PETROLOGY AND TECTONIC SETTING OF RELATIVELY LOW TEMPERATURE ECLOGITES AND RELATED ROCKS IN THE DALSFJORD AREA, SUNNFJORD, WEST NORWAY

VOLUME 1 - TEXT

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ABSTRACT

An area to the south of Dalsfjord has been mapped and four lithological units differentiated. These are (from the top downwards) the Vardheia unit, consisting of heterogeneous paragneisses; the Flekke unit, consisting of metabasic, ultrabasic and oxide-rich rocks, frequently with corona structures; the Gjorlanger unit, consisting of dioritic to granodioritic orthogneisses with common metabasic bodies and websterites, and the Basal Gneisses, with pink granodioritic to monzonitic orthogneisses, paragneisses and pegmatites. The latter is separated from the overlying unit by a zone of protomylonites. Eclogites are found in all the units.

Gradational or intrusive relationships show that all the units are mutually autochthonous. Many eclogites had demonstrable low-pressure igneous protoliths and/or intrusive relationships with the gneisses, indicating a crustal, eclogite-facies metamorphism of all the lithologies mapped. Relics of early granulite-facies assemblages occur in most lithologies.

Bulk-rock geochemistry of Gjorlanger unit lithologies indicates calc-alkaline affinities, resembling magmatic arc rocks but possibly modified during granulite-facies metamorphism. Associated eclogites have been metasomatically altered but retain some tholeiitic characteristics. Websterites are tentatively related to the orthopyroxene eclogites of More and Romsdal. The Flekke unit rocks have affinities with some layered basic intrusions typical of mid-Proterozoic anorthosite suites.

Mineral chemistry and parageneses of a variety of lithologies indicate an early granulite-facies event (M_1) at 7-13 kb, 750-1000° C, 4-10 kb (M_2) followed by rapid compression to eclogite-facies conditions at 597+/-30° C (M_3) then almost adiabatic decompression to below 6 kb (M_4). A thermal discontinuity may have existed between the Basal Gneisses and overlying rocks.

The derived P-T path is incorporated into a continental collision model for the Scandinavian Caledonides involving transient "subduction" of the Basal Gneiss Complex in a Himalayan-style collision zone.

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CHAPTER 1 - INTRODUCTION

CHAPTER 1 - INTRODUCTION

The purpose of this chapter is to outline the location and geography of the area under study, followed by a discussion of its regional geologic setting and previous work in the Dalsfjord area. Finally the main aims of the Thesis will be set out.

Section 1.01 Location and Geography of the Hellevik - Flekke area.

The area considered in this Thesis lies to the South of Dalsfjord, approximately 100 kilometres north of Bergen on the west coast of South Norway. It lies entirely within the Fjaler Kommune in the Sogn og Fjordane Fylke (County) in the northern part of the peninsula defined by Sognefjord in the south and Dalsfjord in the north.

Dalsfjord is in one of the southernmost parts of the Vestlandet region of Southern Norway, which is famous for its mountainous terrain dissected by spectacular fjords. The area between Sognefjord and Fordefjord is commonly known as Sunnfjord, and will be referred to as such from hereon.

The area studied lies between the villages of Hellevik to the west and Flekke to the east and extends as far south as the hill Klibbern and the southern extremity of the lake Breidvatnet.

It is covered by the 1:50,000 scale Topografisk Kart 11171, "Dale". 1:20,000 maps and 1:5,000 scale maps are also available from the "Teknik" office in Dale. 1:5,000 scale maps were kindly made available to the author by A.Korneliussen (N.G.U., Trondheim) and Fylkesgeolog B.O. Russenes (Sogn og Fjordane Fylkeskommune, Utbyggingsavdelinga, 5840 Hermansverk, Norway). Aerial photographs of the area have been obtained from Fjellanger Videröe, Trondheim.

Topographically the area generally consists of steep sided hills reaching about 450 metres above sea level cut by valleys which usually contain lakes such as Tyssedalsvatnet, Jyttevatnet and Breidvatnet. Numerous small lakes lie in outland areas particularly to the south of the broad depression extending eastwards from Gjörlanger.

The area is generally heavily forested, the trees covering the tops of all but the highest hills and cultivated farmland is generally restricted to small farms on the shores of Dalsfjord, Gjörlangerfjord, Breidvatnet, Flekkefjord and Tyssedalsvatnet. The largest settlements are Hellevik and Flekke with numerous small settlements, often merely collections of a few houses, for instance Straumsnes and Gjörlanger. The major commercial centre in the outer Dalsfjord area is Dale which lies a few kilometres to the north east of Flekke. The area is traversed by one major road, route 57, which is the main link from Bergen to Förde and passes through Flekke. Route 607 passes along the west shore of Flekkefjord then passes south through Gjörlanger and hence to Hellevik and on to Hyllestad by Afjord.

Another minor road (unnamed) passes along the shore of Dalsfjord from Tysse via Straumsnes to Andalsvik. Numerous small unmetalled roads and tracks are present not all of which are suitable for vehicles. Figure 1.01 outlines the main geographic features of the area.

Rock exposure in this area is generally rather poor largely due to the heavy forest cover. Even on the unforested hill tops large areas of continuous exposure are rare in contrast to the bare rock mountains facing the area across Dalsfjord. Due to the steep nature of many of the hillsides much of the exposed rock is inaccessible or only approachable with care. However, good exposures are found along the fjord and lakeshores and blastings carried out during construction of roads and forest tracks provide numerous excellent outcrops.

Section 1.02 Regional Geological Setting

The Hellevik - Flekke area lies in the southern part of a large region largely underlain by high grade gneisses and schists known as the BASAL GNEISS COMPLEX (BGC) as shown in figure 1.02. The area in which this complex outcrops will be referred to as the Basal Gneiss Region (BGR) from here on. The BGC forms the deepest structural level of the Caledonian Orogenic Belt of Scandanavia which occupies most of Norway north of Stavanger and the western part of Sweden (Holtedahl and Dons, 1960; Roberts et al., 1981). The BGR is well known for the common occurrence of eclogites and garnetiferous peridotites, the former of which provides the focal point for this study. The origin and age of these and other less obvious high pressure parageneses is a matter of continuing debate whose various arguments will be introduced as they become relevant in the text. Many of the arguments are reviewed by Bryhni et al. (1977), Lappin (1977), Lappin and Smith (1978), Smith (1980, 1981 and 1982), Cuthbert et al. (1983) and Griffin et al. (in press). A geographical map showing importance place-names is given in figure 1.03.

Broadly speaking the debate revolves around two main points of contention: The first relates to the tectonic mechanism by which the high pressure lithologies reached

their present position. Were the eclogites introduced into their host rocks tectonically from some other presumably deeper location in the crust or mantle or were they formed by metamorphism in situ within their host rocks?.
Obviously the choice of mechanism will have important consequences for the implied history of the BGC. In the latter case the high pressure lithologies take on a great importance as their metamorphic history will reflect that of the very large volume of crustal rocks in which they are enclosed.

The second point of contention relates to the age of the high pressure lithologies and is intimately bound up with the age of the other lithologies composing the BCC. Arguments in favour of either a "main metamorphic/deformational event" in the Proterozoic (Pigeon and Raheim, 1972; Raheim 1977, 1979, 1981) or an eclogite-facies metamorphic event of Caledonian age (Krogh et al., 1973; Griffin and Brueckner, 1980, 1982) have been published. In the former case unique evidence for a rather anomolous Proterozoic tectonothermal event in the Baltic shield could be said to be preserved in this region. In the latter case, depending on the choice of tectonic model, studies on high pressure parageneses take on a great importance in deducing orogenic processes operating during the development of the Caledonian orogen.

In view of this implied regional importance of high pressure lithologies in the BGC a brief description of the main geological elements of Norway and parts of Western Sweden is set out below and in figure 1.02. A more comprehensive summary is provided in Cuthbert et al. (1983) which is appended at the end of this thesis (Enclosure 2).

The main tectonostratigraphic units of the Scandinavian Caledonides have been divided into an autochthon/parautochthon, a lower and middle allochthon and an upper allochthon (Roberts et al.1981). Reviews of the tectonostratigraphy can be found in Gee (1975, 1978 and 1980, Hossack and Cooper, (in press) and Andresen and Faerseth (1982). The following summary is largely taken from these publications.

The autochthon is exposed to the south east and east of the Caledonian front in Southern Norway and Sweden and largely consists of pre-Caledonian rocks of Proterozoic age. East of the Caledonian thrust front these are mostly Svecokarelian granites (Gee 1980) whilst in Southern Norway they include Svecofennian and Sveconorwegian (1700 to 900 Ma) granodioritic orthogneisses, charnockites, anorthosites and the volcanics and sediments of the Telemark supracrustals (Holtedal and Dons, 1960; Oftedahl, 1980). The BGC is included with the autochthon but despite lithological similarities to these rocks it shows significant differences from them and will be discussed further below.

Lying directly on the basement there are platform and miogeoclinal shales and sandstones (Jamtland Supergroup, Vidda Group) which appear to have acted as décollement surfaces for the overlying nappes. The overlying lower and middle allochthon consists of tectonic repetitions of the same basement and cover.

The upper allochthon appears to have a dual nature. The lower part consists largely of high grade crystalline rocks often with a proven Proterozoic age including the Seve Nappe, the Jotun Nappe and the Hardanger-Ryfylke Nappe complex. The Jotun Nappe is very large with a geophysically estimated thickness of about 16 kilometres (Smithson et al. 1974 and Battey and McRitchie, 1975). Overlying these is a series of eugeoclinal rocks which include parts of postulated ophiolites (greenstones) island - arc volcanics, continental rift volcanics and associated sediments. These form the Köli Group, the Trondheim Super Group, the Sunnhordland Igneous Complex and the Major and Minor Bergen Arcs. In the Bergen area the tectonostratigraphy is rather anomolous and the eugeoclinal rocks lie directly above the basement (BGC) and are overlain by Proterozoic crystalline rocks including large masses of anorthosite (Anorthosite Complex) and gneisses (Ulrikkens Gneiss Complex) (Sturt et al 1975). Elsewhere the eugeoclinal rocks are the highest tectonic unit.

Gee (1975, 1978), Gee et al. (1981) and Andresen and Faerseth (1982) have produced rather similar tectonic models to explain the formation of the Caledonide tectonostratigraphy. In summary they involve obduction of Iapetus Oceanic crust on to the Baltic continental margin in the early Ordovician followed by considerable basement shortening in the middle and late Silurian resulting from collision of the Baltic and Greenland plate margins. As a result slices of basement and cover were imbricated and stacked together. Finally the composite thrust pile was translated across the Proterozoic basement on a decollement surface provided by the miogeoclinal/platform sedimentary veneer possibly aided by uplift of the basement.

It may be a significant observation that eclogites occur in a number of places at high tectonostratigraphic levels including the Anorthosite Complex of the Bergen Arcs (Griffin, 1972 and Austrheim and Griffin, 1982) and the Seve Nappe (Andresen et al., 1981 and van Roemund, 1983) the high level Tromsö Nappe Complex and the Glomfjord area in Northern Norway (Griffin et al., in press).

The BGC consists of a wide variety of lithologies whose nature and relationships are by no means fully elucidated as yet. Studies by Bryhni (1966) in the Nordfjord area revealed two main groups of lithologies; a rather monotonous group of augen gneisses, granitic rocks and migmatites (the Jostedal Complex) overlain by a more heterogeneous group of lithologies characterised by layered gneisses, ultrabasites, metagabbros, eclogites and rocks of the "anorthosite kindred" (the Fjordane Complex). The "anorthosite kindred" rocks include mangerites, mangerite-syenites and other charnockitic rocks, some resembling rapakivi granites (Carswell and Harvey, 1983 and Harvey, 1983) ultrabasic rocks and anorthosites. These associations are much the same as those found in parts of the upper allochthon and in the gneisses of Southern Norway. Eclogites are also found in the Jostedal Complex (Krogh, 1980 and this work) but ultrabasites and anorthosites appear to be absent there.

The association of heterogeneous "cover" sequence over a more homogeneous "basement" seems to be widespread in the BGR and has been recognised in the Tafjord area (Brueckner, 1977), Grotli (Strand 1969), Breimsvatn (Bryni and Grimstad, 1970) and Sunnfjord (Skjerlie, 1969 and Skjerlie and Pringle, 1978). Bryhni and Grimstad (1970) have suggested that the sequence in the Breimsvatn area may be the result of the juxtaposition of a number of thrust sheets which were subsequently tightly folded.

Skjerlie and Pringle (1978) have drawn similar conclusions for the Sunnfjord area.

A critical area for elucidating the relationships of units in the BGC with the allochthon is that between Oppdal and Surnadal. Gee (1980) has traced units of the allochthon from the thrust front in Sweden via a number of basement windows into this area (the Trollheimen Antiform) where the basal décollement to the allochthon passes into an imbricated crystalline basement. Correlatives of the Seve, Sarv and Offerdal Nappes and slices of basement and cover have been recumbantly folded with the basement then re-folded with the overlying units with the Trondheim Supergroup. The autochthonous sedimentary veneer correlates with rocks of known Cambrian age further east showing that the deformation here is of Caledonian age. Krill (1980, 1983a, b) has demonstrated that the grade of metamorphism increases downwards (westwards) from the lower boundary of the Trondheim Supergroup until eclogites appear by pro-grade metamorphism from amphibolites at between five and twenty five kilometres (along the present land surface) from there. Krill (1983a, b) suggests that this metamorphism took place in situ beneath the allochthon and that the metamorphism is Caledonian. It would seem that some of the allochthonous units of the Trollheimen can be traced well into the eclogite bearing part of the BGC (Griffin et al., in press).

Hence in the northern and north eastern parts of the BGR it can be demonstrated that rather than being just a simple basement to the Caledonian allochthon the BGC probably comprises imbricated and interfolded basement and "cover" including representatives of the allochthon. Direct correlation of this area with more southerly and westerly parts of the BGR, especially that to the south of Nordfjord, are difficult as strong deformation and metamorphism have obscured many of the original relationships. Lithological differences between the two areas also complicate matters; the quartzites and anorthosites which are so common to the south of Nordfjord are less common further north where metadoleritic rocks and garnetiferous peridotites are more frequent. However it seems possible that a similar situation exists in the southern BGR as in the north-east, particularly in view of the observations of Bryhni and Grimstad (1970).

Rb-Sr whole rock isochrons from gneisses in the BGR bear close similarities to those recorded from the gneisses of Southern Norway ranging from about 1800 to 1000 M.a. (e.g. Brueckner, 1972, 1979 and Skjerlie and Pringle, 1978). The exact meaning of these ages is a matter of debate at present, but it appears that the majority of the rocks forming the BGC have Proterozoic (dominantly pre-Sveconorwegian) ages for the formation of their protoliths. The possibility therefore exists that these rocks could have been affected by plutonic and metamorphic events in Svecofennian, post-Svecofennian, Sveconorwegian and Caledonian times and one might therefore encounter evidence for a very complex history.

Most of the units of the allochthon in central Norway can be recognised in coastal areas betwen Sogneford and Nordfjord. On the northern side of Dalsfjord the Dalsfjord Nappe, a large sheet of mangerite-syenite overlies the Basal Gneisses and is in turn overlain by the Stavfjord Nappe containing greenstone and schists with ophiolitic ocean island and island-arc affinities (Skjerlie 1969, 1974 and Furnes et al 1976). Skjerlie (1969) correlates the Dalsfjord Nappe with the Jotun Nappe at Leikanger, Sognefjord. The rocks of the Stavfjord Nappe and related schists near Hyllestad and north of Fordefjord are assigned a lower Palaeozoic ("Cambro-Silurian") age (Skjerlie, 1969). These rocks are generally metamorphosed in the greenschist facies and a strong metamorphic break may exist between them and their underlying gneisses although little information is available on their mineral parageneses.

Also of interest in this area is the presence of a number of areas of conglomorates and sandstones of Devonian age (Holtedahl and Dons, 1960, Roberts et al, 1961 and Kildal, 1970). These have been interpreted as fault controlled late orogenic intramontane basins resulting from movements on hinged normal faults (Nilsen, 1973 and Bryni, 1981) or strike/slip faults (Steel, 1976 and 1981). The sediments are unmetamorphosed and generally lie upon the lower Palaeozoic schists, but late thrusting of "Svalbardian" age has juxtaposed their eastern margins over the Basal Gneisses. As a consequence of the fault movement which resulted in the formation of the Devonian basins the Gneisses now outcrop in a series of horsts, a configuration which has been accentuated by Devonian deformation producing a series of four large folds along the coast (Kolderup, 1960).

Section 1.03 The gneisses of the Sunnfjord area:

The area described here lies between Fördefjord and Sognefjord and forms the southern half of the area covered by the 1:250,000 scale geological map Maloy (Kildal, 1970). In this map (see figure 1.04) five units have been differentiated which are from the highest downwards:

5. Devonian fault bound sedimentary basins.
4. Rocks of " Cambro-Silurian Age" (schists and greenstones).
3. Metamorphic supracrustals (presumed to be of late Precambrian to Lower Palaeozoic age).
2. Overthrust charnockitic rocks including mangerite/ syenites and charnockites and anorthosites (for instance the Dalsfjord Nappe).
1. A "Basal Gneiss Complex" consisting of pre-Caledonian rocks transformed in the Caledonian orogeny.

The northern part of the Malöy Sheet corresponds to the area studied by Bryhni (1966) in which he differentiated the Jostedal and Fjordane Complexes (Section 1.02). The relationships in the Dalsfjord area are fairly similar to those near Nordfjord except that large anorthosite masses are not as common and the related charnockitic masses appear to be less intimately involved with the gneisses. Also eclogites and the metadolerites are associated with the mangerites to the north of Nordfjord (Lappin, 1966) but none are recorded in the Dalsfjord mangerite syenite nappe between Dalsfjord and Sognefjord.

Kildal's (1970) group 3, the metamorphic supracrustals, correspond to Bryhni's (1966) Fjordane Complex and her group 1., the Basal Gneiss Complex corresponds to the

Jostedal Complex. In the Sunnfjord area examples of the Jostedal Complex generally outcrop as culminations within the Fjordane Complex gneisses.

The division of the gneisses below the Cambro-Silurian Schists into two groups as outlined above was studied in detail in the Breimsvatn area to the north east of Förde (Bryni and Grimstad, (1970) where it was concluded that the heterogeneous sequence corresponding to the Fjordane Complex consists of three thrust nappes thrusted on to a basement complex contiguous with the monotonous gneisses of the Jostedal culmination (Jostedal Complex).

In the Sunnfjord area to the south of Förde Skjerlie (1969) differentiated the rocks underlying the Stavfjord nappe (Lower Palaeozoic schists) into a basal gneiss unit overlain by the Holsen and Askvoll groups.

The basal gneisses are exposed in between the coast and inner Sognefjord and in a large culmination called the Gaularfjell anticlinorium and westward extensions of this. They consist of a group of granitic, quartz monzonitic or granodioritic gneisses with migmatitic or occasionally intrusive appearance containing pegmatites (Gaularfjell Group) and generally in the west a group of quartz rich gneisses, augen gneisses, mica schists, quartzites and common massive reddish granitic gneisses (Viksdalen Group). Skjerlie (1969) considered that these gneisses are of pre-Cambrian age and correspond to the Jostedal Complex of Bryhni (1966).

The Holsen Group consists largely of greyish meta-arkoses and more quartz rich rocks often developed as augen gneisses or flagstones.

The Askvoll Group is largely composed of meta-greywackes which was originally considered by Skjerlie (1969) to show a transition into the Holsen Group below and the Stavenes Group above with a change in metamorphic grade from green schist facies at the top to amphibolite-facies near the base where eclogites occur. Homogeneous gneisses of granitic or quartz monzonitic composition occur near the base of the Askvoll Group and were considered to be "palingenic basal gneisses" by Skjerlie (1969). In addition amphibolites, ultrabasites, meta-anorthosites and quartz rich gneisses occur.

In a re-interpretation of Skjerlie's (1969) work Furnes et al. (1976) showed that the lower and upper parts of the Askvoll Group are different lithologic units separated by a major fault running along Dalsfjord. The upper part retains the name "Askvoll Group". Skjerlie and Pringle (1978) renamed the lower part of the original Askvoll Group the " Vevring Complex". The lithological association forming the Holsen Group and Vevring Complex corresponds closely to that of the Fjordane Complex of

Brynhi (1966). Skjerlie and Pringle (1978) noted that the contact of this heterogeneous sequence with the Basal Gneisses is frequently marked by a "distinct thrust zone" and interpreted the Holsen Group and Vevring Complex as a thrust sheet, the Sunnfjord Nappe.

Section 1.04 Previous work in the outer Dalsfjord area:

Detailed work in this area has tended to concentrate on the Lower Palaeozoic greenstones and supra-crustals with only brief comments on the high grade gneisses below (for instance Kolderup, 1921; Skjerlie 1974; Furnes et al. 1976). Large scale studies have touched upon aspects of this area.

Irgens and Hiortldal (1864) and Möhl (1977) both described eclogites and associated ilmenite-magnetite ores from Sördal near Hellevik. Eskola (1921) also mentions this occurence along with a description of a rather curious eclogitic rock from a locality which he called Hordens near Hellevik. The exact position of this locality is not clear but it may correspond to the hill "Hovden" also known as Aurevagen to the south east of Hellevik.

Kolderup (1928) discussed a number of the lithologies in the outer Dalsfjord area including the massive grey gneisses and large amounts of amphibolite along with eclogites, serpentinites and ilmenite ores which he considered to be related to the igneous rocks of the "Bergen-Jotun Kindred" (i.e. the anorthosite-charnockite suite). "Saussurite-gabbro-schists" and an olivine bearing diallagite from near Gjörlanger were also described.

Kolderup and Rosenqvist (1950) described giant garnets from near Gjörlanger.

Kolderup (1960) described four large Devonian synclinal structures along the west coast between Sognefjord and Nordfjord. The area described in this thesis lies on the northern side of his Syncline 1. He considered that most of the gneisses formed as a result of "granitisation" of pre-existing rocks, but noted the magmatic nature of some of the granitic gneisses. The amphibolites, eclogites and metagabbroic rocks were thought to be derived from Caledonian intrusive rocks (see also Holtedahl and Dons, 1960). In addition to this he drew attention to the tectono-stratigraphic similarity between parts of the BGC and the central Norwegian nappe area the "Faltungsgraben" and inferred that the anorthositic rocks near Nordfjord are allochthonous.

Skjerlie's (1969) work covered the outer Dalsfjord area which embraces his Basal Gneisses and Vevring

Complex (see section 2.01) but little detailed description of the area is given. Kildal (1970) covered the area in the Malöy 1:250,000 sheet assigning a Caledonian age to the rocks corresponding to the Vevring Complex hence inferring that the metabasic rocks are also Caledonian. This hypothesis is thrown into doubt in the light of the geochronological work of Skjerlie and Pringle (1978) and a Proterozoic Age now seems to be more likely.

Cuthbert (1981) described some of the localities in the Gjörlanger area in the excursion guide of Griffin and Mörk (1981) and Cuthbert and Carswell (1983) discussed various aspects of the geology of the Hellevik-Flekke area relevant to the petrogenesis of eclogites in the BGR. The area has recently been studied for the economic viability of rutile concentrations in eclogites (A. korneliussen, N.G.U., personal communication 1980, 1981).

Section 1.05 Aims of the Thesis:

Recent studies by Krogh (1980) have shown the presence of rather unusual low-temperature eclogites in the Forde area of Sunnfjord. It was apparent from reconnaissance visits by D.A. Carswell, W.L. Griffin and E.J. Krogh that large amounts of metabasic rock outcropped in the area to the south of Dalsfjord and that studies in this area might prove fruitful.

Field work by this author subsequently showed that the area contained evidence which might prove important in elucidating some of the problems involved in interpretation of eclogites in the BGR including the choice of tectonic mechanism for the formation and emplacement of the eclogites and the comparative metamorphic histories of the eclogites and their enclosing rocks. As a result a threefold approach to the study has been employed as outlined below:-

1) Detailed fieldwork to evaluate the relations of the various rock units (especially the relations of the eclogites to their host rocks) and sampling of the important lithologies.

2) Whole rock geochemical analysis to throw some light on the origins and protoliths of the lithologies involved.

3) Petrographic and mineral chemical analysis to evaluate the P-T history of a variety of lithologies with particular emphasis on the use of various mineral thermometers and barometers.

In addition some geochronological work has been carried out in order to place some absolute time constraints on the history of the area.

In this way a picture has been built up of the crustal history of this area. This will be compared with studies of the adjacent areas and its regional significance will be discussed. Finally conclusions will be drawn on the tectonic consequences of the observations made therein.

Several aspects of the geology of the Hellevik-Flekke areas deserve more detailed scrutiny than a general study of this nature can provide. Hence the concluding section will also attempt to point the way towards possible further research.

CHAPTER 2 - GEOLOGY AND PETROLOGY

CHAPTER 2 GEOLOGY AND PETROGRAPHY

In this chapter the results of field work in the Hellevik-Flekke are are discussed with some general petrographic notes on some of the lithologies sampled. The reader must be aware that boundaries are poorly exposed and that mapped units are mainly interpolated. All specimen and photograph localities are given in Appendix 3.

Section 2.01 Introduction

Enclosure 1 is a geological map of the Hellevik-Flekke area. From this it can been seen that four main lithological units have been differentiated, these are from the structurally highest downwards:

1.) A unit of heterogeneous banded gneisses lying in northern part of the area. It is best exposed on the tops of Vardheia and Arsteinheia and in road cuts by Route number 607 between Elde and Tysse and by the road to Straumsnes and Asnes along the side of Dalsfjord. This is named the Vardheia Unit and seems to form part of the Vevring Complex of Skjerlie and Pringle (1978). A narrow strip of this unit is exposed above the iron ore mine at Sördal on the northern slope of Saurdalsfjellen. This appears to correspond to the "Silurian Schists" mentioned by Kjerulf in Irgens and Hiortldal (1864).

2. A unit consisting of meta-anorthositic and ultrabasic rocks, ilmenite rich rocks, meta-gabbros, amphibolites and eclogites. These rocks are exposed at Flekke to the north of Haheia, near Solvik by Gjörlangerfjord and on Aurevagen near Hellevik. This unit is called the Flekke unit and appears to be a deformed and metamorphosed layered basic-ultrabasic complex. Similar rocks are widely exposed on the south slopes of Saurdalsfjellen and around Instetjörna where associated lithologies of more intermediate composition are found also.

3. Homogeneous grey granodioritic gneisses containing significant volumes of basic material as well defined intrusions or diffuse bodies. This is exposed in a broad band between Hellevik and Flekke and is particularly well displayed in a number of road cuts by Route numbers 57 and 607 to the south of Flekke and on Route 607 by Tyssedalsvatnet and Gjörlangerfjord. A number of intrusive websterites are exposed within these gneisses. This group of lithologies is termed the Gjörlanger unit.

4. The lowest unit exposed in this area lies below a zone of strong attenuation defining the southernmost extension of the Flekke unit in the west and the Gjörlanger unit in the east. It consists of grey and pink granodioritic and monzonitic gneisses often massive with augen texture. These are simply termed the Basal Gneisses and seem to correspond to the Josterdal Complex of Bryhni (1966) and possibly the Gaularfjell Group of Skjerlie (1969). Some white-mica rich gneisses occur locally near the top of this unit and may be representatives of the Holsen Group or perhaps the Viksdalen Group of Skjerlie (1969). Pegmatites are common in this unit but rare in the other units. Pods and bands of eclogite occur locally. The top of this unit may correspond to the thrust zone defining the base of the Sunnfjord Nappe of Skjerlie and Pringle (1978).

These units are described in detail below:-

Section 2.02 The Vardeheia Unit:

The top of the Vardeheia Unit is not exposed in the investigated area. The dominant lithology is a more or less strongly banded mica-plagioclase-quartz gneiss containing epidote or, more rarely, garnet. Sphene, apatite and carbonates are common accessory minerals. The banding is defined by mica + epidote +/- K-feldspar and quartz + plagioclase rich layers of varying thickness but with continuity on the scale of the outcrop in many cases (Figure 2.01).

Other lithologies are mica-amphibole-epidote schists, meta-psammites, granitic gneisses and augen gneisses. Meta-basic rocks are fairly common including bands of hornblende-biotite-epidote schists and boudins of eclogite and garnet-amphibolite. Road cuts on Route 607 by Flekkefjord and the minor road to Straumsnes by Dalsfjord provide a reasonably continuous traverse through this unit. Just to the north of Leirpoll micaceous garnet-amphibolites and eclogites of the Flekke Unit pass northwards (upwards) over less than 50 metres into more biotite rich amphibolites then biotite rich grey gneisses appear commonly containing pods of amphibolite and eclogite bordered by sheaths of white mica and vein-quartz.These are well exposed by a small inlet of Flekkefjord near Tytebaerhaugen north of Leirpoll.

A few hundred metres north of Leirpoll near Elde, road cuts exhibit fairly typical stripey banded gneisses with alternating quartzo-feldspathic and biotite-epidote rich layers. Specimen D126 taken from a micaceous band consists of roughly equal amounts of khaki green biotite and sodic plagioclase with subordinate epidote and K-feldspar. Sphene, apatite and carbonate are very common accessories and pyrite crystals up to 25 mm across occur occassionally. White mica occurs as small inclusions as sulphide and plagioclase grains. Fine intergrowths of biotite and K-feldspar may be breakdown products of a previous phengitic white mica (cf. Heinrich 1982, Griffin et al., in press).

Specimen 79/19 consists of fine quartzofeldspathic and micaeous bands, the former sometimes containing augen-like clots of pinkish feldspar. The felsic bands consist dominantly of an irregular fine mosaic of sodic plagioclase and quartz as strained sutured grains. Augen consist of cores of perthite or mesoperthite rimmed by granular mortar textured plagioclase + K-feldspar. The micaeous bands consist of khaki green biotite and epidote. Relics of a fairly coarse (up to 1 mm) white mica with faint yellowish pleochroism occurs in these bands. It is usually bent and strained and breaks down marginally to biotite + K-feldspar + quartz. Some of these white micas (phengites) develop in strongly planar orientated sheaths around the rims of the feldspar augen (Figure 2.02). Another type of white mica which is very fine grained and colourless forms fine rims around the biotites usually associated with the development of chlorite. The present appearance of this rock therefore appears to be, at least in part, a result of cataclasis and breakdown of a more augen rich gneiss.

