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Geologisk beskrivelse av Sulitjelma -feltet , med hovedvekt pü bergartene i Sulitjelma -gabbro- kompeks. Dette er en uregelmessig lagdelt intrusjon som er folda til ei synform. Inrtusjonen er delvis invertert. Det er lagt sërskilt vekt pü mineralogien i gabbro-bergartene, samt ü forsöke ü sette disse inn i en större strukturgeologisk sammenheng.

THE SULITJELMA GABBRO COMPLEX

- by R. Mason, B.A., Christ's College -

Dissertation submitted for the degree
of Doctor of Philosophy of the
University of Cambridge.

DECLARATION

I hereby declare that except where otherwise stated, the observations and ideas in this thesis are my own, and that no part of the thesis has been submitted to any other University for any degree.

Roger Mason
October 1966.

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P R E F A C E

The six-figure references introduced in the text by the letters g.r. refer to the Universal Transverse Mercator grid, Zone 33W. If the references were quoted in full, they would be preceded by the letters WQ.

The sketches of outcrops shown in some illustrations are traced directly from field notebooks, with no embellishments whatever.

INTRODUCTION

1. Description of area and general statement.

The Sulitjelma mountains lie on the Norwegian-Swedish border at 67° 10' N, 15° 20' E. They include the highest summit in Arctic Norway, Suliskongen, 1914 m. The slopes of the mountains are covered by extensive glaciers, but above the 900 metre contour vegetation is scant and during the summer the rocks are very well exposed for geological study. Glaciation was clearly far more extensive in the recent past, with ice-scratching and polishing, roches moutonnées, and old moraines widely visible on the lower slopes of the mountains. The action of the ice has tended to emphasise variations in relief due to varying hardness of the rocks, and this has proved very useful during the field investigation of the gabbro. The high ground covers an area about 12 km. E-W by 10 km. N-S, matching approximately the outcrop of the Sulitjelma gabbro complex.

A classic account of the geology of the whole Sulitjelma region was given by Th. Vogt (1927) and the Swedish Sulitjelma region has recently been described by Kautsky (1952) as part of his investigation of the Sulitjelma-Salojaure region. The greater part of the mountains, including their highest summit, lie in Norway, and were mapped geologically by the present writer during the summers of 1963, 1964 and 1965. (See map in pocket).

The Norwegian part of the Sulitjelma massif consists of two areas of high peaks separated by a lower col at 1200 m. covered by an icecap-like glacier. The northern, smaller part of the massif consists of three summits (heights 1702 m., 1688 m. and 1798 m., from W to E, g.rs. 543520, 549521, 556527) on a rounded ridge running about 2 km. SW-NE, known collectively by their Lapp name, Sorjusčokka or by their Norwegian name, Kokedaltind. The southern massif is higher and much more extensive and consists of the summits (from W to E), Vardetoppen 1722 m., Stortoppen 1830 m., Vaknačokka 1700 m., Point 1717 m., Point 1787 m. and Suliskongen 1914 m. (g.rs. 547481, 553482, 561467, 574492, 588493, 599484). Apart from Vaknačokka these form a rather discontinuous ridge crossed by snowfields between Stortoppen and Point 1717, between Point 1717 and Point 1787 and between Point 1787 and Suliskongen. The ridge runs in an arc for about 5 km. convex to the north, forming a wall of peaks north of the main Sulitjelma glacier, which Vogt referred to as Salajekna. The peak Vaknačokka lies to the SW of the main glacier, separated from Stortoppen by a deep cwm with a small glacier falling into it from the main glacier.

To the south and north the area is bounded by lakes. To the south lies Låmivann and to the north the two lakes Øvre and Nedre Sorjus, lying in the eastern part of the valley Sorjusdal, which runs down to them from the extreme NW corner of the gabbro outcrop. To the west the mountains are bounded by a high, rather irregular depression, containing a number of small lakes, a group in the north being known as Småsorjus, and a group further south as Duoldagop.

The well known Sulitjelma copper mines lie to the SW of the Sulitjelma mountains, after which they are named. The nearest settlement is at Ny Sulitjelma, which was used as a base during the investigation. While most of the mines are on the northern side of a deep valley, Ny Sulitjelma lies up at 590 m. in the mouth of a large cwm, about 3 km. S of the Duoldagop lakes.

Access to the mountains is simplified by the existence of two alternative footpaths into Sweden, which are conspicuously marked by the Sulitjelma Turistforening (Rambling Club), who have excellently equipped mountain huts at the western ends of Lamivann (g.r. 521460) and Øvre Sorjus (g.r. 543552). The tracks leave from Ny Sulitjelma and go to the head of the cwm where they diverge (at g.r. 506483). The western track then goes north between the two lakes of Duoldagop, passes east of the Småsorjus lakes and over a pass into Sorjusdal. It runs down the southern side of the valley to the western end of Øvre Sorjus, and then south of the two Sorjus lakes and north of Hammeren into Sweden. The eastern track crosses a low ridge into the valley north of Vardetoppen, goes up this to the glacier, and over the snow col between the two massifs of the Sulitjelma mountains. From the other side of the glacier it proceeds north down the wide shallow

Fig. 0.1.

Geological sketch-map of Sulitjelma.

Scale 1:100,000. Based on earlier geological maps by Sjögren, Vogt and Kautsky, and recent work by Henley, Larsen, Nicholson and Mason.

Legend.

Gasak nappe.

- Schists and calc-silicate rocks.
- Micaceous psammite.
- Amphibolites.
- Gabbro complex.
- Granites.

Junction unit.

- Dioritic gneiss.

Pieske-Vasten nappe.

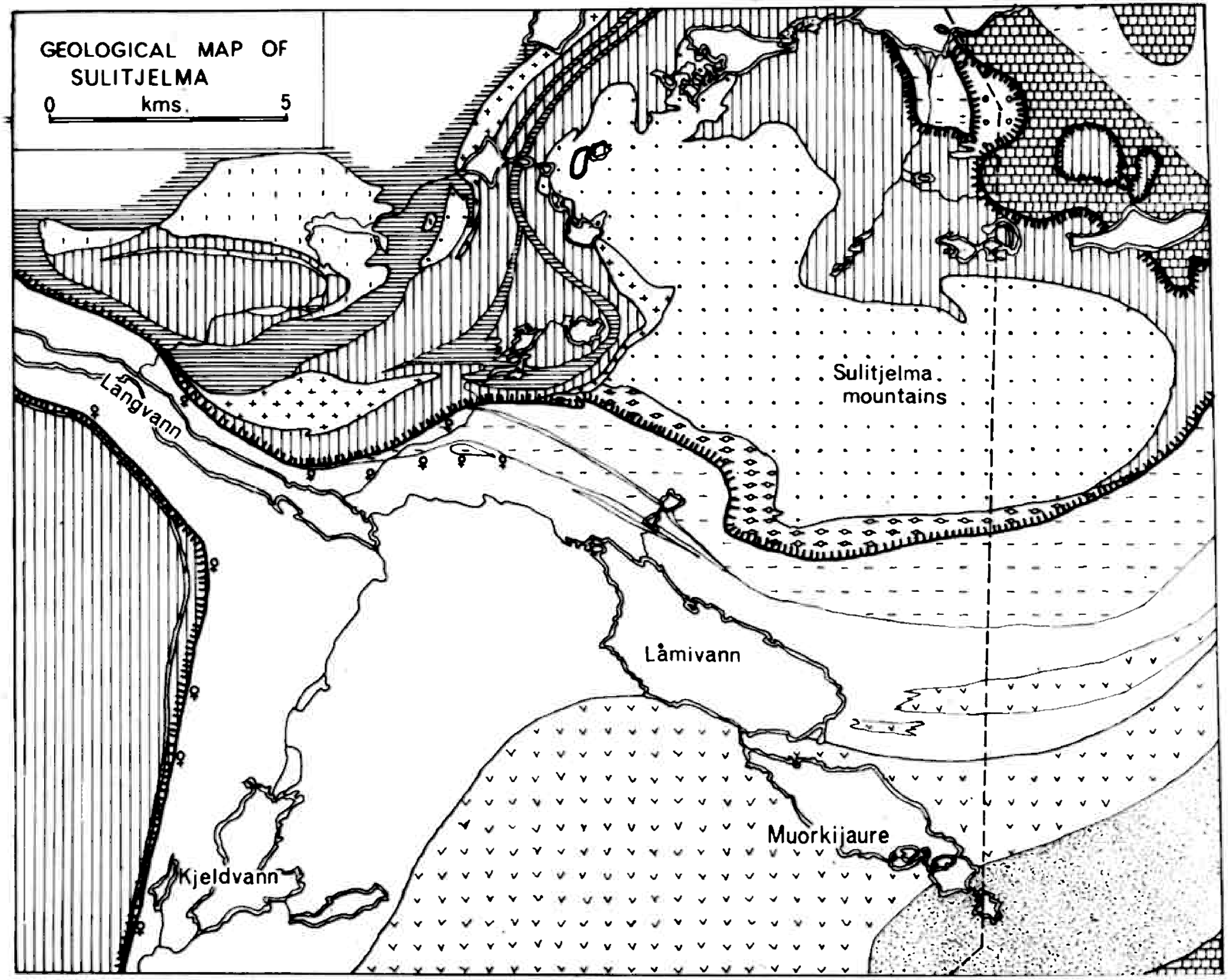
- Amphibolites.
- Furulund schist group with amphibolite lenses.

Muorki schist group

- Laotak series (psammitic).
- Marbles.

Thrust plane.

Copper mines. ♀


GEOLOGICAL MAP OF
SULITJELMA
0 kms. 5
Sulitjelma
mountains
Långvann
Låmivann
Muorkijaure
Kjeldvann

valley west of Hammeren to rejoin the western track south of Nedre Sorjus (g.r. 602563). At the eastern end of Nedre Sorjus the tracks pass another mountain hut belonging to the Swedish Turistforening.

The central area of the Sulitjelma mountains is composed of the rocks of the Sulitjelma gabbro complex. These form all the highest summits and with their metamorphic derivatives cover an estimated area of 44 square km. on the Norwegian side of the border. If, as Kautsky's map indicates, there is about half this area on the Swedish side of the border, this figure agrees well with the figure of 65 square km. given by Vogt for the area of the olivine-gabbro. (Vogt 1927, 281).

The principal rock type of the gabbro complex is olivine-gabbro, which appears in the field as a massive, yellow-weathering rock. Some bands show large, dark, ophitic crystals of pyroxene on weathered surfaces. More basic gabbros, peridotites and pyroxenites also occur, which normally weather rusty brown, and have a characteristic irregular weathered surface. There are also rocks consisting of some 90% labradorite, and in the field these can be recognised by their white colour. In localised regions within the complex, and over an extensive area in its SW corner the primary igneous rocks have been uralitised, to produce massive green metagabbros, which still display many of the features of the unaltered gabbros, such as banding and relict ophitic texture. In a few places the gabbro has had a crude schistosity imposed upon it to yield a rather coarse-grained amphibolite, not displaying any obvious gabbro features.

The structure and petrography of the complex will be described later.

Surrounding the gabbro complex to the N and W is a zone normally less than 10 m. thick, of massive hornfelses or their derivatives. There is also an area of hornfelsed contact rocks S of the gabbro complex on Vaknačokka, and in the cwm between Vaknačokka and Stortoppen.

Associated with the gabbro complex are igneous breccias. There is a large outcrop of these on the ridge N of Point 1787, NW of Suliskongen (g.r. 590500) and smaller outcrops at the contacts of the complex in the valley NE of Sorjusčokka (g.r. 568527), on the northern side of Sorjusdal (g.r. 527555), near Småsorjus (g.r. 517533) and on Vaknačokka (g.r. 558464). These rocks have a light coloured matrix, with an igneous texture, usually rich in biotite, and contain particles of country rocks of varied composition, now thermally metamorphosed to hornfelses.

The country rocks surrounding the gabbro complex have been assigned to two tectonic units in this thesis. Their names have been taken from Kautsky's divisions of the Seve nappe across the border in Sweden. (See p. 17). The gabbro and the rocks with which it lies in primary igneous contact are assigned to the Gasak nappe. Structurally below these rocks lie amphibolites and schists, which can be traced to the E into rocks assigned by Kautsky to two nappes, the Vasten nappe above and the Pieske nappe below. In the area studied there is no evidence of a major structural or stratigraphical break in this sequence so the rocks have been grouped into one unit, which will be termed the Pieske-Vasten nappe. Henley (in preparation) describes these two structural units as the upper and lower unit.

Throughout the region to the south of the gabbro complex at the contact of the Gasak and Pieske-Vasten nappes is a horizon of amphibolites containing lenses of metagabbroic character, and also lenses similar to the metaporphyritic amphibolite lying at the top of the Pieske-Vasten nappe. The writer considers this horizon to represent a tectonic mélange formed at the contact of the two nappes. The evidence for this view will be presented later. The field name "dioritic gneiss" was given to this unit because of a superficial resemblance between the metagabbro lenses and a coarse-grained diorite, and because two of Vogt's analyses from this horizon (Vogt 1927, 305-306 analyses XX and XXI) approximate to the composition of diorite.

2. Historical and previous research.

The Sulitjelma area has been of interest to geologists and other natural historians for two main reasons. The first is, of course, the important deposits of copper ore which are mined in the settlement of Sulitjelma, the second the fact that the Sulitjelma mountains are one of the highest mountain massifs in northern Scandinavia. The early period of geological research in Sulitjelma is summarised in Th. Vogt's Memoir (1927) and he also provides a list of publications about the area. However, since his account is in Norwegian, a brief summary of work which relates to the gabbro complex will be given here.

A remarkable scientific study of the glaciers of the Sulitjelma mountains was made as early as 1808 by the Swedish natural philosopher G. Wahlenberg, who camped at Virijaure in Swedish Sulitjelma, ascended Suliskongen, and produced a map of the peaks and glaciers. J. D. Forbes in his book "Norway and its glaciers" (Edinburgh 1853) gave a good account in English of Wahlenberg's work (p. 228-229). He considered Wahlenberg's study to be comparable in quality with De Saussure's work in the Mont Blanc area and far in advance of any other glaciological studies made in Scandinavia at the time.

The first geologist to visit Sulitjelma was K. Pettersen in 1875. He identified gabbro boulders in the moraine below the southern

Sulitjelma glacier, and therefore suggested that there was gabbro in the high peaks; although according to Th. Vogt (p. 3) "he still interpreted them as essentially formed of schist". However, he failed to discover the ore deposits. The ore was discovered shortly after by a Lapp, Mons Petter, and a brief account of the deposits was given in 1879 by T. Lassen who led the first miners to the region. Meanwhile F. Svevonius in 1877 found gabbros in situ in the northern Sulitjelma mountains. He later returned to Swedish Sulitjelma and described the olivine-bearing rocks of that area, including those of Hammeren, in 1896.

J. H. L. Vogt also first visited Sulitjelma in 1877 while working for the Norwegian geological survey. He ascended Vardetoppen and in a survey memoir (1890) gives a brief description of the gabbros, metagabbros and amphibolites he saw on this excursion.

"Along the route Langvann (Sandnes) - Hankabakken - Vardetoppen - the Langvann schists [i.e. Furulund schists] commence, striking about ENE and dipping northwards, up to a height of about 1250 m. above sea-level, - thereafter follows first 'flaser-gabbro' ... and later the ordinary massive gabbro which is sometimes fresh, though most often, as for example on the peak of Vardetoppen, strongly altered".

J. H. L. Vogt visited Sulitjelma frequently in subsequent years, but his work was primarily concerned with the copper ore. He came to the conclusion that the ore had formed magmatically, in association with the injection of a large gabbro intrusion; an idea his son Thorolf was to extend and clarify in his 1927 memoir.

In 1892 a systematic geological survey of the Sulitjelma district was begun under Hj. Sjögren, with O. Nordenskjöld and P. J. Holmquist acting as his assistants. The results of this work were published in the Geologiska Föreningens Förhandlingar of Stockholm at regular intervals over the next few years, the final results being published in 1900 along with a remarkably detailed 1:75,000 geological map. Sjögren established a stratigraphical sequence for the various metamorphic rock-types in the area which is compared with the sequence proposed by the present writer in table 1. (facing p.38). He was also the first to describe the fossiliferous marbles east of Låmivann. There can be little doubt that when this work was complete the Sulitjelma area was one of the best described and mapped parts of the Caledonian mountain chain. All subsequent researchers in Sulitjelma owe a great debt to Sjögren and his co-workers for their careful work. Th. Vogt acknowledged this, dedicating his memoir on the Sulitjelma area to Sjögren, but since it is the English summary of Vogt's memoir which has been most widely read, Sjögren's work has tended to be overlooked.

The next few years saw the continuation of geological and mineralogical work on the ore-deposits. Sjögren considered the ores to be "epigenetic" in origin i.e. to have formed from fluids percolating along planes of movement, while J. H. L. Vogt, W. C. Brøgger and C. W. Carstens considered them to be magmatic. In the preparation of the local sheet of the 1:200,000 geological survey, G. Holmsen mapped the northern contact of the gabbro complex from Småsorjus east to the

Swedish border. In 1921 Th. Vogt published his first paper about Sulitjelma "Om Sulitelmakisenes geologi" and in 1922 a general summary of the work he expounded later in his memoir.

The publication of Th. Vogt's memoir "Sulitelmafeltets geologi og petrografi" (The geology and petrography of the Sulitjelma region) in 1927 marked the end of the early period of research in Sulitjelma. Vogt summarised and interpreted the work of the earlier researchers and added a wealth of observations of his own. He was interested in four major interconnected problems :-

1. The mode of origin of the copper ores.

2. The relationships between the various basic igneous or meta-igneous rocks.

3. The progressive regional metamorphism of the Furulund schists.

4. The relationship of the fossiliferous marbles to the other metamorphic rocks, and the light this sheds on the age of the rocks of the Norwegian Caledonides as a whole.

It is fair to say that these remain outstanding problems in the area. Vogt considered Item 1, the origin of the ore, to be so important that it was to have a whole volume of the memoir to itself. Unfortunately this was never written. The volume which was published dealt comprehensively with Items 2, 3 and 4. This thesis is concerned primarily with Item 2, the basic igneous rocks. K. J. Henley has been studying Item 3, the progressive regional metamorphism of the Furulund schists and R. Nicholson has been studying Item 4, the fossil locality.

Vogt considered the Sulitjelma gabbro complex and the amphibolites to the south of it to be parts of the same intrusion, which had sill-like extensions to the north-east into Sweden and to the west and south in the thin amphibolite and greenstone layer which persists throughout the Sulitjelma area just above the ore bodies. The southern (lower) part of the intrusion and its sill-like offshoots had been retrogressively metamorphosed and he mapped a sequence of zones of increasing retrogressive metamorphism within it (Vogt 1927, 282-283, figs. 71 and 72). This intrusion he called the "great Sulitjelma phacolite". On p. 380, he listed the assemblages characteristic of each zone, subdividing the zones yet further into a total of fourteen subzones. He considered that these zones represented a facies-sequence and that they had formed under progressively different conditions of metamorphism of the gabbro. He also emphasised that this process occurred simultaneously with the regional metamorphism of the country rocks.

It is probably best to use Vogt's own words to explain the mechanism by which he thought the intrusion formed (English summary 477-478).

"1. The pressing up of the magma masses from the unknown depth seems to be directly connected with the folding down of a mountain range trough, that caused a hydrostatic rise of the magma. This extensive vertical movement in the Earth's crust is mainly of a flexure-like nature without vertical faults or subsidence of blocks. At the bottom of the mountain range trough fractures and absorptions may have taken place, but nothing definitely is known about this.

2. The strata intruded by the magma have been heated to a

relatively high temperature which has been fairly uniform over large areas. Without entering into a discussion of the relation between the magma injections and the regional metamorphism, a relation that apparently exists, it may be stated that the magma, as a rule, intruded strata that were already heated.

3. The magma is under the influence of the mountain range stress which is conceived of as a combination of a load and a pushing pressure resulting in a partial movement of the strata.

4. As a result of the combined action of the high temperature of the strata and the mountain range stress the magma is enabled to migrate as an independent mass along the bedding planes, covering large areas before it finally comes to rest.

5. Owing to the presence of the mountain range stress the igneous masses may be pushed horizontally over considerable areas of their substrata after their crystallization. This especially takes place in the marginal areas."

Vogt added eight analyses of gabbros, amphibolites and chloritic rocks from his "phacolite" to the three analyses made for Sjögren. He related the compositions of these rocks to Bowen's (1914) and Anderson's (1915) synthetic data on the systems forsterite-albite-anorthite, forsterite-diopside-anorthite, forsterite-clinoenstatite-anorthite and hypersthene-albite-anorthite. He noted that the more plagioclase rich rocks contained more magnesian olivine, and considered that early crystallisation of olivine and labradorite had occurred, followed by later crystallisation of hypersthene and clinopyroxene. He attributed the dioritic composition of the amphibolites in the offshooting sills of the phacolith to a filter pressing mechanism, which removed a dioritic magma from a crystal mush of initial gabbro composition. He gave a careful description of the mineral composition of the amphibolites in terms of the facies-concept. Altogether his memoir is an attempt to apply the relations observed in synthetic systems to an actual group of basic igneous rocks, and it is a tribute to Th. Vogt that it was written in the same year as N. L. Bowen's "The Evolution of the Igneous Rocks" (1927) which introduced this approach to igneous petrology.

References will be made to Th. Vogt's memoir throughout this thesis, and his ideas will be considered in more detail where appropriate. He continued as director of the Geological Institute of the Norwegian Technical University at Trondheim until 1951, and under him a number of diploma students wrote theses on aspects of Sulitjelma geology. These are mostly concerned with the problem of the ore genesis, and so do not concern this thesis directly, although some of them describe the petrography of the amphibolites associated with the ore in some detail. Papers on the geology of the ore deposits were published by Carstens (1932) and Krause (1956). The magmatic hypothesis for the origin of the ore was abandoned, as evidence grew for a complex sequence of ore-producing events.

The first major challenge to Th. Vogt's synthesis came from G. Kautsky. He undertook an extensive programme of geological mapping in the years 1945-7 in Swedish Sulitjelma and the Salojaure region to the north in what was now the Sarek National Park. He published the results of this work in 1952. In this area the metamorphic rocks of the Scandinavian Caledonides can be seen to be thrust over a basement of granitic Archaean rocks, and a thin layer of Hyolithus zone Cambrian sediments, in a manner analogous with the Moine thrust over the Lewisian, Torridonian and Cambrian rocks in the NW Highlands of Scotland. The metamorphic rocks are described by Swedish geologists as the "great Seve nappe".

Kautsky considers that in the Sulitjelma region the Seve nappe can be further subdivided into three nappes which he calls (from the base upwards) the Pieske nappe, the Vasten nappe and the Gasak nappe. To the north of Sulitjelma a fourth nappe is present between the Vasten nappe and the Gasak nappe, called the Salo nappe. He describes the lithologies of formations within the nappes in detail. He considers the Sulitjelma gabbro complex to be intrusive into the highest nappe, the Gasak nappe, the porphyritic amphibolites to the south of the gabbro complex to lie in the Vasten nappe, and the Furulund schists below the ore horizon to lie in the Pieske nappe. The thrusts between the nappes formed after the main regional metamorphism, though a system of large scale anticlines and synclines, including the Langvann anticline which folds the ore bodies, formed after the thrusting. Kautsky also suggests that the Sulitjelma ore bodies formed from ore-bearing fluids permeating along the thrust at the base of the Vasten nappe, and cites the "en echelon" relationship of the Charlotta, Giken and Palmberg ore bodies as evidence for this point of view (p. 203). He gives a correlation table (p. 206) showing how his lithological divisions compare with those of Sjögren, Holmquist and Th. Vogt.

Kautaky's important suggestion, that Vogt's "Sulitjelma phacolite" is in fact a basic igneous complex lying above a formation of metamorphosed lavas, with a major tectonic break between the two has been accepted by the present writer (p. 5-6) and evidence to support this view will be produced in due course (p.28-29).

Since 1951, workers from University College, London have been engaged in detailed geological work in the coastal parts of Norway at the latitude of Sulitjelma and to the south. Much of the ground has been geologically mapped on a scale of about 1:16,000. Interim reports on this work were given to the 21st International Geological Congress in 1960 (Hollingworth, Wells and Bradshaw 1960; Rutland, Holmes and Jones 1960; Ackerman and Nicholson 1960) and a detailed review of the structural conclusions of the work was delivered to the Geological Society of London last year (Rutland and Nicholson 1965). The work so far has been mainly structural, and has shown that in the central belt of the Caledonides, the metamorphic rocks have undergone polyphase deformation in a similar manner to the metamorphic rocks of the Highlands of Scotland. However, although the dominant mode of deformation in the rocks has been by plastic deformation, Rutland and Nicholson also consider that important thrust structures occur (see their concluding discussion p. 101-102).

3. <u>Scope of the present research.</u>

Thus recent work, both to the west and east of Sulitjelma, has suggested that thrusting played a significant role in the formation of this part of the Caledonian mountain belt. The presence of a major thrust in the Sulitjelma region itself would clearly upset much of Th. Vogt's synthesis of the geological structure and history of the area. It was for this reason that new research in Sulitjelma was undertaken. Henley began work in 1962, and the present writer and Larsen, of the University of Oslo, in 1963. Nicholson and Rutland have been extending the detailed work from the coastal region near Fauske to Sulitjelma, and a paper on the section from Bodø to Sulitjelma is shortly to be published.

The writer of this thesis was therefore faced with the following problems when he commenced work :-

1. Was Th. Vogt's "Sulitjelma phacolite" in fact one igneous intrusion, or was it two unrelated groups of basic igneous rocks, on either side of a major thrust plane?

2. If this was the case, what was the form of the Sulitjelma gabbro intrusion? Was there any validity in Th. Vogt's differentiation sequence and metamorphic facies sequence in the basic rocks?

3. Was the thrusting of the post-metamorphic nature proposed by Kautsky, or of the disjunctive syn-F_1 (pre-metamorphic) nature of the nappes described by Rutland and Nicholson?

4. How would the thrusting affect the stratigraphical sequences determined by Sjögren and Vogt?

It is hoped that this thesis will provide partial answers to these questions.

CHAPTER ONE

Stratigraphy of the Country Rocks.

The author puts forward the following tentative stratigraphical scheme for the rocks surrounding the Sulitjelma gabbro :-

Gasak Nappe (Upper Unit)

Western sequence at Duoldagop

(g) Calc-silicate group of Duoldagop.

(f) Micaceous psammite with marble bands.

(e) Kyanite-schist group.

Eastern sequence S of Sorjusjaure

(e) Kyanite-schist group.

(d) Calcareous semi-pelite.

(c) Calcareous amphibolite.

(b) Graphitic schist.

(a) Calcareous amphibolite.

Pieske-Vasten Nappe (Lower Unit)

(d) Porphyritic amphibolite.

(c) Schistose amphibolite group.

(b) Intermittent thin micaceous quartzite.

(a) Furulund schist group.

1. The Pieske-Vasten Nappe (Lower Unit)

(a) The Furulund schist group.

An extensive study of the Furulund schist group has been made by Henley. The writer has therefore begun his study above this horizon. However, for the sake of completeness, a brief account of the Furulund schist group is given here.

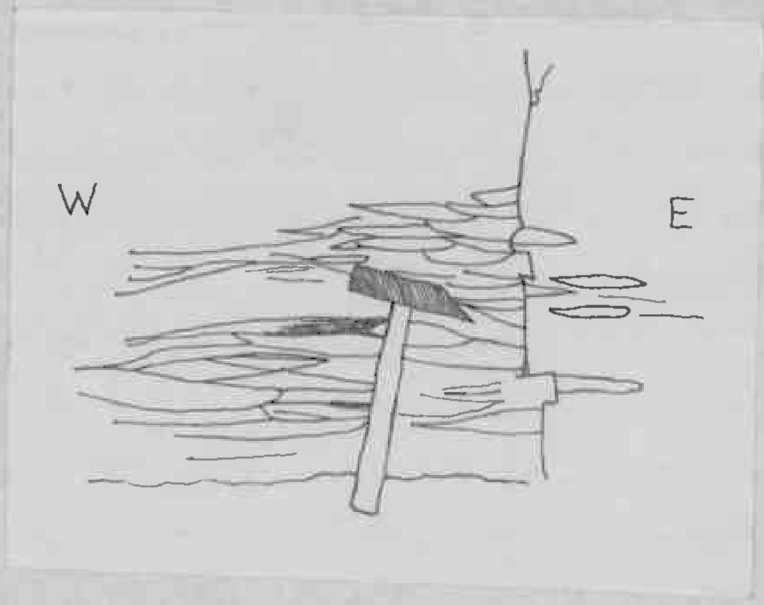
The group consists predominantly of calcareous mica-schists of varying grade, as described by Vogt (1927) and Henley. There is a characteristic mineral lineation in some horizons, produced by needles of hornblende lying in a preferred direction upon schistosity planes. Henley has described the structures within the Furulund group. Two of his fold types have been identified by the writer immediately below the contact with the schistose amphibolite group in the area north of Låmivann; F_2 folds on E-W trending axes F_{3a} folds on N-S axes (See table 2).

There are schist bands in the schistose amphibolite horizon above the Furulund group which are similar in lithology and structure to the main Furulund schist group, but lie among rocks which Vogt thought were part of the great Sulitjelma phacolite.

(b) Micaceous quartzite at the contact of the Furulund schist and the schistose amphibolite groups.

This is a whitish micaceous rock, forming a band up to about 3-4 metres thick between the Furulund schist and the overlying schistose amphibolite group. It is only found east of the stream running into Låmivann from Otervann. (The outcrop begins at about g.r. 550451). In places rusty weathering bands, about 1 m thick, equivalent to the pyrite impregnated horizon found further to the west, occur above and

Fig. 1.1. "Lensoid" character of micaceous psammite.



below it. It has a cleavage parallel to that of the rocks above and below, and in places is closely interbanded by schist. The regional lineation, expressed as a mineral elongation, occurs within this unit. In detail it sometimes shows a "lensoid" structure, similar to the structures found in the schistose amphibolites above (fig. 1.1).

(c) The schistose amphibolite group.

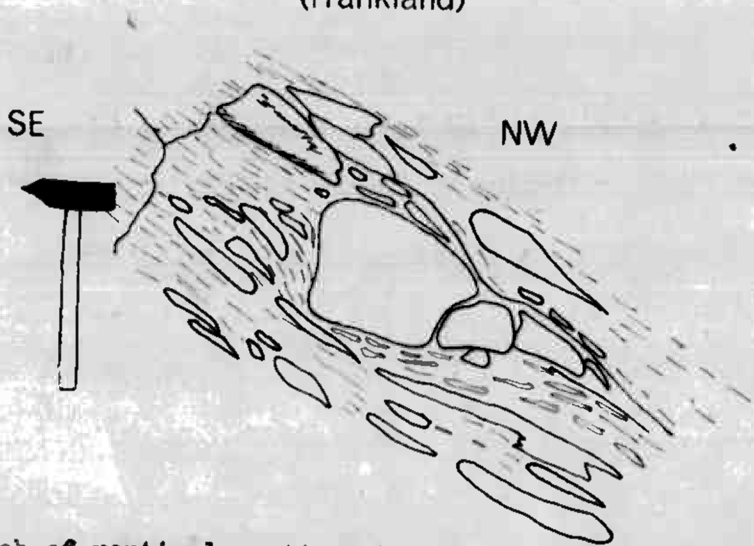
The lower contact of this group corresponds to the base of Vogt's "Sulitjelma phacolite", and this group and the porphyritic amphibolite above he included in his epidote-amphibolite zone within the phacolite. The contact runs WNW to ESE along the steep slope north of Låmivann, the amphibolites forming high ground to the north, and the Furulund schist group lower ground to the south. The contact dips northwards into the hillside, as can be clearly seen for example where the stream running out of Otervann has cut a deep chasm (g.r. 533460). The schistosity near the contact is parallel to it.

Lithologically the rocks within the group vary considerably. Near the base chlorite schist bands are common. In the Otervann area, throughout the group, but more particularly near its base, calcareous rocks occur. East of Otervann (g.r. 537459) there is a band of impure marble about a metre thick above the lower schist strip, but at the lake a greenstone veined by calcareous material is more commonly found at this level. The greenstone particles show a WNW-ESE elongation, parallel to the regional lineation. Similar rocks are found rather less frequently

FIG. 1·2.

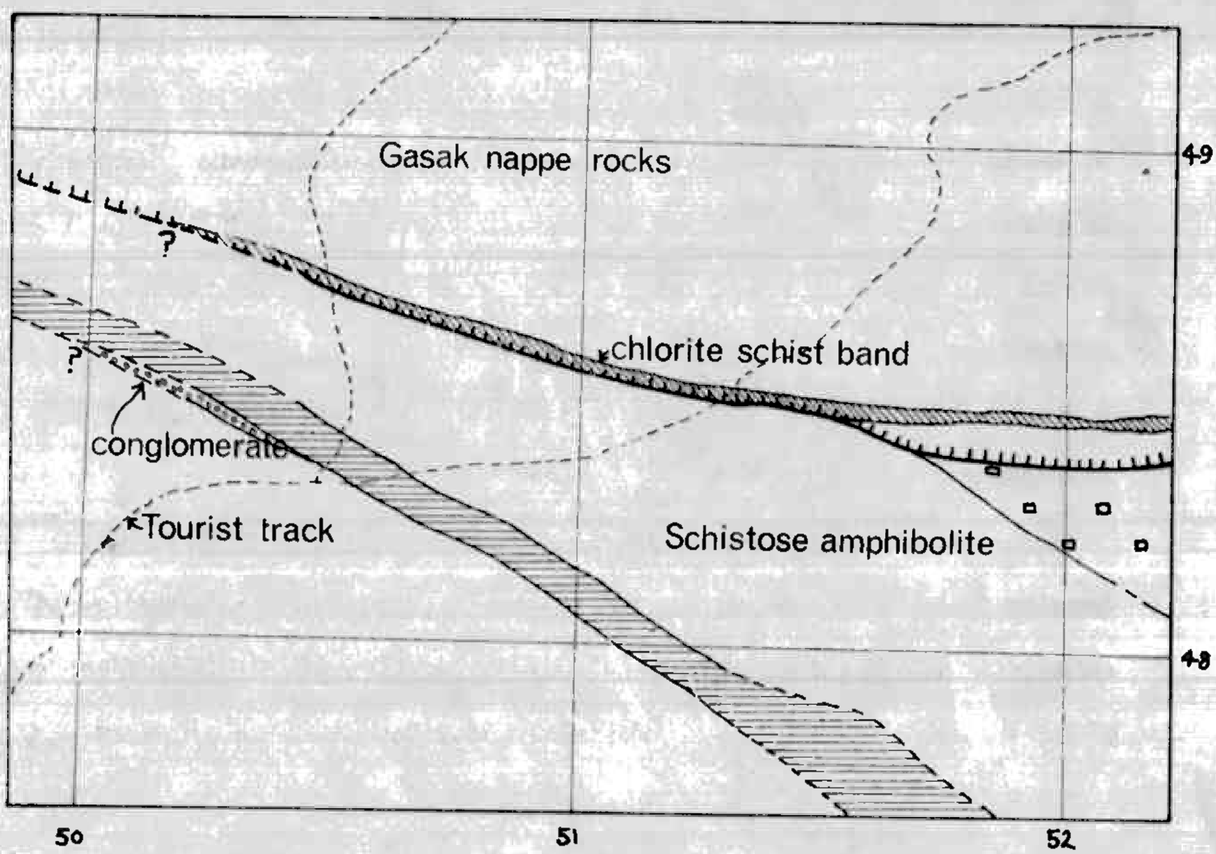
DEFORMED CONGLOMERATE IN SCHISTOSE AMPHIBOLITE.

(Frankland)



1. Sketch of **vertical section** through conglomerate. Note that the foliation produced by flattening swings round the large block.

2. Location of conglomerates (grid figures as on main map). There is a band of chloritic schist in the dioritic gneiss at the base of the Gasak Napp



in the group all the way east from Otervann to the glacier.

The group attains its greatest thickness on the plateau immediately east of Ny Sulitjelma. The rocks here are fairly uniform schistose amphibolites. However, north of Ny Sulitjelma, just west of the point where the tourist tracks cross the upper schist strip there is a patch of conglomeratic rocks with a calcareous matrix (g.r. 502485). These were mapped and described for the writer by R. Frankland in 1964 (fig. 1.2).

The variation within the unit may be seen by considering the section through it at Otervann (fig. 1.3). Below the base of the amphibolite horizon, in the Furulund schist south of the lakes, there is a thin zone about ½ metre thick of schist which has been impregnated with pyrite, and also contains a vein of asbestos. This is the eastern extension of the ore-horizon which is mined in Sulitjelma. Impregnation by pyrite is found just below the base of the amphibolites to the east as far as the glacier, sometimes in one thin band, in other places as two. However, ore suitable for economic exploitation has only been found for ½ km or so east of Ny Sulitjelma, and working of all ore east of Ny Sulitjelma has now ceased.

The basal band of the schistose amphibolite group forms a barrier which dams up the southern lake of Otervann. It consists of schistose amphibolites with calcareous veins without any lineation, and chlorite schist. North of this lens comes the lower mica-schist strip,

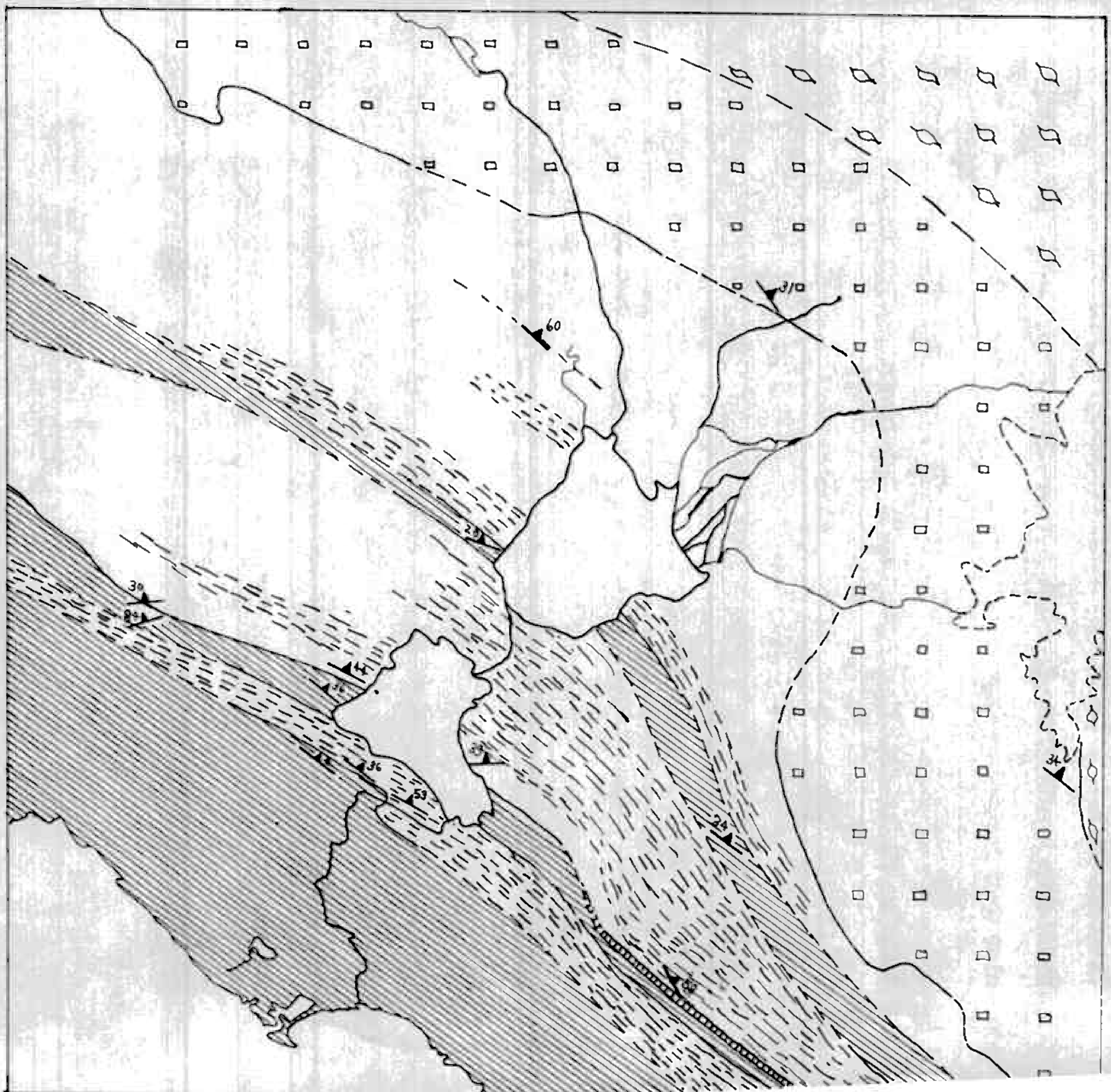


Fig. 1.3

Geology of the Otervann area.

Dioritic gneiss.

Porphyritic amphibolite.

Schistose amphibolite.

Calcareous chlorite schist.

Mica schist.

Scale 1:15,000.

which has a band of sheared pegmatite lying in it, parallel to the schistosity and the contacts. North of this comes a thicker horizon with rather more massive amphibolites, containing much calcareous material surrounding elongated fragments, producing a NW-trending lineation with a gentle plunge (see structural overlay in pocket). There is a parallel elongation of needle-like hornblendes. There are also thin impersistant lenses of schist and quartzite.

The upper schist strip is garnetiferous. The garnets show tails on the schistosity planes parallel to the lineation which occurs in the rocks below. The schistose amphibolite group to the north contains rather more massive amphibolites, though some bands are still calcareous. Bands of porphyritic massive amphibolite appear also. There are still bands of chlorite schist. Some of the amphibolitic rocks are composed of numerous elongated particles, and may represent stretched conglomerates or agglomerates. Eventually the massive porphyritic bands predominate, and the rocks are then assigned to the porphyritic amphibolite group.

(d) The porphyritic amphibolite.

This unit is characterised by bands of massive amphibolite alternating with bands of more schistose amphibolite. Vogt described this rock-type as "epidote-amphibolite without clinozoisite" (p.303) as follows :- "On the plateau between Ny Sulitjelma and Vardetoppen ... two different types appear. One is coarse *flaser*-gabbro with rather large felspar fragments, and the other a *fine*-grained and dark, almost black amphibolite, in which one can scarcely see anything but hornblende without a lens".

Kautsky also describes this unit (p. 67-75), and gives it the name "porphyrite-amphibolite", which has been adopted in this account. The coarse-grained bands contain white patches which are either crystals of felspar or pseudomorphs after felspar, set in a fine-grained amphibolitic matrix. The crystals appear rectangular in the sections seen on the rock surface. The bands of this rock do not show any schistosity or foliation. The ratio of "meta-phenocrysts" to "groundmass" varies from band to band, some bands containing more than 50% of the metaphenocrysts, as estimated in the field. The massive bands vary in thickness from about 1 m to about 10 m.

In the east, on the "peninsula" of rock projecting north between the Norwegian and Swedish branches of the main Sulitjelma glacier, dykes of fine-grained amphibolitic material were found cutting the porphyritic amphibolite (g.r. 595454). Kautsky describes similar dykes as characteristic of this formation in Sweden (p. 220).

The outcrop of this unit ceases abruptly to the west on the plateau west of Vardetoppen (g.r. 515485) although to the east it quickly becomes a thick band (about 500 metres on Vaknacokka). The lithology is remarkably uniform from the west to the east of the outcrop, so it seems unlikely that the disappearance to the west can be the limit of all the original lava-flows. It seems more likely that the unit has been cut out tectonically by the thrust zone under the Gasak nappe. This theory is supported by the frequent presence of lenses of the porphyritic amphibolite in the base of the dioritic gneiss.

The fine-grained bands show a schistosity parallel to the bands of more massive amphibolite, and also display a lineation of the hornblende needles which is parallel to the lineation in the schistose amphibolite below and the dioritic gneiss above. Occasionally lenses of schist, with large garnets, are found among this group. The bands of massive porphyritic amphibolite frequently show boudinage, and more rarely bands of massive fine-grained amphibolite have been seen with the same structure.

In a few localities to the east, on the rock promontory in the glacier and above the cliffs north of Lamivann the porphyritic amphibolites are net-veined by leucocratic material.

Conclusions concerning the lithology of the Pieske-Vasten nappe.

The persistance of the regional lineation of the Furulund schist up into the predominantly amphibolitic rocks described above, and the presence of the two schist bands of similar lithology to the Furulund group suggest that all these rocks belong to the same sequence. The presence of intercalations of schist and more rarely of quartzite, which lie parallel to the lithological banding in the amphibolites, makes Vogt's theory that these rocks represent the base of a large metamorphosed gabbroic intrusion, extremely unlikely. The porphyritic appearance of some of the amphibolites, and the primary fragmental character of some of the rocks in the schistose amphibolite group also make this theory implausible.

On the field evidence, the writer regards these rocks as metamorphosed volcanic and hypabyssal rocks with sedimentary intercalations, and petrographical evidence will be brought forward later to support this view (see also Kautsky p. 67). There is no evidence in this area for a major structural break at the base of the schistose amphibolite group, as Kautsky suggests. The lensing-out of some parts of the schistose amphibolite group to the east into the Furulund schist group may represent a facies change from volcanic rocks in the west to pelites in the east.

The amphibolitic rocks are therefore regarded in this account as the stratigraphical continuation of the Furulund schist group. They now lie above the Furulund schist, but no sedimentary structures have been found which might throw light onto the original way-up of the sequence. Since the Furulund schist in turn overlies fossiliferous limestones of Ordovician age (Vogt 1927, p. 481, Kautsky 1952, p. 27-35) apparently without a structural or stratigraphical break, all the rocks of this sequence can confidently be assigned to the lower Palaeozoic.

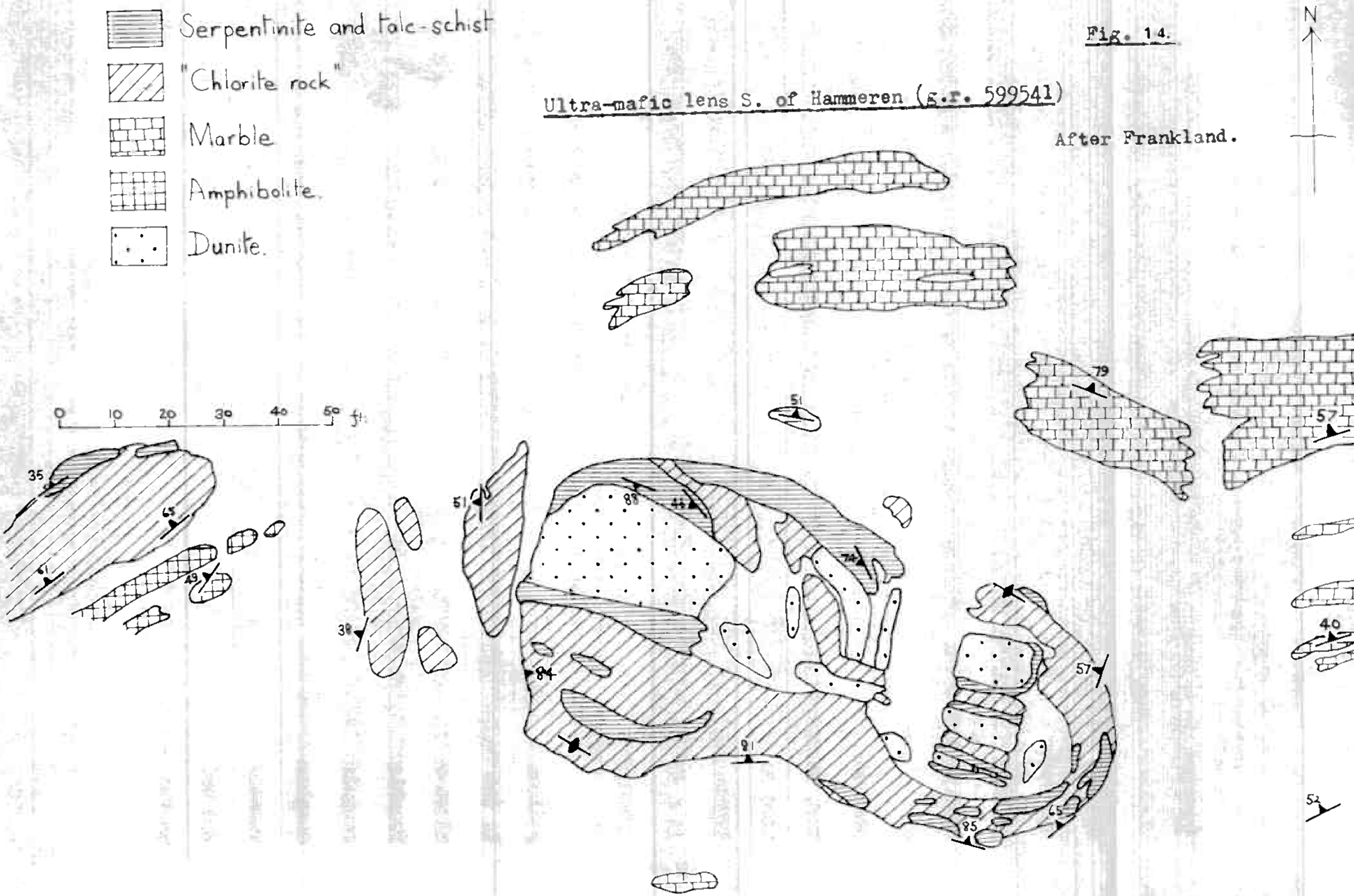
The rocks of the Pieske-Vasten nappe north of the Sulitjelma gabbro complex.

In the valley which runs north from the Sulitjelma massif into Nedre Sorjusjaure occur meta-igneous rocks which the writer considers also represent part of Kautsky's Pieske or Vasten nappes. They show a marked contrast in lithology and structure with the surrounding rocks

Fig. 14.

Ultra-mafic lens S. of Hammeren (g.r. 599541)

After Frankland.



(see map in pocket).

They consist of amphibolites, some of which show distinct ophitic texture in hand-specimen, along with more leucocratic rocks. The rocks are banded, and sometimes the leucocratic types can be seen to vein the amphibolites, but the characteristic "porphyritic amphibolite" type is not seen. The bands have a predominant NE-SW strike and dip NW, and a lineation is developed along the strike. This is in marked contrast with the rocks seen higher up the sides of the valley which are very calcareous schists forming a series of minor closures round even more calcareous rocks which might be termed calcareous semi-pelites or impure marbles (g.r. 580559). To the east above the amphibolitic group is a thin band of marble and talc-schist, (g.r. 601550) and above this again the ultramafic rocks which form the mountain Hammeren.

East of Hammeren there is an extensive outcrop of very pure yellowish marble, mapped by Kautsky as "marble with soda-granite veins", in the Vasten nappe. A small area of the region with amphibolite, ultra-mafics and marbles was mapped SW of Hammeren (g.r. 599541) by R. Frankland, with the writer making the structural observations - a reproduction of Frankland's map is fig. 1.4 and gives some idea of the complexity of this region. It cannot be said that the structural relations of the various rock-types in this area have been worked out; and the writer is following Kautsky in assigning the marbles to the Pieske-Vasten nappe.

Between the amphibolite group and the rocks above occurs a thin junction unit which will be described in more detail a little later. The contact is nearly horizontal in the south but runs steeply down to Sorjusjaure in the north.

On the scanty evidence so far obtained from these rocks it is not possible to correlate them with any particular unit in the sequence to the south of the gabbro complex.

Junction Units.

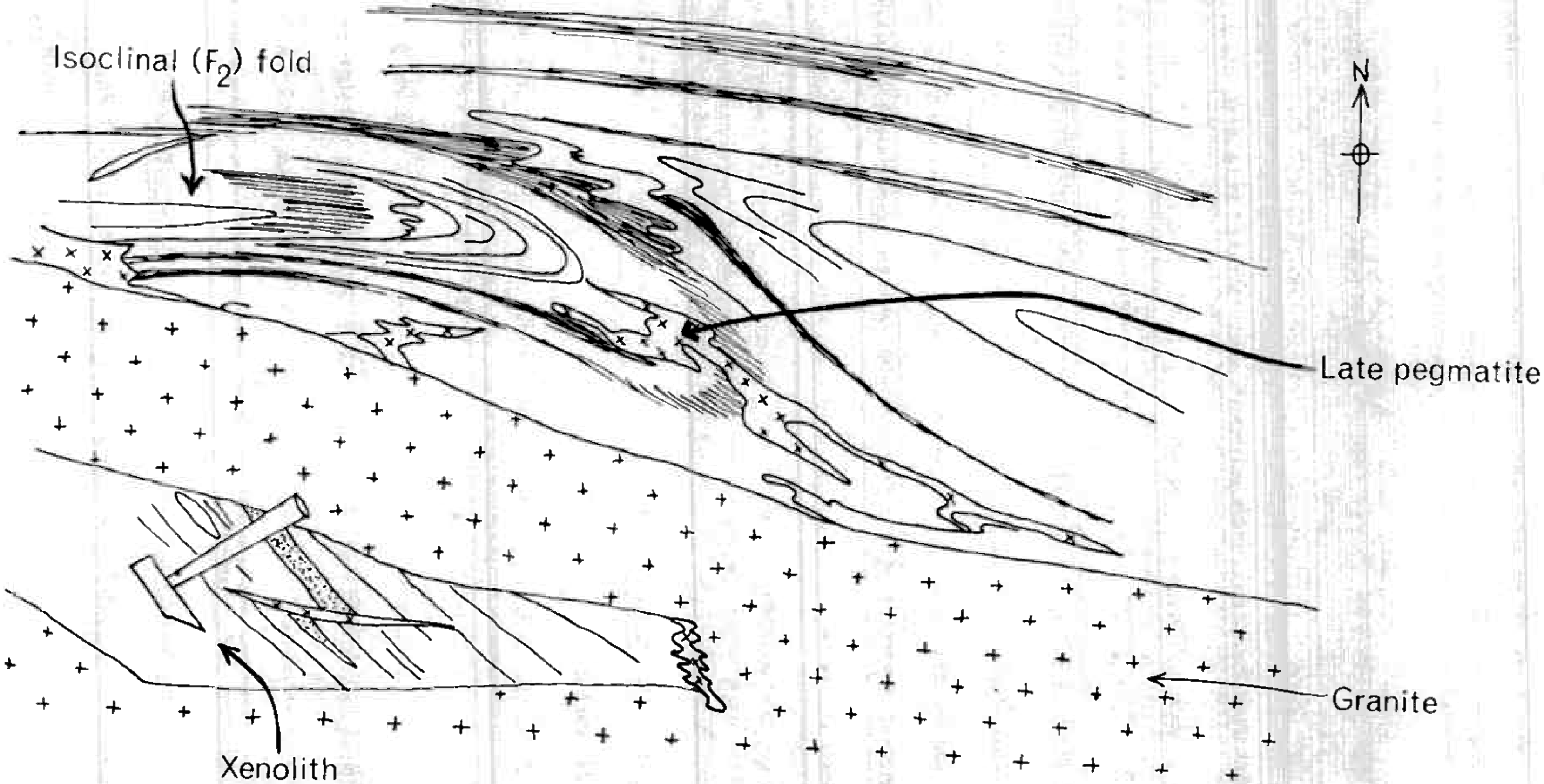
(a) The Dioritic Gneiss.

