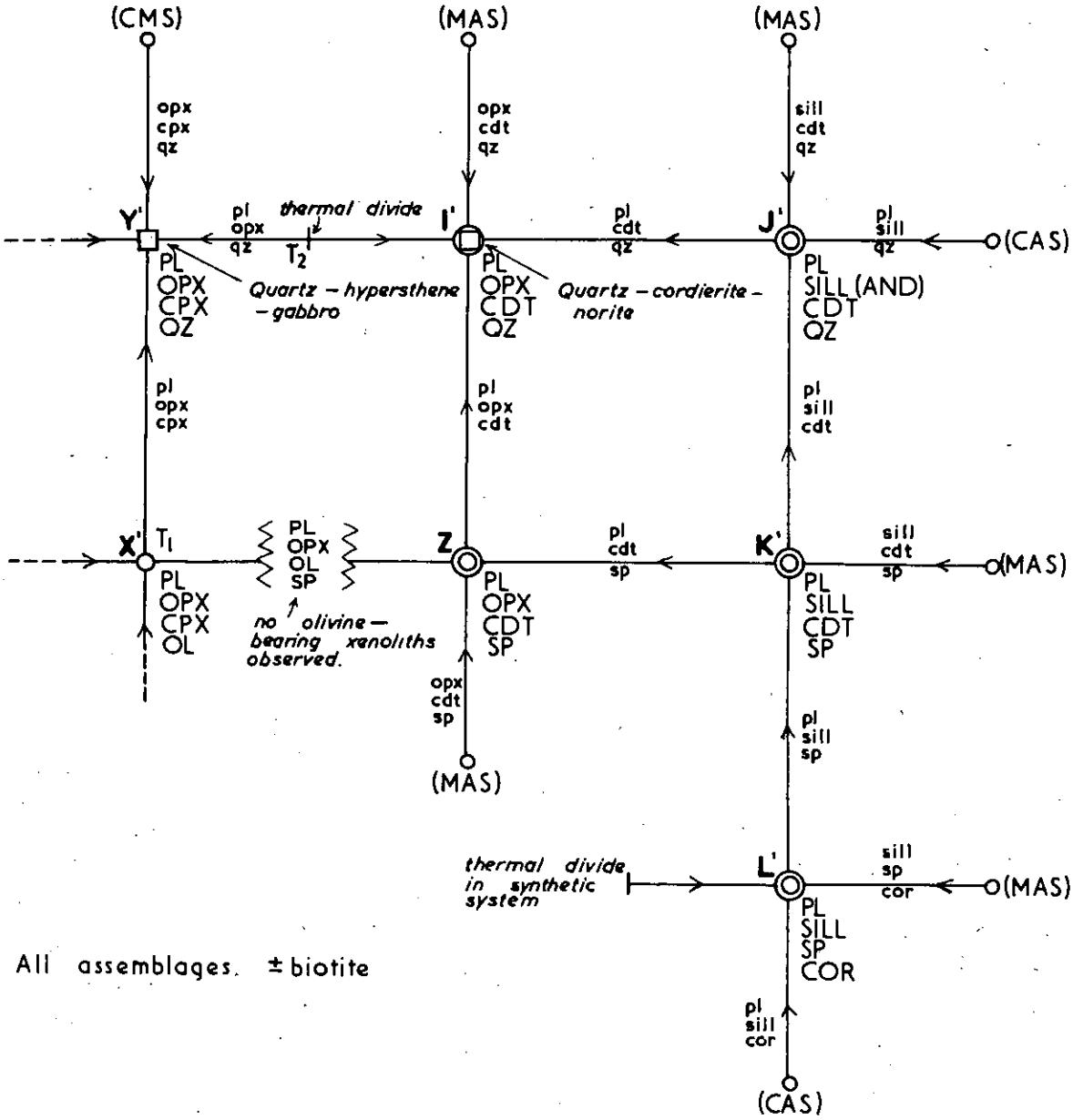
Some Haddo country rocks and unhomogeneous rocks plotted into liquidus diagrams for the 20, 25 and 30% Al_2O_3 planes in the system CMAS.

FIG. 15

(for the natural Haddo rocks and also used for the Arnage rocks) should be compared with the position of the plane anorthite-enstatite-tridymite from the synthetic 4-component system CMAs fig. 5B. However, the distribution of analyses with respect to the plane anorthite-orthopyroxene-quartz in fig. 13 does not change and the two distinct groups remain on either sides of the plane anorthite-orthopyroxene-quartz.

In fig. 15 some of the Haddo analyses have been plotted into the CMAS system so that each analysis could be depicted on the nearest planes of the tetrahedron for Al_2O_3 = 20%, 25% and 30%. The primary phase volume boundaries and the liquidus isotherms for these planes of fixed Al_2O_3 composition had previously been constructed by Osborn et. al. (1954). The Haddo quartz-cordierite-norite analyses plot in the low temperature valleys on these planes; e.g. 68M plots near the join of 4 primary phase volumes anorthite, pyroxene, cordierite and tridymite.

The geochemical data for the Haddo rocks supports a hypothesis of partial melting for the origin of the unhomogeneous rock group, and therefore it should be possible to construct a flow sheet for the Haddo rocks which incorporates the petrographic mineral assemblages actually observed at Haddo. This flow sheet should also be applicable to the Arnage rocks. A flow sheet depicting various phase relations in/



All assemblages. ± biotite

□ Quaternary eutectic point

○ Quaternary invariant point

○ Ternary invariant point

} Pseudo-quaternary points

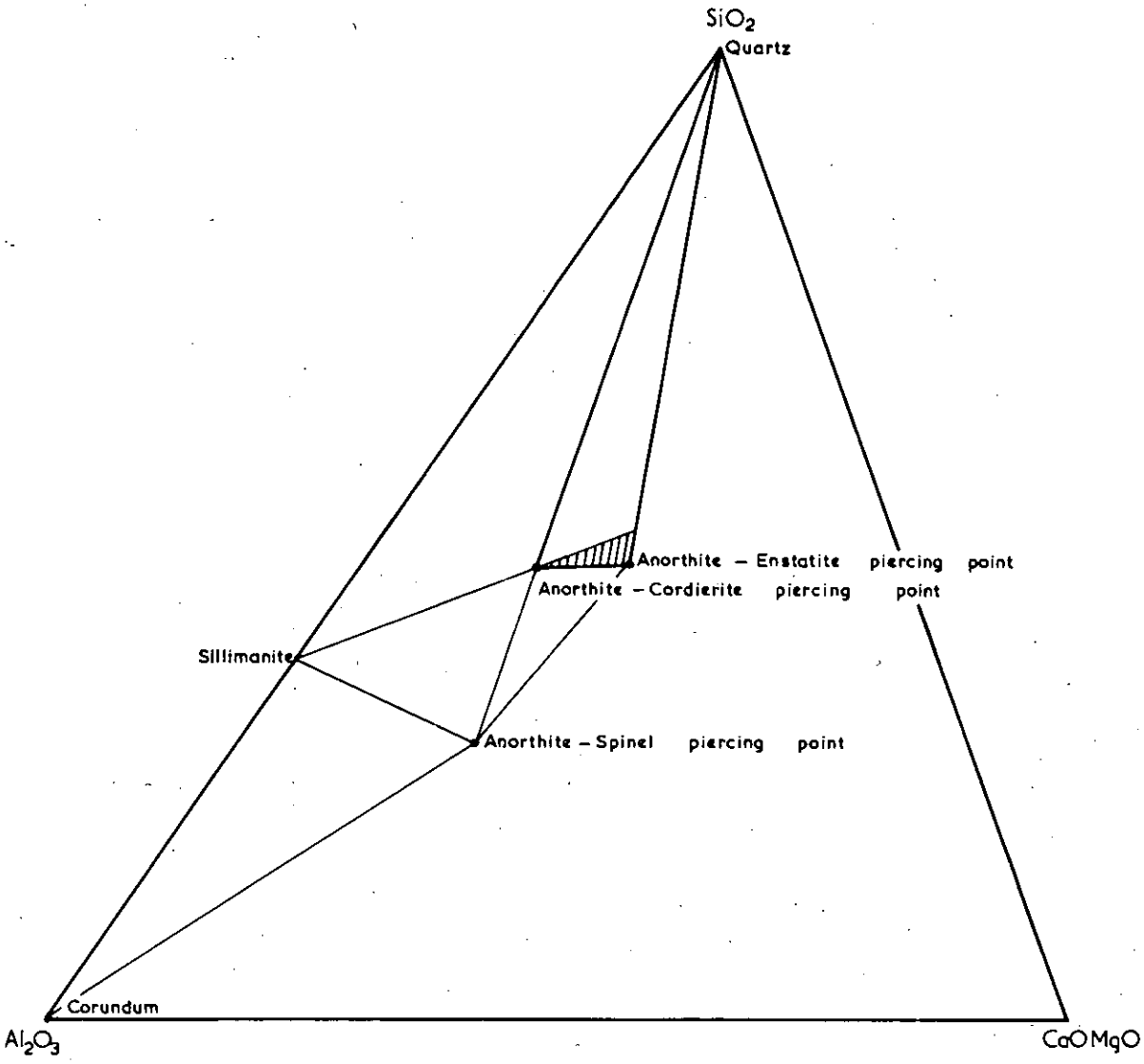
◯ Liquids lying inside tetrahedron plagioclase – orthopyroxene – cordierite – quartz (the tetrahedron anorthite – enstatite – cordierite – quartz. in the synthetic system CMAS)