Further north still in a road cut by the north side of Eldevika is a rare occurrence of garnetiferous gneiss (specimen 79/21). Felsic layers consist of sodic plagioclase + quartz both heavily strained often with skeletal garnets up to 5 mm across forming along quartz grain boundaries. Micaceous bands consist of coarse (up to 1.5 mm) phengitic white mica with streams of inclusions of sphene. The phengite is locally replaced by biotite. Euhedral fairly complete garnets occur in these bands within inclusions of sphene. Epidote is quite common in the felsic bands. The phengite defines tight isoclinal folds but are bent around later open folds or crenulations (Figure 2.03). Biotite grows more randomly and is unstrained. Chlorite locally replaces the biotite and garnet. On the Straumsnes road by Dalsfjord at Raudenebben (west of Eikerol) the gneisses are locally very micaceous with bands of phengite-amphibole-epidote schist. Specimen 79/22 comes from one of these bands and is a medium to dark green crenulated schist consisting dominantly of coarse strained phengite with secondary biotite. Subordinate olive green-blue green-yellow amphibole, epidote, sodic plagioclase and carbonate are the other major phases. Phengite, epidote and amphibole define early isoclinal folds refolded by open folds which bend or fracture these phases.

West of Raudenebben the gneisses become more homogeneous at first though fairly micaceous. Augen of K-feldspar are quite common. At Solvesteintaa where the coast turns south into Asnesvika the gneisses are pink coloured and net-veined with dark biotite rich streaks (Figure 2.04). The leucosome and melanosome are often strongly attenuated and folded. Well banded migmatite are microscopically very similar in appearance to 79/19 with early mesoperthite relics, secondary phengite, sodic plagioclase and epidote and late biotite. Leucosomes have a strong flattening fabric consisting mostly of heavily granulated strained sodic plagioclase, K-feldspar and quartz with a few ragged grains of biotite and strings of small epidotes apparently resulting from the mechanical fragmentation of larger grains with allanite cores.

On the hills Vardheia and Arsteinheia the lithologies seem to be similar to those seen in the road cuts below. Metabasites are quite common. A linear belt of small pods of garnet amphibolite, epidote amphibolite and eclogite lies just to the north of Vardheia and can also be found on the prominent spur of Bauten on the opposite side of Tyssedal.

The coast between Asnes Skifabrikk and Agnalsvika by Gjörlangerfjord provides good exposures of the Vardheia Unit. On the shore near Andalsvik where the coast turns from east-west to north-south are well foliated poorly banded mica-plagioclase-epidote-quartz gneisses. Towards the north this rock becomes pinker, more massive and has a weaker foliation. This consists of large deformed perthites breaking down to fine plagioclase and white (phengitic) mica usually being replaced by biotite. Biotite is often found intergrown with quartz and may therefore be replacing hypersthene. The steep sided hill to the north of the coast here (Grimskaret) largely consists of this massive rock.

On the promontary to the south of Asnes the gneisses contain pale quartzitic or psammitic bands which show extreme attenuation and are locally folded into very tight recumbant isoclinal folds. These bands consist of quartz + sodic plagioclase + phengite + garnet + epidote and sometimes microcline with secondary biotite and K-feldspar and accessory sphene Fe-Ti oxide and apatite. Mafic pods are common in this area and locally form boudinaged rootless recumbent isoclinal fold pairs (Figure 2.05). The pods may be epidote amphibolite (rich in biotite) garnet-amphibolite or more or less fresh quartz-eclogite.

On the south shore of this promontary is a broad area of quartz-phengite eclogite. This is attributed to the top of the Flekke Unit in this area and is probably part of the same sheet that outcrops further south near Solvik. At the top of this sheet (i.e. the bottom of the Vardeheia Unit) the eclogite is full of veins of siliceous material often poorly foliated, seemingly protected from strong deformation by the eclogite. Locally the veins can be seen to extend into the eclogite from the overlying psammitic gneisses. The veins are interpreted as metamorphosed anatectic back veins formed by melting of country-rocks on intrusion of an igneous precursor to the eclogite. The veins often have rather diffuse margins and show gradational contact with the eclogite. The eclogite consists of a granoblastic aggregate of euhedral garnets, omphacite, phengite, rutile and rare quartz. By the veins the eclogite shows an increase in the amount of phengite and develops atoll garnets with cores of quartz and phengite (similar atoll garnets occur in the overlying psammitic gneisses). Quartz then becomes very common until within the vein it becomes dominant over garnet, phengite and ompacite (Figure 2.06). Omphacite becomes increasingly symplectised and altered to amphibole towards the core of this vein. Passing into the gneiss the rock consists of quartz + phengite + garnet + albite + epidote with secondary biotite + K-feldspar and accessory rutile rimmed with ilmenite.

In summary, the Vardheia Unit consists largely of gneisses of broadly granitic or granodioritic composition, but with much small-scale heterogeneity. Subordinate mafic, pelitic and more psammitic lithologies occur. Evidence exists for the presence of migmatitic lithologies including mesoperthite - bearing augen-gneisses. The features identifying these are only locally preserved and appear to be have been largely obliterated by later deformation, first of all associated with the formation of phengite-bearing assemblages (and eclogites) then biotite-bearing assemblages, the latter of which are now dominant.

The well-banded nature of the gneisses, along with their small-scale lithological heterogeneity and the presence of psammitic and pelitic types indicate that these gneisses are derived, at least in part, from sedimentary rocks. An ultimate supracrustal origin can, therefore, be inferred for much of this unit. However, the presence of significant amounts of intrusive material cannot be discounted particularly in the case of the more mafic rocks.

The back-veining in the top of the underlying eclogite sheet shows that the contact of the Vardheia Unit with the Flekke Unit is primary and hence the likelyhood of large-scale tectonic movements along the contact can be discounted. The common mafic inclusions in the lower part of this unit may be disrupted small intrusions into the gneiss precursors related to the intrusion of the eclogite's igneous protolith. Alternatively, there may be fragments of the eclogite sheet which have been torn from the parent body and included in the gneiss during tectonism.

Section 2.03 The Flekke Unit

The Flekke Unit is quite well defined by the generally basic or ultrabasic character of its constituent rocks. Descriptions of various localities will be set out below before attempting to construct a unifying picture for the whole unit.

2.03.1 The Base of the Flekke Unit:

In the area around Flekke on the east side of Flekkefjorden the lowest rocks of this unit lie above fairly leucocratic, fine grained granodioritic gneisses of the Gjörlanger Unit. On a small promontory to the west of Flekke, by a sawmill, these gneisses pass gradationally into a phengite-zoisite-quartz eclogite or garnet amphibolite and then into coarse garnet amphibolites rich in iron ore over a few metres. Overlying this on the east side of the headland are chlorite-peridotites with numerous pods and bands of dunite and garnet rich amphibolites.

To the north of the hill Haheia the base of the Flekke unit is marked by a conspicuous band of tremolite-chlorite peridotite (Figure 2.07). A sample from the knoll Varden by the lake Storetjorna (D 130) consists of about 60% subidiomorphic olivine grains which are often overgrown by pale green wispy chlorites and are full of serpentine filled fractures defining a weak planar fabric. Patches of fairly coarse (0.7-1.0 millimetres) tremolitic amphibole and pale green chlorite and some magnetite make up the rest of the rock and small olivine grains form inclusions in the amphiboles. The peridotite band is about 20 metres thick at this locality and passes southwards into peridotite with conspicious streaks or bands rich in chlorite and clots of garnet and iron oxide up to 50 centimetres long. This zone is about 2-3 metres thick and passes in 0.75 metres through a chlorite-amphibolite and then a dark green hornblendite or garnet amphibolite. The amphibolite grades rapidly into a quartz-rich biotite-plagioclase gneiss which passes in 3-4 metres into a pale grey-green quartz-white mica-zoisite amphibolite assigned to the Gjörlanger unit. Further east at a small waterfall this peridotite passes northwards into coarse porphyroblastic garnet amphibolites and coronitic metagabbros and southwards grades rapidly into garnet amphibolites which become rich in mica and become intimately interveined with quartz-plagioclase-biotite gneisses assigned to the Gjörlanger unit.

The thickest development of this peridotite occurs to the north of the small lake Svartetjörna, where it is exposed in a steep rocky scarp in a waterfall. It is about 100 metres thick here, contains small patches of garnetite and is petrographically similar to its counterpart further north. The band thins considerably further west and difficult terrain prevented following it eastwards, but it was not observed to the east of Jyttevatnet.

The base of the Flekke unit is not always marked by this peridotite. To the west of Sördalsvatnet several large areas of meta-anorthositic gabbro are exposed which appear to pass directly downwards into the gneisses of the Gjörlanger unit. To the east of Sordalsvatnet a number of patches of garnet amphibolite or eclogite are intimately interbanded with massive granodioritic augen gneisses at their margins.

2.03.2 Middle Part of the Flekke Unit:

The middle part of the Flekke Unit consists largely of rocks of broadly anorthositic troctolite composition. These have rather variable mineralogy depending on their degree of metamorphism.

The most primitive mineralogical type of anorthositic troctolite can be found in a blasting on the north shore of Instetjörna. The rock has fine layering on the scale of a few centimetres defined by variations in the proportions of cloudy white or pale brownish purple plagioclase and mafic minerals, which are dominantly olivine with subordinate augitic clinopyroxene and hypersthene (Figure 2.08). Grain size varies from 2-3 millimetres to 4-5 centimetres. No obvious systematic size gradation or variation in the ratio of plagioclase to mafic minerals occurs in individual layers.

Specimen D143 comes from this outcrop and consists of about 60% plagioclase which is idiomorphic or subidiomorphic and usually marginally zoned. Large anhedral olivines form about 30% of this rock. These are fairly equant, often in polycrystaline patches and have lobes and processes filling gaps between the plagioclase grains. They occasionally show weak optical zoning but this is often complicated by strain-induced undulose extinction. Brown pleochroic hypersthene often forms rims around olivines with negative crystal form against plagioclase. Locally, greenish-brown clinopyroxene with dendritic lamellae of opaque oxide forms a discontiniuous, rather thick rim over the hypersthene against the plagioclase (Figure 2.09). Green spinel forms small, rounded grains usually embedded in the hypersthene. Small grains of phlogophite occur as inclusions in olivine or plagioclase. Sample D 170 comes from the same locality and is poorer in olivine. Here the hypersthene is often in graphic or symplectic intergrowth with opaque oxide or green spinel. Fine orthopyroxene + clinopyroxene + spinel symplectites often form lobate masses at the contact with the coarser spinels and hypersthene and extremely fine pyroxene + spinel symplectites form thick (up to 0.3 millimetres) rims between olivine and plagioclase. The plagioclase is usually clouded with fine acicular needles which seem to be zoisite or locally mica. Fine rims of garnet up to 10 microns thick form between the pyroxene-spinel symplectites and the plagioclase (Figure 2.10) and between the hypersthene and the plagioclase, apparently overgrowing the zoisite clouding. Fine, fibrous colourless amphibole usually intervenes between the garnet and the hypersthene.

Apart from slight undulose extinction in some mineral grains, this rock is undeformed and layering can be ascribed to igneous accumulation processes. Textural relationships suggest that the rock is an orthocumulate or possibly a mesocumulate. If classified by its complete mineral content it is an anorthositic gabbroic troctolite but classified in terms of its primary precipitate (cumulus) phases it is an anorthositic troctolite. Similar, though much coarser rocks are found as loose boulders near the small farm at Sördal, which probably have an origin on the northern scarp of

Saurdalsfjellen.

Meta-anorthositic rocks with similar chemical composition are widely developed in the hills to the north of Instetjörna. One particularly well exposed example consists of a pale green actinolitic amphibole + garnet + paragonitic white mica +/- zoisite. The garnets form sinuous trails and rings resembling bead necklaces and, by analogy with some of the rocks described below, probably form as coronas by reaction between plagioclase and a mafic phase. The outcrop displays a striking resemblance to the rhythmic layered sequences seen in many basic intrusions. Individual units vary from 10 to 30 centimetres thick and have sharply defined bases overlain by coarse, dark grey green amphibole rich patches with subordinate interstitial white mica + zoisite (Figure 2.11). The dark and light patches are taken to be pseudomorphs of igneous cumulus and intercumulus grains. Passing upwards the size of individual patches decreases and the white patches become predominant until the sharp, rather irregular base of the next unit occurs. Some very coarse, pseudopegmatitic units cut across the rythmic layers at low angles and may be onlapped across them. At one locality rythmic units are displaced by about 5 centimetres across a small vein of amphibolite with very diffuse margins (Figure 2.12). This appears to have been a syn-igneous normal fault. Deformation of this lithology produces a schistosity which obliterates the pseudomorphed rythmic layering. This produces medium-grained, well foliated white mica-zoisite-garnet amphibolite in which white mica + zoisite form anastomosing schleiren (often defining isoclinal folds) between elongate patches of grey-green amphibole and pinkish garnet (Figure 2.13). Such amphibolites are widely developed in the hills surrounding Instetjörna.

On Aurevagen, near Hellevik, more meta-anorthosites occur. At the base of the hill are micaceous garnet amphibolites similar to those described above. A few metres up the steep, wooded cliffs which skirt the hill the foliation is much weaker and the rock consists of patches of grass-green clinopyroxene or dark grey-green amphibole up to 5 centimetres across rimmed by coronas of deep red or pink garnet. The coronas are surrounded by extremely fine grained white or pale green material. Patches of white mica and deep red rutile are common. Where the rock is foliated the coronas are rather elongate and granular, but the foliation generally disappears upwards, leaving a striking bright green and white rock with massive garnet coronas.

An example of such a rock is specimen D 132. The cores of the coronas consist of granoblastic mosaics of fairly coarse (up to 2 millimetres) pale green omphacitic clinopyroxene with anhedral patches of rutile.

The garnet coronas are usually about 1 millimetre thick and consist of interlocking grains up to 1 millimetre across with a poorly formed, rather granular inner rim but with euhedral crystal faces at the outer rim. A narrow zone of fine inclusions with low first order birefringence occurs in the outer part of the corona and these are colourless omphacites. The fine, white material consists of a granular mosaic of colourless omphacite about 1 to 5 microns across intergrown with slightly larger subhedral to euhedral kyanite (Figure 2.14). Paragonite blades sometimes occur in this part of the rock, along with late poikiloblastic colourless amphiboles.

A common variant of this rock type, particularly on the top of Aurevagen, is exemplified by specimen D133. Whilst being superficially similar to D132, the white parts of the rock are overgrown by idiomorphic garnets about 0.5 millimetres across (figure 2.15), which are full of elongate omphacite inclusions. The rock has the macroscopic appearance of eclogite in which the omphacitic and garnetiferous patches have an idiomorphic form suggesting static replacement of a coarse- grained igneous rock. This is probably the rock from "Hordens" described by Eskola (1921).

Large areas of coronitic meta anorthosite occur between Aurevagen and Sördalsvatnet. Further examples occur on top of the prominent spur to the north west of Instetjörna and to the west of the small lake Svartetjörna, stratigraphically above the thick peridotite unit. Rounded blocks of meta-gabbroic anorthosite can be found around the shores of Instetjörna, including one in which the corona cores are composed of talc and tremolite (sample D 171).

2.03.3 Upper Part of the Flekke Unit - Solvik:

The shoreline on the east side of Gjörlangerfjord between Gjörlanger and Solvik exposes lithologies which form the upper half of the Flekke Unit. Blastings by a gravel road above the shoreline expose gneisses and metabasites of the Gjörlanger Unit at their southern end. An exposure gap of a few tens of metres is followed by a series of well foliated metabasites and metaperidotites. The rocks represented by the exposure gap may be seen on a broad bench on the southern slopes of Vardheia known as Gjörlangernova. Exposure is rather poor here, but small outcrops of chlorite peridotite and coronitic meta-gabbroic anorthosites are common. Another type meta-anorthosite also occurs here, consisting dominately of white mica and coarse zoisite with subordinate pale green amphibole + quartz + plagioclase. Large grains of euhedral garnet give this lithology a characteristic porphyroblastic texture. The mica is extensively replaced to an extremely fine intergrowth of plagioclase and sillimanite (Figure 2.16). The amphiboles either form large "sieve textured" grains or coarse blocky symplectic masses intergrown with plagioclase and quartz and very probably formed from the breakdown of omphacitic clinopyroxene. The garnets contain abundant conclusions of a blue-green amphibole and zoisite. The foliation formed by the micas and zoisites is folded into open undulations which bend these phases.

A traverse up the steep slopes to the north of Gjörlangernova passes through coronitic meta-gabbroic anorthosites very similar to those of Aurevagen. Above these are chlorite rich peridotites (whose contact with the meta-anorthosites is not exposed) about 20 metres thick, overlying by a band of garnet amphibolite. This amphibolite has a sharply defined contact with the overlying banded gneisses of the Vardheia Unit which appears to be undeformed and is considered to be a primary intrusive contact.

To the north of the exposure gap on the road by Gjörlangerfjord poikiloblastic white mica-zoisite-garnet amphibolites akin to those on Gjörlangernova appear, passing into more amphibole rich varieties and then a fresh, equigranular eclogite interbanded with garnet amphibolite. The eclogite consists of euhedral garnets in a matrix of well orientated pale green omphacites with rutile as a common accessory and rare interstitial quartz (e.g. samples 79/34A and D205). The amphibolite is texturally very similar to the eclogite but the dominant chain silicate is an actinolitic amphibole and garnet is rather more abundant (e.g.D206). Amphibole and omphacite coexist at the boundaries of the bands and locally within the bands (Figure 2.18). Inclusions of dark green hornblendic amphibole occur in the cores of the garnets and omphacite or actinolite occur nearer the rims (Figure 2.19). These rocks will be discussed in some detail in Chapter 4.

These eclogites and amphibolites pass into chlorite-magnetite harzburgites and chlorite-enstatite schists which are very characteristic of the upper part of the Flekke unit. A typical example is specimen D203 in which large (up to 15 millimetres long) enstatites lie in foliation planes formed by coarse chlorite. These grow over narrow trails of magnetite. Radiating fibrous grains of anthophyllite grow across this foliation. Both enstatite and anthophyllite are replaced by pseudomorphic masses of talc rimmed by olivine. The foliation is folded around fairly open, slightly asymetrical folds. Chlorites show undulose extinction and enstatite develops subgrain boundaries in response to this deformation. Anthophyllite and talc also appear to have been deformed during this folding (Figure 2.20).

These ultrabasic schists contain boudins of very garnet rich metabasites and bands of hornblendite. Specimen D34 comes from a garnet rich pod by a gate close to the end of the road at Solvik (Figure 2.21). The garnet forms massive aggregates of grains up to 0.5 milimetres across in between which large (up to 3 millimetres) plates of chlorite and laths of pale green clinopyroxene occur. Small garnets are frequently poikilitically enclosed within chlorite and pyroxene. Hornblendic amphibole forms reaction rims between the chlorite and the pyroxene and similar amphiboles are very common as small inclusions within some of the larger garnets. Apatite occurs in clots of rounded grains as does iron-titanium oxide, which commonly includes grains of chlorite. Zircons are common accessories, are usually brown coloured and have well developed pleochroic halos developed in enclosing chlorite and amphibole. This rock can be described as a chlorite-pyroxene-garnetite or possibly a chlorite eclogite.

In this road section the ultramafic schists have a direct contact with the overlying gneisses of the Vardheia Unit. The sequence is repeated three times in the road section by upright asymetrical folds. A similar sequence is found on the shoreline below the road, where chloritic schists pass westwards (downwards) into banded eclogites and coarse hornblende garnetites. On the west side of a small inlet at Solvik small exposures of massive, rather heavily fractured coronitic meta-anorthosite appear and further west at another inlet (Balsarvika) there is an excellent exposure of coarse metabasic rocks. IT SHOULD BE NOTED THAT THIS LOCALITY HAS RECENTLY BEEN DECLARED A NATIONAL SCIENTIFIC MONUMENT AND IS THEREFORE PROTECTED FROM UNAUTHORISED COLLECTING BY NORWEGIAN LAW (J. Brommeland, personal communication, 1980 and W.L. Griffin, personal communication, 1982).

Two lithologies occur at Balsarvika. The dominant type is superficially similar to the coronitic meta-gabbroic anorthosites found further to the west on Aurevagen. Very fine grained dense white material encloses either fairly coarse (1-3 millimetres) dark grey-green amphibole or, locally, grass green clinopyroxene which forms idiomorphic patches on the rock surface (Figure 2.22). Locally these patches consist of single black diallage grains up to 3.0 centimetres across. These mafic patches are rimmed by pink garnet coronas. The other lithological type forms a thick band within the meta-anorthosite and consists largely of extremely coarse (up to 15 centimetres across) rather ovoidal black diallage clinopyroxene with narrow (up to 1.5 centimetres) rims of pink garnet. The textural relationships of the different mineralogical elements of these rocks strongly suggest an origin as a very coarse cumulate igneous rock. Obvious rythmic layering, as seen near Instetjörna, is absent, but sharp contacts between the meta-pyroxenite and the meta-anorthosite and between more mafic and more felsic types of meta-anorthosite are observed locally. Blocky patches of white material, apparently anorthostic in composition, occur locally within these coronites (Figure 2.23).

A rather spectacular variety of the meta-gabbroic anorthosite occurs in irregular areas up to 3 metres across and essentially consists of grass green omphacite and pinkish garnet in blocky monomineralic aggregates. Their textures indicate that they are pseudomorphs after a cumulate igneous protolith (Figure 2.24). A common feature of these eclogites is the presence of veins up to 1.5 centimetres wide filled with essentially pure omphacite. The veins stop at the boundary of the surrounding coronitic meta-anorthosite. Both the coronitic and eclogitic variety are traversed by veins filled with coarse (up to 1 centimetre) hornblende and plagioclase. These cross cut the omphacite veins and therefore post-date them. Locally the omphacite veins have hornblende rich cores and these appear to have been weaknesses exploited during the formation of the hornblende veins.

The white material, which presumably replaces plagioclase, consists of a fine intergrowth of jadete and zoisite (Figure 2.25). Retrograded varieties consist of plagioclase, zoisite and colourless amphibole. Shearing induces the formation of abundant paragonitic white mica in this portion of the rock. The mafic cores of the coronas consist of single crystals of augite, heavily clouded with ilmenite (Figure 2.26) (D 194), granoblastic masses of green omphacitic pyroxene with clots of coarse rutile or very pale green colourless actinolitic amphibole (6-5-5). The garnet coronas may be up to 5 millimetres thick and are usually full of inclusions of jadeite or omphacite. The eclogitic variety is essentially similar except that in place of the jadeite/ zoisite intergrowth there are masses of euhedral garnets full of omphacite inclusions (D35, D192).

At Sördal, to the south of Gjörlanger a transition from these coronites into Fe-Ti rich metagabbros occurs. Southerly dipping porphyroblastic white-mica bearing garnet amphibolites on Sördalshaugen pass southwards (upwards) into coarse, coronitic meta-anorthositic rocks which are quite similar to those at Balsarvika. Passing across Sördal an increase in rutile and magnetite can be discerned until a band of magnetite-ilmenite-ore appears above the spoil tip of an old mine entrance. This is the locality which was described by Kjerulf in Irgens and Hiortldahl (1864).

By the mine addit entrance the rock contains up to 100% ilmenite-magnetite ore, but a considerable variety of associated lithologies can be found in the adjacent spoil tip, most of which are quite ultrabasic. Some of these are described below:

79/41A is the most ore-rich specimen sample, consisting of about 60% magnetite with lamellae of ilmenite, the rest of the rock being colourless chlorite with rare grains of green spinel.

79/41C is mineralogically similar but much richer in chlorite and green spinel. A strong foliation is defined by the chlorite, which appears to be replacing the spinel in places. This specimen also contains a band rich in fine (0.3 mm) granular garnet which is intergrown with magnetite and chlorite. Relics of green spinel are associated with the magnetite.

79/41B consists dominantly of a massive aggregate of finely granular garnet in which occur polygonal patches of magnetite and ilmenite ore and a few grains of colourless chlorite. This specimen shows no evidence of deformation, its texture is reminiscent of some coarse igneous rocks, in particular, the negative crystal form show by the magnetite where it is in contact with the garnet (Figure 2.27). Polygonal clots of apatite are occasionally found within the garnetite. In the field magnetite, chlorite and garnet-rich types are interbanded or grade into each other on the scale of a few tens of centimetres.

The garnet-magnetite-chlorite rich rocks show a gradation towards rocks similar to those found in pods and bands in the ultrabasic schists near Solvik. Specimen D 155 has a macroscopic textural similarity to a coarse gabbroic rock, with lath-shaped masses of garnetite and interstitial opaque oxide, olivine, apatite and late poikiloblastic hornblende. Chlorite is intergrown with the oxide. Specimen D 153 is largely an equilibrium intergrowth of equant diopside, lath-shaped chlorite and interstitial opaque oxide. Large tabular poikiloblastic hornblendes overgrow these phases and also relics of garnet. Specimen D 152 is rather poor in opaque oxide and consists of alternating zones of large (2 to 3 centimetres wide) granular garnetite masses and intergrowths of diopside and chlorite. Apatite is a common accessory mineral in coarse patches about 1 millimetre across.

50 metres west of the mine by the gravel road past Sördalsvatnet a road cut displays coarse coronitic eclogites or garnet amphibolites, chlorite-schists and pods of dunite. These lithologies pass south westwards above the magnetite-ilmenite rich band. This passes upwards into a phengite-bearing garnet amphibolite or ecolgite (specimen D 41) which becomes interbanded with banded biotite-plagioclase-quartz-K-feldspar gneisses at the base of the cliffs skirting Saurdalsfjell.

2.03.4 Upper Part of the Flekke Unit - Flekke:

Returning to the Flekke Area, shoreline exposures reveal the relationships of the meta anorthosites with the overlying ultrabasic schists. On the eastern side of

Flekkefjord the southern end of the promontary opposite Leirpollen consists of porphyroblastic garnet amphibolites and coronitic meta gabbroic anorthosites. Passing northwards (upwards) these become progressively poorer in garnet and richer in magnetite, chlorite, enstatite and olivine so that they grade over about 25 metres into enstatite-anthophyllite-chlorite-magnetite schists and chlorite-cummingtonite-magnetite peridotite. No true magnetite-ilmenite ores occur here, unlike at Sördal.

Most of the rocks in the Flekke area above the meta gabbroic anorthosites are chlorite-magnetite harzburgites. To the west of the junction of the road from Flekke to Haugland with that of the road to Igelkjon these ultrabasic rocks pass northwards (upwards) into white mica-zoisite-garnet amphibolites about 10 metres thick overlain by banded gneisses containing abundant amphibolite pods. The amphibolite can be traced south eastwards in the crags lining the hollow in which Flekke lies. This is locally eclogitic and is underlain by chloritic peridotites or harzburgites. In the corrie north of the ridge enclosing Flekke similar eclogite amphibolites appear to be underlain by banded gneisses. The field relationships here are often obscured by scree or vegetation cover and are therefore rather ambiguous. However, it seems possible that either this unit is transgressive or that more than one such unit exists and the gneiss is interleaved between them. The latter seems to be the case at Solvik also, where the ultrabasites are in direct contact with the gneisses by the roadside, but a very similar micaceous eclogite-amphibolite to those found at Flekke and Sordal is found in the cliffs above. This can be traced some distance northwards along the coast and is probably the same unit found below the Vardheia Unit gneisses south of Asnes.

As at Solvik, a number of metabasic pods occur in the ultrabasic schists near Flekke. A few metres northwest of the village shop at Flekke a low hummock consists of well foliated chlorite-magnetite-harzburgite with secondary talc after enstatite. This encloses a pod of coarse grained rather dark coloured eclogite. Specimen D 12 comes from this outcrop and consists of emerald green clinopyroxene and garnet, each forming distinct mono-mineralic patches. Large up to (7 millimetres) idiomorphic grains of zircon are quite common.

On the west side of Flekkefjord where a stream issues into it at Leirpollen a band of massive garnet amphibolite lies within chlorite schists. Macroscopically it consists of dark green amphibole with centimetre scale streaks and pods of pink garnet, magnetite, apatite and zircons. Where the deformation is weaker the rather blocky texture seen in the pseudomorphic eclogite at Balsarvika can be made out, suggesting an origin as a coarse cumulate igneous rock (Figure 2.28). Its contact with the chlorite schist is marked by a band of rather fragmented zircons intergrown with pale green amphibole and garnet. This passes into a garnet-magnetite-amphibole rock and the amphibole can be seen replacing omphacitic clinopyroxene locally. Bands or patches rich in magnetite, apatite and zircon are common throughout the rest of the rock.

A common feature of the ultrabasic schists near the school at Flekke is the occurence of white boudins and bands within them (figure 2.29). On close inspection these can be seen to consist largely of rather sugary masses of zoisite with subordinate hornblende and garnet. The pods usually have blackwall reaction selvages against the surrounding peridotite.

Specimens D 140 and D 141 come from one of these zoisitite boudins. The pod is about 5 centimetres across at its thickest point. The reaction selvage around the core of the zoisitite pod (D 140) consists of an inner, discontinuous rim of hornblende, followed outwards by a continuous rim of pink garnet with small zoisite inclusions. Then hornblende reappears, garnet decreases and green chlorite appears. About 7 millimetres from the zoisitite rim green chlorite forms about 90% of the rock with a few grains of diopside intergrown with it. The chlorite selvage is about 1 to 2 centimetres thick and has an abrupt contact with an actinolite-magnetite selvage (D 141) with actinolite fibres up to 4 millimetres long orientated normal to the chlorite backwall. This passes into a zone consisting of talc-olivine-magnetite +/- actinolite about 7 millimetres wide which stops abruptly against the country-rock, which is a granoblastic aggregate of almost pure olivine +/- magnetite +/- chlorite.

Specimen D 138 is from a similar zoisite band found amongst chlorite-peridotites and metabasic layers in a blasting in the yard of the new school at Flekke. The zoisitite contains fine creamy pale-green lenses or streaks which prove, upon microscopic examination, to consist of a fine symplectic aggregate of diopside and plagioclase (characteristic of the breakdown of omphacite, though none survives here), overgrown by coarser skeletal hornblende. The zoisitite is bordered by a selvage of garnet + symplectite + late hornblende then a broad (5 millimetres) symplectite band overgrown by laths of pale green hornblende, interbanded with narrow bands of zoisitite. The relationships in this rock suggest that the hornblende in specimen D 140 also results from the replacement of diopside-plagioclase symplectites and that an earlier assemblage of zoisite with subordinate garnet and omphacitic clinopyroxene existed in these rocks.