It should be emphasised that this name was given because of the appearance of the rocks in the field and has no genetic connotations whatever. The unit is found in a conspicuous band from west to east, with its eastern extremity concealed by the glacier. Its thickness varies considerably, from about 100 metres in the extreme west of the area to about 350 metres below the lower summit of Vaknacokka. As a unit it is characterised by :-

1. The presence of lenses of coarse-grained amphibolite ("diorite") composed of large crystals of hornblende and felspar,

2. The presence of a well-marked lineation of the hornblende crystals in the coarse-grained lenses mentioned above and also in the finer-grained parts of the rock. The rocks within the unit are all amphibolites, and near the contact with the gabbro some of the coarse-grained lenses show the yellow weathering which indicates the presence of

FIG. 1·5. FOLD & GRANITE VEINS IN THE DIORITIC GNEISS. g.r. 521491.



unaltered pyroxenes and olivine in their cores. The contact of this unit with the gabbro complex is a gradational one and the actual line drawn on the map between "metagabbro" and "dioritic gneiss" is rather arbitrary. The contact was taken where the amphibolites seemed to be beginning to show a well-developed secondary schistosity, although well within the area mapped as metagabbro patches of rock with a distinct secondary schistosity and lineation of hornblendes were found.

On Vaknačokka however, there is a patch of hornfels and igneous breccia between the dioritic gneiss and unaltered gabbro, but unfortunately a snowfield obscures the contact with the dioritic gneiss. The gneiss on Vaknačokka does not show quite so well developed a lineation as that further west, and the very coarse amphibolitic lenses are larger, but otherwise there is little variation in the lithology from east to west.

Granite veins, now very deformed, are found in the gneiss in one locality in the western part of the outcrop. The coarse-grained gneiss fragments enclosed in the granite veins show a banding which clearly formed prior to the injection of the granite; it can also be seen that this banding was earlier than the predominant foliation of the gneiss (figs. 1.5, 1.6).

The dioritic gneiss unit lies on the extension of the contact between the Gasak and Vasten nappes, mapped by Kautsky in Sweden. The reasons for assuming that it represents a junction unit

Fig. 1.6. Structures in the dioritic gneiss.

1. Photograph of outcrop shown in fig. 1.5.

2. Early banding in coarse grained lenses of dioritic gneiss.

between the Gasak and Pieske-Vasten nappes are as follows :-

1. The variation in the rocks found in contact with this unit above and below. In the west the dioritic gneiss lies above the schistose amphibolite group, while to the east it lies above porphyritic amphibolite, which steadily thickens eastwards. In the extreme west marbles and micaceous psammite lie above it on the ground now being mapped by J. E. Larsen. Proceeding eastwards, it is overlain by very deformed granite and a patch of very contorted calc-silicate rocks, then deformed and amphibolitised gabbro and finally on Vaknačokka hornfelses and igneous breccias. While variations in facies of both meta-igneous and meta-sedimentary rocks occur within the Sulitjelma area, it is felt that these changes are too abrupt to be explained in this way.

2. The strong lineation developed within the unit. This is parallel to the lineations developed in the amphibolitic groups below and in the Furulund schist, where Henley has explained it as due to a "homogenous strain" mechanism. However, north of the dioritic gneiss in the west the lineation changes its character becoming the down-dip mineral lineation and crenulation found in the Duoldagop region, and no lineation occurs in the hornfelses and gabbros above the dioritic gneiss to the east. The very well-developed lineation in the dioritic gneiss unit, compared with the rather rare lineation in the metagabbros in the gabbro complex above and the less well-developed lineation of the

amphibolite rocks below, suggests that in these rocks, unlike the Furulund group, strain during the formation of the D_2 lineation was not homogenous. The dioritic gneiss horizon was a zone of concentrated strain, which is tantamount to calling it the horizon of movement of a thrust.

3. The difference in structure in the rocks above and below the dioritic gneiss. The dominant small scale structure in the rocks below the dioritic gneiss is the lineation mentioned above, but the schists in the schist strips also show a variety of small scale folds, which can be correlated with the sequence of structures described by Henley in the Furulund schist group. In the rocks above at Duoldagop there is a well marked down-dip lineation, plunging NW parallel to the axes of F_2 minor folds in the micaceous psammite. While these folds may be correlated structurally with the F_2 phase of folding in the Furulund schist, their style is quite different. Further east the hornfelses seen above the dioritic gneiss near Vaknacokka are massive but show a banding which was folded before the alteration of the rocks to hornfels.

The great contrast between the rock types above and below the dioritic gneiss makes it impossible to estimate the distance of travel of the upper unit relative to the lower, as this would require a correlation of some part of the upper sequence with the lower.

(b) <u>The junction unit south of Nedre Sorjus</u>.

These rocks are rather seldom seen, and occupy a layer about

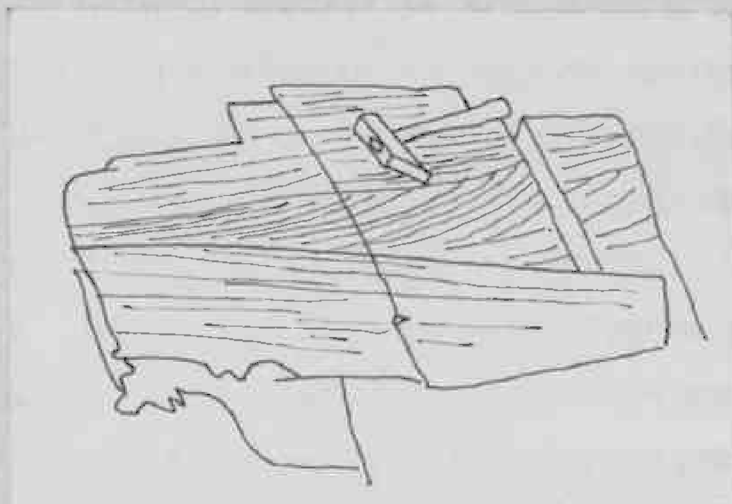
5-10 m. thick between the amphibolites tentatively assigned to the Pieske-Vasten nappe, and assorted rocks of the Gasak nappe. They crop out near the edge of the lake, and in the beds of small streams running down the sides of the valley west of Hammeren. They are mostly mica schists occasionally with garnets, but sometimes rather more psammitic rocks are seen. On the scale of the outcrop they show no unusual degree of deformation, nor are they more strongly lineated than the rocks above or below.

2. The Gasak Nappe. (Upper Unit).

This is the unit of metamorphic rocks into which the Sulitjelma gabbro complex has been injected. From the Swedish border in the east to just west of Vardetoppen the southern contact of the complex is with dioritic gneiss, although much of this contact is hidden beneath the glacier. The only exception so far seen is the small area of hornfelses on the ridge on Vaknačokka, mentioned earlier. Another possible area of metamorphic rocks is the southern part of the Suliskongen nunatak (see map in pocket g.r. 598478) but this has not been visited. Metamorphic country-rocks are seen to the west and north of the gabbro, with only one lithological unit being traced continuously from one area to the other, the "kyanite-schist group".

The rocks surrounding the twin lakes called Duoldagop are currently being studied by J. E. Larsen for a Diploma dissertation in the University of Oslo and the mapping of the rocks in this area was done

Fig. 1.7. Current bedding in quartzite band in calcareous amphibolite.



by him. However, the lithology and structure of the region are crucial to any study of the neighbouring gabbro complex and the writer is therefore offering a tentative interpretation of the region based on a week's intensive field work with Larsen, and numerous observations made near the gabbro complex on other occasions.

The structure in the Duoldagop region appears to be synformal (for a detailed interpretation of the structure see fig. 2.11), so that the rocks outcropping near the lakes are structurally uppermost, and the following sequence is based on this assumption.

There is also one piece of evidence that suggests that the sequence for the Gasak nappe given on p. 17 may be the correct way up stratigraphically; a solitary observation of current bedding from a thin quartzite band just north of the northern contact of the gabbro (see map and fig. 1.7). Correlations so far made with the sequence described by Kautsky north of Sorjusjaure also indicate that the sequence described here is the same way up. Kautsky considers that the variation of particle size in the highly-metamorphosed conglomerate at the base of the Gasak nappe, overlying supposed basement granitic gneiss, indicates that the sequence he describes in the Gasak nappe north of Sorjusjaure is the right way-up.

The lithological units will be described as before, from the lowest upwards.

(a) Calcareous amphibolite.

These rocks are seen in contact with the gabbro complex along all its north-eastern boundary. They include amphibolites and calcareous schists often with pods of calc-silicate minerals, or of carbonates. They usually have a well-developed schistosity developed by the preferred orientation of the micas and amphiboles. This unit is indistinguishable from unit (c) and the two have only been marked differently on the map because they are separated by a well-defined band of graphitic schist. They also include a white quartzite band about 1 m. thick which was described on p. 31.

(b) Graphitic schist.

This forms a well-defined unit running from the complex region south of Hammeren in the east, to the gabbro contact about 1 km. south of the western end of Øvre Sorjusjaure. It is composed of mica-schists; typically with quite abundant graphite (enough to mark paper), but also includes schists without graphite, but with porphyroblasts of kyanite and garnets similar to those seen in the kyanite-schist unit. The schistosity planes of the schist are usually steep and the kyanites may show a preferred orientation.

The outcrop is displaced by folds, which are not easily recognised in the schist itself, but can be distinguished in the surrounding calc-silicate rocks. They will be described later (p.55). The continuous line of the outcrop is apparently interrupted in the valley west of Hammeren by the thrust separating the Pieske-Vasten and Gasak nappes in this valley. However, exposure hereabouts is not good, and elsewhere the band shows great variations in thickness. However, graphitic schists certainly do not appear in the small gorge cut by the stream in the bed of the valley (g.r. 589549) though they appear within 100 m. on the eastern side. The western side is rather marshy, and graphitic schists are not seen for some 250 m.

The schist strip is thermally metamorphosed at its contact with the gabbro complex; the gabbros near the contact at this point are sometimes enriched in graphite.

(c) Calcareous amphibolite.

This unit resembles that seen south of the graphitic schist, but towards the north the patches of impure marble become more conspicuous. It includes schist and amphibolite horizons, one particularly massive amphibolite band forming the line of hills south of Øvre Sorjusjaure. Like the schist and calcareous amphibolite to the south it displays a lineation.

(d) Calcareous semi-pelite.

These rocks form the low ground between the two Sorjus lakes, (this area has not been included on the map) and also the lower part of the western slope of the valley west of Hammeren (g.r. 580559) where they show a complex folded contact with the calcareous amphibolites above (in a structural sense). They were distinguished from the calcareous amphibolite group in the field by their much larger carbonate content. They show a much less distinct schistosity, and are easily scratched by a hammer. They include lenses of relatively pure marble but mostly contain some mica. Some bands are composed of fragments which are rather more carbonate-rich in a slightly more micaceous matrix.

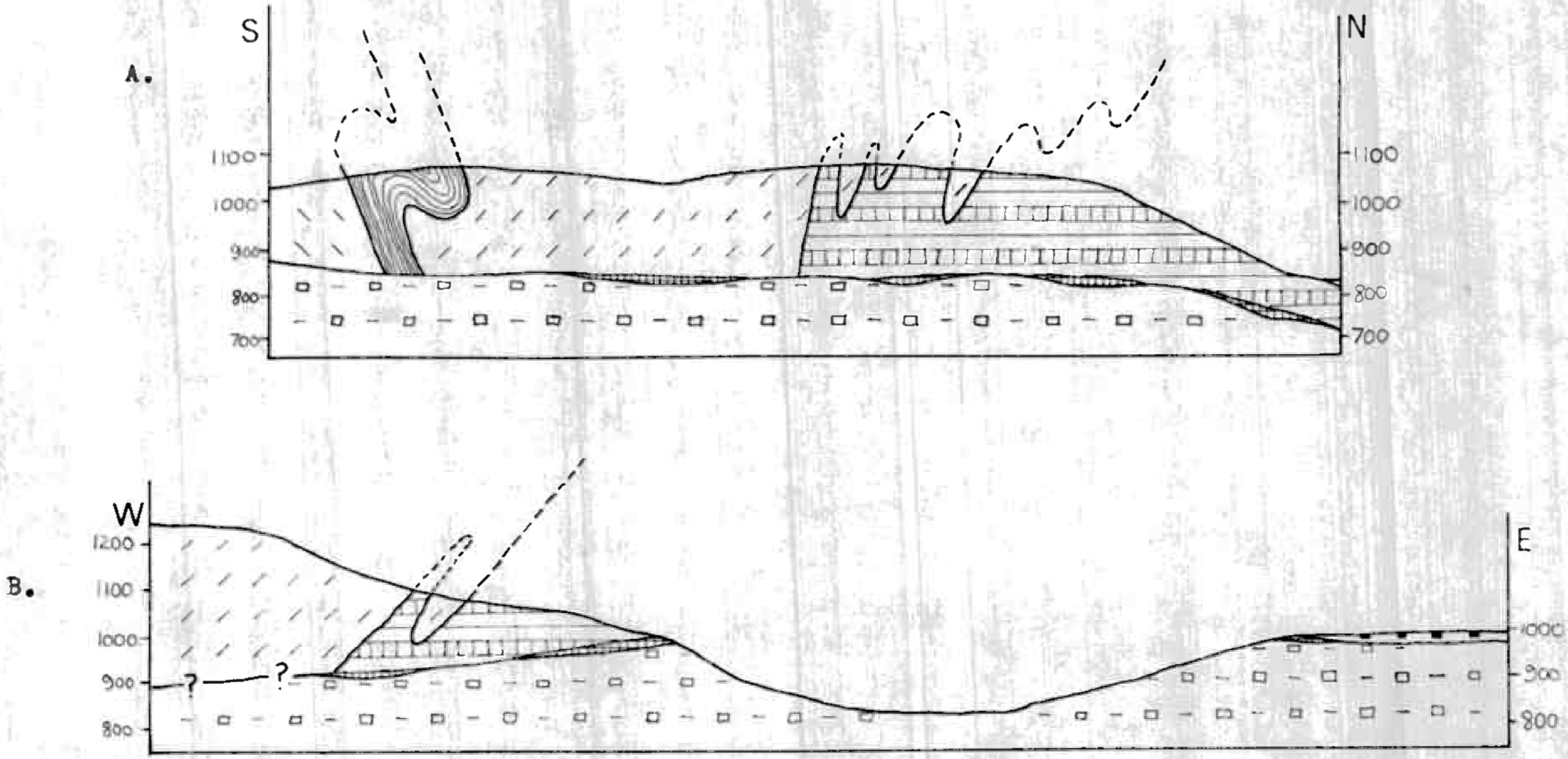
At this point in the sequence there is a break, caused by the two Sorjus lakes and the arm of the gabbro extending to the western end of Øvre Sorjus, which divides the rocks north and south of the lake. The country north of the two lakes has only been very scantily reconnoitered, but at the western end of Øvre Sorjus the kyanite schist group is seen north of the arm of the gabbro complex referred to above. Further to the east, the kyanite schist group lies north of the calcareous semi-pelite, but no detailed study of this region has been made. In view of the inversion of the sequence on the western side of the valley west of Hammeren, (geological section fig. 1.8) and in light of reconnaissance to the north of Nedre Sorjus, the placing of the kyanite schist group immediately above the calcareous semi-pelite group must be treated with reserve. The present proposal is that the arm of the gabbro has injected the relatively soft calcareous semi-pelite so that this lithological group is not seen at the western end of Sorjusjaure.

(e) <u>The kyanite schist group</u>.

This group is one of the more characteristic horizons. It

FIG. 1.8.

N-S and E-W geological sections in valley S of Nedre Sorjus.



Vertical scale = horizontal = 1 : 15,000.

Showing an interpretation based on the assumption that there is a thrust horizon on the sides of this valley. Positions of sections marked on structural overlay.

tends to have resisted erosion better than the calcareous groups so far discussed, and forms a line of hills north of the Sorjus lakes, coming into contact with the gabbro complex west of Øvre Sorjus and continuing in contact with the complex until it is lost among the complications of the major thrust horizon to the south. However, throughout its contact with the gabbro complex the width of its outcrop narrows progressively, and since the dips throughout most of this region are mostly steep or vertical it seems that this narrowing represents a thinning of the group. The group continues across the border into Sweden, forming the peak Almajalosjakna, and correlates with the rocks Kautsky describes as "staurolite-mica schist" lying in his Gasak nappe sequence.

The rock is a coarse grained mica schist, usually with garnets, and porphyroblasts of kyanite, which take the form of prisms often with a preferred orientation parallel to the regional lineation. Porphyroblasts of staurolite can sometimes also be recognised in hand-specimen by their yellow colour. Contact metamorphic effects upon this group due to the gabbro are rather rarely seen in the field, but sometimes the kyanite schist alters to a finer grained, schistose rock which is rusty weathering (e.g. a strip of this rock occurs as a screen a couple of metres thick in the gabbro north of lake 933 in Sorjusdal (g.r. 516542). There is a strong resemblance between this rock and the "schistose hornfels" occurring between the Furulund granite and the gabbro complex, and it seems that most of the rocks in that strip may be regarded as contact metamorphosed kyanite schist.

The kyanite schist is distinguishable to the west of Duoldagop (J. E. Larsen, see map), and also may be correlated with a thin strip of kyanite bearing schist which occurs south of the lens of Furulund granite which forms the northern slope of Kobbertoppen, west of the gabbro (M. Wilson pers. comm.). The group is lithologically very similar to the lowest staurolite schist in the Baldoaive sequence to the south (Sjögren, Vogt and Henley). The N-S sections given by Vogt (pl. XXXVI) also correlate these two staurolite schist horizons. Larsen's and Wilson's work will certainly throw more light on this correlation.

The other members of the Gasak nappe sequence are seen in the structure at Duoldagop, lying in the core of the synform. They continue round to the north of the kyanite schist group north of Sorjusdal, but have not yet been mapped in detail. On the eastern side of the Duoldagop synform they appear as an inverted sequence below the gabbro and Furulund granite, dipping steeply north-eastwards, while west of the synform they are almost vertical.

(f) Micaceous psammite with marble bands.

Sjögren described this unit as "black rusty schist" and Vogt in a copy of Sjögren's map of Duoldagop, (p. 88, fig. 24) calls it "mørke fyllit" which literally translated is "dark phyllite". Larsen refers to it simply as "fyllit" (pers. comm.). The rock is a flaggy micaceous psammite, very fine grained, splitting easily along well defined planes which sometimes show crenulations. It weathers a characteristic rusty colour, and contains carbonate rich bands which weather out preferentially.

Associated with the horizon are persistent bands from 1-5 m. thick, of relatively pure marble. In the Duoldagop region these lie mostly stratigraphically below the psammite (and therefore on the east side structurally above it), but north of Smasorjus the marble is found enclosed within the psammite. Towards the Swedish border marble replaces psammite entirely, and this group can be correlated with the lower of the two marble horizons described by Kautsky within his staurolite schist group.

The micaceous psammite has proved a very useful stratigraphical marker horizon.

(g) Calc-silicate group of Duoldagop.

These rocks are very poorly exposed in the core of the Duoldagop synform. This is a low lying area, covered by glacial debris and the two lakes, and the rocks are only seen in the beds of a few streams. Here they appear to be banded calc-silicate rocks, without a marked cleavage. In the few exposures seen there are no marble bands or pockets.

Correlations.

The principal rock types surrounding the gabbro complex have

TABLE 1.

Eastern Sulitjelma (Vogt 1927)	Central Sulitjelma (Sjögren 1900)	N.E. Sulitjelma (Mason 1966)	Swedish Sulitjelma (Kautsky 1953)	
Upper Sulitjelma schists	4. Calcareous mica-schist	(g) Calc-silicate group of Duoldagop	Limestones in garnet-mica schist	
	5. Limestones 6. Quartzite lenses 7. Black rusty schists	(f) Micaceous psammite with marble bands		
	8. Furulund schist	(e) Kyanite schist group	Staurolite schist	Gasak Nappe
These units not seen in west		(d) Calcareous semi-pelite (c) Calc-silicate group (b) Graphitic schist (a) Calc-silicate group (Dioritic gneiss)	Acid and intermediate volcanics and lavas Varied dolomite rich series with graphitic schists Graphitic schist Highly metamorphosed conglomerate	Gasak Nappe
magmatic contact				
Sulitjelma phacolith	Sulitjelma gabbro	(d) Porphyritic amphibolite (c) Schistose amphibolite	Porphyritic amphibolite with dolomite bands	Vasten Nappe
magmatic contact				
Lower Sulitjelma schists	8. Furulund schist	(b) Micaceous quartzite (a) Furulund schist	Brown and green schists	Pieske Nappe

now been described. Part of the interest of the NE Sulitjelma area is that it is the ground between the Sulitjelma sequence, regarded until recently as a continuous stratigraphic sequence of rocks which have undergone regional metamorphism (Vogt and Sjögren), and the rocks described by Kautsky across the Swedish border, which he regards as a pile of thrust sheets. It has been stated earlier that in the NE Sulitjelma region only one major tectonic discordance has been recognised, and this is correlated with the base of Kautsky's "Gasak nappe". Correlations within the two structural units are shown in the accompanying table (Table 1). Where one group in this sequence can be correlated with certainty with a group in a previous worker's sequence, the contacts of the two units have been joined by a straight line. Sjögren numbered his units from the top of the sequence downwards; the uppermost units in his sequence are only seen in the south and west.

CHAPTER TWO

The Structure of the Gabbro Complex.

Detailed mapping of the banding and contacts of the Sulitjelma gabbro complex has revealed something of its original form, and of the deformation it has undergone since consolidation. Contrary to the opinion of Th. Vogt (p. 464) the gabbro is not concordant with the lithological banding or the schistosity of the country rocks. This is well illustrated by the graphite schist strip in the NE which runs into the contact of the complex. The cross cutting nature of the complex can also be seen by its progressive transgression across the kyanite schist group. The isolated patch of gabbro west of Duoldagop which has been mapped by Larsen is also transgressive with respect to the lithology of the country rocks and comes into contact with the micaceous psammite group.

The detailed nature of the contacts of the gabbro complex is well illustrated in the valley Sorjusdal, in the NW part of the complex. The contact of the gabbro runs along the northern slope of this valley, but its attitude and direction are very variable. On the hill immediately west of Øvre Sorjus (g.r. 538550) it can be seen covered by a roof of hornfelsed schists which form the top of the hill. The foliation of the schists outside the narrow band of massive hornfels is vertical and is almost perpendicular to the plane of contact. Further

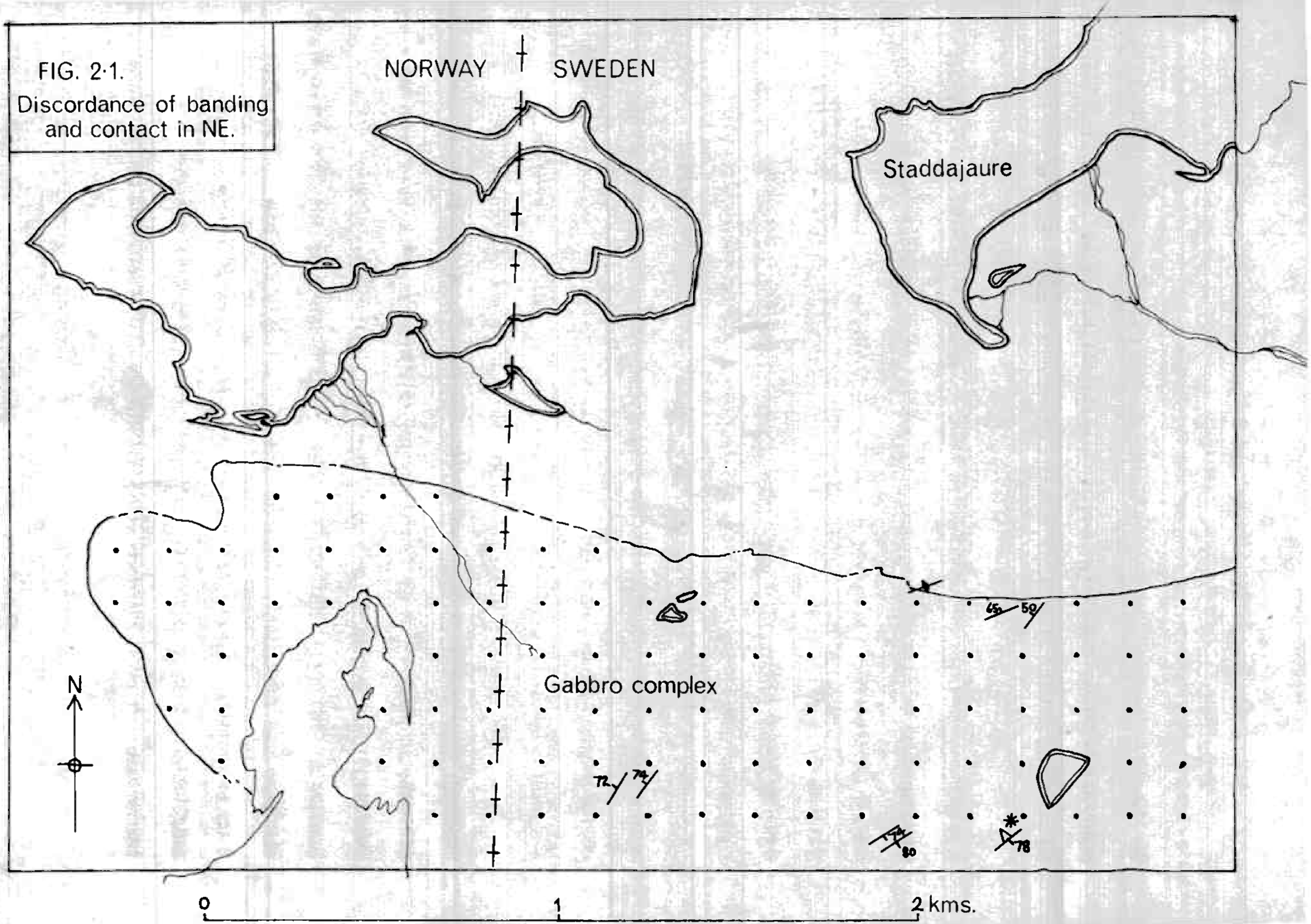


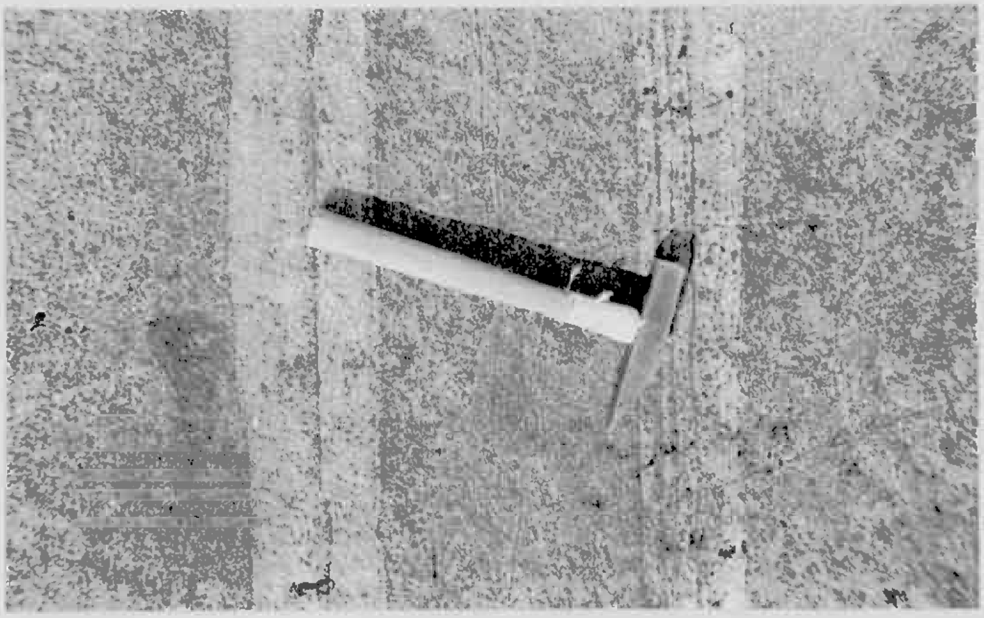
FIG. 2·1.
Discordance of banding and contact in NE.
NORWAY
SWEDEN
Staddajaure
Gabbro complex
N
0
1
2 kms.

to the west north of lake 933 at the head of the valley, the contact is apparently vertical and concordant with the schistosity. Here a screen of hornfels can be seen running into the gabbro (g.r. 516542).

On the bed of the valley there is a large raft of hornfels, now quite massive, surrounded by gabbro (g.r. 534544). It lies along a continuation of the trend of a large screen which includes the graphite schist group, and it is possible that it may represent a foundered portion of that screen. There are extensions of the gabbro into the country rocks also, the most spectacular example being the wide apophysis which runs north from the main part of the complex at the western end of Øvre Sorjus. Another point where the discordance of the gabbro complex is seen is on the ridge north of point 1787, where a screen of hornfels runs across the gabbro outcrop (g.r. 598508), but here the situation is complicated by the presence of igneous breccias.

The gabbros of the complex show a distinct primary igneous banding, produced by variations in the proportions of the main minerals present, in particular by the variation of the ratio of plagioclase to ferromagnesian minerals (see p. 58). It is not strictly rhythmic banding in the sense that regular layers which are enriched in olivine at the base and labradorite near the top can be distinguished. Bands from 1 cm to several metres thick show different mineral proportions from neighbouring bands, producing an appearance rather like striped sandstone. This banding is very similar to that described in the Newer

Fig. 2.2. Appearance of primary banding of gabbro complex.



1. In the valley N of Vardetoppen.

2. Near the summit of point 1787.

Gabbros of Scotland (Shackleton 1948) but not really like the more regular banding of the great layered intrusions, such as Skaergaard or Rhum, to which the term "rhythmic banding" is strictly applicable. In this account the non-committal term "primary banding" will be used.

The banding of the gabbro is discordant with the contacts of the complex. This was observed in the extreme NE corner of the area studied, across the Swedish border (fig. 2.1) and also in the valley north of Vardetoppen. As the banding disappears about 100 m. from the contact (see p. 61) it is not possible to demonstrate discordance at the contact itself, but where it first appears the banding makes a high angle with the plane of contact.

Banding is well marked in a zone running across the complex in an approximately E-W direction (fig. 2.2, 3.3). The gabbros north and south of this zone show far less well developed banding. In the well banded zone, the banding is vertical or dips steeply N. Further north, banding is almost entirely absent, and a few scattered observations of inclined surfaces in the region of lake 933 in Sorjusdal (g.r. 520540) show no clear pattern. To the south of the well banded horizons observations are fewer because of the massive nature of the gabbro, and the inaccessibility of the high mountain summits and ridges which form this part of the complex. Such observations as there are show banding near horizontal or dipping gently south (see structural overlay).

In two localities in the well banded gabbros apparent "wash-

Fig. 2.3.

Possible "cross bedding" in primary banding.

(g.r. 621506).

outs" in the banding appear to indicate a way up, suggesting that the gabbros "young" northwards (fig. 2.3). However, this evidence is in direct conflict with that provided by the iron to magnesium ratios of the ferromagnesian minerals, which increase across the well banded zone to the south. Figure 2.3 shows the nature of the field evidence, and it is considered that the mineralogical evidence of way up is more reliable. A possible synformal structure for the gabbro complex is illustrated on the N-S section in the map pocket. This fits the observed banding pattern quite well, but its main basis is the variation of composition of the ferromagnesian minerals, so it will be discussed in more detail in chapter 3 (p. 72).

The evidence for the original form of the complex can therefore be summarised as follows :-

1. In detail, the contacts of the gabbro complex are discordant with the original bedding of the country rocks. They are also locally discordant with the schistosity. But, as Vogt observed, there is a large scale tendency for the schistosity of the country rocks to run parallel to the contacts.

2. The primary banding and igneous lamination of the gabbro complex are discordant with the contacts.

3. The primary banding is also discordant with the bedding of the country rocks.

Thus it can be seen that :-

1. The cross-cutting nature of the complex and its rather irregular contacts mean that it has not the relatively simple structure which enables it to be described as a batholith, sill, lopolith or other such term. If a name must be given to the intrusion, Daly's term "chonolith" seems the best. (See Daly "Igneous Rocks and the depths of the Earth" 1933, p. 105 for a discussion of this name).

2. Assuming the primary igneous banding to have been near horizontal when the intrusion solidified, it is apparent that the bedding of the country rocks, which makes a high angle with the banding in at least two localities (figs. 2.2 and 2.4) must already have been tilted from the horizontal.

Igneous Breccias.

The igneous breccias associated with the gabbro complex occur mostly as small patches at the contacts, particularly where screens of country rock run into the gabbro. However there is one large area of breccia on the ridge north of point 1767. The breccias consist of fragments of country rock, now metamorphosed to hornfels, in an igneous looking, often biotite-rich matrix. The fragments vary in size from a few centimetres to several metres across. Occasionally they show a distinct elongation or flattening.

Material similar to the matrix of the breccias has been seen veining the gabbro, and it seems reasonable to conclude that they were formed after it consolidated. In some localities two generations of breccia were seen, one veining the other.

The Furulund granite.

Only one contact has been observed between the main mass of the Furulund granite and the gabbro complex (fig. 2.5), but vein-like offshoots of granite do cut the gabbro complex elsewhere. The granite was therefore probably intruded slightly later than the gabbro.

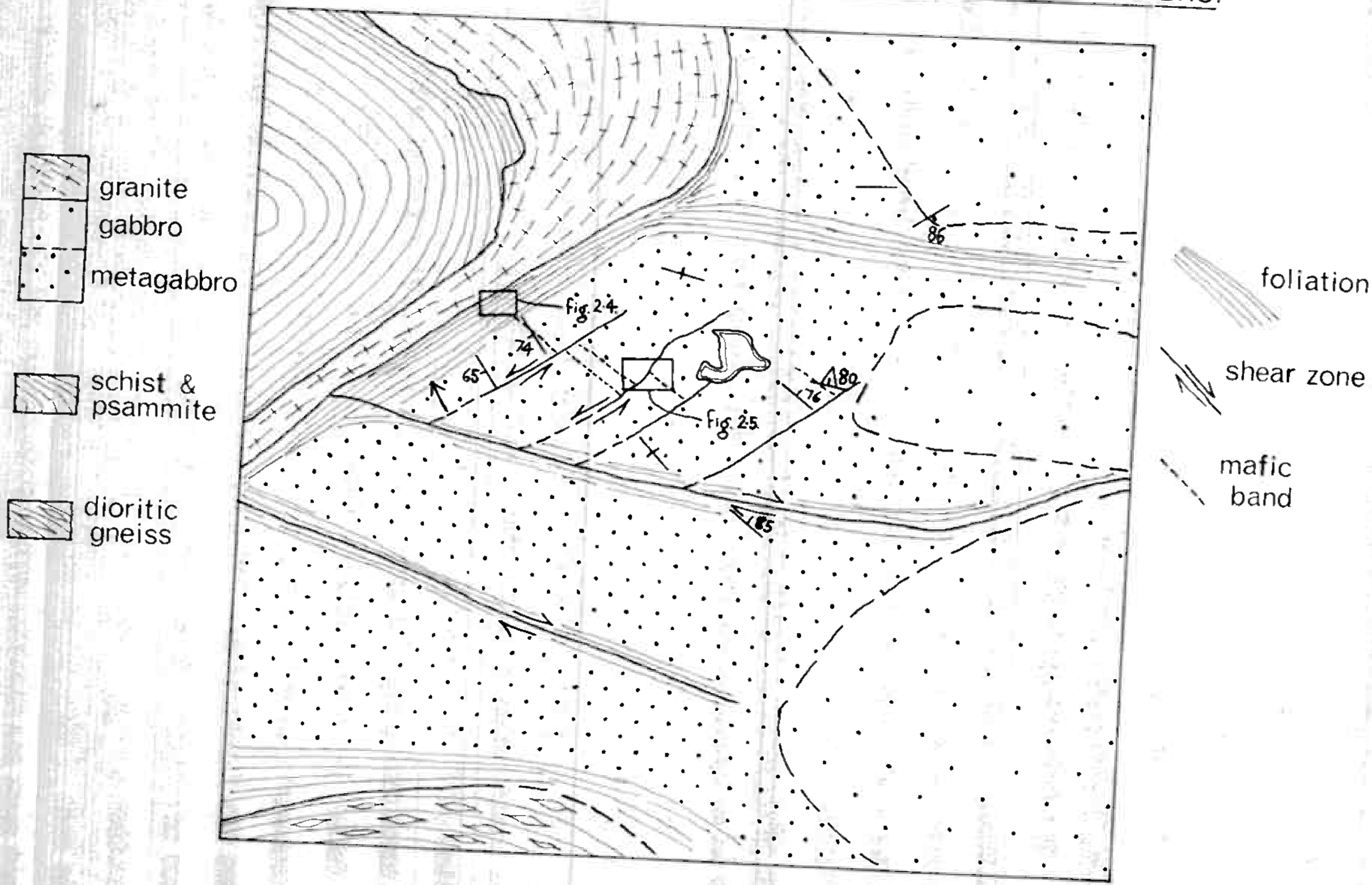
The main intrusion of the Furulund granite just W of the gabbro complex is a lens-shaped body. It is foliated, and the regional D_2 lineation has been imposed upon it. In the thickest part of the lens, the central parts of the granite are less well foliated than the margins, and have a well developed augen texture. No contact hornfelses have been found surrounding the granite. The granite lens has been folded in the Duoldagop synform, and the structures imposed on it will be described along with those of the Duoldagop region.

It has not been possible to determine the relative ages of the Furulund granite and the igneous breccias.

Other intrusions.

At the NW contact of the gabbro complex are a number of small intrusions which are coloured similarly to the Furulund granite on the map. However they are distinctly richer in dark minerals than the granite and may represent a different phase of magmatic activity. They vein the gabbro, but their age relations to the granite and igneous

FIG. 2.4. DEFORMATION OF THE SW CORNER OF THE SULITJELMA GABBRO.



Scale 1:15,000.

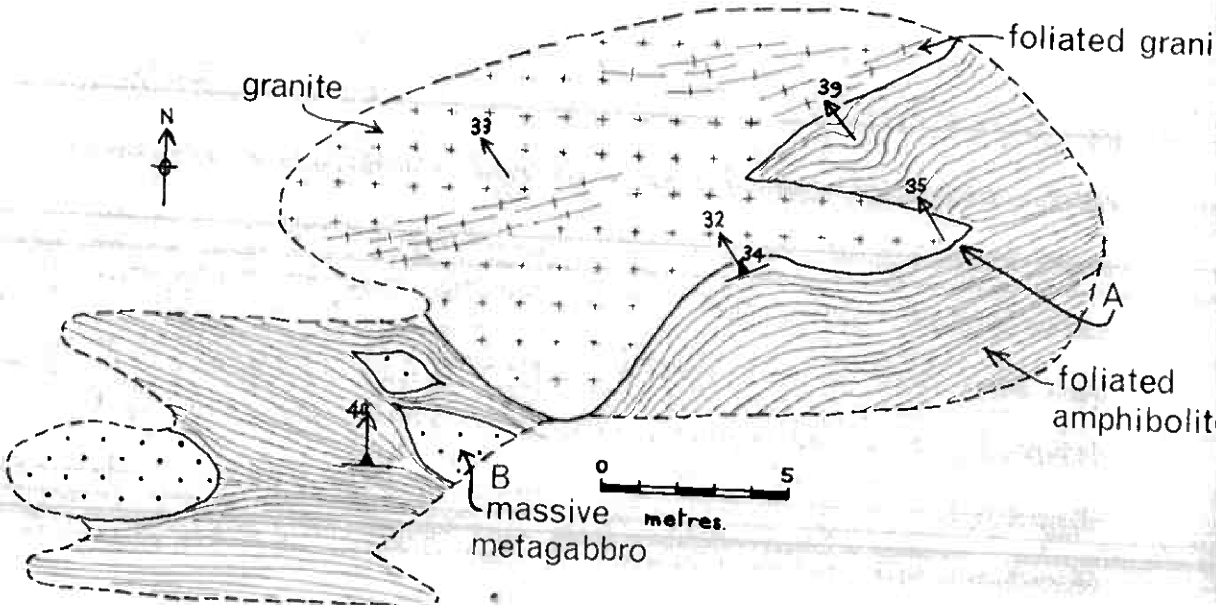
breccias are uncertain.

Deformation of the gabbro complex.

The deformation of the gabbro complex was studied in detail in the SW corner. Here deformed banded gabbros with occasional bands of olivine-rich gabbro and peridotite show a variety of types of deformation. Many of the small scale structures seen in metamorphosed sedimentary rocks are duplicated here; in addition to small folds and faults there are boudins, often showing a rotation. The dominant mode of deformation however is by fracture, the folds being drag-folds associated with shear planes. One of the more mafic bands has been mapped over ½ km. or so (fig. 2.4).

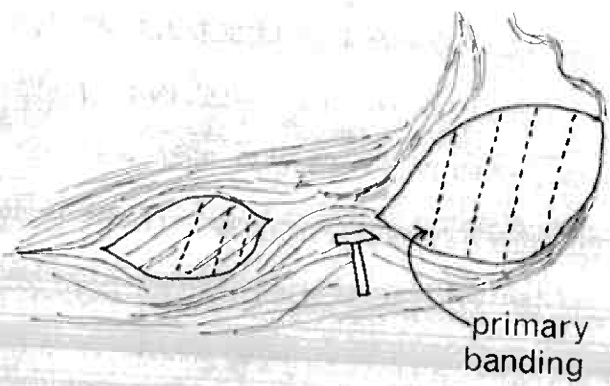
In the shear zones the gabbro has been metamorphosed to a coarse grained amphibolite, the small scale banding obliterated and a crude foliation parallel to the direction of the shear developed. Near the shear zones the gabbro displays small scale folds and veins of pegmatite often follow the shear planes. Blocks of gabbro, still for the most part metamorphosed into green metagabbro, but relatively undeformed, occur between the shear zones. The result of the shearing seems to have been to produce an overall extension in an approximately E-W direction (fig. 2.4). A lineation appears on some surfaces in the shear planes, and is parallel to the axes of many of the folds. It also runs parallel to the D_2 lineation imposed upon the dioritic gneiss to the south and the Furulund granite to the north.

FIG. 2·5. GRANITE CONTACT WITH GABBRO AT G.R. 533503.

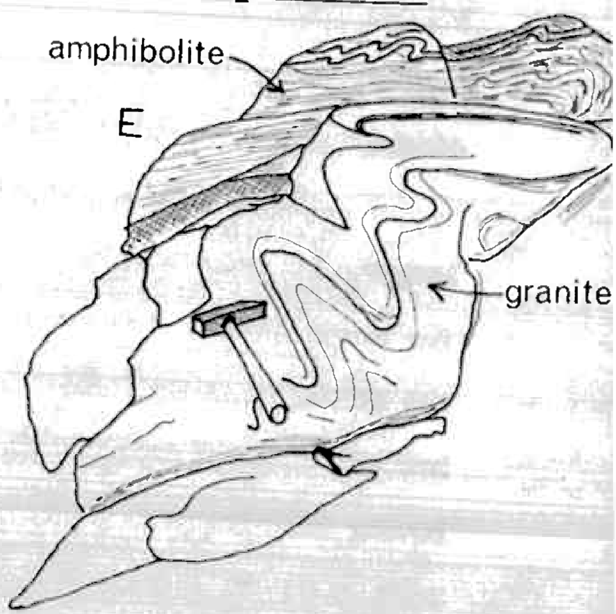


1. Sketch map of exposure.

2. Boudins at B.



3. F_2 fold at A.

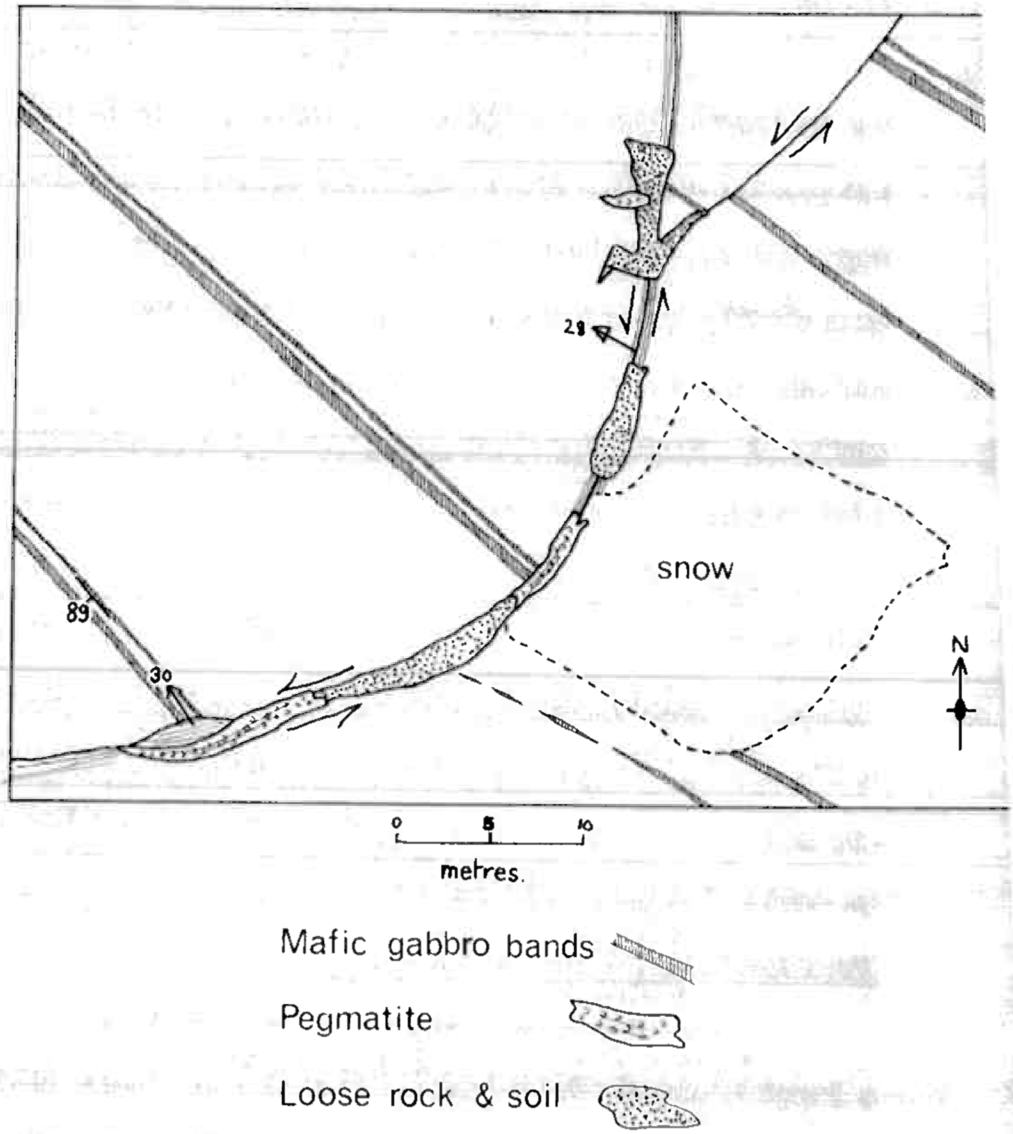


Near the contact with the granite the gabbro is particularly strongly metamorphosed and deformed, and has taken on a foliation. A large scale sketch map of a small part of the granite-gabbro contact shows the nature of the structures seen in this horizon (fig. 2.5). The contact is far from being the simple curved surface shown on the map when considered in this detail. A similar detailed map of a less deformed part of the south western corner of the complex shows the displacement of two mafic gabbro bands by a medium sized sinistral shear direction, and some of the associated structures which are developed (fig. 2.6).

The intensity of deformation increases towards the south-west and on the south side of the valley the highly deformed gabbros merge imperceptibly into the dioritic gneiss. The region near the contact between granite and dioritic gneiss shown on the map in the west is a complex zone with lenses of metagabbro, granite and calc-silicate rocks caught up in a tectonic mélange.

To the east, the blocks of undisturbed metagabbro become larger, and un-metamorphosed gabbro becomes commoner, until eventually the shear planes, often with veins of pegmatite, are the only parts of the rock mass which have undergone any amphibolitisation. It is striking how the veins of more basic gabbro seem to resist amphibolitisation far better than the more plagioclase rich varieties, so that where the main part of the gabbro has been amphibolitised they remain as boudins or bands

FIG. 2.6. SKETCH MAP SHOWING DEFORMATION OF BAN GABBRO AT G.R. 536502.



weathering in their characteristic rusty manner.

In the rest of the complex the field evidence for deformation can be seen in the attitude of the banding. It is difficult to know the precise original dip of the banding, but in the Skaergaard intrusion Wager and Deer estimate the original dips in the layered series to have been $0^{\circ}-30^{\circ}$, the latter value only being reached very close to the contact with the border group (Wager and Deer 1939, p. 61). A possible synformal structure for the gabbro complex has already been described (N-S section in map pocket). If the assumptions concerning the mode of formation of the banding are correct, the complex must have undergone folding and partial inversion after consolidation. The axis of the synform is displaced relative to the axis of the later of the two synforms constituting the Duoldagop structure W of the gabbro complex (p. 54), but it may be that the two structures are related to one another, in some way that is not clear at present.

Structures in the Country rocks.

The interpretation of the structures in this thesis is based to a large extent on the work of Henley (pers. comm.) on the Central and Southern Sulitjelma areas. A summary of his conclusions concerning deformation is shown in Table 2. He recognises three main phases of rock deformation, which he terms D_1, D_2 and D_3, each associated with a characteristic style and orientation of minor structures. The sequences of deformation and metamorphism he describes do not differ greatly in the

TABLE 2

Summary of Structural History of the Three Units

(Henley 1966)

<table>
<tr><th>Upper Unit
(Gasak nappe)</th><th>Lower Unit
(Pieske-Vasten nappe)</th><th>Junction Unit</th></tr>
<tr><td>D_1 Development of fine grained schistose fabric (S_1).

D_2 Plastic flowage (homogenous strain) with minor folds developed with axes trending parallel to the direction of flowage (F_2).
F_2 folds are :-
1. tight
2. on E-W axes
3. with good axial plane schistosity (S_2).</td><td>D_1 Development of fine grained schistose fabric (S_1) possibly with folding on axes trending 240-250° (F_1) ?

D_2 Homogenous strain.

F_2 folds are :-
1. isoclinal
2. on E-W axes
3. with good axial plane schistosity (S_2).</td><td></td></tr>
<tr><td>D_3 Minor open folds developed (F_3).
F_3 folds are :-
1. open
2. on E-W axes
3. axial planes dip S.
4. with incipient axial plane cleavage.</td><td>D_3 Several phases of minor folding in different parts of the region.
<u>In Furulund Schist</u> :-
F_{3a} folds are :-
1. open
2. on N-S axes
3. with axial planes dipping NW.
4. with axial planar strain slip cleavage.
F_{3b} folds are :-
1. open
2. on E-W axes
3. with axial plane strain slip cleavage in pelitic beds.</td><td>Brecciation & chloritisation

Disharmonic folds which are :-
1. on N-S axes
2. open
3. with axial plane strain-slip cleavage.</td></tr>
<tr><td colspan="3">D_4 Open symmetrical folding on N-S axes with vertical axial planes (formation of Baldoaive synform?).
Open large scale folding on approximately E-W axes to form Langvann antiform.</td></tr>
</table>

Gasak and Pieske-Vasten nappes.

Deformation in the rocks of the Pieske-Vasten nappe.