Flow sheet for the Haddo unhomogeneous rocks

FIG. 16

in the silica-rich part of the synthetic system CMAS was described in chapter II, and a model constructed so that the synthetic data might be applied to natural rocks. Fig. 16 is a flow sheet constructed for the natural rocks of Haddo, and it is not surprising that certain differences between the flow sheets for natural rock assumblages and synthetic assemblages occur (c.f. fig. 6 chapter II, with fig. 16). The flow sheet for the synthetic system CMAS has to take into account every assemblage produced in experiments carried out with mixtures of every possible composition. In a natural system only those assemblages which actually occur can be used, and thus that part of the flow sheet for the synthetic system in which forsterite appears (reaction points E and F, fig. 6, chapter II) is omitted in the 'natural-rock' flow sheet, as olivine-bearing xenoliths are never seen at Haddo (or Arnage). Sapphirine-bearing inclusions also, are absent.

N.B. O'Hara (unpublished) described rules whereby one can determine whether a quaternary invariant equilibrium is a reaction equilibrium, a biresorption, (distributary) or a triresorption equilibrium, etc. It depends on where the liquid lies with respect to the subsystem containing the phases encountered at the invariant equilibrium and how many tetrahedral faces (of the subsystem) can be seen from the position of the liquid. In fig. 17, if a liquid plots in the/



~~*A projection from Anorthite showing*~~ *The trace of tetrahedron Anorthite — Enstatite — Cordierite — Quartz on the plane CaOMgO — Al_2O_3 — SiO_2 of the system CaO — MgO — Al_2O_3 — SiO_2.*

FIG. 17

the unshaded part of subsytem anorthite-cordierite-quartz (triangle S-AnCdt-AnEn in the plane CM-A-S of the CMAS system) then 2 faces of subsystem anorthite-cordierite-andalusite-spinel (triangle Sill-AnCdt-AnSp) can be seen and point K' in the flow sheet fig. 16 is a distributary equilibrium (AnCdt is the piercing point of the join anorthite-cordierite in the plane CM-A-S). If the liquid lies in the shaded part of the subsystem anorthite-enstatite-cordierite-quartz then only one face of the subsystem anorthite-cordierite-sillimanite-spinel can be seen and K' would be a reaction equilibrium.

Since this flow sheet has been constructed for the natural rocks of Haddo (and Arnage) it seems worthwhile to reconsider some of the important points raised in chapter II concerning the application of data from the flow sheet for the synthetic system (CMAS) to natural rocks. In particular the series of questions which O'Hara and Schairer (unpublished) considered are now re-examined with reference to the actual Haddo rocks.

The first question concerned how partial melting of pelitic hornfelses of variable compositions could give rise to a liquid, whose composition always lies inside the tetrahedron anorthite-enstatite-cordierite-tridymite (analogous in nature to a quartz-cordierite-norite). This liquid surrounded xenoliths ranging from quartzitic to plagioclase-cordierite-hypersthene-containing/

containing at low temperatures, and alumina-rich (silica-poor) xenoliths if the temperature is high (sillimanite-spinel-cordierite-bearing etc.) It is probably a difference in original bulk compositions of rocks undergoing partial melting which produces the main differences between the Haddo unhomogeneous rocks and the Arnage unhomogeneous rocks. At Haddo the country rock was pelitic (Fyvie schist) and the production of a quartz-cordierite-norite matrix enclosing aluminous xenoliths is predictable, although original psammitic material led to the presence of occasional quartzitic xenoliths in the quartz-cordierite-norites and associated rocks. At Arnage the country rock was much more quartzitic (Mormond Hill quartzite and Ellon gneiss parents) and partial melting produced a liquid of quartz-cordierite-norite composition enclosing xenoliths of a more quartzitic nature in general. Some differences in the conditions under which the unhomogeneous rocks of Arnage formed led to the formation of xenolithic quartz-cordierite-biotite-plagioclase gneisses compared with the xenolithic quartz-cordierite-norites of Haddo. More H_2O could have been present in the Arnage rocks during the partial melting and subsequent consolidation. This difference is apparent from the chemical analyses of the matrices in both areas tables .4. and .5. The Haddo rocks are lower in silica, alkalis and water, than the corresponding Arnage rock types.

The/

The path a liquid would follow with increasing temperature in the CMAS flow sheet fig. 16 would depend upon the original bulk composition of the material undergoing partial melting. If the original material was rich in MgO or FeO the liquid formed might proceed with rising temperature along the path I'-Z'-K', enclosing FeO, MgO rich residual solid phases (equivalent to the orthopyroxene-rich xenoliths found in the quartz-cordierite-norites of Haddo). Thus the flow sheet shows all the relationships observed in the unhomogeneous rock group at Haddo. The appearance of cordierite-bearing rocks with a variety of xenoliths is explained. The absence of corundum-bearing xenoliths in the quartz-cordierite-norite group is explicable if the temperatures developed in the partial melt country rocks were insufficient for invariant equilibrium L' to be reached, although the small country rock fragments trapped in the gabbros did attain a temperature sufficiently high to form corundum in the residual core of the xenolith.

It is of interest to note that the quartz-cordierite-K-feldspar-garnet xenolithic rocks of Craigmuir Wood and Braik's Belt in the Haddo and Arnage districts might correspond to the quaternary eutectic point K in the system K_2O-MgO-Al_2O_3-SiO_2 (Schairer 1954, also chapter II, fig. 7B).

The second question O'Hara and Schairer discussed was the actual contact relationships to be expected at gabbro/country rock contacts if partial melting had taken place. They mentioned/

mentioned five categories and rock types ranging from uncontaminated gabbro through xenolithic gabbro, hybrid mixture of gabbro and partial melt country rock, xenolithic partial melt country rock, to hornfelsed country rock. The Haddo rocks range from uncontaminated olivine-hypersthene-gabbro through xenolithic quartz-hypersthene-gabbro, to xenolithic quartz-cordierite-norites (and other members of the unhomogeneous rock group) and finally to hornfelsed country rocks.

The third question concerned the nature of the xenoliths. O'Hara and Schairer discussed the immersion of an argillaceous xenolith in a gabbro magma and explained that the aluminous xenolith would not be in equilibrium with its surrounding liquid and depending on what happened to the liquid formed by the interaction between xenolith and magma, the xenolith could either be 'dissolved' slowly into the magma, or a solid screen of quartz-orthonoritic composition would form between the xenolith and the enclosing magma. This orthonorite would constitute the hybrid zone (as proposed by O'Hara and Schairer) which might also appear as gabbro/country rock contacts. At Haddo orthonorites are very rare and usually occur as outer zones to some xenoliths or as small wispy 'xenoliths' in quartz-gabbro. These wispy stringers or xenoliths might actually be parts of a disrupted orthonoritic screen originally between the unhomogeneous rocks and the gabbroic rocks.

They/

They also proposed that it might actually be possible to proceed from olivine-gabbro to quartz-cordierite-norite by progressive contamination, because no thermal divide exists on the an-fo equilibrium between the liquid in equilibrium with an-fo-di-en (1238°C) and that therefore the contamination process proposed by Read (1935) for the formation of the unhomogeneous rock group at Haddo could operate. However, if a contamination process operated one would expect to find a complete range of different rock groups, decreasing in abundance from quartz-gabbro ⟹ quartz-cordierite-norite. At Haddo quartz-orthonorites are scarce, only being found as small wispy xenoliths enclosed in quartz-hypersthene-gabbro (e.g. 347-21A) which is exactly what would be expected if the thermal divide was effective.

The fourth question posed by O'Hara and Schairer considered the conditions existing in the country rock at the time of its partial melting.

The experiments of Chinner and Schairer (1962) were carried out at atmospheric pressure in the dry state. They considered that the thermal divide which separates a liquid of quartz-hypersthene-gabbro composition from a liquid of quartz-cordierite-norite composition might become ineffective at high water vapour pressures. At 10Kb P_{H_2O} the join anorthite-forsterite which is an effective divide at 1 atmosphere pressure, is replaced by the join enstatite-diopside-spinel (Yoder and Chinner/

Chinner, 1960).