The noses of many of these zoisitite pods commonly contain much more garnet than in the rest of the body and small garnetite pods are commonly found in their vicinity.

The association of garnetites and other calc-silicate rich bodies with chloritic backwalls and metaperidotites found in the Flekke area bears similarities with some metarodingites found in the Swiss Alps (Evans et.al. 1979; Evans et al. 1981). Although garnet rich bodies and meta-gabbroic anorthositic rocks such as those described in this section are also closely associated with the meta peridotites, the rather extreme mineralogical composition of some of these zoisitites and garnetites may point to a rather different origin for them. Some further observations will be made in Chapter 3.

2.03.5 Summary:

By combining the observations made at the localities described above a generalised lithostratigraphic sequence can be reconstructed for the Flekke Unit. This is shown schematically in figure 2.30. Due to the lithological variability within this Unit such a generalised sequence cannot be taken to be representative of a vertical section at any one locality. However, sufficient similarities between the described localities are considered to exist to make the suggested sequence valid for the Unit as a whole within the Hellevik-Flekke area. Lateral variability can probably be ascribed to original variations, changes produced by deformation leading to the thinning out or thickening up of some members of the Unit and simply poor representation of members due to poor or discontinuous outcrop.

Some general comments on this sequence are appropriate at this stage:

1) The contacts of the Flekke Unit with the overlying Vardheia Unit and the underlying Gjörlanger Unit are either gradational, involve veining or mixing of one Unit within the other or, rarely sharp, undeformed and slightly irregular contacts are seen. This is taken to indicate that the Unit is autochthonous with respect to its bounding units and therefore has not moved significantly relative to them since its formation.

2) The preservation of igneous mineralogies or textures and the general basic or ultrabasic nature of the rocks leads to the conclusion that most, if not all of the lithologies in this Unit have igneous protoliths. Indeed the interbanding of different lithologies and the presence of cumulate textures and structures strongly suggest that the Unit represents a layered basic-

ultrabasic intrusion (or possibly more than one intrusion) now heavily deformed and metamorphosed. Gradational changes at the contacts between anorthositic and ultrabasic lithologies suggest a genetic relationship between the two types probably by igneous fractionation processes.

3) Some mineralogical variations in the sequence are possibly significant. The peridotites at the base of the sequence contain tremolite and lack orthopyroxene, whereas the peridotites in the upper part of the sequence contains abundant orthopyroxene and lack tremolite. Most of the meta-anorthosites give no evidence for significant amounts of igneous clinopyroxene (it is certainly not a primary precipitate phase where good igneous assemblages are preserved) but the Balsarvika meta-anorthositic gabbro, which is close to the overlying meta peridotites, contain a band of clinopyroxene and petrographic evidence suggests that clinopyroxene may have been a fairly common primary precipitate phase there. Iron-titanium oxides and possibly spinel are important constituents of the upper part of the sequence, in particular the transition from the basic to ultra basic lithologies. Apatite and zircon become locally important in the upper part of the sequence, particularly in association with metabasic layers or pods in the meta- peridotites. This may reflect considerable concentration of incompatible elements during its crystallisation.

One of the lithologies allotted to the Flekke Unit do not conform to this rather simplified sequence.

It is a metagabbro exposed in a low lying area of pastureland around Straumsnes. It lies structurally below the banded gneisses of the Vardeheia Unit and where least deformed consists of a fairly homegeneous mesocratic rock in which lath shaped white, cloudy plagioclase grains define a dolerite-like texture with a matrix of rather soft, dark green material which is in fact partially serpentinsed orthopyroxene, clinopyroxene, fine grained pale green fibrous amphibole and dark brown biotite. Microscopic examination of a fairly coarse-grained sample from a road cut 100 metres east of Straumsnes (D56) shows that the plagioclase is overgrown by a dense, very fine grained, felted mass of zoisite and white mica. Iron-titanium oxide is a common accessory around which biotite tends to form coronas. Accessory amounts of K-feldspar occur also.

These metabasic rocks are unusual as they entirely lack garnet. Where undeformed their texture is obviously igneous and weak rythmic layering occurs near its south boundary on the coast to the south of Straumsnes. The boundary at this locality is gradational, with a transition over 3 metres from the metabasite into a plagioclase-K-feldspar-biotite-quartz gneiss containing deformed mafic schleiren and quartz veins.

Similar rocks occur in road cuts on the opposite side of Dalsfjord to the south of Holmedal. A sample of a fairly basic lithology from the Dalsfjord Mangerite - Syenite Nappe (79/MA) was collected for comparison with the rocks from south of Dalsfjord and its mineralogy and alteration is remarkably similar to that of specimen D 57, the main difference being a higher K-feldspar content.

Inclusions of similar, nongarnetiferous metabasites are common in the gneisses to the north of Asnes Skifabrikk, but an abrupt change occurs at a stream flowing into Dalsfjord by the ski factory and boudins of garnet amphibole or eclogite are the norm. A feature running eastwards from here can be traced in aerial photographs to the south of Eikerolheia as far as the east side of Flekkefjord and this may be an important fault.

Although this lithology occurs in a similar stratigraphic position to the Flekke Unit it is definitely not typical of the normal lithologies of which this Unit is composed. Similar rocks were observed immediately to the north of Leirpollen on the west shore of Flekkefjord, apparently below the ultrabasic schists of the Flekke Unit. They may therefore represent the Gjörlanger Unit, the Flekke Unit having thinned into non-existence below the gneisses to the south of the Asnes Skifabrikk.

SECTION 2.04 The Gjörlanger Unit

2.04.1 The Grey Gneisses:

The dominant feature of this unit is the presence of mesoscopically homogeneous massive grey gneisses. Unlike the gneisses of the Vardeheia Unit these are normally unbanded and lack psammitic or micaceous layers. The dominant feldspar in the Gjörlanger Unit grey gneisses is usually plagioclase giving them a broadly granodioritic compostion. In contrast, the Basal gneisses are commonly pink and k-feldspar rich and monzonitic, adamellitic or granitic.

Close inspection of outcrops of the grey gneisses reveals a number of intergrading textural and mineralogical types. Texturally they vary between a coarse, massive unfoliated variety closely resembling a plutonic igneous rock (figures 2.31 and 2.32), via augen gneisses with variably developed foliation to fine to medium grained, well foliated equigranular gneisses. In many cases the augen gneisses can be seen to have formed by a mechanical transformation of the unfoliated variety. This is well demonstrated in roadside blastings on Route 57 by the northern end of Renestraumsvatnet, south of Flekke and by the unmetalled road from Gjörlanger to Solvik.

The well foliated fine grained variety rarely shows evidence for such an origin and thus have had a fine grained or non-porphyritic protolith. However, fine grained grey gneisses sometimes develop in sub-metre width zones of extreme flattening within the unfoliated or augen varieties, but here the original large feldspar megacrysts remain as granulated "pennies" in a matrix of biotite and epidote (figure 2.33). The coarse unfoliated variety sometimes shows a rather patchy or streaky variation in grain size and proportions of its constituent minerals (figure 2.31). This, together with their "porphyritic" appearance and rather massive character suggests that the grey, granodioritic gneisses are derived from plutonic igneous rocks and are, therefore, orthogneisses.

The wide mineralogical variety encompassed by the grey gneisses can be ascribed to differences in bulk composition and intensity of metamorphism, the latter often being related to the degree of deformation.

The earliest mineralogical type is, in fact, the rarest. It has only been found at one locality in woodland a few metres from Route 57 where it meets Route 607 to the south of Flekke. Sample D99 (figure 2.34) comes from this locality and consists of plagioclase (50%), bluish quartz (10%), pink to green pleochroic hypersthene (25%), diopsidic clinopyroxene (7%) and k-feldspar (5%) with accessory ilmenite, magnetite, apatite and zircon.

The quartz and plagioclase form a granoblastic mosaic around clots of coarse, anhedral hypersthene (up to 2.5 millimetres across) and clinopyroxene (up to 0.5 millimetres). The hypersthene usually contains narrow lamellae of clinopyroxene. This rock is, therefore, a two-pyroxene granodiorite or charno-enderbite of the charnockite series (see Chapter 3 for a detailed discussion of the classification of these rocks). The plagioclase is densely clouded with minute acicular or platey clinozoisite grains. The hypersthene and oxides are rimmed with very fine bead-necklace-like coronas of euhedral garnets which appear to overgrow this clouding. A fine rim of colourless, fibrous amphibole often intervenes between the garnet and the hypersthene and an outer rim of deep green hornblende may occur where the garnet is absent. A slight parallel elongation of the hypersthene gives a weak planar fabric to this rock.

The most common massive, unfoliated variety of grey gneiss can be found at several localities as undeformed relics in coarse grained augen gneisses. Examples can be found near the junction of Routes 57 and 607 to the north of Renestraumsvatnet; in blastings by the unmetalled road from Gjörlanger to Solvik; in the northern part of the peininsula which bisects Tyssedalsvatnet, near Tyssekvam and by Route 607 to the north east of where Tyssedalsvatnet flows into Gjörlangerelva.

The least deformed variety (figure 2.35) has no foliation and consists of plagioclase crowded with inclusions of clinozoisite and less common white or green mica, perthitic K-feldspar and quartz. In a few cases relics of hypersthene occur in clots similar to those found in sample D 99, but these are usually pseudomorphed by feathery masses of pale green actinolite and minute specks of magnetite associated with iron-titanium oxides, quartz, apatite and zircon. The actinolite is frequently rimmed or replaced by a zone of fine grained khaki-green biotite and quartz. Iron titanium oxides are rimmed by masses of tan coloured biotite in these mafic clots. Garnet forms a fine bead-necklace corona around the mafic clots against the surrounding plagioclase, either by the biotite or directly abutting the actinolite. On the plagioclase side of this corona fine, green biotite or idiomorphic hornblende can be observed overgrowing the zoisite clouding. Discrete oxides in the feldspathic groundmass are rimmed by well developed garnet coronas, which also overgrow the zoisite clouding in the plagioclase. A mass of fine tan coloured biotite often intervenes between the garnet and the oxide. Examples of this lithology are specimens 79/33A, 79/43A, D 44, D 97A, D 97B, D 98, D 100, D 137 and DG-6.

Progressive deformation of the lithology described above causes marginal or complete granulation of feldspars. The perthites develop microcline twinning and break down to fine grained (less than 0.3 millimetres) mosaics of microcline and plagioclase.

The zoisite clouding is enhanced along the new grain and sub-grain boundaries, as is development of fine white or pale green mica. Further recrystallisation produces much coarser laths of clinozoisite or stubby equant anhedral epidote up to 1.00 millimetres across. The mafic clots recrystallise to form elongate patches of biotite laths, skeletal subidiomorphic hornblende, rounded garnets, sphene, apatite and zircon (Figure 2.36). Near these patches phengitic white mica may be common. Where the cores of large feldspars remain as relics, a characteristic augen-texture results, but in zones of strong flattening the augen disappear and a well foliated streaky or banded grey mylonitic gneiss remains. This can be observed in figure 2.33. Specimen 79/12 is a typical augen gneiss.

The finer grained, well foliated grey gneisses are exemplified by specimens 79/4 and D 97. They are mineralogically similar to the augen gneisses but tend to be more homogeneous. However, plagioclase, quartz and K-feldspar all have lobate, sutured grain boundaries, abundant sub-grain boundaries and undulose extinction and, therefore, apear to have formed by the mechanical breakdown of larger grains. Epidotes tend to be anhedral with inclusions of white mica, biotite and quartz and have low birefringent zoisitic cores. White mica also occurs rarely as inclusions in the larger feldspars. Biotites are rather wispy, anhedral and define a foliation.

Sphene is the dominant (or only) titanium bearing phase. Hornblende is found in the more basic varieties of this lithology, where garnet tends to be more abundant. Chlorite is occasionally found replacing biotite or garnet.

The grey gneisses sometimes contain metre sized bands of more siliceous, less mafic lithology which contain up to 40% quartz and have slightly more K-feldspar than plagioclase in some cases (for example specimens 79/29, D78, D79, DG-1 and DG-3). These usually have the assemblage quartz + microcline + albite + phengitic white mica + clinozoisite + garnet. White mica usually defines a good planar fabric in association with the clinozoisite, and is rarely found as foliated sheaths around augen-like relics of early clouded plagioclase. The white mica is often rimmed by secondary plagioclase and fibrous sillimanite or biotite, but appears to co-exist with biotite in some of the more mafic varieties.

From the observations made above, it can be inferred that all the grey gneisses in the Gjörlanger Unit have devloped by the mechanical and metamorphic transformation of charnockitic precursors. Whether the charnockitic mineralogy is, in turn, of metamorphic origin or results from the recrystallisation of igneous rocks is uncertain. The textures of the least altered examples certainly do not preclude an origin by direct igneous crystallisation.

2.04.2 The Metabasites:

Perhaps the most characteristic feature of the Gjörlanger Unit is the association of the grey gneisses with abundant metabasic material. The metabasites manifest themselves in three main modes of occurence; as small dyke or sheetlike bodies a few metres wide; as small bodies with diffuse margins showing intermixing and mineralogical and compositional gradations with the grey gneisses and as large bodies up to hundreds of metres thick, concordant with the regional foliation.

Dyke-like metabasites are exposed by the eastern shore of Gjörlangerfjord in roadside blastings on the road from Gjörlanger to Solvik and on a track leading from this to a small quay by the waterside. The country rocks are coarse, grey, granodioritic augen gneisses with charnockitic relics. 200 metres to the north of the junction with Route 607 a complex shaped mass of metabasic material cuts through the gneisses (figure 2.37), consisting of a number of bifurcating sheets up to 2 metres thick, usually highly discordant to the local gneiss foliation. Where it is roughly concordant with the foliation the margin of the metabasite is slightly sheared, developing a weak foliation defined by micas and amphiboles. This is the classical form of gneiss/metabasite contact found in the BGR, but is, in fact, the exception at this locality.

Normally, the dyke margins are sharp and unfoliated or slightly diffuse, with a gradation over a few centimetres from pale grey leuco-gneiss to dark grey-green metabasite (figure 2.38). The metabasite commonly contains small felsic backveins by its margin and diffuse lobes of metabasite occasionally project into the gneiss (figure 2.39).

Specimens collected from the dykes of this locality (D 80, D 81, D 82, D 83 and D 83A) largely consist of small (less than 0.3 millimetres) garnets with collars of plagioclase in an extremely fine grained matrix of amphibole-plagioclase symplectite. Relics of omphacite with a rather feathery appearance in cross-polarised light occur locally, as do white micas. These micas are usually replaced by symplectic intergrowths of biotite and K-feldspar. Local pale green areas on the outcrop proved to consist of fresh omphacite + garnet +/- rutile and are, therefore, true eclogites.

By the track to the quay on the shore of Gjörlangerfjord 20 metres from its junction with the Gjörlanger-Solvik road, a blasting exposes a similar dyke to those described above. However, the dyke rock at this locality (specimens D 134 and D 135) is a medium grey colour and consists of pinkish pleochroic hypersthene, pale olive-green clinopyroxene, heavily clouded plagioclase and accessory iron titanium oxide, green spinel, K-feldspar, apatite and zircon (figure 2.40).

The pyroxenes are marginally or completely altered to fibrous colourless amphibole, the oxides are rimmed by tan coloured biotite and the clouding in the plagioclase seems to be acicular zoisite and white or pale green mica, though these are often too fine to resolve clearly under the microscope. Garnets rim the hypersthene, amphibole and biotite and overgrow the zoisite.

A dyke of similar material to D 134 and D 135 outcrops by the junction of Route 57 and 607 to the south of Flekke (figure 2.41). The country rock is a coarse grained, undeformed altered charnockitic rock. The margin of the dyke is unsheared and sharp (figure 2.42) and thin felsic backveins locally pass into the dyke from the margin. Under the microscope, the transition from country rock to dyke rock involves a decrease in grain size by approximately a factor of three, a decrease in the quantity of quartz and feldspar and an increase in the amount of pyroxene and oxide over a distance of about 2 millimetres (specimen D 100). A backvein presumably formed by melting of the country rocks upon intrusion of the dyke-magma, contains an identical primary mineral assemblage to that in the country rock, ie quartz + plagioclase + K-feldspar +/- hypersthene +/- clinopyroxene.

The evidence from these localities shows that these dykelike bodies are intrusive rocks. The presence of eclogitic parageneses within some of them demonstrates conclusively that these basic rocks have suffered an eclogite facies metamorphism whilst directly enclosed within their present country rocks. The eclogite protolith had a broadly basaltic mineralogy which could have been a primary igneous assemblage or possible a granulite-facies assemblage co-facial with that in the charnockitic country rocks, as suggested by the backvein in specimen D 100.

A number of small metabasic sheets can be found in mafic gneisses between Gjörlanger and Hellevik between Route 607 and the shore of Gjörlangerfjord. These are, at first glance, discordant to the foliation in the gneisses, but the sheets have suffered the same recumbent isoclinal folding as the gneisses and the schistosity passes uninterupted through them. The sheets are mineralogically similar to the more amphibolitised metabasites on the eastern shore of Gjörlangerfjord though no relics of omphacite have been found in them.

Large metabasic bodies, generally concordant with the local foliation are closely associated with the grey gneisses. They do not appear to occupy a unique horizon within the Gjörlanger Unit, indeed, changes from gneisses to metabasites occur so frequently and on such variable scales that mapping of individual metabasite bodies often proved futile and only the larger bodies are shown on the geological map (Enclosure 1). Generally speaking, the grey gneisses dominate over the metabasites and the latter appear to form concordant sheetlike bodies within the former.

The transition between grey gneiss and metabasite usually proves to be gradational. A commonly observed transition involved the passage from massive, unfoliated enderbite into finer grained, foliated biotite and epidote bearing granodioritic gneisses which have a rather streaky appearance (transgressing the foliation) with more leucocratic and melanocratic portions (figure 2.43). At this stage small schleiren and pods of amphibolite with diffuse margins appear along with veins of quartzite and become more common (figure 2.44). The gneiss itself becomes enriched in amphibole until the margin of the metabasic body (normally eclogitic) appears. The sequence is well exposed in blastings in the track leading down to the quay on the eastern shore of Gjörlangerfjord.

Intimate intermixing of the grey gneiss lithology with amphibole-rich or, more rarely, clinopyroxene-rich rocks is very common throughout this Unit. By a forest track on the southern slopes of Dauramaisnipa to the south of Flekke this type of intermixing is well exposed. On the north east shore of the eastern arm of Tyssedalsvatnet fine grained, foliated granodioritic gneisses intergrade and alternate with garnet amphibolites and eclogites on scales from a few centimetres to a few tens of metres. At Bogevika, by this lakeside coarse grained zoisite-white mica-eclogite with secondary barroisitic amphibole (specimen D 129) occurs in a body about 15 metres across. To the south east the eclogite passes gradationally over 1.5 metres into fine grained granodioritic gneisses with a relative derease in clinopyroxene, garnet, amphibole and zoisite and a relative increase in quartz, albitic plagioclase and biotite.

The large metabasites themselves are rather variable in composition, but tend to be rather aluminous and usually contain zoisite, white mica and even kyanite. All the bodies sampled are more or less amphibolitised eclogites. Some examples are described below:-

To the south of the top of the hill Haheia is a sheet of coarse eclogite within granodioritic gneiss. Specimen D 123 from here contains omphacite, garnet, kyanite, white mica and zoisite.

The garnets contain abundant inclusions of zoisite and acicular green amphibole (figure 2.45) and the omphacites enclose zoisite and white mica. Zoisite, white mica and omphacite form a good planar fabric. These phases are overgrown by large poikiloblastic colourless or pale blue-green barroisitic amphibole. A broad area of similar eclogite (figure 2.46) occurs at the base of the southern slopes of Haheia between Jyttevatnet and Botnatjörna, occupying the position above the Basal Gneisses held by the Flekke Unit further west.

Well foliated metabasites are extensively exposed southwards from the bridge across the southern end of Flekkefjord on Route 607 on the west side of the lakes to the north of Breidvatnet. These are mostly fine grained, pale, grey-green garnet amphibolites consisting of fine grained granular masses of hornblende intergrown with plagioclase and, occasionally, quartz between which are elongate patches of stumpy clinozoisite intergrown with white mica or its replacement product of biotite + plagioclase or plagioclase + sillimanite. Small, rounded, subidiomorphic garnets are common in clots associated with the clinozoisite. Examples of this lithology are specimens D 15 and D 103. D 101 is mineralogically similar, but contains more clinozoisite and garnet, less quartz and common relics of omphacite. These rocks often grade into fine grained granodioritic gneisses with diffuse amphibolitic schleiren.

A rather different, less aluminous type of eclogite comes from this area and consists of garnet, omphacite, quartz, rutile and later poikiloblastic barroisite. This seems to pass westwards into mica-zoisite-quartz-garnet amphibolites with associated quartz veins up to 1 metre thick.

On the ridge between Tyssedalsvatnet and Jyttevatnet aluminous metabasites are extensively exposed. Specimen D 95 comes from the north side of this ridge. It consists of patches of extremely fine grained amphibole-plagioclase symplectite with rounded blebs of quartz and rare omphacite relics surrounded by kyanite. In shear zones the plagioclase is replaced by coarse (up to 1 millimetre long) streaks of zoisite +/- kyanite +/- quartz +/- rare white mica. Small (less that 0.2 millimetre) garnets form discontinuous bead-necklace coronas around the amphibole symplectites and omphacites.

The eclogite sheet by the quay on the east shore of Gjörlangerfjord has already been alluded to above. Three specimens were collected from a blasting by the quay. D 175 consists of about 25% quartz in long narrow ribbons between which are narrow (about 1 millimetre wide) bands of very fine grained amphibole and plagioclase symplectites (or omphacite) + garnet + rutile and kyanite + zoisite + white mica. The kyanite is extensively altered to pseudomorphs of fibrolitic sillimanite (figure 2.47).

The early parageneses seems to have been omphacite + garnet + quartz + zoisite + white mica + kyanite + rutile, which formed a strong planar fabric prior to apparently static breakdown to the present assemblage. D 175 is an intermediate lithology in the passage from fine grained foliated granodioritic gneiss to metabasite borders on a fine grained eclogite (specimen D 176). It consists of finely granular omphacite with streaks rich in kyanite, quartz and, more rarely white mica and zoisite. Zoisite becomes more common by the contact with D 175 where a thin seam of zoisite + kyanite + quartz occurs. The kyanite is pseudomorphed by sillimanite. The core of the eclogite sheet (D 177) consists of garnet and quartz in equal quantities, forming about 60% of the rock, the rest being made up of fine granular amphibole and plagioclase (possibly after omphacite), zoisite, white mica, rutile, apatite and zircon.

2.04.3 Eclogites and Amphibolites of Intermediate and Acidic Compostion:

A major lithology in the Gjörlanger Unit is a rather quartz rich aluminous amphibolitic or eclogitic rock. It forms a broad band running from Hellevik along the coast of Gjörlangerfjord, across the slopes to the south of Varden and the top of Haheia to the west shore of Flekkfjord. On the north east side of Sördalsvatnet, fine, grained, foliated, grey granodioritic gneisses with amphibole-rich schleiren pass gradually westward into this lithology with a decrease in biotite and plagioclase and an increase in amphibole or omphacite, white mica and kyanite forming a rather brittle well foliated green rock with elongate white streaks. It is this lithology which lies against the peridotites forming the base of the Flekke Unit to the north west of Haheia (section 2.03.2).

Specimen D 24 is a fairly fresh example of this lithology from a road cut by Route 607 near the northern shore of Sördalsvatnet. Deformed metabasic sheets and schlieren of amphibolite with diffuse margins occur nearby. The rock consists of omphacite with rather low maximum birefringence intergrown with quartz and small clots of rounded garnets crowded with minute quartz inclusions. The omphacites are often heavily altered to a symplectic mass of amphibole and plagioclase which appears to post-date the exsolution of rounded blebs of quartz. The omphacites frequently have a feathery appearance in cross polarised light and sometimes form lobate intergrowths of two pyroxenes (this is especially well developed in specimen 79/15 as shown in figure 2.48). Between the patches of omphacite + quartz are elongate, lenticular quartz mosaics and swarms of kyanite +/- white mica +/- zoisite or zoisite +/- white mica, marginally co-existing with quartz where they may also be replaced by late poikiloblastic plagioclase. Rutile and apatite are common accessories, the former being particularly abundant.

A lithology of rather deceptive appearance is found in close association with coarse, unfoliated charnockitic gneisses and their augen gneiss equivalents in road cuts by the western shore of Tyssedalsvatnet on Route 607. At the outcrop it is massive, generally lacking a planar fabric, rather brittle and apparently very fine grained. It has a dull, medium grey- green colour and on close inspection has a rather streaky appearance (on the centimetre scale) with portions which are paler, coarse grained and others which are darker and finer grained. This passes gradationally into paler charnockitic or augen gneisses e.g. specimen 79/43A.

Microscopically this lithology exemplified by specimens 79/28 (figure 2.49), 79/B, C, D and D 184. It is composed of rounded or sub-rectangular patches of an extremely fine grained amphibole-plagioclase symplectite up to 2 millimetres across with rounded blebs of quartz. These patches occasionally contain relics of omphacite with rather low birefringence. Well developed coronas of garnet rim these patches and they are associated with clots of rutile, discreet stubby apatite grains and occasionally zircons. Forming a matrix to these patches are large (3 millimetres) grains of plagioclase and quartz which have a tendency to develop an internal mosaic of sub-grains. The plagioclase is heavily altered to rather equant white mica (usually less than 0.1 millimetres across) and needles of zoisite. The white mica is often replaced by finer khaki biotite. In sample D 168, from a small roadside outcrop 200 metres south of Flekke Post Office on Route 57, slight flattening deformation is associated with more advanced breakdown of the plagioclase to zoisite + white mica + kyanite + quartz.

Despite their different mineralogy this lithology has textural similarities with the unfoliated charnockitic gneisses. In particular the association of apatite, zircon and rutile with omphacitic clinopyroxene and the shape of the pyroxenes and symplectic pseudomorphs suggest mimicking of pyroxene + iron titanium oxide + apatite + zircon clots found in the charnockitic rocks. The replacement of the plagioclase by zoisite, white mica and biotite is probably a more advanced stage of the clouding seen ubiquitiously in the charnockitic rocks. It is interesting in this respect that this lithology is chemically very similar to the least altered charno-enderbite, D 99. Furthermore, it bears mineralogical and chemical similarities to the quartz rich aluminous eclogites and amphibolites such as D 24 described above. Slight flattening deformation of this lithology produces a fine grained plagioclase + K-feldspar + biotite + epidote + hornblende + garnet + ilmenite gneiss which is rather similar to some of the fine grained, foliated granodioritic gneisses (e.g. specimen 79/43E). It seems that all these rocks are mineralogical and textural variants of the same original intrusive rock-type.

2.04.3 Websterites:

A suite of garnetiferous pyroxenites (garnet websterites) occurs in a string of exposures between Hellevik and Flekke and are restricted to the Gjörlanger Unit. Major occurrences outcrop on the small rocky knoll Halehaugen to the west of Gjörlanger; on either side of Gjörlangerelva to the east of Gjörlanger; on the western side of the promontary which divides Tyssedalsvatnet and on either side of Flekkefjord to the west of Flekke. A number of smaller occurrences outcrop along the southern shore of Gjörlangerfjord. The country rocks to these websterites are either grey granodioritic gneisses or the sheetlike metabasites.

Detailed investigation of a websterite in the wooded area to the south of Gjörlangerelva reveal that it is a flat lying sheet 3 to 4 metres thick and concordant with the local gneiss foliation. The websterite on Halehaugen is about 70 metres thick and is thought to be a continuation of the body at Gjörlangerelva. It dips northwards here and can be traced past the mouth of Gjörlangelva to the eastern shore of Gjörlangerfjord.

By the road from Gjörlanger to Solvik about 60 metres from its junction with Route 607 the upper contact of this websterite body with the grey gneisses is exposed. It takes the form of a closely packed breccia of angular blocks of rather leucocratic grey gneiss up to 20 centimetres across in a matrix of dark green amphibolite (figure 2.50). The amphibolite is considered to be derived from a websterite protolith such as that exposed on the opposite side of the road. Adjacent to the amphibolite the gneiss becomes almost white coloured (figure 2.51). Quartz veins are common in the gneiss above the breccia. Although the contacts between the gneiss blocks and the amphibolite are often sharp they are sometimes rather diffuse and gradational with felsic schleiren intruding the amphibolite and fine amphibole rich streaks extending into the gneiss blocks. The amphibolite and the gneiss blocks have a concordant foliation defined by amphiboles and micas respectively and the gneiss foliation does not appear to have been rotated within the amphibolite matrix. Hence the foliation post dates the formation of the breccia. The foliation in the country rock grey gneiss, the breccia blocks and the amphibolite have all been folded in a mesoscopic upright asymetrical fold (Figure 2.61).

Specimen 79/32 is taken from the breccia. The amphibolite consists of about 75% finely granular hornblende (0.3 millimetres) poikiloblastically enclosed within optically continuous patches of plagioclase up to 0.7 millimetres across with interstitial quartz and accessory ilmenite mantled by sphene. No pyroxene relics remain. The pale rims to the breccia blocks consist of almost monomineralic plagioclase (up to 90%) with minor quartz. Apatite and zircon are common accessories, becoming more abundant towards the amphibolite. In the cores of larger blocks laths of phengitic white mica up to 2 millimetres long and quartz +/- zoisite +/- garnet predominate. The phengites define a good planar fabric but are bent around later asymetrical microfolds and frequently altered to fine granular masses of alkali feldspar and biotite. The cores of these blocks are rather similar to the more siliceous country rock gneisses in this area (for example specimen D 79).

The breccia is interpreted as an intrusion breccia formed during the forcible intrusion of the websterite protolith into the grey gneiss country rock. The websterite in the breccia was subsequently altered to amphibolite.