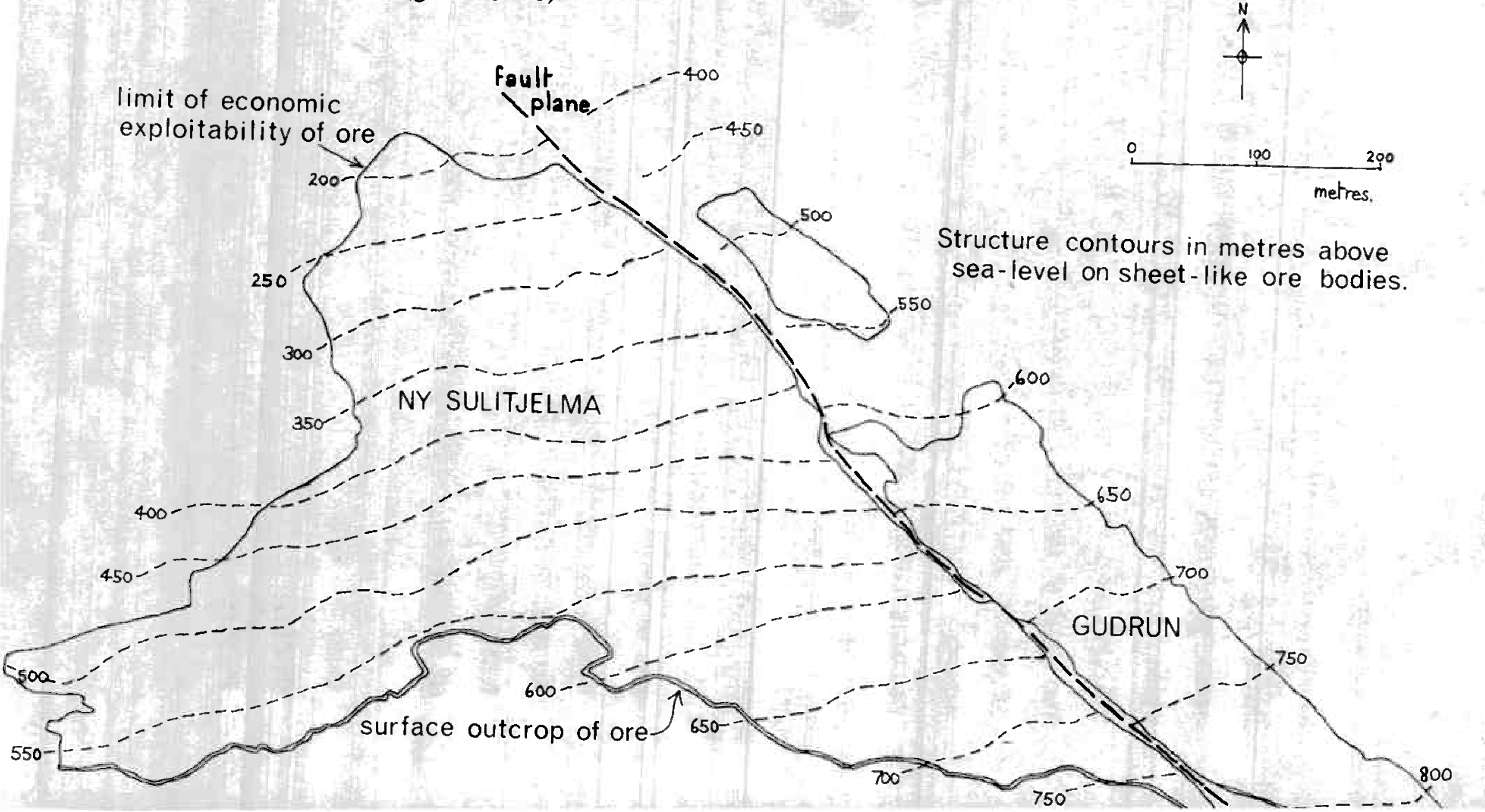
The deformation of the rocks in the Pieske-Vasten nappe south of the gabbro complex is essentially similar to that described by Henley in the Furulund schist of the central Sulitjelma region. In the Furulund schist immediately below the amphibolites, and in the schist strips within the amphibolite, folds of F_2 and F_{3a} style and direction are seen. In one case an F_{3a} fold is seen folding an F_2 fold (g.r. 542454). The amphibolites do not display folding, but the more fine grained bands show a marked preferred orientation of hornblende prisms parallel to the D_2 lineation, and there is some boudinage of the more massive bands, with the axes of the boudins elongated in the same direction. D_1 structures are not seen in the field at all, but many garnets from the schist horizons show "S" shaped trails displaying an early fine grained fabric in the core.

There is a local anomaly in the D_2 lineation in the Ny Sulitjelma area which was noted by Henley and is confirmed in the present study. The lineation changes in trend from E-W to NE-SW and from running approximately along the strike of the schistosity to running down the dip. This anomaly is probably associated with the Duoldagop structure. North of Låmivann the lineation trends approximately NE-SW, but is almost horizontal.

There is little evidence of faulting as opposed to low angle

FIGURE 2·7. THE NY SULITJELMA AND GUDRUN ORE BODIES.

(g.r. 493476)



thrusting on any large scale within the rocks of the Pieske-Vasten nappe. Henley does not describe any large scale faults (though the Furulund schist group displays excellent jointing, well described by Vogt p. 116-136). However, quite a large fault separates the ore-body of the Ny Sulitjelma mine from that of the now abandoned Gudrun mine to the east. The throw of the fault increases down the dip of the ore-body which is an elliptical lens elongated E-W, and concordant with the surrounding schists. While the main ore-body is displaced by the fault, a later impregnation by pyrite runs up the plane of the fault between the two bodies. The fault is vertical, and its trend is roughly down the dip of the sheet-like ore-body (fig. 2.7).

Structures within the dioritic gneiss junction horizon.

The dominant structure seen in the gneiss horizon is the very well developed lineation. The schistosity of the fine grained amphibolite between the lenses of coarser grained material seems to have developed at the same time as this lineation. Some of the lenses show an earlier foliation, which is cross cut by the schistosity. This may be a relict of the primary banding of the gabbro.

Folding is not usually seen in the junction horizon, although there are some isoclinal folds in calc-silicate rocks mapped within the dioritic gneiss on the southern slopes of Vardetoppen. These have axes parallel to the D_2 lineation.

The prevalence of the lineation suggests that the formation of the dioritic gneiss melange was a D_2 event. According to Henley the D_2 lineation represents an episode of homogenous bulk deformation of the Furulund schist. On this interpretation the dioritic gneiss horizon is a zone of concentrated movement (see p. 28-29). The relatively rigid gabbro complex was unable to participate in the homogenous deformation, and a zone at the base of it became converted into a tectonic melange of amphibolitic rocks. This does not imply that there has been a great amount of movement of the Gasak nappe rocks relative to the Pieske-Vasten nappe rocks; but the cross cutting of lithological groups and the impossibility of correlation between groups above and below the dioritic gneiss are difficult to explain unless quite large scale movement occurred.

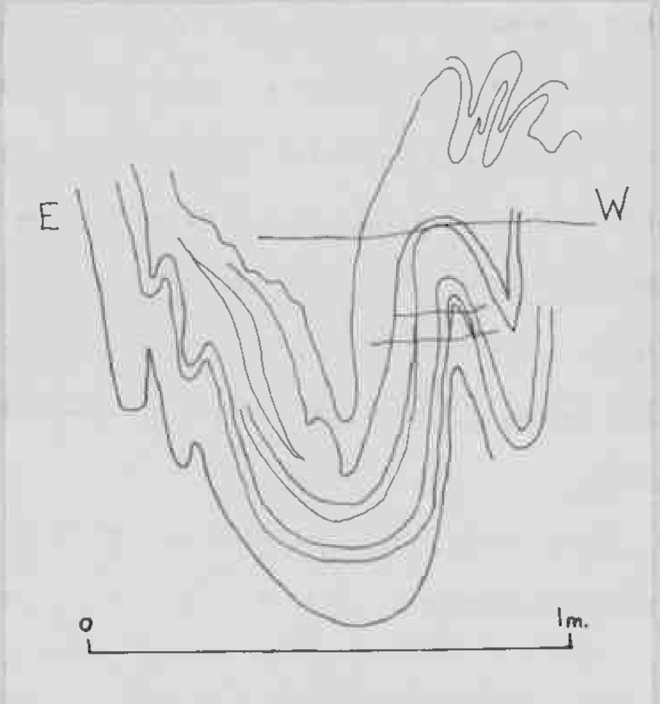
The northern outcrop of the thrust horizon, south of Sorjusjaure, has not been investigated in very great detail.

Deformation in the Gasak nappe.

The present study confirms Henley's conclusion that the sequence of structural events in the Gasak nappe is similar to that observed in the Pieske-Vasten nappe. The injection of the gabbro complex represents a clearly defined event during the orogeny, and the study of the structures in the surrounding rocks is therefore clarified by a study of the structures in the gabbro complex itself, and in the zone of hornfelses surrounding it.

Fig. 2.8.

Minor fold in hornfels raft, Sorjusdal.



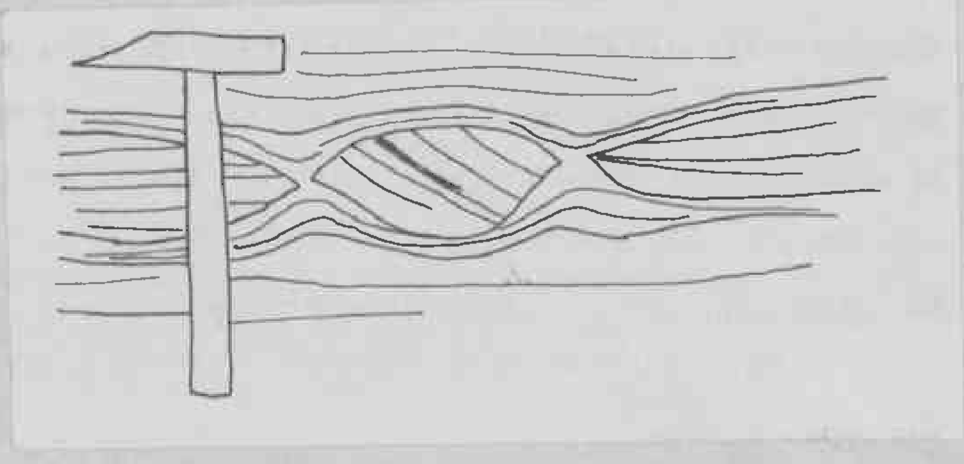
1. Structures earlier than the injection of the gabbro complex.

The structures which most certainly pre-date the intrusion of the gabbro complex are seen in the xenoliths and rafts which occur in the gabbro. The most spectacular of these are to be seen in Sorjusdal, in a large raft in the gabbro at the bottom of the valley which is crossed by the tourist track to Sorjusjaure (g.r. 534544). The rocks in this raft are hard, fine grained hornfelses, but minor folds can be seen in them (fig. 2.8). Another raft occurs in the igneous breccia just north of point 1797 (g.r. 598508). In this pre-hornfels boudinage can be seen (fig. 2.9).

Less certain pre-injection structures occur in the hornfels surrounding the gabbro. They are less certainly pre-injection in that it is not always clear in the field whether the structures near the contacts of the gabbro formed prior to hornfelsing, or have been imposed on the hornfelses later. Often examination of thin sections can help, but sometimes even this evidence can be ambiguous. A fairly large scale fold in hornfelses occurs south of the small patch of breccias on Vaknačokka (g.r. 557465). There are also folds in hornfelses near Småsorjus (g.r. 515527). Not enough pre-gabbro structures have been identified to make possible any generalisations about their geometry, but it seems clear that at the time of injection of the gabbro complex the rocks had already undergone a considerable amount of deformation. As the D_2 structures are imposed on the gabbro complex, the pre-gabbro structures are assigned to

Fig. 2.9.

Pre-hornfels boudinage in raft on ridge N of point 1787.



Henley's D_1 deformation episode. There is a possibility that several episodes of deformation occurred prior to the injection of the gabbro, and that the events described as D_1 by Henley are different from those which produced the pre-gabbro structures. However, at the moment the term D_1 is applied to any structures clearly earlier than the formation of the main lineation and schistosity.

2. Structures later than the gabbro complex.

These will be described from two different areas.

The Duoldagop area.

This area, round two small lakes west of the gabbro complex, is of great interest in any study of the structure of the NE Sulitjelma region. It shows anomalous features compared with the rest of the Sulitjelma region :-

1. The schistosity and bedding show large scale intense folding. Other large scale structures, such as the Langvann anticline, involve relatively gentle folding.

2. The D_2 lineation steepens on a NW trend, and runs down the dip of the schistosity, rather than along the strike.

Vogt (p. 87-94) presents a detailed account of the deformation in this region, based on Sjögren's map of lithologies. While his interpretation is highly ingenious, and explains the pattern of surface outcrops quite well, the minor folds he postulates do not occur. An attempt is made here to provide an interpretation more in accord with the

Fig. 2·10

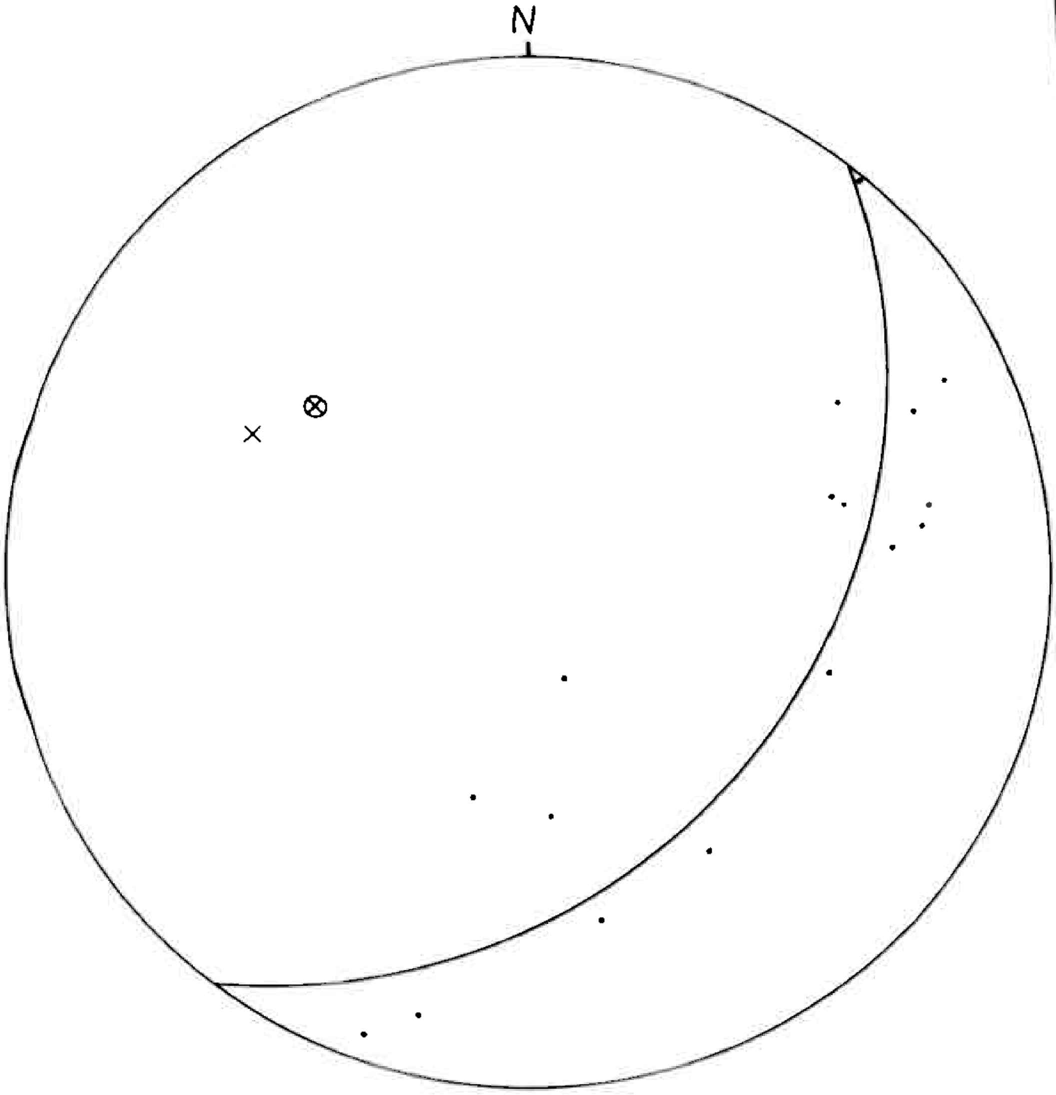
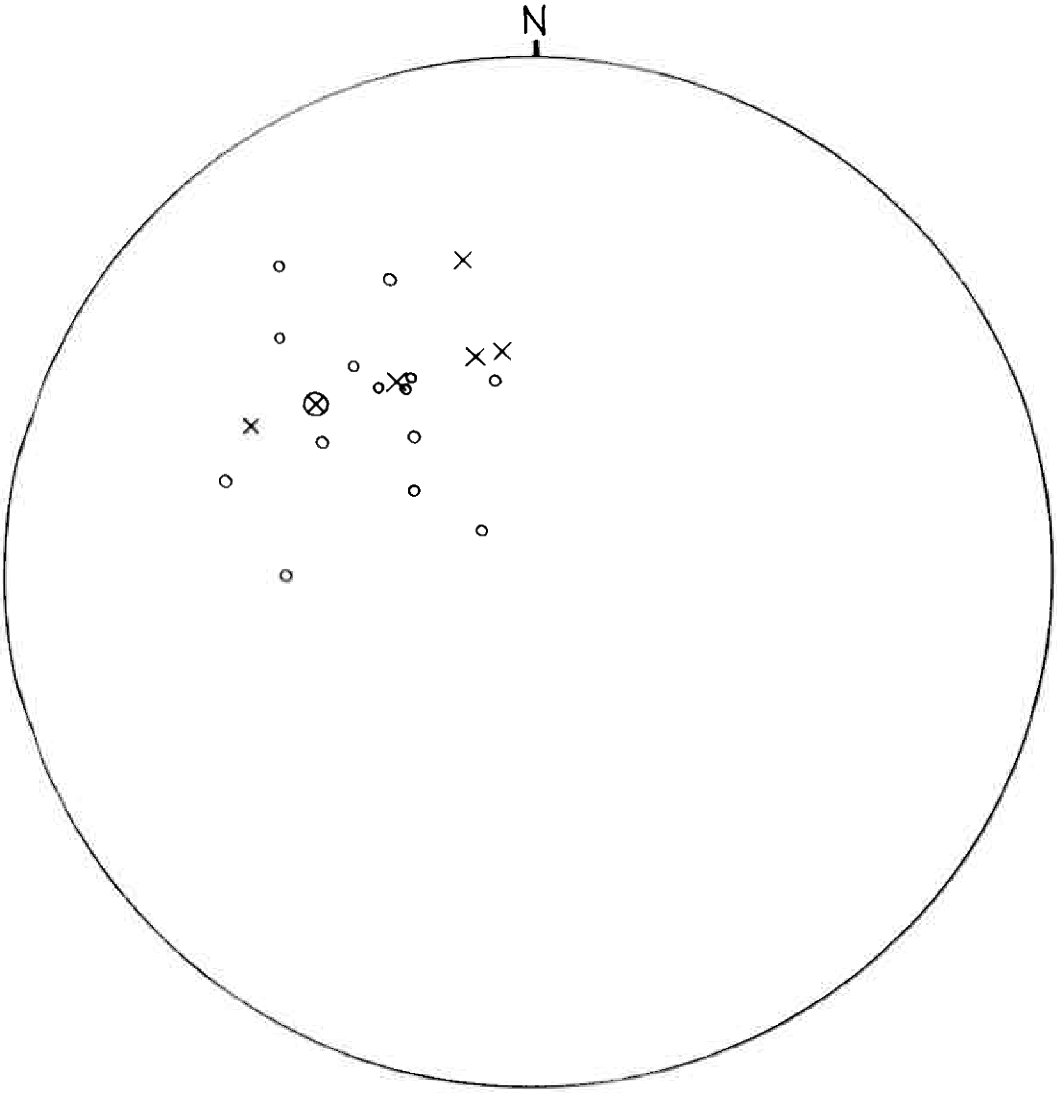


Fig. 2·11.



Stereograms.

Fig. 2.10 Folding of foliation of granite.

Fig. 2.11 Parallel fold axes and lineation.

Lambert equal area projection (lower hemisphere).

· normal to foliation surface

⊗ pole of great circle through foliation

× F_2 fold axes

∘ lineations

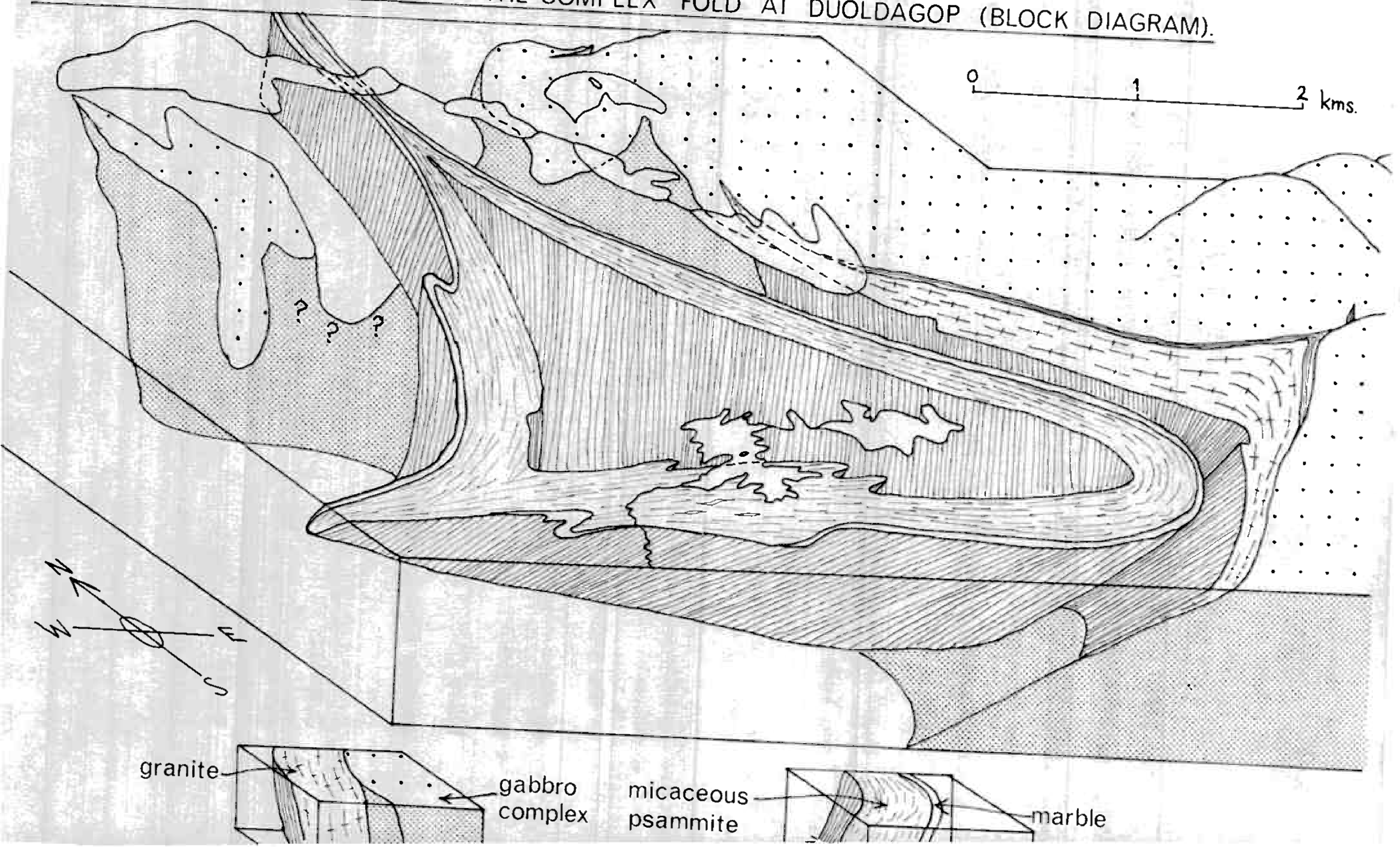
field evidence. The observations described were made with J. E. Larsen, who is studying the area west of the gabbro, but the interpretation is by the writer. Larsen is continuing to work on the area, and it may well be that he will modify the conclusions reached here.

In the micaceous psammite and kyanite schist groups minor folds can be recognised. The axes and axial planes have been measured. The axes lie approximately parallel to the D_2 lineation and there is a well developed axial plane schistosity, which is the main schistosity of the area. These folds are therefore termed F_2 and the schistosity S_2. The wavelength of the folds is of the order of 5-10 m. and they are revealed by the preferential weathering of rather calcareous bands in the psammite.

The closure of the fold in the granite was also studied in some detail. The axis of the folding of the foliation of the granite lies parallel to the axes of the F_2 folds and the D_2 lineation, as is shown by the stereograms (figs. 2.10, 2.11). The fold does however, rotate the D_2 schistosity and also the axial planes of the F_2 folds and is therefore regarded as later than the main D_2 deformation episode.

In the channel of the stream flowing into the eastern Duoldagop lake from the south post D_2 folds are seen (g.r. 521496). These have almost horizontal axes trending approximately E-W, and a penetrative axial plane schistosity develops near the hinges. They may be termed F_{3a} folds, as they refold the main D_2 schistosity. Their age relative to the major fold in the granite is uncertain (this is termed F_{3b}).

FIG. 2·12. INTERPETATION OF THE COMPLEX FOLD AT DUOLDAGOP (BLOCK DIAGRAM).



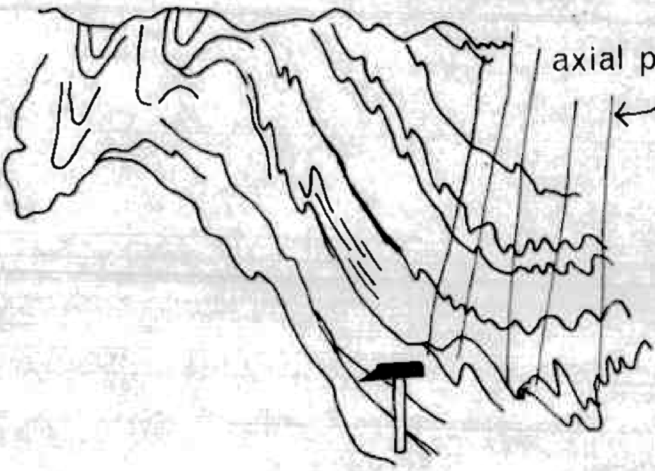
The early syncline trace illustrated on the structural overlay is based on the closures observed in the micaceous psammite, but the precise position of the axial trace in the central Duoldagop region is only inferred due to the poor exposure in this area. The axial trace of the later fold of the granite is mapped in the positions of greatest curvature of the refolded schistosity. Schryver (1966) questions the validity of this method of plotting axial traces of minor folds, but in major folds of this kind no other method of plotting the axial trace has yet been put forward.

Fig. 2.12 illustrates the interpretation of the Duoldagop structure. It has been drawn in perspective, roughly to scale, the top surface on the sketch representing the present ground surface. An offshoot of the gabbro complex occurring west of Smasorjus is shown joined to the main mass under the early synform. This outcrop consists largely of amphibolites, but with a little relatively unaltered gabbro which in thin section closely resembles the main Sulitjelma gabbro. The join below ground is pure speculation but might possibly be confirmed by a gravity or magnetic survey.

In the region north of Småsorjus, there is a change in the direction of the schistosity from a N-S strike to more NE-SW. This has not been studied in any detail but may be a structure of the same episode as the late major fold at Duoldagop. It is well seen on the slope of the hill north of Smasorjus.

FIG. 2.13. F_3 fold, S. of Sorjusjaure (g.r. 567551).

Looking E.



South of Sorjusjaure.

The other area where the structures surrounding the gabbro complex have been studied is south of Sorjusjaure (on the extreme north of the map). The outcrop pattern is not so complex here as at Duoldagop - the lithological units strike E-W and the schistosity is approximately vertical. The bedding is more or less parallel to the schistosity.

The D_2 lineation seems to be in a similar attitude to that observed round the NW corner of the gabbro complex i.e. nearly vertical. A later set of folds have been imposed on the early schistosity, producing another lineation plunging gently westwards (fig. 2.13). These later folds show a spectacular series of closures in the calcareous semi-pelite west of Hammeren, which are mapped out on the lithological map. They are also responsible for the displacements in the outcrop of the graphite-schist band. These folds seem similar in style and direction to the F_{3a} folds at Duoldagop, but more detailed structural work must be carried out before this correlation can be anything but tentative.

Conclusions.

The country rocks of the gabbro complex have undergone polyphase deformation, the sequence of events being similar to that described by Henley for the rocks in the Baldoaive sequence. The gabbro was intruded after the first (D_1) event, the evidence for this phase (or phases) of deformation being structures seen in thermally metamorphosed xenoliths in the gabbro complex, and in the narrow band of hornfels. Deformation after the intrusion of the gabbro complex has imposed a conspicuous lineation on the country rocks and the more deformed parts of the gabbro complex, and this D_2 phase of deformation seems also to be the phase during which the "dioritic gneiss" horizon associated with the base of the Gasak nappe was formed.

Minor folds coaxial with the D_2 lineation can be recognised both west and north of the gabbro complex, and are termed F_2. In the Duoldagop region a major synform is thought to be associated with these minor folds, and to have been refolded later with a different axial plane, to form a complex basin-shaped structure. North of the gabbro complex a later set of minor folds on E-W axes has refolded the D_2 structures.

CHAPTER THREE.

The Petrography of the Gabbro Complex.

1. General Comments.

The Sulitjelma gabbro complex is a layered basic igneous complex which has undergone extensive post-consolidation alteration. In this chapter the primary mineralogy of the complex will be discussed and also the changes brought about after consolidation. These changes are in chronological order :-

1. Deuteric or early post magmatic alteration. The formation of kelyphitic borders, brown hornblende, clouding of felspars etc.

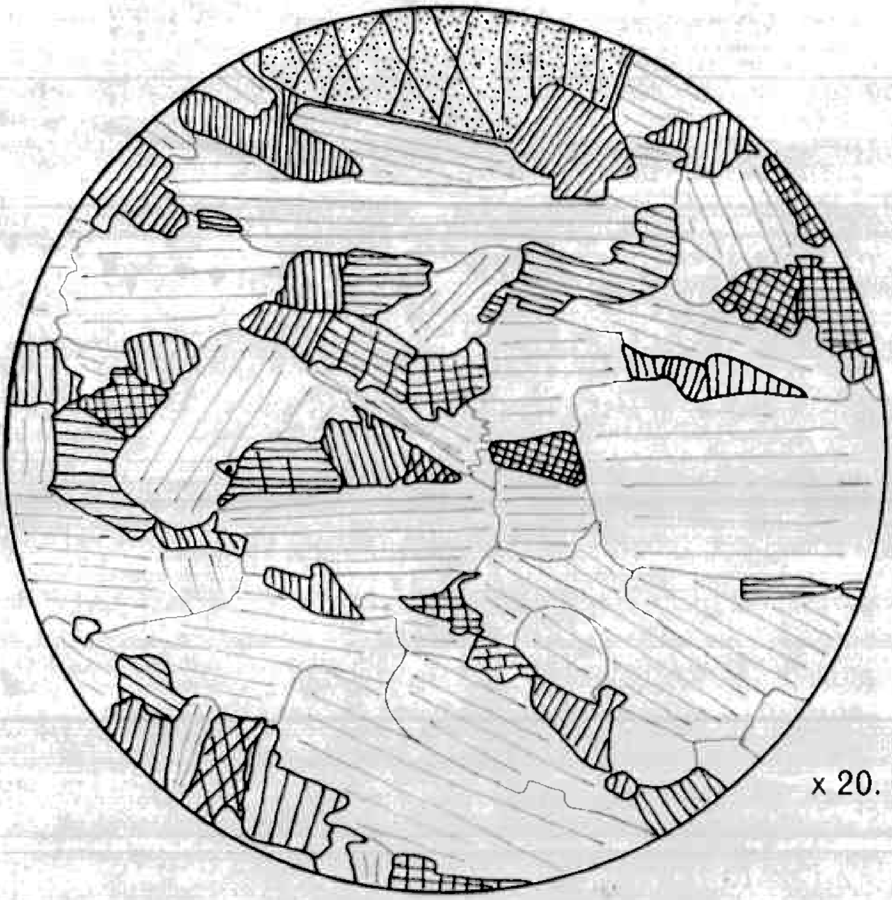
2. Cataclasis producing strain effects and granulation of primary igneous minerals associated with the D_2 structural event in the surrounding country rocks.

3. Amphibolitisation of the gabbro complex contemporary with the cataclasis, or immediately following it.

The primary minerals in the Sulitjelma gabbro complex are in approximate order of abundance labradorite, augite, olivine, orthopyroxene and pyrrhotite. There is a variation in the composition of the ferromagnesian minerals from different parts of the gabbro complex, which has been studied using the electron-probe X-ray emission microanalyser. The five phases listed above are present throughout the complex, and all five are present in nearly all the unaltered rocks. In addition very many of the otherwise unaltered rocks contain a small

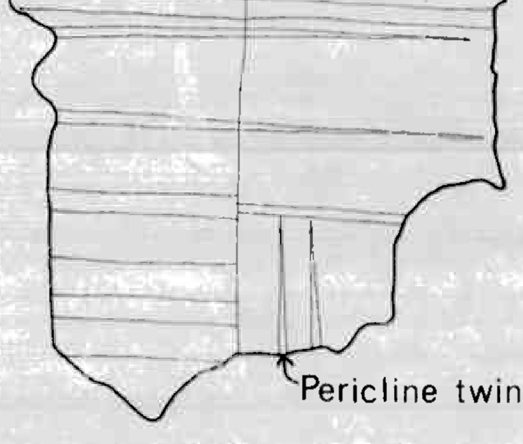
FIG. 3·1.

1. Igneous lamination of plagioclases in specimen T138.



x 20.

2. Plagioclase grain 3 from S174.



x 100 approx.

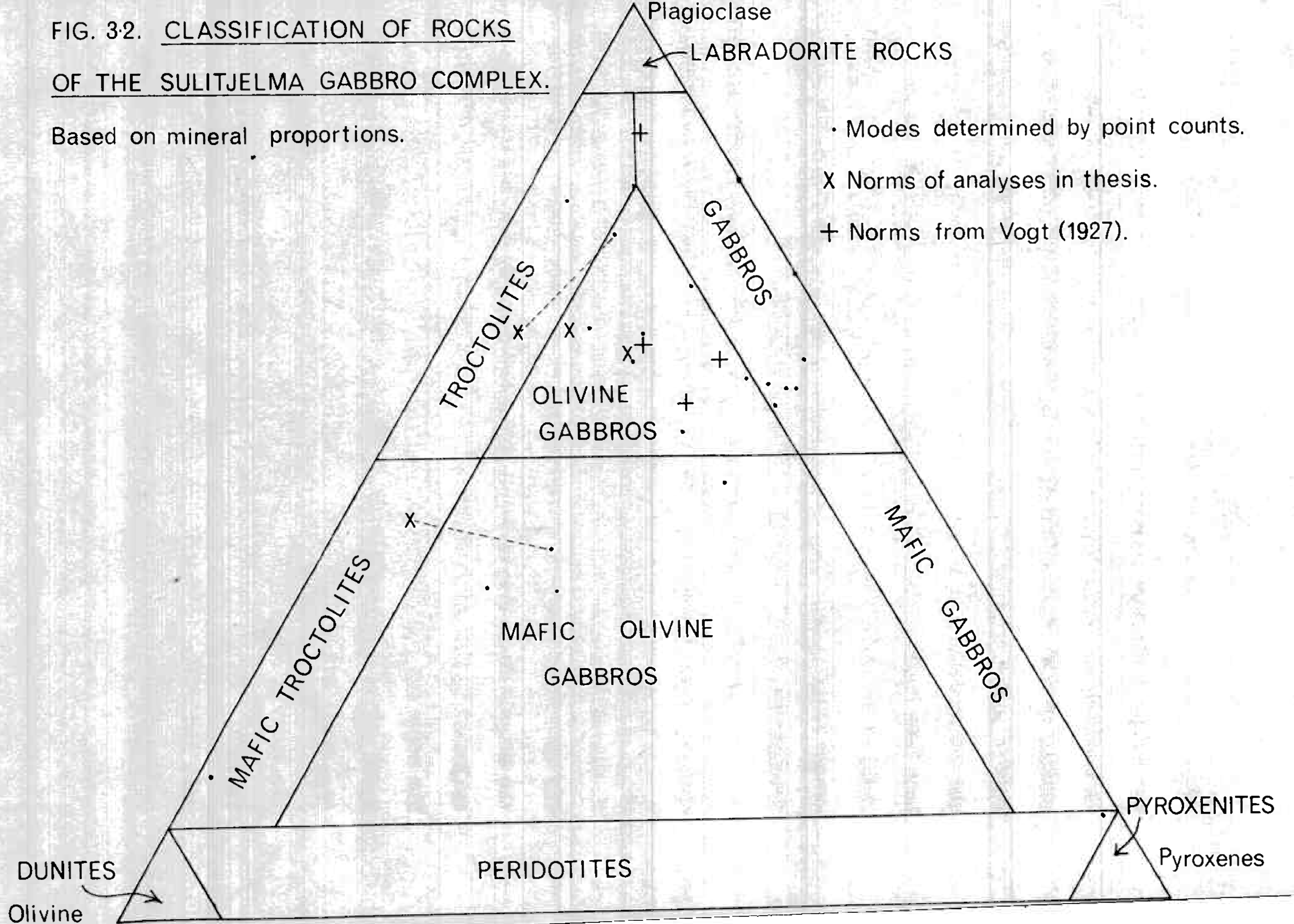
amount of brown hornblende. The status of this mineral as a primary crystallisation product or as a product of post-consolidation alteration is not certain. The writer favours the second view, while Vogt supported the first. The relative proportions of the mineral phases vary greatly, often within a short distance, and it is this mineral variation which produces the banding described in chapter 2.

The rocks of the Sulitjelma gabbro complex are "cumulates" as defined by Wager, Brown and Wadsworth in 1960. The field evidence for the formation of the banding of the complex by the settling of crystals has already been presented (p. 40). Textural evidence for crystal accumulation can be seen in many thin sections. Igneous lamination of tabular felspars is particularly well shown in slide T138, fig. 3.1. There has been a little intercumulus growth of the plagioclase crystals indicated by slight zoning with a more sodic rim. This growth, while greater than that described by Wager et al. in the cumulative gabbros from the Skaergaard intrusion, is still probably small enough for the rocks to be described as "orthocumulates" in their classification scheme for cumulative rocks. The other common cumulus mineral, in addition to plagioclase is olivine, and pyroxenes are also found as cumulus minerals in the more mafic rocks.

The plagioclase crystals are tabular in habit and in thin section perpendicular to the plane of igneous lamination have a rectangular appearance about 1½ mm. long and ½ mm. across. Cumulus olivine appears as slightly smaller grains, usually rounded. Frequently

FIG. 3·2. CLASSIFICATION OF ROCKS OF THE SULITJELMA GABBRO COMPLEX.

Based on mineral proportions.



the original olivine crystals have been granulated by post-consolidation deformation and their outline modified by the growth of kelyphitic borders so that it is not possible to determine their original shape. Cumulus pyroxenes, both ortho and clino, form stumpy prismatic grains. The intercumulus clinopyroxene forms large ophitic crystals. These have been found in thin section up to about 1 cm. across and in the field up to several cms. across. The intercumulus pyroxene also forms grains fringing olivine. Plagioclase apparently crystallised from the intercumulus liquid onto the cumulus crystals.

In this account the rocks have been classified by the relative abundances of plagioclase, olivine, and pyroxenes plus brown hornblende, in accordance with the scheme shown in the triangular diagram fig. 3.2. On this diagram the modes of 21 specimens of unmetamorphosed rocks from the Sulitjelma gabbro complex are plotted and recalculated to 100% of the components in the corners of the diagram. 19 of these rocks were collected by the writer and two are from the Harker slide collection. The modes are listed in appendix 2 and are based on point-counts of 2,000 points for each specimen. The spread of the plotted points on fig. 3.2 gives an indication of the variation in mineral composition of the rocks of the gabbro complex, but the figures should be treated with caution. In many of the rocks kelyphitic borders round olivine are well developed. The modes have been corrected to allow for this and to represent as closely as possible the original mineral composition, on the assumptions concerning the formation of the kelyphitic borders which are given in chapter 4, p. 97.

C.I.P.W. norms of rocks analysed by the writer and of the analyses quoted by Vogt are also plotted on fig. 3.2. In the two cases where analysed rocks have been point-counted the two corresponding points are joined by a dotted line. It will be seen that the correspondence is not very good. This is probably due to the factors mentioned above, and also to sampling errors as most of the point-counts were performed on one thin section only. C.I.P.W. norms represent weight percentages of minerals of hypothetical composition, but for gabbros which are practically anhydrous and contain minerals with similar specific gravities, and with chemical compositions about the same as those of the C.I.P.W. components, the difference between the norm and mode should not be great.

When these reservations are borne in mind, what does fig. 3.2 show? It appears that only one of the determined modes corresponds to the composition of peridotite, and that falls in an extreme part of the field. Thus it seems that olivine and pyroxene did not accumulate together in large quantities, except when plagioclase was accumulating also. This would suggest that during the crystallisation of the complex olivine + plagioclase, pyroxene + plagioclase or olivine + pyroxene + plagioclase were crystallising, and settling to form a mush of cumulus crystals.

The commonest rock type is olivine gabbro with about 10% olivine, 57% plagioclase and 33% pyroxenes. Rocks with over 80% of pyroxenes, olivine and labradorite also occur, but none have been found with more than 90% of these components, either by Vogt or the present writer i.e. there are no dunites, pyroxenites or "anorthosites" (labradorite rocks) in the commonly accepted usages of these terms.

The reason for describing the rocks of the Sulitjelma complex as gabbros rather than norites is succintly stated by Vogt (p. 284) :-

"In spite of the fact that all these rocks contain hypersthene I have counted them as olivine gabbros and not as olivine norites. For hypersthene is found in noticeably smaller proportions than diallage and often there is only a minute trace present. The boundary between the gabbros and the norites must in all cases be set at a somewhat higher hypersthene content than is present here."

While a few specimens do show more ortho than clinopyroxene, this statement certainly holds good for the great majority of the rocks of the gabbro complex.

As was mentioned earlier (p. 41) a narrow zone just inside the contacts of the complex is not banded. This zone is often obscured by metamorphism, but where fresh rocks are present they seem to be rather troctolitic gabbros (e.g. S96, T158, T39). These rocks are not fine grained and cannot be said to represent a chilled margin to the complex. The two chemical analyses performed on these rocks (appendix 2) are different from one another. The only fine grained marginal facies found is represented by specimen T136. This is a fine grained doleritic rock with granular plagioclase, clinopyroxene, green and brown hornblendes forming by alteration of the pyroxene, abundant ore and appreciable apatite. The rock was described in the field as a hornfels and was collected within a metre of the contact. It has not been chemically analysed, but the presence of apatite as a major mineral, and the presence nearby of a similar rock with pyroxene rich patches (which may be fragments of partially assimilated country rock) suggest that it should not be regarded as a sample of the parental magma of the complex.

2. Igneous Mineralogy.

1. Plagioclase.

Plagioclase is the most abundant mineral in the Sulitjelma gabbro complex. When apparently unaffected by metamorphism its composition varies in the range An_{60}-An_{75}. The crystals are slightly zoned, the borders having an anorthite content up to about 5% lower than the cores. Complex twinning is characteristic of the plagioclase crystals, and during routine petrographic examination of thin sections of the gabbro it proved possible to perform plagioclase determinations using extinction angles to the twin planes in Carlsbad-albite twins and the table in Tröger (p. 102). The alpha refractive indices of some plagioclases which had been separated as powders were determined, using the technique outlined in Deer, Howie and Zussman, Volume 4, p. 131.

Specimen	alpha R.I.	Mol. % anorthite
S6 (unaltered portion)	1.5606 ± 0.003	64 ± 4
S6 (altered portion)	1.5606 ± 0.003	64 ± 4

TABLE 3.

Chemical analyses of plagioclases from S96 and T15.

	S96	T15
SiO_2	50.65	56.80
Al_2O_3	31.93	27.46
Fe_2O_3	0.00	0.14
FeO	0.24	0.07
CaO	14.07	9.71
Na_2O	3.88	5.53
K_2O	0.05	0.08
TiO_2	0.07	0.05
Total	100.89	99.17

Proportions of cations on a basis of 32 (0).

	S96	T15	
Si	9.163	10.197	
Al	6.806	5.810	
Fe^{3+}	0.0	0.019	
Fe^{2+}	0.036	0.011	
Ca	2.726	1.867	
Na	1.360	1.924	
K	0.011	0.017	
Ti	0.009	0.006	
Albite	33.2	50.5	Molecular %
Anorthite	66.5	49.0	Molecular %
Orthoclase	0.3	0.4	Molecular %
Albite	31.9	49.1	Weight %
Anorthite	67.8	50.5	Weight %
Orthoclase	0.3	0.4	Weight %
	1.5640	1.5569	
(calculated)	1.5670	1.5608	
	1.5706	1.5654	

Specimen	alpha R.I.	Mol. % anorthite
S96	1.5640 ± 0.003	71 ± 4
S152	1.5665 ± 0.003	77 ± 4
S174	1.5577 ± 0.003	58 ± 4
T144	1.5619 ± 0.003	67 ± 4
T202	1.5630 ± 0.003	70 ± 4

The high value of the anorthite content of the plagioclase from S152 was confirmed by the Carlsbad-albite twin determination.

One separated plagioclase from specimen S96 was fully analysed chemically. The analysis, with a calculation of the unit cell contents is given in table 3, along with the analysis of plagioclase from a metagabbro (T15). A Universal stage examination was made of the plagioclase in the very labradorite rich gabbro S174. Crystal grains were studied by the Rittmann zonal method and the Faderov method, with the following results :-

No. of crystal	Twin Laws present	Composition (assuming low-temperature optics)	Method of examination
1.	Albite	An_{59}	Rittmann
	Ala A.	An_{61}	
2.	Albite	An_{65}	Rittmann
	Acline A	An_{68} *	
	Manebach		
3.	Albite	An_{67}	Rittmann
	Pericline	An_{69}	
	Ala A.		

No. of crystal	Twin Laws present	Composition	Method of Examination
4.	Albite	An_{45}*	Federov
	Ala A.	An_{68}	
		An_{60}	
		An_{60}	

(Determinations marked * are not very accurate).

The study of crystal 4. also showed that the positions of the principal vibration directions lay nearer the curves for plagioclase in the low structural state. Values obtained for $2V_\gamma$ were 82°, 81°, 79½° and 83½°. This suggests a composition about An_{65} for plagioclase in the low structural state. The pericline twins are wedge-shaped at the edge of the crystal, and may well be deformation lamellae. See fig. 3.1.

X-ray diffractometer scans were made of separated powders in $CuK\alpha$ radiation, and the values of the angular separations

$\Gamma = 2\theta(131) + 2\theta(220) - 4\theta(\bar{1}31)$ and $B = 2\theta(1\bar{1}\bar{1}) - 2\theta(\bar{2}01)$

(Smith and Gay 1958) were determined.

Specimen	Γ	B	Wt. % An based on value of Γ. (Low structural state)
S96	1.002	0.822	69
S6 unaltered portion	0.882	0.870	65
S6 altered portion	0.814	0.848	64
S8	0.653	0.836	61
S93	0.773	0.848	63

If the weight percentage anorthite obtained by chemical analysis for S96 (67.8%) is used on the figures in Smith and Gay (fig. 1 p. 749, fig. 2. p. 754) the values lie very close to the curve they obtained for Γ against composition in low structural state plagioclases. This curve was plotted largely on the basis of data from analysed plagioclases from the Stillwater and Skaergaard layered basic intrusions. The B value also lies near the low temperature curve.

The plagioclases have undergone alteration, even in gabbros which retain the mineralogy and texture of primary igneous precipitates. Clouding is almost universally present and the small amount of iron and titanium appearing in the chemical analysis of S96 may well partly be from exsolved ore in the plagioclase. The clouding is due to minute specks of ore. Sometimes these are rod like with a marked preferred orientation in the crystals, sometimes they are granular, and sometimes they are rod like but run in random directions. Many grains are strained. It has been mentioned already that some pericline twin-lamellae may be due to strain, but in addition clear evidence of strain is seen as strain-shadows between crossed polars and in the bent albite lamellae which occur in many sections.

The data on plagioclase composition reveals no systematic variation in the gabbro complex. None of the data is very accurate however, and it may be that a systematic variation exists, but has not been detected.

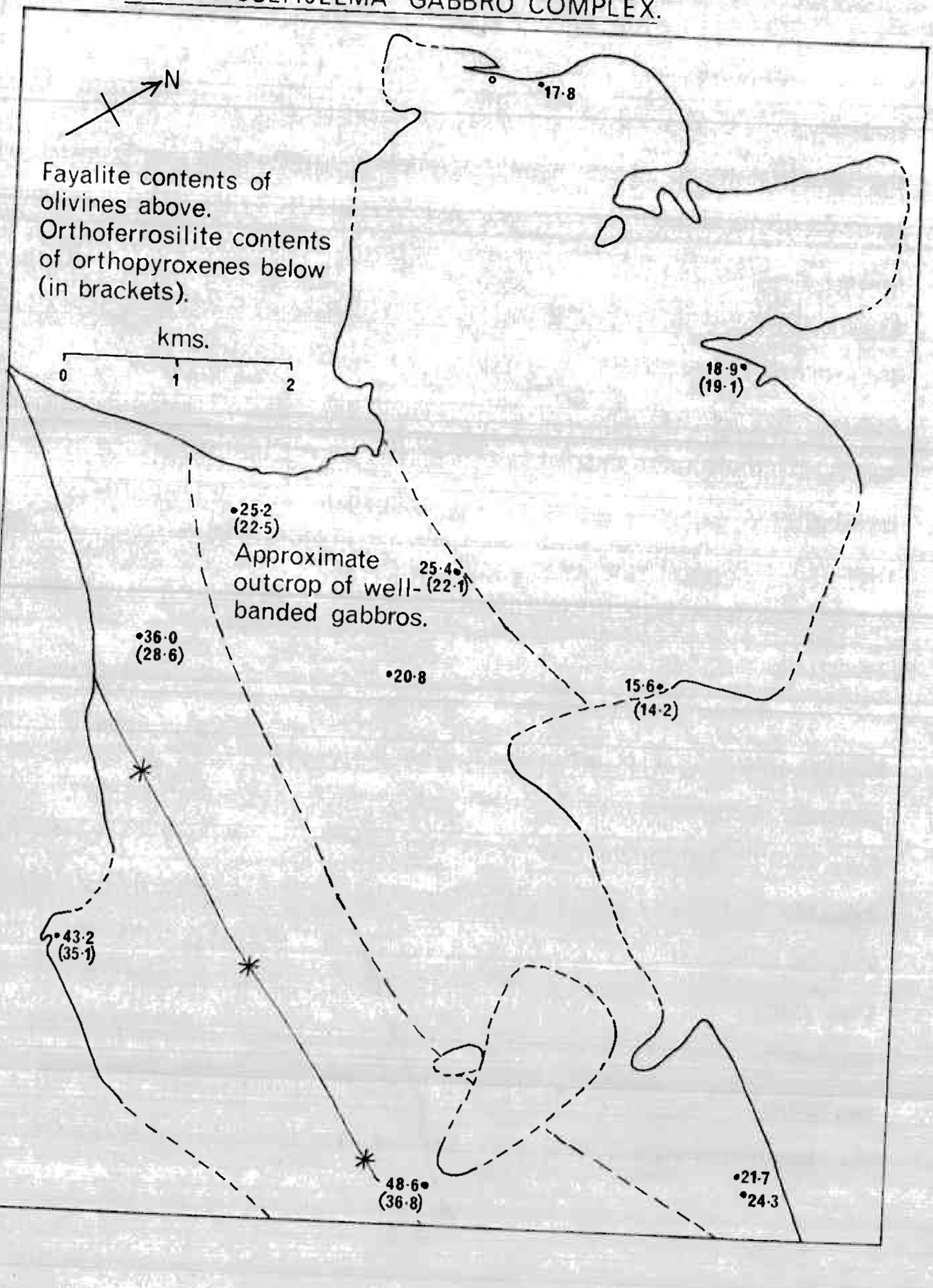
2. <u>Olivine</u>.

Olivine is characteristic of the rocks of the Sulitjelma gabbro complex. It is found in all the unaltered rocks although in some it is only present in small amounts. In a few thin sections it has been pseudomorphed by a fine talc mineral and magnetite but it is not seen altered to serpentine. In most sections it is found as large irregular or tabular grains, often surrounded by kelyphitic borders of hyperstbene and an amphibole-spinel intergrowth. These have been studied in detail, and chapter 4 is devoted to them. The olivine often contains cracks which are filled with granules of ore. Strain shadows are often visible between crossed polars and the original grains have sometimes been broken up into a number of smaller grains.

The olivine is colourless in thin section and golden in hand specimen. Occasionally it shows well-developed {100}, {010} and {001} partings so that the grains may be mistaken for pyroxene at a first glance. Attempts were made to detect cryptic layering in the gabbro complex by looking for variations in the composition of olivine. One method tried was that described by Yoder and Sahama (1957) in which olivine compositions are determined from the d_{130} spacing in the crystal lattice. d_{130} was found from an olivine powder by measuring the Bragg angle of the d_{130} line in the powder pattern in a focussing-crystal X-ray diffractometer, using quartz as an internal standard and Co Kα radiation. The variations found were small, as only olivines from the marginal troctolitic facies and the upper part of the layered series were examined. The results which were obtained on the two specimens of the olivine which were analysed chemically are given in table 5. An attempt was also made to determine the composition of olivine by measuring the optical axial angle 2V, using the Universal stage. This method was also abandoned as the angles were found to lie very close to 90°, and it was not possible to find sufficient suitably oriented grains for accurate determination. As it was considered at this stage that the variation was relatively slight (on the basis of the X-ray data), it was thought that indirect methods of estimating 2V would not be sufficiently accurate to detect it.

In the end it was decided to investigate the variation in olivine composition by means of the electron-probe microanalyser, determining the compositions of the other major ferromagnesian minerals at the same time. Olivines from 11 specimens of rocks from different parts of the gabbro complex were studied. The full results of the microanalysis are listed in appendix 3, with a discussion of the accuracy of the results. Table 4 gives the results in the form of forsterite and fayalite compositions, after corrections have been made for various systematic errors in the analysis, which are discussed in appendix 3. The writer would like to acknowlege here the assistance of Dr. S.J.B. Reed and Mrs. P.K. Mason of the Natural History Museum, who performed these corrections using an I.B.M. 7090 computer.