It has been argued that the Haddo gabbros were probably intruded under a pressure of P_{load} = 3 Kb in the "dry" state, i.e. no vapour phase present (chapter IV). The textural features and mineral phases present in the unhomogeneous rocks of Haddo would suggest that no water vapour phase was present during the rocks' consolidation. In the quartz-cordierite-norites the minerals which crystallise are orthopyroxene, plagioclase, cordierite, biotite and quartz. Biotite constitutes a small percentage of a rock's mode (usually $<10\%$) and amphibole is absent. The biotite would appear to have formed in the rock, by using up any H_2O present in the liquid melt from which the rock crystallised. The lack of cavities and pore spaces in the rocks of this group also tends to support the conclusion that the unhomogeneous rocks of Haddo crystallised with no water vapour phase present.

In chapter II it was stated how most of the experiments on the melting of natural rocks - granites, shales, etc. were carried out in water saturated conditions. Under these conditions the most basic partial melt produced was one of tonalite composition from the partial melting of a greywacke with high Na/K ratio at P_{H_2O} = 2 Kb. (Winkler and Von Platten, 1961). At Haddo the pressure during crystallisation was perhaps/

perhaps 3 Kb with no vapour phase present. The gabbros of north-east Scotland have alkali-basalt affinities and in the Haddo region might have been intruded crystallising olivine+ plagioclase+?pyroxene. At atmospheric pressure this could represent a temperature of intrusion of 1150°C. (Yoder and Tilley, 1962, p.382). However, at 3 Kb with no water vapour phase present, phases appear at higher temperatures (Yoder and Tilley, 1962, Eclogite section) and thus the temperature of the magmatic liquid at the time of intrusion in the Haddo (and Arnage) region might have been in excess of 1150°C. Johnson (1962, 1963) believed that biotite formed in regional schists in the Buchan region throughout the period F_1 to F_4 with the metamorphic climax which produced cordierite-andalusite-(sillimanite) assemblages, having temperatures as high as 600°C. Bell (1964) could not separate the climax of the Buchan metamorphism from the intrusion of the basic sheet. Therefore, the basic sheet must have been intruded at depth into country rocks which already were at high temperatures. The difference in temperature between country rocks and magma (at least 500°C) would provide ample heat with which to raise the temperature of the country rocks adjacent to the gabbro to a stage when anatexis would commence.

There might have been enough H_2O in the original country rock for the initial melting to begin in the presence of a water vapour phase, thus ensuring that anatexis began at low temperatures/

temperatures ($< 700^{o}C$?) which would be substantially below the temperature of the intruded basic sheet. The diffusion of water from the country rocks both away from the gabbro into country further away, and into the magmatic liquid as was proposed in chapter III and IV of this thesis, would tend to remove the initial water vapour present, and further melting in the country rocks would take place under water-poor conditions.

In the synthetic system no FeO, Na_2O and K_2O were present but as was stated in chapter II the effect of addition of these components would be to generally lower temperatures of reaction equilibria, etc. Chapter II discussed in more detail the effects of K_2O, Na_2O and FeO in the synthetic systems based on the work of Schairer (1954), and Yoder and Schairer (1964) in particular.

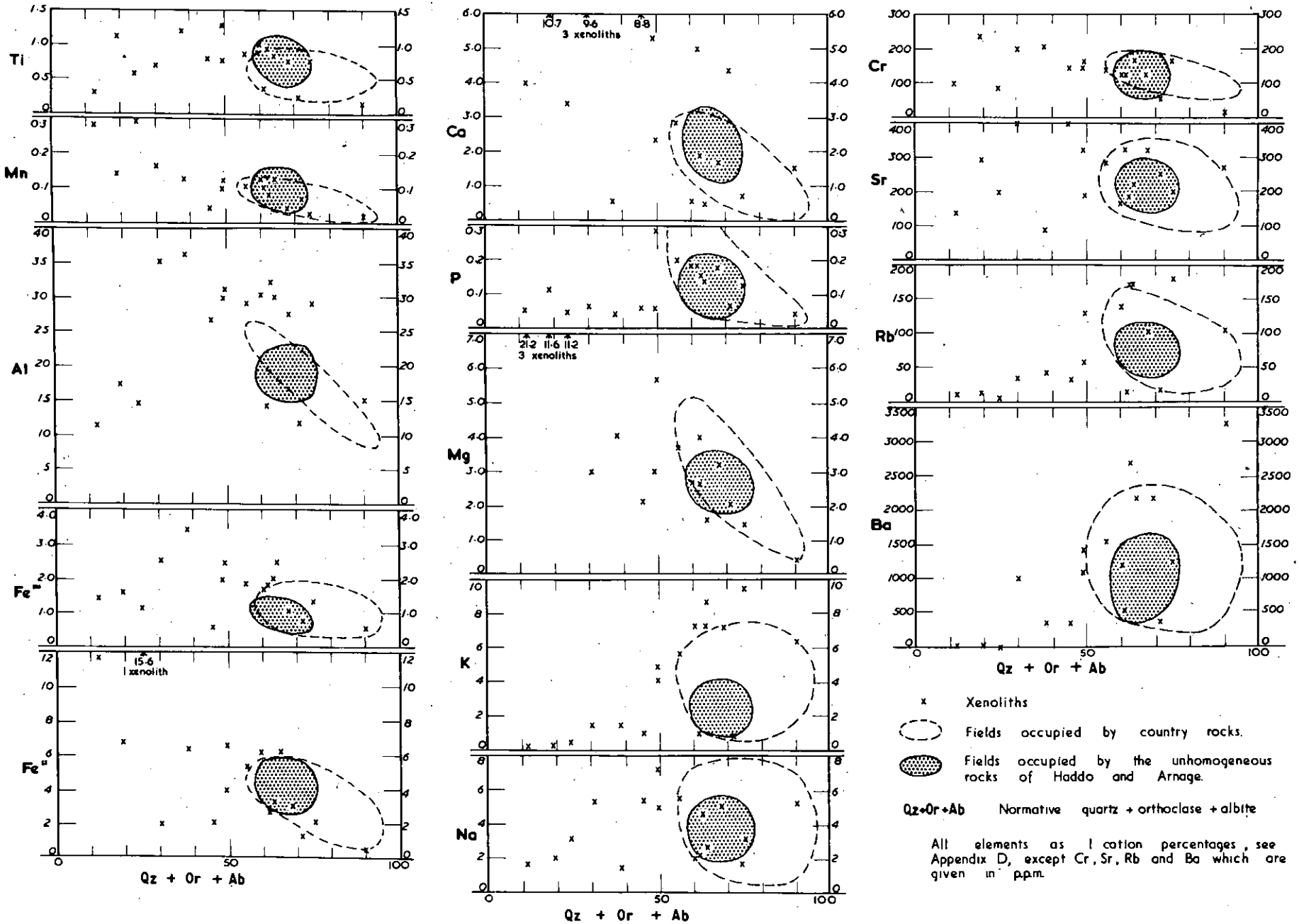
In the light of this new theory for genesis of the Haddo House (and Arnage) unhomogeneous rock group it is important to return to their geochemistry. Read and Farquhar (1952, p.434) stated that "the matrix of the Arnage gneiss has been mobilised and flowed ... /but/ possesses, considered as a magmatic rock, a quite abnormal mineralogical and chemical composition." The xenolithic gneisses formed from Fyvie schists south of Methlick constitute quartzo-feldspathic material which was mobilised and which surrounded more aluminous xenoliths. Since there would appear to be evidence of mobilisation and partial/

partial melting of the country rocks near the gabbro producing xenolithic gneisses, quartz-cordierite-norites, and other members of the unhomogeneous rock group, the chemical constituents of these rocks, and their xenoliths have been plotted against normative Qz+Ab+Or (i.e. an index of an 'acidic' melt). Evans (1964) used a similar index to plot the chemistry of hornfelses and xenoliths of Connemara schists from the aureole of the Cashel-Lough Wheelaun intrustion in Ireland, after arguing that the evidence pointed to fractional melting of these schists and the 'sweating-out' of a granitic liquid. At Haddo and Arnage the liquid formed by partial melting of the country rocks will contain cordierite; however, since cordierite is not a normative constituent, the index used is the grantic 'liquid' of Evan's (1964) i.e. Qz+Ab+Or.

In fig. 18, each element has been plotted as a 1-cation percentage (see appendix D) against this index and the 'area' covered by each group of rocks is outlined. The trace elements chromium, strontium, rubidium, barium are in ppm.

The Fyvie schists and Ellon gneisses analysed by the author, chapter III, have also been plotted and these show a great spread of compositions because they include pelitic and psammitic members. The alkali content of the unhomogeneous rocks is variable probably because the Fyvie schists and Ellon gneisses have Na-rich psammites, and K-rich pelites (table 1). The country rocks contain subordinate calcareous bands

(110/



Elemental variation in the country rocks, unhomogeneous rocks and xenoliths of Haddo and Arnage.