More often that not the contact of the websterite with its country rock is quite sharp, tectonised and amphibolitised. However, a conspicious roadside blasting by Route 607 to the east of Gjörlanger (opposite a layby and some chalets) exposes part of the websterite sheet found on the southern side of Gjörlangerelva where its western (upper) boundary has escaped heavy amphibolitisation. The country rock is a fine grained, equigranular biotite-epidote-garnet granodioritic gneiss and the main websterite mass is a massive medium green garnet poor variety or, locally hornblendite (described below). About 10 centimetres from the western contact the rock takes on a pale, creamy green colour and shows a marked fining of grain size. The contact with the gneiss is quite sharp and concordant with the gneiss foliation. Specimen 79/2 transgresses from the contact zone. The pale green rock up to 10 cm from the contact, consists of almost entirely fine grained (up to 0.3 millimetres long) pale green clinopyroxene with a strong parallel orientation. A few colourless blades of amphibole are also aligned in this fabric and more equant poikiloblastic pale green hornblendes overgrow the pyroxenes. The pyroxenes become increasingly altered to an extremely fine grained, dense diopside-plagioclase or amphibole-plagioclase symplectite towards the gneiss contact. Euhedral garnets up to 0.25 millimetres across become gradually more common towards the contact. These are usually rimmed by a narrow kelyphite of hornblende, particularly where the pyroxene is heavily symplectised. Rutile and sulphide are common accessories in this part of the specimen which is a true eclogite where it is most garnetiferous. The passage into the country rock involves coarsening of the amphibole-plagioclase symplectite and the appearance of white mica or its replacement products-brown biotite + K-feldspar. From the first appearance of the mica there is a gradational change over 3 millimetres to a rock consisting of garnet, white mica and subordinate plagioclase. The transistion zone probably consisted of garnet + omphacitic clinopyroxene + white mica prior to symplectitisation and hydration. This contact rock is rather similar to the felsic veins near the upper contact of the eclogite sheet to the south of Asnes (section 2.02). The marginal planar fabric and the mineralogical character of the contact appear to have formed under the conditions necessary for the stability of eclogite.

A characteristic feature of the marginal parts of the websterites is the presence of garnet-rich veins or bands. On the opposite side of the road to the intrusive breccia described above massive green garnetiferous clinopyroxenite contains veins up to 40 cm long and 2 cm wide consisting of garnet + phengitic white mica +/- quartz +/- zoisite. The phengite forms a matrix of grains from 0.3-2.0 mm long between anhedral garnets up to 2.0 mm across. Sometimes the phengite is intergrown with equal quantities of granoblastic quartz and locally the phengite is absent leaving a garnet + quartz rock. Garnet rarely forms less than 50% of the rock and at the vein margins is usually pure garnetite, passing via an eclogite zone 3-5 mm wide into the host clinopyroxenite. As with the majority of these garnet rich veins, zircon is very common, with up to ten grains per microscopic field-of-view under a low-power objective lens.

The most spectacular example of the garnet-rich veins is found in the roadside outcrop to the east of Gjörlanger (figure 2.52). The massive websterite forms the host to veins of garnetite up to 3 m long and 18 cm thick, occurring singly or in parallel groups. The veins frequently anastomose. Rimming the garnetite against the host pyroxenite is a selvage of almost pure pale green clinopyroxene. Similar clinopyroxene occurs as bodies enclosed within anastomosing portions of individual veins. The pyroxenite selvage has a gradational margin over about 1 centimetre with the host rock.

Specimen 79/11 comes from one of the larger garnetite veins. The garnetite consists of about 80 to 90% garnet in a granoblastic mosaic with interstitial granular masses of colourless clinopyroxene which seem to have formed from the mechanical breakdown of larger grains up to 1.5 millimetres across. These are often overgrown by pale blue-green poikiloblastic amphiboles which also form in sinuous fractures through the garnets. The garnets are riddled with fine inclusions which are of two types: The first type is acicular zoisite which often forms strongly linear trails through the garnets. The trails are poorly developed in the garnet cores where they co-exist with deep blue green hornblendic amphibole and may be rotated by up to 90°. Garnet rims are densely filled with slightly curved zoisite trails. Early syntectonic growth of garnet is therefore indicated here, followed by later post-tectonic growth over the zoisite planar fabric. The second type of inclusion is a clinopyroxene which tends to develop adjacent to the interstitial granular pyroxenes described above. Subhedral zircons with euhedral cores and rounded overgrowths are common in the garnetite as inclusions in garnets (cores or rims) pyroxenes and amphiboles. These have been separated for geochronological studies (see Chapter 3).

The clinopyroxenite selvage consists of tabular pale green omphacite up to 3.0 millimetres long. Their margins are often slightly symplectised and they often have dusty looking cores full of minute rutile inclusions. Rutile is also an accessory mineral here. These pyroxenes are similar to some of the less granulated grains within the garnetite. Zircons are absent in this zone as is garnet. The clinopyroxenite passes into an amphibole rich host with an increase in pale green or colourless amphibole at its margin, with local remnants of the characteristic dusty lamellar clinopyroxene found in the host websterite (see below).

At the eastern extremity of the pyroxenite in this outcrop the rock takes on a rather striking banded appearance (figure 2.53). The bands are formed from concentrations of amphibole, clinopyroxene or garnet. The thickest garnetite band is 20 centimetres thick at its widest and resembles the garnetites in the veins 50 metres further west in the outcrop. The finest bands are 1 to 2 millimetres thick and are often layers 1 to 2 grains broad. Other bands vary in thickness between these two extremes.

Specimen 79/9A comes from a garnet rich band 1.5 centimetres thick and consists of 50% idiomorphic garnets up to 1.0 millimetre across in a matrix of pale green omphacite 0.2 to 1.0 millimetre across with a strong planar orientation. Rutile, apatite and white mica are very common accessory minerals in the centre of the band and form up to 15% of the rock at one edge. At the outer edge is a fairly sharp contact with an amphibole band. The omphacites and the amphiboles appear to co-exist at the contact and a few omphacites occur in apparent textural equilibrium within the amphibole band. The amphiboles are of a pale bluish green to very pale yellowish green pleochroic actinolitic type. Some of the amphibole rich bands may contain up to 20% garnet or dusty clinopyroxene, the latter usually being replaced by the amphibole (as in sample TYS1, collected by W.L. Griffin of the Mineralogisk-Geologisk Museum, Oslo). A common feature of the garnet rich bands is an abundance of zircon grains, which suggests an infinity with the garnet rich veins found in this outcrop and in the other websterites.

The banding at this locality is associated with a layer-parallel planar fabric and the foliation has been folded by an asymetrical mesoscopic fold (Figure 2.62). Some of the bands have a true eclogite- facies mineralogy (e.g. 79/9A) which defines the planar fabric. This, along with their obvious afinity which the garnetiferous veins leads to the conclusion that the banding formed by strong shearing of garnetite veins at the margin of the body during an eclogite facies metamorphic event.

Garnet rich bands and veins have also been found in small exposures of websterite or amphibole rock along the southern shore of Gjorlangerfjord and to the south of Tyssekvam, usually near the adjacent country rock. The similarity of some of the more micaeous veins with the backveins found to the south of Asnes may suggest a similar origin. No direct connection of a vein with the country rock has been found, but the garnet-mica rock at the western contact of the exposure to the east of Gjörlanger is very similar to the garnet-mica veins found in the websterite by the road on the east shore of Gjörlangerfjord.

Turning now to the websterites themselves two main types can be differentiated, a type in which plagioclase or its breakdown product can be recognised and a type where they are absent. The latter type is the most abundant and is the dominant type to the west of Haheia whereas the former type is less common but is dominant in the Flekkefjord area.

Specimen 79/18 is an example of the plagioclase bearing type. This consists of approximately equal proportions of pyroxene and plagioclase and is really a gabbro-norite rather than a pyroxenite. The rock has no planar fabric and in hand specimen consists of interconnecting patches of black granular pyroxene between which dense opaque white clouded plagioclase occurs. The pyroxene patches consist of an interlocking mosaic of slightly rounded augite and hypersthene with some interstitial almost opaque dark brown clinopyroxene and tan coloured biotite. The plagioclase is densely clouded with extremely fine acicular grains which may be zoisite. Ghosts of lamallar twins show through the clouding. This is considered to be a slightly altered igneous rock.

Specimens D13, D124 and D40 come from Eikeskog to the south west of Flekke, the western shore of Flekkefjord near Solheim and the western shore of Tyssedalsvatnet respectively. These are similar to 79/18 but contain up to 90% pyroxene and are true websterites. The plagioclase is in a more advanced state of breakdown, producing a mass of toothy or acicular zoisite intergrown with a mineral similar in appearance to the jadeite in some of the coronitic meta-anorthosites from the Flekke Unit. This is rimmed by a well developed corona of garnet which is overgrowing and including the alteration products of the plagioclase. Frequently the plagioclase is completely replaced by garnet riddled with inclusions. The pyroxene adjacent to the garnet is often altering to a feathery mass of fine grained colourless amphibole, often with cores full of minute rutile needles where it has replaced clinopyroxene.

Specimen D45 is a typical example of the plagioclase free type of websterite coming from the large mass on the promontary south of Tyssekvam. The rock consists of equal quantities of rather dusty clinopyroxene and pale brown pleochroic hypersthene 1 to 2 millimetres across which is marginally altered to blades of colourless to very pale green actinolitic amphibole and colourless lamellar twinned chlorite. These pyroxenes may also be seen altering to fine, granular masses of clearer pyroxene with some chlorite and opaque oxide but this too is replaced by the amphibole. Larger masses of fine chlorite blades up to 2 millimetres across with random orientations are quite common, usually associated with opaque iron-spinel or transparent green pleonaste. The chlorite is replaced by masses of garnet (figure 2.54), usually riddled with inclusions of chlorite and to a lesser extent, amphibole. Specimen 79/22 from Halehaugen is very similar to D45.

Specimen D79/8 comes from the roadside blasting to the east of Gjörlanger. This also consists of clinopyroxene and hypersthene altering to amphibole and chlorite, but it has much less garnet and the garnet is full of amphibole inclusions rather than chlorite. The chlorite is commonly associated with phlogopite and rarely, olivine relics.

Some examples of this type of websterite lack hypersthene and consists of clinopyroxene replaced solely by colourless pale green actinolitic amphibole. Clots of white mica up to 3 millimetres wide occur in one example from the eastern shore of Gjörlangerfjord rimmed by coronas of euhedral garnets. This is the outcrop with the garnet mica veins and the mica clots may be related to these and could therefore be wall rock contamination.

The final result of amphibolitisation of these websterites is a granular dull grey green rock consisting almost entirely of pale green actinolitic amphibole with a little sphene, rutile and garnet locally (for example specimens 79/6 and D27).

The websterites are cut by narrow dykelike bodies in three localities. These are on the forested hill Eikeskog, south west of Flekke, near the shore of Tyssedalsvatnet 400 metres to the west of Tyssekvam and on the tope of the knoll Halehaugen, near Gjörlanger. At Eikeskog the dykes are 2 centimetres to 3 metres wide and are petrographically and chemically similar to the enclosing websterite though rather more amphibolitised (specimen D14). The dykes near Tyssekvam are up to 40 centimetres wide. These contain relatively more garnet than the host websterite in the form of thick interconnecting coronas forming about 50% of the rock between which occur masses of granular feathery colourless clinopyroxne with rather low birefringence Rutile is a common accessory (specimen D46). This seems to be a true eclogite and is petrographically and chemically different from other members of the pyroxenite suite, containing rather more Fe, Ti and Na and less Mg. Its affinities are not certain, but it may be related to the other dykelike bodies in which case these post date the intrusion of the websterites into the grey gneisses. This cannot be a firm conclusion, however on the basis of field evidence alone as the dykes are not seen to pass into the grey gneiss country rocks. The dykes from Halehaugen were not sampled.

2.04.5 Summary:

To summarise the features of the Gjörlanger Unit, the dominant lithology is a broadly granodioritic grey gneiss with a demonstrably charnockitic precursor, but now having a wide variety of mineralogical types varying between 2-pyroxene granulites, garnet-biotite-epidote and garnet-clinozoisite-phengitic mica gneisses and omphacite bearing gneisses. A variety of types of metabasite occur within the Unit including obvious dykes as well as concordant sheets and diffuse-margined pods. Evidence for localised melting of the gneiss precursors and hybridisation with a basic melt is common. A separate suite of websterite has obvious intrusive relationships with the grey gneisses but their relationship with the metabasic dykes is uncertain from field evidence alone. All the metabasic lithologies including the websterites as well as some of the gneisses contain eclogite facies mineral assemblages (see Chapter 5), and this Unit provides further conclusive evidence for an eclogite facies metamorphic event affecting all the lithologies in this area.

There is apparently no systematic variation of the lithologies with stratigraphic position in the Gjörlanger

Unit. The situation is rather complicated by considerable variation in mineralogical type (and thus degree and type of metamorphism) which may lead to strong differences in the appearance of even chemically similar rocks in the field. However the three largest exposures of websterite to the west of Haheia may represent a single sheetlike body up to 70 metres thick and therefore occupy a single horizon. Also, the dyke-like metabasites all occur very close to the anorthositic and ultrabasic rocks of the Flekke Unit and although no direct connection has been found in the field between them it is tempting to suggest that the dykes represent feeders to the basic-ultrabasic complex, particularly as no such dykes are found in either the Flekke or Vardheia Units.

Finally, the common observation of marginal anatectic veins and hybrid rocks indicate that some, if not all the metabasic rocks will have had their bulk chemistry modified with respect to their original magmatic composition even before any metamorphic open system behaviour came into operation. Strong tectonism would probably erase such evidence for contamination. As intensely tectonised margins to metabasites are common in most parts of the BGR it is apparent from the evidence presented above that considerable caution should be employed when making deductions about the chemical affinities of such rocks. (See also Krogh, 1980 and 1981 and this Thesis Chapter 3).

Section 2.05 The Basal Gneisses:

The Basal Gneisses have only been mapped in detail where it was necessary to define their contact with the overlying Gjörlanger or Flekke Units. However, some of the constituent lithologies are described below:-

Some of the lithologies belonging to the Basal Gneisses bear a close resemblance to those in the overlying Gjörlanger Unit, being coarse, grey granodioritic augen gneisses. However, these are not associated with the abundant metabasic material found in the latter Unit. Furthermore, whilst being petrgraphically similar to the grey gneisses of the Gjörlanger Unit, there are some subtle but consistant differences as can be seen in specimens 79/37 and D117 from road cuts by Route 57 on the eastern shore of Breidvatnet and 79/39 from road cuts on the same road adjacent to the waterfall Harfossen (not shown in figure 2.2). Firstly, the K-feldspars are water clear and free of the brownish clouding found in the gneisses further north. Secondly, the zoisite and mica clouding in the plagioclase consists of rather coarser inclusions. Thirdly, the hydrated mafic clots are associated with plates of khaki brown biotite up to 2 mm long with a good parallel orientation. These are usually rimmed by a fine bead necklace garnet corona. Fourthly, orange coloured allanite commonly occurs as an accessory mineral in the grey gneisses from the Basal Gneisses, but these are much rarer in similar rocks of the Gjorlanger Unit. No relics of hypersthene or diopside have been found in these specimens, but the petrographic features which they share with the obvious hydrated charnockitic rocks described in Section 2.4 suggest they were present at some stage.

Pink generally homogeneous K-feldspar rich gneisses are the dominant lithology in the investigated part of the Basal Gneisses. A typical example is specimen 79/45 from the eastern shore of Briedvatnet. This is an augen gneiss consisting of elongate augen of pink perthitic K-feldspar up to 7 millimetres long surrounded by finer-grained (up to 1 millimetre) plagioclase (An8) and microcline associated with khaki biotites up to 1 millimetre long, stubby, subhedral epidotes with allanitic cores, skeletal garnets (less than 0.5 millimetres across) and accessory magnetite, apatite and sphene. The K-feldspar augen are usually polygranular and appear to have formed from the mechanical breakdown of one or more larger grains, especially marginally where the grains may be mortar textured. The plagioclase tends to form a granoblastic mosaic around these augen and thus produce a resemblance to a "rapakivi" texture. The rock is quite quartz poor (less than 10%) and has a broadly monzonitic to syenitic composition. It may have formed by the mechanical transformation of a coarse, plutonic igneous rock, or, by analogy with the grey gneisses, a charnockitic lithology.

Specimen 79/46, from near Svinevik on the eastern shore of Hovlandsvatnet is a superficially equigranular, medium grained monzonitic rock in which thin (2 to 3 millimetres) biotite rich streaks up to two centimetres long form a strong foliation. Rounded albitic plagioclase grains are intergrown with granulated or mortar textured K-feldspar in equal proportions, together forming 75% of the rock. Biotite occurs as well developed laths up to 1 millimetre long or as curious wispy grains in a granular mosaic with K-feldspar. This texture is reminiscent of the breakdown of phengite, though no white mica has been found in this specimen. The biotite is associated with epidote (with allanitic cores) and accessory magnetite, sphene, apatite and garnet. Quartz forms less than 5% of this specimen. Finely granulated mylonite bands cut across the foliation at a low angle and are up to 0.5 millimetres wide.

To the south of the southern outcrop of the Flekke Unit, west of Jyttevatnet, the Basal Gneisses locally have a rather different character. To the south of the hill Klibbern the gneisses are medium grained, pale pink and quartz rich. An example is specimen D67, consisting of 40% quartz, 35% feldspar (approximately equal proportions of albitic plagioclase and microcline), 15% phengitic mica and 10% epidote. The phengite forms a good foliation and is partly altered to khaki biotite. Epidote has cores of clinozoisite. The quartz and feldspars are heavily strained and granulated. Magnetite, sphene, apatite and rare zircon are accessories. This rock thus closely resembles some of the psammitic gneisses in the Vardheia Unit. Further south, towards Espedal these are replaced by pink granitic or monzonitic gneisses with deformed pegmatites (no pegmatites have been observed in the Gjörlanger Unit), the relationship between these two types has not been mapped in detail.

Eclogites are found in the Basal Gneisses, taking the classical form of bands and boudins within the gneisses, with tectonised and amphibolitised margins. Three examples are described below:-

The first comes from within the quartz rich phengite bearing gneisses to the south west of Jyttevatnet (specimen D69). The margin of the body is not exposed but it has a maximum horizontal extent of about 10 metres. It is massive, subequigranular with prismatic omphacites defining a strong planar fabric folded into kinks with a wave length of 2 to 3 centimetres. Garnets are generally less than 0.5 millimetres across, euhedral and contain inclusions of rutile and, rarely white mica. They have weak colour zoning with rims paler pink than cores. The garnets are partially or completely enclosed in poikiloblastic omphacites which show undulose extinction and quite coarse angular diopside-plagioclase symplectites. Rutile is a common matrix phase. Omphacite and garnet are replaced by poikiloblastic anhedral deep blue green amphibole associated with white mica and epidote. This type of eclogite is quite common in the hills to the south of Jyttevatnet and resembles that from Ramsgrönova described by Eskola (1921, page 103).

A rather different type of eclogite is found in road cuts on Route 57 along the shores of Breidvatnet and Hovlandsvatnet enclosed in granodioritic and monzonitic augen gneisses. They form bands and strings of boudins up to 2 metres thick, concordant with the gneiss foliation. The rims of the eclogite bodies consist of garnet poor epidote amphibolite, eclogite only being preserved in the cores. Some of the smaller bands and boudins consist entirely of epidote amphibolite. One such pod outcrops on a promontory projecting into Breidvatnet halfway along its eastern shore south of a sharp bend in the road. Specimen 79/36 is from this locality and consists of 33% ragged skeletal hornblende, 25% khaki biotite, 30% sodic plagioclase 10% epidote and accessory sphene, apatite and magnetite. The skeletal hornblende is in complex intergrowths with plagioclase and the occasional presence of relict fine grained diopside-plagioclase symplectites suggests an origin as an eclogite.

Specimen D116 comes from the core of one of these bodies by a stream in a bay to the north of the promontory and consists of equigranular subhedral garnet, omphacite and phengite. The garnets frequently contain inclusions of omphacite and form atoll structures around the phengites (figure 2.55). The phengites break down to symplectites of tan coloured biotite and K-feldspar, overgrown by more euhedral blades of biotite. The omphacites break down marginally to well developed fingerprint symplectites of green diopside and plagioclase, replaced by hornblende and plagioclase. The garnet also occasionally contains small inclusions of blue coloured amphibole (figure 2.56), some of which co-exist with omphacite inclusions. This is the only observed occurence of blue coloured amphibole in the Hellevik-Flekke area. However, glaucophane bearing eclogites have been described from Jostedal Complex gneisses near the junction with the Vevring Complex at Kvineset and Naustdal near Förde (Krogh, 1980) and eclogites containing glaucophane and atoll garnets around phengites are found near Vevring, Fördefjorden (B. Robins, Personal communication, 1982).

The contact of the Basal Gneisses with the overlying units is marked by a zone of sub-mylonitic rocks up to 50 metres wide. To the west of Jyttevatnet the junction with the overlying porphyroblastic garnet amphibolites is well exposed to the north east of Klibbern where the contact is sharp and the rocks on either side have a strong foliation concordant with it. This is in contrast to the rather gradational contacts found between the metabasites and gneisses in the overlying units.

Between Jyttevatnet and Botnatjörna exposures in heavily forested terrain reveal flaggy blastomylonites folded into tight similar folds. Mylonites are also exposed in the eastern and western shores of Breidvatnet. A feature of these is the presence of thin (1 to 30 centimetres) bands of epidote amphibolite which appear to be attenuated forms of the eclogite and amphibolite sheets and boudins found just to the south, giving the rock the appearance of a well banded gneiss. Specimens 79/44A, B and C come from a road cut on the eastern shore of Breidvatnet by a sharp bend in the road. At this locality the grey and pink augen gneisses pass into a zone of very fine grained pale pink flaggy mylonite. The blastomylonites (79/44B) have a foliation defined by thin biotite rich bands about 2 millimetres thick associated with streams of small (0.2 millimetres) epidotes which can be seen to have derived from the breakdown of larger grains locally. In some less deformed microcline rich bands (79/44C) strain is restricted to undulose extinction and mortar texture and a few grains of randomly orientated white mica survive. The mylonite foliation at this locality has been folded around asymetrical similar folds with axial planes dipping to the south east.

The mylonites will be discussed further in the next section (2.07).

In summary the Basal Gneisses consist of two types of gneiss; quartz rich psammitic gneiss and granodioritic or monzonitic augen gneisses. Eclogites are found in this group but their relationships with the enclosing gneisses do not allow firm conclusions to be drawn as to their origins. Although they are unique within the Hellevik-Flekke area these eclogites bear similarities to those found in an analogous tectonostratigraphic position elsewhere in Sunnfjord. A zone of mylonitic rocks separates the Basal Gneisses from the overlying Flekke and Gjörlanger Units.

Section 2.07 Structural Relationships:

A detailed structural analysis of the rocks of the Dalsfjord Area has not been carried out. However, general observations on the main structural features were made in the field along with measurements of the orientations of foliations and lineations. These are discussed below along with a summary of the relationships of mineral assemblages to fabric elements.

2.06.1 Mesoscopic Structures:

Deformation in the Hellevik-Flekke area is rather inhomogeneous as will be apparent from the descriptions above. All variations between undeformed igneous or massive charnockitic rocks and mylonites can be observed, sometimes over distances of a few tens of metres. This inhomogeneity renders the area particularly valuable for reconstructions of the complex crustal history of this part of the BGC.

The main foliation in the area (S_1) is nearly alway parallel to the compositional layering found in the gneisses, metabasites and meta-peridotites (S_0). An instructive exception to this is found to the northwest of Instetjorna at the locality where the rhythmic layering is preserved in meta-anorthositic rocks (figure 2.11 and 2.57). Here the layering (S_0) dips steeply to the north and is locally cut at a high angle by a flattening fabric. This stretches the corona structures and produces a foliation defined by elongation of zoisite and white mica. The foliation dips southwards at a low angle. Assuming that the coarser, more mafic side of each graded unit represents its base the layers young upwards and northwards. Onlapping relationships suggest the same orientation. The high angle between the foliation and the compositional layering suggests that this locality may be close to the axis of an F_1 fold which presently faces upwards and to the north. How this has been affected by subsequent refolding is not certain. The S_1 foliation postdates intrusion of metabasic dykes, anorthosites and metapyroxenites.

The S_1 foliation is folded around mesoscopic and microscopic similar folds whose style is rather variable depending on the lithology. These vary from very tight isoclinal folds in banded gneisses (as in figures 2.02 and 2.58) to tight or more open sharp hinged similar folds (chevron folds) in eclogites and garnet amphibolites (figures 2.13, 2.59 and 2.60). This fold phase (F_2) appears to be associated with boudinage of eclogites in the gneisses and metabasite layers in metaperidotites.

In zones of extreme attentuation these boudins take the form of rootless isoclinal intrafolial folds (figure 2.05). This boudinage and stretching also disrupts reaction zones between metabasites and their enclosing metperidotites. There is no observed new foliation associated with F_2 folds. However, prismatic minerals such as amphiboles, clinopyroxenes and zoisites tend to be elongated parallel to the axis of these folds. Deformed feldspar augen are also elongated parallel to axies of F_2 folds forming a fine rodding structure on many foliation surfaces.

Another type of mesoscopic structure commonly found in this area takes the form of asymetrical similar folds with axial planes dipping to the south-southeast and plunging to the east-northeast. These are fairly open folds compared to F_2 and fold boudinaged layers and the S_1 foliation. These are therefore assigned to an F_3 fold generation (figures 2.61, 2.62 and 2.63). These appear to be associated with millimetre scale crenulations, particularly in chlorite schists, but the folding is nowhere intense enough to produce a crenulation cleavage. In some banded gneisses, where lithological layering results in large competency contrasts, striking disharmonic folding of quartzo-feldspathic layers is associated with crenulations in biotite rich layers (figure 2.01).

Broad, open upright mesoscopic folds (figure 2.64) are commonly found folding the S_1 foliation and are locally found folding the limbs of F_3 folds. These are, therefore assigned to an F_4 generation. Their axes trend east-west and plunge to the east. In some cases the relationships of these folds to earlier structures are not observed and the possibility remains that some of them may be F_3 folds with a different style to those elsewhere perhaps as a result of their position on a major fold.

The latest structural feature found in the Hellevik-Flekke area is the ubiquitious development of sub-vertical fractures. These are particularly conspicuous in metabasic rocks such as eclogites where they are associated with symplectisation and amphibolitisation of omphacite and garnet, forming dark lines on the rock surface. The fractures are frequently filled with carbonate. Locally acicular green epidote is found on the surfaces formed by these fractures. The orientation of the fractures was not measured, but they appear to be associated with large linear features such as the valley in which the north-south arm of Tyssedalsvatnet lies. These may be major fracture zones, but no significant dislocations are revealed by the outcrop patterns. Locally the fractures lie close enough together (less than 1.00 centimetre) to form a weak fracture cleavage.

The mylonitic rocks found at the top of the Basal Gneisses have a foliation which is concordant with S_1 elsewhere and have suffered the same fold episodes. The mylonisation therefore appears to be a result of an early event in the structural history of the area. No intrusive rocks were observed cutting the mylonite fabric.

2.06.2 Macroscopic Structures:

The area considered in this Thesis is rather small for the delineation of major structures. However, inspection of the geological map of the area (figure 2.02) shows that the foliation S_1 strikes generally east to west or east north east to west southwest to the west of Haheia, but to the east of this hill it turns north-south or north-northwest to south-southeast before turning east-west again on the eastern side of Breidvatnet. This configuration is reflected in the outcrop of the ultrabasic schists of the Flekke Unit in the vicinity of Flekke. The change in strike is quite sharp as can be clearly seen on the top of Haheia and at Trollfossen near the northern end of Renestraumsvatnet. It appears to be the culmination of an antiform with a corresponding synform to its south. The axial traces trend east north east to west south-west and they plunge towards the east north east.

Orientations for poles to foliations (S_1) are plotted on equal area projections, contoured by the Mellis method (see Turner and Weiss, 1963, pages 62 and 63). Figure 2.65A shows all the points from the area. There is a considerable spread of data, but a weak great circle girdle can be seen which corresponds to an upright asymetrical fold with an axis trending about 080 degrees and plunging towards the east. A weaker concentration of points seems to form a partial small circle girdle at approximately 35° to 45°, suggesting that some of the spread of the data may be due to later refolding or doming of the above fold type. However, it seems likely that the complex polyphase structural history of the area and the inhomogeneity of deformation has contributed to this spread. The reproducibility of this pattern has been confirmed by plotting alternate data points which produces a very similar configuration.

Dividing the area into two sub-areas, one to the east of Haheia (figure 2.65B) and one to the west of Haheia (figure 2.65C), two rather different patterns become apparent. The concentration of poles around 60.035 corresponding to fairly flat lying foliations is common both areas. but figure 2.65B shows a more well defined girdle than 3.65A which is probably a result of the dominance of measurements from the culmination in this area. Figure 2.65C has a greater east west spread of data and a prominent gap at the orientations corresponding to the lowest dips, but has a strong concentration of points around 45.165 which is absent in figure 2.65B and may correspond to a fold limb.

The S-pole projections seem, therefore, to correspond to the large folds suggested by the outcrop pattern in the field, but a simple explanation of the S-pole distribution is precluded by the large spread of data. The similarity of trend and, to some extent, style suggests that these structures are related to the mesoscopic F_3 folds.

Plotting lineations on an equal area stereographic projection (Figure 2.65D) also reveals a large spread of data. Axes of similar folds, elongation of augen and mineral lineations fall in the same field, which falls very approximately on a great circle. An attempt to unfold the lineations around the axis to the best fitted S-pole girdle (13.065) failed to reduce the spread of lineation trends but did significantly reduce the spread of plunges, which suggests that the folding which produced the S-pole girdle had a small effect on the lineations, but that their spread probably pre-dated this folding.

The Hellevik-Flekke Area lies on the northern limb of a large antiformal culmination whose core is occupied by the Basal Gneisses (see Skjerlie, 1969 and Kildal, 1970). This culmination is a westward extension of the

Gaularfjell anticlinorium and the main outcrop of the Jostedal Complex. (Bryhni, 1966 and Skjerlie, 1969). It brings to the surface the deepest exposed structural level seen near the west Norwegian coast and is flanked by synforms containing successively higher tectonostratigraphic units, the uppermost of which is the Devonian sandstones and conglomorates (see figure 1.03).

Skjerlie (1969) considers that the deformation which produced these large structures (which he allocated to his F5 and F6 fold generations) were responsible for the horst-graben system in which the Devonian sandstones and conglomorates were deposited. These may correspond to the mesoscopic open upright F_4 folds found in this study. The asymetrical east northeast to west northwest trending folds (F_3) of this study are tentatively correlated with Skjerlie's (1969) F_4 structures which he equates with the development of the depression in which the Jotun Nappe lies (the "Faltungsgraben"). The foliation (S_1) and intense F_2 isoclinal folding found in the Hellevik-Flekke area may therefore correspond to the F_3 folds of Skjerlie (1960), which he considers to post date the thrusting of the Dalsfjord and Stavfjord Nappes. The correlations are necessarily rather tentative.