FIG. 3·3. VARIATION IN COMPOSITION OF OLIVINE & ORTHOPYROXENE IN THE SULITJELMA GABBRO COMPLEX.



Three of the analysed olivines are from the marginal troctolitic facies and are appreciably more magnesian than those from the layered series. Olivines from the layered series have been listed in order of increasing iron content, and it can be seen that there is quite a marked variation, from 20.8 to 48.6 molecular % fayalite. In figure 3.3 the locations are shown of the specimens in which olivines were analysed along with the fayalite contents of the olivine in each specimen and also the orthoferrosilite content of the orthopyroxene under the fayalite content in brackets. Despite the field evidence that the banding of the gabbro complex "youngs" northwards, the olivines become more iron rich to the south. This anomaly will be discussed in more detail when the variation in the other ferromagnesian minerals has been described.

Determinations were made in the cores and borders of large olivine grains in some specimens to detect any zoning that might be present. Relatively little zoning was found, and that is always normal i.e. with Fe increasing, and Mg decreasing outwards (table 4). A more detailed examination was made of the zoning in the olivine from specimen S96, in connection with the investigation of the kelyphitic borders. (See chapter 5). Two olivines (S152 and S96) were fully analysed chemically (appendix 2) as a check on the accuracy of the electron-probe analysis. The calculated molecular compositions are given in table 4 for comparison with the electron-probe values, and it can be seen that

TABLE 4.

Electron-probe microanalyser determinations of olivines, listed in order of increasing molecular proportion of fayalite.

Marginal troctolitic facies

	Fa	Fo	No. of determinations
T158	15.6	84.4	3
S96	17.0	83.0	see chapter 4
U67	18.9	81.1	3

Layered series

	Fa	Fo	No. of determinations
S152	20.8	79.2	4
T206	21.7	78.3	6
T204	24.3	75.7	4
T12	25.2	74.8	3
T150	25.4	74.6	3
T74	36.0	64.0	3
T101	43.2	56.8	4
T191	48.6	51.4	3

Zoning in olivines

Fayalite contents in core and margin

	Core	Margin
T158	15.4	15.6
S152	19.7	21.9
T150	25.1	26.3
T101	43.8	44.2

Additional data on 2 olivines :-

Chemical analysis (see appendix 2)

	S96	T152
Forsterite	82.0	79.5
Fayalite	17.8	20.0
Mn_2SiO_4	0.2	0.3
Ca_2SiO_4	trace	0.2
d_{130}	2.779	2.781
composition on this basis	Fa_{20}	Fa_{22}
2V	87°	-

agreement is good.

3. Clinopyroxene.

Vogt described the clinopyroxene of the Sulitjelma gabbro complex as "diallage", presumably because it has a very well developed {100} parting. It is an augite containing an appreciable amount of titanium (though not sufficient to merit description as a titan-augite) which gives it a faint purplish colour in thin section. The grains are ophitic in habit and little zoned. Exsolution lamellae appear parallel to {100} emphasising the diallage parting. They show straight extinction between crossed polars and a lower birefringence than the surrounding augite, and are probably orthopyroxene. The augite also contains exsolved plates of translucent ore. These lie in the {100} and {110} planes and tend to be rectangular in outline with the edges of the rectangles parallel and perpendicular to the [001] direction. The augite has extinction angles up to about 40° in sections in the prism zone.

The variation in the compositions of the clinopyroxenes from different parts of the gabbro complex has been studied by means of the electron-probe microanalyser. Difficulty was experienced with the calcium determinations in many specimens, due to a lack of reproducibility of standard counting rates, and so relatively few acceptable analyses were obtained. These are listed as molecular proportions of clinoenstatite, wollastonite and ferrosilite along with the

TABLE 5.

Electron-probe determinations of pyroxenes.

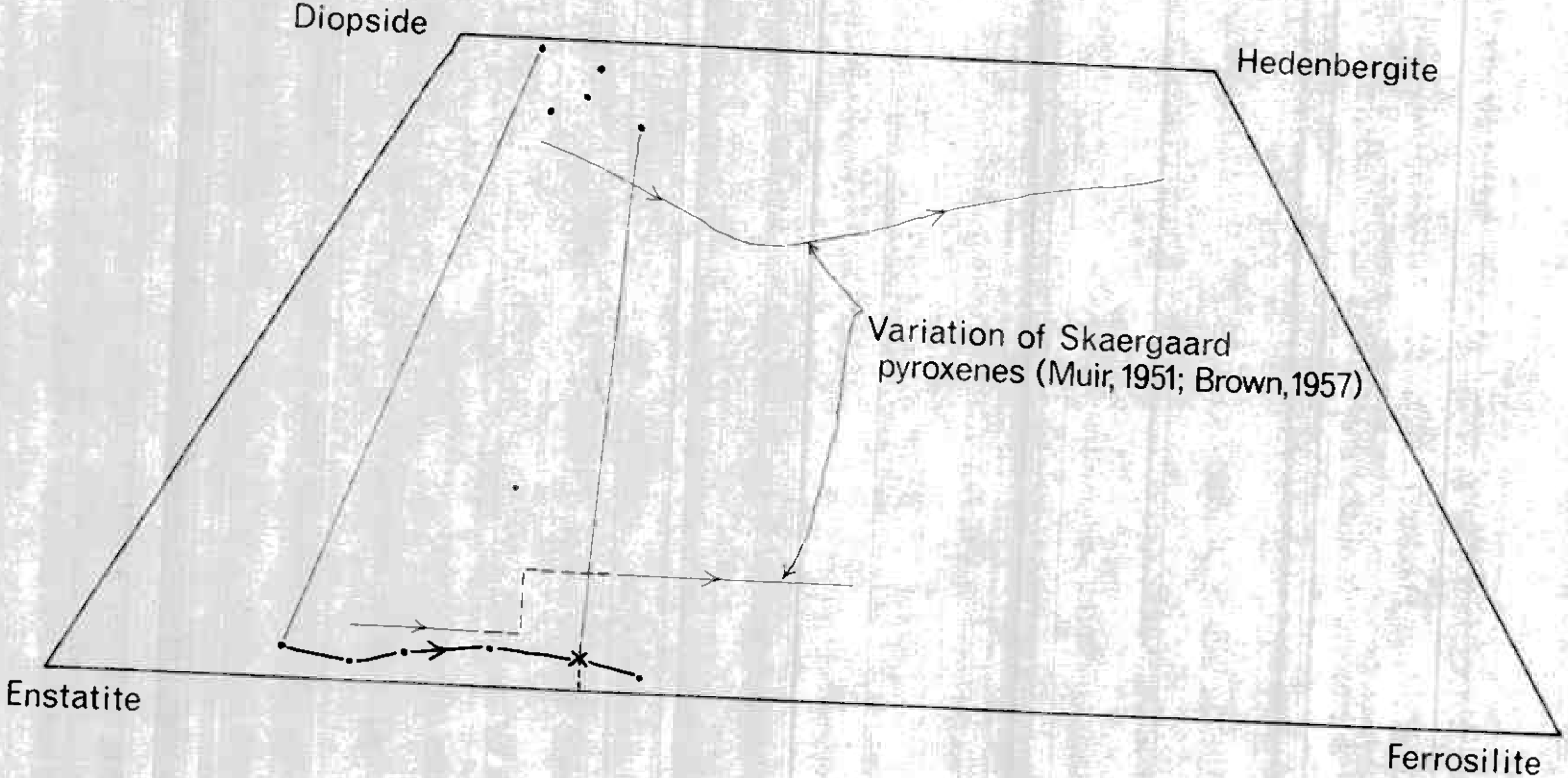
1. Clinopyroxenes.

	Fs.	Wo.	Clinoens.
Marginal troctolitic facies:-			
T158	5.9	49.3	44.8
Layered series:-			
S152	9.0	44.4	46.6
T206	10.9	45.5	43.6
T204	10.5	47.9	41.6
T101	15.6	43.4	41.0

2. Orthopyroxenes.

	Intercumulus			Kelyphitic		
	Ofs.	Wo.	Ens.	Ofs.	Wo.	Ens.
Marginal troctolitic facies:-						
T158	14.2	2.2	83.6			
S96				16.7	0.3	83.0
U67	19.1	1.5	79.4	21.1	0.2	78.7
Layered series:-						
T12	22.5	2.3	75.2			
T150	22.1	2.8	75.1	23.7	0.3	76.0
T74	28.6	3.0	68.4			
T101	35.1	n.d.	64.9	25.9	0.4	73.7
T191	38.9	1.0	60.1			
Cumulus orthopyroxene:-						
T191	36.8	3.9	59.3			

FIG. 3·4. VARIATION OF PYROXENES



orthopyroxene analyses in table 5. In figure 3.4 the compositions of ortho and clinopyroxenes are plotted on a conventional diagram. Two pairs of pyroxenes coexisting in the same rock are joined by lines. It can be seen that the variation in the clinopyroxene is less than that in the olivine and orthopyroxene, mainly because of its relatively smaller iron and magnesium content. The iron to magnesium ratio varies in the same way as that in the olivines and orthopyroxenes. The clinopyroxenes contain between 0.5 and 2.2 weight % TiO_2 and up to 7.5% Al_2O_3. The full analytical results are given in appendix 3.

Ophitic crystals of clinopyroxene may sometimes entirely enclose plagioclase laths, which are distinctly smaller than the laths forming the main part of the rock, as shown in fig. 3.5 drawn from specimen T76. The crystals are occasionally granulated, so that what was once a large ophitic crystal now consists of numerous small crystals but retains its original outline. The clinopyroxene is frequently associated with brown hornblende, and has undergone alteration to fibrous amphibole in the metagabbros.

4. Orthopyroxene.

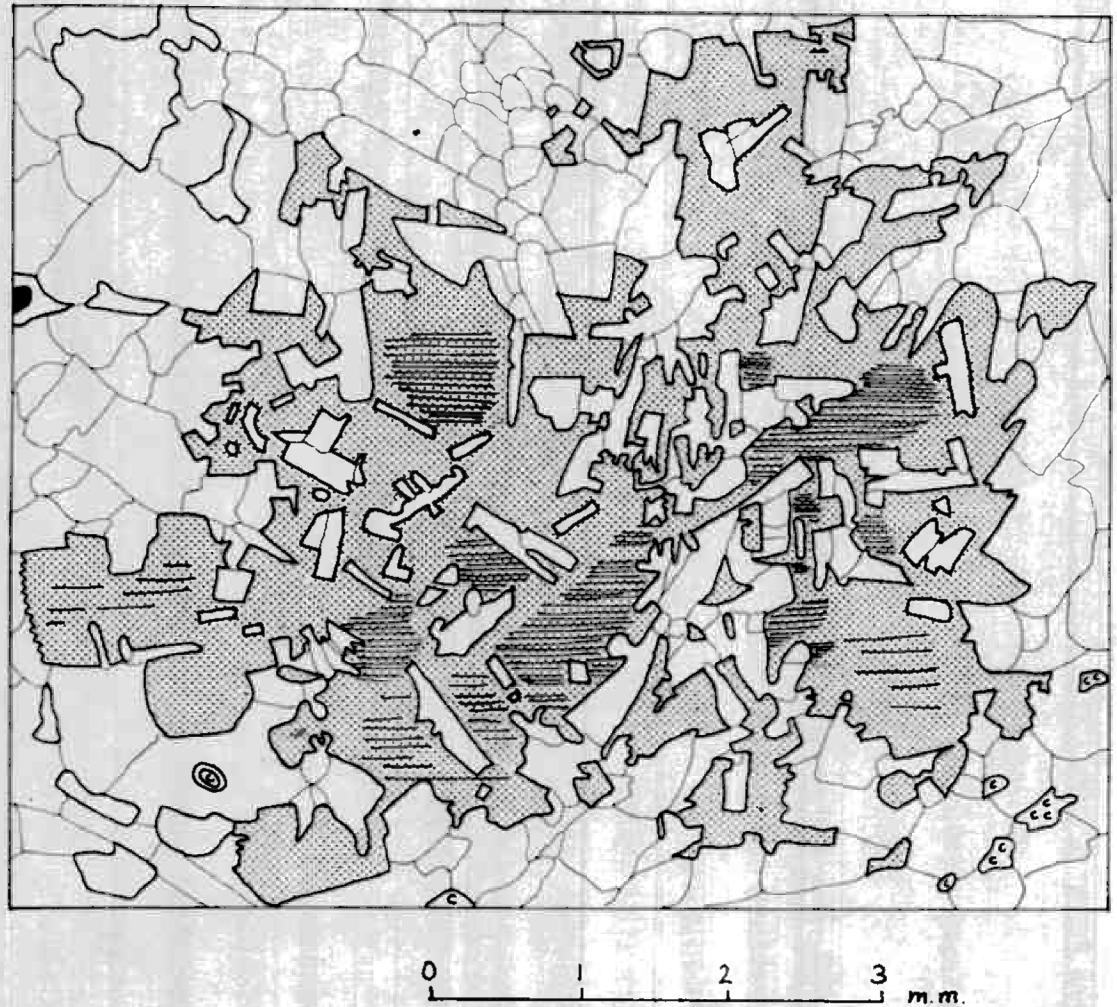
The orthopyroxene present in the rocks of the gabbro complex occurs in three distinct textural varieties (fig. 3.6) :-

1. Cumulus orthopyroxene, occurring as stumpy prismatic grains often with exsolution lamellae of clinopyroxene. This is only found in the more mafic rocks. Sometimes the grains show slight pleochroism.

FIG. 3·5.

Ophitic augite from S152.

x 10



2. Intercumulus orthopyroxene which often mantles olivine. It is sometimes difficult to distinguish from the orthopyroxene in the kelyphitic borders round the olivine but usually consists of larger grains and forms a much wider border to the olivine.

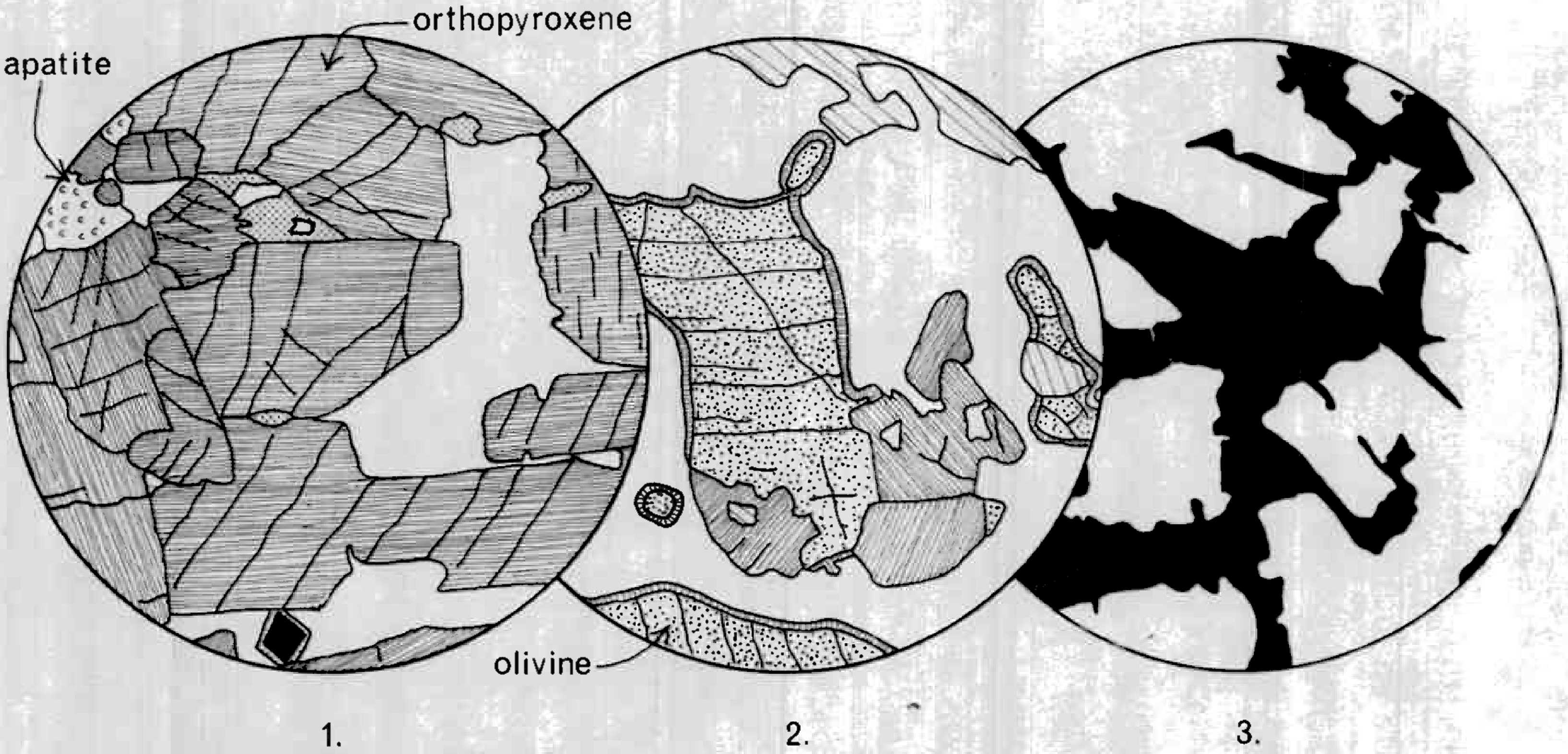
3. The orthopyroxene in the kelyphitic borders. This is not a primary mineral.

The exsolution lamellae of clinopyroxene appear parallel to {010} but are only found in type 1. The orthopyroxene often also contains exsolved plates of ore similar to those observed in the clinopyroxene. In many gabbros orthopyroxene is absent or very rare. The proportion seems to increase with the total proportion of ferro-magnesian minerals in the rock. Like the other primary minerals, orthopyroxene shows the effects of deformation after consolidation as strain shadows or bent or granulated crystals.

Electron-probe microanalysis showed the same trend of iron enrichment in orthopyroxenes as in olivines and clinopyroxenes, and also distinguished clearly the three textural varieties of orthopyroxene described above, by their different calcium contents. Cumulus orthopyroxene was only present in specimen T191 of those selected for analysis, but in this specimen the wollastonite content of the cumulus orthopyroxene is much higher than that of the intercumulus orthopyroxene (table 5). The majority of the analyses in table 5 are of intercumulus orthopyroxene, but where analyses are available of kelyphitic

FIG. 3.6.

Textures in orthopyroxene and ore.



1.	x 25	T191	Cumulus orthopyroxene.
2.	x 65	T12	Orthopyroxene mantling olivine.
3.	x 25	S174	Intercumulus pyrrhotite.

orthopyroxene these are listed alongside. In all cases the kelyphitic orthopyroxene has only a fraction of a percent of the wollastonite component whereas the intercumulus orthopyroxene has over 1%.

The compositions of intercumulus orthopyroxenes have been plotted on the conventional diagram in fig. 3.4.

5. Ore and accessory minerals.

The ore mineral of the Sulitjelma gabbro complex is pyrrhotite. It was determined by electron-probe microanalysis (the results of these determinations have not been corrected and so can only be regarded as semi-quantitative) and by a brief examination in reflected light of polished thin sections. It often shows a distinct intercumulus habit, for example in specimen S174, a labradorite-rich gabbro from the layered series (fig. 3.6). The other accessory mineral is apatite.

Cryptic layering.

The electron-probe data on the iron to magnesium ratios of the ferromagnesian minerals makes it clear that in addition to the primary layering visible in the field the Sulitjelma gabbro complex displays cryptic layering. Wager and Deer (1939) defined cryptic layering as being displayed in the layered series of the Skaergaard intrusion in two ways :-

1. By the variation in the composition of minerals which show continuous variation between two or more end-members, from higher temperature forms in the lower, earlier crystallised, portion of the

intrusion, to lower temperature forms higher in the intrusion.

2. By the appearance and disappearance at particular levels in the layered series of a mineral species.

Cryptic layering of the first type is displayed by the Sulitjelma gabbro complex, that of the second is not. In fig. 3.4 the comparison of the trends of composition variation in the Skaergaard and Sulitjelma intrusions shows that the variation in composition is far more marked at Skaergaard than at Sulitjelma. In both cases the trend is from more magnesian minerals to more iron rich, and this trend appears in many other layered gabbros. Limited iron-enrichment on the Sulitjelma scale is far commoner than extreme iron enrichment of the Skaergaard type.

There can be little doubt therefore, that the rocks with more iron rich minerals at Sulitjelma crystallised later than those with more magnesian minerals. The fact that the most magnesian olivines, orthopyroxenes and clinopyroxenes at Sulitjelma come from the marginal troctolitic facies confirms this. It is on this basis that the way-up indications from the banding seen in the field are rejected. However, the pattern of mineral variation in the layered series is not simply that the mineral become more iron rich to the S. For example, the minerals in the gabbro from Vaknacokka in the extreme south (lower left of fig. 3.3) are appreciably less iron rich than those in the pyroxenite from the summit of Suliskongen (centre bottom of fig. 3.3). But field evidence suggests that the banding at both these places dips gently or is horizontal, and the specimen from Suliskongen comes from a higher altitude (1914 m.) than that from Vaknacokka (about 1600 m.). If the structure proposed earlier for the gabbro complex (N-S section in map pocket) is correct, the difference in altitude approximately represents the difference in "stratigraphical" level in the layered gabbro complex of the two specimens. It seems possible that the impressive south face of Suliskongen may display a vertical section through much of the gabbro complex, but even to reach the foot of this face would be quite a difficult feat of mountaineering.

3. Deuteric or early post-magmatic alteration.

Effects due to early post consolidation alteration of the gabbro complex include :-

(a) Clouding of plagioclase.

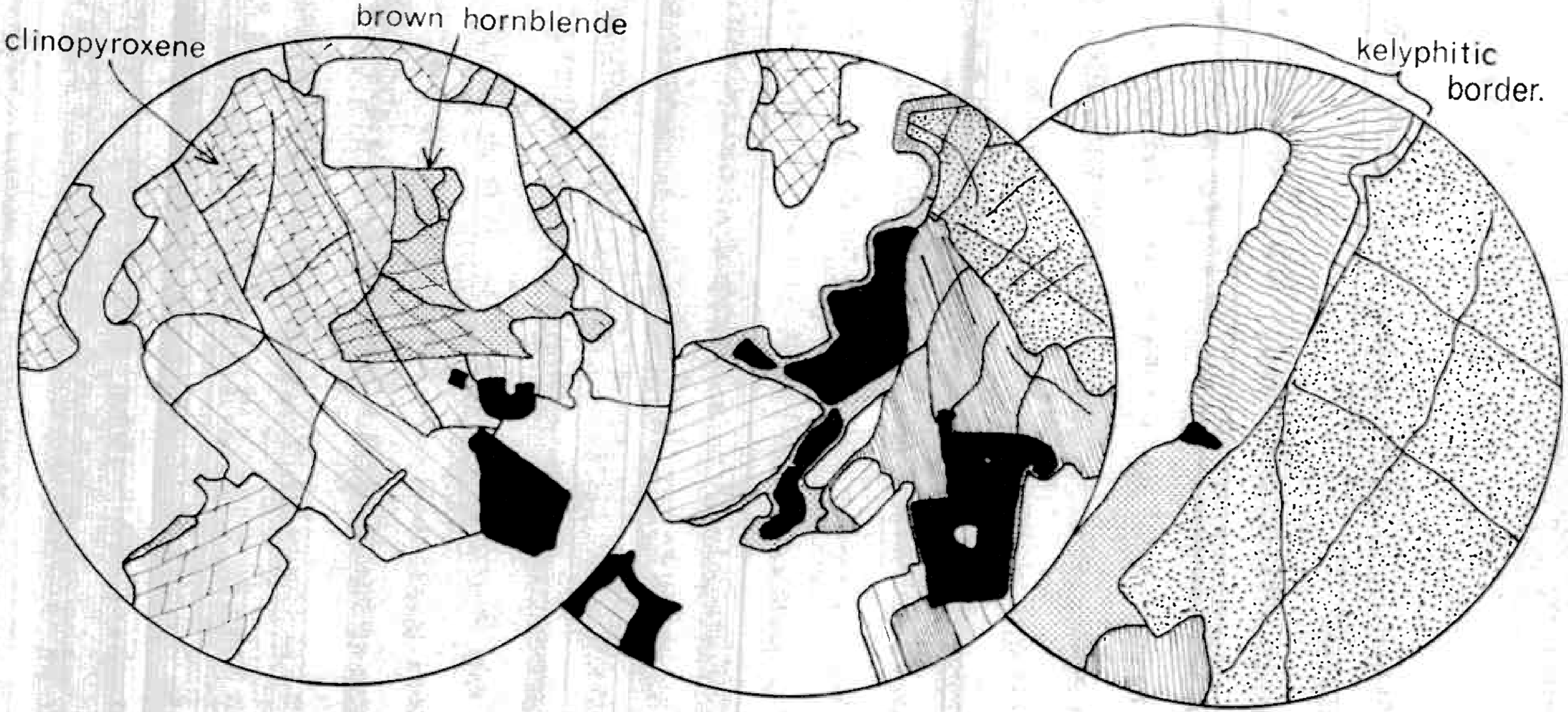
(b) Formation of kelyphitic borders round olivine.

(c) Formation of brown hornblende.

The first has been adequately discussed in the section on the plagioclase, and the second is the subject of the next chapter of the thesis. The formation of brown hornblende will be discussed here. There has been some doubt whether brown hornblende formed as a primary igneous precipitate or as an alteration product of olinopyroxene after consolidation. Alteration would involve the introduction into olinopyroxene of soda, titania and potash, and the removal of silica and lime. Brown hornblende is also found in association with orthopyroxene.

FIG. 3.7.

Textural relationships of brown hornblende (stippled).



1. 2. 3.

1. x 140 S152 Brown hornblende with its c-axis parallel to that of clinopyroxene.

2. x 65 T101 Brown hornblende forming rim round pyrrhotite.

3. x 400 T101 Relationship between brown hornblende and kelyphitic border.

Vogt gives a good description of its pleochroic scheme and optical properties (p. 289-290).

The brown hornblende most often occurs as patches fringing pyroxene crystals and as rims round ore grains (fig. 3.7 and fig. 3.6, drawing 1). Sometimes the brown hornblende grows with its c crystallographic axis parallel to the c-axis of the clinopyroxene, and with the ac planes also parallel (fig. 3.7). It occurs as large grains in the gabbro pegmatites occasionally found in the gabbro complex, in which it often encloses plagioclase and pyroxene crystals. A rock (T179) was found consisting of brown hornblende, hyperesthene and labradorite only. Its texture resembled that of a hornfels and it was found in an area where hornfelses and igneous breccias are common. The hornblende was separated from the rock and analysed (table 10). Brown hornblendes from different parts of the gabbro complex were analysed by the use of the electron-probe microanalyser (appendix 3).

Fig. 3.7, drawings 2 and 3 show the relation between brown hornblende rimming pyroxene (in this case orthopyroxene) and the kelyphitic border of the olivine. The brown hornblende appears to be continuous with the outer amphibole-spinel intergrowth border round the olivine. This suggests that some brown hornblende at least formed at the same time as the kelyphitic borders and electron-probe data will be given later (chapter 4) which suggest that these formed by solid-state reaction after the consolidation of the gabbro.

The formation of the brown hornblende occurred before the amphibolitisation of the gabbro complex along shear planes and in the SW corner. The green hornblende formed by this amphibolitisation occasionally has brown hornblende in its core whereas brown hornblende is never found mantling green hornblende.

The information concerning the time of crystallisation of the brown hornblende may be summarised as follows :-

1. The hornblende frequently rims clinopyroxene with an intercumulus habit.

2. It is found in gabbro pegmatite veins.

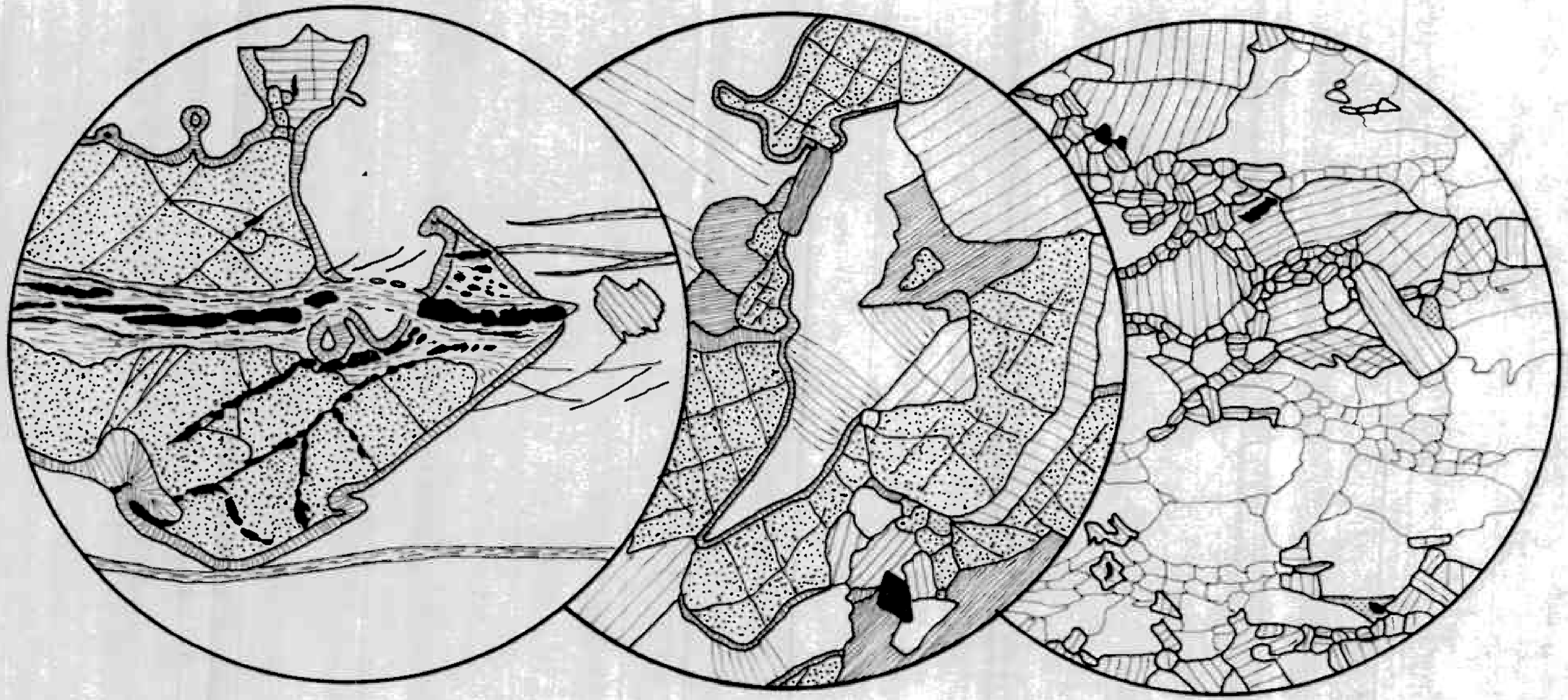
3. It seems to be associated in some thin sections with the formation of kelyphitic borders round olivine.

4. It is mantled by the green hornblende formed during the metamorphism of the gabbro complex.

These observations suggest that the formation of the brown hornblende dates from a late stage in the crystallisation of the gabbro complex. Residual liquid was still present and was segregated into veins to form the gabbro pegmatites. Possibly in the consolidated parts of the complex reaction between olivine and plagioclase produced the kelyphitic margins while residual fluid permeating along grain boundaries altered small patches of pyroxene to brown hornblende. The chemistry of the brown hornblende will be discussed in appendix 1 when it is compared with the green hornblende found in the metamorphosed gabbros.

FIG. 3·8.

Cataclastic alteration of gabbros.



1. 2. 3.

1. x 25 T68 Fracture accompanied by alteration of olivine to talc and magnetite, disrupting kelyphitic borders.

2. x 65 T168 Localised fracturing of plagioclase.

3. x 65 T151 Sheared gabbro (N.B. plagioclase crystals are outlined in this drawing.)

It is interesting to note here that Herz (1951) considers the brown hornblende of the Baltimore gabbro complex, Maryland, U.S.A. to have formed in a deuteric episode with temperatures at about 800°C, whereas Williams in his original account (1886) considered it to be a product of primary crystallisation. However Herz goes further and considers the uralitised gabbros with green hornblende to be primary igneous products or the result of deuteric alteration during cooling, and rejects the suggestion that the Baltimore gabbro complex has been metamorphosed. The comparison between the Baltimore and Sulitjelma gabbro complexes will be discussed in chapter 7.

4. Cataclastic effects.

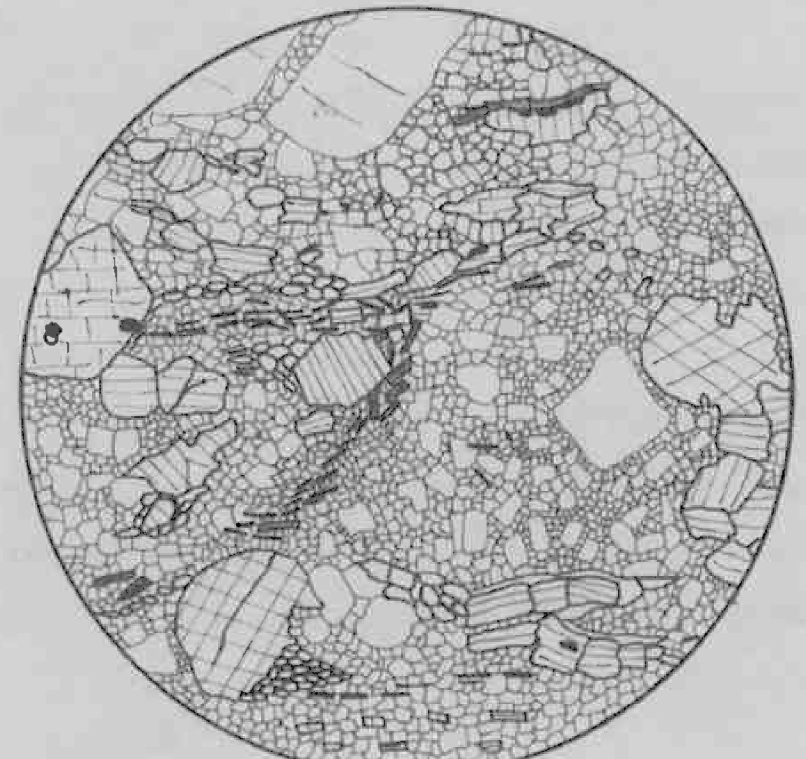
Very few rocks have been examined in which there is not some evidence for post consolidation deformation of the constituent minerals. Strain effects and granulation of minerals have already been described. Small shear zones run through many of the gabbros, showing little or no displacement of the minerals on either side. They are marked by particularly finely ground minerals and sometimes by alteration of pyroxenes to fibrous amphiboles and of olivine to talc and magnetite (fig. 3.8, 1). Some rocks display more severe deformation, still without the appearance of new mineral phases, and have a completely granular texture with clots of olivine or pyroxene grains representing the original larger crystals of those minerals. One locality where such effects are particularly marked is the col (g.r. 553513) where lensing out of pyroxene

FIG. 3·9.

1. Sheared gabbro, as seen in the field (g.r. 552513).

2. Gabbro mylonite (plagioclase grains outlined).

x 65 T8 There is a small amount of biotite in the rock.



crystals can be seen on the rock surface in the field (fig. 3.9, 1). Catasclastically altered gabbros are also found near the southern contact with the dioritic gneiss on Vardetoppen, Stortoppen and Vaknacokka. The most strongly deformed rocks become very fine grained and are described as gabbro mylonites (fig. 3.9, 2). They are found near the contacts of the complex in the north and west.

The astonishing thing about this cataclasis is that it has occurred with so little alteration in the mineral species present. The gabbro mylonite in fig. 3.9 contains a little biotite and green hornblende but many cataclastic rocks show olivine, orthopyroxene, clinopyroxene and labradorite only. Since crushing promotes the rate of reation in experimental systems towards an equilibrium assemblage and it can be inferred from the presence of kelyphitic margins that olivine and labradorite were not in equilibrium with one another soon after the consolidation of the gabbro complex, some factor must have prevented reaction occurring. Two possibilities are :-

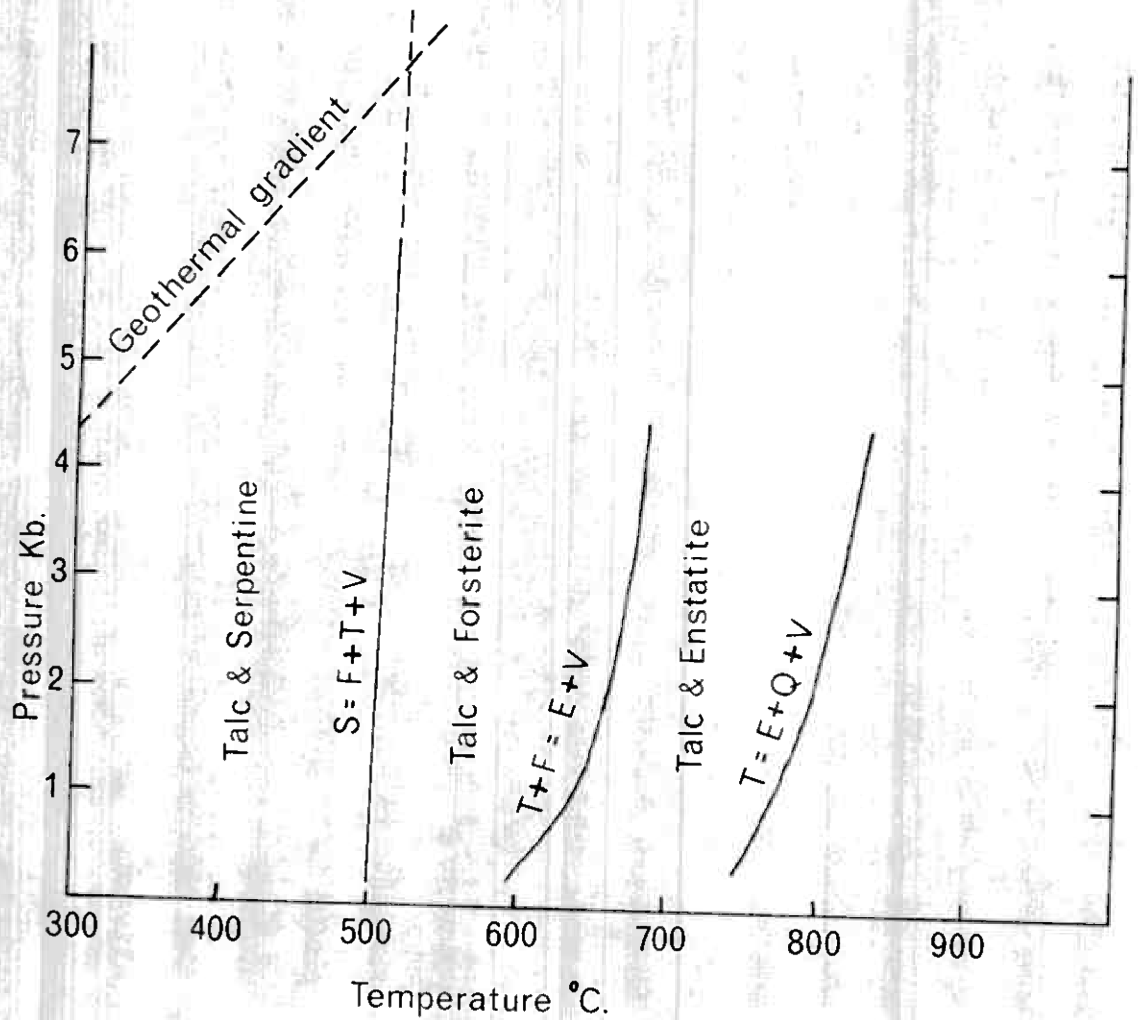
1. When the rocks were crushed, the temperature was relatively low so that reaction rates were so slow that appreciable reaction towards an equilibrium assemblage could not occur in the time available.

2. When the rocks were crushed they were in a dry condition. This would slow reaction rates even at high temperatures and prevent the formation of hydrous phases such as hornblende.

The existence of metamorphism to amphibolite facies in the SW

FIG. 3.10.

Data on the MgO-SiO_2-H_2O system. (Bowen & Tuttle 1949).



corner of the complex, associated with shearing of the gabbro (see p.
suggests that some deformation at least occurred while the gabbro was hot.

The reaction seen in some fractures :-

olivine + water vapour = talc + magnetite

may also give a clue to the temperature at which they formed. As has been stated earlier, the alteration of olivine to serpentine has not been observed, although the possibility remains that some serpentine may be present along with the very fine grained talc. However, assuming that serpentine has not formed, and that the reactions in the magnesium rich phases from the gabbros occurred under conditions comparable with those under which the reactions occur in the iron-free system $MgO-SiO_2-H_2O$, limits can be set in a crude way to the temperature of formation of the cracks, using Bowen and Tuttle's (1949) data.

Fig. 3.10 is a tracing of Bowen and Tuttle's temperature and pressure diagram, showing the two curves representing the maximum stability in the $MgO-SiO_2-H_2O$ system of talc and serpentine. For these phases to be present at all an excess of the silica component over the stoichiometric proportion for forsterite must be present. It is assumed that this is supplied by the breakdown of the fayalite component in the olivine.

From the diagram it can be seen that the lower limit of the possible temperature range over a wide variation in pressure is about 500^oC. The upper limit increases with pressure between about 750 and 850^oC.

These figures must be treated with reserve. The assumptions made are very sweeping. The fayalite content of the olivine cannot be simply regarded as decomposing to provide silica. Strictly speaking the relevant data should be quoted from the four component system $MgO-FeO-SiO_2-H_2O$. As far as the writer is aware synthetic data on this system is not yet available. In such a system an additional variable appears due to the effect of the chemical potential of oxygen on the oxidation state of iron. But bearing this in mind, it seems fair to say that the formation of talc from olivine is not compatible with the crusing of the gabbro at a temperature of 600-700°C.

Prof. H. W. R. Rutland has pointed out to the writer that it is possible that the amphibolitisation of the SW corner of the gabbro complex may have occurred along pre-existing fracture planes, which would provide easy access for the fluids which took part in the metamorphic recrystallisation. This would permit a cold deformation phase before the metamorphism. While this theory accounts for the observed field and microscopic relations, the writer feels that without any further evidence to support it, it should be eliminated by Occam's razor, as it introduces further complexity into the post consolidation history of the Sulitjelma gabbro, which would have to cool and then be reheated during the D_2 metamorphic event.

The writer prefers the theory that the cataclasis took place while the gabbro complex was still hot, and the country rocks were undergoing regional metamorphism to amphibolite facies. This means that the cataclasis of the gabbro can be correlated with Henley's D_2 structural event.

5. Amphibolitisation of the gabbro complex.

This is a very widespread process. The majority of specimens collected from the gabbro complex display some amphibolitisation of pyroxenes. The term "uralitisation" has been applied to describe the alteration of the pyroxenes of gabbros to fibrous amphiboles, having been first used by Williams in 1886 of the gabbros in the Baltimore complex. It has been used occasionally in this account, an in a descriptive sense it is an appropriate term, although there are differences of opinion on whether the process is to be regarded as a deuteric or metamorphic one. The writer prefers the more cumbersome term "amphibolitisation" in that this conveys to the reader more clearly the meaning; alteration of pyroxenes to amphiboles leading in the ultimate case to the formation of amphibolite.

The nomenclature of the more or less amphibolitised rocks from the gabbro complex presented some problems, as a large number of specimens which had undergone various degrees of amphibolitisation had to be classified. The following scheme proved useful for this purpose. The rocks are classified on the basis of :-

1. The proportion of pyroxenes altered to amphibole.
2. The degree to which the original igneous texture is retained.

Amphibolitised gabbros.

These show an appreciable degree of alteration of pyroxene to amphbiole, but pyroxene remains as a greater proportion than 10% of the ferromagnesian minerals.

Metagabbros.

Less than 10% of the ferromagnesian minerals remain as unaltered pyroxene. The rock retains its ophitic texture, the amphiboles pseudomorphing the original pyroxenes and olivine.

Metagabbroic amphibolite.

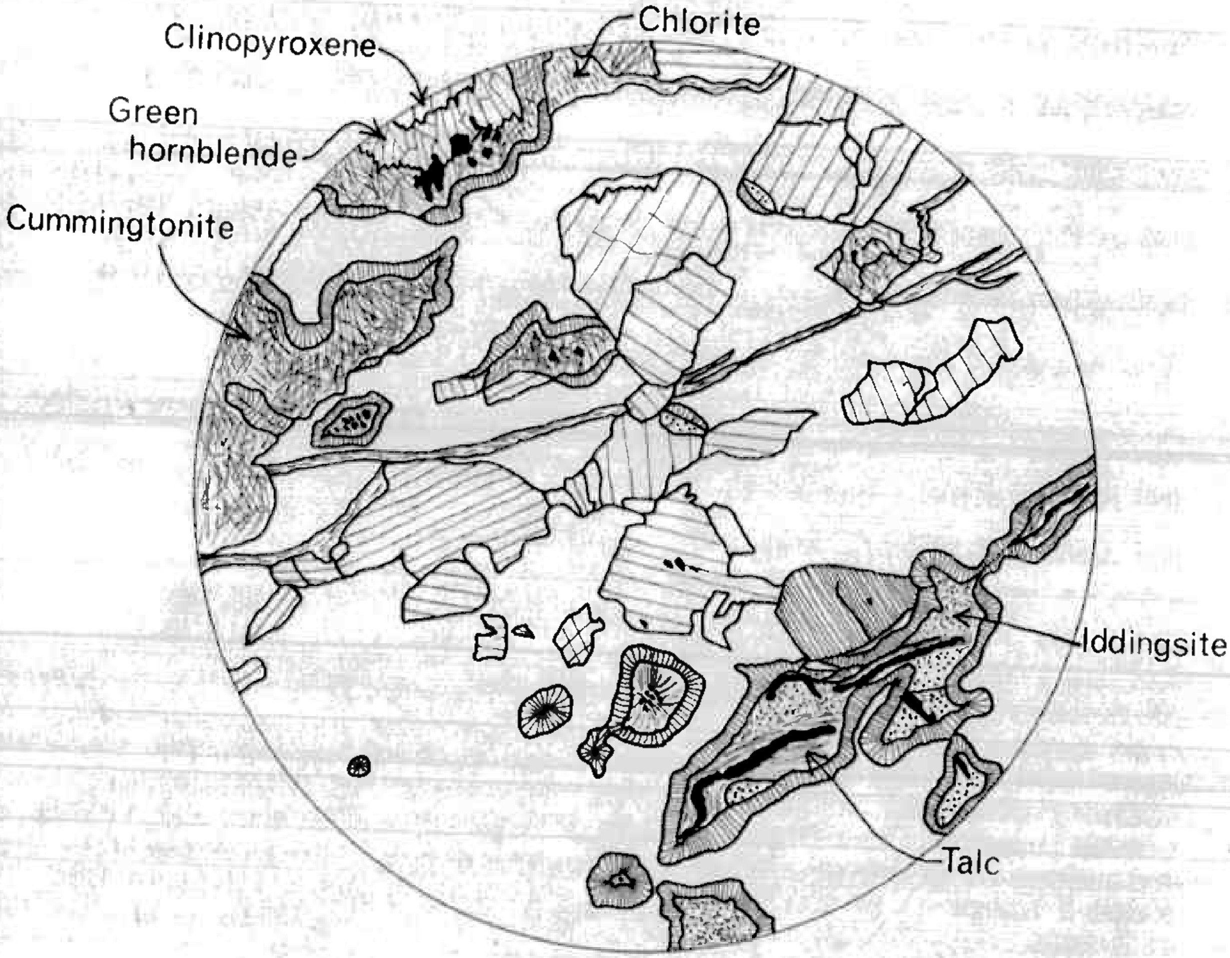
These are amphibole-plagioclase-clinozoisite rocks, which do not show relict ophitic texture. They are still clearly formed from rocks of the gabbro complex. Evidence for this may be an occasional large relict plagioclase lath showing complex twinning or even in some cases merely the location where the specimen was collected. If no evidence of formation from the rocks of the gabbro complex is forthcoming, the non-commital term "amphibolite" is used.

These nice distinctions are important as many of the country rocks surrounding the gabbro complex are amphibolites. It proved possible to distinguish metagabbroic amphibolites from the others in most cases.

Alteration of the minerals of the gabbros.

In many thin sections of amphibolitised gabbro two or more varieties of amphibole can be recognised. Both tend to be fine-grained

FIG. 3·11. AMPHIBOLITISED GABBRO S6.



x 65 S6 In this thin section, three different types of alteration of olivine may be seen. In the upper left it has altered to fibrous cummingtonitic amphibole, in the lower right to magnetite and talc, and also to a brown iddingsitic material. The pseudomorphs after olivine at the top left are surrounded by the relicts of kelyphitic borders, indicating that these formed before the amphibolitisation of the olivine.

and fibrous in the less amphibolitised gabbros. Orthopyroxene is replaced by an optically positive colourless amphibole with oblique extinction between crossed polars, and clinopyroxene by an optically negative pale green amphibole which also has oblique extinction. In metagabbros only one amphibole is present, a green hornblende in coarser aggregates than the fibrous amphiboles of the amphibolitised gabbros. This often contains small blebs of quartz.

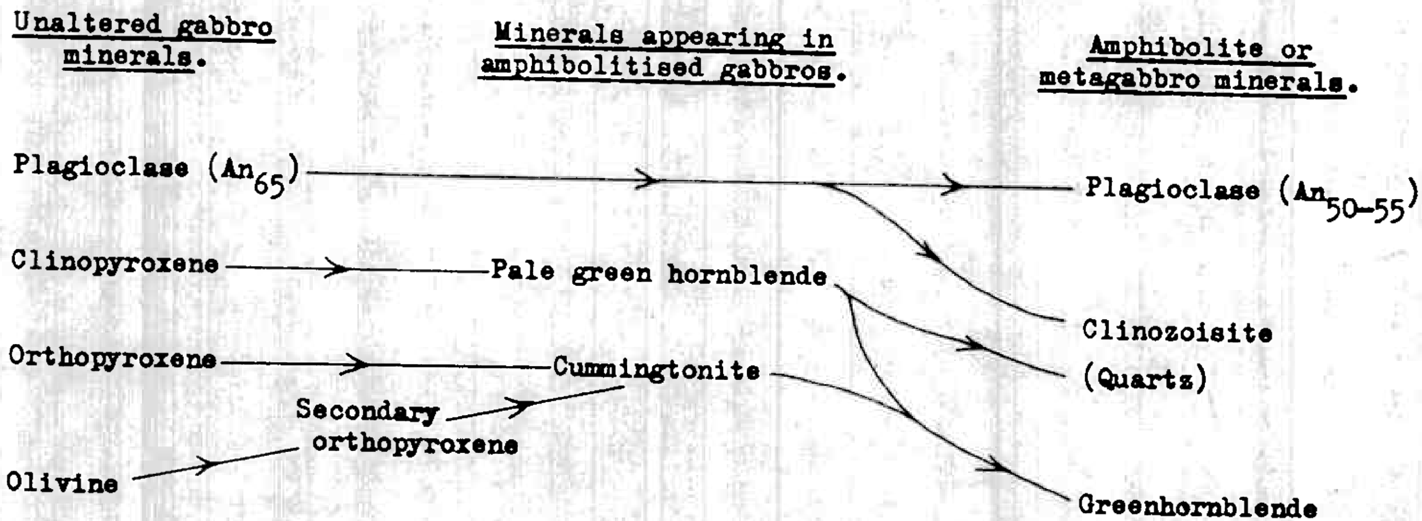
Sometimes clinozoisite grows at the interface between amphibole and plagioclase. It is usually myrmekitic in habit and its appearance was described by Vogt as follows (p. 302) :-

"The clinozoisite is not found dispersed throughout the plagioclase but has a very characteristic occurrence at the contact between plagioclase and hornblende. Here it forms blister like clinozoisite individua which sit on the hornblende and have their convex part against the plagioclase, so that they give the impression of having grown into that mineral. The whole appearance very much recalls the ordinary plagioclase-quartz myrmekite, which grows blister like into potash felspar. The clinozoisite has grown myrmekitically along with a colourless birefringent mineral which can scarcely be determined, but which I assume to be albite which was separated during the formation of clinozoisite. The proportion of clinozoisite is fairly small, and can be estimated at 2%."

As Vogt observed the formation of this clinozoisite is accompanied by decalcification of the plagioclase. This changes in composition from about An_{65} to An_{50-55}. The clouding disappears but good albite twinning remains though complex twins become rarer. The change may be illustrated by comparing the composition of the analysed plagioclase from metagabbro T15 in table 3 with that of the primary igneous plagioclase of specimen S96. Often numerous small crystals of

TABLE 6.

Summary of mineral changes due to amphibolitisation of gabbro.



The arrows only indicate obvious replacements; transfer of various chemical components between phases must also have occurred e.g. transfer of silica into olivine, or of magnesium and iron out of olivine to form orthopyroxene.

plagioclase wholly or partly replace the original large laths, but it is uncertain whether this is due to recrystallisation of the plagioclase during amphibolitisation, or to cataclastic granulation similar to that described in the previous section of this chapter. The plagioclase grains often display quite strong zoning and their outer rims approach andesine in composition.

Olivine is never seen altering directly to amphibole. Many of the amphibolitised gabbros do not contain any olivine although it is present in all the unaltered gabbros. The alteration of olivine to orthopyroxene is observed, so it seems probable that early in the process of amphibolitisation olivine altered to orthopyroxene, which subsequently altered to amphibole. The changes in the minerals on amphibolitisation are summarised in table 6. There is textural evidence that amphibolitisation occurred after the formation of kelyphitic borders round olivine (fig. 3.11). As has been stated earlier (p. 76) green hornblende mantles brown.