FIG. 18

(110, appendix B) and mica-rich (garnet-bearing) lenses in the pelites which must be Si-poor and MgO, FeO rich, but which were not analysed.

In chapter III it was argued that there might have been a diffusion of H_2O away from the gabbro, i.e. outwards from the inner aureole. This diffusion could have been accompanied by a diffusion of K_2O away from the rocks near the gabbro leading to the replacement of cordierite by muscovite (and quartz) in the pelites north of Methlick (see argument, chapter III). In chapter IV it was stated how the formation of quartz-hypersthene-gabbros at Haddo and Arnage depended on an introduction of water (+ SiO_2 and K_2O) into the fractionating magmatic liquid, changing its trend from a nepheline-normative one (as at Insch) to a hypersthene- or quartz-normative trend as at Haddo and Arnage.

The above points would imply that these rocks of partial melt origin immediately next to the gabbro would tend to be poor in SiO_2 and K_2O (and H_2O also, although water is excluded from the graphs as 1-cation percentages are used). Specimens 68M, 69, 88 and 89 (Haddo) and 345-4M and 345-13 (Arnage) are the unhomogeneous rocks formed closest to the gabbroic sheet, and these have very low amount of K_2O and SiO_2 and have been omitted from figure 18. Specimens 345-15M, 100M, 118 and 250M also have been omitted because these might contain unremoved xenoliths. Many of the analysed xenoliths are/

are too rich in K_2O due to poor removal of K-feldspar surrounding xenoliths a fact mentioned before, p.138.

Differences in the original bulk compositions of the partially melted country rocks and in the conditions under which the liquids of partial melt origin finally crystallised produced variations in the composition of the matrix of the unhomogeneous rock group although this variation is small as the matrix compositions are limited to a field within the limits 60 to 74% Albite+Orthoclase+Quartz. The variation in amounts of the various elements in each group has been shown as a field in each graph. The differences in xenolith compositions predicted in the model of partial melting (chapter II) and shown in the flow sheet (fig. 16) can be seen to be very great (each xenolith is plotted separately and not as part of a combined area). The geochemical data would appear to fit the partial melt theory of origin for the unhomogeneous rocks of Haddo and Arnage, but proof of this theory would involve knowledge of melting temperatures of the natural rocks, under conditions similar to those at the time of the partial melting. The initial melting temperature of a quartz-orthonorite (say T_2) i.e. the temperature of the thermal divide, should be higher than the melting temperatures of a quartz-hypersthene-gabbro and a quartz-cordierite-norite (invariant points Y' and J' in fig. 16). If the temperature of the basic magma intruded at Haddo is T_1 (i.e. the olivine-hypersthene-gabbro) then $T_1 > T_2$.

The/

The following points are worth considering with regard to the unhomogeneous rock group of Haddo (and Arnage). Some of the points have been discussed in this chapter, and some in previous chapters in this thesis.

(1) i) The formation of the unhomogeneous rock group, xenolithic quartz-cordierite-norites, etc. was considered by Read (1935) to be due to the intruded gabbro assimilating quantities of country rock material. The hypothesis of Bowen (1928) was used in applying the assimilation theory, and it was evident that in many respects the Haddo House rocks apparently supported the assimilation theory of origin.

ii) This assimilation would imply large quantities of transitional types between olivine-hypersthene-gabbros and quartz-cordierite-norites.

iii) The rocks which are most different from the gabbros at Haddo, the quartz-cordierite-K-feldspar±garnet rock assemblages should contain the most aluminous xenoliths as the gabbros must have 'sweated-out' more material from the xenolith to change the composition of its enclosing matrix so much.

iv) Bowen (1928) showed that under certain conditions (long time and no drop in temperature) a xenolith rich in sillimanite could react with the enclosing magma producing a reaction rim rich in corundum, spinel and cordierite.

In contradiction to point 1 above,

(2) i) There are virtually no transitional rocks at Haddo between/

between the gabbros and the cordierite-norites. True orthonorites are very rare.

ii) The rocks most different from the gabbros at Haddo, the quartz-cordierite-K-feldspar-garnet rocks do not contain the most aluminous xenoliths, and the most aluminous xenoliths in this group are contained in the quartz-cordierite-norites (c.f. 85I and 345-4I with 100I).

iii) Corundum-bearing xenoliths, only found in the quartz-hypersthene-gabbros, have cores of corundum (and spinel) and have a zone of plagioclase±hypersthene±quartz between them and the surrounding magma.

(3) No large xenoliths are ever present in the unhomogeneous rock group.

(4) No xenoliths which have the composition of a Fyvie schist (pelite) have ever been observed (Read, 1935).

(5) The Haddo rocks appear to fit a partial melt theory of origin proposed initially by Chinner and Schairer (1962) and developed by O'Hara and Schairer (unpublished).

(6) If the analysed Haddo rocks are plotted into the system $CaO-MgO-Al_2O_3-SiO_2$ with the original analyses recalculated to these 4 components, the gabbros plot at one side of the thermal divide observed in the synthetic system (the plane anorthite-enstatite-quartz) and the unhomogeneous rocks - quartz-cordierite-norites, etc., plot on the other. There are no transitions between the 2 groups. The Arnage rocks show a similar/

similar division.

(7) A self-consistent flow sheet can be drawn illustrating necessary and reasonable phase relationships which must exist if the unhomogeneous rock group is to have a partial melt origin.

(8) The Arnage rocks are similar to the Haddo rocks in many ways, the main difference being compositional. The Arnage unhomogeneous group could be partial melt rocks from a more quartzitic parent.

Although not discussed in the petrogenesis section the Kinharrachie xenolithic gneisses of Arnage could be formed in a like manner, perhaps from the subordinate hornblende-schist member of the Ellon gneisses as suggested by Read and Farquhar (1952), but insufficient chemical evidence is available to support this theory.

CHAPTER VI

Summary and Conclusions

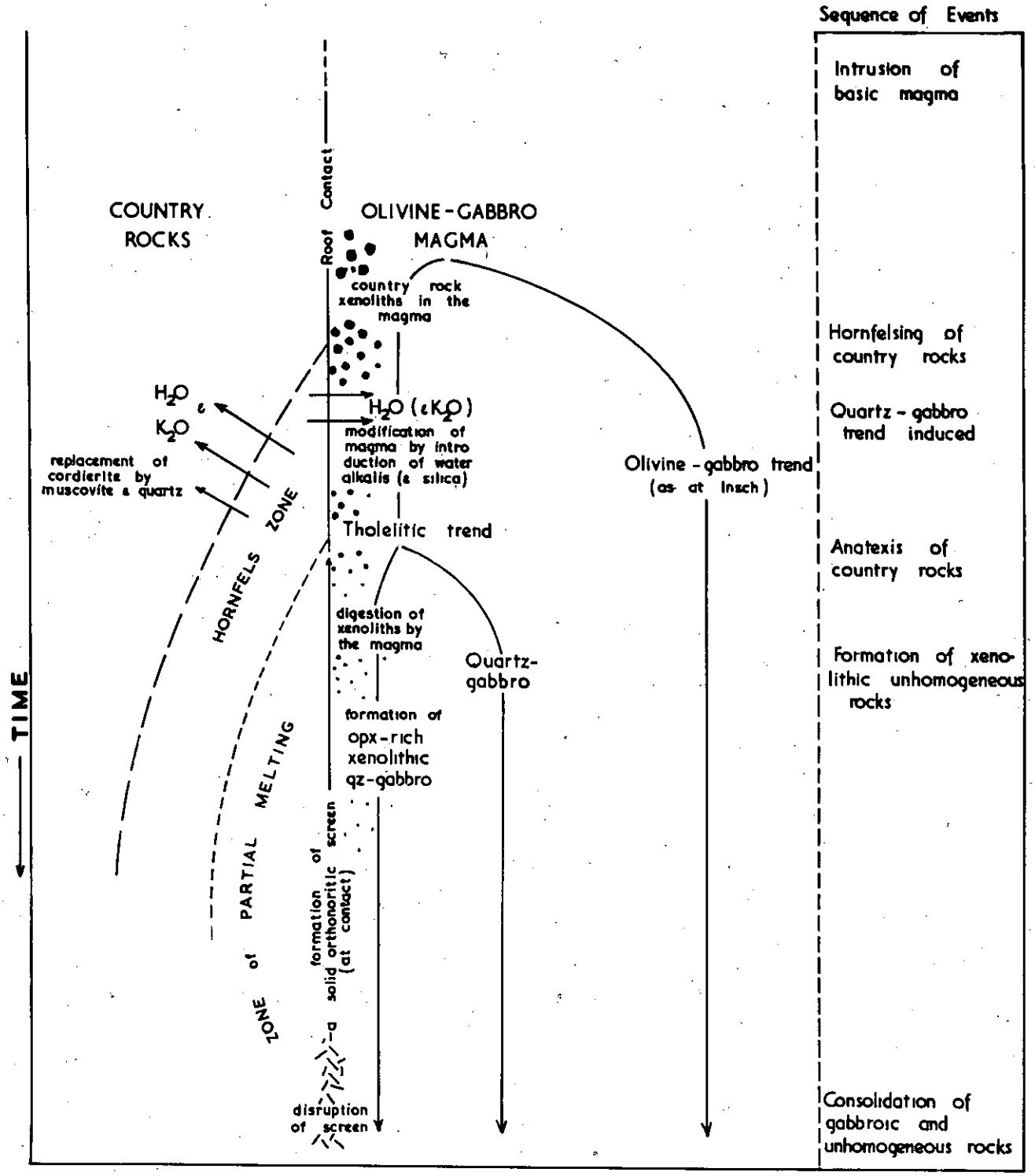
A broad thermal metamorphic aureole surrounds the Haddo basic mass and is best observed north-west of the gabbro, in the Fyvie schist s exposed beside the river Ythan. As the gabbroic sheet is approached the country rocks show an increase in grain size. Large prismatic sillimanite crystals and clear cordierite crystals develop in the Fyvie schists. Nearer the gabbros the schists lose their foliation and appear gneissose, with bands of quartzo-feldspathic material becoming more abundant. Finally, within a quarter mile of gabbro/country rock contact, mobilised xenolithic gneisses outcrop. The heat from the gabbro probably produced a diffusion of water (and alkalis) outwards from the schists nearest the gabbro. Accession of these materials to schists 1½ miles north-west of the gabbro caused the replacement of cordierite by muscovite and quartz. The gabbro sheet probably dips shallowly to the north-west of the Haddo district, closely underlying the schists in the Ythan valley. Hence the diffusion of the materials which led to the replacement of cordierite by muscovite and quartz, most likely took place over a much shorter distance than 1½ miles. Some water displaced from the inner aureole was probably dissolved in the basic magma. This vapour perhaps carried silica (and alkalis) into/