2.06.3 Structures and Mineral Parageneses:

In the micaceous banded gneisses of the Vardheia Unit the earliest planar fabric is defined by the parallel orientation of phengitic white mica, clinozoisite or epidote, pale green amphibole and trails of sphene grains.The white micas follow the form of F_2 folds (e.g. sample 79/21) but are unstrained at the fold hinges and therefore probably crystallised or recrystallised during this folding (figure 2.03). Quartz and feldspars rarely develop a good equilibrium texture and usually have lobate or sutured irregular grain boundaries and sub-grain boundaries. This mineral paragenesis can locally be seen forming from the breakdown of an earlier assemblage (figure 2.02). Despite the granulation, undulose extinction and the development of mortar texture the early assemblage can be seen to have originally consisted of a perthitic or mesoperthitic K-feldspar, quartz and plagioclase in an equilibrium granoblastic mosaic. Plagioclase is clouded with zoisite and white mica and randomly orientated intergrowths of biotite and quartz locally survive. These relics therefore have a close textural resemblance to some of the least deformed hydrated charnockitic rocks found in the Gjörlanger Unit.

Biotite commonly defines a foliation or compositional banding in these gneisses and locally defines small scale crenulations, particularly in zones of disharmonic folding. The biotite is often found to be replacing the phengitic mica (figure 2.66) and often merely mimics the foliation defined by the phengite. Epidotes tend to be more pistacitic where biotite is abundantly developed.

In the well foliated eclogites found in all the geological units the foliation is defined by elongation of prismatic omphacite, zoisite, kyanite, trails of rutile and locally barroisitic amphibole and by parallel orientation of white mica. Where coronitic meta-anorthosites develop a flattening fabric these same minerals take on parallel orientation, garnet coronas are disrupted (figure 2.17) and a characteristic structure develops with anastomosing streaks and schleiren of white mica and zoisite in a matrix of omphacite and amphibole. This structure can be recognised even in zones of extreme attenuation indicating that even strong deformation has failed to completely chemically and mineralogically homogenise the rock. This fabric can locally be found folded around F_2 folds without straining of mineral grains.

Retrogressive assemblages in the eclogitic rocks tend to result from static breakdown rather than shearing. This is witnessed by the very common preservation of delicate diopside or amphibole and plagioclase symplectites after omphacite, kelyphites around garnet, wispy biotite-K-feldspar intergrowths or symplectites after phengites and, more rarely fibrolitic sillimanite pseudomorphs after kyanite (figures 2.55 and 2.47). It is considered that even moderately strong deformation would obliterate these structures. Also, late amphibole growths in eclogites tends to be randomly orientated. In some cases, as in the banded meta-pyroxenites east of Gjörlanger and the banded eclogite/garnet amphibolites by the Gjörlanger-Solvik road omphacite and barroisitic amphibole form a common foliation and appear to be in textural equilibrium (as shown in figure 2.18).

To the south of Asnes where the eclogite in contact with the psammitic gneisses contains felsic backveins, the backveins locally have a foliation defined by parallel orientation of phengites. This foliation passes into the eclogites and the gneisses in both of which strong foliations partly defined by phengite and clinozoisite occur. On this basis the eclogite foliation and the early phengite-clinozoisite foliation in the gneisses are believed to be coeval. The amphibole overprint in the eclogites and the biotite overprint in the banded gneisses are also probably coeval.

A foliation defined by white mica and clinozoisite is also locally found in the gneisses of the Gjörlanger Unit, particularly in the more quartzo-feldspathic varieties. However, in granodioritic augen gneisses deformation tends to produce a foliation defined by biotite, amphibole, epidote and trails of sphene and garnet. As was mentioned in Section 2.04 some varieties of these gneisses, including the quartz rich aluminous eclogitic rocks (e.g. specimen 79/24) contain omphacite, garnet, zoisite, kyanite and white mica and these may either grow statically, pseudomorphing the earlier possible charnockitic assemblage or form a foliation. Deformation of some of the statically metamorphosed examples produces the biotite-epidote foliation commonly found in the augen gneisses and fine grained grey gneisses.

Hence in these rocks an early foliation formed from combinations of omphacite, clinozoisite, kyanite, white mica and rarely biotite appears to be post-dated by an apparently co-planar foliation defined by biotite, epidote and amphibole. Locally the biotites have a fine grained, wispy appearance when associated with K-feldspar and relics of white mica occur locally, perhaps indicating that a phengite foliation was once much more common than at present and that this too has been mimiced by the biotite foliation in some cases. Where these gneisses are phengite rich the phengites are bent around open, rather asymetrical F_3 folds which cause undulose extinction (figure 2.68).

In the chlorite-harzburgites of the Flekke Unit the foliation is defined by chlorite, orthopyroxene and trails of magnetite and ilmenite (figure 2.20). In places these phases follow the traces of F_2 folds whilst maintaining an equilibrium texture (as in specimen D144). Late anthophyllites grow across this foliation and therefore post-date it (figure 2.69). Both orthopyroxene and anthophyllite are replaced by randomly orientated talc and olivine in pseudomorphs. The chlorite-orthopyroxene foliation is bent by late F_3 folds causing an undulose extinction. These folds also bend the talc/olivine pseudomorphs.

The gneisses in the mylonite zone have been described in Section 2.05. These rocks show the most extreme granulation of feldspars and quartz of all the gneisses sampled in this study (figure 2.70) and have foliations delineated by biotite and epidote or locally by white mica. The white mica occasionally has a random orientation and is overprinted by biotite. The mylonite foliation is folded around F_3 folds, but no obvious F_2 folds have been observed.

It should be noted that although mylonites are best developed at the top of the Basal Gneisses, strong granulation of quartz and feldspars is a very common process in the formation of the gneissic fabric in the Hellevik-Flekke Area. In many cases the gneisses can be seen to have derived their present fabric from coarser, more massive lithologies which had equilibrium granoblastic textures or igneous textures.

It is concluded from this that the mylonite zone represents a zone of rather stronger relative motion (or shearing) than was experienced in the adjacent rocks, but that the formation of the regional gneissic fabric and the mylonites was broadly coeval. The shearing in the mylonite zone produced an early white mica +/- biotite foliation, but continued movements obliterated the white mica and dominant biotite foliation formed.

Section 2.07 Summary of the Geological Relationships:

The Hellevik-Flekke Area embraces a wide variety of lithologies with a complex history. However, relationships between the lithostratigraphic units above the Basal Gneisses suggest that the contacts between them are non-tectonic and hence all these lithologies belong to the same tectonostratographic unit. This probably corresponds to the Vevring Complex and the Holsen Gneiss of Skjerlie and Pringle (1978). A tectonic contact between the Basal Gneisses and the overlying units is marked by a zone of flaggy mylonitic gneisses. The extent of this movement is unknown.

The position of the Flekke Unit between apparently plutonic granodioritic rocks (Gjörlanger Unit) and banded gneisses of possible supracrustal origin (the Vardheia Unit) indicates that one or more large basic-ultrabasic intrusion(s) has been injected along the contact between these two rock units. This contact may have been a basement-cover unconformity or the upper limit of the intrusion of granodiorites into the supracrustals. The field observations do not discriminate between these two hypothese. It is significant that obvious minor intrusive basic bodies permeate the Gjörlanger Unit below the basic ultrabasic complex since these may be feeders to this complex.

Inhomogeneous deformation in the Hellevik-Flekke Area provides windows for the observation of a complex history. Evidence for early charnockitic mineralogy is common in the gneisses and in some metabasites, suggesting that large volumes of such rock types existed in the Gjörlanger Unit and possibly even the Vardheia Unit. If this is the case in the Vardheia Unit then the field occurrence of migmatitic structures indicates that any granulite-facies assemblages which may have existed post date anatexis which in turn must post date any deposition of the sedimentary precursors.

This evidence raises the possibility that considerable volumes of the BGC originally consisted of pyroxene granulites related to the charnockite suite prior to the development of the present tectonic fabric. A specimen of an undeformed mangerite-syenite collected by the author from Flatraket, Statlandet shows strong mineralogical similarities to some of the charnockitic rocks from the Hellevik-Flekke area, containing hypersthene, diopsidic clinopyroxene and later garnets in coronas around these phases against plagioclase. Similar lithologies, though lacking hypersthene have been described by Lappin (1966) and Bryhni (1966) from Flatraket and Malöy.

The close field association of anorthositic and peridotitic rocks is of interest as it may shed some light on the origins of the Fe-Ti garnetiferous peridotites (Carswell et al., 1983) found to the north of Nordfjord. Fe-Ti garnet peridotites were found associated with layered orthopyroxene eclogites by Schmitt (1964) at Eiksundal, near Alesund. The Eiksundal Complex may be similar to the Flekke unit, but has suffered a higher grade of metamorphism. The lithologies observed in this study show obvious gradational relationships with each other which strongly suggests a genetic link between them. It may be that some garnetiferous peridotites have a similar origin, evidence for which is now tectonically obliterated, in which case they cannot have formed as tectonic interdigitations of sub-continental mantle. Brastad (1983) has reported the occurrence of rodingite-like rocks from an anorthosite-serpentinite contact at Björkedalen near Nordfjord which are not dissimilar to those found at Flekke.

One of the most significant contributions made by this area to the elucidation of the problems of the BGC is the presence of abundant evidence to show that the eclogites formed by metamorphism of basic precursers _in situ_ within their present country rocks. A wide variety of protoliths have been transformed into eclogites. These include basic dykes, coarse cumulate igneous rocks, intrusive pyroxenites and basic sheets and layers in metaperidotites. Furthermore eclogite-facies parageneses are found in rocks ranging in composition from basaltic to granodioritic. The untectonised contacts between the layered basic-ultrabasic complex and its enclosing gneisses precludes its origin as a fragment of oceanic crust. This is all very compelling evidence that not only the metabasites but also all the enclosing gneisses have suffered an eclogite facies metamorphism.

This adds to a growing body of evidence that low pressure crustal precursors have been transformed into eclogites in the BGC. Coronitic metadolerites are common near the west coast between Nordfjord and Kristiansund (Gjelsvik, 1950; Griffin and Raheim 1973 and Raheim, 1972). High pressure parageneses in the gneisses have also been discovered in the recent years (Mysen and Heier, 1972; Krogh, 1980, 1981 and Griffin et al. in press). However, the eclogitic parageneses and associated coronite mineralogy differ from those to the north of Nordfjord and suggest rather lower equilibration temperatures. This is discussed further in Chapter 4. The formation of eclogites is related to the earliest structural elements in the area, the S_1 foliation and the F_1 and F_2 folds. However, eclogitic parageneses have developed in two ways: Some have formed during tectonism producing eclogites with a strong tectonite fabric. These are minerologically and chemically homogeneous on the scale of a few grains. Other eclogites have formed by static metamorphism producing the common corona structures. A similar duality applies to retrogressive assemblages; many have formed by static breakdown, often mimicking earlier textures whilst localised deformation has produced retrogressive assemblages with their own tectonite fabric. These phenomena and the common preservation of mineralogies predating eclogite formation suggest that kinetic factors have strongly influenced the metamorphic development of the lithologies in this area. Finally, the evidence gained from field work can be used to make deductions about the relative age relationships of the mapped lithologies. The presence of obvious intrusive relationships between both the basic dykes and the websterites with the grey gneisses of the Gjörlanger Unit shows that these lithologies post-date the igneous precursors of the gneisses. The relationships of the basic dykes to the websterites are not certain but the presence of dyke-like sheets of coronitic eclogite which cut the pyroxenites near Tyssekvam suggest that at least some of them postdate the websterites.

The strong likelihood that the basic and ultrabasic complex of the Flekke Unit was intrusive into its enveloping gneisses implies that these rocks are younger than the gneiss precursers. If the basic dykes are feeders to this complex then they are of the same age and may both be younger than the websterite suite. The field evidence does not conclusively demonstrate this however, and chemical evidence indicates that the dykes which cut the pyroxenites are different from those cutting the gneisses (see Chapter 3).

The present tectonite fabrics and their associated metamorphic mineral parageneses entirely postdate these intrusive events as well as a granulite-facies event which has left its inprint on some of the least deformed lithologies. Hence although the eclogite facies metamorphism is associated with the earliest observed deformation episodes it appears to be a rather late episode in the crustal history of the area.

CHAPTER 3 - WHOLE ROCK GEOCHEMISTRY

CHAPTER 3 WHOLE ROCK GEOCHEMISTRY

Major and trace element compositions have been determined for all the lithological types outlined in Chapter 2. The aim of this Chapter is to characterise and classify the rocks in terms of their whole rock chemistry, to compare them with similar rocks elsewhere and, where appropriate, to draw conclusions on the petrogenesis of their pre-metamorphic precursors. In a number of cases, the observations made in this Chapter have significant consequences for lithologies found elsewhere in the BGR. These will be discussed where they become apparent and summarised at the end. Analytical methods are described in Appendix 1.

Section 3.01 The Gneisses of the Gjörlanger Unit and the Basal Gneisses

3.01.1 Introduction:

Major element analyses and CIPW norms of these gneisses are provided in Table 3.1 and trace element analyses in Table 3.2. The gneisses have been sub-divided on the basis of their appearance in the field and their petrographic characteristics as outlined in Chapter 2, Section 2.03.3.

The "massive green gneisses" and "K-poor gneisses" are those described under the heading "Eclogites and Amphibolites of Intermediate and Acidic Composition". The former variety is the lithology which contains omphacite relics, is associated with the grey gneisses and has coronitic textures apparently mimicking a charnockitic precursor. The latter variety corresponds to the green, foliated quartz rich aluminous eclogites or amphibolites. The Basal Gneisses are all pink, orthoclase-rich gneisses. Samples D 110, D 112 and D 120 are rocks of intermediate composition which come from an area assigned to the Flekke Unit between Stõretjorna and Leirpoll (Enclosure 1) and are included with the massive green gneisses as they are petrographically identical to them.

Before embarking on an examination of the chemistry of these rocks, it is appropriate at this stage to summarise the features of them which could be profitably explored in terms of their bulk composition and to present any hypotheses which the chemical data could be used to test. The relevant points are listed below:-

1. The appearance of the grey and pink gneisses in the field indicate that they may be igneous in origin and are, therefore, orthogneisses. Hence, they may be expected to exhibit trends of variation typical of magmatic fractionation processes and element concentrations typical of igneous rocks. Following on from this, comparisons with well known igneous suites may enable some inferences to be made on their origin.

2. The massive green gneisses show evidence for having undergone eclogite-facies metamorphism. Field and petrographic evidence indicates that these are directly related, or even equivalent to the grey gneisses. Chemical data should show whether these lithologies are consanguinous or not and perhaps throw some light on the reasons for their mineralogical differences. The conclusions to be drawn from this may provide at least a partial explanation for the apparent rarity of eclogite-facies mineral assemblages in the more salic rocks of the BGR.

3. Petrographic evidence for intermediate-pressure granulite parageneses in the grey and pink gneisses indicates similarities with the charnockitic lithologies common in Precambrian shield terrains.

3. (cont'd)

   Comparisons with Archaean granulites and rocks of the predominantly Proterozoic Anorthosite-Mangerite-Rapakivi granite suite would, therefore, seem to be profitable for elucidating their affinities.

4. Granulite-facies rocks commonly have geochemical characteristics which distinguish them from rocks of otherwise similar composition, but lower metamorphic grade (see for instance Heier, 1973). Hence, the gneisses discussed here might be expected to exhibit similar characteristics, despite subsequent metamorphic episodes. Such a chemical signature might be useful in unravelling the history of other parts of the BGR where pervasive recrystallisation has obliterated evidence for the early history of the rocks.

5. Field evidence suggests that the metabasic rocks, which are common in the Gjörlanger Unit, have become hybridised with the gneisses. Geochemical studies should provide some evidence as to the scale and nature of any hybridisation and the relationship of the gneisses to the metabasites. Much of the discussion of this subject is deferred until Section 3.2.

6. The similarity of these gneisses to those of Precambrian high grade gneiss terrains suggests that their protoliths are at least 1000 Ma old. Some isotopic data are presented which attempt to define the age of the rocks and provide some evidence for their origin.

3.01.2 Element Variation:

Various major elements have been plotted (as oxide mass percent) against the differentiation index of Thornton and Tuttle (1960) in Figure 3.01. Samples from the metabasic dykes by Gjörlangerfjord have also been plotted on these diagrams for comparison (samples D 80, D 81, D 82, D 83, D 134, Tables 3.5 and 3.6). In these diagrams and all the others in this Chapter the major element analyses have been recalculated to 100% free of H_2O in order to remove the compositional variability caused by inhomogeneous hydration during amphibolite-facies metamorphism. Petrographic evidence suggests that most of the lithologies considered here were anhydrous at least immediately prior to development of their present mineral assemblages.

In the diagrams in figure 3.01 the grey and massive green gneisses show continuous trends of variation which are typical of igneous rock series. The groupings outlined above are well differentiated along these trends, but there are no compositional gaps between them.

The basic dykes fall on or close to the basic ends of these trends, indicating that some genetic link exists between them and the gneisses.

Several of the diagrams show the differences between the K-poor gneisses, the Basal Gneisses and the other groups. At any value of the differentiation index, the K-poor gneisses contain less TiO_2, total FeO and alkalis than the other groups. The rather leucocratic augen gneisses D 78 and D 79 appear to show similar features and fall on the same variation trend as these rocks and may be related to them on this basis. There seems little doubt that they form a separate group from the grey and massive green gneisses despite their close association in the field. The Basal Gneisses are significantly enriched in Al_2O_3 and alkalis and contain less SiO_2 when compared to the other groups at any value of the differentiation index. On this basis, these also appear to form a distinct geochemical group.

The differentiation index used here reflects the increase in alkali-aluminium silicates typical of successive residual liquids produced during magmatic differentiation (Thornton and Tuttle, 1960). The smooth trends of variations shown in figure 3.01 including the progressive decrease of Al_2O_3, CaO, total FeO, MgO and TiO_2 and the progressive increase in alkalis and SiO_2 are considered to reflect the progressive evolution of these rocks towards "petrogeny's residua system".

Hence, an igneous origin is favoured for all these rocks rather than a sedimentary origin. The latter might be expected to produce a preponderance of silicic, aluminous or calc-silicate rich lithologies, chemical trends indicative of quartz and heavy mineral enrichment or an abundance of clay minerals and considerably more scatter than exhibited in figure 3.01. A volcanic origin cannot be discounted by chemical evidence alone, but lack of banding in the field mitigates against this. They can therefore, be classified as orthogneisses. These conclusions are consistent with the evidence from field work and will be further substantiated throughout this section.

The magmatic characteristics of these rocks extend to the trace elements as can be seen in figure 3.02. Various trace elements have been plotted against the Larsen differentiation index (as modified by Nockolds and Allen, 1953). Depletion of the first transition metals V, Mn and Ni as well as Sr in the more salic rocks relative to the more basic ones is typical of igneous fractionation processes as is the enrichment in Rb, Y and Zr (Nockolds and Allen, 1953, 1954, 1956). The maximum on the Zr trend (figure 3.02f) for the grey and massive green gneisses may be due to concentration of Zr in the melt followed by removal in zircon. The maximum on the Y trend (figure 3.02e) may be a result of a decline in the crystalisation of calcic pyroxene and apatite following the solidification of the more basic members of the series leading to enrichment of Y in the melt, followed by removal in zircon.

The early decrease in the Ca/Sr ratio can be attributed to the early preference of plagioclase for the Ca^{2+} ion rather than the larger Sr^{2+} ion. Loss of Sr from basic samples may contribute to this, however. The wide scatter in the Cr plot (figure 3.02b) is curious when compared to the relatively well defined trends of the ferromagnesian trace elements (ie those replacing Fe and Mg). No simple explanation for this behaviour is at hand at present.

The differences between the various gneiss groups is apparent on these trace element plots. The more "primitive" nature of the K-poor gneisses is apparent in their high concentrations of Ni, Cr and Sr and lower concentrations of Y, Zr and Rb at any value of the Larsen index. On the other hand, the Basal Gneisses contain less Cr and more Mn, Rb and to some extent, Sr than the grey and massive green gneisses, the latter two reflecting their more feldspathic and K-feldspar rich nature.

When plotted on triangular diagrams for AFM and K_2O-Na_2O-CaO (figure 3.03) these gneisses again show trends of variations typical of igneous rock series. In particular, the fairly consistent FeO/MgO ratio is more typical of calc-alkali series than alkali or tholeiitic series, where the hooked trends on the AFM plots due to early iron enrichment are more common (Nockolds and Allen, 1953, 1954 and 1956). The more magnesian and less potassic nature of the K-poor gneisses is obvious on these diagrams, whilst the rather potassic nature of the Basal Gneisses is also apparent. As in figure 3.01, the metabasic dykes fall close to the ends of the gneiss trends.

3.01.3 Classification of Lithological Type:

Having established that these rocks are orthogneisses an attempt to classify them in terms of accepted igneous rock nomenclature follows.

The variety of mineralogical changes which the gneisses have undergone during their polymetamorphic history (see Chapters 2 and 4) renders modal classification impossible for all but a few samples. As a result, the approach of Streckeisen (1976a) and O'Connor (1965) will be used here, in which the normative composition of the rocks is compared with the norms of a large sample of rocks of known modal composition.

The method of Streckeisen (1976a) uses the nomenclature system accepted by the IUGS Sub-Commission on the Systematics of Igneous Rocks, as outlined by Streckeisen (1976b). Normative feldspar compositions are plotted on two triangular normative ab-or-an diagrams (figure 3.04) sub-divided according to an/or ratios. Fields for compositions of rocks of known modal composition are delineated on each plot, one for rocks with more than 17% normative quartz (3.04a) and the other with less than 17% normative quartz and less than 7% normative nepheline. The modal rock names are derived by virtue of their position in the QAPF (modal quartz-alkali feldspar-plagioclase-feldspathoid) diagram. Use of simple an/or ratios without arbitrary or empirical distribution of normative albite between plagioclase and alkali feldspar, gives a good separation of rock types by this method (see discussion in Streckeisen, 1976a).

The quartz-feldspar rocks (figure 3.04a) fall into the fields of syeno-granites, monzo-granites and granodiorites, with one sample approaching the composition of trondjemites (D 78). The only sample from the Basal Gneisses to occur in this diagram (79/44a) has characteristics more akin to the most differentiated grey gneisses of the Gjörlanger Unit. The grey gneiss in the syenogranite field (DG-1) is very leucocratic and may, therefore, be described as an alaskite. The K-poor gneisses on this diagram do not fall in any of the fields defined by Streckeisen (1976a) and must be considered to be rather unusual in this respect.

They might be considered as very quartz rich diorites. They also have higher ab/(ab + an + or) values than most of the grey gneisses except for the two approaching the trondjemite field (D 78, D 79) which show affinities to the K-poor gneisses in the differentiation index plots (figures 3.01 and 3.02).

The feldspar rocks (figure 3.04b) exhibit clearly the differences between the Basal Gneisses and those of the Gjörlanger Unit. The Basal Gneiss samples are classified as syenites and monzonites whilst the Gjörlanger Unit grey gneisses are diorites and rather sodic gabbros. The massive green gneisses and basic dykes fall in the gabbro an/or range, but have higher ab/(ab + an + or) values than the field outlined by Streckeisen (1976a). One exception is basic dyke sample D 134, which falls low in the diorite field. One sample of K-poor gneiss is classified as gabbroic.

The method of classification is beset with a number of problems, which mainly apply to the more basic rocks.

Some of the rocks classified as gabbros are not strictly of basaltic composition. Applying the chemical screen for basaltic rocks of Manson (1967) the K-poor gneiss D 24, the hypersthene bearing grey gneiss D 99 and the massive green gneisses D 114, D 115 and D 184, all fail to pass the screen, mainly because of their rather high SiO_2 and low MgO contents.

D 114 has an abnormally high Na_2O content. In addition, the K_2O contents of the anomalous rocks are rather low for their SiO_2 contents. As the concentrations of SiO_2, Al_2O_3, MgO and CaO in these anomalous rocks are more compatible with average diorite compositions than average gabbros or dolerites (cf Le Maitre, 1976) classification of them as diorites is preferred. An increase in K_2O and a decrease in Na_2O would bring these rocks into the diorite field in figure 3.4b.

Streckeisen (1976a) acknowledges that this classification scheme has difficulties for the more mafic rocks. Part of the problem is that normative plagioclase components are camouflaged in the modal mafic minerals. Sample D 99, for instance, contains a considerable amount of modal clinopyroxene with significant calcium tschermaks and acmite components and modal mildly aluminous hypersthene (see Chapter 5). An increase in normative anorthite due to calcium tschermaks substitution would have little effect on the classification as the dioritic and gabbroic fields trend towards to the anorthite apex and the fields overlap slightly. However, an increase in normative albite due to sodium in solid solution in pyroxene might significantly effect borderline samples producing the distribution seen here. Alternatively, the rather low K_2O contents of some of these rocks might indicate that anomalous feldspar compositions in the protoliths or the crystallisation of a K-poor mafic phase (eg a pyroxene)

This may have been the case if these rocks crystallised directly to a granulite-facies charnockitic assemblage.

A further consideration here is that alkalis are known to be mobile during metamorphism at a variety of grades. The more mafic rocks under discussion here alternate with the more salic rocks on the scale of a few tens of metres in some cases. In the presence of a suitable carrying fluid, alkalis may migrate across the resultant compositional gradients, modifying bulk rock compositions. Any classification system based on alkali elements will, therefore, be open to errors in this respect. This subject is further discussed with respect to metabasites in section 3.02.

Finally, Streckeisen (1976a) set up this method using mostly normal plutonic rocks rather than charnockitic types. The difficulties of modal classification of charnockites have been discussed by Hödal (1945), Philpotts (1966), De Waard (1969), Tobi (1971) and Austrheim (1978). One of the main problems appears to be the distribution of alkali feldspar and plagioclase in hypersolvus feldspars between modal A and P in the QAPF diagram. If, as a result of these difficulties, the modal charnockitic and "normal" plutonic rocks are not chemically equivalent, then a normative classification, such as that used in figure 3.04, is of little value even of leucocratic rocks. Note that Streckeisen used a number of "mangerites" to define field (9) (monzodiorites).

In contradiction with this Tobi (1971) and Streckeisen (1976b) modally classified mangerites as equivalent to field eight (monzonites).

The petrographic evidence for the earlier charnockitic nature of these orthogneisses requires a classification using the appropriate names for the charnockitic suite of rocks. Hence, the Basal Gneisses are classified as hypersthene syenites and mangerites or jotunites. The grey gneisses are charnockites, farsundites, charno-enderbites, norites and gabbros. Use of this classification is made cautiously in the light of the discussion above. A more rigorous chemical classification would require a study similar to that of Streckeisen (1976a) using modal and chemical analyses of charnockitic rocks.

A further attempt to classify these gneisses was made using the "immobile element" discrimination diagrams of Floyd and Winchester (1978). If the orthogneiss trends on the variation diagrams (figures 3.01 and 3.02) are assumed to approximate to liquid lines of descent it seems valid to employ these diagrams, although strictly speaking they are for use with volcanic rocks. The results show a poor consistency with the method of Streckeisen (1976a) (figure 3.04). However, some observations of value may be made;

Firstly, the massive green gneisses are classified rather more realisticly in these diagrams than they are in those of Streckeisen (1976a), plotting in or close to the andesite (diorite) field. Samples D 114 and D 115 are exceptional in this case, plotting either in the phonolite (nepheline syenite) or dacite/rhyodacite (monzo-granite, granodiorite) fields. Their very high Zr contents appear to be the cause of this anomaly.

Among the fine grained grey gneisses, although most of them fall in the diorite field of Streckeisen (1976a) only two fall in the andesite fields in figure 3.05, the rest falling in either the dacite/rhyodacite field (figure 3.5a) or the trachyandesite field (figure 3.05b). This is a consequence of their high Zr contents. Two of the massive augen gneisses show consistency in all three diagrams, but one (79/33a) has a high Zr content, producing a similar anomaly to that of some of the fine grained grey gneisses. The leucocratic augen gneisses D 78 and D 79, fall in the trachyte (monzonite and monzodiorite) field in figure 3.05a and in or near the rhyolite (syenogranite) field in figure 3.05b, apparently as a result of their very low Y contents and high SiO_2.

The K-poor gneisses appear to defy consistent classification. D 23 and D 121, which do not comply with any of Streckeisen's (1976a) compositional fields, plot in the andesite and alkali basalt fields in figure 3.05a which is inconsistent with their high SiO_2 and low K_2O contents.

Their Nb and Y contents are close to the analytical detection limit so that large errors in the Nb/Y ratio make the method unreliable. In figure 3.05b they plot in the rhyodacite and dacite (monzo-granite and granodiorite) field, probably as a result of their high SiO_2 contents. D 24 falls in the andesite (diorite) field in figure 3.05b, which is broadly consistent with its major element chemistry, but plots as an alkali basalt in figure 3.05a and a gabbro in figure 3.04b.

The Basal Gneisses are anomalous in figure 3.05 with respect to figure 3.04, apparently due to rather low Zr/TiO_2 and Y/Nb ratios.

In short, the most successful results for the mobile element discrimination are for the more mafic rocks, indeed in a number of cases, this method may be more reliable than one using normative feldspar ratios, particularly if akali metasomatism has occurred. However, the more differentiated rocks produce poorer results due to their high Zr contents. The exceptionally high Zr contents of the grey gneisses is a characteristic of Archean grey gneisses (Tarney, 1976). Thus, the diagrams of Floyd and Winchester (1978) probably have a limited value for rocks from ancient grey gneiss terrains.

In view of the problems of chemical classification encountered here and the wide compositional range of these orthogneisses, it would appear that a more rigorous attempt at classification by these methods requires the use of a much larger sample population. In this way, a more objective appreciation of which samples are anomalous would be possible. Such an extensive analytical programme is obviously not practicable in study such as this.

In summary, the classification reflects the differences in chemistry noted previously. The grey and massive green gneisses follow a trend from gabroic and dioritic rocks, via granodiorites and monzogranites to syeno-granites. The pink, K-richer Basal Gneisses pass from monzodiorites and monzonites to syenites and alkali syenites. The K-poor gneisses do not correspond to any common igneous rock type and appear to be rather silica rich diorites whose more differentiated relatives are trondjemites or sodic granodiorites.