In order to determine whether or not amphibolitisation was an isochemical process, a specimen (S6) from the eastern end of the valley N of Vardetoppen (g.r. 547502) was examined. This contained streaks of metagabbro running through unaltered gabbro. Fig. 3.12 shows a photograph of the outcrop it was taken from. The amphibolitised portions of the specimen were cut away from the unaltered portions by means of a diamond saw. The two portions were then ground until they

Fig. 3.12.

Amphibolitisation of gabbro.

1. Outcrop from which the analysed specimen S6 was taken. The darker stripes are amphibolitised gabbro.

2. Outcrop nearby showing relation of pegmatite vein to amphibolitisation.

TABLE 7.

Amphibolitised and unaltered portions of S6, comparison of chemical analyses.

	Unaltered portion	Amphibolitised portion
SiO_2	48.55	47.79
TiO_2	0.33	0.32
Al_2O_3	19.44	19.51
Fe_2O_3	0.76	0.65
FeO	5.62	5.58
MnO	0.10	0.08
MgO	10.14	10.13
CaO	12.24	12.24
Na_2O	2.42	2.42
K_2O	0.16	0.14
H_2O+	0.80	1.98
H_2O-	0.00	0.00
Total	100.77	100.84

Recalculated to 100% of anhydrous oxides :-

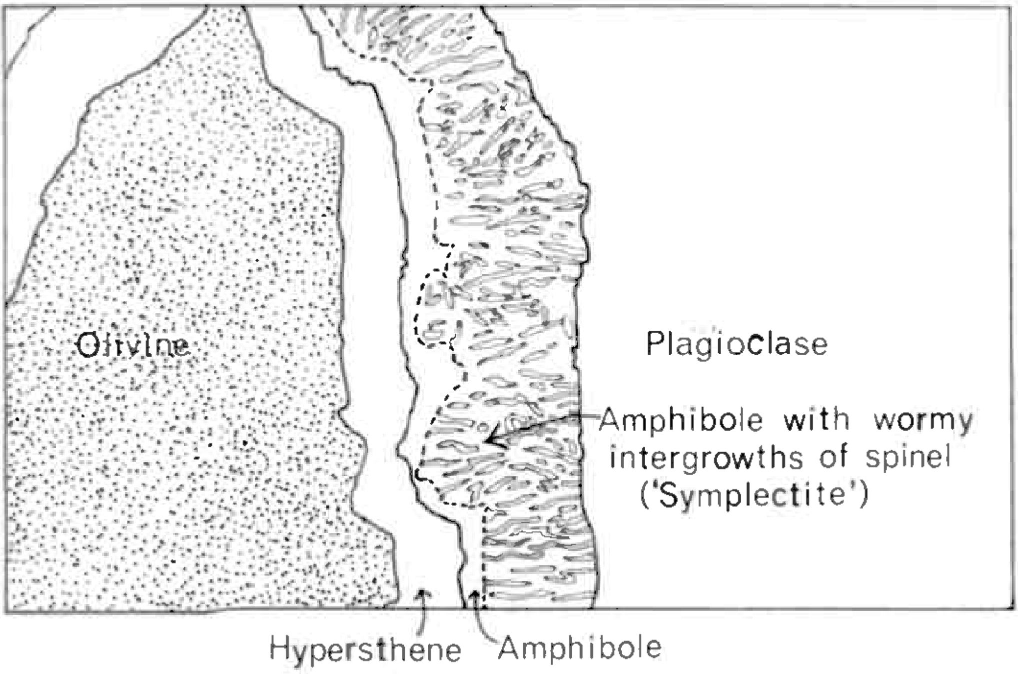
	Unaltered portion	Amphibolitised portion
SiO_2	48.67	48.34
TiO_2	0.33	0.32
Al_2O_3	19.49	19.73
Fe_2O_3	0.76	0.66
FeO	5.63	5.64
MnO	0.10	0.08
MgO	10.16	10.25
CaO	12.27	12.41
Na_2O	2.43	2.45
K_2O	0.16	0.14

passed through a 90 mesh sieve and analysed chemically. The results are given in table 7.

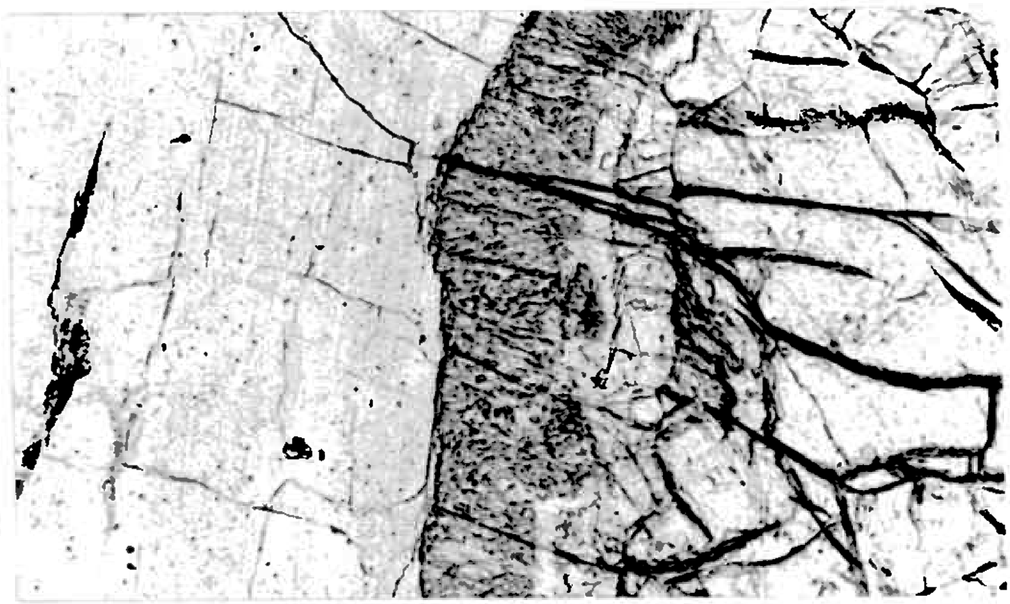
It can be seen that for all major oxides, the differences between the two analyses are of the same order of magnitude as the analytical error. The only large difference is in the percentage of H_2O driven off above 105°C, which is higher in the amphibolitised gabbro. It is interesting that there is no significant difference in the proportions of soda and potash, as amphiboles contain considerably more of these oxides than pyroxenes. It can be concluded that in the formation of amphibole not only pyroxene but an appreciable amount of plagioclase was replaced.

The green hornblende of the metagabbros is distinctly different in chemical composition from the brown hornblende found in the unaltered gabbros. Table 10 compares the composition of brown hornblendes with the composition of green hornblende from metagabbro specimen T15. The significance of these results and the results of spectrophotometric determinations of absorption spectra from these hornblendes are discussed in appendix 1.

FIG. 4·1. KELYPHITIC BORDERS TO OLIVINE IN SPECIMEN S96.



x 400.



CHAPTER FOUR

Kelyphitic borders and their formation.

General Remarks.

The kelyphitic borders surrounding olivine crystals in the otherwise unaltered rocks of the Sulitjelma gabbro complex have been mentioned several times already. Vogt gave a good description of the reaction rims of various types surrounding olivine (p. 388-398) and was careful to draw a distinction between reactions zones produced by the reaction of two solid phases and those produced by the reaction of cumulus crystals and intercumulus residual magma (to use the modern terminology of Wager et al.).

"Kelyphitic borders" in this account is the name given to the reaction zones which Vogt ascribed to solid state reaction. They are easily recognisable and distinct from the hyperathene rims produced by reaction of olivine with magma. Fig. 4.1 shows a photomicrograph of kelyphitic borders in the specimen which has been studied by means of the electron-probe microanalyser.

The inner border of orthopyroxene usually consists of quite large grains which run across the whole width of the border and may extend along it for a distance several times the width. Rarely, the border consists of small orthopyroxene prisms with their c-axes perpendicular to the plane of the orthopyroxene-olivine interface. The orthopyroxene is usually colourless, but in one or two specimens displays slight pleochroism.

The narrow middle border of amphibole alone is not always present. The amphibole has a similar composition to that in the outer border, and individual crystals extend across both middle and outer borders. It is pale green.

The outer border is an intergrowth of amphibole and spinel. The spinel forms small, colourless, isotropic worm-like bodies roughly perpendicular to the interface with plagioclase. The intergrowth shown in fig. 4.1 is coarser than the average. In some specimens the spinel is so fine that it can scarcely be seen at all even under the high power of the microscope, which may explain why Vogt did not describe the spinel phase in the outer border although he described on the same page of the memoir spinel in kelyphitic margins from Andopen, in the Lofoten Islands of Northern Norway.

The borders are found in many parts of the Sulitjelma gabbro complex. They are commoner and better developed in the western part of the complex than in the east, and tend to be best developed in the marginal troctolitic facies. Kelyphitic borders of this type are common in other gabbros in the Caledonian mountain chain. Kelyphitic borders round olivine appear in the troctolites and peridotites on Sørøy in the Troms region of Northern Norway (Ramsay and Sturt 1963, Sturt and Ramsay 1965). An example from the Seiland gabbro in N. Norway is figured in Barth (2nd Edition 1952) p. 272, and one from Risør in S. Norway in Hatch, Wells and Wells (Twelfth Edition 1961) on p. 316. Kelyphitic borders round olivines are also figured in Brøgger's (1934) classic account of the hyperites of southern Norway. The writer has examined similar borders from the Huntly gabbro in Aberdeenshire (Watt 1914, Read 1923) and they have also been described from the gabbro complexes at Haddo House (Read 1935), Insch (Read, Sadashivaiah and Haq, 1961) and Belhelvie (Stewart 1946). Examples from basic igneous rocks from other parts of the world are also numerous.

Controversy has arisen over the origin of these borders, a recent example being an argument in the correspondence columns of "Nature" between Weedon (1965) and O'Hara and Stewart (1966) on the relation of the kelyphitic borders in the gabbro complexes in Aberdeenshire to the pressure at which the complexes crystallised. Kelyphitic borders in olivine gabbros are frequently referred to as "coronites". In this account this name has not been used as it is applied to metamorphic reaction borders generally (Shand 1945, Murthy 1958). The arguments in this chapter apply solely to orthopyroxene-amphibole-spinel coronites which are found surrounding olivine crystals in basic igneous plutons.

Electron-probe X-ray emission microanalysis of kelyphitic borders.

In order to obtain more specific data relating to the formation of kelyphitic borders, a detailed study was made of the compositions of the mineral phases present using the electron-probe X-ray emission microanalyser in the Department of Mineralogy and Petrology, Cambridge. A recent account of the design and operation of this instrument, with a description of methods for correcting the results has been given by Reed (1964). For this account it is sufficient to state that the instrument enables analyses to be made for elements with atomic numbers of 12 or more on a very small volume (approximately 1 micron cubed) on the surface of a polished specimen coated with a thin layer of a conducting material.

In the interpretation of the results it should be borne in mind that the accuracy of a determination increases with :-

1. The atomic number of the analysed element (for the elements discussed here).

2. The total number of counts made in the characteristic X-radiation for the element.

3. The quality of the polish of the specimen surface.

Other factors also affect the accuracy of an analysis, but those listed above are the most important ones which may vary in the analyses quoted in this thesis. To give some idea of the absolute accuracy of the results, it is probably best to quote Reed (p. 265) :-

> "At present the figure usually quoted for the accuracy of electron-probe microanalysis is $\pm$ 1% of the concentration measured, for reasonably large concentrations (more than 10% say). As has been shown here, reproducibilities considerably better than this can be achieved, but it is doubtful if better absolute accuracies than this can be obtained, especially when corrections are large. Accuracy is also less when analysing small grains, and when the area analysed is very inhomogeneous."

The last sentence applies particularly to some of the analyses quoted in this chapter.

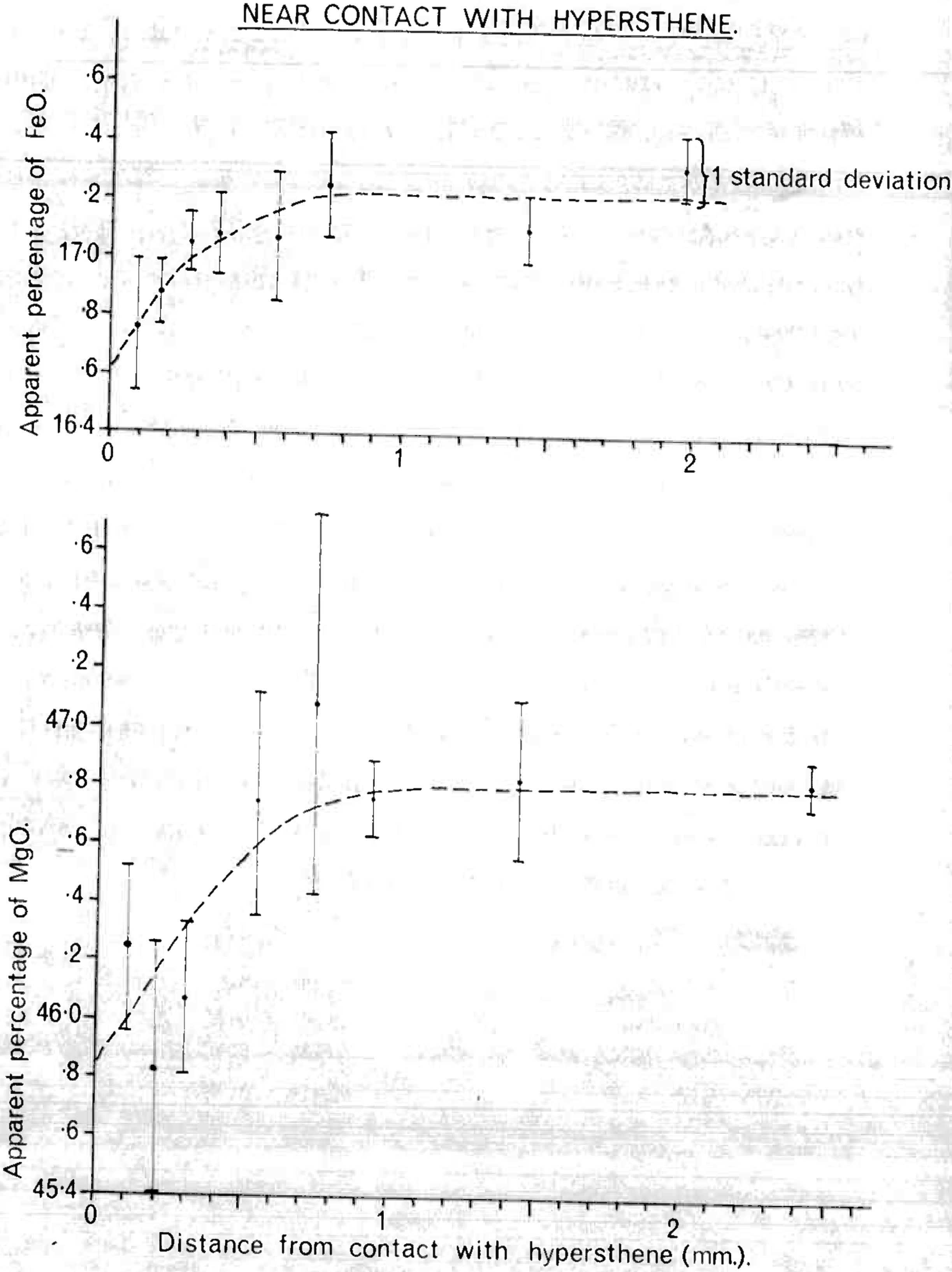
The kelyphitic borders in specimen 896 were studied. The olivine and plagioclase from this rock have been fully analysed chemically (table 3 and appendix 2) and a bulk rock analysis has also been made (appendix 2). The mode of the rock is also given in appendix 2. Almost all the orthopyroxene in the modal analysis is in the kelyphitic border. The term "symplectite" used in appendix 2, and later in this chapter refers to both the middle and outer borders. The total of orthopyroxene and symplectite gives a measure of the development of the borders; 24.4% of the rock. A polished, copper coated, thin section was used for microanalysis.

All the results have been corrected for dead-time, background radiation, absorption and atomic number by hand calculation methods described by Reed. The fluorescence corrections are negligible.

Olivine.

The olivine grains were examined in detail in an attempt to detect any zoning which might be present. This would clearly be slight, as the grains show no perceptible variation in birefringence in thin section. Some grains did show a slight variation in iron content between core and margin, so a series of point analyses for iron were made along line traverses in selected grains. The variation was comparable in

FIG. 4·2. APPARENT DECREASE IN IRON & MAGNESIUM IN OLIVINE NEAR CONTACT WITH HYPERSTHENE.



magnitude to the random variation of the count-rate of the instrument, so five counting periods of ten seconds each were spent on each spot, and the standard deviation of the counts was calculated. This enabled an error to be quoted for the oxide percentage derived from the count-rate, but this figure represents only the random error of counting and does not take into account a great number of sources of systematic error (appendix 3 and Reed 1964). The results are shown on the graph (fig. 4.2). It can be seen that there is a significant decrease in the proportion of iron at distances less than 0.5 mm from the contact of olivine with orthopyroxene.

A similar traverse was made performing point analyses for magnesium on the same crystal, as close as possible to the line traversed for iron (fig. 4.2). Five counting periods were again taken at each point, but the counting time was increased to 100 seconds. The apparent zoning seemed to be similar but smaller in amount to that seen in the iron i.e. a decrease in the magnesium content within 0.5 mm of the boundary. But the random variation in the count-rate for magnesium was greater than for iron, so it is uncertain whether the apparent decrease is significant.

The measured silica contents were :-

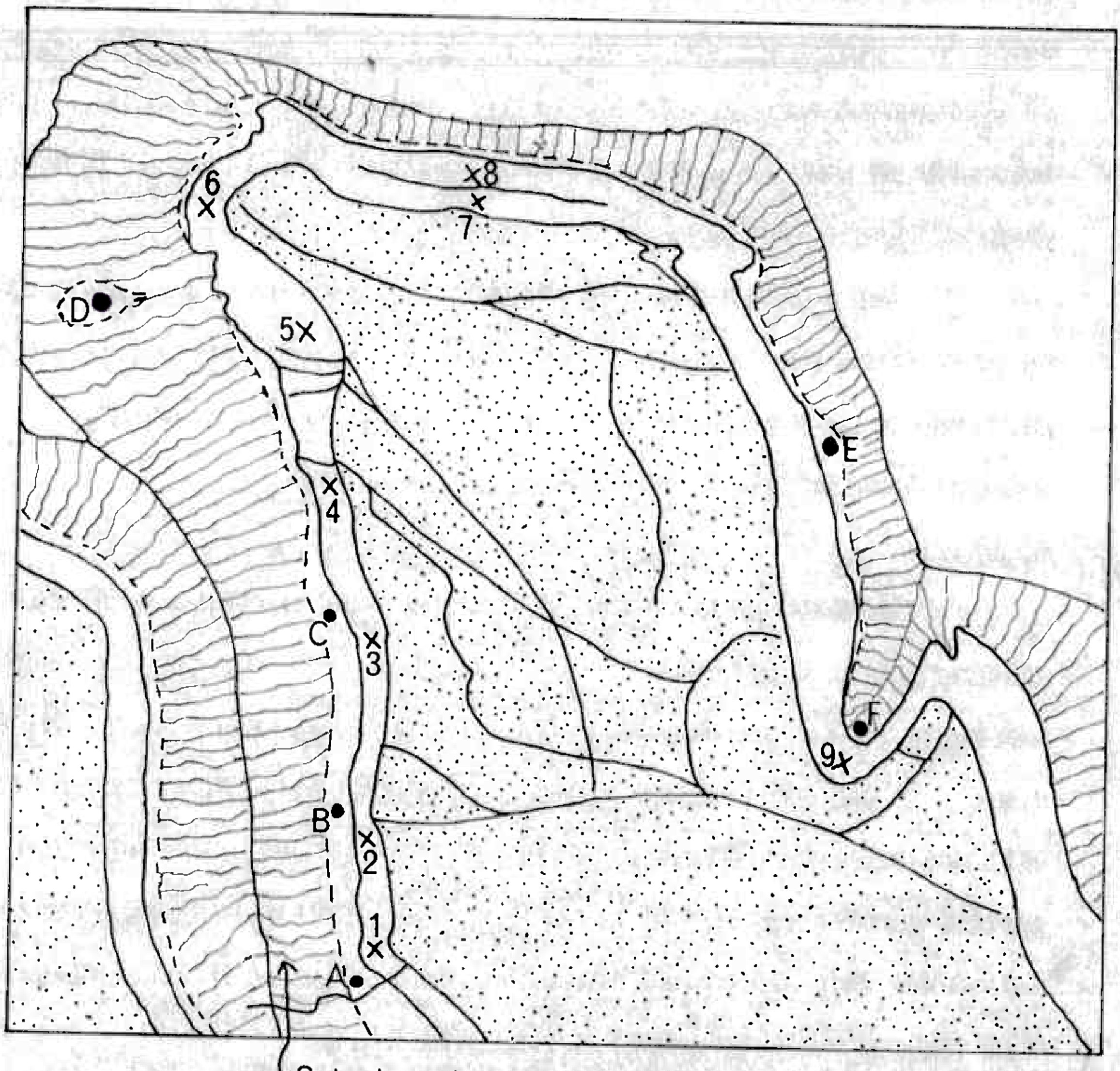
Distance from contact	% SiO_2
0.18 mm.	38.92 ± 0.29
0.48 mm.	40.50 ± 0.38
0.88 mm.	40.56 ± 0.24
2.88 mm.	38.60 ± 0.39

Attempts were made to detect variations in Ni, Ca and Mn in the olivine, but they were only present in trace quantities, and no appreciable variation could be seen. It may be that Al increases near the contact with orthopyroxene. Al was not measured, but the proportion in orthopyroxene is very low indeed, so it was assumed that olivine also contained very little.

The significance of the low values for iron and magnesium near the boundary is uncertain. It is possible that they are due to some property of the instrument, although the distance of some of the low readings from the contact with the orthopyroxene rules out the possibility of the variation being due to increased absorption of characteristic X-radiation close to the contact. Not all grains showed the decrease in Mg and Fe towards the margin but it was detected in others in several traverses, and on two widely separated occasions, (December 1964 and November 1963). One possibility is that the apparent decrease is caused by a decrease in the smoothness of the specimen as the olivine-orthopyroxene boundary is approached, but if there is such a variation it could not be seen under the reflected-light microscope. The decrease may be connected with the migration outwards of Mg and Fe in the formation of the kelyphitic borders.

The uniform values from the centre of the grain suggest a molecular composition for the olivine of forsterite 83.0%, fayalite 17.0%.

FIG. 4·3. LOCATION OF ELECTRON-PROBE ANALYSES IN TABLE 8 ROUND A SINGLE OLIVINE GRAIN.



Spinel analyses made here.

Orthopyroxene.

Point analyses of the orthopyroxene were made at nine points round the margins of one olivine grain (fig. 4.3). These are given in table 8. Analyses 7 and 8 were made at the same part of the margin but at different distances from the contact with the olivine. The analyses were made at points which appeared to be smooth in reflected light, and clear of cracks and inclusions in transmitted light.

The analyses are very similar to one another, the totals tending to be a little greater than 100%. The mean analysis was recalculated to give molecular proportions of the end-members enstatite (83.0%), orthoferrosilite (16.7%) and wollastonite (0.3%).

Amphibole.

Analyses were made at six points round the contact of the olivine grain. (fig. 4.3). The analyses were made in both the middle and outer border, and the composition of the two borders appears to be the same. It was not possible to make a complete analysis as the instrument will not determine sodium or water, or the oxidation state of iron. The partial results are listed in table 8. The unit cell contents were calculated from the partial analysis on the basis of 24 (O,OH) assuming that the amphibole is a hornblende (table 8).

Spinel.

The analysis of this phase presented severe problems as the worm-like intergrowths are only 3-5 microns across. To obtain a

TABLE 8.

Electron-probe analyses of minerals in kelyphitic borders

Orthopyroxene

	1.	2.	3.	4.	5.	6.	7.	8.	9.	Mean
SiO_2	55.5	55.7	55.9	56.1	55.0	55.4	55.8	55.2	55.5	55.5
FeO	11.9	11.6	12.3	12.0	12.2	12.0	12.3	11.9	12.0	12.0
MgO	33.3	33.9	33.4	33.0	33.6	33.2	33.6	33.2	33.9	33.4
CaO	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2
Total	100.9	101.4	101.8	101.3	101.0	100.8	101.9	100.5	101.5	101.1

Molecular composition on this basis :-

Enstatite 83.0% Ferrosilite 16.7% Wollastonite 0.3%

Amphibole

	A.	B.	C.	D.	E.	F.	Mean
SiO_2	45.8	46.5	46.3	45.8	45.1	43.5	45.5
Al_2O_3	16.6	16.8	17.3	19.1	18.3	19.8	18.0
FeO	5.1	5.4	5.3	6.0	5.4	5.2	5.4
MgO	19.4	20.3	19.8	18.0	18.0	17.7	18.9
CaO	11.2	11.2	11.2	11.0	11.2	10.9	11.1
Total	98.1	100.2	99.9	99.9	98.0	98.1	98.9

Recalculated structural formula, on the basis of 24 (O,OH), assuming the alkali and water content, and the ferrous:ferric iron ratios are similar to those of the analysed hornblende from T15.

Si	6.00	8.00
Al	2.00	
Al	0.80	5.09
Fe	0.58	
Mg	3.71	
Ca	1.57	

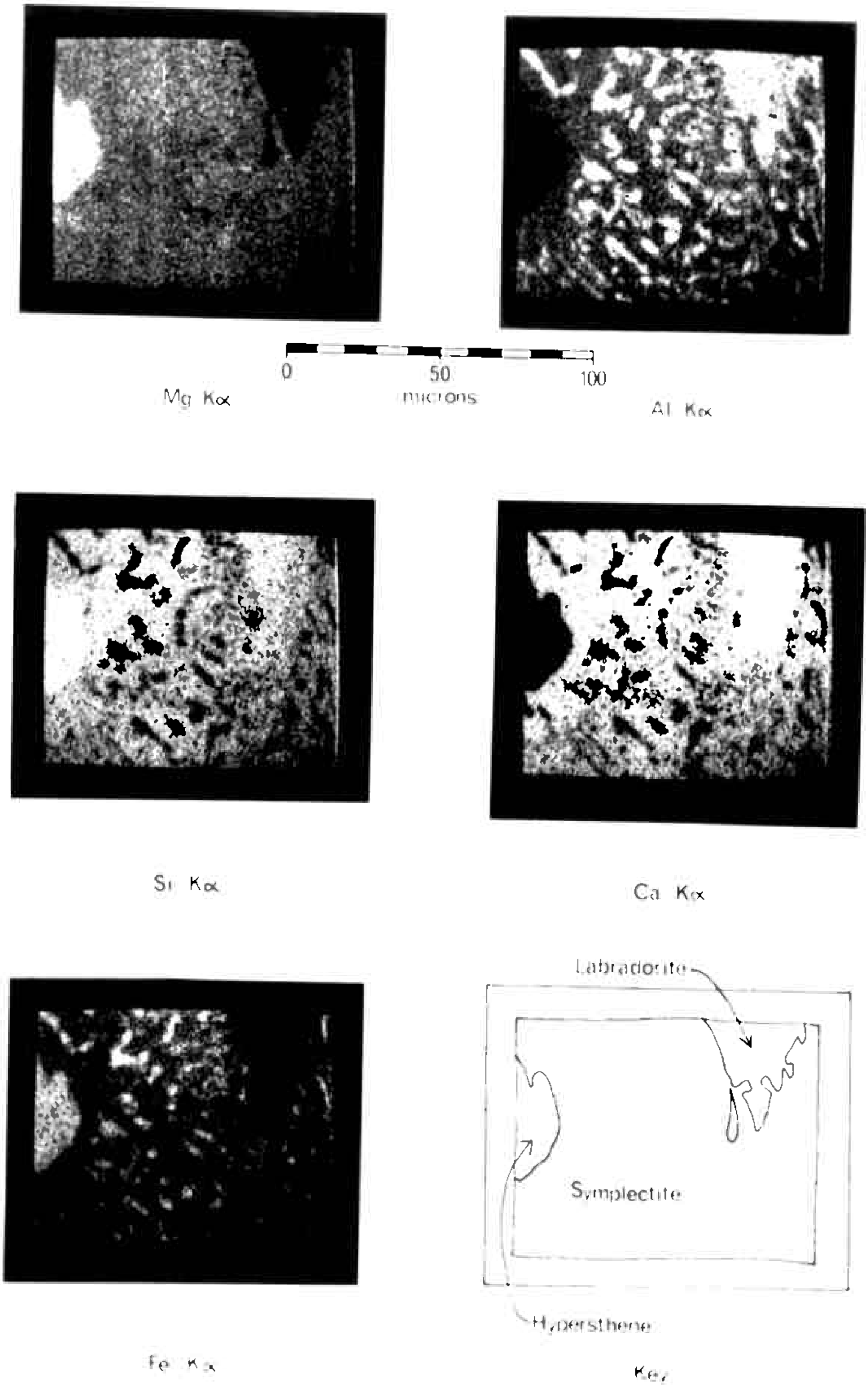
Spinel

	1.	2.	Mean
SiO_2	1.4	4.2	2.8
Al_2O_3	67.9	68.5	68.2
FeO	15.2	13.1	14.1
MgO	16.1	14.7	15.4
CaO	0.5	0.6	0.5

Structural formula on the basis of 32 (O)

Si	0.6	16.5
Al	15.9	
Fe	2.3	7.0
Mg	4.5	
Ca	0.1	

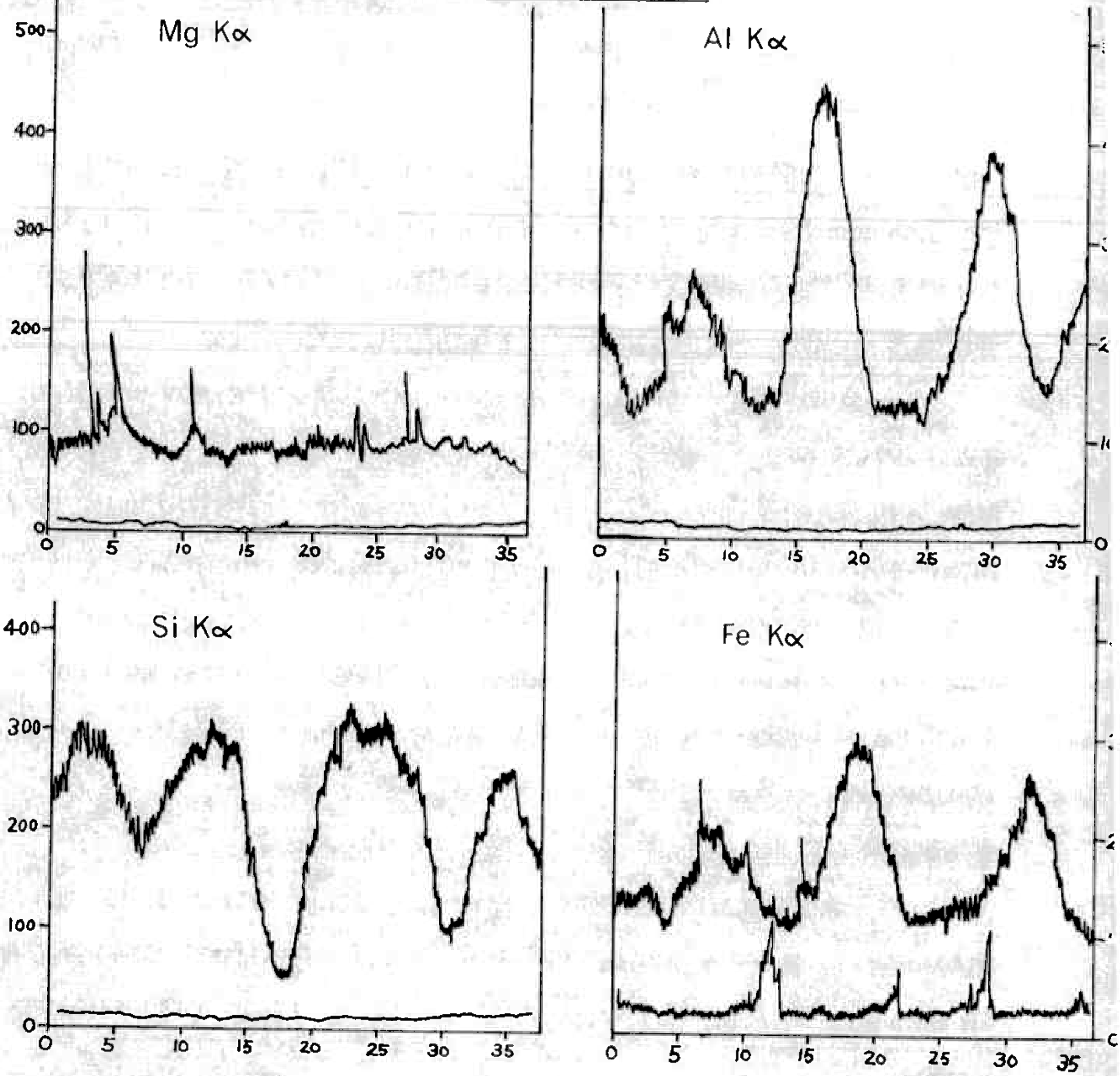
Fig 4.4 X-ray scanning pictures of symplectite for various different elements



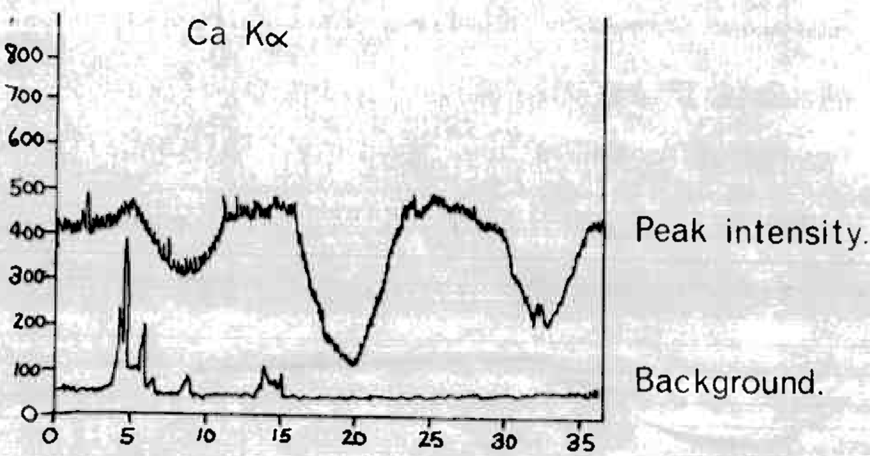
preliminary indication of the differences in concentration between the spinel and amphibole phases in the symplectite, X-ray scanning pictures of a small area were made (fig. 4.4). In these pictures, the intensity of illumination increases with the concentration of the analysed element. In fig. 4.4 the analysed element and the type of X-radiation used in the analysis is written under each photograph. Aluminium and iron are concentrated in the spinel phase, and calcium and silicon in the amphibole. No concentration of magnesium can be seen.

In the quantitative determination of the spinel, the following procedure was used. The current of the electron beam was reduced to 1/5 its normal value. This increased the effective power of the electron lenses, and so reduced the size of the area analysed. Unfortunately it decreased the number of counts obtained for any element by 1/5, and produced a corresponding reduction in the accuracy of the results. While in the previous determinations it had proved sufficiently accurate to locate the electron beam by eye, viewing the specimen in transmitted light, a different method of location was used in this case. The electron beam was scanned slowly along a line across part of the symplectite and the intensity of the silicon Kα radiation was monitored. The position of the electron beam was recorded as the x-coordinate on a cathode ray tube, and the intensity of the silicon Kα radiation as the y-coordinate. This produced patterns of the type shown in fig. 4.5. Different areas were scanned in this way and when the Si intensity recorded on the spinel worms

FIG. 4·5. LINE SCANS OVER SYMPLECTITE.



Horizontal scale - microns.
Vertical scale - X-ray intensity in counts per second.



approached the background value the beam was fixed in this position on the line scan, and Al, Si and Mg determinations were made. Then the position of the electron beam was readjusted if necessary to minimise the Ca intensity, and Fe and Ca determinations were made.

Even with these precautions the two best analyses include a small amount of calcium and silicon (table 8). The unit cell contents have been recalculated on a basis of 32 (O). It can be seen that there is an excess of silicon and aluminium ions above 16, suggesting that the SiO_2 in the analysis is due to "contamination" from the surrounding amphibole due to lack of resolution by the instrument. The iron and magnesium are also deficient. This may be due to inaccuracy, particularly in the magnesium analysis.

Calculation of the bulk composition of the symplectite.

In order to compare the chemistry of the borders it is necessary to know the composition of the amphibole + spinel intergrowth. In this calculation, the middle border has been included with the outer border.

The volume percentage of spinel in these two outer borders was estimated from the X-ray scanning pictures shown in fig. 4.4. The aluminium Kα and calcium Kα pictures which gave the best "positive" and "negative" images of the spinel phase were traced and a composite tracing based on these was used to estimate the proportion of the surface of the thin section which was composed of spinel. The Ca Kα picture suggested a smaller area of spinel than the composite tracing, and the Al Kα picture a larger area. The composite tracing was point counted at 1 mm. intervals (N.B. fig. 4.4 is reduced to about 2/3 the size of the original scanning pictures). A total of 2,941 points was counted, yielding a volume percentage in the symplectite of spinel 10.0%, amphibole 90.0%. Specific gravities of 4.14 and 3.09 respectively were assumed for the two phases. These were derived from the calculated molecular proportions and the figures in Deer, Howie and Zussmann (Volume 5 p. 61, and Volume 2 p. 296). Once again, it was assumed that the amphibole is a hornblende.

From this data the composition of the symplectite was calculated as follows (weight percentages) :-

	SiO_2	40.0
	Al_2O_3	24.6
Total iron as	FeO	6.5
	MgO	18.4
	CaO	9.8
	"Total"	99.3

Interpretation of the results.

To make the comparison of the compositions of the borders easier, the chemical analyses of the olivine and plagioclase, and the mean electron-probe analyses of the orthopyroxene and symplectite are set down again here :-

	Olivine	Orthopyroxene	Symplectite	Plagioclase
SiO_2	39.4	55.5	40.0	50.7
Al_2O_3	0.0	-	24.6	31.9
Total iron as FeO	16.7	12.0	6.5	0.2
MgO	43.4	33.4	18.4	-
CaO	trace	0.2	9.8	14.1
Ratio MgO:MgO + FeO	0.722	0.736	0.739	-

(The Al_2O_3 value in the olivine analysis is added to SiO_2, see appendix 3).

The values for the MgO:MgO + FeO ratio make a late magmatic origin for the kelyphitic borders as proposed by Herz (1951) and Weedon (1965) exceedingly unlikely. There is abundant evidence that late magmatic fluids are enriched in iron relative to the early crystallised phases, whereas the orthopyroxene and symplectite borders have much the same MgO:MgO + FeO ratio as the olivine.

It seems most likely that the borders formed by chemical reaction between olivine and plagioclase in the solid state. A simple reaction will be considered here, making the following assumptions :-

1. The present symplectite-orthopyroxene interface represents the original plagioclase-olivine interface. This is reasonable on textural grounds (fig. 4.1). It follows that orthopyroxene formed from olivine, and symplectite from plagioclase.

2. The mobile elements were iron and magnesium, and to a much

smaller extent calcium. Silicon and aluminium were passive.

3. The replacement of olivine by orthopyroxene and of plagioclase by symplectite took place at constant volume.

Let us first consider the alteration of plagioclase to symplectite. We can calculate the composition which arises if iron and magnesium are added to the plagioclase analysis until the weight percentage of silica drops to that in the symplectite (40%). The MgO:FeO ratio is kept at the same value as in the olivine. This gives this result :-

SiO_2	40.0
Al_2O_3	25.1
FeO	5.8
MgO	15.4
CaO	11.1

If we assume that this composition change took place at constant volume there is an increase in the specific gravity of the symplectite over that of the plagioclase by 21.2%. The assumed specific gravity of the symplectite which was used in the weight percentage composition calculation was 3.20. The composition of the plagioclase suggests an estimate of its specific gravity at 2.72 (Deer, Howie and Zussman Volume 5, p. 137). These figures give an increase in specific gravity of 17.6%. Thus the working hypothesis accounts for the change from plagioclase to symplectite quite well.

However, difficulties arise with the alteration of olivine to orthopyroxene. It is possible to obtain a close approximation to the composition of the orthopyroxene by subtracting FeO and MgO in the appropriate ratio (Murthy 1958). But this indicates nothing more than that the MgO : (MgO + FeO) ratios are similar, as both phases consist almost entirely of the three components FeO, MgO and SiO_2. The assumptio of equal volume replacement runs into severe difficulty as orthopyroxene and olivine of these compositions have almost the same specific gravities, and yet the postulated loss of iron and magnesium means a reduction in the mass of the olivine on conversion to orthopyroxene. This produces a reduction of 28% of the original volume of olivine on conversion to orthopyroxene. In specimen S96, in which orthopyroxene constitutes 9.5% of the rock this implies a reduction in the total volume of the rock of some 3.8% when the kelyphitic borders formed. There is no textural evidence for such a reduction.

If the assumption of equal volume replacement is retained difficulties are encountered over the chemistry of the borders. It becomes necessary to assume that silica and alumina were mobile and not only diffused across the hypersthene-symplectite contact but across the symplectite-plagioclase and hypersthene-olivine contacts. This seems unlikely to have occurred in view of the relatively slight zoning of olivine and plagioclase.

In spite of the volume difficulties, the writer considers the simple diffusion model outlined earlier to be the most plausible for the formation of the kelyphitic borders. Few of the kelyphitic borders in the olivine gabbros occupy as large a volume percentage of the rock as those in S96. Specimen S96 is from near the contact of the gabbro complex, and parts of the specimen have undergone amphibolitisation. It may be that this masks any textures which might have arisen from a volume change when the kelyphitic borders formed. It seems most likely that the diffusion took place in an aqueous fluid which entered the rock along grain boundaries and permeated the olivine and plagioclase for a small distance on either side of the interface.

The theory proposed here for the origin of the kelyphitic borders may be summed up as follows :-

1. They were formed by reaction in the solid state.

2. A simple process of 2-way diffusion across the original interface between olivine and plagioclase with iron and magnesium diffusing into the plagioclase, and a little calcium diffusing into the olivine explains the chemical composition of the borders quite well but creates volume difficulties.

3. Textural evidence cited in the previous chapter suggests that they formed before the D_2 deformation episode and the accompanying amphibolitisation of the gabbro complex.

4. The formation of amphibole from plagioclase indicates that water must have been introduced when the borders formed. The extensive

development of the borders near the contacts of the gabbro complex suggests that this water may have been derived from the country rocks. It was probably the transporting medium for ions across the olivine-plagioclase interface.

CHAPTER FIVE

The petrography of the country rocks.

A brief account will be given of the petrography of each unit in the stratigraphical sequence on p. 17.

1. The rocks of the Pieske-Vasten nappe.

(a) The Furulund schist group.

The petrography of the Furulund schist group has been studied in detail by Henley. A brief summary of his results is given here. He considers the main schistose fabric to have arisen during the D_2 deformation episode and therefore designates the main schistosity surface as S_2. The growth of the porphyroblast minerals garnet and hornblende started before or during the D_2 episode, so that their cores sometimes retain an earlier fine grained planar fabric, which he designates S_1.

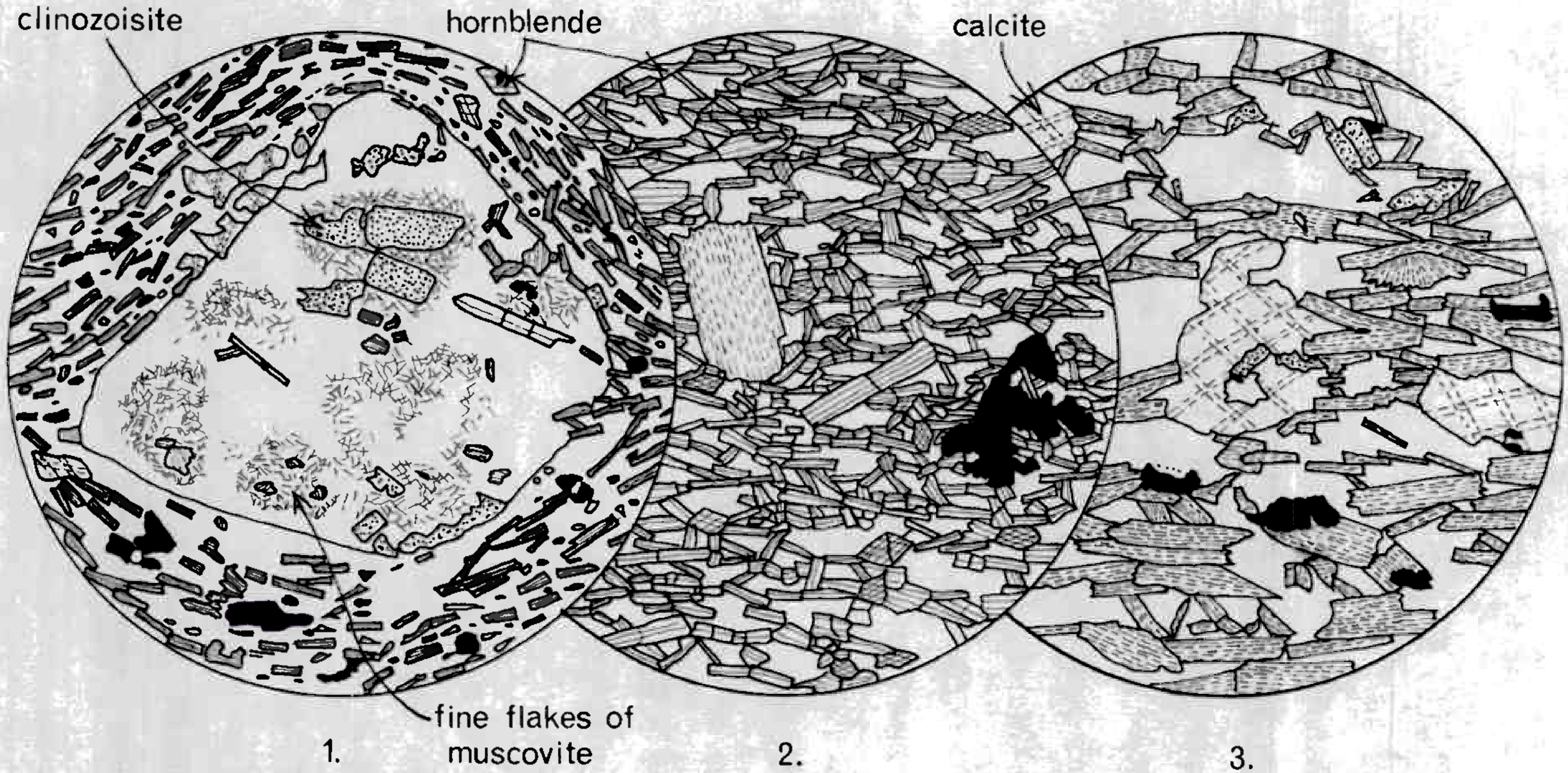
This account is concerned with the meta-igneous rocks which lie above the Furulund group. It is sufficient to say that the bands of garnet-mica schist in the schistose amphibolite group display all the features described by Henley in the main part of the Furulund schist group.

(b) Micaceous psammite.

Only two specimens from this unit were taken for examination in thin section. Both are fine-grained and display a well-developed schistosity arising from preferred orientation of mica flakes. One

FIG. 5·1.

Micaceous psammite and schistose amphibolites.



1. x 65 U49 Plagioclase augen in micaceous psammite.
2. x 140 S48 Schistose amphibolite with late chlorite.
3. x 65 S59 Calcareous chlorite schist.

specimen (U48) is a quartz-muscovite-epidote-ore assemblage. Epidote takes the form of subhedral prismatic porphyroblasts. The other specimen (U49) is a quartz-biotite-hornblende-calcite-clinozoisite assemblage. The hornblende appears as prismatic porphyroblasts, with the c-axes lying in the plane of schistosity. Calcite forms lenses parallel to the schistosity planes and clinozoisite appears near the edges of these lenses. There are augen-like metacrysts of plagioclase about 2 mm. across. These show occasional relict polysynthetic twinning, but not sufficient for an accurate composition determination, though their low R.I. suggests that they are more sodic than the oligoclase found in the schistose amphibolites above. They have minute inclusions of clinozoisite, muscovite, biotite, quartz and hornblende. The schistosity sweeps round them suggesting that they may be pre-schistosity features (fig. 5.1,1).

(c) The schistose amphibolite group.

The rocks in this group display as much variety in thin section as they do in the field. Many are calc-silicate rocks composed of epidote, quartz and plagioclase, or schists composed of chlorite, epidote and quartz. True amphibolites do occur interbanded with these other varieties. The amphibole is usually a green hornblende, though it is sometimes rather pale. The carbonate minerals are very abundant forming lenses and patches in rocks throughout the group. Both calcite and dolomite seem to be present. The textures of the rocks are also very variable. Sometimes hornblende forms large porphyroblasts with a preferred orientation parallel to the D_2 lineation. Many rocks are banded with more calcareous bands richer in epidote or clinozoisite alternating with more hornblende rich bands.

Plagioclase is rather rare and not often twinned but measurement on a few grains suggest that it is oligoclase with composition An_{20-25}. In one section (T216) large augen of potash felspar are found along with relict metacrysts of plagioclase, similar to those found in the porphyritic amphibolite. The matrix of the rock is chlorite schist and it comes from just above the lower schist band, to the east of Otervann (g.r. 536461). In this rock the chlorite grows in the schistosity planes in a similar way to biotite or muscovite in the pelites. In the amphibolites it may grow at random angles to the schistosity planes (fig. 5.1,3). Chlorite schists are usually found near the base of the schistose amphibolite group, or immediately above the pelitic bands. Late chlorite of the type shown in fig. 5.1,2 is found in all types of rocks in the Sulitjelma region, including metagabbros from the gabbro complex. It seems to have formed during a late phase of retrograde metamorphism.

The particles seen in some rocks from the schistose amphibolite group in hand specimen or on the outcrop cannot be observed in thin section unless it is in the variations in the proportions of the minerals. The presence of limestones and pelites in the schistose amphibolite group shows that part of this group formed under sedimentary conditions. Many rocks, like the chlorite schists, are difficult to assign either a sedimentary or an igneous origin, while it seems likely that amphibolites such as S49 (fig. 5.1,2) may be meta-igneous. Near the top of the group undoubted meta-igneous rocks resembling the porphyritic amphibolites occur.

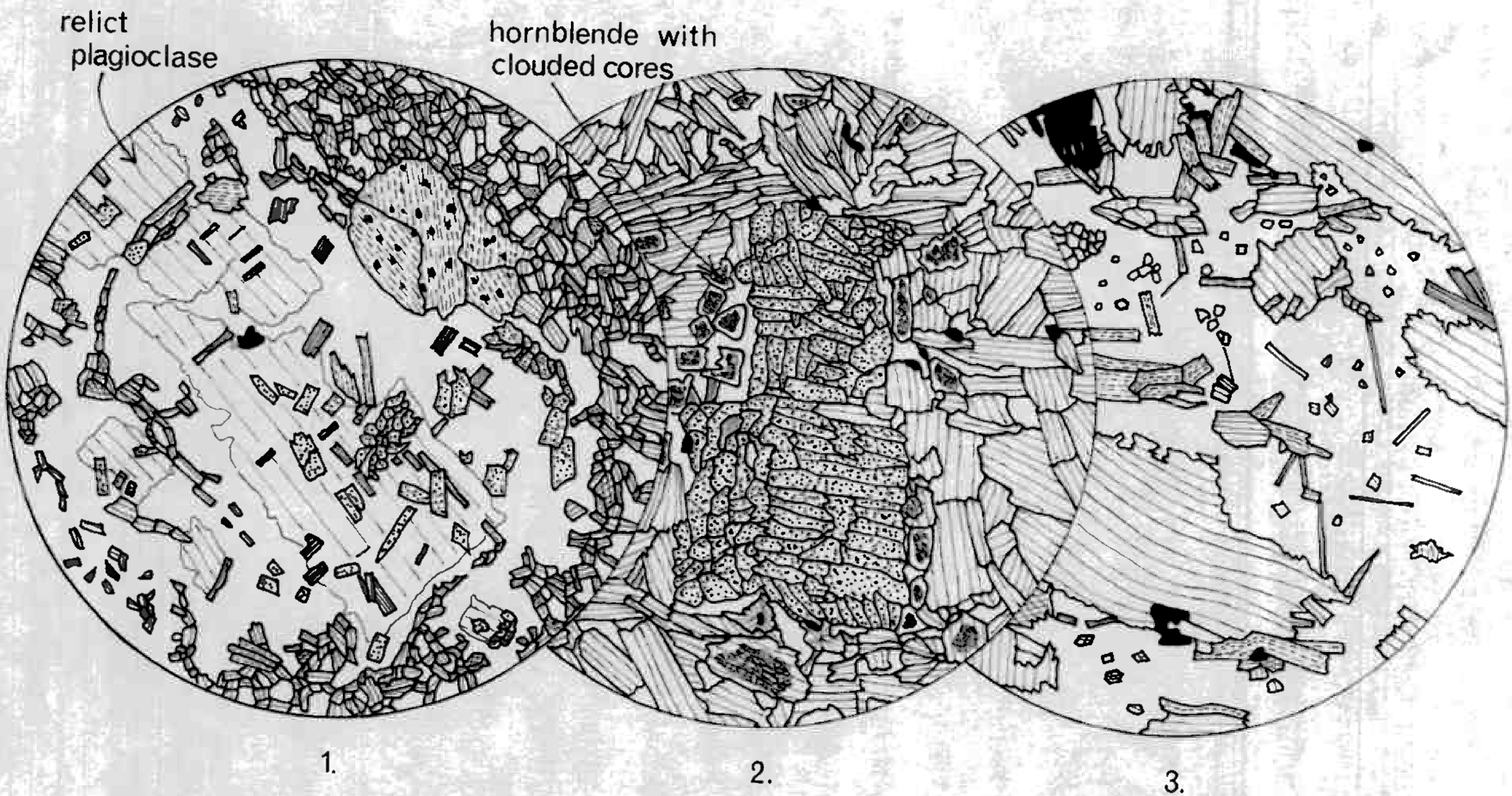
(d) The porphyritic amphibolite.