into the magma further depleting the immediate peripheral country rocks in SiO_2 (and K_2O). The fractionation trend of the basic sheet was thereby changed giving rise to a silica-oversaturated trend, with the appearance of hypersthene- and quartz-normative gabbros at Haddo House and Arnage, instead of the under-saturated, nepheline-normative 'basic' rocks observed as fractionation products of the gabbros at Insch.

The gabbro was probably intruded at depth, under a load pressure of c. 3-5 Kb, into country rocks which had just passed through a thermal maximum during regional metamorphism. Since the country rocks were at relatively high temperatures and the gabbros well insulated, the heat from the intrusive basic sheet partially melted relatively large volumes of the country rocks closest to it and produced ~~endem~~xenolithic rocks in which both matrix and xenolith were derived from the same parental material. No metasomatism mixing or diffusion between country rocks and gabbros was involved in the production of the quartz-cordierite-norites, etc.

The hypothesis that these rocks might have been produced by the basic magma assimilating country-rock material is not accepted, principally because an unbroken sequence of transitional rock types in diminishing order of abundance from olivine-hypersthene-gabbro to quartz-cordierite-norite is not observed. Nevertheless, contaminated (xenolithic) gabbros are also present, and are the products of partial melting of schist xenoliths/

xenoliths, accompanied by complex diffusion and by liquidisation effects when the partial melt liquid interacted with the enclosing basic magma. Fig. 19 is an attempt at a diagrammatic representation of the genesis of the Haddo rock groups.



A diagrammatic representation of the genesis of the Haddo House rocks.

FIG. 19

If the xenolithic quartz-cordierite-norites, etc., of Haddo House and Arnage are derived from partially melted country rocks, then it is reasonable to assume that this hypothesis could apply to other areas where similar rock types occur.

Small scale occurrences of partial melts corresponding in composition to eutectic I in the CMAS flow sheet (fig. 6) have been observed. Kynaston and Hill (1908, p.129) described a buchite containing cordierite, quartz, feldspar, spinel and pyroxene, formed at the contact between a camptonite dyke and the country rocks (phyllites) into which the dyke was intruded, at Sailean Sligenach in Argyll. The Survey thought the pyroxene was "probably augite" and specimens from this locality were examined by the author who found it impossible to ascertain if pyroxene was present. Chinner and Schairer (1962) referred to a similar occurrence, where a quartz-cordierite-norite melt is formed in a mica-schist at its contact with an olivine-diabase, in Argyll. Wyllie (1959) described the occurrence of a micro quartz-cordierite-norite formed in Torridonian arkoses at their contact with a picrite sill, on the island of Soay.

On a larger scale, several areas are known to contain rocks similar in character to those seen in the Haddo House and Arnage districts. In these other areas basic rocks have been intruded into country rocks with the development of "transitional types"/

types" at the contact zone. Most previous workers have proposed that these "transitional" rock types represent either assimilation products or metasomatised rocks, with the intrusive magma always contributing considerably to their final composition.

Lacroix (1899) described rock groups very similar to those of Haddo from the Pallet area in France. Lacroix believed that an intrusive olivine-gabbro had assimilated country rocks producing cordierite-bearing norites, etc. Every rock type contained xenoliths which were often aluminous, containing minerals such as spinel, sillimanite and cordierite. There was usually an outer zone rich in plagioclase±cordierite± hypersthene between the xenolith and the enclosed matrix. It is interesting to note that although Lacroix (1899) described transitions from olivine-gabbro to norite (two pyroxene-bearing basic rock with opx $\geq$ cpx) he did not record the occurrence of any orthonorites, which would be required if a complete assimilative sequence from olivine-gabbro to quartz-cordierite-norite existed.

Read (1923b) described contaminated rocks in north-east Scotland, associated with the basic masses of Huntly and Insch. The contaminated rocks of Huntly comprised quartz-cordierite-norites±garnet±K-feldspar enclosing xenoliths containing spinel, sillimanite and cordierite, the most aluminous phases appearing in the centre of the xenolith (1923b, p.129, fig. B). Read (1923b) thought that these rocks were produced by the basic magma/

magma assimilating country rocks. At Insch similar rocks were described, and the author visited Govals quarry at the eastern edge of the Insch basic mass. Xenolithic cordierite-bearing rocks appear at Govals which closely resemble the rocks found at Craigmuir Wood in the Haddo district. In both areas it seems possible that a partial melt theory of origin for these xenolithic cordierite-bearing rocks could apply.

In his account of the Bushveld complex, Hall (1932) described many xenolithic rocks, and although he considered these assimilation products, he stated (p.416) that ... "some of the outcrops suggest that the sediments were rendered more or less plastic under their metamorphism." Hall (1932) revealed that he did not know whether these xenolithic 'mixed' rocks were altered sediments or contaminated basic rocks. Nel (1940) described the occurrence of quartz-cordierite-norites associated with the Bushveld igneous complex and although he thought that these rocks were hybridised diabases, the contact relations between them and the underlying country rocks were obscure.

Barker (1964) described many aluminous assemblages from the Cortlandt complex in the U.S.A. Pelitic schists peripheral to a gabbro had been metamorphosed and large schistose blocks included in the basic body. These inclusions now appear as aluminous xenoliths with corundum, sillimanite, spinel and sapphirine present. Barker (1964) considered that

a/

a metasomatic interaction took place between xenolith and enclosing magma which produced the alumina-rich assemblages now present in these rocks. Butler (1936) described xenoliths which had feldspar-rich 'rims' between xenolith and magma from the same complex and these closely resembled xenoliths found in the quartz-hypersthene-gabbro at Häddo (chapter IV, p.138).

Grout (1933) described argillaceous and quartzitic xenoliths in a gabbro containing quartz and cordierite (probably a quartz-cordierite-norite) associated with the Duluth gabbro in North America.

Evans (1964) discussed the origin of the pelitic hornfelses in Connemara, Ireland, found peripheral to the Cashel-Lough Wheelaun basic intrusion. The hornfelses show development of aluminous minerals such as corundum, spinel and sillimanite. Evans put forward three possible hypothesis to explain the formation of the hornfelses. Two of these hypotheses were carriage of elements in a hydrous diffusion, and elemental diffusion. These were rejected because there would have been insufficient H_2O available for the first process to have taken place; and the second process would have had to have been extremely slow and one way (schist $\longrightarrow$ intrusion). Evans (1964) decided that the most attractive hypothesis was one of fractional melting chiefly because the fractionation of trace elements in the aureole was similar to/

to that occurring in crystallising magmas and the rocks appeared mobilised in the field. Evans (1964, p.142) stated that ... "since there is no evidence that the melt moved outwards from the contact zone, it is likely that it became dissolved in the basic or ultrabasic magma."