3.01.4 Classification of Magma Type:

In this section, an attempt is made to find the affinities of the gneisses of the Gjörlanger Unit and the Basal Gneisses in terms of the commonly accepted magma series. The classification is largely based on the methods of Irvine and Baragar (1971).

Examination of the CIPW norms (Table 3.1) reveals that none of these rocks have normative acmite, while several of them contain normative corundum, Al_2O_3 exceeds Na_2O + K_2O and these facts show that the rocks are peraluminous. They are mostly oversaturated, only three having normative olivine. All except sample D 117 are hypersthene normative. Figure 3.06.a is a plot of SiO_2 versus total alkalis. The grey, massive green and K-poor gneisses are discriminated as subalkaline, and pink Basal Gneisses as alkaline and the basic dykes straddle the alkaline-subalkaline divider, with the least altered of the eclogitic dyke samples (see Section 3.02) falling just in the alkaline side. These have small amounts of normative nepheline. The dykes fall on the low SiO_2 and alkalis end of the trend of the Gjörlanger Unit gneisses.

Many of the grey and massive green gneisses fall within Kuno's (1960) field for the high alumina basalt series field and their trend parallels the trend for that series. The K-poor gneisses fall along a similar trend, but at lower alkali values. Figure 3.06.b is a plot of CaO versus SiO_2. Using this in combination with figure 3.06a a Peacock alkali-lime index of about 59 is indicated for the grey and massive green gneisses. This corresponds to the calc-alkali series according to Peacock (1931). However, many tholeiitic suites have alkali-lime indices in this range (Carmichael et al, 1974, Page 48).

Their calc-alkaline nature is confirmed on a plot of normative An in plagioclase versus Al_2O_3 for all samples except D 79, which falls well into the tholeiite field and the least anorthitic samples, for which discrimination is poor in this diagram. Sample D 79 comes from the wall rock of a basic dyke which appears to have lost alkalis, particularly, K_2O (see Section 3.02) and is, therefore, probably unrepresentative of a primary igneous composition. The other an-poor gneisses may still be classified as calc-alkaline on the basis that they fall on the same differentiation trends (figures 3.01 and 3.2) as the more obviously calc-alkaline samples.

3.01.5 Comparison with other Rock Suites:

The average composition of the grey and massive green gneisses is shown in Table 3.3 along with the average continental crust composition derived by Taylor (1964). The Gjörlanger Unit gneisses are superficially similar to the average crust, but a number of elements show significant differences. K_2O and Rb are much lower than average crustal values and Ba is much higher. Na_2O, Sr and Pb are broadly similar, however. MgO, Ni and Cr are lower than average crustal values, although total FeO is very similar. Zr is higher in the Gjörlanger Unit gneisses. As a result of these differences, K/Rb and Ba/Rb are much higher than the crustal average and Rb/Sr is much lower.

Also shown in Table 3.3 are averages for the K-poor gneisses and the Basal Gneisses (excluding sample 79/44A). The K-poor gneisses are poorer in TiO_2, total FeO, MgO, K_2O, P_2O_5, Rb and Pb than the average crustal composition and are richer in SiO_2, Na_2O, and Sr. They are also relatively impoverished in Ni and Cr, but not to the same extent as for the grey and massive green gneisses. Contrary to the case for the latter rocks, the K-poor gneisses contain less Zr than the average continental crust. They have very high K/Rb and Ba/Rb and very low Rb/Sr ratios.

The Basal Gneisses are significantly enriched in Al_2O_3 and alkalis relative to the average crust, but are relatively impoverished in CaO. The ferromagnesian elements MgO, total FeO, Ni and Cr are highly impoverished, but Zr, Sr and particularly Ba are enriched. Despite the high K_2O content, the average Rb value for the Basal Gneisses is rather lower than the average crustal abundance. Hence, they have rather high K/Rb and Ba/Rb ratios and, on average, a low Rb/Sr ratio, though individual values for Rb/Sr are somewhat variable.

The calc-alkaline nature of the orthogneisses as deduced above, suggest affinities with the rocks of volcanic arcs at destructive plate margins. The high maximum SiO_2 and high Ba and Zr contents seem to rule out an island-arc environment although lithologies as basic as some of the massive green gneisses are rather rare in continental (Andean-type) arcs (Jakes and White, The Tuolumne Intrusive Series of the Sierra Nevada Batholith is used for comparison here. An average of 22 analyses from this intrusion is presented in Table 3.3, taken from the study of Bateman and Chappel (1979). The average composition of the Gjörlanger Unit grey and massive green gneisses is rather more basic than that for the Tuolumne Series. This may be partly due to sampling bias favouring the more mafic rocks. The true proportions of mafic to salic varieties is difficult to ascertain in the field due to poor exposure, but the general impression gained by this author is that the grey gneisses are much more abundant than the massive green gneisses and hence a more realistic average composition may be more salic. Even so, average compositions for the fine grained and augen gneisses (Table 3.3) show that even the more siliceous types are rather richer in total FeO and, to some extent, TiO_2, MgO, CaO and P_2O_5 than the Tuolumne rocks, though their ranges show considerable overlap. K_2O in the Tuolumne Series is higher than in the Gjörlanger Unit gneisses on average. At any SiO_2 level the Tuolumne granitoids lie on the high side of the range exhibited by these gneisses but both Series show a similar trend of K_2O enrichment (see figure 3.09B).

The trace elements Ni, Cr and V (from hereon termed ferromagnesian trace elements) are slightly more abundant in the gneisses than the Tuolumne Series, but still show the rather low values characteristic of orogenic igneous suites (Jaces and White, 1972).

The most significant differences in the trace elements between the two groups are in Zr and Ba, which are much higher in the gneisses and Rb which is much lower. Sr in the gneisses falls in the lower side of the Tuolumne range and Y is rather higher. Pb is quite similar. K/Rb and Ba/Rb ratios of the Tuolumne Series are more similar to the average crustal values than the gneisses, as is the Rb/Sr ratio.

The K-poor gneisses are also significantly richer in the ferromagnesian trace elements than the Tuolumne Series and are also richer in CaO and Na_2O. Zr and Sr are quite similar to the Tuolumne Series, but Ba is actually lower. Rb is very much lower in the K-poor gneisses.

The Basal Gneisses are differentiated from the Tuolumne granitoids by their lower average SiO_2 and Rb and higher Al_2O_3, Na_2O, K_2O, P_2O_5, Zr, Y and Ba. Their high Ba and Zr values, low Rb values and K/Rb, Ba/Rb and Rb/Sr ratios are features shared with the grey and massive green gneisses. CaO and the ferromagnesian trace elements show similarities with the latter, however.

A feature of Proterozoic gneiss terrains of the continental shield areas is the anorthosite-mangerite-rapakivi granite suite of rocks. These frequently have granulite-facies mineral assemblages and are, therefore, frequently assigned to the "charnockite suite".

There does not appear to be any clear distinction between these two suites in the literature, although anorthosites and their associated rocks do not always carry hypersthene bearing granulite-facies assemblages (de Waard, 1969). Also, the "charnockite suite" embraces a wider range of rocks than just those of the anorthosite-mangerite-rapakivi granite suite (see, for instance, Subramaniam, 1959). Recent work indicates that Proterozoic massif anorthosites along with their associated troctolitic intrusions and granitoids were emplaced at shallow crustal levels and that their present charnockitic nature is the result of a separate, possibly unrelated tectonothermal event (Morse, 1982 and Valley and O'Neill, 1982). Nevertheless, charnockitic and anorthosite-mangerite-rapakivi granite suite rocks are common in southern Scandinavia (see, for instance, Holtedahl, 1960 and Oftedahl, 1980) and occur in zones of Caledonian orogenesis (Hodal, 1945; Battey and McRitchie, 1973 and 1975; Griffin et al, 1974 and 1978) some of which contain eclogites (Austrheim, 1978, 1981; Austrheim, 1982; Sturt et al, 1975). Granulite-facies mangerite syenites occur in eclogite-bearing parts of the BGR (Bryhni, 1966 and Lappin et al, 1979) and Harvey (1983) suggested that eclogite-bearing orthogneisses in the Molde area have chemical affinities with the anorthosite-mangerite-rapakivi granite suite.

Emslie (1973 and 1978) has studied the chemical characteristics of the anorthosite-mangerite-rapakivi granite suite. He found that these rocks are;

1. rich in Fe relative to Mg and alkalis,

2. high in alumina and

3. have high K_2O contents relative to SiO_2, although they are not unusually potassic.

In addition, Philpotts (1966) in a study of anorthosites and related rocks in southern Quebec, found that the mangerites had high Ba and Sr values showing affinites with calc-alkali rocks and very high Zr contents akin to those in alkaline rocks (cf Nockolds and Allen, 1954).

Referring once more to figure 3.03, it can be seen that even the most basic varieties of the gneisses are not particularly iron rich. Emslie (1973) showed that most "anorthosite-suite" rocks fall above the divider of Irvine and Baragar (1971) in the tholeiitic field, although some of the Fennoscandian examples show calc-alkaline affinities.

Figure 3.08 shows the aluminous character of these gneisses. Emslie (1973) indicates that despite showing tholeiitic characteristics in the AFM diagram, most anorthosite-suite rocks fall above the divider of Irvine and Baragar (1971) in the Al_2O_3 versus normative plagioclase diagrams. The more mafic varieties of the gneisses do not show this duality. However, characterisation of the more alkalic Basal Gneisses in the AFM diagram is difficult. The very aluminous nature of these gneisses shown in figure 3.08 is interesting in view of their broadly "mangeritic" chemistry and in this sense they show some similarities with mangerites and mangerite-syenites from the Jotun Nappes and Bergen Arcs. Compositions of some typical mangeritic lithologies are set out in Table 3.3.

Figure 3.09A shows the relationship of SiO_2 to K_2O for the Gjörlanger Unit and Basal Gneiss orthogneisses in comparison with various anorthosite-mangerite-rapakivi granite suites. The K_2O-rich nature of these suites is obvious on this diagram and the grey and massive green gneisses plot at lower K_2O values at any value of SiO_2 except at the less siliceous end of the diagram where some overlap occurs due to the presence of anorthositic or noritic members. Some overlap with the Nain anorthosite-suite rocks occurs, however.

In contrast, the more potassic Basal Gneisses show some similarities with the anorthosite-suite rocks in figure 3.09. Their similarity is also manifested in their very aluminous nature and high Ba and Sr contents. Mangeritic rocks from the Adirondacks (Reynolds et al, 1969) and the Bergen Arcs (Austrheim, 1978) are characterised by high K/Rb ratios considerably greater than the crustal average of 230 derived by Taylor (1964). This also is a feature shared by the Basal Gneisses. The rather high Zr contents of the Basal Gneisses are similar to those of the Mangerites of the Bergen Arcs (Austrheim, 1978) but do not approach the extreme values of those in the Morin Series (Philpotts, 1966). Finally, the Basal Gneisses do not appear to be as iron rich as many of the mangeritic rocks.

Charnockitic rocks sensu lato (as opposed to those strictly related to anorthosites) from the type area near Madras, India (Howie, 1955 and Subramaniam, 1959) have similarities with the gneisses of the Gjörlanger Unit. Their element variation trends are similar and a sub-division into K-richer (charnockites and intermediate rocks, diorites and norites) and K-poorer (enderbites) varieties has been made by Howie (1955). These rocks are plotted in figure 3.09B, where the low-K nature of the enderbites is apparent. Some overlap occurs with the Gjörlanger K-poor gneisses and the dioritic, intermediate and charnockitic varieties show some similarities with the massive green and grey gneisses.

Average compositions for the Madras lithological groups are presented in Table 3.3. The major elements have some similarities, the most obvious differences being the rather higher Al_2O_3 in the Gjörlanger Unit rocks. Excluding the ultrabasic division of the Madras rocks, they show a similar range of composition to the Gjörlanger Unit gneisses, with basic varieties apparently being more common than in the Tuolumne Intrusive Series. Charnockites are poorly represented in the Gjorlanger Unit gneisses, the averages in Table 3.3 reflecting the predominance of more intermediate lithologies. However, sample DG-1 shows similarities with the average for the Madras charnockites.

Like the anorthosite-mangerite-rapakivi granite suite, Madras charnockites are characterised by very high Ba, Sr and Zr and mostly low Rb contents.

Howie (1955) suggested that the Madras charnockites were calc-alkaline igneous rocks which have undergone high grade metamorphism. He drew a parallel between the intermediate rocks and the enderbitic rocks with the high-K andesites of Lassen Peak and the low-K andesites respectively of Crater Lake described by Nockolds and Allen (1953). This analogy appears to be applicable to the Gjörlanger Units gneisses as well.

Grey, granodioritic and tonalitic gneisses of both amphibolite and granulite-facies are major components of the ancient continental crust. The geochemistry of the Archaean high grade gneisses has been reviewed by Tarney (1976). They appear to be orthogneisses with calc-alkaline characteristics and have high Ba, Sr and Zr, with moderately high Ba/Sr ratios. These are features which they share with continental calc-alkali rocks, the anorthositic and charnockitic suites described above and the orthogneisses under discussion here. Furthermore, the granulite-facies types have low Rb, very high K/Rb and very low Rb/Sr ratios. However, unlike the anorthosite-mangerite-rapakivi granite suite and the Madras charnockitic suite, Archaean gneisses are significantly depleted in K_2O and show no increase in K_2O in later differentiates, giving them rather low K/Sr ratios. This is clearly displayed in figure 3.09B and on this basis the Gjörlanger Unit grey and massive green gneisses differ from the Archaean granulites.

The low-K gneisses are perhaps more similar to the Archaean granulites. However, numerous workers prefer a metasomatic process to explain this K-depletion (see sub-section 3.1.6). It is difficult to visualise such a process working on only a part of the gneiss complex in the Dalsfjord area whilst leaving the rest virtually chemically unaffected unless they are greatly different in age.

The Basal Gneisses, with their potassic, highly aluminous nature are clearly different from the Archaean granulites.

On the basis of the comparisons made in this sub-section, the gneisses of the Gjörlanger Unit show strong affinities with Cenozoic calc-alkali igneous rocks as well as charnockitic igneous rocks with calc-alkaline characteristics. Rocks of the anorthosite-mangerite-rapakivi granite suite have trace element patterns common to some calc-alkali suites, but their high K_2O contents and enrichment in iron relative to magnesian and alkalis sets them apart. The Basal Gneisses, however, seem to have more in common with granitoids associated with Proterozoic anorthosites, although the rather small sample and their well-evolved nature makes assessment of any iron enrichment trends impractical.

3.01.6 Large Ion Lithophile Element Chemistry:

The relative behavior of Rb/Sr and Ba in the gneisses is shown in the ternary diagram of el Bouseily and el Sokkary (1975) in figure 3.10. The distribution of points in relation to the empirically derived compositional fields corresponds fairly well with the chemical classification outlined in sub-section 3.01.3 and the petrographic types. The Gjörlanger Unit gneisses show a trend typical of magmatic rocks with Sr depletion accompanied by an increase in Ba, presumably as a result of increasing influence of K-feldspar crystallisation relative to plagioclase.

The Rb contents are notably low in relation to Ba and Sr.

The Basal Gneisses, with one exception, fall in the field of "anomalous granites". This field covers the composition of rapakivi granites (el Bouseily and el Sokkary, 1975). Harvey (1983), found that the less differentiated orthogneisses from the Molde area fell in, or close to this field. He considered that they have affinities with mangerites and rapakivi-type granites. This may be further evidence of similar affinities for the Basal Gneisses of the Hellevik-Flekke area.

The Ba/Sr ratio is useful in deducing the geotectonic environment in which these rocks originated. This has been discussed Tarney (1976) in relation to the origins of Archaean high grade gneisses. As was mentioned above, high Ba, Sr and Zr concentrations are characteristic of continental margin calc-alkali suites as opposed to those of oceanic island arcs. High Ba/Sr ratios (usually greater than 1.0) are also characteristic of continental margin suites. Figure 3.11 shows that most of the gneisses considered here have Ba/Sr ratios exceeding 1.0 with only the most mafic examples falling below this value. However, similar geochemical characteristics are found in granitoids associated with anorthosites (see Philpotts, 1966, Table 4) which are thought to be anorogenic igneous suites (Emslie, 1973 and 1978 and Morse, 1982).

It is therefore, possible that such geochemical patterns might have been inherited by partial melting of previously existing deep continental crust (Tarney, 1976). Such an origin has been proposed for the mangeritic and rapakivi-type granitoids with high Zr contents (Emslie, 1978) and may be applicable to the Basal Gneisses. However, the evidence presented above to show that the Gjörlanger Unit gneisses have evolved from magmas approaching basaltic composition mitigates against large scale involvement of continental crustal material in their evolution.

A recurring theme in the discussion of the geochemistry of these gneisses is their low Rb contents compared with those of high level plutonic granitoids and the average crustal composition (Tables 3.2 and 3.3). Rb depletion is typical of granulite-facies terrains (see, for instance, Heier, 1973; Sheraton et al, 1973 and Tarney and Windley, 1977). Figure 3.12 is a plot of K versus Rb. All of these gneisses have K/Rb ratios well above the crustal average of 230 (Taylor, 1964) and are similar to those from the granulite-facies mangerites of Lofoten (Heier, 1973) and the Scourian granulites (Lambert and Holland, 1976, figure 5). However, the K contents of the gneisses are close to the average crustal value, unlike the strongly depleted Scourian granulites.

Rb/Sr ratios are generally below the crustal average (0.24) with only the most differentiated samples showing higher values (figure 3.13). Only the most mafic samples have Rb/Sr ratios as low as the Scourian granulites (less than 0.05; Sheraton et al, 1973 and Tarney and Windley, 1977, figure 7).

A number of processes leading to alkali depletion under granulite-facies conditions have been proposed. Removal of the low melting component during partial melting may be responsible (Fyfe, 1973) but the common high concentrations of Ba in granulite-facies gneisses mitigates against this, as Ba might be expected to be removed into the melt fraction (Tarney, 1976 and Tarney and Windley, 1977). This observation also applies to the gneisses considered here. The conspicuous lack of pegmatites or granite sheets in the Gjörlanger Unit indicates that no anatexis has occurred there.

Metasomatic removal of alkalis during open-system metamorphism is a further possibility. A common suggestion is that the formation of anhydrous mineral assemblages during granulite-facies metamorphism might lead to loss of elements for which they are no suitable lattice sites in the new assemblages. The breakdown of biotite might be expected to lead to loss of Rb, which is preferentially held in the mica relative to K-feldspar (Heier, 1973).

Sheraton et al. (1973) have found that the most K-depleted Scourian gneisses of the Assynt area are those which are diopside normative. K is lost according to the reaction;

$$\mathrm{Di} + \mathrm{Or} = \mathrm{An} + \mathrm{Hy} + 5\mathrm{Qz} + \mathrm{K_2O}$$

This might be expected to produce Rb loss as well. The most diopside normative rocks in the Gjörlanger Unit do indeed have the lowest K, Rb and Rb/Sr values, while the most differentiated rocks with low normative diopside or normative corundum have more normal values. To what extent this is due to magmatic differentiation or to metasomatism is uncertain.

Perhaps a simpler explanation for the Rb depletion is that Ba is preferentially incorporated into feldspars when in competition with Rb. This is because the ionic radius of Ba is closer to that of K than Rb. Also, incorporation of Rb may be further inhibited when the feldspar is crystallising at high temperatures close to the solvus (Taylor, 1965). The low Rb contents of such rocks may, therefore, be a primary feature. Alteration of the feldspars in the gneisses make petrographic or chemical investigation of their original nature difficult. As a result, it has not been possible to examine the feldspars in order to more fully resolve the nature of the Rb depletion.

Such a process might be expected to cause concentration of Rb in residual liquids producing a significant decrease in K/Rb ratios in the most differentiated rocks of this Series. This does not appear to be the case as the lowest K/Rb ratios are still well above the crustal average (see figure 3.12). Hence, a metasomatic origin for the Rb depletion is preferred here.

The demonstration that these charnockitic rocks have a chemical signature common to many granulite-facies rocks may prove to be of use in palaeotectonic reconstructions. If gneisses in the BGR which are now entirely transformed into amphibolite-facies assemblages can be shown to have alkali depleted characteristics, it might be possible to infer a previous granulite-facies metamorphism. Retrogressive metamorphism seems to have no effect on alkali depletion patterns (Tarney and Windley, 1977). Information on Th, U and Cs would help to confirm the patterns shown by K and Rb in relation to Sr and Ba (cf. Heier, 1973 and Tarney and Windley, 1977).

3.01.7 Rb-Sr Isotopes:

A reconnaisance study of the Rb-Sr isotope systematics of these rocks has been carried out. Analyses of the gneisses of the Gjörlanger Unit for Rb and Sr isotope compositions were made at the Mineralogisk-Geologisk Museum, Oslo with the kind permission of Professor W L Griffin.

Analytical results are set out in Table 3.4.

Samples were collected on an outcrop scale from a fresh roadside cutting by Route 57 close to the junction with Route 610 near Renestraum. The outcrop consists of variably foliated and retrogressed gneisses including common charnockitic relics with heavily clouded feldspar and hydration of pyroxenes to actinolitic amphibole and biotite. Eight samples were collected including one from a leucocratic alaskite band (DG-1). Unfortunately, these samples had rather low Rb/Sr ratios with a small range of values and only three were suitable for isotopic analysis (samples DG-1, DG-5 and DG-7). These all have a foliation defined by either amphibole, biotite and epidote (DG-5 and DG-7) or white, phengitic mica and epidote (DG-1). These samples were all located within three metres of each other and had volumes of approximately 1 litre.

Samples collected from the rest of the Gjörlanger Unit were also analysed. These are mostly massive or augen gneisses with a recognisably charnockitic nature and little or no flattening fabric (samples 79/12, 79/33A, 79/43A and D 44). They all exhibit the corona-textures resulting from garnet growth and hydration reactions typical of these gneisses. Two fine-grained foliated gneisses were also included (79/4 and D 30). Distances separating the sample localities exceed 100 metres. Due to the regional scale of sample distribution, there is some uncertainty as to whether the "same age" and "same initial ratio" conditions required for a true isochron are satisfied.

The smooth trends exhibited on the variation diagrams (figures 3.01 and 3.03) seem to indicate a common origin for them, hence it is concluded with some caution that these conditions are fulfilled. Even so, the scale of diffusion for Rb and Sr at each sample locality remains undefined.

The results of the analyses have been plotted on an isochron diagram in figure 3.14. The small range of $^{87}Rb/^{86}Sr$ reflects the low Rb/Sr ratios. The points are widely scattered and the grey gneisses define an "errorchron" age of 1254.7 +/- 309.2 Ma with an initial ratio of 0.70400 +/- 0.00175. Reference isochrons of 1200 Ma and 1500 Ma are provided on the diagram. The MSWD of 653.80 is well above that due to analytical error. Despite the scatter, the initial $^{87}Sr/^{86}Sr$ ratio is quite well defined. The scatter of the samples from the Renestraum roadside blasting is of the same order as that for the regionally collected samples, thus it is only necessary to infer disturbance of the Rb-Sr isotopic system over volumes of a few cubic metres at the most, unless, of course, the "same age" and "same inital ratio" conditions are not satisfied for all the samples.

This scattered linear array of points on an isochron diagram resembles those typical of Proterozoic granulite-facies suites in Norway and might be explained by Rb depletion at few hundred million years after their intrusion (Mearns and Lappin, 1982).

This would tend to shift the points unevenly to the left producing an anomalously steep array giving a meaninglessly old apparent age. However, preliminary results for a U-Pb isotope study on zircons from garnetite veins in a pyroxenite indicate an age of about 1500 Ma. This is interpreted as the age of intrusion of the pyroxenites and thus provides a minimum age for the grey gneisses. Simple Rb depletion cannot account for the shallow slope of the array of points in figure 3.14. One must infer either incomplete homogenisation of Sr at very approximately 1200 Ma ago or preferential removal of ^{87}Sr. With the present evidence, either mechanism is equally plausible. As a result, the validity of any petrogenetic conclusions to be drawn for the low initial ratio must be viewed as somewhat dubious.

Tentative conclusions from this reconnaisance study are as follows:

Following intrusion of the grey gneiss precursors at least 1500 Ma ago, open system resetting of the Sr-isotope system occurred. Retention of the rather low ^{87}Sr/^{86}Sr initial ratio and the limited range of ^{87}Rb/^{86}Sr ratios may be due to prior Rb depletion or low primary Rb concentrations. Plausible model ages based upon an initial ratio of 0.704 range from 920 to 1495 Ma with other more extreme values coming from samples with the lowest ^{87}Rb/^{86}Sr ratios.

This is taken to indicate that the resetting occurred before the Caledonian orogeny and is likely to be of late Proterozoic Sveconorwegian age.

Pre-Sveconorwegian radiometric ages approaching 1500 Ma have been reported from a number of localities in the BGR, including mangerite-syenites and grey gneisses from Flatraket, Stadlandet (Lappin et al, 1979, Mearns and Lappin, 1982) and augen orthogneisses from the Molde peninsula (Harvey, in press). Sveconorwegian ages have also been derived from gneisses in the BGR. Brueckner (1979) interprets these as igneous rocks intrusive into an older (Svecofennian) basement. However, geochronological studies in the Southern Gneiss Region in western south Norway indicate that amphibolite and granulite-facies reworking of pre-existing basement and cover has occurred during the Sveconorwegian orogeny between 1200 and 950 Ma ago (see, for instance, Versteeve, 1975). Widespread open-system behaviour of Rb-Sr systems occurred at this time (Versteeve, 1975). This scenario is broadly consistent with the situation found in the Gjörlanger Unit grey gneisses. An Rb/Sr study of Jostedal Complex gneisses in the Gaular area to the west of Dalsfjord by Skjerlie and Pringle (1978) is geographically the closest to the Hellevik-Flekke area to date. Recalculation of their results with a Rb decay constant of 1.42×10^{-11} gives an age of 1510.8 +/- 97.0 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70300 +/- 0.00292, MSWD 12.48.

Their age was interpreted as a metamorphic age. However, there is some controversy as to whether this and other Rb-Sr ages from the BGR are more likely to represent slightly disturbed intrusion ages (Griffin and Krill, 1981). The reader is referred to Cuthbert et al. (1983, appended in this thesis) for a fuller discussion of this subject.

3.01.8 Summary and Discussion:

The geochemical investigations described above demonstrate that both the Gjörlanger Unit gneisses and the Basal Gneisses have a magmatic origin. The Gjörlanger Unit contains two petrographically and chemically distinguishable gneiss groups, both of which have calc-alkaline characteristics, varying from basaltic and dioritic types via granodiorites to alaskite granite. The Basal Gneisses are more aluminous and potassic but are also broadly calc-alkaline in character. They chemically resemble monzonitic and syenitic lithologies.

The Gjörlanger Unit gneisses show similarities with Cenozoic plutonic calc-alkali suites and have characteristics in common with some granodioritic charnockitic rocks, in particular, the type charnockites of the Madras area in India. By analogy with similar rocks whose tectonic environment is known, an origin for the Gjörlanger Unit grey and massive green gneisses by generation at a convergent plate margin is inferred.

The trace element chemistry indicates that an Andean-type plate junction rather than an oceanic island arc environment is a more likely tectonic setting. The basic chemistry of the least differentiated gneisses indicates that they have a dominantly mantle or oceanic crust derived parent magma. The K-poor gneisses seem to be analogous to primitive arc lithologies, with the more potassic grey and massive green gneisses being more evolved (Jakes and White, 1972 and Brown, 1981). These conclusions are in line with modern concepts of crustal growth and the origin of Archaean and Proterozoic grey gneiss suites (Brown, 1981; Barker et al, 1981 and Sleep and Windley, 1982).

The Basal Gneisses, with their potassic and aluminous nature, resemble the granitoids associated with the Proterozoic massif anorthosites (Emslie, 1973 and 1978). This suite of rocks is thought to have originated in an extensional tectonic environment similar to that in which the Hebridean province igneous suite and the Nigerian Younger Granites formed (Emslie, 1978). However, further sampling will be required to show whether an iron enrichment trend is present in the Basal Gneisses as this will make such an analogy more certain. Without this constraint their origin as highly evolved potassic members of a convergent plate margin calc-alkali suite analogous to the shoshonites (Jakes and White, 1972) cannot be entirely discounted.

Harvey (1983), while preferring an origin for the orthogneisses of the Molde peininsula as members of the anorthosite-mangerite-rapakivi granite suite, notes that they lack the iron enrichment trend characteristic of this suite. One might infer a highly evolved magmatic arc setting for the Molde rocks as well on this basis.

The Rb depleted nature of the gneisses has been discussed above. Should it transpire that large volumes of the BGC consist of lower crustal granulite-facies rocks depleted in radioactive heat-producing elements, this might have important consequences for the metamorphic development of this part of the Caledonian orogen. Firstly, rocks far removed from the mantle heat flux during orogenic crustal thickening would lack a significant radiogenic heat component and possibly maintain anomalously low temperatures whilst deeply buried. This will manifest itself in the resulting metamorphic mineralogy of the rocks. Secondly, removal of granitophile elements might retard migmatite development in the core of the orogen. This will only occur if extensive K and possibly Na depletion has occurred as in the Archaean grey gneisses but it does not seem to be the case here.

Both field and geochemical evidence support the contention that the grey and massive green, omphacite-bearing gneisses are contiguous and genetically linked.

The massive green gneisses are consistently more basic than the associated grey gneisses with higher CaO, total Feo, MgO and Na_2O and lower K_2O. The K-poor gneisses are also omphacite-bearing, but have rather low total FeO contents. Their Na_2O contents are similar to the massive green gneisses, however, and they have very low K_2O. The massive green gneisses have similar FeO/MgO ratios to the grey gneisses, but rather lower normative Ab/(Ab + An) ratios. It would seem that the bulk composition of the rocks has played a significant role in determining whether or not omphacite is stable relative to plagioclase. Finally, reconnaisance isotopic geochronological studies suggest that the Gjorlanger Unit gneiss precursors were intruded at least 1500 Ma ago and suffered disturbance of their Rb-Sr isotopic system at some time prior to the Caledonian orogeny.

Section 3.02

The Metabasites of the Gjorlanger Unit and the Basal Gneisses.