Two main types of rock can be recognised in the group. The coarse grained "porphyritic" rocks contain two different assemblages, hornblende-plagioclase-quartz$\pm$epidote$\pm$biotite forming the groundmass, and clinozoisite-muscovite-plagioclase in pseudomorphs after calcic plagioclase. Sometimes the plagioclase phenocrysts survive (fig. 5.2,1). When they do they are strongly zoned, and their cores may be as calcic as An_{50} whereas the plagioclase in the groundmass and near the edges of the phenocrysts has a composition of An_{30-35}. Some of the rocks do not contain hornblende but have a very high proportion of the pseudomorphs after the plagioclase phenocrysts and a matrix composed of clinozoisite, muscovite, quartz and plagioclase. In some sections chlorite is quite abundant and appears to have formed later than the other minerals.

The finer grained amphibolites consist of the hornblende-quartz-plagioclase-epidote-biotite assemblage. Some show relict ophitic texture and occasionally relict pyroxene is seen surrounded by green hornblende. There are also leucocratic lenses of fine grained rock with a little hornblende but mainly composed of granular quartz, plagioclase and potash felspar. These may be metamorphosed acid igneous rocks.

FIG. 5·2.

Porphyritic amphibolites.



1. x 25 U24 Relict plagioclase lath in porphyritic amphibolite (outlines of small plagioclase grains omitted).
2. x 65 S144 Plagioclase almost entirely replaced by clinozoisite.
3. x 65 U76 Amphibolite from rocks S. of Sorjusjaure.

Pieske-Vasten nappe rocks S of Sorjusjaure.

Only a few thin sections of these rocks have been examined. They include pelites, amphibolites and calcareous schists. They contain green biotite and blue-green hornblende with a rather low birefringence. The plagioclase is less calcic than that in the amphibolites south of the gabbro complex. A rough determination based on the maximum symmetrical extinction angles suggests a composition about An_{12-15}. Some of the grains retain more calcic cores (up to about An_{25}).

The rocks have no obvious relict textures comparable with the meta-phenocrysts of the porphyritic amphibolite group to enable their pre-metamorphic nature to be discovered.

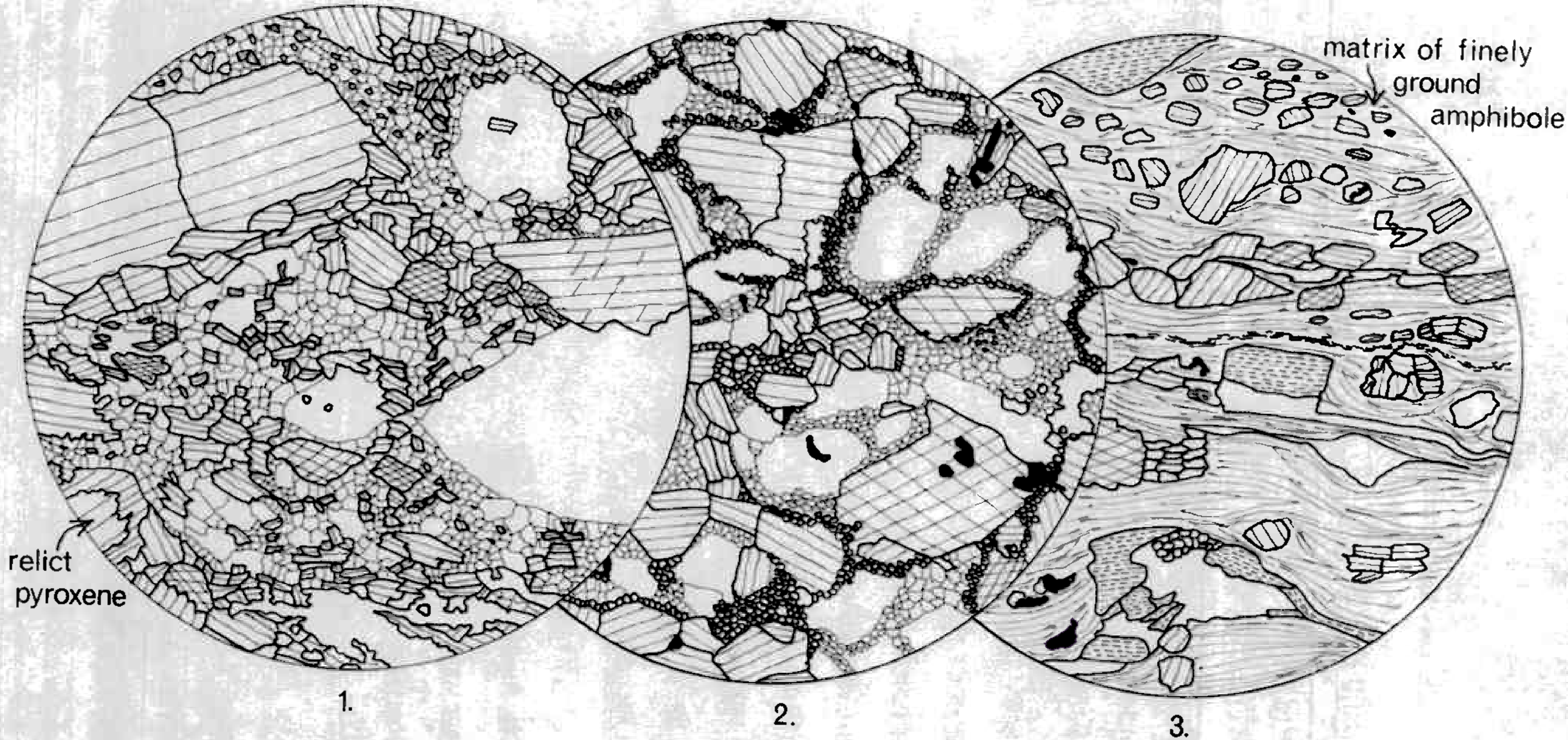
2. Junction Units.

The dioritic gneiss.

A representative sample of specimens were collected on a traverse across the dioritic gneiss approaching the summit of Vaknačokka from the SW. Almost all the rocks from Vaknačokka show signs of cataclasis. As the top of the dioritic gneiss is approached this cataclasis becomes more and more intense, and eventually produces a foliation. The upper part of the dioritic gneiss consists essentially of tectonised amphibolitised gabbros. The two processes seem to have gone on simultaneously. Near the top of the dioritic gneiss brown hornblende is sometimes found in the cores of green, both replacing the ferromagnesian minerals of the gabbro

FIG. 5·3.

Dioritic gneiss and associated rocks.



1. x 25 T228 Dioritic gneiss (outlines of plagioclase grains shown).

2. x 65 T231 Cataclastically deformed brown hornblende gneiss from near the top of the dioritic gneiss unit.

(in rocks as deformed as this it is not possible to determine which mineral a particular amphibole grain is replacing). The brown hornblende may indicate that the onset of formation of the dioritic gneiss had already commenced during the earliest stage of post-consolidation alteration of the gabbro complex.

The specimen from the traverse most typical of most of these from the rest of the dioritic gneiss horizon is shown in fig. 5.3,1. The appearance of the dioritic gneiss in thin section confirms the field observation that this unit is a tectonic melange of basic igneous rocks. A chemical analysis was performed on a specimen from the base of the unit (T222, appendix 2) which was taken from a coarse-grained lens. It does not resemble the gabbros in composition being noticeably richer in silica and iron and poorer in magnesia.

The Junction unit S of Nedre Sorjus.

It was stated earlier that on the scale of the outcrop the schist which forms the junction between the Pieske-Vasten nappe rocks and the Gasak nappe rocks in the valley W of Hammeren shows little sign of tectonism, such as the lineation and lensoid character observed in the dioritic gneiss.

It is impossible to generalise about the petrography of this thin schist band as only three specimens from it have been brought back to examine in thin section. One (T270) is a rather fine-grained quartz-biotite-plagioclase schist with garnet porphyroblasts. The other specimens (U43, U44) come from the S shore of Nedre Sorjus (g.r. 586561) and are very peculiar.

U43 is a graphitic schist with crystals of pyrite which have been broken up and streaked into lenses along with quartz and biotite. Other lenses contain quartz, biotite and untwinned plagioclase. The matrix material between the lenses is very fine-grained schist with graphite, biotite, muscovite and quartz. The schistosity sweeps round the mineral lenses. U44 has a matrix of the graphitic schist surrounding rod-like masses about 1cm. in diameter, elongated parallel to the D_2 lineation. These are composed of granular quartz and biotite flakes in random orientation, with sieve-like crystals of cordierite and porphyroblasts of garnet and clinozoisite, which appear to have grown later than the development of the fabric of the rock.

It is not possible to understand the significance of these specimens without extensive further study in the area.

The rocks of the Gasak Nappe.

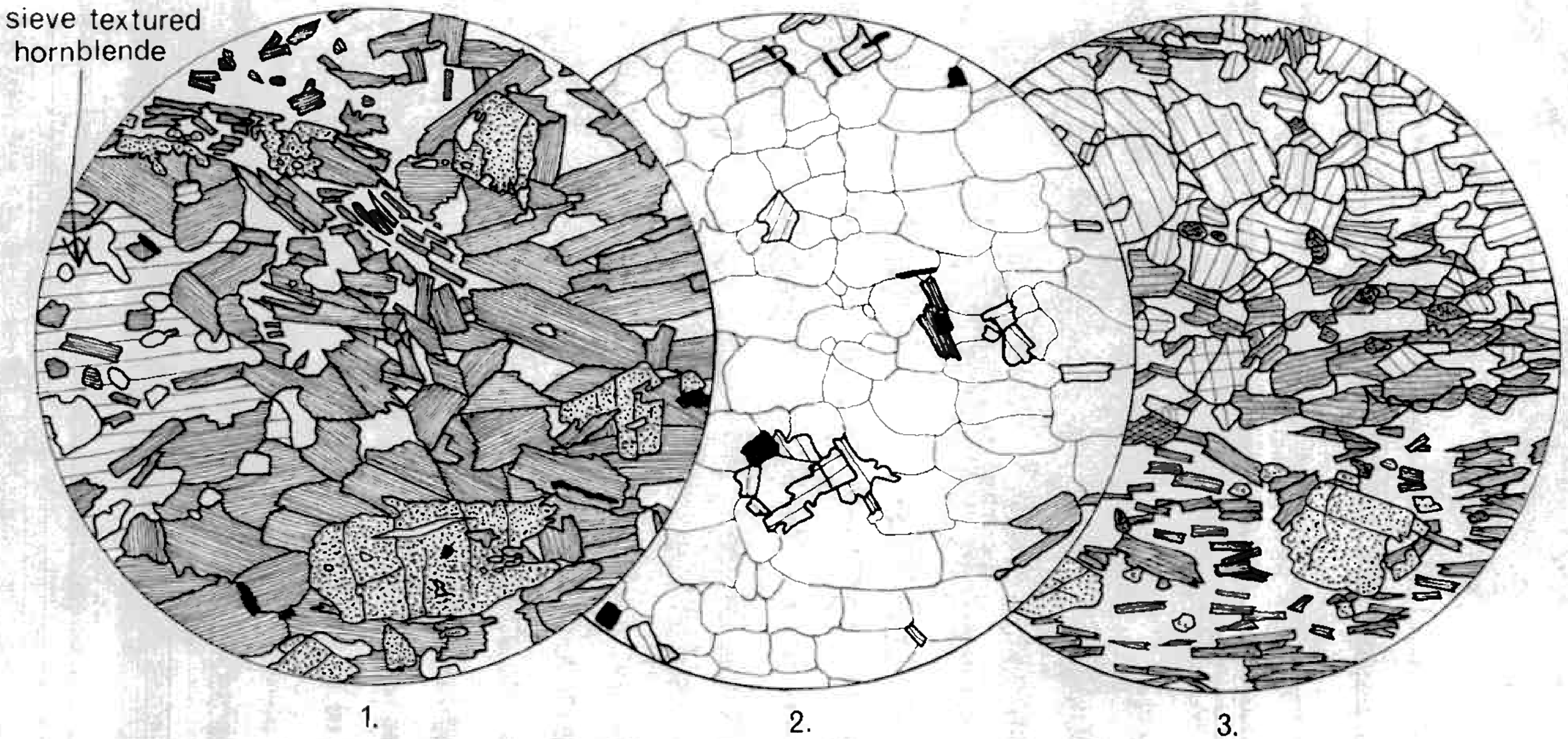
(a) and (c) The calc-silicate groups.

The rocks from these two groups are described together because of their great resemblance both in the field and in thin section. Broadly speaking, three rock-types can be distinguished; calcareous schists, amphibolites and calcareous rocks with diopside.

The calcareous schists have mineral assemblages such as biotite-quartz-plagioclase-epidote$\pm$ hornblende. Some of the less calcareous rocks

FIG. 5.4.

Calc-silicate groups, and quartzite band.



1. x 65 T42 Biotite-plagioclase-quartz-epidote-hornblende schist. The biotite is dark green.

2. x 140 T195 Quartzite from band in calc-silicate group (a). Quartz grains outlined.

3. x 140 T55 Transition between pelitic (bottom) and calcareous (top) bands in calc-silicate rock. Hornblende has been shaded to distinguish it from diopside. The dark coloured, high relief, grains are sphene.

have almandine garnet rather than epidote. Both epidote and garnet occur as porphyroblasts which appear to have grown after the development of the main schistose fabric of the rock. The biotite is green and the plagioclase has a composition of An_{25-30} and shows slight normal zoning.

The amphibolites have green hornblende, plagioclase, quartz and clinozoisite. The plagioclase is strongly zoned with cores as calcic as An_{40} but the edges seem to approach the composition of the plagioclase in the calcareous schist.

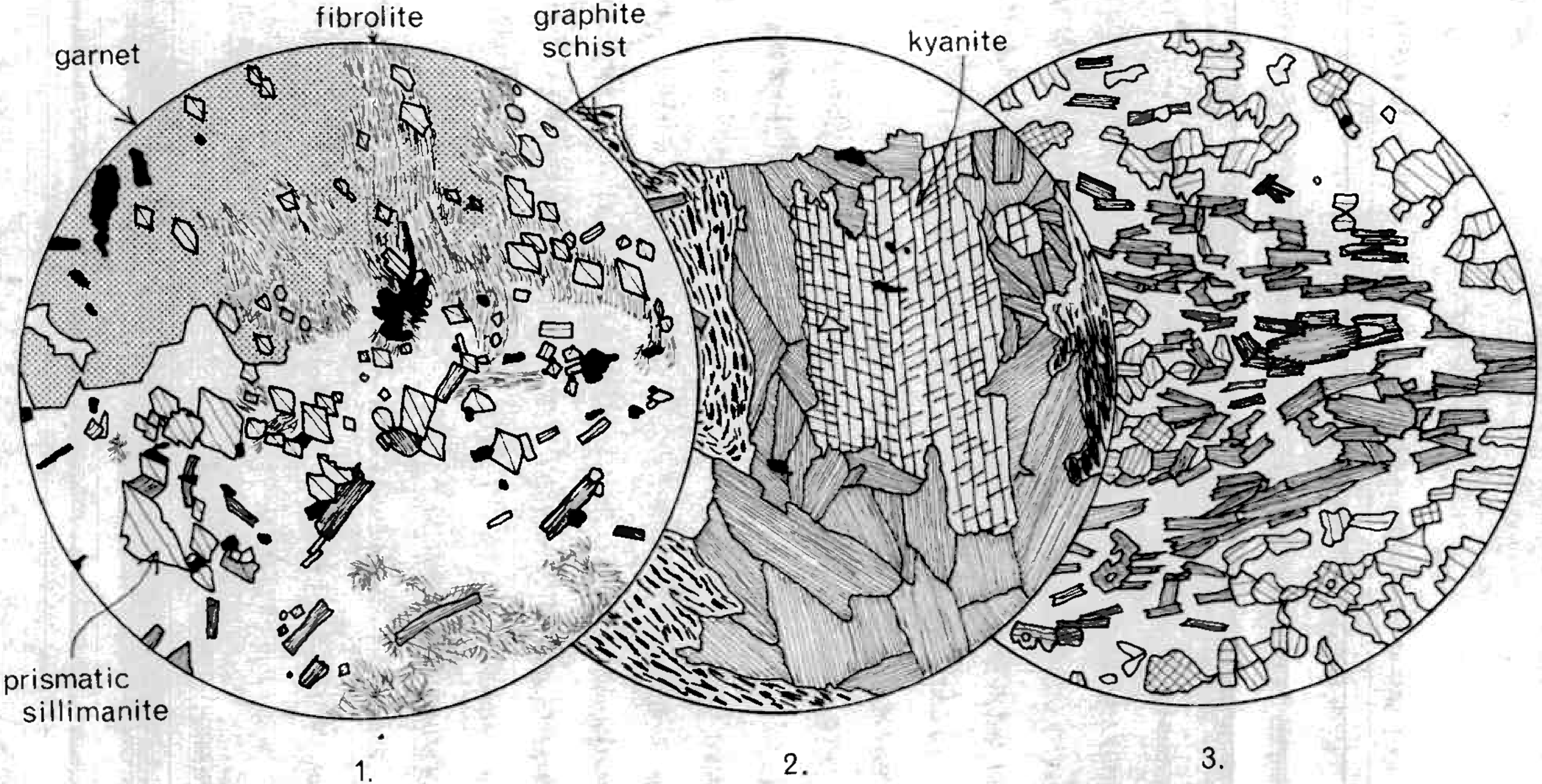
The most lime-rich rocks contain diopside, plagioclase and quartz. The plagioclase seems to have a composition about An_{40}, but in some thin sections the diopside-andesine assemblage appears to be breaking down to hornblende- clinozoisite-oligoclase (fig. 5.4).

(b) Graphitic schist.

The pelitic rocks surrounding the gabbro complex are of greater interest than the calcareous rocks in that the aluminosilicate minerals and garnets in them give an indication of several phases of mineral growth. As a few thin sections from the hornfelses and igneous breccias also contain aluminosilicate minerals and garnets, whose textures may be compared with those in the country rocks, it is possible to show that growth of some minerals preceeded and of others succeeded, the injection of the gabbro complex. For the moment, however, the sequence of minerals in rocks which show no evidence of hornfelsing due to the injection of the gabbro complex will be described.

FIG. 5.5.

<u>Graphite schist group, and calcareous semi-pelite.</u>



1. x 140 U13 Relationship between sillimanite, garnet and biotite.
2. x 140 U39 Kyanite porphyroblast altering to muscovite in graphite schist.
3. x 25 U79 Microfold in calcareous semi-pelite.

The rocks from the graphite schist group are not always graphite bearing. (The graphite bearing rocks tend to have assemblages such as muscovite-quartz-graphite-plagioclase). Assemblages such as quartz-plagioclase-muscovite-biotite-almandine-aluminosilicate occur. Some rocks contain staurolite. Two aluminosilicate minerals are present in the graphite schist group and other pelitic rocks in the NE Sulitjelma area, kyanite and sillimanite. Sillimanite occurs in two different habits, as quite large prismatic crystals and as very fine "fibrolite" needles. Kyanite and garnet form porphyroblasts, kyanite often being partly altered to muscovite (fig. 5.5,2).

Fig. 5.5,1 illustrates the relationship seen in a thin section of specimen U13 between garnet and the two forms of sillimanite. It appears that prismatic sillimanite grew before the garnet which encloses it and the fibrolitic sillimanite later as it overgrows both garnet and the prismatic sillimanite. It also overgrows biotite. The relationship between kyanite and sillimanite in this rock is not clear as kyanite appears as isolated porphyroblasts not associated with sillimanite.

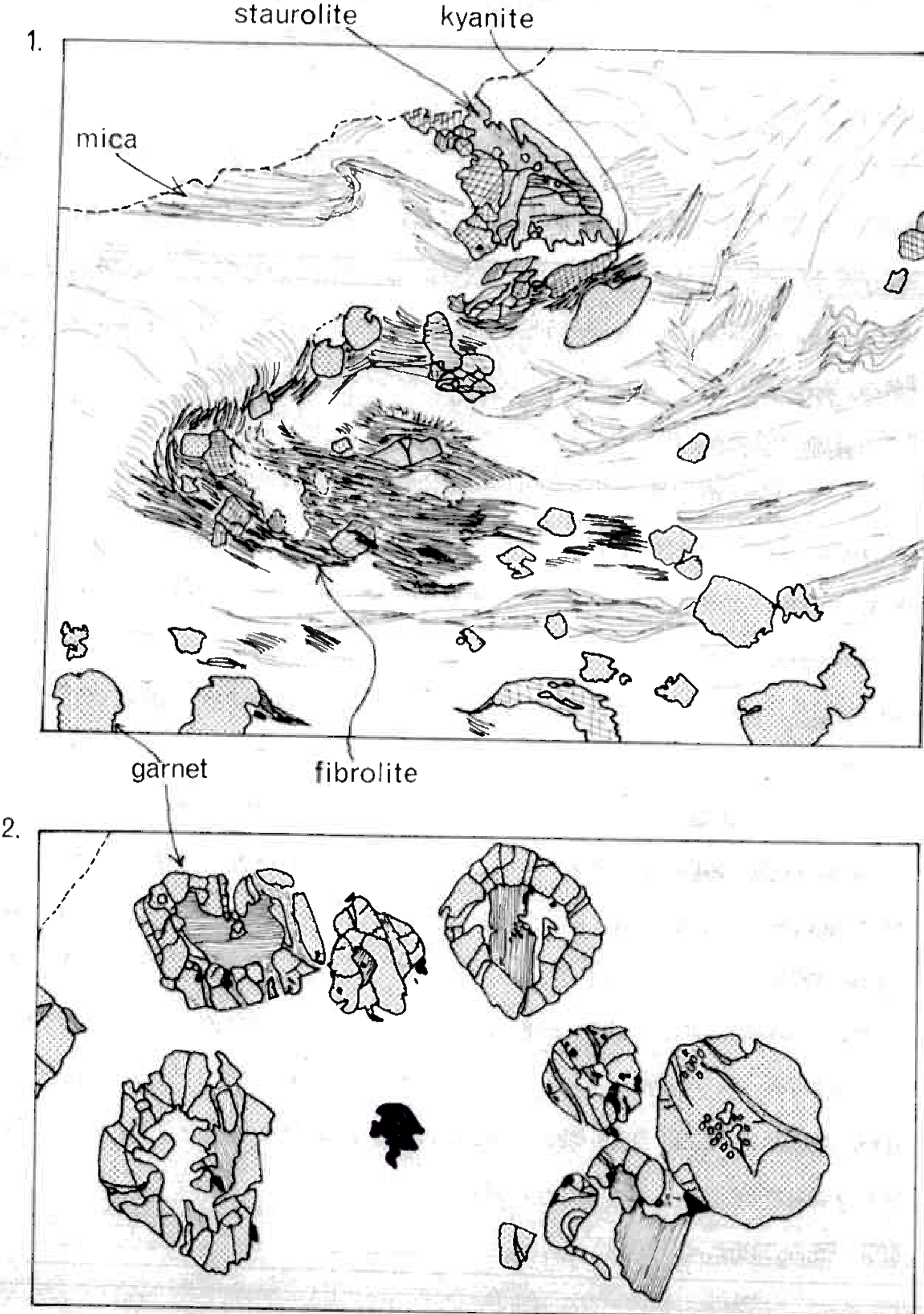
(d) Calcareous semi-pelite.

The rocks in this group which were examined in thin section turned out to be very similar in their mineralogy to the calc-silicate groups. They contain a higher proportion of carbonate minerals and some specimens show a decussate texture of the micas.

A specimen (U79) was taken from the closure of one of the

FIG. 5·6.

Kyanite schist group.



1. x 10 T284 Microfold in kyanite schist, showing folding of micas and fibrolite.

2. x 10 T48 Atoll garnets (matrix omitted, but internal assemblages in garnets shown).

possible F_{3a} folds discussed on p. 55. Micro-folds could be recognised folding the biotite bearing bands in a diopside-quartz-plagioclase rock. The biotite has recrystallised since the formation of the folds. In the hinges of the folds it shows an axial planar orientation but further down the limbs it retains an orientation parallel to the compositional banding (fig. 5.5,3).

(e) Kyanite schist group.

The minerals found in this group are similar to those of the graphite schist group, except that graphite does not occur. Kyanite, staurolite and garnet occur as porphyroblasts. The same two forms of sillimanite are seen, although fibrolite is commoner than the prismatic variety. Late muscovite is abundant in some sections associated with sillimanite. The large porphyroblasts of kyanite which often lie orientated parallel to the D_2 lineation can be seen to be deformed and fractured in thin section, and are usually overgrown by fibrolitic sillimanite. Fig. 5.6 shows a kyanite schist from the Duoldagop region (g.r. 528505). A band rich in kyanite, staurolite and fibrolite passes round a microfold. This fold formed late in the crystallisation sequence as it folds even the biotite and the fibrolite. The other sketch shows some atoll garnets from the kyanite schist group close to the contact with the gabbro complex (g.r. 568540).

(f) Micaceous psammite group.

These rocks are rather fine-grained psammites with a granular or mosaic texture of the quartz and felspar grains (both plagioclase and potash felspar are found). Small oriented flakes of biotite and muscovite lie parallel to the cleavage. More aluminous bands contain prismatic sillimanite, and more calcareous bands epidote.

(g) Calc-silicate group of Duoldagop.

These rocks will not be described here. An account of their petrography will be given by Larsen.

Conclusions.

The porphyroblast minerals in the pelitic rocks can be divided into two types, those such as kyanite and staurolite which crystallised at the same time or earlier than the formation of the main schistose fabric (S_2) and those such as garnet and epidote which tend to overgrow the main fabric. Biotite, muscovite, quartz and plagioclase make up the main fabric of the rock, though in section U79 there is evidence that biotite recrystallised after the formation of an F_3 fold. Fibrolitic sillimanite overgrows garnet, biotite, kyanite and staurolite and so must have crystallised very late in the sequence of minerals. Muscovite and chlorite often appear to have grown later than the formation of the main fabric of the rock. The calcareous assemblages show that diopside developed as a regional mineral but later altered in some specimens to hornblende.

A detailed description of phases of growth of metamorphic minerals in relation to phases of deformation, and to the injection of the gabbro will be postponed until the petrography of the hornfelses immediately surrounding the gabbro complex has been described.

The maximum metamorphic grade of the rocks seems to be fairly uniform in the country rocks of the Gasak nappe surrounding the gabbro (neglecting the hornfelsing due to the injection of the gabbro complex). In the pelitic rocks the assemblages quartz-kyanite-staurolite-muscovite-plagioclase-biotite and quartz-almandine-muscovite-biotite-plagioclase seem to have been stable throughout the area. Plagioclase in equilibrium in the groundmass tends to have a composition An_{25-30}.

It appears that the conditions of metamorphism corresponded to the almandine-amphibolite facies of Fyfe, Turner and Verhoogen (1958). If the early formation of kyanite and the later formation of silliminite are a guide to a change in the conditions of metamorphism (silliminite can hardly be said to have grown in equilibrium with all the other minerals in most rocks) then there was a change from conditions corresponding to the staurolite-quartz subfacies to those corresponding to the silliminite-almandine subfacies.

Hornfelses.

Hornfelses are found in two different situation associated with the gabbro complex. They form a narrow zone round the contacts of the complex, and they occur as particles in the igneous breccias. Both types show evidence of metamorphism to the pyroxene hornfels facies, but the particles in the breccias show a wider range of variation in bulk rock composition. In this section only the contact hornfelses of the gabbro complex itself will be described.

The massive hornfelses found near the contacts of the gabbro complex and occasionally in xenoliths in the gabbros show a variety of mineral assemblages. The commonest are :-

clinopyroxene - plagioclase ± quartz ± biotite

orthopyroxene - clinopyroxene - plagioclase ± quartz ± biotite

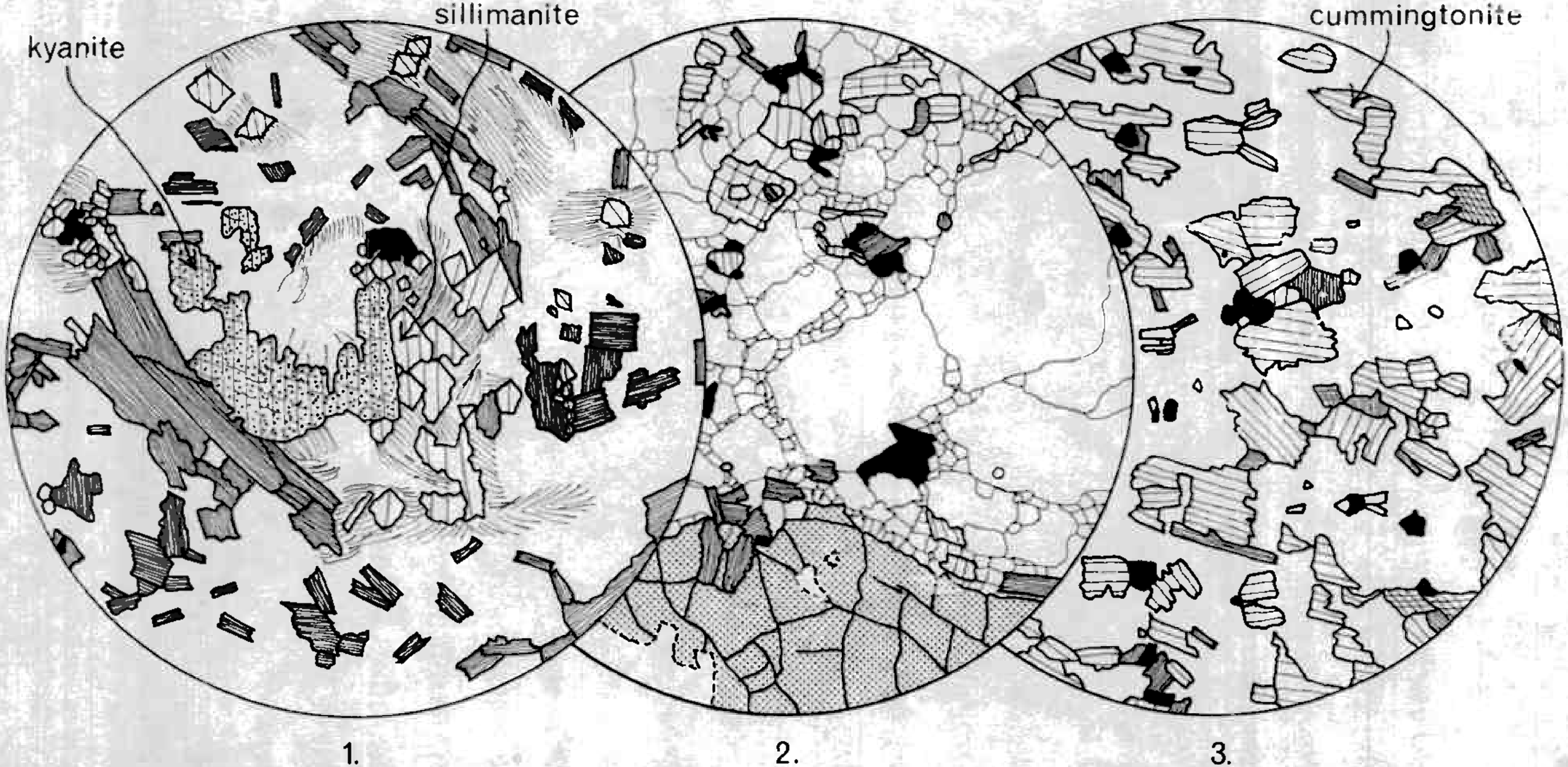
orthopyroxene - plagioclase ± quartz ± biotite

These rocks have a granular texture and are fine grained. The plagioclase varies in composition from An_{65-70} in xenoliths in the gabbro to An_{45-50} in some of the hornfelses from the contact aureole. Calcareous hornfelses occur, with assemblages such as clinopyroxene (diopside)-quartz-calcite, but as these are more extensively developed in the igneous breccias they will be described there. Aluminous hornfelses contain sillimanite and kyanite when silica saturated, or spinel when undersaturated with silica. The spinel is the green ferriferous variety pleonaste, and in one thin section is rimmed by orthopyroxene and in another by a colourless spinel. Scapolite is also found in some hornfelses.

Some of the hornfelses have been altered since the thermal metamorphism. They do not show alteration comparable with the deuteric or early post consolidation alteration phase in the gabbro complex itself (see p.57) but they do show the effects of cataclasis, and of

FIG. 5.7.

Hornfelses.



1. x 140 S26 Relationship between kyanite, prismatic sillimanite and fibrolite.
2. x 65 T111 Garnetiferous cataclastic hornfels.
3. x 140 S100 Cummingtonite bearing "metahornfels".

amphibolitisation of pyroxenes. A hornfels which has undergone cataclasis is shown in fig. 5.7,2. Amphibolitisation has led to the production of cummingtonite from orthopyroxene, and of green hornblende from clinopyroxene. Clinozoisite appears in the calcareous hornfelses, and almandine garnet in pelitic hornfelses, overprinting the hornfelsic texture.

What light do the hornfelses shed on the sequence of growth of the Al_2SiO_3 polymorphs? Two specimens only were found to contain both kyanite and sillimanite, S26 and S107. Sillimanite is quite widely developed in the schistose hornfels strip SE of Smasorjus, but whether it formed during the thermal metamorphism, or during the superimposed later regional metamorphism is uncertain.

Specimen S107 and S26 are sufficiently interesting and crucial to the dating of the intrusion of the gabbro complex to be described in detail :-

S107. This comes from a large yellow weathering xenolith in the gabbro, near its northern contact N of lake 933 (g.r. 517542). It consists mostly of quartz grains in a mosaic pattern, but among these are grains of rutile and of the prismatic variety of sillimanite. Kyanite appears as lenses of large grains with inclusions of rutile and as occasional small crystals in the quartz mosaic. It shows some alteration to muscovite. Prismatic sillimanite shows a tendency to preferred orientation in the plane of the kyanite lenses. Kyanite is not found in contact with the prismatic sillimanite, so direct evidence of the time-relations of these two minerals is not available.

The significance of this specimen lies in the presence of the kyanite in a xenolith in the gabbro. The surrounding gabbro is not amphibolitised, although it shows some cataclastic deformation. This means that it is unlikely that the xenolith recrystallised after thermal metamorphism, i.e. it seems unlikely that the kyanite grew after the intrusion of the complex. The kyanite inclusions are lenses, and not veins; and the small crystals of kyanite in the quartzite tend to occur in streaks parallel to the lenses. There is no fracturing of the quartz mosaic near the lenses. While it must be admitted that this evidence is all rather negative, it seems probable that kyanite crystallised before or during the intrusion of the gabbro complex.

S26. This is a hornfels of semi-pelitic composition, collected from a large area of hornfels associated with igneous breccias, just NE of the Småsorjus lakes (g.r. 516529). The specimen was collected about 2 m. away from the contact with the gabbro. The thin section includes some amphibolite.

The main part of the section consists predominantly of quartz, plagioclase (A_{46} in the cores, irregularly zoned) and biotite. The biotite has a decussate texture. In this matrix are very irregularly shaped porphyroblasts of staurolite and kyanite, and masses of sillimanite. Fibrolitic sillimanite fringes both kyanite and prismatic sillimanite.

In one place, kyanite, fibrolite and prismatic sillimanite can be seen together. The relationship is shown in fig. 5.7,2.

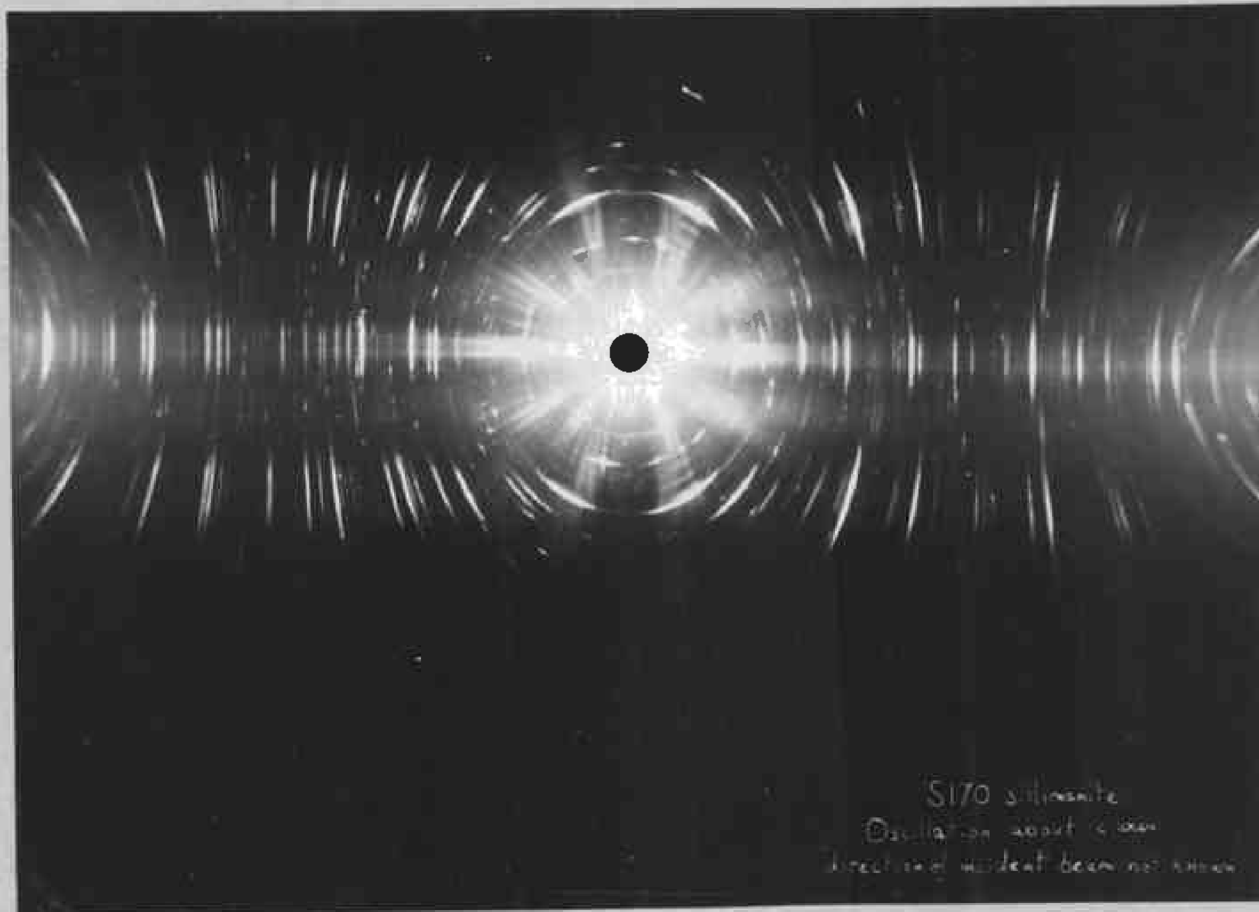
It is not possible to state beyond argument that the kyanite formed before the sillimanite, but the irregular shape of kyanite crystals suggests that they may be partly broken down, whereas the sillimanite crystals retain their crystal outlines.

In parts of the section there has been some late-stage growth of muscovite and clinozoisite. Accessory minerals are apatite and ore.

This section provides the best evidence for the order of growth of the Al_2SiO_5 polymorphs that has been found. It is tentatively suggested on this basis that kyanite grew before the intrusion of the gabbro complex, that prismatic sillimanite grew during or a little after the intrusion, and that fibrolitic sillimanite grew afterwards. An obvious alternative theory is that the kyanite grew at the time of injection of the complex, and both generations of sillimanite later. But it is difficult to explain the textures of the minerals on the assumption that kyanite grew after the intrusion of the gabbro complex.

The strip of hornfels running SE from Smasorjus from g.r. 521521 to 539510 between the gabbro complex and the Furulund granite has undergone particularly marked cataclasis, and also some regional metamorphism. This has produced sillimanite schists with occasional patches of less altered hornfels, and other patches resembling deformed igneous breccias.

... photograph of sillimanite aggregate.



CuKα radiation. Radius of camera 3 cms. Axis of rotation approximately parallel to c-axes of sillimanite.

Both fibrolite and prismatic sillimanite are present. The latter often shows a preferred orientation parallel to the pronounced D_2 lineation which has been imposed on this strip. Specimen S170 is particularly remarkable in that the sillimanite occurs as augen-like bundles of fibres, elongated parallel to the D_2 lineation, and partly altered to muscovite. The basal sections of a bundle of the fibres gives a rather indistinct centred positive acute bisectrix figure on examination between crossed polars in convergent light and in a prism section the fibres show extinction positions lying within a spread of about 5° under orthoscopic illumination, under crossed polars. This suggests that the augen are formed of fibres of sillimanite with almost, but not quite the same orientations; the long axis of the cluster being almost parallel to the c-axes of the sillimanite fibres. This was confirmed by taking an X-ray oscillation photograph of one of the augen, oscillating about the axes of the fibres which were perpendicular to the X-ray beam. The result was a photograph intermediate in character between an oscillation photograph and a powder photograph, the spots smearing out into rings (fig. 5.8 c.f. Henry, Lipson and Wooster fig. 124.2). The repeat distance along the c-axis corresponds approximately to that in sillimanite.

It seems difficult to explain this preferred orientation of the sillimanite fibres if each grew independantly. It seems more likely that the augen are pseudomorphs, but whether after kyanite or a single large crystal of sillimanite is impossible to say.

Fig. 5.9.

Variation in matrix composition round a xenolith in igneous breccia.

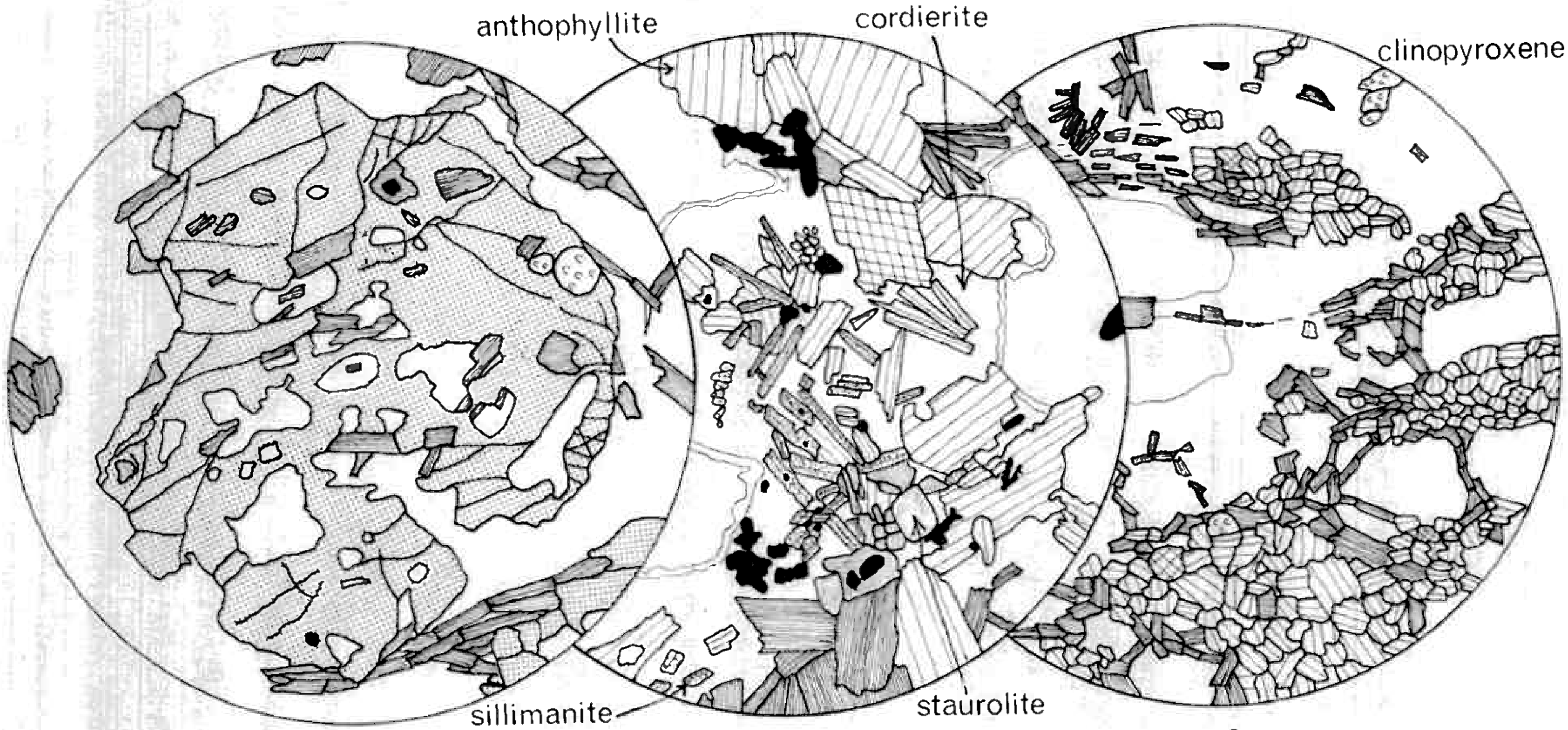
Photograph by C. Halls.

Igneous breccias.

The location of these rocks in the gabbro complex has already been described (p. 5). They show a remarkable variety of rock type and textures. Only a brief petrographic account of them will be given here, as they are not directly concerned in the main topic of this thesis, but they deserve more detailed attention in the future. Although they are probably igneous rocks, and formed slightly later than the gabbro complex, they are described in this chapter on the country rocks because the particles in them may be compared with the hornfelses which have just been described, and there is a possibility that the rocks as a whole may have formed by melting of country rock near the contacts of the gabbro complex. Vogt, in his memoir mentions the existence of igneous breccias in the "great Sulitjelma phacolite" (p. 146). However, these occur in the amphibolites in the upper part of the Pieske-Vasten nappe, and probably correspond to the leucocratic net veining of the porphyritic amphibolite group mentioned briefly on p. 23 of this account.

The igneous breccias which will be described here consist of rather rounded fragments, from 1 cm. to several metres across in an apparently igneous rock matrix. While occasionally there is some evidence of post consolidation alteration, both of cataclasis and of amphibolitisation, on the whole the rocks retain their original igneous character. It may be that they have been protected from post consolidation deformation and metamorphism by the hornfelses and gabbro which surround them. The matrix material of the igneous breccias

FIG. 5·10.



1. x 25 S182 Skeletal garnet overgrowing biotite and quartz in igneous breccia matrix.

2. x 140 S32 Anthophyllite, biotite and quartz.

3. x 25 S193 Possible relict ophitic texture in hornfels xenolith.

consists essentially of plagioclase (An_{35}-An_{65}) potash felspar (microcline or orthoclase, often perthite), biotite and quartz. It is usually coarse grained, the biotite flakes being up to 2 mm. long. The felspars and quartz tend to be granular with rather irregular grain boundaries. In one thin section there are micrographic intergrowths between quartz and plagioclase. In addition to the minerals described above, almost all specimens contain very large skeletal garnet crystals, overgrowing the other minerals (fig. 5.10). Apatite is an abundant accessory mineral, and in one section forms a major constituent. Ore is also present in irregular grains. One thin section contained cordierite, mostly altered to the micaceous substance known as "pinite". In some specimens potash felspar is not abundant, and the matrix material may be described as "trondhjemite". The others may be described as granites or granodiorites, although their composition is very varied.

In the field it is often possible to recognise that the composition of the matrix alters in the neighbourhood of a xenolith; for example a pelitic xenolith may be surrounded by more garnetiferous matrix material.

The xenoliths in the igneous breccias are hornfelses, and all the types recognised in the contact aureole of the gabbro complex appear as xenoliths in the igneous breccias also. The greatest variety of xenoliths is in the large area of igneous breccia on the ridge N of pt. 1787 (g.r. 590500). Here among others, can be seen pure quartz xenoliths, xenoliths composed of relatively pure marble, with aluminous and siliceous bands, and xenoliths showing a meta-ophitic texture, suggesting that they were once gabbros.

A number of calcareous xenoliths were found at g.r. 593505. They were relatively large, 4-5 m. long and 1-2 m. across. In the xenoliths calcite and quartz remain stable together. The xenoliths are banded, some bands being rich in calcite, some in diopside and some in grossular. Plagioclase (about An_{70}) can be seen partly altered to scapolite. Microcline and biotite are found in some bands, and accessory sphene is present. A smaller xenolith nearby contained wollastonite in the core. A thin section (T182) right through the xenolith was studied. The matrix material is trondhjemitic (quartz-plagioclase-biotite) but the plagioclase has an unusually high anorthite content (zoned normally An_{61} to An_{70}), and pale green crystals of secondary hornblende are present. The outermost part of the xenolith is a quartz-diopside-plagioclase (An_{74}) assemblage. The middle zone consists of diopside-scapolite-calcite with myrmekitic clinozoisite and a little green hornblende, which are probably secondary minerals. The core of the xenolith is composed of wollastonite only.

It is thought that the production of wollastonite in the small xenolith but not in the large may be a result of different pressures of CO_2 at the time of thermal metamorphism. In the large, calcite rich xenoliths, the partial pressure of CO_2 in the centre of the xenolith would be appreciable, while in the smaller xenoliths CO_2 could escape into the surrounding igneous magma. The reaction

$$\text{calcite} + \text{quartz} \rightleftharpoons \text{wollastonite} + CO_2$$

is sensitive to the partial pressure of CO_2 (Harker and Tuttle 1956). The upper limit of stability of calcite + quartz is 600°C at a partial pressure of CO_2 of 5,000 lbs/in^2 (0.34 kb) and 770°C at 40,000 lbs/in^2 (2.76 kb). The total pressure at the time of formation of the breccias was probably higher than this, but the proportion of the total pressure represented by the partial pressure of CO_2 is unknown. The higher temperature is probably nearer the temperature of formation of the breccias.

It appears that the anorthite content of the plagioclase in the matrix material of the breccia rises appreciably near the calcareous xenoliths. One specimen from close to the edge of the large xenoliths shows curious sieve-textured plagioclases with a composition about An_{70}. They contain globular inclusions of quartz.

The brown hornblende bearing hornfels T179, from which the analysed hornblende was separated, also comes from a block in the igneous breccia. Brown hornblende appears in several other specimens also, including some from the col between pt. 1787 and Suliskongen (g.r. 597492) which contain patches which resemble the pyroxenite found on the summit of Suliskongen (specimen T191). Some hornfelses have been found which show possible relict ophitic textures, where the original large pyroxenes have been replaced by aggregates of equant grains, and many of the plagioclase laths have also been replaced in a similar way by small grains, although others apparently remain unrecrystallised (fig. 5.10). The hornfels also contain substantial amounts of biotite, and the plagioclase shows patchy irregular zoning.

Sillimanite was found in a remarkable specimen from the patch of igneous breccia N of Såmsorjus (fig. 5.10) (Specimen S32, g.r. 516532.) This specimen consists of a very aluminous xenolith in a trondhjemitic matrix. The core of the xenolith is rather coarser grained than the outer parts. The outer part of the xenolith is typical pyroxene hornfels with plagioclase (strongly zoned, outer portion about An_{20}), quartz, pleochroic orthopyroxene and ore. The inner part consists of the assemblage biotite-staurolite-anthophyllite-cordierite-quartz. Large garnets grow in this, and also prismatic grains of sillimanite. Between cordierite and quartz a narrow reaction rim occurs. It has low birefringence and a lower R.I. than the quartz and the cordierite, but the rim is too narrow to obtain an interference figure. The anthophyllite occurs in rather irregular prismatic grains, and the staurolite forms euhedral to subhedral crystals, some even showing the characteristic "cross" twins.

The cordierite-anthophyllite-quartz association is an interesting one. According to Fyfe, Turner and Verhoogen an assemblage of this kind is characteristic of the hornblende-hornfels facies, for which their type example is the granite aureoles at Orijärvi, described by Eskola in 1915. In the pyroxene hornfels facies quartz-cordierite-hypersthene would be stable instead. The division occurs with the reaction

$$\text{anthophyllite} \rightleftharpoons \text{enstatite} + \text{silica} + H_2O.$$

In the case described here it is unlikely that a change in metamorphic facies appears within the thin section. It seems probable that the reaction is driven to the left by a high chemical potential of water, which might well arise locally in a xenolith in igneous breccia. Cordierite-anthophyllite assemblages have been recorded from thermal aureoles, for example by Tilley in 1935 from Kenidjack and Botallack, Cornwall, but when they occur on a wide scale the composition of the rocks has been altered by metasomatic processes.

Sufficient has been said here to indicate the variety and petrological interest of the igneous breccias. Their mode of formation is not obvious, but it seems very likely that the small areas of fringing hornfels, such as that on Vaknačokka (g.r. 558465) or that by Småsorjus (517534) might have formed by local remelting of screens of country rock by the magmatic heat of the gabbro complex. The extensive area of igneous breccia on the ridge N of pt. 1787, however, seems unlikely to have formed in this way, unless it is merely a relatively thin sheet overlying the gabbro complex, forming only the crest of the ridge. This is by no means impossible, as the foot of the cliffs east of the ridge has not been visited. But the breccias do outcrop over a vertical range of some 500 m. or more, so the sheet would have to be folded in conformity with the topography, or else be very thick. Alternatively, the breccias in this extensive area may be intrusive, with the granitic matrix representing a true magma, more or less contaminated by the fragments of country rock it has accumulated. But speculation is useless without more evidence than is available at present. What is required is detailed mapping of the northern slopes of Suliskongen, and an extensive programme of sampling, but the area is remote and only clear of snow during late July and August.