Stewart (1946) described similar hornfels in the country rocks peripheral to the Belhelvie gabbro in Aberdeenshire. No aureole could be traced in the country rocks due to lack of exposures. The basic rocks adjacent to the hornfelses were olivine-gabbros which fitted into the normal differentiation sequence displayed at Belhelvie and which "/contained/ no xenoliths and show no signs of contamination," (Stewart, 1946, p.476). In neither of the above cases is a partial melt liquid (quartz-cordierite-norite) seen enclosing the alumina-rich hornfelses, and only Evans (1964) proposed that the liquid evolved from a fractional melting of the country rocks might have been dissolved in the nearby gabbros. Evans (1964, p.128) remarked that ... "migmatisation and later deformations destroyed the contact relations of many of the intrusions," and Stewart (1946, p.492) argued that the basic rocks were "tilted very considerably since /their/ deformation." Since post-intrusive folding movements occurred in each area the partial melt formed in the country rocks at the time of the intrusion of the basic bodies could have been removed by some filter-press process and not necessarily dissolved/

dissolved in the basic magma. At Belhelvie this could happen prior to the consolidation of the basic magma (see argument, chapter II, p. 24).

Proof of a partial melt origin for xenolithic rocks similar to those found at Haddo (including the rocks from areas described in this section) can only be achieved by examination of field relations and considerable petrographic and chemical work being carried out on the different types of rocks combined with appropriate experimental studies. Analyses of both matrix and xenolith should be performed and subsequently plotted into the CMAS quaternary system. A flow-sheet diagram should be constructed which encompasses all the observed mineral assemblages in the area examined as was attempted with the Haddo (and Arnage) rocks.

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APPENDIX A

Locations of the rocks analysed by the author in this thesis, from the Haddo House and Arnage districts, Aberdeenshire.

Fyvie schists

192	(NJ) 841392	andalusite-cordierite-schist.
16	842391	quartz-plagioclase-feldspar psammite.
20	845386	andalusite-cordierite-(sillimanite)-schist.
22	847383	(andalusite)-schist; cordierite has been replaced by quartz and muscovite.
27	851381	psammite with garnet.
28	852379	andalusite-sillimanite-(fibrolite)-schist.
39	859374	quartz-rich andalusite-schist with large prismatic sillimanite crystals and clear cordierite crystals present.
45	861371	altered andalusite-(sillimanite-cordierite)-schist similar to 39.
51	864367	quartz-biotite-feldspar-'gneiss'.

Mormond Hill quartzite

280	915329	impure quartzite with garnet, potash-feldspar and cordierite present.

Ellon gneiss

164	946308	quartz-biotite-cordierite gneiss.
340	947306	psammite.

Igneous/

Igneous rocks etc.

57	878357	olivine-hypersthene-gabbro.
276A	913332	olivine-hypersthene-gabbro.
76	897355	quartz-hypersthene-gabbro.
78	898353	quartz-hypersthene-gabbro.
63	889361	quartz-hypersthene-gabbro.
59	879357	altered quartz-hypersthene-gabbro.
86	900352	altered quartz-hypersthene-gabbro.
245	913322	quartz-hypersthene-gabbro.
345-14	930375	quartz-hypersthene-gabbro.
124	867364	uralitised quartz-hypersthene-gabbro.
126	911337	uralitised quartz-hypersthene-gabbro.
145	863365	uralitised quartz-hypersthene-gabbro.
168	877386	uralitised quartz-hypersthene-gabbro.
171	879379	uralitised quartz-hypersthene-gabbro.
64M	889361	xenolithic quartz-hypersthene-gabbro.
347-21B	898352	xenolithic quartz-hypersthene-gabbro.
345-4M	930374	quartz-hypersthene-gabbro.
68M	889360	quartz-cordierite-norite.
69	889360	quartz-cordierite-norite.
88	899352	quartz-cordierite-norite.
89	899352	quartz-cordierite-norite.
99	891351	quartz-cordierite-hypersthene-K-feldspar-garnet rock (+ biotite).
100M	891351	quartz-cordierite-K-feldspar-garnet rock.
113	891352	quartz-cordierite-hypersthene-garnet rock.
117	891352	quartz-cordierite-K-feldspar-garnet rock.

118/

118	891352	quartz-cordierite-K-feldspar-garnet rock.
345-15M	930375	quartz-cordierite-norite.
231M	912326	quartz-cordierite-K-feldspar-garnet rock.
236	913325	garnet-bearing Arnage gneiss.
250M	915323	garnet-bearing Arnage gneiss.
256M	916318	garnet-bearing Arnage gneiss.
273M	919322	altered Arnage gneiss.
345-6	930374	Arnage gneiss.
345-13	930375	quartz-biotite gneiss (knots of alteration products might have replaced cordierite).
346-1	932382	quartz-cordierite-K-feldspar-garnet rock.
296	923321	quartz-biotite-K-feldspar gneiss (garnet-bearing)-Ardlethen gneiss.
322M	920312	Ardlethen gneiss + cordierite (c.f. 231M).
309M	926313	quartz-hornblende-gneiss (Kinharrachie gneiss).
64I	889361	orthopyroxene-rich xenolith in quartz-hypersthene gabbro.
74I	897356	corundum-spinel bearing xenolith in quartz-hypersthene gabbro (contains in addition, plagioclase, cordierite, sphene, lazulite and brookite).
347-21A	898352	altered quartz-orthonorite xenolith in quartz-hypersthene-gabbro.
85I	899352	sillimanite-rich xenolith in quartz-cordierite-norite.
68I	889360	orthopyroxene-rich xenolith in quartz-cordierite norite.

83I	898352	quartzitic inclusion in quartz-cordierite-norite.
68I	889369	orthopyroxene-rich xenolith in quartz-cordierite-norite.
83I	898352	quartizitic inclusion in quartz-cordierite-norite.
90I	899352	quartzitic inclusion in quartz-cordierite-norite.
100I	891351	spinel-coriderite inclusion in quartz-cordierite-K-feldspar-garnet rock (matrix).
101I	891351	sillimanite-rich inclusion in quartz-cordierite-K-feldspar-garnet rock (matrix).
231I	912326	spinel-bearing xenolith in quartz-cordierite-K-feldspar-garnet rock (matrix).
250I	915323	altered spinel-bearing inclusion in Arnage gneiss.
255I	916318	spinel-sillimanite-bearing inclusion in an Arnage gneiss matrix + K-feldspar + hypersthene. This matrix is probably similar to 99 or 113.
273I	919322	altered sillimanite-bearing xenolith in altered Arnage gneiss (matrix).
322I	920322	biotite-rich (cordierite-bearing) xenolith in Ardlethen gneiss (matrix).
346-4I	932382	spinel-rich xenolith in quartz-hypersthene-gabbro.
345-4I	930374	cordierite-spinel xenolith in Arnage gneiss.
345-15I	930375	2-pyroxene xenolith in quartz-cordierite-norite.

301I/

301I	922317	clinopyroxene-bearing xenolith in Kinharrachie gneiss.
309I	926313	amphibole-rich xenolith in Kinharrachie gneiss.
97	902348	quartz-dolerite.
110	892351	calc-silicate band in Craigmuir Wood.
105	892348	quartzitic band near Craigmuir Wood, perhaps in the Auchedly granite.

Locations of rocks given in modal analysis tables.

Olivine-hypersthene-gabbros.

61	878359
62	879359
123	900336
235	912325
282	914330

Quartz-hypersthene-gabbro.

87	900352
71	889360
248	914322
345-3	930374

APPENDIX B

ROCK ANALYSES

District: HADDO

Rock Type	Quartz-dolerite (dyke)	Quartzite	Limestone
Rock no.	97	105	110
SiO_2	48.94	85.70	50.16
TiO_2	3.08	0.35	0.49
Al_2O_3	13.27	7.64	10.75
Fe_2O_3	7.40	0.86	0.76
FeO	7.27	1.14	3.18
MnO	0.20	0.027	0.060
MgO	5.00	0.59	12.21
CaO	9.05	0.53	15.44
Na_2O	2.74	0.82	0.58
K_2O	0.58	1.70	3.56
H_2O+	1.50	0.65	1.42
P_2O_5	0.32	0.076	0.11
Total	99.35	100.09	98.72*

* does not include CO_2

All analyses carried out by author on rock powder dried at 110°C for 2 hours.

Trace elements in ppm

Cr	82	58	89
Ba	245	345	550
Sr	283	58	277
Rb	10	52	116

ESKOLA NORMS (given below for completeness - based on 1-cation percentages).