3.02.1 Introduction:

The field evidence presented in Chapter 2, demonstrates conclusively that many of the eclogites in this Unit were originally basaltic igneous intrusive rocks. Other studies of eclogites in the BGR have attempted to demonstrate geochemically that they had a protolith produced by magmatic fractionation at low pressures (Mysen and Heier, 1972; Bryhni et al, 1977; Krogh, 1980; Krogh and Brunfelt, 1981) or at high pressures (Smith, 1976). The field evidence from the Hellevik-Flekke area renders such a study somewhat superfluous. However, the chemical features of these eclogites are outlined below as the conclusions drawn from them might be applicable to similar rocks whose origins are less well constrained by field and petrographic evidence. Analyses and norms are presented in Tables 3.5 and 3.6.

3.02.2 Alteration:

Previous geochemical studies of metabasites have shown that they have frequently suffered chemical alteration and hence, do not closely approximate to their original compositions (Bryhni et al, 1969; Krogh, 1980; Krogh and Brunfelt, 1981; Liégeois and Duchesne, 1981 and Floyd and Winchester, 1983).

Before any consideration of the original chemical affinities of these rocks can be made, some evaluation of any alteration must be attempted.

Four samples from an eclogitic dyke by the track between Gjörlanger to Solvik were collected in a traverse across the intrusion, which is 1.5 m wide. The samples were D 80, D 81, D 82, and D 83. Their positions are marked on figure 2.37 and analyses appear in Tables 3.5 and 3.6. The dykes at this locality have been described in Chapter 2. The samples were collected to avoid areas where extensive mixing with the wallrock has occurred as far as possible. The upper margin (by D 80) is sharp, but has a very weak foliation defined by dark green barroisitic amphibole, whilst the lower margin (by D 83) is slightly more diffuse and a small amount of admixture of wallrock seems to have occurred. The rock is extensively retrograded to an extremely fine symplectite of pyroxene or amphibole and plagioclase, but common relics of omphacite and garnet attest to the earlier eclogitic nature of the rock. The margins show heavier amphibolitisation than the core, with more common overgrowth of poikiloblastic barroisitic amphibole over the symplectite and development of plagioclase collars around the garnets.

Profiles for concentrations of major and trace elements across this dyke are shown in figure 3.15. The composition of the adjacent tonalitic gneiss is also plotted for comparison.

Most elements show significant variation across the body. Variation might be ascribed to:

1. primary magmatic fractionation,
2. wallrock assimilation, or
3. metasomatic alteration during metamorphism.

The obvious increase in SiO_2 towards the lower margin can be ascribed to wallrock assimilation in view of the field observation suggesting minor hybridisation. Such an increase in SiO_2 may be expected to dilute the other major elements. The asymetrical depletion of Al_2O_3 and perhaps total FeO towards the margins might result from this. Evaluation of absolute depletion or enrichment of elements as opposed to relative movement is complicated by such "constant sum" effects. Bryhni et al (1969) attempted to get around this problem by using the Barth (1946) standard cell method where components are normalised to 160 oxygens. However, this method is invalidated where oxygen is mobile. Both water (combined as hydroxide ions in hydrous phases) and the oxidation ratio of iron vary across the body. It was, therefore, found preferable to present the raw analytical data in mass percent or ppm in figure 3.15 and to evaluate the patterns on the merits of all the other information available.

Two possible effects of magmatic differentiation might be possible. Simple fractionation during inwards consolidation of the dyke magma should produce increases in FeO/MgO, P_2O_5, alkali metals, Ba, Pb, Zr and possibly SiO_2 with concurrent decrease in MgO, TiO_2, Cr, Ni and V. Alternatively, concentration of phenocrysts in the centre of the dyke by flow differentiation should produce patterns recognisable as being related to plagioclase or one or more mafic phases. The slight enrichment of MgO and Ni and depletion of CaO and Y in the two inner samples favours concentration of olivine or orthopyroxene in the dyke core. However, the strong relative enrichment of alkalis, Ba, Sr and to some extent, Al_2O_3 mitigate against this. Even so, this may be a result of metasomatic migration discussed below. The rather constant concentrations of TiO_2, P_2O_5 and Zr suggest that strong fractional crystallisation has not occurred during consolidation of the dyke.

The relative depletion of K_2O, Na_2O, Sr, Rb, Ba and Pb at the dyke margins seem unlikely to be a result of simple magmatic wallrock assimilation as the adjacent gneiss has higher concentrations of all these elements than the dyke except for Na_2O. These elements are known to be mobile during hydrous amphibolite-facies metamorphism where rocks of contrasting composition are in juxtaposition (Floyd and Winchester, 1983). However, a curious feature of the example discussed here is the relative depletion of these elements adjacent to country rock in which they are much more enriched.

In most cases, eclogite margins have suffered relative enrichment of alkali and associated elements (Bryhni et al, 1969; Krogh, 1980 and Krogh and Brunfelt, 1981).

A factor touched upon in Section 3.01 was that the metamorphic history of a rock can have some effect on its bulk rock chemistry. Garnet and clinopyroxene, the main phases of which eclogites are comprised, can accommodate very little K, Rb, Sr and Ba and these would tend to be expelled from the rock in the presence of a carrying fluid. Petrographic observations show that micas co-exist with garnet and omphacite in many of the eclogites in this area and this may accommodate these phases in this case. However, the stability and relative quantity of mica depends upon the availability of other elements such as Al when in competition with garnet and omphacite. The eclogitised dykes by Gjörlangerfjord contain only accessory amounts of mica. Bryhni et al (1969) have noted that eclogites from the Nordfjord area in the BGR have rather low K_2O content and attribute this to the lack of suitable acceptor minerals in eclogite facies parageneses. This may well be the case in the rocks discussed here, but such a conclusion is apparently at odds with the inverse correlation between H_2O and the marginally depleted elements, which points towards their expulsion during the development of barroisitic amphibole.

A more "normal" alteration pattern is found in an eclogite from a roadside cutting on Route 57 by Breidvatnet within the Basal Gneisses. Samples 79/38a and 79/38b come from the rim and core of this body respectively. Sample 79/37 is representative of the country rock to this eclogite. The core consists of rather symplectised omphacite and phengite with garnets having marginal hornblende kelyphites. The margin consists of well foliated biotite-epidote-albite amphibolite with only relics of clinopyroxene and is similar to the "sheared margins" commonly found around eclogites in the BGR.

Examination of Tables 3.5 and 3.6 reveals that the margin is enriched in SiO_2, MnO, K_2O, H_2O, Ba, Rb and perhaps Pb relative to the core and depleted in MgO, Ni, Cr and V. The $Fe_2O_3/(Fe_2O_3 + FeO)$ ratio is higher in the margin. This example, therefore, differs from that by Gjörlangerfjord in that the country rock is significantly more alkalic, the margin has been more severely crystallised and it has apparently formed a lower grade mineral paragenesis. Potassium-related elements have been enriched in the margin of this body.

It is concluded from these observations that the marginal change in composition of these eclogites relative to their cause is controlled by a combination of wallrock composition and crystallisation history.

These will determine whether each co-existing assemblage will act as a source or a sink for elements which have become incompatible due to a change in mineral paragenesis. Strong tectonism of the Briedvatnet eclogite may have aided more complete retrogression so that new biotite could form at the expense of hornblende whereas the largely static retrogressive breakdown of the eclogitic parageneses in the Gjörlangerfjord dykes has allowed the retention of barroisitic amphibole (a poor accepter for potassium-related elements), the only biotite to form resulting from in situ breakdown of white mica. The tonalitic gneiss was also a poorer source of the mobile elements. The profiles seen in figure 3.15 might also conceivably result from imperfect mobility of K_2O, Na_2O, Ba, Sr, Rb and Pb during eclogite formation so that some remained in otherwise energetically unstable environments in the dyke core.

A pre-eclogite-facies contamination of the dyke margin during intrusion causing anatexis and assimilation of the wallrock is indicated by the evidence from Gjörlangerfjord. A further complication may be Rb depletion during granulite-facies metamorphism as discussed in Section 3.1.

An important observation here is that TiO_2, P_2O_5, and Zr all show flat profiles in both examples discussed above. These elements are often considered to be immobile (Pearce and Caan, 1973 and Floyd and Winchester, 1973, 1978 and 1983) and appear to be so here also. Y is also considered to be relatively immobile. This seems to be the case Briedvatnet eclogite, but the Gjörlangerfjord dyke has a 'V' shaped profile which cannot conclusively be proved to be unaltered. The similar marginal enrichment of CaO may indicate that the primary coherence of Y and CaO has been preserved and hence Y has remained immobile.

In summary, a combination of magmatic and metasomatic processes has altered the margins of the eclogites so that only the cores are likely to approach their protolith compositions. The potassium-related elements are apparently most affected and TiO_2, P_2O_5, Zr and perhaps Y, are virtually unaltered. Apart from the oxidation ratio of iron, the ferromagnesian elements show relatively small changes which might be metasomatic or due to igneous fractionation.

Krogh (1980) and Krogh and Brunfelt (1981) have discussed chemical mobility in eclogites from Kvineset, near Förde which have apparently suffered similar metamorphic conditions to those in the Hellevik-Flekke area. They conclude that primary igneous compositions have only been preserved in the cores of bodies in excess of 5 metres thick. In this case, one cannot assume that the composition of the cores of the bodies discussed above are representative of their protoliths, except perhaps for the "immobile elements".

3.02.3 General Chemical Characteristics:

Applying the chemical screen for basaltic compositions of Manson (1967) all the samples are basaltic, although the kyanite eclogite D 123 has a rather high Al_2O_3 content.

The samples cover a broad compositional range, but the rather small number of samples makes any systematic subdivision rather difficult. The following observations are of value, however;

The two kyanite eclogites (D 77 and D 123) are characterised by fairly high Al_2O_3, MgO/(MgO + FeO) and Ni. They are petrographically similar to eclogites from a large metabasic sheet lying between Ramsgrövatnet and Langevatnet to the south-west of the Hellevik-Flekke area. This sheet contains relics of layered plagioclase-rich rocks, the plagioclase now replaced by sugary pseudomorphs of zoisite, white mica and perhaps jadeitic pyroxene (this author, personal observations). Both the samples shown in Table 3.5 come from extensive sheet-like eclogite bodies. It would seem that the kyanite eclogites discussed here may have affinities with these, possibly having originated as plagioclase-rich cumulates. This is supported by their high normative plagioclase. Their rather high Ni and normative olivine contents may indicate that the precursors to these kyanite eclogites were olivine-rich. They show similarities with some of the meta-anorthositic troctolites of the Flekke Unit (Tables 3.14 and 3.15).

Samples D 1, D 103 and D 105 exemplify a group of quartz-bearing zoisite-white mica-garnet amphibolites (locally eclogitic) which show gradational relationships with the fine-grained foliated grey gneisses in the field. They are characterised by high SiO_2 and K_2O values along with high Zr and Ba relative to the other Gjörlanger Unit metabasites. Two of them are quartz normative. Sample D 134 from a basaltic dyke shares this chemical characteristics despite its different field setting and petrography.

Sample D 95, which comes from an extensive area of zoisite-rich garnet amphibolites is unique amongst the other metabasites in its combination of high Al_2O_3 and high Na_2O. It has a high $MgO/(MgO + FeO^T)$ ratio but low concentrations of ferromagnesian trace elements, Y and Zr.

The remainder of the metabasites of the Gjörlanger Unit are all olivine-normative and some are mildly nepheline normative. Their SiO_2 contents are similar to average values for olivine-normative basaltic rocks (Manson, 1967). They have fairly normal basaltic $MgO/(MgO + FeO^T)$ values. Their TiO_2 and P_2O_5 values are generally rather low and reminiscent of tholeiitic basalts rather than alkalic types. However, the dyke-like eclogite from Tyssekvam (sample D 46) has high TiO_2 and P_2O_5, more similar to alkalic basalts. Their Na_2O contents are generally rather high compared with average values for tholeiitic basalts (Manson, 1967) but their K_2O contents are low. Bryhni et al (1969) have noted the rather low K_2O contents of eclogites from the Nordfjord area. They concluded that this was not a primary feature, but was the result of metasomatic loss of K during eclogite-facies metamorphism. The evidence for alkali loss outlined in the previous section also indicates that alkali concentrations are likely to have been disturbed. This renders normative classification of the metabasites somewhat unreliable, particularly in view of their proximity to, and gradational nature with, the gneisses.

Compared with average trace element compositions for basaltic rocks (Prinz, 1967) this group has rather low Ni and Cr (except D 38), normal or high V, normal Y and low to normal Zr (perhaps more representative of tholeiites). Ba is highly variable, but rather low. Sr is also very variable, tending to be highest in the zoisite-bearing varieties and D 46, which is particularly enriched. Rb is very low in all the samples in this group, a feature which may result from Rb-depletion under granulite-facies conditions combined with further loss during eclogite-facies metamorphism as indicated in the previous secton.

Two types of eclogite can be differentiated from the Basal Gneisses on their petrographic and chemical features. D 69 is a bimineralic eclogite and is similar to the group described above. The remainder are phengite eclogites which differ significantly from the metabasites of the Gjörlanger Unit in their high TiO_2, K_2O and Rb (in the least altered samples), P_2O_5 and Zr. These features suggest affinities with alkali basaltic rocks (Manson, 1967 and Prinz, 1967).

Element variation diagrams employing the Larsen index as modified by Nockolds and Allen (1953) are presented in figure 3.16. Elements considered highly mobile have been excluded. In most cases, the Gjörlanger Unit metabasites fall close to the trend defined by the grey gneisses, particularly the more siliceous types (note that the trends were partly defined with the metabasic dyke samples). The kyanite eclogites often plot well away from the gneiss curve, particularly for some of the ferromagnesian elements (TiO_2, FeO, Ni and V). The likelihood that the kyanite eclogites were cumulate rocks may explain this anomaly. The spread in the values for Al_2O_3 may also be a result of accumulation, in this case of plagioclase. Sample D 129 also frequently falls away from the gneiss trend. This lithology shows gradational relationships with the grey gneisses, but is banded (figure 2.59) and may also be cumulative.

The phengite eclogites from the Basal Gneisses are often distinctive in these diagrams, having lower Al_2O_3 and SiO_2 and higher TiO_2, FeO, P_2O_5, Ni and Zr than the Gjörlanger Unit metabasites, in general.

It would, therefore, appear that the metabasites of the Gjörlanger Unit are either plagioclase-rich cumulates or are chemically related to the grey and massive green gneisses. The phengite eclogites from the Basal Gneisses form another group, but the bimineralic eclogite (D 69) seems to be more closely related to the Gjörlanger Unit types.

As some of the Gjörlanger Unit metabasites fall close to the trend for the gneisses, their common origin by magmatic fractionation seems likely. However, the apparent mixing of amphibolitic or eclogitic and gneissic material seen in the field may indicate that some of the more mafic gneisses have been produced by hybridisation. Evidence for this on a small scale has been discussed in relation to the dyke by Gjörlangerfjord, where some marginal anatexis seems to have occurred. The relatively large volume of mafic gneisses compared to that of dykes, sheets and pods of metabasites makes large-scale hybridisation seem unlikely. In view of this it is considered that the metabasites mostly have a common magmatic origin with the gneisses and that hybridisation is restricted to small volumes of rock in the proximity of basic intrusives.

3.02.4 Chemical Affinities:

Standard methods used for the chemical classification of basaltic rocks often employ alkali contents in discrimination diagrams (Kuno, 1960 and Irvine and

Baragar, 1971). The evidence outlined above for alkali mobility renders these methods of little value in the characterisation of the metabasites discussed here. However, the apparent low mobility of Ti, P, Zr and Y makes these elements more promising indicators of the chemical affinities of these rocks. These so called "immobile elements" are commonly used for discriminative purposes and are employed in this section. Rocks considered to be cumulative are excluded from this discussion.

Pearce and Cann (1973) have used the Y/Nb ratio to ascertain whether basic rocks are alkaline or tholeiitic. Tholeiitic types are thought to have Y/Nb greater than 1.0, alkali rocks less than 1.0. All the metabasites have Y/Nb greater than 1.0 (Table 3.5) except D 123, which is thought to be cumulative. Floyd and Winchester (1975 and 1976) have combined the Y/Nb ratio in a diagram with TiO_2 with the divider at Y/Nb at 1.0. On this diagram (figure 3.17A) all the samples fall in the tholeiite field, including a phengite eclogite from the Basal Gneisses. Most of the samples form a horizontal trend which is characteristic of oceanic tholeiites. This is clearly at variance with their geological setting within sialic country rocks. Inspection of Table 3.6 reveals that the concentrations of Nb in the metabasites are very low, often near the detection limit of the analytical method. Hence, relatively small variations or errors in Nb values are likely to produce large variations in the Y/Nb ratio. Note that four of the metabasic dyke samples (from the same intrusion) are responsible for much of the spread of data along the trend.

Discriminant diagrams for P_2O_5 versus Zr, TiO_2 versus Zr, TiO_2 versus Zr/P_2O_5 and Nb/Y versus Zr/P_2O_5 (Floyd and Winchester, 1975 and 1976) are also presented in figure 3.17. A predominantly tholeiitic character is apparent for all the rocks except some of the phengite eclogites from the Basal Gneisses, which seem to be mildly alkaline. The low Nb/Y ratios in figure 3.17E of many of the metabasites indicate a continental environment (Floyd and Winchester, 1975). The dyke in the pyroxenite at Tyssekvam (D 46) seem to have rather aberrent chemical characteristics and usually falls outside the fields for the various basalt types in the Floyd and Winchester diagram. Its high TiO_2 and P_2O_5 suggest alkaline affinities, but its Zr content is unusually low.

The use of discriminant diagrams for elucidating tectonic setting for these rocks is instructive, but of little positive value. The method employed here is that of Pearce and Cann (1973), as shown in figure 3.18. In the Ti-Zr-Y diagram (figure 3.18A) most of the points fall in the overlapping fields of calc-alkali basalt, ocean-floor basalt and low-K tholeiite, in other words on the Y-rich side of the critical divider between the within-plate basalts and other types. Samples falling outside the delineated fields have more extreme concentrations of Ti, Zr or Y. Further discrimination on the Tr-Zr diagram (figure 3.18B) seems to indicate affinities with the ocean-floor basalts, although the samples fall near the periphery of this field. The phengite eclogites from the Basal Gneisses have rather high values of both Ti and Zr and fall outside the delineated compositional fields.

Due to the small number of samples no great significance can be attached to the results on the Pearce and Cann (1973) diagrams. Furthermore, the results are obviously anomalous as in most cases the field relationships clearly show that the metabasites are not ocean-floor basalts. Bryhni et al (1979) have pointed out that the major element chemistry of eclogites from the Nordfjord area resembles that of abyssal tholeiites although some of the features (for instance, low K_2O) may be secondary and they do not have the consistency of composition of such basalts.

Plausible demonstration that eclogites in gneisses with tectonised margins have oceanic affinities may be a powerful argument in favour of their exotic origin. However, the apparently oceanic chemistry of the Gjörlanger Unit metabasites, many of which are demonstrably not exotic, sheds doubt on the validity of such discriminative methods. Some obviously continental basalts are known to have trace-element chemistry similar to abyssal tholeiites (Floyd and Winchester, 1975 and Pearce et al, 1975) as do some amphibolites and eclogites from the Seve Nappe (Solyom et al, 1975 and Van

Roermund, in press) and are thought to have been emplaced during rifting of continents prior to the opening of oceanic basins. However, recent work by Zeck and Morthorst (1982) even sheds doubt on this conclusion and they recommend the use of the TiO_2-K_2O-P_2O_5 diagram of Pearce et al (1975). Alkali mobility renders this diagram inapplicable for eclogites of small volume and it is not used here. It would seem that the Pearce and Cann diagrams should be used only with extreme caution on tectonised "country-rock" eclogites and corroborating evidence from field work should be used to back up the results of such geochemical studies.

3.02.5 Summary and Discussion:

The original chemistry of the metabasites has been altered by interactions with their country-rocks during emplacement as magmatic intrusions, during eclogite-facies metamorphism or early retrogression and, in some cases, during strong recrystallisation and retrogressive metamorphism. Modification during granulite-facies metamorphism may have occurred also (by analogy with the grey gneisses). Hybridisation is thought to be limited to small volumes of rock near the metabasites. The potassium-related elements have been most severely effected. TiO_2, P_2O_5, V, Zr and perhaps Y, have been little effected. Such alteration severely limits the applicability of standard methods of chemical classification.

"Immobile element" patterns indicate that the Gjörlanger Unit metabasites have tholeiitic characteristics despite being of nepheline-normative nature. The kyanite eclogites seem to have been plagioclase-rich cumulates while the rest show a relationship with the grey and massive green gneisses. The rather sodic and aluminous amphibolite from north of Jyttevatnet (D 95) stands apart from the other metabasites. It might conceivably be a basic member of the low-K gneiss group. The dyke-like eclogite from within the pyroxenite at Tyssekvam has rather curious chemistry. Its high TiO_2, Na_2O, P_2O_5 and Sr suggest alkaline affinities (c.f. Prinz, 1967) although this is at variance with its low K_2O and Zr. It does not appear to be related to the other dyke rocks in this Unit.

The Basal Gneiss phengite eclogites are more alkalic in nature than those of the Gjörlanger Unit, although their Y/Nb ratio suggests that they are tholeiitic.

Commonly used discrimination diagrams for tectonic setting determination give apparently meaningless results. A larger sample population might improve the validity of the results, particularly in the Ti-Zr diagram. The likelihood that the metabasites were consanguinous with the calc-alkali gneisses suggests that they may have originated at a convergent plate margin. It is interesting, in this respect, that most of the specimens from the Gjörlanger Unit lie outside the "within-plate" field and in the fields for plate-margin basalts on figure 3.18A. A useful line of further research would be to locate further dyke-like metabasites from correlatives of the Gjörlanger Unit. A larger sample population from such dykes which may represent liquid compositions might allow more rigorous treatment of their chemistry and provide some insight as to the nature of the parent material of the grey and massive green gneisses.

Griffin and Mörk (1981) have shown that the Sunnfjord eclogites are generally alkaline in nature whereas those further north are tholeiitic (c.f. Bryhni et al, 1969). The Sunnfjord eclogites such as those near Naustdal tend to have rather high TiO_2, P_2O_5 and Zr and low SiO_2 and have "within-plate" characteristics (Krogh, 1980 and Korneliussen, personal communication, 1981). The Basal Gneiss phengite eclogites seem to resemble these. Chemically similar metabasites are found elsewhere in Scandanavian gneiss terrains, including Lofoten (Misra and Griffin, 1972) and Southern Norway (Gjelsvik, 1950, Table 9). The Gjörlanger Unit metabasites show a resemblance to some of those from basement windows in the Caledonides of Central Norway and Sweden including the Olden II metabasites and the Central Scandanavian Dolerite Group (Johansson, 1980). They have similar immobile element patterns, including very low Nb contents. Their age (1200 Ma) appears to be somewhat younger than Gjörlanger Unit metabasites, assuming that the latter were roughly contemporaneous with the gneisses.

Section 3.03

The Webserites in the Gjörlanger Unit.

Major element analyses and CIPW norms for these rocks are presented in Table 3.7, trace elements in Table 3.8. The norms reflect the dominant effect of pyroxenes on their composition. The petrographic evidence for the presence of chrome-spinel and pleonaste may indicate that the anorthite component of the norm is exagerated with respect to their real primary mineralogy and hence the diopside component is correspondingly low in some samples.

Most of the samples do not have true basaltic compositions. They are characterised by low aluminium and alkalis and high MgO and CaO. These features clearly differentiate them from the metabasites, which also have lower MgO/(MgO + FeO) values than the websterites. A sample from the eastern shore of Tyssedalsvatnet (D 40) has an extreme value for Al_2O_3, apparently due to a rather high proportion of plagioclase, but it shares the other characteristics of the websterite suite.

The websterites also have much higher concentrations of Ni and Cr than the metabasites, probably reflecting higher contents of orthopyroxene and clinopyroxene, as well as spinel, in their protoliths. They have lower TiO_2, V and Zr, although the high Zr values found in some samples may be a result of contamination from the country-rocks as shown by the garnetite veins.

Websteritic lithologies are known from elsewhere in the BGR. They usually have well crystalised eclogite-facies mineralogies in contrast to those described here, which retain relics of igneous assemblages in various stages of recrystalisation. They occur as layers and lenses in peridotites, associated with garnet lherzolites ("internal eclogites" - Carswell, 1968a, b, 1973, 1981; Carswell and Gibb, 1980; Carswell et al., in preparation; Eskola, 1921; Medaris, 1980, 1983 and Schmitt, 1964) and as bodies enclosed by gneisses ("external" orthopyroxene eclogites - Lappin and Smith, 1978 and Carswell et al., in press).

The "internal eclogites" are of two types which correspond to the subdivision of their host peridotites as described by Carswell et al. (in preparation). One type is relatively rich in Mg and Cr and is associated with olivine-rich "alpine-type" peridotites. The other is relatively Fe and Ti rich and interlayered with olivine noritic rocks of possible cumulate origin.

Compositional fields for Mg-Cr and Fe-Ti peridotites and associated pyroxenites are shown in figure 3.19. The Gjörlanger Unit websterites transgress both these fields and the gaps between them, but show a closer similarity to the Mg-Cr type (the websterite analyses in these diagrams come from Table 3.4 but are supplemented by some kindly supplied by A Korneliussen of NGU, Trondheim).

A closer examination, however, reveals that the Mg-Cr pyroxenites contain less TiO_2, K_2O and total Feo and more Al_2O_3 and MgO than the Gjörlanger Unit websterites. They also have a higher MgO/(MgO + FeO^t) ratio. In contrast, the Fe-Ti type pyroxenites have more TiO_2, total FeO and Na_2O, and less CaO, but similar MgO/(MgO + FeO^t).

The "external" orthopyroxene eclogites are more similar to the Gjörlanger Unit websterites, both chemically and in that they are associated with gneisses rather than peridotites. Compositions of a number of orthopyroxene eclogites are plotted on figures 3.19 and 3.20. In figure 3.19, the two groups show some overlap, but the orthopyroxene eclogites extend to lower MgO/(MgO + FeO^T) ratios. In figure 3.20, despite considerable scatter, the two groups overlap, especially between 17% and 20% MgO, although the orthopyroxene eclogites tend to contain more total FeO and TiO_2 and their range of Al_2O_3 does not extend as low as the Gjörlanger Unit websterites.

Pyroxenites also occur in ultrabasic layers in the pyroxene-gneisses of the Jotunheimen (Battey and McRitchie, 1975). They usually form the margins to olivine-rich bodies and are dominated by clinopyroxene. They contain more olivine and less orthopyroxene than the Gjörlanger Unit websterites and appear to be more calcic. These features along with the lack of olivine-rich rocks in direct association with the websterites discovered here dictate that these two groups are probably unrelated. Pyroxenites also occur associated with the mangerites of the Bergen Arcs (Austrheim, 1978) but they are alkaline in nature.

In short, the Gjörlanger Unit websterites most closely resemble some of the orthopyroxene eclogites of the BGR, but they are by no means identical. The origins of the orthopyroxene eclogites are rather obscure. They have a wide range of composition and are, therefore, likely to have diverse origins. The extent of contamination by the country rock has not been evaluated for all the analyses in the compilation used in figures 3.19 and 3.20, although Rb-Sr isotopic studies by Griffin and Brueckner (1982) show that these eclogites have suffered extensive interaction with the gneisses. Carswell et al. (1983) suggest that they represent cumulates of igneous pyroxenes. The existence of apparently igneous websterites in the Hellevik-Flekke area may give some credance to this hypothesis and presents the intriguing possibility that at least some of the orthopyroxene eclogites had protoliths similar to the websterites described here. Unequivocal evidence for cumulate textures or structures has not been found in the websterite, indeed granoblastic textures in the least altered varieties indicate metamorphic recrystallisation. The presence of fine-grained dyke-like websterite sheets which are chemically and mineralogically virtually identical to their coarser grained hoster rocks (for instance, at Eikeskog, specimens D 13 and D14) indicates that these rocks have crystallised from liquids of similar composition. This does not rule out the possibility that some of the websterites are cumulative, however.

The association of garnet-rich veins with the websterites has been mentioned in Chapter 2. Regrettably, successful major element analyses of the veins from the body to the east of Gjörlanger (figure 2.52) were not achieved, but trace element analyses are presented in Table 3.8. A complete analysis of a mica-garnet vein from near Gjörlangerfjord (D 174) is also presented. The differing mineralogies and compositions correspond to differences in the adjacent country rocks. D 174 was taken from an outcrop adjacent to grey gneiss and probably represents an admixture of a low melting fraction of this country rock with the websterite parent magma (this may also explain the rather high K_2O content of the host as found in specimen D 66). The lack of mica and abundance of pyroxene and zoisite in the example from east of Gjörlanger shown in figure 2.52 (79/11E) may be due to the assimilation of the more basic (now eclogitic) country rock, now exposed at the eastern end of the outcrop.

High abundance of Zr in the veins is puzzling. An origin by melting and redistribution of zircon is unlikely as zircon is highly refractory, with a melting point at 1676_{oC} (Bayer et al, 1978). Such temperatures would induce large amounts of melting of the country rock and thus inhibit relative concentration of zirconium in the veins. Also, the country rock near the garnet-pyroxene-zoisite-rich veins contains less zircon (from petrographic observations) than the gneisses adjacent to the garnet-rich veins, but the latter contain less zirconium.

The process preferred here for the concentration of zirconium in the veins involves a kind of zone-refining. Prolonged residence of a partial melt fraction resulting from anatexis of the country rock adjacent to the intrusive websterite might result in a reaction concentrating disbursed Zr from residual phases (eg, pyroxene or perhaps mica) in the melt. This is likely as Zr is highly magmatophile (Liégeois and Duchesne, 1981). The process may have been aided by high concentrations of alkalis in the melt in the case of the garnet-mica veins, as zirconium is known to be more mobile in alkaline environments (Bayer et al, 1978).

The anatexis hypothesis is supported by the following points:

1. Close association of the veins with the margins of the websterite bodies (indicating a source in the country rock).
2. The high concentrations of Zr in the veins relative to the host rock (suggesting that Zr has been introduced in the veins).

3. The inclusion of the zircons in all other phases (indicating that they were introduced at least prior to the present metamorphic assemblage).
4. The prismatic, euhedral habit of the zircon cores (indicating a magmatic origin for them).

Section 3.04 The Flekke Unit

3.04.1 Introduction:

Evidence from field work and petrographic studies has been presented in Chapter 2 to show that the metabasites and metaperidotites found in the Flekke Unit form a complex of basic or ultrabasic rocks of cumulate origin. Gradational relationships and interbanding indicate that the metabasites and metaperidotites are genetically related (Section 2.03).