It seems that in some specimens, almandine grew after the consolidation of the igneous breccia, and the hornfelsing of the xenoliths in it. The skeletal habit of the garnets is difficult to explain otherwise. That the garnet is almandine was checked by a chemical analysis of a garnet (appendix 2). This gave a recalculated composition as follows :-

Almandine	64.8
Andradite	2.6
Grossular	2.3
Pyrope	27.4
Spessartine	2.8

Conclusions.

In this chapter a petrographic description of the rocks which surround the gabbro complex has been given in order to demonstrate that :-

1. There have been several phases of mineral growth in the regional metamorphic rocks surrounding the gabbro complex.

2. The earliest phase, the growth of kyanite and staurolite porphyroblasts, preceded the intrusion of the gabbro complex, or possibly was contemporary with it.

It has been assumed, following Henley, that the main schistosity (S_2) displayed by most of the country rocks formed during the D_2 deformation episode, and therefore after the intrusion of the gabbro complex. While specific petrographic evidence for this assumption has not been provided it explains two observations well :-

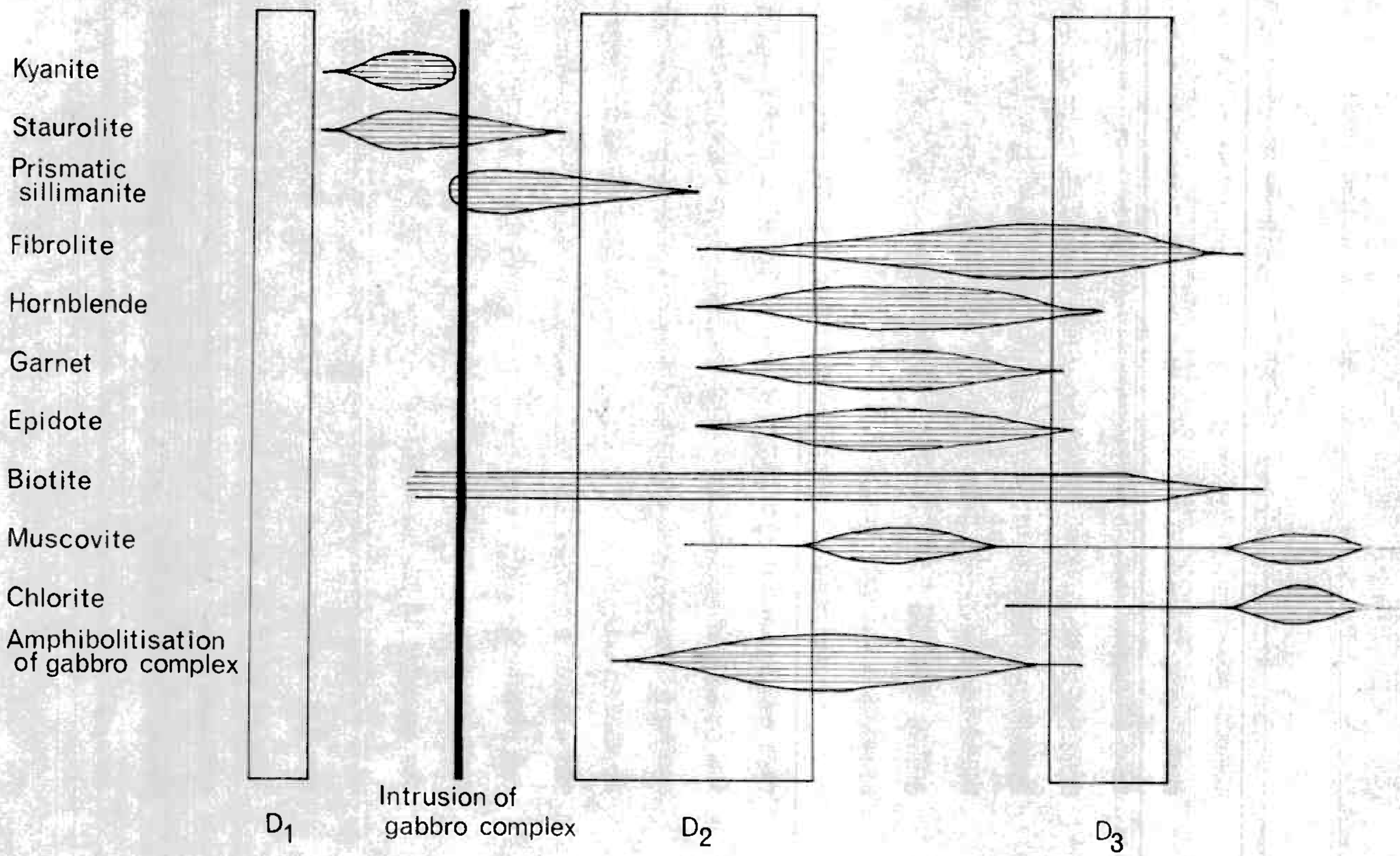
1. The very narrow contact aureole round the gabbro complex. Further out, the less massive contact metamorphic assemblages have been obliterated by the later recrystallisation during and following the D_2 deformation episode.

2. The large scale concordance between the contacts of the gabbro complex and the country rock schistosity, noted by Vogt.

In addition the imposition of foliation and lineation on the gabbro complex itself associated with the metamorphism of the primary igneous assemblages to amphibolites, supports the suggestion that extensive recrystallisation occurred during and after the D_2 episode. The imposition of foliation and lineation on the Furulund granite occurred during the same episode.

FIG. 5·11.

SUMMARY OF MINERAL GROWTH IN COUNTRY ROCKS.



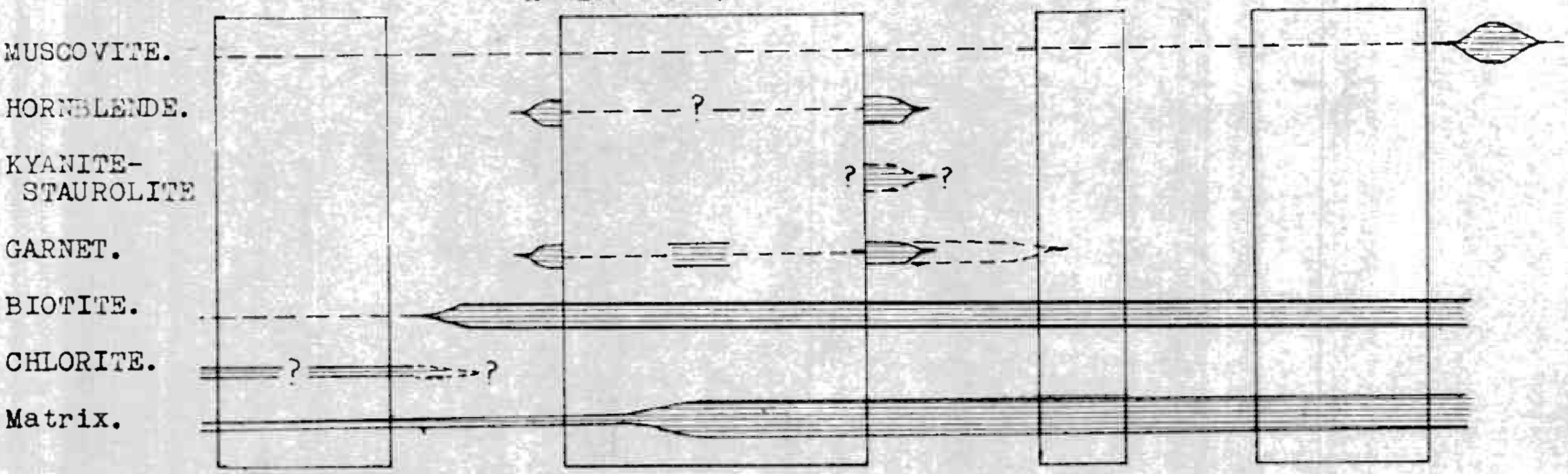
It is now possible to present an account of the deformation, mineral growth and intrusion in the Gasak nappe rocks of the NE Sulitjelma area during the Caledonian orogeny. This is given in fig. 5.11, in which time is represented as the horizontal axis, and the growth of metamorphic minerals shown in bars of varying thickness. For comparison, Henley's synthesis of data on mineral growth in the same unit is given, (fig. 5.12) based largely on his observations in the Baldoaive synform SW of the gabbro complex. It should be noted that his conclusions for kyanite and staurolite are only tentative.

One thing a comparison of the two diagrams does make clear is that the intrusion of the gabbro complex forms a well-defined event in the early part of the structural and metamorphic sequence, which makes it easier to decide which minerals grew before the main D_2 structural event. It will be seen that the two schemes agree in placing the main growth of the almandine amphibolite facies minerals, hornblende, almandine, epidote and fibrolitic sillimanite after the D_2 episode. But one important difference is that Henley regards this as the climax of metamorphism. For example, he has observed "S" shaped trails in garnets which correlate with electron-probe determinations, showing that the cores of these garnets are far more manganese rich than their margins (Harte and Henley 1966). This he takes as evidence that the garnets grew in a prograde environment, although he points out that other explanations are possible. These observations, however, are from rocks in the Pieske-Vasten nappe. The

Fig. 5.12.

SUMMARY OF DEFORMATION AND METAMORPHISM OF THE UPPER UNIT (GASAK NAPPE).

Henley 1966.



D_1

Formation of early fine grained fabric (schistosity S_1).

D_2

Penetrative differential movements giving rise to the present main schistosity (S_2) and mica lineation. Movement possibly W to E. Hornblendes oriented. F_2 tight folds with axes trending E-W and axial planar schistosity.

slight compression

D_3

Open assymmetric folds. Incipient axial planar schistosity.

In addition there is a later D_4 episode of open folding, not shown in the diagram.

rocks in the Gasak nappe do not give such clear evidence of mineral growth during rock deformation. The present writer, on the other hand, believes that kyanite and staurolite were present in the country rocks before the intrusion of the gabbro complex. Admittedly, the textural evidence for this is not irrefutable, but the alternative is to regard the kyanite and staurolite found in the hornfelses as the result of contact metamorphism, and the kyanite and staurolite in the country rocks away from the gabbro complex as due to later regional metamorphism.

If it is assumed that kyanite and staurolite grew before the intrusion of the gabbro complex, two possibilities arise. Either the rocks underwent two phases of almandine-amphibolite facies metamorphism, the first to kyanite grade, the second to sillimanite grade, with a cool period intervening during which the gabbro was intruded, or the gabbro was intruded into rocks undergoing amphibolite facies metamorphism. The writer prefers the second hypothesis, partly because of the similarity between the Sulitjelma gabbro and the Hasvik gabbro on Søröy (Sturt 1966) for which there is more positive evidence of intrusion during amphibolite facies metamorphism, and partly because a number of observations can be explained by this hypothesis. These are :-

1. The unusual degree of development of kelyphitic margins and brown hornblende, which can be explained if the surrounding country rocks were hot, by the long time available for deuteric reactions to occur while the complex was at elevated temperatures after consolidation.

2. The local remelting of the country rocks to form igneous breccias. If the rocks were already hot, less magmatic heat from the consolidating gabbro complex would be required to melt them.

3. The transition from brown to green hornblende in rocks near the top of the dioritic gneiss horizon on Vaknačokka. If movement commenced on the thrust plane shortly after the consolidation of the gabbro complex while it was still hotter than the country rocks brown hornblende might form initially, and common green hornblende later, when the temperatures became closer to the regional value.

4. The inversion of the metamorphic zones on the slopes N of Lamivann shown in Vogt's map of the metamorphic zones in the Furulund schist (Pl. XXXIX). This observation has been confirmed by Henley. It can be explained if a mass of relatively hot rock was thrust over the cooler Furulund schists. This suggestion was originally made by Prof. E. W. R. Rutland.

All this should not be taken too seriously. It does seem likely, however, that there is a difference in the structural and metamorphic histories of the Pieske-Vasten and Gasak nappes.

FIG. 6·1.

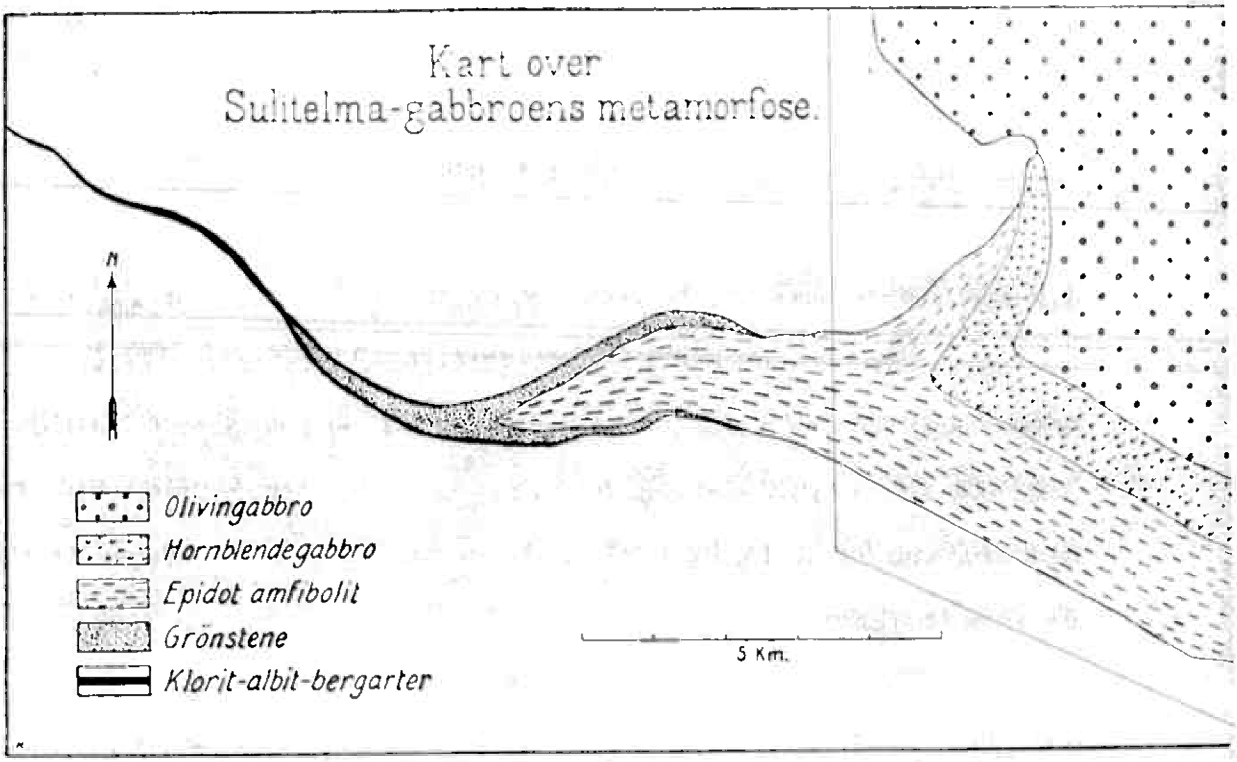


Fig. 71.

The outline of the map in the pocket of this thesis has been added.

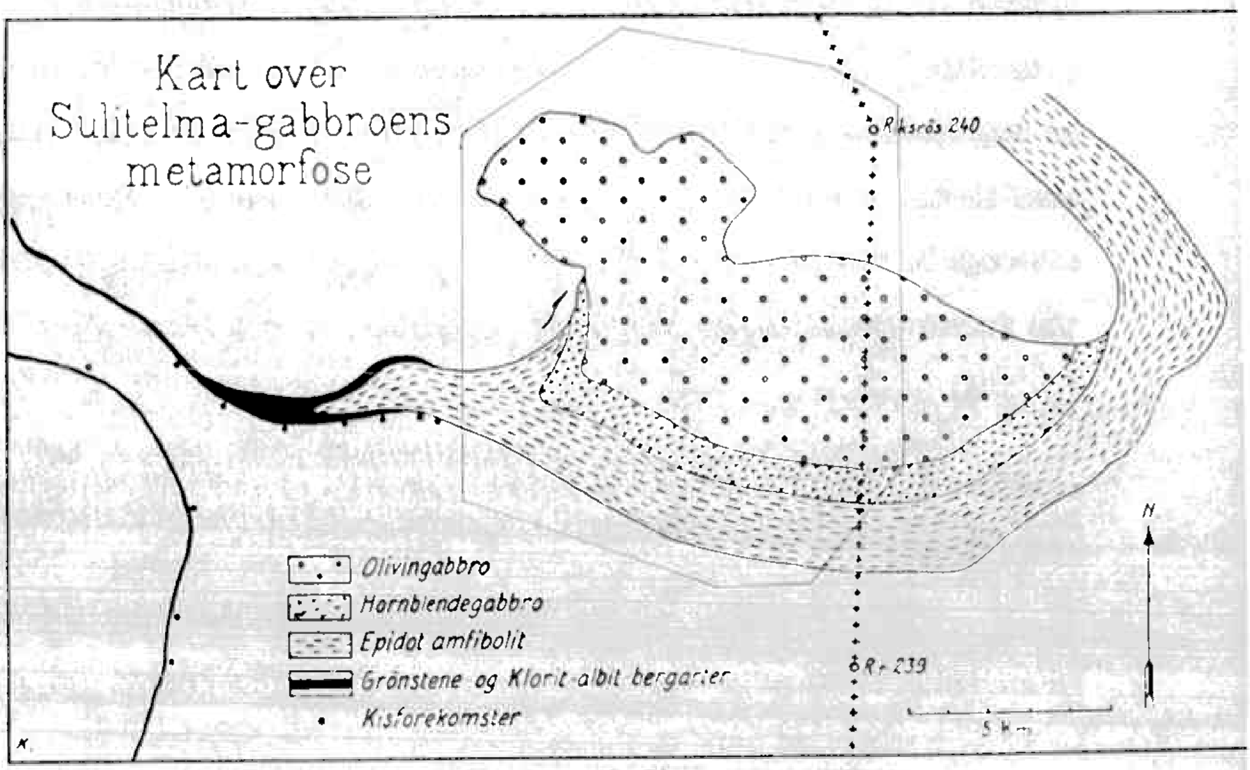


Fig. 72.

CHAPTER SIX.

A discussion of Th. Vogt's facies sequence in the Sulitjelma phacolite.

Since it is Th. Vogt's classic account of the mineral assemblages in the Sulitjelma gabbro in terms of the facies concept that has made the complex famous, now that the writer has recorded his own observations it is appropriate to explain why Vogt's synthesis is rejected in this account.

The broad outline of Vogt's views concerning the gabbro complex was given in the introduction (p. 10-13). Table 9 is copied from his memoir, and shows the detailed facies-sequence of assemblages he recognised in the phacolite. Fig. 6.1 is a reproduction of his figures 71 and 72, showing the metamorphic zones as he believed they occurred in the phacolite. Vogt regarded the metamorphic facies series in the phacolite as representing a series of mineral assemblages approximating to chemical equilibrium in accordance with Goldschmidt's mineralogical phase rule, although he recognised that equilibrium might not be attained in either the facies series in the phacolith, or that in the Furulund schists (p. 374) :-

"In both these series an approximation is reached to equilibrium conditions, which however could seldom have been completely attained. We have series with mostly impure mineral facies, which are combined with gradual transitions."

It is a little difficult to fathom the precise intrusive and metamorphic sequence he envisaged for the gabbro complex, but the present

Table 9.

Sulitelmafeltets metamorfe gabbroserie (hovedserien)

Krystallisasion fra magma		Postmagmatisk metamorfose uten substansforandringer						Metamorfose med ekstraksion av CaO, delvis SiO_2 og til slutt Na_2O			
Olivingabbroer		Hornblendegabbroer		Epidotamfiboliter			Grønnstener			Klorit-albit-fels og klorit-skifer	
1	2	5	6	7	8	9	10	11	12	13	14
Olivin	Olivin										
Hypersten	Hypersten										
Diallag	Diallag	(Diallag)	(Diallag)	(Diallag)							
Anortit	Anortit	Anortit	Anortit	Anortit	Anortit						
Albit	Albit	Albit	Albit	Albit	Albit	Albit	Albit	Albit	Albit	Albit	
	Brun hornblende	Grønn hornblende	Grønn hornblende	Grønn hornblende	Grønn hornblende	Grønn hornblende	Grønn hornblende	Aktinolitisk hornblende			
			Myrmekitisk klinozoisit	Klinozoisit, Epidot	Epidot	Epidot	Epidot	Epidot	Epidot		
					Litt klorit	Litt klorit	Klorit	Klorit	Klorit	Klorit	Klorit
							(Kvarts)	Kvarts	Kvarts	Kvarts	Kvarts

writer's interpretation would be something like this :-

1. The gabbro magma was intruded in successive pulses, while regional metamorphism and mountain building deformation were going on.

2. The earliest intrusion of magma formed a thin sill, just above the present copper ore horizon. At this stage, metamorphism had only reached a low grade (chloritic grade) and the sill was metamorphosed to a chlorite bearing greenstone. Local metasomatism altered it to a chlorite-albite rock.

3. More magma was intruded above this sill. By now the country rocks were hotter, and the dolerites were metamorphosed to amphibolites.

4. Finally, a great intrusion of gabbro magma occurred and bulged up the roof of the sill, so that it became a "phacolite". This produced complex folding of the country rocks, for example in the Duoldagop region. The lower part of the bulge was metamorphosed to "hornblende-gabbro" (the rocks described as metagabbros in this thesis) while the upper remained hotter, so that the primary igneous minerals were in equilibrium. In a thin border round the top of the phacolite, the country rocks were converted to hornfelses. The country rocks were now at their highest temperature, the stable assemblage in the Furulund schist being quartz-oligoclase-hornblende-almandine-biotite.

Vogt thought that the influx of gabbro magma might be associated with the increase in temperature in the country rocks, and that the magmatic heat of the successive injections helped metamorphose the now solid and cooler rocks in the phacolite below. Thus he considered the phacolite to be in a true sense syntectonic.

There is one severe inconsistency in his account of the differentiation of the gabbro complex. He described the variation in the Fe:Mg ratio of the ferromagnesian minerals in the unaltered gabbros and came to the conclusion that the more felspathic gabbros contained more magnesian minerals. The present writer would ascribe this conclusion to inadequate sampling. Unfortunately Vogt gave no indication of the part of the complex his specimens came from, so comparison with the data in this account is impossible. He decided on this basis that the unaltered gabbros were the rocks in the phacolite which were most enriched in early crystallised components, following J. H. L. Vogt's (1922) scheme of differentiation of igneous rocks. The more siliceous igneous rocks from the lower parts of the phacolite were more enriched in "rest-magma components". This means that the rocks he considered to be intruded last of all crystallised from the parental magma, and the rocks he considered had been intruded earlier crystallised from magmas which had undergone differentiation. Vogt overcame this difficulty by suggesting that the magma in the early sill would be more susceptible to differentiation by filter pressing than that which flooded into the bulge of the phacolite. But surely even in 1927 it must have been clear that the reverse is the case. Extreme crystal fractionation differentiation is observed in large basic intrusions, while thin sills have more uniform chemical and mineralogical compositions.

But Vogt's ingenious sequence must be rejected on the basis of observation of the rocks themselves. The present research confirms Kautsky's conclusion that Vogt's phacolite is in fact two different groups of basic rocks separated by a major thrust horizon. The realisation that orogeny and metamorphism are complex processes involving numerous episodes of deformation and much greater lengths of time than was realised when Vogt wrote his memoir, also makes his theory more implausible.

Vogt's observations of mineral assemblages and compositions however are accurate and if his theories are rejected it is necessary to explain his observations in some other way. The main purpose of this chapter is to do this.

1. <u>The gabbro complex</u>.

Vogt's map of the unaltered gabbro outcrop agrees quite well with the more detailed mapping done for this account. The altered SW corner of the gabbro complex was mostly assigned by Vogt to the hornblende gabbro zone, although a small portion was put into the epidote amphibolite zone. Thus it can fairly be assumed that he regarded the metamorphism of the gabbro complex as having taken place under different PT conditions (corresponding to the metamorphic facies of his zones) in different parts of the complex. The present writer on the other hand considers the different metamorphic assemblages of minerals in the SW part of the gabbro complex to have formed under much the same conditions of metamorphism, corresponding to Fyfe, Turner and Verhoogen's almandine-amphibolite facies. The equilibrium assemblage produced by metamorphism was an amphibolite with plagioclase of composition about An_{30}, green hornblende and clinozoisite, and rocks approximating to this composition are found in the SW corner of the gabbro complex near the contact with the Furulund granite. Vogt mapped them as part of the epidote-amphibolite zone. The "hornblende gabbros" (metagabbros) with and without clinozoisite and with varying plagioclase compositions the writer regards as rocks which represent partial attainment of equilibrium, the particular assemblage which occurs being determined by the availability of water during metamorphism and by the degree of cataclasis which occurred during the D_2 deformation episode.

2. <u>The dioritic gneiss.</u>

Most of the dioritic gneiss horizon was also mapped by Vogt in the hornblende gabbro zone, although its western end falls into his epidote amphibolite zone. The greenstone zone and zone of chlorite-albite rock are only found west of the area considered in this account (fig. 6.1). As the dioritic gneiss consists mainly of cataclastically altered and amphibolitised gabbros, it is similar to the metagabbros of the SW corner of the gabbro complex.

3. <u>The schistose amphibolite and porphyritic amphibolite.</u>

There is a gradual decrease downwards in metamorphic grade in these units, which is displayed by the pelitic bands which occur in the schistose amphibolite horizon. The garnet isograd in the lower of these bands crosses the band near Otervann, the schists E of the lake being garnet free, while those to the west are garnetiferous (Henley pers. comm.). This is simply the extension upwards of the progressive increase in metamorphic grade observed in the Furulund schist N of Langvann. So recent work by Henley agrees with Vogt that the lower parts of the "phacolite" show an increase in metamorphic grade upwards.

In the amphibolitic rocks it is not possible to document the increase in metamorphic grade so easily, but if the plagioclase composition may be taken as a grade indicator these do show an increase upwards in metamorphic grade. It is possible however that the variation in plagioclase composition may be due to the varying degrees of attainment of chemical equilibrium in the porphyritic amphibolites.

Vogt did not record the presence of chlorite-albite rock or chloritic greenstones east of Ny Sulitjelma. The present writer finds this odd in view of the quite abundant chlorite schists near Otervann, which would have provided evidence in support of his theory. The chlorite-albite rocks he describes are those which form much of the gangue in the copper ores, which the miners call "klorit". His "greenstones" are the chloritic amphibolites found immediately above the ore horizon. These rocks fall beyond the scope of this account, and in fact are being included in a detailed study by M.D. Wilson of the University of Manchester. The present writer would make two comments concerning the chloritic rocks however :-

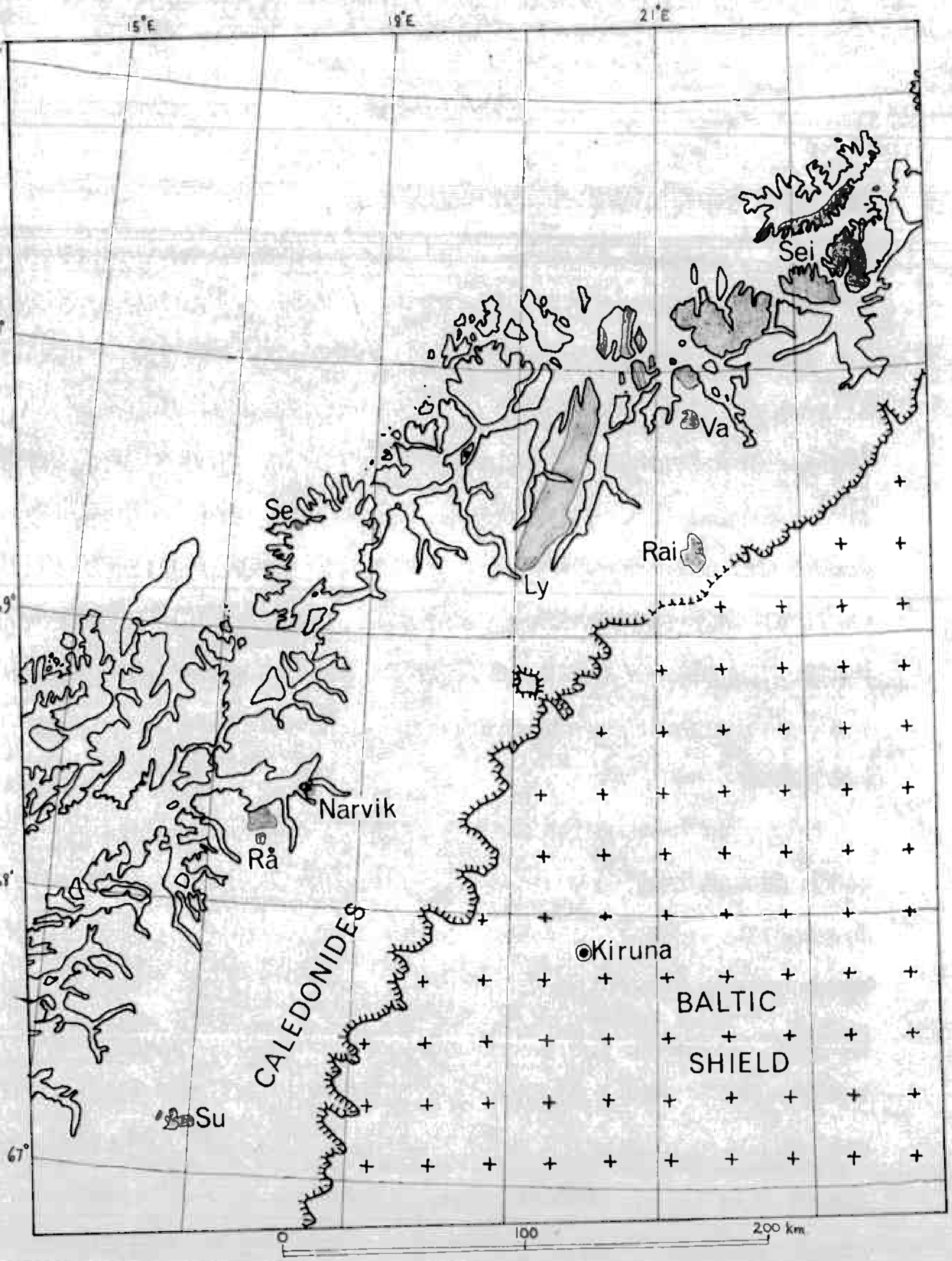
1. There is abundant evidence for late stage formation of chlorite in many of the rocks at Sulitjelma. Vogt observed this, and described it as a diaphthoresis of chlorite to biotite. Both Henley and the present writer have found late crystallised chlorite in rocks of many kinds (see fig. 5.1 for example).

2. In the region near Otervann it may be that during the main post D_2 metamorphic event, a high chemical potential of CO_2 due to the presence of marbles, and carbonate rich rocks in or near the basic rocks stabilised chlorite rather than amphibole (see Fyfe, Turner and Verhoogen 1959 p. 220).

Conclusions.

Thus it is possible to account for the facies sequence which Vogt described by a number of ad hoc hypotheses, in line with the present theories of the nature and history of the basic rocks of the NE Sulitjelma region. In defence of Vogt, however, it is necessary to add that until Kautsky's (1952) investigation of the Sulitjelma-Salojaure region across the border in Sweden no one considered that the basic igneous rocks of the Sulitjelma region were not one intrusion. Both J. H. L. Vogt and Sjögren seem to have regarded them as all part of one intrusion. Th. Vogt was still alive when Kautsky gave a first account of his conclusions, and while he admitted that a little local thrusting may have occurred at Sulitjelma, he denied that it had played a major role in the geological history of the area. Furthermore, at the most accessible part of the gabbro complex, its SW corner, only gradual transitions can be seen between schistose amphibolite and dioritic gneiss, and dioritic gneiss and metagabbro. It was only visits to more remote areas such as the summit ridge of Vaknačokka that demonstrated convincingly to the present writer the difference between the gabbro complex proper and the assorted amphibolites which now lie structurally below it.

FIG. 7·1. CALEDONIAN GABBROS OF NORTHERN NORWAY.



CHAPTER SEVEN.

Comparison with Other Areas.

1. Caledonian gabbros of northern Norway.

The Sulitjelma gabbro complex is one of several large gabbroic or noritic intrusions occurring in the northern part of Norway. Fig. 7.1 shows the locations of some which have been described in the literature. They are from north to south, the Seiland gabbro complex (Sei), the Vaddas complex (Va), the Senja gabbro complex (Se), the Lyngen gabbro complex (Ly), the Raisoddar-Haldde gabbro complex (Rai), the Råna norite (Rå) and the Sulitjelma gabbro complex (Su). This is not an exclusive list, but these are all basic complexes which have features in common with the Sulitjelma complex. There are also numerous smaller amphibolitic intrusions which have chemical affinities with the large intrusions (Foslie 1921).

The two largest intrusions are the Seiland and Lyngen complexes, which form much of the spectacular coastline of Norway between Tromsø and Hammerfest. The Seiland complex is the better known of the two, partly because it is the more accessible, and partly because it has associated alkaline igneous rocks. It is not one single intrusion, but includes basic rocks of different ages. On the island of Sørøy in the northern part of the complex Sturt and Ramsay (1965) have recognised three distinct phases of intrusion of basic igneous rocks. The first phase of intrusion formed the large Breivikbotn gabbro, and occurred at about the same time as the earliest fold movements (F_1). The smaller Hasvik gabbro complex formed between the F_1 and F_2 movements, while the rocks were undergoing regional metamorphism at almandine-amphibolite facies (Sturt 1966). Finally, between different episodes of deformation in the F_2 folding phase, norites, pyroxene-mica diorites, leucogabbros and diorites were intruded.

It is the Hasvik gabbro which displays the most similarities with the Sulitjelma gabbro complex. Kelyphitic margins are found round olivines, particularly in the olivine-rich troctolites which occur in the complex, and there is only a narrow thermal aureole. In this aureole can be seen pseudomorphs composed of pyroxene hornfels facies minerals after almandine amphibolite facies minerals. Almandine amphibolite facies minerals also grew after the hornfelsing. For example, almandine garnets are pseudomorphed by sillimanite, spinel, hypersthene and ore, but within these pseudomorphs the thermal minerals have been partly reconstituted to almandine. The complex shows distinct banding, but this is of the "Sulitjelma" rather than the Skaergaard type. The ore minerals in the Hasvik gabbro are pendlandite and pyrrhotite, often intergrown.

Other parts of the Seiland complex have also been studied in detail, but unfortunately little work has been done on the nature of the contacts, so that it is uncertain which phase of basic intrusion the complexes described may belong to. Barth (1953) has given an account of the layered gabbro complex on the island of Seiland itself, and from his account it is clear that the banding is of the Sulitjelma type. Oosterom has given a careful account of the layered gabbros on the island of Stjernøy (1954, 1956, 1963). The Lille Kufjord gabbro which he describes has three distinct peridotite bands, and is almost completely unaltered. Olivine ceases to be stable above the base of the second peridotite band and orthopyroxene predominates over clinopyroxene, so that in the upper part of the complex the rocks are in the strict sense norites. The complex shows no contact aureole. However, much of the country rock surrounding the complex is described as "gabbro gneiss" and this may well be an earlier basic intrusion which has been partly amphibolitised. Oosterom does not describe kelyphitic margins round olivine. The gentle dips of the banding in this complex, and its unaltered nature may be indications that it is a later intrusion that the Hasvik gabbro, but without detailed structural data it is impossible to be certain. Heier (1961) has also described layered gabbro from Stjernøy. The rocks of the adjacent Økafjord peninsula were studied by Krauskopf (1954). He found intercalations of nepheline syenite in the gabbro complex, and also xenoliths of limestone. He decided that the best explanation of these field relations was a process of "gabbroization" (sic) by analogy with granitisation, but in fairness it must be added that he had many reservations about this view.

The Lyngen gabbro has been less studied than the Seiland complex, largely because of the mountainous terraine that it forms. A brief account of some field relations and petrography has been given by Bugge (1942). As well as gabbros, he found serpentinised ultra-mafic rocks. Randall (1958) has written a Ph.D. dissertation for the University of Newcastle about the area but the present writer has not yet had the opportunity to read this. Parts of the gabbro complex have been metamorphosed, and some primary banding can be recognised. In his account Bugge also describes a small area of norites and peridotites near Hamn, on the island of Senja.

The Vaddas gabbro complex was described by Vogt in the same memoir as the Sulitjelma gabbro (1927). It is similar to the Sulitjelma complex in that unaltered olivine gabbros overlie amphibolites which extend as a sill-like body among the country rocks. Vogt considered it to be a syntectonic phacolite, similar to the great Sulitjelma phacolite.

Hausen (1942) has given a careful field and petrographic account of the Raisuoddar-Haldde gabbro complex on the Norwegian-Finnish border. He considered it to be similar to the Sulitjelma complex. For example, it is characterised by olivine bearing rocks such as dunite, troctolite, harrisite and allivalite, but true peridotites are rare. The olivine is very forsteritic. In most of the complex only clinopyroxene is found, but two pyroxene gabbros appear near the lower contact. However, Hausen considered that the mineral variation was not due to crystal settling under gravity, but to a filter-pressing mechanism. His main reason for coming to this conclusion seems to have been the indistinct nature of the layering by comparison with layered intrusions such as Skaergaard or Rhum. The complex has been partly metamorphosed and is situated close to the basal thrust of the great Seve nappe. Hausen described the complex as a "Caledonian ophiolite" and considered it to be syntectonic. He drew attention to the existance of several such masses in the northern Scandinavian Caledonides, citing as other examples the Råna norite and Sulitjelma gabbro.

Apart from the Sulitjelma gabbro, the Råna norite mass is probably the other Caledonian basic intrusion in northern Norway which is familiar to English-speaking petrologists, as it was described by Foslie in 1921 in the Journal of Geology. This complex has three distinct parts :-

1. A central zone of quartz norite.

2. A marginal zone of normal norite which is found at the upper and lower contacts of the lens-shaped mass.

3. Small bosses and bands in the marginal zone which are composed of lherzolite, troctolite and olivine gabbro.

In the norites the olivines are always rimmed by orthopyroxene and their composition (determined by optic axial angles) remains the same throughout the mass. Foslie considered that the rocks of parts 2 and 3 formed by magmatic differentiation by convection currents and that the central quartz norite was filter pressed from the crystal mush before consolidation was complete. However later work by Foslie (1942) revealed that the norite mass lies on the axis of a major synform and is probably to be interpreted as a synform overturned to the south (Strand, in Holtedahl 1960). Thus the quartz norite which is now surrounded and partly overlain by the normal norite probably originally formed above it in a layered intrusion. A small norite mass lies on the axis of the synform at Sørfjorden and is probably part of the same intrusion. The Råna norite has undergone partial amphibolitisation.

The investigations carried out on these complexes are very varied in scope and quality and the amount of detailed chemical and mineralogical work done on them is small. However, several points of comparison with the Sulitjelma gabbro complex can be mentioned :-

1. Primary igneous banding, of the type displayed by the Sulitjelma gabbro complex is often found.

2. Olivine is present as a primary mineral, at least at some stage of the crystallisation.

3. The igneous rocks have undergone extensive deformation and metamorphism after consolidation.

It is interesting to observe that in addition to Vogt and the present writer, other workers have described the gabbros in a broad sense as "syntectonic". In the case of the Hasvik gabbro, the parallel is even closer, in that the intrusion is supposed to have occurred between the first and second deformation episode, although it should be remembered that Ramsay and Sturt's F_1 and F_2 may not correspond in time with the present writer's D_1 and D_2. None of the other workers have performed any detailed structural analysis of the deformation of the country rocks, but it is reasonable to regard "syntectonic" in their accounts as implying intrusion during the main deformation and metamorphism of the country rocks. Several workers are at present studying large basic intrusions in northern Scandinavia, and it is likely that further information will soon be available which may confirm the general conclusions suggested here.

2. The Jotunheim complex.

It is a remarkable coincidence that the highest mountains of southern Norway should also be composed of basic igneous rocks. A classic account of these was given by Goldschmidt in 1916, and a recent account of part of the area has been given by Battey (1965). Two associations of igneous rocks have been recognised. One retains relict ophitic textures and some primary minerals while the other consists of rocks which have been recrystallised at granulite facies. Both have undergone subsequent retrogressive metamorphism along shear zones to amphibolites. They have also been altered to mylonite along fault planes.

In the area described by Battey, the ophitic association is represented by the Mjølkedola purple gabbro. This consists of plagioclase (An_{40}), orthopyroxene and clinopyroxene. The plagioclase is clouded, and the pyroxenes have exsolved ore plates. Pyroxene and ore have kelyphitic borders; the pyroxene of hornblende and garnet, and the ore of biotite and garnet. Sometimes iron ore is partly converted to green spinel and plagioclase to scapolite. Battey considers the metamorphism to be "dynamic" in character because the rocks have developed a secondary foliation and are crossed by a series of low-angle movement planes. It seems possible, however, that these rocks may have undergone quite extreme temperatures and pressures but that relatively little recrystallisation of the primary minerals occurred due to a lack of an aqueous medium, as has been suggested in this account for the non-amphibolitised portions of the Sulitjelma gabbro complex. But the resemblance between the Mjølkedola gabbro and the Sulitjelma gabbro cannot be said to be very great.

The other group of basic rocks are two-pyroxene granulites. Dietrichson (1958) and Battey (1965) consider that they are a metamorphosed layered igneous intrusion, but the arguments on this are not relevant to this thesis. The Jotunheimen complexes lie in a large thrust mass, but this thrust is post metamorphic and unlike the Gasak nappe. While the basic igneous rocks have obviously been both deformed and metamorphosed, there is no evidence at the moment to suggest that they are not pre-tectonic.

3. The newer gabbros of the NE Highlands of Scotland.

A number of large basic igneous plutons are found in the Dalradian rocks of the NE Highlands of Scotland. It is not proposed to describe them in detail here, as summaries of their geological settings have been given by Read (1961, pp. 668-669) and Mercy, in Craig's "Geology of Scotland" (1965 pp. 243-245). It is sufficient to say that there is good evidence that they were intruded after the "Older Granites" but before the "Newer Granites".

Shackleton (1948) has drawn attention to the existance of primary igneous banding, apparently inverted, in one of these intrusions, the Huntly complex. His "way-up" evidence is graded bedding of cumulus crystals, and as the banding is of the relatively indistinct Sulitjelma type, the present writer feels this should not be taken as a reliable guide. But there is no doubt of the steep attitude of the banding. The intrusions post-date the early fold structures, but Johnson and Stewart (1961) consider that they were folded by the later Boyndie-Buchan group of folds. Read, however, who has done much research in the area, considers that the steep banding is a primary feature, and the intrusions are essentially post tectonic. He has produced palaeomagnetic evidence to support this point of view (Blundell and Read, 1958).

The intrusions show many of the features seen in the Sulitjelma gabbro complex, including well developed kelyphitic borders and some amphibolitisation of the primary pyroxene and olivine bearing assemblages. It is generally stated that their metamorphic aureoles overprint the regional metamorphism, but Fettes (pers. comm.) who has been studying the rocks surrounding the Huntly complex, believes this may not be the case. Unfortunately, the Newer Gabbros are very poorly exposed, so that it is difficult to investigate the nature of their contacts in detail. However, they do not seem to have the very narrow thermal aureoles of the Sulitjelma and Hasvik complexes.

Cryptic layering has been discovered in the Insch mass (Read, Sadashivaiah and Haq, 1961) and in the Belhelvie complex (Wadsworth, Stewart and Rothstein 1966). Variation in the large Insch mass is considerable and simple crystal fractionation differentiation may be complicated by partial assimilation of country rock. The variation in the Belhelvie complex is very limited (olivine Fa_{14-20}, orthopyroxene $Ofs_{15-18\frac{1}{2}}$, clinopyroxene $En_{51}Fs_{7}Wo_{42}$-$En_{48}Fs_{11}Wo_{41}$) and it was only by very accurate mineral determination that Wadsworth et al. were able to detect it. It was their paper which suggested to the present writer that it was worth while looking for small systematic mineral variations in the Sulitjelma gabbro complex. They also mention unpublished data from other workers which suggest that the variation in the other Newer Gabbros is similar. They ascribe the banding and cryptic layering in the Belhelvie complex to gravitative differentiation in place , and support Johnson and Stewart's contention that the Newer Gabbros are parts of a single layered intrusion, which was deformed during the late folding episodes.

Thus it appears, assuming that Johnson and Stewart are right, that in the Scottish Caledonides as in N Norway, there was some intrusion of large differentiated basic igneous plutons during the Caledonian orogeny. The Newer Gabbros are probably not as close in time to the main episode of deformation and metamorphism as the Sulitjelma and Hasvik gabbro complexes, but they still probably predate the last fold movements of the Caledonian orogeny.

4. Metamorphosed basic igneous plutons in the Appalachian mountain chain.

The Baltimore gabbro complex Maryland, U.S.A., displays many features in common with the Sulitjelma gabbro complex and the Newer Gabbros of Scotland. It is best known from Williams' description (1886) of the alteration of pyroxenes to fibrous amphiboles, a process which he named "uralitisation". The city of Baltimore covers much of the outcrop of the gabbro, and exposure is not good, but apparently before the city was built rounded weathered blocks of gabbro worked to the surface, and were used by farmers for building walls. They were called "nigger heads" and Williams was able to map the gabbro by their occurrence. Since Williams' account, Cohen (1937) and Herz (1951) have written papers about the complex. Cohen made a structural study. He distinguished primary banding, which he attributed to a flow mechanism, from secondary foliation which he considered had been imposed by later deformation. The distinction was often difficult because the banding and foliation are nearly always parallel. Cohen thought that perhaps the gabbro had been intruded between the two major phases of movement in this part of the Appalachian mountain chain.

Herz made a mineralogical study of the complex, having examined a section through the contact exposed in a new aqueduct. He found two maximum concentrations of plagioclase composition at An_{78-83} and An_{64-70}. The variation in compositions of olivine, orthopyroxene and clinopyroxene is very similar to that in the Sulitjelma complex, and the sequence of amphiboles forming from the pyroxenes on amphibolitisation is similar to that shown in table 6. But serpentine formation from olivine has occurred. Herz, however, rejects Cohen's suggestion that the complex has undergone metamorphism and deformation and ascribes all these changes to deuteric alteration. His views on the hornblendes in the complex have been mentioned already (p. 77). He considers the granular plagioclase-hornblende rocks to be the products of primary magmatic crystallisation, and gives them a new rock name, "bojite". His reasons for deciding these rocks are primary seem to be the calcic composition of the plagioclase, and the fact that it shows well developed complex twinning. The present writer would describe Herz's "bojites" as metagabbroic amphibolites, and tends to support Cohen's views on the history of the complex.

Another Appalachian partly metamorphosed basic igneous complex is the Cortlandt complex, Peekskill, New York, which Shand described in 1942. He developed a new technique of field investigation which he called "phase petrology", which involved the mapping of critical mineral phases within the complex. Hornblende is one such mineral, forming in large poikilitic crystals in some parts of the complex. Shand considered this mineral formed by solid state reaction, but at a deuteric stage rather than during regional metamorphism.

Probably the largest deformed and partly metamorphosed basic igneous complex is the Bay of Islands complex in Newfoundland (Cooper 1936). This complex is banded and strongly differentiated, but has been separated into a number of separate areas by post consolidation deformation.

It would be possible to multiply the number of basic igneous plutons, partially metamorphosed and deformed, by going to other orogenic belts. Some of the "ophiolites" in the Alps probably come into this category. However, since the writer has not studied the literature on them in detail they cannot be treated here.

It is hoped that this account of broadly synorogenic gabbro or norite plutons in the Caledonian and Appalachian mountain chains has shown that while they are far more synorogenic granites than gabbros, the latter are by no means rare. Some of them, at least, seem like the Sulitjelma gabbro complex to have been intruded while the rocks were undergoing regional metamorphism, and close in time to major deformation episodes in the country rocks. These synorogenic complexes often have kelyphitic margins round olivines and the relatively indistinct banding which has been described from the Sulitjelma complex. They seem to show less extreme cryptic variation than the complexes in stable parts of the earth's crust, but this may be because the orogenic complexes have been fragmented, so that no single piece shows the variation which the original complex had.

CHAPTER EIGHT.

Conclusions.

At the end of the introduction, the four main problems which faced the writer at the beginning of the study of the Sulitjelma gabbro were outlined. It is now appropriate to summarise the solutions which have emerged.

1. Vogt's "Sulitjelma phacolite" is a basic igneous pluton which has been thrust over a series of basic meta-igneous rocks, some of which are pyroclastic.

2. The Sulitjelma gabbro complex is a layered intrusion of irregular form, folded into a synform. Part of the intrusion has been inverted. It displays a marked degree of cryptic layering, implying a certain amount of differentiation in place. This probably occurred by fractionation due to crystal settling under gravity. At times magma currents were present during the settling of crystals.

3. The main phase of movement on the thrust below the gabbro complex occurred during the D_2 deformation episode. That is to say it was contemporary with the major deformation of the country rocks, although an earlier phase of deformation can be recognised. It occurred shortly before or during a phase of growth of minerals of the almandine-amphibolite facies. Thus the thrusting is similar to neither the post-metamorphic thrusting described by Kautsky, nor the pre-metamorphic

syn-F_1 thrusting described by Rutland and Nicholson.

4. A stratigraphical scheme taking account of the presence of the thrust is compared with Sjögren and Vogt's stratigraphical schemes in table 1.

Future research.

While the writer considers that the major features of the Sulitjelma gabbro complex have emerged from the past three years' research, certain aspects need to be better described. More mineral analyses, by both traditional chemical analysis of separated mineral concentrates and by physical techniques are required to confirm the differentiation trends. For this purpose more samples from the high ridges in the interior of the Sulitjelma mountains are required. There is a need also for measurements of the primary banding of the gabbro complex in these areas. The igneous breccias deserve further study.

More structural and lithological mapping is required in the Sorjusjaure region if correlation between Norwegian Sulitjelma and the ground described by Kautsky is to be certain. Nicholson, Wilson and the writer have done a little reconnaissance north of Sorjusjaure, which raises serious problems in structure and correlation.

The topic of the first appendix is only related to the Sulitjelma area in that the study was performed on analysed hornblendes from the gabbro complex, but it also indicates the possibility of an interesting line of mineralogical research with relatively simple apparatus. The writer hopes to do more of this in the future.

APPENDIX ONE.

The colours of green and brown hornblendes.

1. Explanations and definitions.

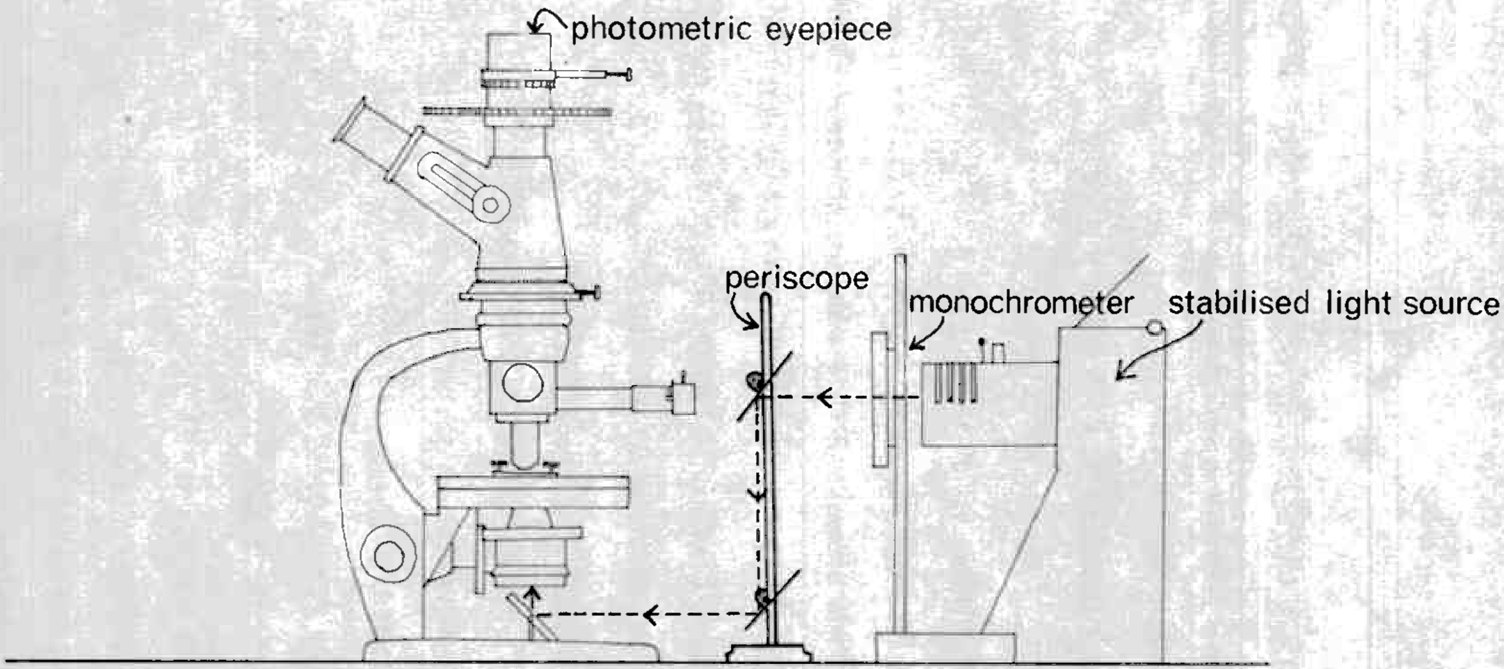
Recent work has shown that the interpretation of the colours of many minerals can yield information concerning the electronic configuration of transition metal ions within the crystal structure by using a branch of electron orbital theory known as crystal field theory (Burns 1965a, 1965b, Burns and Fyfe 1964). In common speech "colour" means the impression given to the eye by changes in the intensity of light with wavelength, within a limited range of wavelengths (3,900-7,700 Å) called the "visible spectrum". This definition is not sufficiently precise for the study of crystalline materials by crystal field theory, so colours are described in terms of "absorption spectra". Absorption spectra measure the absorption of radiation of different wavelengths passing through a transparent substance. Absorption may be expressed mathematically as the logarithm of the ratio of the intensity of incident (I_o) to transmitted (I) light of a particular wavelength.

$$A = \log_{10}(I_o/I)$$

A plot of the variation of absorption A with wavelength gives an absorption spectrum. For comparisons between crystals of different thicknesses and compositions a different expression of absorption is used. This is the molal extinction coefficient, defined by the

FIG. A·1.