Orthoclase	9.25	10.65	9.85
Albite	25.70	7.80	-
Anorthite	20.35	2.20	11.65
Clinopyroxene	19.68	-	50.96
Orthopyroxene	4.92	1.84	-
Olivine	-	-	8.39
Quartz	5.94	71.26	-
Corundum	-	4.27	-
Magnetite	9.03 (includes 1.75% Haematite)	1.28	1.04
Ilmenite	4.48	0.52	0.68
Apatite	0.65	0.18	0.20
Nepheline	-	-	8.43
Leucite	-	-	8.80

APPENDIX C

MINERAL ANALYSES (+ partial analyses)

Mineral	OPX	OPX	OPX
Rock Group	ol-hy-g	qz-hy-g	qz-cdt-no
From Rock No.	57	76	68M
SiO_2	54.36	53.05	47.32
TiO_2	0.27	0.26	0.73
Al_2O_3	1.70	1.34	4.25
Fe_2O_3	2.33	2.84	1.88
FeO	13.06	17.45	31.76
MnO	0.34	0.49	0.74
MgO	26.86	23.45	12.08
CaO	0.89	0.90	0.18
Na_2O	0.072	0.076	0.12
K_2O	0.062	0.053	0.083
H_2O+	none	none	none
P_2O_5	n.d.	n.d.	n.d.
Total	99.94	99.91	99.14
	No. of ions on the basis of 6 oxygens		
Si	1.952	1.952	1.881
Al	0.071 } 2.023	0.058 } 2.01	0.143 } 2.024
Al	0.001	-	0.05
Ti	0.007	0.007	0.022
Fe^{3+}	0.063	0.079	0.056
Mg_{2+}	1.438	1.286	0.716
Fe	0.392 } 1.953	0.537 } 1.967	1.056 } 1.952
Mn	0.010	0.015	0.025
Ca	0.034	0.035	0.008
Na	0.005	0.005	0.009
K	0.003	0.003	0.004
Mg	74	66	38.5
Fe	24	32	61
Ca	2	2	0.5
$100Mg/(Mg + Fe^{2+} + Fe^{3+} + Mn)$	75.6	67.1	38.6
% Al in Z group	3.52	2.89	7.06

APPENDIX C (contd.)

MINERAL ANALYSES (+ partial analyses)

Mineral	OPX	CPX	CPX	OLIVINE
Rock Groups	qz-cdt-no inclusion	ol-hy-g	qz-hy-g	ol-hy-g
From Rock No.	68I	57	76	57
SiO_2	48.10	-	-	-
TiO_2	0.31	0.46	0.82	0.048
Al_2O_3	4.18	2.38	5.72	0.58
Fe_2O_3	1.34	2.32	10.02 Fe'''	22.89 as Fe''
FeO	31.46	7.69		
MnO	0.66	-	-	-
MgO	12.92	18.91	16.99	35.15
CaO	0.31	16.20	11.73	0.073
Na_2O	0.27	0.52	-	-
K_2O	0.096	0.10	-	-
H_2O+	none	-	-	-
P_2O_5	n.d.	-	-	-
Total	99.65	-	-	-

No. of ions on the basis of 6 oxygens.

Si	1.894	2.008			
Al	0.114		0.104	0.250	
Al	0.080				
Ti	0.009		0.013	0.023	numbers of ions in CPX extremely dubious as SiO_2 was not calculated
Fe^{3+}	0.040		0.064	0.066	
Mg_{2+}	0.758	1.983	1.039	0.936	
Fe	1.036		0.237	0.244	
Mn	0.022		0.006	-	
Ca	0.013		00.640	0.454	
Na	0.020		0.037	-	
K	0.005		0.004	-	
Mg	41		52	3545	
Fe	58.5		16	19	
Ca	0.5		32	27	

$100Mg/(Mg + Fe^{2+} + Fe^{3+} + Mn)$ 40.8

% Al in Z group 5.68

CPX formulas (both sub-calcic)

(57) $Ca_{32}Mg_{52}Fe_{16}$

(76) $Ca_{27}Mg_{54}Fe_{19}$

APPENDIX D

1-CATION PERCENTAGES

Rock No.	192	20	22	28	39	45	51	16	27
Si	58.14	55.50	51.50	54.31	52.69	49.48	65.22	76.38	69.20
Ti	0.86	0.88	0.79	0.70	0.75	0.71	0.50	0.39	0.43
Al	21.78	22.45	24.70	25.56	25.07	25.72	17.52	10.80	15.36
Fe	0.91	1.10	1.72	1.07	0.90	1.44	0.88	0.33	0.42
Fe	4.61	5.42	5.31	5.22	4.36	4.68	3.19	1.63	2.47
Mn	0.10	0.08	0.06	0.12	0.10	0.10	0.06	0.04	0.05
Mg	3.60	4.66	5.08	4.08	4.21	4.37	2.77	1.57	2.27
Ca	1.59	1.22	0.91	1.27	1.52	2.94	1.51	1.04	2.00
Na	4.50	3.96	3.60	3.01	7.26	5.35	4.63	6.46	6.57
K	3.70	4.60	6.11	4.58	3.04	4.37	3.62	1.29	1.20
P	0.13	0.12	0.22	0.08	0.11	0.83	0.10	0.07	0.04
Total	100.01	99.99	100.00	100.00	100.00	99.99	100.00	100.00	100.01

Rock No.	280	164	340	57	276A	76	78	63	59
Si	80.11	54.30	73.01	43.15	44.83	49.85	50.58	49.88	48.76
Ti	0.59	0.70	0.37	0.45	0.47	0.60	0.58	0.88	0.78
Al	9.05	21.67	13.49	19.33	19.64	19.04	19.11	17.74	19.85
Fe	0.66	1.08	0.57	0.94	1.14	1.08	1.07	0.64	1.17
Fe	1.47	4.70	1.92	5.20	6.00	4.29	5.40	6.26	5.71
Mn	0.02	0.06	0.04	0.10	0.12	0.11	0.14	0.13	0.14
Mg	0.64	4.50	1.92	17.68	14.08	11.36	10.54	10.04	9.29
Ca	0.31	1.58	1.66	9.57	8.97	8.58	7.83	7.72	8.71
Na	1.51	5.41	4.89	3.09	4.03	3.96	3.65	4.96	4.21
K	5.61	5.94	2.11	0.45	0.66	1.05	1.02	1.61	1.28
P	0.03	0.06	0.04	0.05	0.07	0.07	0.07	0.14	0.10
Total	100.00	100.00	100.01	100.01	100.01	99.99	99.99	100.00	100.00

Rock No.	86	245	345 -14	124	126	145	168	171	64M
Si	49.02	50.30	48.93	47.40	52.04	49.43	51.86	43.71	49.18
Ti	1.86	0.61	0.56	1.77	1.07	1.92	1.92	3.43	0.86
Al	18.70	16.29	20.06	20.77	19.10	17.17	17.24	17.59	21.62
Fe	1.45	0.70	0.95	1.85	1.20	2.14	2.18	3.25	1.20
Fe	5.84	5.57	4.41	6.99	5.92	6.75	6.32	7.64	5.80
Mn	0.13	0.12	0.11	0.14	0.14	0.16	0.14	0.17	0.12
Mg	7.81	15.89	11.56	6.73	6.82	7.15	4.42	9.06	8.11
Ca	9.34	8.02	8.48	8.63	5.66	8.32	6.77	10.17	7.04
Na	4.35	1.47	3.92	4.86	5.14	5.21	6.58	4.18	4.87
K	1.27	0.97	0.96	0.70	2.51	1.52	2.28	0.76	1.17
P	0.21	0.06	0.06	0.16	0.39	0.24	0.28	0.04	0.03
Total	99.98	100.00	100.00	100.00	99.99	100.01	99.99	100.00	100.00

APPENDIX D (contd.)