Geochemical treatment of metamorphosed accumulative rocks is difficult for three reasons:-

1. The rocks do not represent liquid compositions, but crystal accumulations from perhaps several compositionally and thermally different locations in an evolving magma body. Evaluation of liquid lines of descent therefore require more indirect methods.

2. The primary mineralogy has, in most cases, been obliterated so that reconstruction of the detailed cyrstallisation history of a body of magma and estimation of modal igneous composition is very difficult if not impossible.

3. Tectonic disruption and, in this case, poor

3. (cont'd)

continuity of exposure prevent estimation of the volumes of different cumulate rocks.

As a result, the conclusions drawn here are, to a great extent, based on analogies with well known layered intrusions elsewhere.

The peridotites and associated metabasites will first be described and compared with other peridotites in the Scandinavian Caledonides. This will be followed by a description of the meta-anorthositic troctolites, gabbros and related rocks prior to attempting to reconstruct a unifying picture for the unit as a whole.

3.04.2 The Meta-peridotites:

Major element analyses and norms for the metaperidotites are set out in Table 3.8 and trace element analyses in Table 3.9.

The metaperidotites vary from dunites to chlorite peridotites, both of which only rarely contain calcic phases. Common mineralogical varieties are dunites, chlorite-dunites, chlorite-harzburgites and chlorite-orthopyroxenites. Truely lherzolitic varieties are absent. They are frequently characterised by abundant Fe-Ti oxides (Section 2.03). In Tables 3.9 and 3.10, they are subdivided into dunites and chlorite-peridotites, but there is a gradation between the two types. The dunites occur both structurally below the main mass of meta-anorthositic troctolites and gabbros of the Flekke Unit and structurally above them. The latter form meter-size pods in chloritic schists and amphibolites or eclogites or as layers gradational with chlorite-harzburgites whilst the former make up mapable units several hundred metres in length and tens of metres thick (Section 2.03 and Figure 2.01).

The dunitic rocks from low in the unit can be differentiated from those higher in it by their higher CaO, $MgO/(MgO + FeO^T)$ and Ni and lower total FeO, P_2O_5 and MnO as exemplified by specimens D111 and D130. These come from the dunite unit which traverses the northern slopes of Haheia near Storetjörna (Figure 2.01), which is characterised by small amounts of tremolitic amphibole. Tremolite is also found in the large dunitic body to the north of Svartetjörna (specimen D128), which also lies low in the Flekke Unit (Figure 2.00). This sample is not so well differentiated from the other dunites in Tables 3.9 and 3.10 however.

Unlike those low in the Flekke Unit, the metaperidotites lying above the meta-anorthositic troctolites are frequently chlorite-rich, often contain prismatic orthopyroxene and abundant oxide, lack tremolite and characteristically contain small bands and pods of a variety of metabasites (Section 2.03 and 3.4.3). Their mineralogy is, at first glance, belied by their chemistry (Tables 3.9 and 3.10). They have rather low SiO_2 for harzburgites. However, they have a high $Fe_2O_3/(FeO + Fe_2O_3)$ ratio which is reflected in their oxide-rich mineralogy. It seems that the iron has been taken up in ilmenite and magnetite, releasing more SiO_2 for the formation of orthopyroxene rather than olivine. This has also produced the high normative hypersthene values in Table 3.9. The chloritic nature of the rocks is at odds with their low Al_2O_3 contents, but the chlorites are, in fact, low alumina types (see Chapter 4) and the presence of oxides has probably concentrated the amount of aluminium relative to the remaining iron available for silicate phases. All of the chlorite-peridotites as well as some of the dunites are corundum-normative, possibly indicating the previous presence of spinel or highly aluminous orthopyroxene. The low Na_2O, CaO and normative plagioclase contents indicate a lack of primary plagioclase, calcic pyroxene or calcic amphibole. However, the evidence for Ca-metasomatism (Section 3.04.3, below) sheds some uncertainty on this conclusion.

Qvale and Stigh (in press) have classified the ultramafites of the Scandanavian Caledonides into five categories, which are:-

1. layers and lenses within basic intrusions,
2. high temperature ultramafic intrusions,
3. ultramafic nodules or xenoliths,
4. "Alpine-type" ultramafites and,
5. detrital serpentinites.

The "Alpine-type" peridotites are defined as "bodies of ultramafic rocks which form essentially conformable lens-like or tabular masses of varying size within metamorphosed host rocks" (from Moore and Qvale, 1977).

Metaperidotites described in this Section might be classified in both types 1 and 4 above.

Qvale and Stigh superimposed a further, chemically based classification upon this, dividing them into a high-Al and a low-Al group. The high-Al group includes rocks thought to be cumulates, including layers and lenses from basic intrusions, high-Al "Alpine-type" peridotites and ultramafic nodules, whilst the low-Al group (described as "depleted") includes high-T ultramafic intrusions and low-Al "Alpine-type" peridotites. The general chemical features of these groups are outlined in Table 3.11.

Comparison of the analyses in Tables 3.9 and 3.10 with the averages of Qvale and Stigh (in press) in Table 3.11 reveals no consistent similarity. The low-Al harzburgitic-to-dunitic nature of the Flekke Unit metaperidotites suggests affinities with group 4a of Qvale and Stigh (in press), but the latter have much higher Ni, Cr and MgO/(MgO + FeO^T) and lower TiO_2. In general, they are less aluminous, calcic and alkaline and more titaniferous and ferriferous than all of Qvale and Stigh's groups, apparently reflecting smaller contributions of calcic pyroxene, plagioclase and perhaps in the case of group 4b, garnet. Ilmenite and magnetite seem to have played a more significant role in the Flekke Unit metaperidotites, particularly in the chlorite-harzburgites. More calcic, aluminous and alkaline rocks appear to be restricted to metabasic pods and bands within the chlorite-harzburgites (Tables 3.9 and 3.10). It is possible that the wide compositional variability in Qvale and Stigh's (in press) group 1 may conceal similarities to some of the Flekke Unit peridotites in some cases.

The subdivision of garnetiferous metaperidotites in the BGR into relatively Mg-Cr rich and Fe-Ti rich groups by Carswell et al. (1983) has already been mentioned in Section 3.03. The latter type is generally associated with layered basic/ultrabasic complexes (for instance, the Eiksundal Complex, Schmitt, 1964) and anorthosites. Broadly speaking, these features are shared by the Flekke Unit metaperidotites, but detailed examination of their compositions shows that the garnetiferous peridotites are (by definition) more aluminous and calcic and also less siliceous and alkalic. It would appear that low alumina harzburgites and dunites are conspicuous by their absence in the Fe-Ti association (Carswell, personal communication, 1983). The Flekke Unit metaperidotites have higher FeO, Fe_2O_3 and V than the Fe-Ti type, lower $MgO/(MgO + FeO^T)$, but similar Ni and $Fe_2O_3/(FeO + Fe_2O_3)$. Both types have higher P_2O_5 than the Mg-Cr type peridotites. The Flekke Unit metaperidotites have significantly lower Sr than the

Fe-Ti type.

In conclusion, the Flekke Unit metaperidotites bear closest similarities to the Fe-Ti type peridotites of Carswell et al. (in press) both in their chemistry and field association. However, their combination of high iron and titanium and low aluminium, with no lherzolitic varieties, appears to be unique in the BGR. Descriptions of ultramafic rocks from the southern part of the BGR are distinctly lacking in the literature although serpentinites appear to be quite common (Holtedahl and Dons, 1960 and Bryhni, 1966). More detailed studies may reveal further examples of the Flekke Unit type.

3.4.3 Metabasites associates with Metaperidotites:

It will be recalled from Chapter 2 that metabasites occur as pods and bands within the peridotites of the Flekke Unit. They are common in the chlorite peridotites at Flekke and near Solvik, which lie structurally above the meta-anorthositic troctolites (Section 2.03 and 3.4.4) but are absent in the dunitic horizon which lies below them (Figure 2.00). They are mineralogically and chemically diverse, but have features which distinguish them from the main mass of metabasites in the Flekke Unit (Section 3.4.4) or any of the other metabasites in the Hellevik-Flekke area. The occurrence of these metabasites only in the chlorite peridotites is unlikely to be purely fortuitous and on this basis they are considered to be autochthonous with respect to their present day host rocks.

Two types of metabasite can be differentiated which are:

1. A diverse group of garnetiferous amphibolites or eclogites, often rich in chlorite and/or apatite and/or zircon and
2. a group of calc-silicate rich rocks (zoisitites or garnetites) with conspicuous chloritic reaction zones ("blackwalls") against their host peridotites.

Group 1 is exemplified by examples D12 (a zirconiferous eclogite), D118 (an ilmenite + apatite + zircon-rich amphibolitised eclogite) and D148 (a chlorite-garnet amphibolite). Petrographic descriptions for D12 and D118 can be found in Section 2.03.4. D148 is petrographically similar to Specimen D34 from near Solvik (Section 2.3.3) but contains much less apatite and zircon. All three samples have low $MgO/(MgO + FeO^T)$ ratios, D12 and D118 have high TiO_2 and very high P_2O_5, Zr, Y and Nb contents. D12 has high normative Ab/(An + Ab), whereas D118 and D148 have very low Ab/(An + Ab). Whether this reflects the original plagioclase composition, is an artifact produced by original highly tschermakitic pyroxene or spinel or due to Ca-metasomatism is uncertain. Their normative plagioclase composition is significantly more anorthitic than that of the underlying meta-anorthositic troctolites and gabbros despite having lower $MgO/(MgO + FeO^T)$.

The presence of metabasites of apparent cumulate nature with high concentrations of zirconium, phosphorous and titanium indicates that the peridotites within which they occur were crystallising from a liquid saturated in zircon, apatite and ilmenite components. Their low $MgO/(MgO + FeO^T)$ ratios indicate that the mafic cumulate phases were quite iron-rich.

The group 2 metabasites comprise the common zoisitite or garnetite pods and bands found in the Flekke area. Analyses for specimens from a zoisitite, its host dunite and the intervening blackwall reaction zones are presented in Tables 3.9 and 3.10 (samples D140A-C, D141A, B) and reproduced in diagramatic form in Figure 3.21. The reader is referred to Chapter 2 for petrographic descriptions of this specimen.

The most notable feature of the zoisitite core of the body is its low SiO_2 and alkalis and high CaO and H_2O contents. These are significantly different from those in the type 1 metabasites in the peridotites or those in any other host rocks in the Hellevik-Flekke area.

The garnet + hornblende zone contains significant amounts of clinozoisite or epidote, usually as inclusions. It is, therefore, assumed that the original margin of the zoisitite abutted against the present chloritic blackwall, where no further epidote is found. Petrographic evidence indicates that the garnet has in MgO and FeO in this inner reaction zone. The MgO and FeO contents must have their source in the adjacent blackwall or the host peridotite. Completion of this process produces the commonly observed pink garnetite pods found in the peridotites which may be analogous to the eclogitic metarodingites of the Central Alps described by Evans et al. (1979) and Evans et al. (1981). The garnetisation process seems to be similar to that envisaged for the development of garnet in the coronitic eclogites (see Chapter 4). The small increase in Na_2O in the garnet + hornblende zone is more difficult to explain as the rocks on either side contain less Na_2O. A source in the present zoisitite core seems likely in view of the conclusions to be drawn below.

As the original edge of the zoisitite was probably located at the edge of the chloritic blackwall, it seems that the latter was formed by alteration of the peridotite next to the contact. This then must have involved introduction of CaO and H_2O and perhaps SiO_2, the change in FeO and MgO being due to dilution. The adjacent anthophylite zone is considerably enriched in SiO_2. The observed breakdown of anthophylite to talc + olivine requires subsequent addition of more water approximately according to the reaction:

5 anthophylite + 4 H_2O = 9 talc + 4 olivine

The association of calc-silicate rocks with low SiO_2 and high CaO and H_2O with chloritic blackwall rims in serpentinised peridotites is typical of rodingites. It is now well established that rodingites and similar rocks are produced by calcium metasomatism associated with serpentinisation of peridotites (Coleman, 1967; Leach and Roberts, 1978 and Evans, 1977). The metasomatism is thought to occur when alkaline, CO_2-poor solutions release Ca, Al and Mg from the peridotite. These ions invade mafic bodies in the developing serpentinite and progressively replace their primary mineralogy with hydrous calc-silicates such as prehnite and hydrogrossular, also producing chlorite and diopside in the adjacent serpentinite. Release of Si from the mafic bodies is supposed to enhance further serpentinisation. The relative concentration of SiO_2 in the anthophylite zone of the example described above may have its source in the Si depleted zoisitite.

The zoisitite is rich in Al_2O_3 compared with known rodingites (see, for instance, Coleman, 1967, Table 2). This may be simply due to a different pre-metasomatic bulk composition. An origin as a plagioclase-rich cumulate would not be inconsistent with evidence from other metabasites in the Flekke Unit. It might be argued that the zoisitites were originally masses of very anorthitic plagioclase, but their composition would still require further addition of Ca and removal of Si to satisfy their present condition.

The extreme concentration of Sr and the rather high Pb value (Table 3.10) are notable features of the zoisitites. Evans et al. (1981) found that no appreciable coherence between Sr and Ca associated with the formation of rodingites exists in the Central Alps. Enrichment in Sr may require a source of Sr in the host peridotite and a suitable acceptor mineral in the developing rodingite. Zoisite would be a good acceptor for both Sr and Pb. Its formation during Ca-metasomatism is favoured by intermediate Ca activity at high Al_2O_3 and low SiO_2 activities, when it forms in preference to prehnite or hydrogarnet (Coleman, 1967). The source may be plagioclase or apatite in the peridotite, although the phosphorous is thought to be stable during Ca-metasomatism (Evans et al., 1979, Evans et al., 1981) and plagioclase might be expected to act as a sink rather than a source during this process. The possibility that the high Sr content is primary and simply related to a calcic plagioclase is not discounted here, but none of the other metabasites in the Flekke Unit which have been analysed have such extreme Sr values (Tables 3.9, 3.13 and 3.15).

It is, therefore, concluded that the zoisitites and associated garnetites and chloritic reaction zones are the result of two processes:

1. Ca-metasomatism associated with serpentinisation of the host peridotites, followed by;

2. Garnetisation (marginal or complete) during subsequent high-grade metamorphism. Local preservation of diopside-plagioclase symplectites indicate that this may have been an eclogite-facies event.

"Rodingitisation" and serpentinisation are thought to occur at low temperatures (less than 450°C) and low pressures (less than 4 Kbars?) (Coleman, 1967 and Leach and Rogers, 1978). This implies that a very low temperature and low pressure regime prevailed prior to the latest high-grade metamorphism in the rocks of the Hellevik-Flekke area, in a region with a considerable source of water. The present generation of serpentine found in the metaperidotites is not thought to be related to this metasomatism, but is more likely to be a result of late metamorphic retrogression. The features outlined above suggest a high crustal environment.

Evans (1977) commented that metarodingites may have gone largely unnoticed in regional metamorphic terrains. Further recognition of such metasomatites in the BGR would have important consequences for the geological history of this area. Brastad (in press) has recognised similar rocks at an anorthosite-serpentinite contact at Björkedalen near Nordfjord.

This author has noted the presence of sugary, zoisite-rich rocks adjacent to chlorite-harzburgites near Solvik. They are on the margin of the Vardheia Unit quartzo-feldspathic gneisses, into which the zoisite rich rocks pass. These rocks were not sampled, but if as seems likely, they too have suffered Ca-metasomatism, this provides corroborative evidence that the Flekke Unit was in contact with the Vardheia Unit prior to the last high-grade metamorphism. Finally, Ca-metasomatism may explain why the peridotites have such low Ca (and Al) contents as this process tends to remove Ca held in pyroxenes. It may be that the chlorite harzburgites were originally more lherzolitic than they are at present. However, a large volume of peridotite in relation to the metabasites means that even with a small percentage of Ca they could effectively metasomatise any enclosed basic rocks.

3.4.4 Meta-anorthositic Troctolites and Metagabbros:

As described in Section 2.03 and Figure 2.00 these rocks form the bulk of the Flekke Unit, lying either directly above the Gjörlanger Unit gneisses or the intervening basal dunite and below the chlorite-peridotites and their associated metabasites. Two textural varieties are observed:

1. Coronitic or pseudomorphic, apparently mimicking coarse grained cumulate rocks and,
2. Foliated garnet amphibolites and eclogites. Locally the two types are gradational, type 2 being formed by deformation of type 1. Analyses are presented in Tables 3.12, 3.13, 3.14 and 3.15. Where igneous

mineralogies have been preserved in these rocks they prove to be anorthositic troctolite (leucotroctolite) mesocumulates (Section 2.03.2). Due to the problems outlined in Section 3.04.1 as well as the absence of unequivocal genetically related rocks which approximate to liquid compositions it is difficult to infer the nature of the magma from which they crystallised. However, the presence of rims of orthopyroxene around cumulus olivine (Figure 2.09) indicates that the parent magma was tholeiitic. Electron microprobe analyses of cumulus olivine and plagioclase (Table 3.16) give compositions of Fo_{69} and An_{60} respectively. Whole rock analyses of the igneous samples show high MgO/(MgO + FeO) and low Ab/(Ab + An) ratios compared to those with metamorphic mineralogies and are therefore considered to be earlier cumulates. Their olivine and plagioclase compositions are consistent with precipitation from, and at least partial equilibration with, a basaltic magma. Their cumulus mineral compositions more closely resemble those of the early precipitates of layered troctolitic intrusions (for instance, Kiglapait, Morse, 1969 and Michikamau, Emslie, 1969) than those of intrusions like Skaergaard, Stillwater and Bushveld (Wager and Brown, 1968). No zoning is recorded in these phases. Whether this is an original feature or a result of metamorphic redistribution is not known.

The norms of the igneous metabasites (Table 3.12) reflect their anorthositic troctolitic nature. The normative compositions of the coronitic or pseudomorphic metabasites (Table 3.12) are also anorthositic-troctolitic, with variable amounts of diopside and with hypersthene only appearing occasionally.

There is a weak tendancy for TiO_2, P_2O_5 and Zr to increase with decreasing MgO/(MgO + FeO) (Figure 3.22) perhaps indicating an increase in these elements in the liquid trapped in the cumulates. Highest values of TiO_2, P_2O_5 and Zr tend to occur at the lowest MgO/(MgO + FeO) values and may result from precipitation of ilmenite, apatite and even zircon. These tend to occur in rocks high in the metabasite sequences, in other words nearest the ultramafic bodies and the overlying gneisses (for instance, D49, D156). Extreme values of TiO_2, FeO, Fe_2O_3, V, Cr and Mn occur in the ore-rich bodies (Tables 3.12 and 3.13). High values of P_2O_5 are also found in these bodies (eg D155, Table 3.12).

As deformation has often destroyed any textural clues as to the origin of the foliated metabasites it is more difficult to evaluate the significance of their chemistry (Tables 3.14 and 3.15). Specimens 79/34A (i), D206, D32, D33 and D62 occur in close association with coronitic types and chlorite harzburgites and are assumed to be cumulates. They appear to be more gabbroic than the coronitic or pseudomorphic types, having higher normative diopside, except for D62 which resembles a noritic anorthosite. This may reflect an increase in cumulus calcic pyroxene in the very upper part of the metabasite sequence. The coronitic and pseudomorphic metabasites show a slight increase in normitive diopside high in sequence. Samples D90 and D91 are also gabbroic, their high Cr content perhaps resulting from a concentration of clinopyroxene in their protoliths. Their field location gives no clue as to their relationship to the other Flekke Unit rocks.

In short, these metabasites are dominantly troctolitic with significant normative calcic pyroxene only appearing high in the sequence. There is a tendancy towards enrichment in FeO, TiO_2, P_2O_5 and Zr, culminating in the development of Fe-Ti oxide deposits (as at Sördal) locally enriched in apatite. FeO, TiO_2, P_2O_5 and Zr enriched rocks also occur in the overlying ultramafic rocks.

It only remains to mention the phengite-eclogites and amphibolites which occur in sheet-like bodies between the ultramafic rocks and immediately below the base of the Vardheia Unit (Enclosure 1). These differ from the other metabasites in that they are relatively enriched in K_2O, Rb, Ba and Zr (Tables 3.14 and 3.15). In this respect they resemble the "metadolerites" found around Straumsnes (Tables 3.14 and 3.15) and on the west shore of Flekkefjord, and may be recrystallised equivalents of these. It is not clear whether these rocks represent a late differentiate of the suite represented by the anorthositic troctolites and ultramafites or a separate intrusive mass. A gradation from chlorite-harzburgite to phengite eclogite occurs in the field at Flekke (Chapter 2) but a lack of silica or iron enrichment in these eclogites relative to the underlying rocks suggests a separate origin. One might speculate that they represent a chilled, non-cumulate border zone.

3.4.5 Summary and Discussion of the Flekke Unit:

The features of the Unit can be summarised as follows:

1. Field evidence demonstrates the gradational nature of the contact between the metabasic rocks and the ultramafites (Section 2.03).
2. Field and petrographic evidence demonstrate that some, if not all of these lithologies are cumulates (Section 2.03).
3. Most of the sampled metabasites have the composition of an anorthositic troctolite. This indicates that for much of the period over which the magma was crystallising, the liquid composition lay on the boundary curve of the olivine and plagioclase fields in the natural basaltic system, in other words it approximated to a high alumina troctolite (Emslie, 1969).
4. The presence of dunites structurally below the metabasites indicates that olivine was the dominant cumulus phase early in the history of the intrusion. Hence the initial liquid composition may have been

less aluminous, lying within the olivine liquidus field.

5. Calcic pyroxene seems only to have become important in the structurally high parts of the metabasite sequence (where a coarse clinopyroxenite band has been found). Magnetite, ilmenite and apatite also become more abundant there. Late enrichment of total FeO, Fe_2O_3, Ti and P are therefore apparent.
6. Oxide-rich chlorite harzburgites and dunites occur structurally above the metabasites. They are iron rich and contain metabasic bodies enriched in Fe, Ti, P and Zr. They are considered to be late differentiates of the same magma from which the metabasites were derived.
7. The presence of blocky masses of apparently pure plagioclase (now zoisite + jadeite +/- albite +/- white mica) at Balsarvika (Section 2.03) indicates that accumulations of plagioclase (orthocumulates?) developed at high levels in the intrusion.

These features are consistently similar to those found in layered basic intrusions, specifically the leucotroctolite intrusions found in the Proterozoic terrains such as Kiglapait (Morse, 1969) Michikamau (Emslie, 1969) and parts of the Duluth Complex (Weiblen and Morey, 1980). These differ from intrusions such as Skaergaard and Bushveld in that there is no observed hiatus in olivine crystallisation and early olivine and plagioclase compositions are not as extreme (c.f. Wager and Brown, 1968 and Morse, 1969b). The troctolitic intrusions are commonly associated with massif anorthosites and it is thought that the two types may be derived from similar, high-alumina troctolite magmas (Morse, 1969 and 1982 and Emslie, 1969 and 1978). This is particularly interesting as anorthosites are well known from the BGR (Eskola, 1921; Lappin, 1966; Bryhni, 1966; Bryhni et al, 1981 and Brastad, in press).

The presence of peridotites as apparently late differentiates may seem curious. Their appearance in this position, along with the conclusions that they are late differentiates indicate that the magma was progressively depleted in Si and perhaps Al and alkalis. Recent studies of massif-type anorthosites demonstrate that their liquid line of descent involves depletion of Si, Al, Na and K and enrichment of Fe, Ti, Mn and P, assuming a parent of gabbroic anorthosite composition (Ashwall, 1978). The Fe, Ti and P enriched mafic segregations commonly found within anorthosites thus appear to be late differentiates of the melts which produced the anorthosites (Ashwall, 1982), rather than the associated mangeritic rocks, as has been commonly suggested (see, for instance, Philpotts, 1966).

It is suggested that the chlorite harzburgites, their associated P and Zr enriched metabasites and the Fe-Ti ores are late differentiates of the same magma which produced the anorthositic troctolites lying below them. In comparison with the mafic differentiates described by Ashwall (1982) those of the Flekke Unit seem to be very poor in any calcic pyroxene component and are rather rich in olivine. This may be a result of;

1. a different magma composition (more troctolitic and less gabbroic?),
2. Ca-metasomatism and/or
3. input of a new magma batch which precipitated a lot of olivine.

This rather simplified scenario assumes that only one intrusion is present in the Flekke Unit. It is possible that more than one intrusion is present, but distinction of individual intrusions is rendered very difficult by the fragmentary nature of the evidence. Some troctolitic complexes are known to be very complex with numerous intrusions, for instance, the Duluth Complex (Weiblen and Morey, 1980).

Small volumes of ferrodiorite, ferromonzonite or ferrosyenite are known to be associated with many layered basic intrusions and massif anorthosites and, along with the mafic segregations, appear to be the latest residua resulting from their differentiation. No lithologies have been found in the Hellevik-Flekke area which might correspond to such rocks. The phengite eclogites have rather high MgO/FeO ratios and the dioritic rocks of the area to the north Klibbern (Tables 3.14 and 3.15 and Enclosure 1) are rather siliceous, with low K (see, for comparison, Emslie, 1978, Table III).

Finally, the mineralogical evolution of the coronitic metabasites appears to be related to their bulk rock composition. The types which have retained their igneous mineralogy (D96, D143, Table 3.12) have the highest $MgO/(MgO + FeO^T)$ ratios. The coronites have significantly lower $MgO/(MgO + FeO^T)$ ratios. The best developed pseudomorphic eclogites (D35 and D156, Table 3.12) have the lowest $MgO/(MgO + FeO^T)$ ratios and the lowest Ab/(Ab + An) ratios. The best developed "eclogite" from Aurevagen, near Hellevik has rather higher $MgO/(MgO + FeO^T)$ and Ab/(Ab + An) than D35 and D156, so that bulk composition alone cannot entirely explain the completeness of the eclogitisation. As was noted in Chapter 2, the coronites from Balsarvika (D36 and D86, Table 3.12) contain co-existing jadeite and zoisite, whilst those from Aurevagen contain co-existing omphacitic pyroxene, kyanite, garnet and subordinate zoisite. The Balsarvika coronites have significantly higher Na_2O contents than those from Aurevagen. This subject will be discussed in more detail in Chapter 4.

Section 3.05 Summary of the Geochemistry

Major and trace element data have been presented for rocks of the Basal Gneisses, the Gjörlanger Unit and the Flekke Unit. Due to the small number of samples collected from the Vardheia Unit in relation to the lithological variety found within it, no discussion of the chemistry of these rocks is given.

The geochemical data for the lithologies of the Basal Gneisses and the Gjörlanger Unit have been used to characterise them as orthogneisses and to classify them in terms of rock type and magma type. In association with petrographic evidence for early granulite-facies assemblages, their geochemistry sheds light on the early crustal history of this part of the BGC. The Gjörlanger Unit gneisses have the characteristics of magmatic arc lithologies. This, by analogy, provides evidence for the tectonic environment in which the gneiss precursors formed. It is interesting in this respect that recent studies of rare earth elements and U-Pb isotope systematics of zircons in eclogites and associated gneisses from the BGR (location unspecified) by Gebauer et al. (1982) indicate an island-arc origin for "Basal Gneisses" and mangerites, the mangerites giving an age of 1500 Ma. It would, therefore, appear that significant volumes of the BGC have been formed in Proterozoic magmatic arcs. Whether the Basal Gneisses of the Hellevik-Flekke area are arc lithologies or related to an anorthosite-mangerite-rapakivi granite suite is uncertain.

The Rb depleted nature of the orthogneisses is consistent with their earlier granulite-facies nature. Discovery of this geochemical signature in other amphibolite-facies gneisses in the BGR would have important consequences for interpretation of their early history and their Rb-Sr isotopic systematics.

The present metamorphic mineralogy of the gneisses is related to their bulk chemistry. Omphacite and garnet only appear to have developed in gneisses with relatively high CaO and low K_2O. In less basic rocks hornblende and/or biotite and albite and garnet appear. Their genetic geochemical relationship is in agreement with their contiguity in the field.

Geochemical studies demonstrate that the compositions of metabasites within the orthogneisses are unlikely to exactly correspond to those of their protoliths. The nature of the alteration depends upon metamorphic grade and the nature of the enveloping country rocks. These findings are in line with other such studies of eclogites in the BGR (Bryhni et al, 1969; Krogh, 1980 and Krogh and Brunfelt, 1981). Alteration under eclogite-facies conditions might produce superficial similarities to abyssal tholeiites (c.f. Bryhni et al, 1969) and lead to erroneous conclusions regarding their tectonic history. The so called "immobile-elements" appear to have been stable during metamorphism and are, therefore, likely to be the most reliable indicators of the nature of the eclogite protoliths. However, as is noted above, some care is required in interpreting the immobile element patterns.

The websterites of the Gjörlanger Unit are chemically quite different from the other metabasites. The author is not aware of any petrographically similar rocks in the BGR. They show some chemical similarities to the well known orthopyroxene eclogites from north of Nordfjord. Preliminary studies on zircons in garnetite veins from a pyroxenite indicate intrusion at about 1500 Ma. This provides a minimum age for the Gjörlanger Unit gneisses.

The Flekke Unit lithologies show a strong resemblance to those from Proterozoic troctolitic intrusions associated with massif type anorthosites. Their altered nature precludes deduction of a liquid line of descent for these rocks. Hence the contention that the basic dykes of the Gjörlanger Unit acted as feeders to this basic-ultrabasic complex (see Chapter 2) has no geochemical basis and remains speculative. Proof that a direct physical connection existed between the two would demonstrate that the Gjörlanger and Flekke lithologies were genetically connected. However, the observation that layered basic intrusions are often anorogenic (see, for instance, Emslie, 1978 and Morse, 1982) conflicts with the orogenic nature of the gneiss precursors. Further field work may resolve this problem.

The ultramafic rocks of the Flekke Unit can be regarded as an extreme example of the Fe-Ti type peridotites defined by Carswell et al (1983). Like the latter, they are associated with layered basic intrusions, possibly having affinities with massif type anorthosites. The presence of rodingite-like calc-silicate rocks in the peridotites indicates that they have suffered a type of Ca-metasomatism commonly associated with serpentinisation. On this basis it is suggested that these rocks have been subjected to low temperatures and pressures (and thus closely approached the Earth's surface) at some time prior to the last high-grade metamorphism. As it has been demonstrated that the Flekke Unit is autochthonous with respect to the Vardheia and Gjörlanger Units, the three units can be said to have shared the same history.