Apparatus used to determine absorption spectra.



equation :-

$$\epsilon = \frac{A}{ct}$$

where c = the molal concentration (mols/1000 gms), t = thickness of the specimen (cms.). In this account the specimens examined are in normal thin sections cut for petrographic examination (thickness 0.03 mm.) and are both hornblendes, so the absorptions A will be compared directly.

In an anisotropic crystal the absorption spectrum varies with the direction of vibration of the light relative to the crystal structure, which is the phenomenon known as "pleochroism". It is necessary therefore to specify the direction of vibration of the light and this is done by making measurements on light vibrating along the principal vibration directions of the crystal which are here called α, β, γ after the corresponding refractive indices.

2. Apparatus and techniques.

The apparatus used was a microscope with stabilised light-source and photometric eyepiece developed by Dr. N. F. M. Henry for reflectivity measurements on ore minerals (Bowie and Henry 1964). The microscope was already fitted with a substage condenser, diaphragm and mirror for transmitted light, so an improvised periscope arrangement of two plane mirrors was set up to pass light from the interference monochrometer to the substage mirror (fig. A.1). A x20 objective was used, so that the larger hornblende crystals studied covered a substantial part of the field of view.

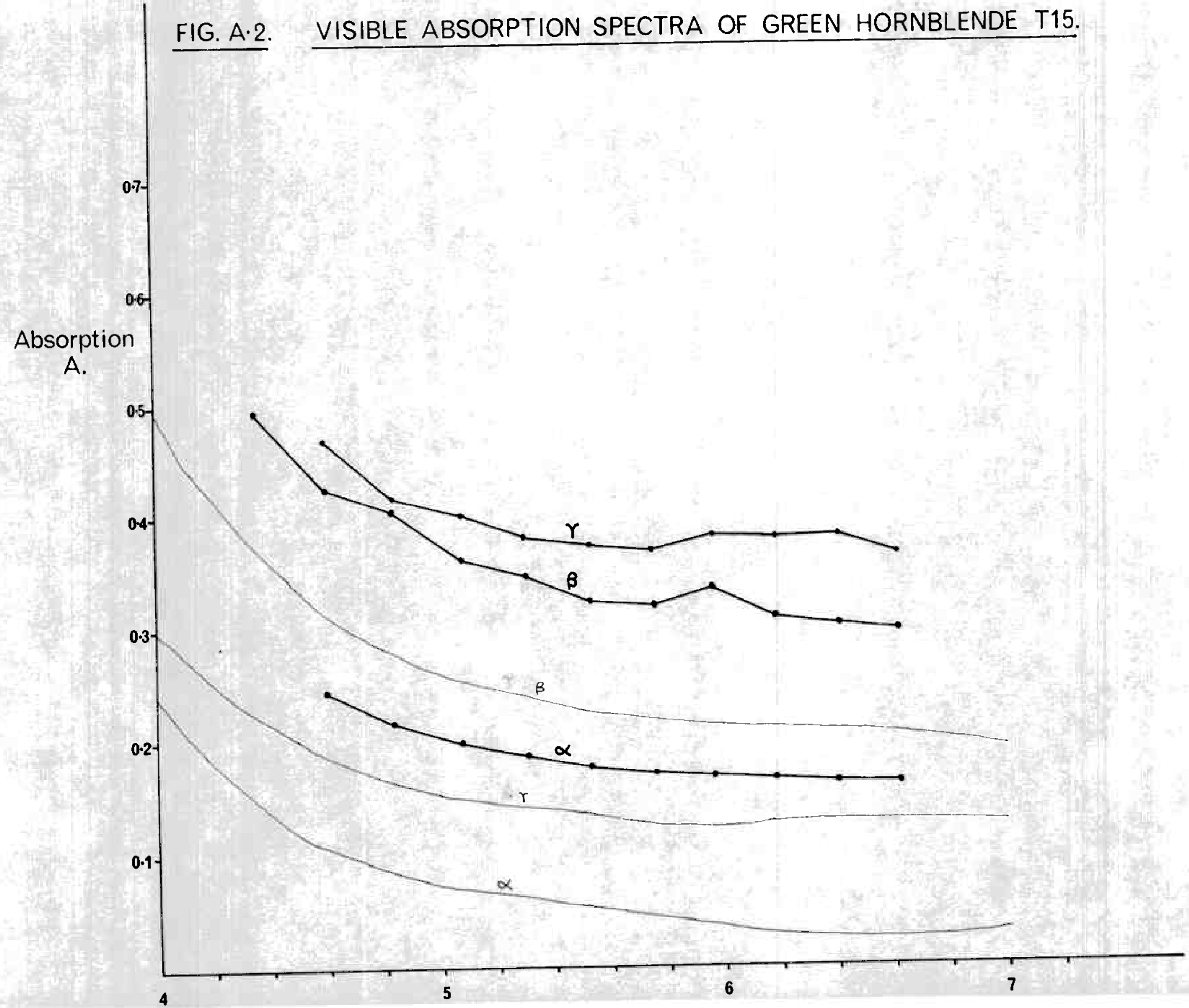
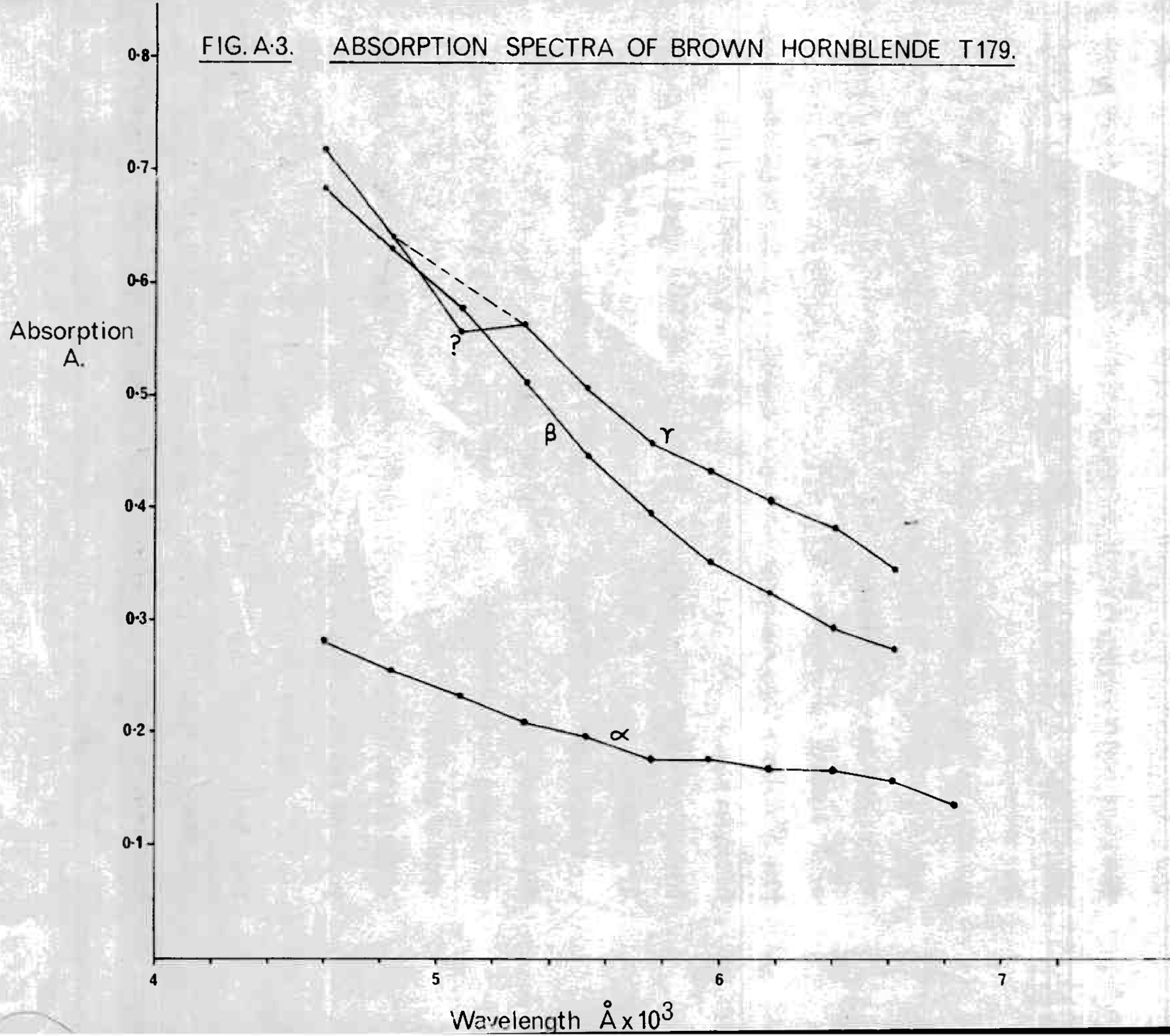


FIG. A·2. VISIBLE ABSORPTION SPECTRA OF GREEN HORNBLENDE T15.
Absorption A.
0·7
0·6
0·5
0·4
0·3
0·2
0·1
γ
β
α
β
γ
α
4
5
6
7

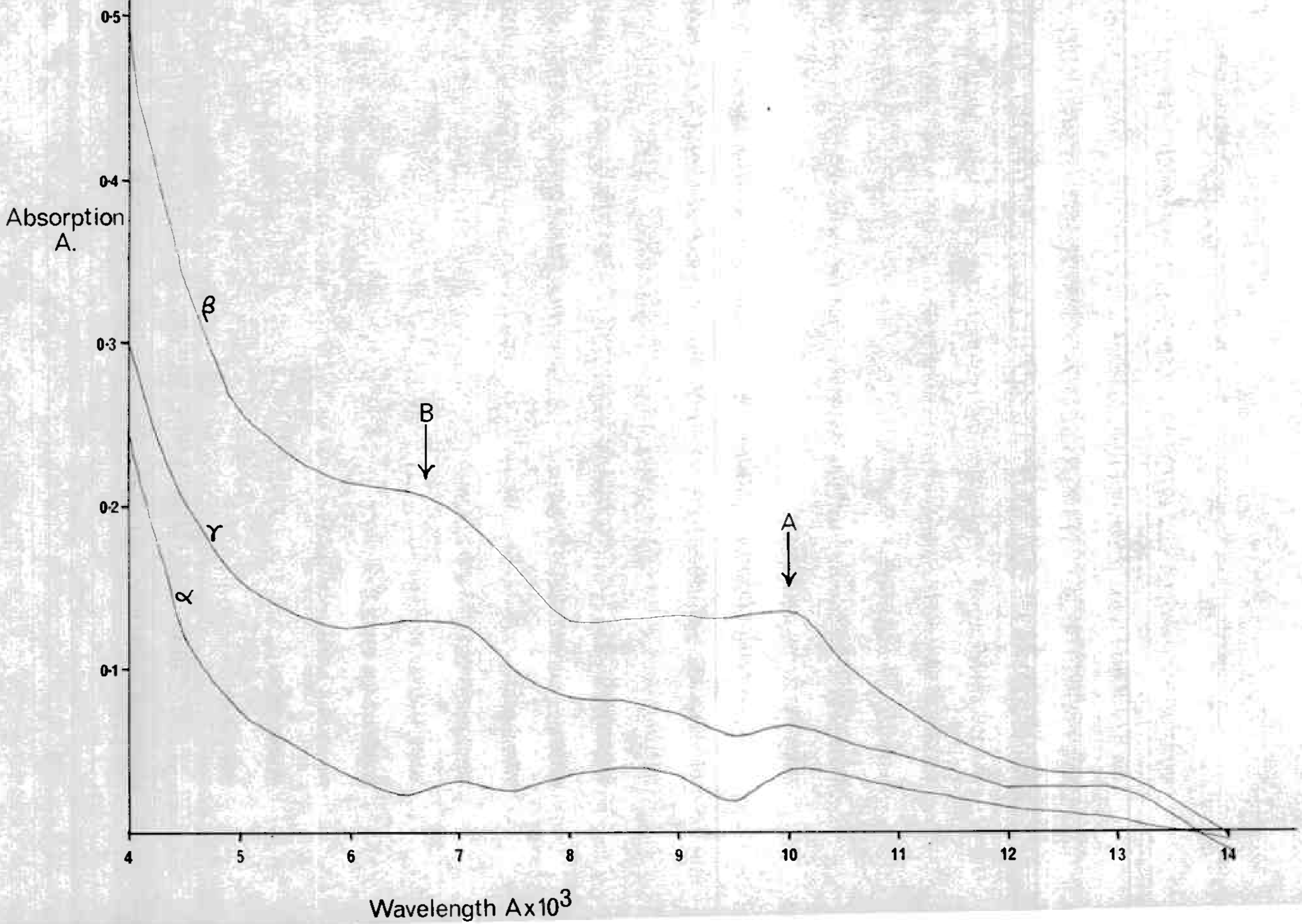
FIG. A·3. ABSORPTION SPECTRA OF BROWN HORNBLENDE T179.



Crystals were selected for examination in which one or more of the principal vibration directions lay in the plane of the section. The cleavages and birefringence of the hornblende were useful rough guides in selecting suitable crystals. A precise check was made by ensuring that the extinction angles onto the cleavages corresponded to those of the principal vibration direction. The field of view of the photometric eyepiece was limited by means of an eyepiece diaphragm so that only light transmitted in the principal vibration direction through the crystal under study reached the photo-electric cell. This was done in white light. The interference monochromator was then interposed in the light beam, and the intensity of the light transmitted through the crystal and that transmitted through a neighbouring area of clear slide determined in light of different wavelengths. As the limits of the visible spectrum were approached the sensitivity of the photo-cell decreased, until accurate measurement could not be made. A mechanical stage was fitted to the microscope to ensure that readings for light of different wavelengths were always made at the same position on the specimen crystal and the clear slide. (The intensity of the light transmitted through different parts of the clear slide varied appreciably).

In this way absorption spectra were obtained from green hornblende in specimen T15 and brown hornblende in specimen T179. These are shown in figs. A.2 and A.3. As a check on the accuracy of the measurements Dr. R. G. Burns kindly made measurements of the absorption

FIG. A·4. VISIBLE & INFRA-RED ABSORPTION SPECTRA OF GREEN HORNBLENDE T15.



spectra of specimen T15 using the Cary model 14 recording spectrophotometer in the department of Chemistry, Cambridge University. He has given a description of this apparatus for mineralogical work (Burns 1966). This instrument is not limited to measurements in the visible spectrum but can extend observation into the short-wave infra-red. The spectra he obtained are shown in full in fig. A.4. and compared with the writer's results in fig. A.2. Burns also tried to determine the spectra of the hornblende in specimen T179, but found the crystals too small for useful results to be obtained.

The object of the trials with the reflectivity apparatus was to see whether this technique might provide a means of determining absorption spectra in the visible spectrum without the use of complex and expensive apparatus like the Cary spectrophotometer. This is by no means the first attempt to determine absorption spectra using an adapted petrographic microscope, but it is only with the introduction of reliable photometric equipment and of the interference monochrometer that such determinations have become sufficiently simple to be regarded as a technique to be applied by anyone who can use a polarising microscope. The measurements recorded here were performed in 2-3 days, and with practice complete absorption spectra could be obtained from specimens in several thin sections in a day.

Henry has now very much improved the sensitivity of the photometric part of his apparatus by using a photo-multiplier in place of the photo-electric cell. This should improve the accuracy and range of the absorption spectra obtainable in the visible region. The writer hopes to try this in the near future.

3. Interpretation of the spectra.

(a) Green hornblende.

The comparison of the spectra obtained by the writer with those obtained by Burns on the Cary spectrophotometer presents various problems. The higher absorption values obtained by the present writer are probably not significant as they depend on the value of I_o. As was stated, the values of I_o obtained from different parts of the clear slide varied and the actual value used is rather arbitrary. Burns' technique however strives to make as accurate a determination of I_o and I as possible so his values are the more accurate.

The difference between the curves for γ is more serious. The writer's technique, which did not involve the use of a Universal stage as Burns' does, may mean that the direction of vibration of the light whose intensity was measured was a few degrees away from the principal vibration direction. But if Burns' curves are accurate, this slight misalignment should not make γ greater than β , although in a β-γ section it might give higher values for γ than the correct ones. The discrepancy may be due to misidentification of the principal vibration directions, but the similarity in shape between the γ curves obtained by each method makes this rather unlikely. The hornblende of T15 is rather zoned and it may be that the grains examined by Burns are different from those examined by the writer.

The spectra show that there is strong absorption in the blue part of the visible region and a weak absorption plateau in the red part of the visible spectrum at about 6,700 A. (Arrow B in fig. A.4.). In the infra-red a further distinct absorption maximum occurs at about 10,000 A. (Arrow A, fig. A.4.).

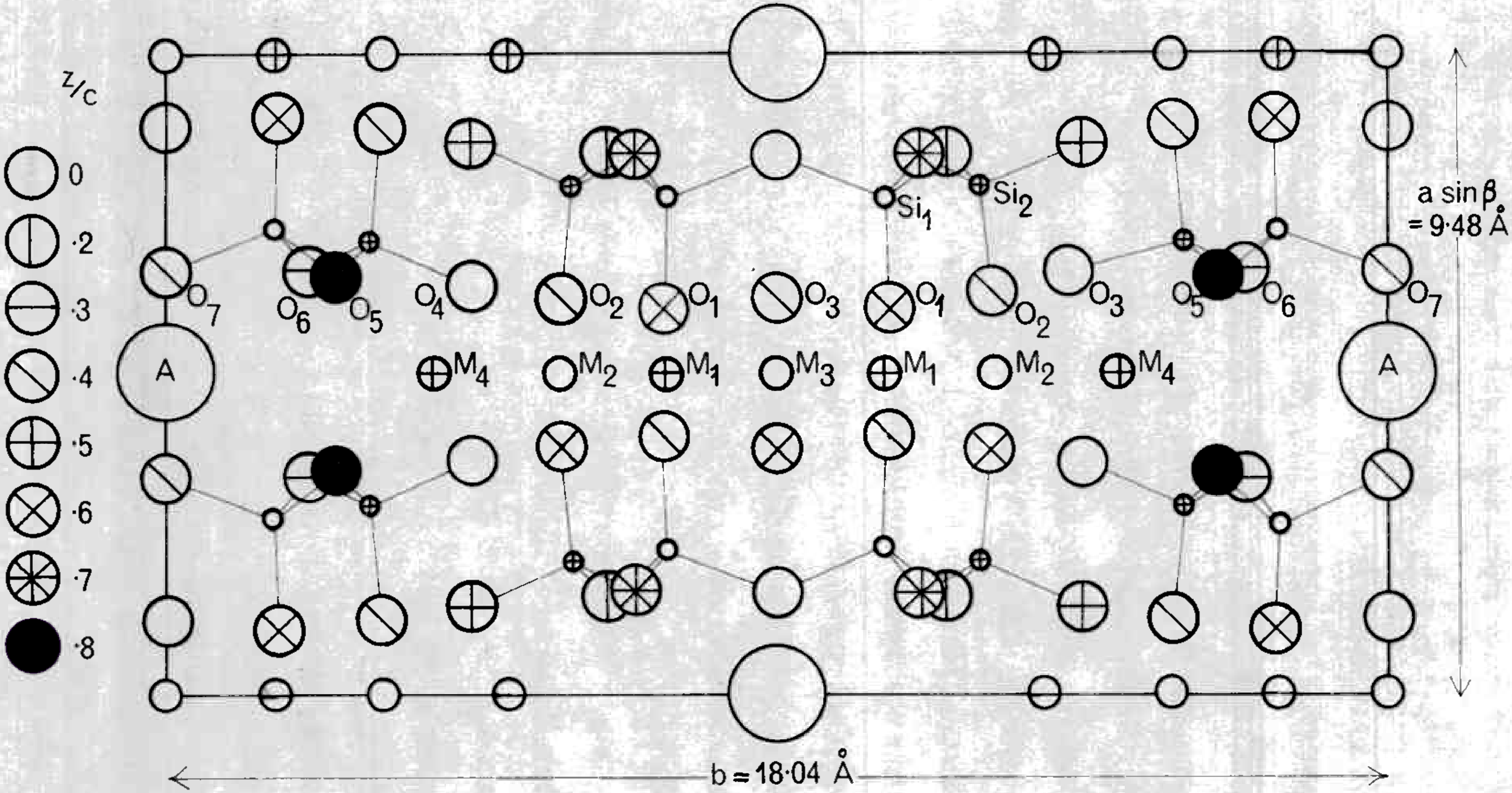
Absorption is due to the removal of energy from electromagnetic radiation passing through the crystal. This energy goes to excite electrons in the crystal structure from low energy states to higher energy states. However, energy will only be absorbed from radiation whose characteristic energy matches the increase in energy of the electron. The electromagnetic radiation will be particularly strongly absorbed at frequencies corresponding to common electronic transitions occurring within the crystal structure. Absorption in the visible spectrum and the short-wave infra-red implies relatively low energy transitions. In the case of hornblende these are probably of two kinds :-

1. Transitions between d-orbitals of slightly different energies in the same transition metal ion.

2. Transitions between the outer electron orbitals of two different ions in the crystal structure. This will cause absorption in the visible and infra-red if the electrons are loosely bound, and have similar energies in the two atoms. This phenomenon is known as "charge transfer".

FIG A·5. STRUCTURE OF HORNBLENDE PROJECTED NORMAL TO [001].

(Based on data from Heritsch et al. 1957)



In order to understand the transitions which occur in hornblendes it is necessary to consider the crystal structure of this mineral in some detail. No complete 3-dimensional structural analysis has yet been performed on hornblende, but an extensive 2-dimensional analysis has been performed by Heritsch, Paulitsch and Walitzi (1957) on a metagabbro hornblende from Radhausberg (Salzburg) which happens to have a chemical analysis quite similar to the hornblende T15. The analysis is given in table 10, along with chemical analyses of the green and brown hornblendes described here. The structure determination gave an R-factor of 0.2 when the calculated intensities of the interference spots were compared with the observed intensities, which implies that the form of the structure is correct, but that some of the atomic coordinates obtained may be inaccurate. Fig. A.5 shows a projection of the structure perpendicular to [001]

There are four sites in the structure which may be occupied by transition metal ions, and they are known conventionally as M_1, M_2, M_3 and M_4. M_4 is an 8-fold coordinated site, and in hornblende is probably occupied by calcium and some alkali ions. (The remaining alkali ions occupy the partly vacant site A). M_1, M_2 and M_3 are 6-fold coordinated sites, the coordination being represented by more or less distorted octahedra. M_3 is relatively undistorted, M_1 is approximately tetragonally distorted, (i.e. it has two axes approximately equal and the third larger) while M_2 has all three axes different.

The transition metal ions present in major amounts in T15 are Fe^{2+}, Fe^{3+}, Mn^{2+} and Ti^{4+}. It is impossible to go into a detailed account of crystal field theory here, so it must simply be stated that the only likely transitions within the orbitals of one ion occur between the d-orbitals of Fe^{2+}, which has four unpaired electrons. Transitions in Fe^{3+} and Mn^{2+} are "forbidden" by the spin-multiplicity selection rules and so are far less likely to occur (i.e. the absorption maxima they produce are very faint). Ti^{4+} has no d-electrons, internal d-electron transitions are impossible.

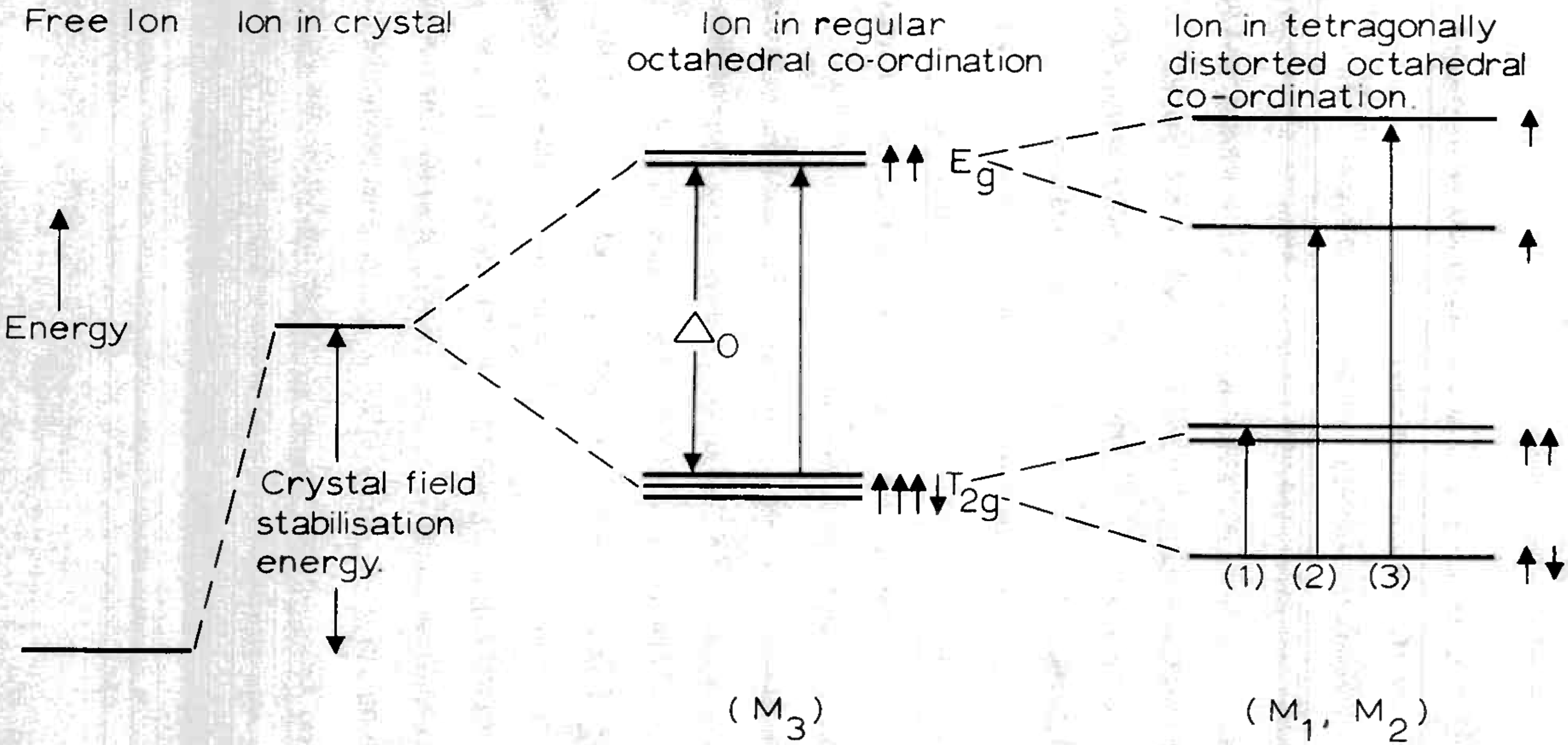
Fe^{2+} has six d-electrons, shared among five 3d-orbitals. In the weak crystal field which is found in very nearly all silicates, four orbitals are occupied by one electron and one orbital by two electrons, spinning in opposite senses. In a free Fe^{2+} ion all the electrons have the same energy, but when the ion is in a crystal, the electric fields of the surrounding anions ("ligands") cause two changes :-

1. The energy of all the electrons is increased.

2. The energies of electrons in different d-orbitals become different.

The differences in energy between the orbitals are relatively small, and so the transition of an electron from one d-orbital to another produces absorption in the visible spectrum or short-wave infra-red. If Fe^{2+} is in regular octahedral coordination, the five d-orbitals divide into two sets; two called the e_g orbitals with a higher energy, and three called

FIGURE A.6: ENERGY LEVEL DIAGRAM FOR FE^{2+}



The small arrows on the right show the electron spins in the lowest energy states

The large arrows indicate possible electronic transitions to higher energy states

(1) Occurs at about 25,000 Å

(2) Occurs at about 9,000 - 10,000 Å

(3) Occurs at about 6,500 - 7,500 Å

g.h.

the t_{2g} orbitals with a lower energy. These changes can be expressed by an "energy level diagram" such as fig. A.6.

Δ_0 is the energy separation between the orbitals. The electrons tend to reach the lowest possible energy state, so one of the t_{2g} orbitals is occupied by the electron pair in Fe^{2+}. If energy arrives in the form of electromagnetic radiation however, one of the paired electrons may "jump" into one of the e_g orbitals, absorbing energy of a characteristic wavelength. For Fe^{2+} in undistorted octahedral coordination in silicates, this value falls at about 10,000 Å. It is very likely that the absorption peak near this value in the green hornblende spectrum (A) is due to such transitions occurring in ferrous iron in the relatively undistorted M_3 site.

If the octahedral coordination is distorted, there is even more variation in the energy levels of the orbitals (fig. A.6). The number of possible transitions increases. In the case illustrated, for octahedral coordination tetragonally distorted along the z axis of the Fe^{2+} ion, three possible energy transitions are shown. Transition 1 is a very low energy transition, and probably produces absorption in the far infra-red. Transitions 2 and 3 are more likely to cause absorption in the visible region, and short infra-red. Possibly transition 2 is producing some of the irregularity between 7,000 and 10,000 Å. in the absorption spectra, and transition 3 the plateau at about 6,700 Å. The plateau may be caused by the different distortions of the M_1 and M_2

sites, which mean that Δ associated with transition 3 is different in each case, so that the plateau is formed of two peaks at slightly different wavelengths.

Absorption will only occur if the plane of vibration of the electromagnetic radiation corresponds to the directions of the appropriate orbitals, so an absorption peak may appear in one principal vibration direction but not in another. It will be seen that longest axes of the distorted octahedra at M_1 and M_2 lie in the a-c (crystallographic) plane. It is therefore interesting that the 6,700 Å absorption peak is more pronounced in the γ than in the β spectrum.

The very strong absorption at the blue end of the visible spectrum is probably due to "charge transfer". This mechanism will be discussed in the brown hornblende.

(b) Brown hornblende.

The comparison of the brown hornblende spectra with the green reveals two things :-

1. The absorption in all the principal vibration directions is greatest in the brown hornblende.

2. The sharp increase in absorption towards the blue end of the visible spectrum in green hornblende extends throughout the spectrum in the brown.

This increased absorption at the blue end of the spectrum suggests electronic transitions of higher energy than those represented

TABLE 10.

Composition of green and brown hornblende.
"Barroisitic hornblende" from Paulitsch 1947.

	T15 Green hornblende	T179 Brown hornblende	"Barroisitic hornblende"
SiO_2	45.13	44.21	45.05
TiO_2	0.74	2.30	1.40
Al_2O_3	13.47	11.43	13.78
Fe_2O_3	1.70	1.57	0.99
FeO	11.68	11.03	9.98
MnO	0.20	0.16	0.20
MgO	11.65	12.95	12.01
CaO	12.08	11.76	10.28
Na_2O	1.49	1.96	3.84
K_2O	0.03	0.93	0.16
H_2O+	2.13	1.09	2.33
H_2O-	0.04	0.03	0.15
Total	100.34	99.42	100.17

Unit cell contents on the basis of 24 (O,OH). T15 and T179 calculated using a programme prepared by Kelsey on the Titan computer in the Mathematical laboratory, Cambridge University. The barroisitic hornblende from Heritsch et al. 1957.

	T15		T179		"Barroisitic hornblende"	
Si	6.528	8.00	6.580	8.00	6.54	8.00
Al	1.472		1.420		1.46	
Al	0.825	5.04	0.585	5.28	0.90	5.00
Ti	0.081		0.257		0.15	
Fe^{3+}	0.185		0.176		0.10	
Mg	2.511		2.873		2.61	
Fe^{2+}	1.413		1.373		1.21	
Mn	0.025		0.020		0.03	
Na	0.418	2.30	0.566	2.62	0.41	2.00
Ca	1.872		1.875		1.59	
K	0.006		0.177		–	
OH	2.055		1.082		not given	

by the peaks at 6,700 and 10,000 Å in green hornblende. It appears not to be a discrete absorption peak, but a wide band, representing a variety of transitions of different energies. Such absorption would be produced by the "charge transfer" mechanism mentioned earlier. If this is the mechanism involved, then charge transfer is easier in brown hornblende than in green. An examination of the chemical analyses of the two hornblendes suggests possible ions between which the electron transfer might occur.

There are two noticeable differences between the brown and green hornblende analyses. The brown hornblende is higher in potassium and titanium (table 10). Note that the Fe^{2+}:Fe^{3+} ratio is similar in each. The potassium is unlikely to participate in charge transfer, as K^{+} is very stable. Ti^{4+} will however accept an electron relatively easily to become Ti^{3+} and Fe^{2+} may lose an electron to become Fe^{3+}. A review of the chemistry of hornblendes has been given by Leake in Pitcher and Flinn "Controls of metamorphism" (1965) pp 299-318. He demonstrates with the aid of numerous analyses from the literature that although the composition of hornblende is determined primarily by bulk-rock composition, everything else being equal, there is an increase in titanium content with grade. The correlation of high titanium content with brown colour in hornblende has been described before, for example by Deer (1938) in igneous hornblendes from the Glen Tilt complex.

An alternative theory for the colours of amphiboles has been

Fig. A.7.

Absorption Curves from Melankholin (1956)

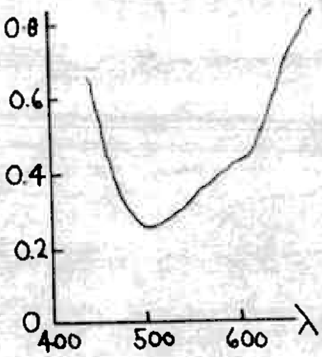


fig. 1

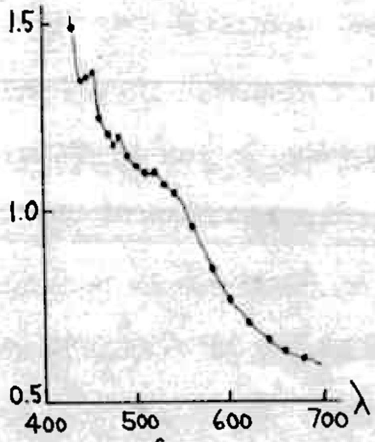


fig. 2.

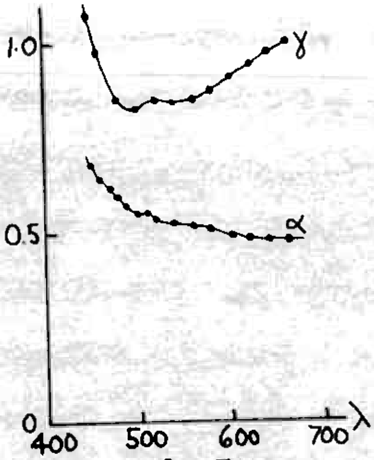


fig. 5.

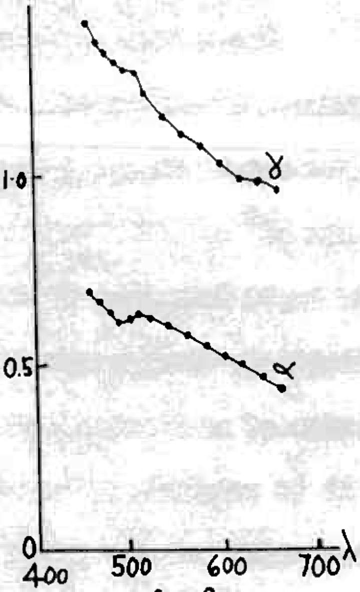


fig. 8.

Figure.

1. Curve for Fe^{++} in crystal.
2. " " Fe^{+++} " "
5. Green Hornblende.
8. Brown Hornblende.

advanced by Melankholin (1956). He obtained absorption spectra from a number of amphiboles, by a technique similar to the one used by the present writer (fig. A.7). However, he interprets the spectra as showing a systematic variation in the content of Fe^{2+} and Fe^{3+}. He shows spectra which he describes as characteristic of Fe^{2+} and Fe^{3+} "in a crystal" and considers his other spectra are intermediate in character between these extremes. He does not, unfortunately, give chemical data on the amphiboles he has studied.

The present writer would hesitate before ascribing all brown colouration of hornblendes to a high titanium content. Brown colour is probably due to charge transfer, but this could be between other ions than Fe^{2+} and Ti^{4+}. This type of study is still relatively new, but the writer hopes he has shown that fruitful results can be obtained by the use of relatively simple apparatus, and with a little extension of the chemical knowledge of most petrologists. Above all, the writer hopes he has shown that it is possible to improve on the subjective descriptions of mineral colours which petrographers have relied on up till now.

APPENDIX TWO.

Analyses of rocks and minerals from Sulitjelma.

Not many rock and mineral analyses were performed by chemical methods, as this research has depended on electron-probe analysis to a great extent. However, in addition to the plagioclase and hornblende analyses already quoted, two olivines and a garnet were fully analysed chemically as a check on the accuracy of the electron-probe data, and for practice in mineral separation and analysis.

Five new rock analyses from the gabbro complex, and one from the dioritic gneiss were made. The ratios of iron to iron, magnesium and manganese for these analyses are quoted, and it can be seen that these show that the marginal troctolitic facies is distinctly more magnesian than the gabbros of the layered series. There are not sufficient bulk rock analyses from the layered series to show if the bulk rock compositions show the same trend as the mineral compositions, and it is in this context that the uncertainty of the locations of Vogt's analysed specimens is particularly regrettable. The $FeO + Fe_2O_3 : FeO + Fe_2O_3 + MnO + MgO$ ratio of a gabbro from the summit of Stortoppen, analysed by R. Mauzelius for Sjögren (Vogt analysis XVII) is 0.4167, which suggests some iron enrichment relative to S6 and the marginal troctolites.

The mineral analyses have been recalculated to the appropriate unit cell contents.

The modes on which fig. 3.2 is based are also given in full in this appendix.

Mineral analyses.

	Olivine S96	Olivine S152	Garnet S182
SiO_2	39.19	38.94	37.74
TiO_2	0.16	0.16	0.30
Al_2O_3	0.19	0.74	22.16
Fe_2O_3	0.00	0.00	0.58
FeO	16.74	18.70	29.55
MnO	0.20	0.27	1.27
MgO	43.43	41.13	7.02
CaO	trace	0.16	1.75
Total	99.91	100.10	100.37

Unit cell contents, olivines on a basis of 4 oxygens, garnet on a basis of 24 oxygens.

	S96		S152		S182		
Si	0.933	0.999	0.994	0.997	Si	5.887	9.996
Ti	0.006		0.003		Ti	0.036	
					Al	4.073	
Al	0.009	2.006	0.022	1.995	Fe^{3+}	0.067	
Fe^{2+}	0.355		0.399		Fe^{2+}	3.853	
Mn	0.004		0.006		Mn	0.168	
Mg	1.639		1.564		Mg	1.631	
Ca	trace		0.004		Ca	0.292	

	S96	S152		S182
Forsterite	82.0	79.5	Almandine	64.8
Fayalite	17.8	20.0	Andradite	2.6
Mn_2SiO_4	0.2	0.3	Grossular	2.3
Ca_2SiO_4	trace	0.2	Pyrope	27.4
			Spessartine	2.8
d_{130} (A)	2.779	2.781		
2V	87^o	-		

Analyses of rocks from NE Sulitjelma.

	S1	S6a	S6b	S96	T158	T222
SiO_2	48.21	48.55	47.79	46.51	44.27	50.89
TiO_2	0.27	0.33	0.32	0.22	0.17	2.22
Al_2O_3	18.44	19.44	19.51	20.39	13.90	15.48
Fe_2O_3	0.84	0.76	0.65	0.18	1.35	2.69
FeO	6.90	5.62	5.58	5.45	7.41	8.61
MnO	0.17	0.10	0.08	0.11	0.13	0.19
MgO	9.96	10.14	10.13	14.35	23.89	4.69
CaO	11.68	12.24	12.24	10.62	7.72	9.35
Na_2O	2.28	2.42	2.42	1.97	1.18	4.65
K_2O	0.13	0.16	0.14	0.14	0.09	0.20
H_2O+	1.73	0.80	1.98	0.58	0.44	1.21
H_2O-	0.00	0.00	0.00	0.09	0.04	0.03
Total	100.61	100.77	100.84	100.61	100.59	100.21
$\frac{FeO + Fe_2O_3}{FeO + Fe_2O_3 + MgO + MnO}$	0.4331	0.3839	0.3790	0.2802	0.2663	0.6984
C.I.P.W. norms :-						
Or	0.1	0.1	0.1	0.1	0.1	0.1
Ab	19.4	20.4	19.4	15.7	10.0	39.3
An	39.8	42.0	42.0	46.4	32.3	20.9
Ne	-	-	0.1	0.1	-	-
Di ($CaSiO_3$	7.7	7.9	7.9	2.7	2.5	10.7
Di ($MgSiO_3$	4.8	5.3	5.3	1.9	1.9	5.5
Di ($FeSiO_3$	2.7	2.3	2.3	0.6	0.5	5.6
Hy ($MgSiO_3$	3.2	0.5	-	-	1.2	-
Hy ($FeSiO_3$	1.7	0.2	-	-	0.3	-
Ol (Mg_2SiO_4	11.8	13.2	15.0	23.8	39.8	4.3
Ol (Fe_2SiO_4	6.2	6.3	8.6	6.9	9.2	4.3
Mgt	1.2	1.2	0.9	0.2	1.9	3.9
Ilm	0.5	0.6	0.6	0.5	0.3	4.3

S1 Metagabbro
S6a Unaltered part of amphibolitised gabbro (see table 7)
S6b Amphibolitised part of amphibolitised gabbro
S96 Marginal troctolite
T158 Marginal troctolite
T222 Coarse grained lens from base of dioritic gneiss.

Modal analyses of rocks from the Sulitjelma gabbro complex

	S96	S149	S152	S174	T12	T39	T74	T76	T101	T136	T138
Plagioclase	59.4	53.3	59.2	78.9	27.3	67.4	51.6	59.4	54.5	63.0	51.6
Clinopyroxene	1.8	30.2	16.3	16.8	20.3	0.3	27.8	14.6	23.1	16.6	26.0
Olivine	14.5	9.4	20.2	*	40.1	17.2	6.6	17.4	3.7	0.0	19.6
Orthopyroxene	9.5	1.0	0.8	-	2.5	3.1	7.4	2.0	4.4	5.2	1.1
Brown Hornblende	-	3.8	2.0	2.5	1.7	0.7	0.9	2.1	4.7	5.1	0.7
Symplectite	14.9	2.0	1.4	-	7.7	10.9	5.4	3.9	0.6	-	0.7
Ore	-	0.2	-	1.7	0.4	*	0.2	0.4	9.0	8.9	0.3
Biotite	-	-	*	*	-	-	-	0.1	-	-	-
Green Hornblende	-	-	-	-	-	0.4	-	-	-	-	-
Chlorite	-	*	-	-	-	-	-	-	-	-	-
Apatite	-	-	-	-	-	-	-	-	-	1.1	-

* = trace.

Modal analyses of rocks from the Sulitjelma gabbro complex

	T150	T158	T168	T191	T202	T204	T205	U67	86337	86338
Plagioclase	15.7	38.3	28.3	8.9	57.0	68.4	58.3	51.0	38.4	53.8
Clinopyroxene	*	0.9	13.6	78.5	33.6	19.4	30.2	5.0	20.5	10.5
Olivine	82.3	38.4	45.9	1.9	7.3	10.3	10.4	33.3	28.3	22.2
Orthopyroxene	-	20.3	2.6	5.9	0.9	1.4	0.6	2.7	3.4	2.6
Brown Hornblende	1.2	0.5	1.2	1.5	0.7	0.1	0.2	1.1	0.5	0.2
Symplectite	-	1.7	7.1	0.3	-	0.3	0.2	6.6	8.3	10.4
Ore	0.7	-	1.2	1.5	0.6	0.1	0.1	0.3	0.6	0.4
Biotite	-	-	-	0.5	-	-	-	-	-	-
Green Hornblende	-	-	-	0.8	-	-	-	-	-	-
Chlorite	*	-	*	-	-	-	-	-	-	-
Tourmaline	-	-	*	-	-	-	-	-	-	-

T202, T204 and T205 are from the same locality. The last two specimens are from the Harker collection (catalogue nos. 86337, 86338) and were collected by Agrell in 1959.

APPENDIX THREE.

Electron probe determinations of minerals from the Sulitjelma gabbro complex.

This appendix is concerned with the electron-probe results given in chapter three. The analyses in chapter four are adequately described there.

The analyses in chapter three were corrected for absorption, fluorescence, and atomic number differences between standard and specimen using a programme prepared for the IBM 7090 computer in Imperial College, London, by Dr. S. J. B. Reed. The data was fed into the computer by Mrs. P. K. Mason. The programme dealt with the data in two ways. The olivine and orthopyroxene data was calculated as molecular proportions of the end members Fe_2SiO_4, Mg_2SiO_4 and so on. These were summed to 100%. It was assumed that silicon and oxygen were in the appropriate stoichiometric ratios, so data on the iron, magnesium and calcium contents of the specimens only were fed to the computer.

The clinopyroxenes and hornblendes were calculated in weight percentages of the oxides MgO, Al_2O_3, SiO_2, CaO, TiO_2 and FeO, summed to 100%. These data were recalculated as molecular proportions (in the case of the hornblendes, using the proportions of H_2O, Na_2O and K_2O found in the analysed brown hornblende T179) by using a programme prepared by Dr. C. H. Kelsey for the Titan computer in the Mathematical Laboratory, Cambridge University.

The correction programme print-out gives data relating to the accuracy of the analysis as well as the results. This can be expressed in two values :-

1. The apparent sum of the analysis. This is the total obtained when the corrected proportions of oxides or end members are summed. The programme alters this sum to 100% in the final presentation of data.

2. The systematic error of the analysis. This is the percentage error due to the assumptions and parameters used in the correction programme. In the tables below it is only given for the olivines, as this was the mineral group for which it was greatest. The systematic error is greatest for the magnesium determinations.

The apparent sums of the analyses were all high, but the systematic errors in the olivines were greater than the departures of the apparent sums from 100%. It should be emphasised that the correction programme is still at a developmental stage, and will probably be improved in the future. Full results of analyses :-

Olivines

Specimen	No. of Determinations	Composition Fa	Composition Fo	Apparent sum %	Systematic Error
T158	3	15.6	84.4	103.4	± 8.6
U67	3	18.9	81.1	107.0	± 8.9
S152	4	20.8	79.2	108.5	± 8.9
T206	6	21.7	78.3	102.7	± 8.9
T204	4	24.3	75.7	107.1	± 9.0
T12	3	25.2	74.8	103.4	± 9.0
T150	3	25.4	74.6	109.9	± 8.5
T74	3	36.0	64.0	107.5	± 9.1
T101	4	43.2	56.8	108.8	± 8.8
T191	3	48.6	51.4	107.1	± 8.5

Orthopyroxenes

Specimen	Composition Ofs.	Wo.	Clinoens.	Apparent total	No. of determinations
T158	14.2	2.2	83.6	99.1	3
U67	19.1	1.5	79.4	97.2	2
U67k	21.1	0.2	78.7	95.4	1
T12	22.5	2.3	75.2	101.5	2
T12k	23.7	0.3	76.0	103.7	1
T150	22.1	2.8	75.1	99.4	3
T74	28.6	3.0	68.4	99.5	2
T74k	25.9	0.4	73.7	101.7	1
T101	35.1	n.d.	64.9	101.3	5
T191	38.9	1.0	60.1	104.6	2
T191e	36.8	3.9	59.3	105.3	3

Clinopyroxenes

	FeO	TiO_2	CaO	SiO_2	Al_2O_3	MgO	Apparent total	No. of determinatns.
T158	3.9	1.3	25.4	49.2	3.7	16.6	104.3	1
S152	5.6	0.6	21.6	51.6	4.2	16.3	105.7	3
T206	6.4	1.3	20.7	44.9	6.1	14.2	112.3	1
T204	7.1	0.9	25.1	47.0	4.2	15.7	106.7	3
T101	9.8	n.d.	21.3	51.9	2.6	14.4	100.7	1

Brown hornblendes

	FeO	TiO_2	CaO	SiO_2	Al_2O_3	MgO	Apparent total	No. of determinatns.
S152	8.2	3.0	12.7	44.1	17.1	15.0	106.8	3
T12	8.7	4.0	14.9	40.4	19.0	13.3	97.5	3
T150	9.4	3.6	15.9	40.7	17.6	12.7	99.5	3
T101	13.0	3.9	12.3	43.1	15.3	12.4	100.7	3
T191	15.1	2.0	11.8	42.6	16.7	11.7	99.8	2

As the totals for the analyses show, the results of electron-probe microanalysis are far from being comparable in quality to chemical analyses. Some of the variation may be due to inadequacy in the computer programme, which is still in the experimental stage. The determinations of minerals may be more fairly compared with indirect optical or X-ray determinations than accurate chemical analyses. The analyses show clearly the trend of mineral variation however, and although the absolute values of iron and magnesium contents may be in error, the relative values between one analysis and another are probably accurate. The analyses given in chapter four, which were performed with more care and corrected by well-proved hand calculations are more accurate than those in chapter three.

APPENDIX FOUR.

Locations of specimens described in this thesis.

Specimen		Grid Reference
S1	Metagabbro	544506
S6	Partly amphibolitised gabbro	542503
S8	Amphibolitised gabbro	548503
S26	Kyanite and sillimanite bearing hornfels	516530
S32	Igneous breccia, xenolith	516533
S48	Schistose amphibolite	508476
S49	Calc-silicate rock	505474
S59	Calcareous chlorite schist	535467
S93	Metagabbro	521543
S96	Troctolitic gabbro	521545
S100	Amphibolitised hornfels	516543
S107	Quartzite with kyanite lenses	517542
S144	Metaporphyritic amphibolite	600442
S149	Olivine gabbro	559503
S152	Olivine gabbro	557506
S170	Schistose hornfels with sillimanite augen	527519
S174	Labradorite rich gabbro	599484
S182	Igneous breccia matrix	592505
S193	Hornfels xenolith from igneous breccia	592505
T8	Cataclastically altered gabbro	521525
T12	Olivine gabbro	532501
T15	Metagabbro	535503
T39	Olivine gabbro	546546
T42	Epidote-mica schist	557544
T48	Garnet-orthoclase-plagioclase-biotite-quartz rock	539568
T55	Garnet-mica schist	548553
T68	Cataclastically altered olivine gabbro	545481
T76	Olivine gabbro	542487
T101	Olivine gabbro	560464
T111	Cataclastically altered igneous breccia	527518
T136	Dolerite	618512
T138	Olivine gabbro	618511
T144	Cataclastically altered olivine gabbro	553515
T150	Olivine rich gabbro	552518
T151	Cataclastically altered olivine gabbro	553514
T158	Troctolitic norite	569524
T168	Olivine gabbro	542504

Specimen		Grid Reference
T179	Hornfels with brown hornblende	592507
T182	Zoned calcareous xenolith in igneous breccia	593503
T191	Pyroxene rich gabbro	599484
T195	Felspathic quartzite	591517
T202	Olivine gabbro	621506
T204	Olivine gabbro	621506
T205	Olivine gabbro	621506
T206	Olivine gabbro	618506
T216	Chlorite schist	535461
T222	Coarse dioritic gneiss	535481
T228	Dioritic gneiss	551462
T231	Brown hornblende gneiss	556465
T235	Mylonite	559463
T270	Garnet-mica schist	600557
T284	Kyanite-staurolite schist	526505
U13	Sillimanite-garnet schist	558549
U24	Metaporphyritic amphibolite	550471
U39	Kyanite-graphite schist	573546
U43	Pyrite bearing graphite schist	585561
U44	Cordierite bearing rock	585561
U48	Micaceous psammite	575440
U49	Micaceous psammite	562444
U67	Olivine gabbro	546542
U76	Amphibolite	590548
U79	Diopside marble with biotite band	582556

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GEOLOGICAL MAP
of the
SULITJELMA GABBRO
Scale 1:15,000
Prepared from A.M.S. 1:50,000 map based on Norwegian topographic survey; and aerial photographs by Widerøes Flyveselskap A/S, Oslo.
Contour interval 30 metres.
Numbers round margins refer to the 1,000 m. Universal Transverse Mercator Grid.
Pieske-Vasten Nappe
Mta-porphyritic amphibolite
Schistose amphibolite
Micaceous quartzite (in east)
Furulund schist with amphibolite bands near top
? Marble east of Hammeren
Amphibolite west of Hammeren
Junction Units
Dioritic gneiss in south
Schist & quartzite in north
Gasak Nappe
Intrusive Rocks
Sulitjelma gabbro complex unaltered
metagabbros
hybrid rocks
Furulund granite
Hammeren ultrabasics
Igneous breccia
Contact metamorphic rocks
Massive hornfels
Schistose hornfels
Regional metamorphic rocks
In north
Kyanite-schist group
Calcareous semi-pelite
Calc-silicate group
Graphitic schist
Calcareous amphibolite
Quartzite band
In west
Calc-silicate group of Duoldagop
Micaceous psammite with marble bands
Kyanite-schist group
Attitude of primary banding of gabbro
dip angles in degrees
Attitude of schistosity or foliation planes
Superficial Deposits
Scree
Moraine
Alluvium
ØV. SORJUSJAURE
NED SORJUS
Hammeren
Sorjuscokka
DUOLDAGOP
Vardetoppen
Stortoppen
Sulitjelma Glacier
Sulitskongen
Vaknacokka
OTERVANN
LÅMIVANN
Norway
Sweden