Rock No.	347 -21B	345 -4M	68M	69	88	89	99	100M	113
Si	50.28	52.93	56.66	56.64	53.59	54.96	72.15	56.02	61.26
Ti	0.85	1.35	1.21	1.11	1.16	1.11	0.53	0.53	0.94
Al	21.34	18.29	20.20	21.00	24.15	20.84	15.74	22.14	18.48
Fe	1.35	1.69	1.01	1.31	1.99	1.94	0.70	1.06	1.21
Fe	5.83	5.97	5.85	6.24	5.66	6.62	2.97	6.21	4.31
Mn	0.14	0.12	0.11	0.12	0.14	0.14	0.07	0.16	0.09
Mg	7.53	6.47	3.99	4.70	4.36	4.38	1.73	1.86	2.88
Ca	7.47	4.29	4.89	4.00	4.21	4.53	2.50	0.66	3.20
Na	3.82	4.83	4.47	3.31	3.38	4.09	2.69	2.22	4.05
K	1.32	4.00	1.52	1.49	1.16	1.31	0.86	8.94	3.45
P	0.07	0.07	0.10	0.07	0.18	0.08	0.05	0.20	0.14
Total	100.00	100.01	100.01	99.99	99.98	100.00	99.99	100.00	100.01

Rock No.	117	118	345 -15M	231M	236M	250M	256M	237M	345 -6
Si	72.03	79.59	59.88	58.84	58.54	73.54	59.93	62.63	66.48
Ti	0.62	0.44	0.81	1.13	0.74	0.58	0.94	0.60	0.48
Al	14.97	11.09	17.26	20.15	21.56	13.36	20.09	19.11	16.91
Fe	0.67	0.53	1.20	1.10	1.29	0.56	1.04	0.77	0.89
Fe	3.09	2.30	3.88	6.03	4.94	2.41	5.29	3.90	3.55
Mn	0.06	0.05	0.09	0.10	0.08	0.05	0.10	0.09	0.12
Mg	1.96	1.29	5.27	3.57	3.63	1.54	3.14	3.19	2.74
Ca	2.04	1.26	4.49	1.27	1.71	0.89	2.88	1.89	3.08
Na	2.48	1.96	4.65	4.04	3.74	3.92	4.34	4.74	3.74
K	2.03	1.43	2.41	3.68	3.70	3.08	2.05	2.99	1.92
P	0.06	0.07	0.06	0.08	0.08	0.06	0.20	0.09	0.08
Total	100.01	100.01	100.00	99.99	100.01	99.99	100.00	100.00	99.99

Rock No.	345 -13	346 -1	296	322M	309M	64I	74I	347 -21A	85I
Si	57.27	63.72	67.22	60.66	57.29	47.81	39.64	52.61	45.07
Ti	0.76	0.68	0.60	0.61	0.66	0.31	0.69	0.78	1.36
Al	18.46	19.82	16.04	19.39	16.01	11.34	35.67	26.54	35.97
Fe	1.35	1.25	0.60	1.08	2.04	1.40	2.48	0.55	3.45
Fe	4.58	4.41	3.45	4.03	4.37	11.70	1.93	2.09	6.41
Mn	0.10	0.10	0.08	0.07	0.09	0.28	0.16	0.04	0.13
Mg	5.91	2.32	2.84	3.64	6.24	21.17	3.00	2.11	4.04
Ca	4.35	1.61	1.59	2.16	5.93	4.04	9.61	8.79	0.56
Na	4.33	2.89	3.86	5.46	5.73	1.52	5.30	5.36	1.41
K	2.73	3.14	3.65	2.82	1.59	0.36	1.45	1.07	1.56
P	0.10	0.06	0.06	0.08	0.05	0.06	0.06	0.06	0.04
Total	99.99	100.00	99.99	100.00	100.00	100.00	99.99	100.00	100.00

APPENDIX D (contd.)

Rock No.	68I	83I	90I	100I	101I	231I	250I	255I	273I
Si	49.47	70.33	70.01	46.69	48.00	50.94	45.24	52.15	77.02
Ti	0.58	0.13	0.47	0.83	0.99	0.75	0.91	0.74	0.21
Al	14.71	14.67	13.92	29.90	30.65	27.26	32.12	28.96	11.68
Fe	1.12	0.51	0.58	2.47	1.67	1.03	1.88	1.28	0.68
Fe	15.65	0.49	2.58	6.47	5.88	2.94	3.32	2.02	1.36
Mn	0.29	0.02	0.07	0.05	0.10	0.04	0.09	0.02	0.07
Mg	11.16	0.54	3.96	1.57	2.70	3.20	2.63	1.45	2.04
Ca	3.43	1.55	5.00	0.53	0.57	1.64	1.74	0.69	4.36
Na	3.02	5.30	2.32	2.73	2.05	5.01	4.73	3.20	1.62
K	0.53	6.41	0.92	8.65	7.21	7.03	7.18	9.35	0.90
P	0.04	0.05	0.18	0.13	0.18	0.17	0.15	0.12	0.07
Total	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.98	100.01

Rock No.	322I	346 -4I	345 -15I	345 -4I	301I	309I	97	105	110
Si	42.79	45.51	48.29	43.34	55.73	44.22	47.35	84.13	46.05
Ti	1.20	0.88	1.13	0.77	0.55	1.15	2.24	0.26	0.34
Al	30.14	29.17	17.39	29.85	14.92	17.19	15.13	8.84	11.64
Fe	1.63	1.59	1.62	2.43	1.56	3.29	5.39	0.64	0.52
Fe	6.04	5.18	6.73	3.84	4.30	7.19	5.88	0.94	2.44
Mn	0.12	0.10	0.14	0.10	0.10	0.16	0.17	0.02	0.04
Mg	5.65	3.60	11.55	3.00	7.99	10.82	7.21	0.86	16.71
Ca	2.35	2.79	10.73	5.40	12.28	9.38	9.38	0.55	15.19
Na	4.90	5.53	2.01	7.23	2.71	5.39	5.14	1.55	2.81
K	4.89	5.45	0.30	3.99	0.38	1.15	1.85	2.13	4.17
P	0.28	0.20	0.11	0.06	0.08	0.06	0.26	0.06	0.08
Total	99.99	100.00	100.00	100.01	100.00	100.00	100.00	99.99	100.00

APPENDIX E

Chemical Analytical Methods

Since the area investigated is badly exposed, rock outcrop available for sampling is poor, but a sample of 2-5 Kg weight of fresh material was taken wherever possible.

(i) Preparation of the Sample:

The rock sample was scrubbed, washed in de-ionised water and dried. It was split into cubes of about 2 cm side, using a hydraulic rock splitter. Any weathered surfaces or vein material was discarded at this stage. After mixing the rock cubes, a grab sample was taken by hand (200-300 gm), and reduced to 14 mesh using a tungsten carbide pestle and mortar. When all the material had been reduced to 14 mesh about one sixth was taken, by means of an automatic sample splitter, for further grinding.

The 35-50 gm of 14 mesh material selected was reduced to 100 mesh powder by grinding in an agate mortar. Care was taken to ensure that no loss of material occurred during the above processes. The rock powder was put into a glass bottle, mixed thoroughly and placed in an oven at 110°C for at least 2 hours. After this, analysis of the rock (powder) could begin.

(ii) Chemical Methods of Analysis (Wet Methods)

Si was determined gravimetrically. After fusion with alkali carbonate and evaporation of the solution with HCl, any soluble SiO_2 remaining was precipitated by addition of gelatin.

Al was determined by spectrophotometry. The method of Mullen and/

and Riley which uses the complex with 8-hydroxyquinoline was employed. $\alpha - \alpha_1$ -dipyridyl hydroxylamine, $BeSO_4$, and sodium acetate was added and the pH adjusted to 4.95. The aluminium was extracted with 8-hydroxyquinoline dissolved in chloroform, and only an interference due to titanium remained. A correction factor was applied to counteract this.

Fe (Total iron) Mn Ti and P were also determined using a spectrophotometer. Total iron was measured by means of the red colour produced by complexing with sodim citrate and ammoniacal thioglycollic acid.

An acid solution of the rock was oxidised with periodate producing a permanganate purple colour from the Mn thus enabling Mn to be determined. A sulphuric acid solution of the rock had H_2O_2 added and the yellow colour produced (pertitanic acid) used to determine Ti. A molybdenum blue complex was used to determine P.

Mg and Ca were determined by titration with ethylene-diamine-tetraacetic acid (E.D.T.A.). Previously the Fe, Al and Ti had been removed by double precipitation with NH_4OH from a solution containing NH_4Cl. The calcium was titrated at a pH of 12 using Patton and Reader's reagent as indicator. Calcium and magnesium were together titrated at a pH of 9 using eriochrome black T as indicator. In both titrations KCN was first added to complex heavy metals and also triethanolamine to complex any Al remaining in solution. The amount of Mg was obtained by difference.

H(as H_2O) was measured gravimetrically. The rock powder was mixed with a flux (2 parts PbO + 1 part $PbCrO_4$) and heated for five minutes/

minutes. The water given off was collected and measured.

Ferrous iron was determined by titration with dichromate using sodium diphenylamine sulphonate as indicator.

X-ray fluorescent techniques were used to determine Rb, Ba , Sr and Cr. U.S. Geological Survey rock standards provided the known amounts of the determined elements, and these were used to set up the standard graphs for each element.

PLATE 1

a) Irregular foliation in the schists at Methlick Bridge.

b) Well-developed, regular foliation in the schists at Gight.

a

b

PLATE 2

a) One of the isolated rock outcrops between Methlick bridge and Gurge Pot.

b) Gneissose textures developed in schists south of Methlick bridge, near Gurge Pot.

a

b

PLATE 3

a) Quartzo-feldspathic segregations in the country rocks at Gurge Pot.

b) Xenolithic gneisses at Bellmuir.

c

d

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