The Ordovician Grøndalsfjell Intrusive Complex, Central Scandinavian Caledonides: field relations, petrography and emplacement

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The Grøndalsfjell Intrusive Complex (GIC) is part of a major plutonic province located in the Gjersvik Nappe of the Upper Allochthon in the Caledonides of Central Norway. Field relationships and petrography suggest that the magmatic evolution of the pre-456 Ma complex took place in three main stages. It commenced with the intrusion of relatively primitive mafic magma and crystallisation of coarse-grained olivine gabbro, presumably in a macro-dyke or smaller intrusive body. This was followed by intrusion of more evolved basaltic melts to form a larger magma chamber, now preserved as the Layered Series, the emplacement of which was characterised by active stoping and incorporation of a large number of xenoliths. Continuous influx of magma led to deposition of a thick pile of layered olivine gabbro cumulates which now form the Lower Zone. As the influx of magma decreased, fractional crystallisation caused an evolution towards gabbronorite in the Middle Zone and quartz diorite in the Upper Zone.

Renewed magmatic activity led to the formation of a third magma chamber represented by the hornblende-diorite-gabbro series. These magmas were hydrous and characterised by hornblende as the predominant mafic cumulus phase. Initial crystallisation of a dioritic crystal mush was succeeded by continuous or intermittent replenishment of comparable, but more basic magma and extensive mingling of mafic and dioritic components. Penecontemporaneous injection of basic magma or crystal suspensions took place along dykes in the Layered Series. Fractionation produced peridotite, olivine gabbro and hornblende-gabbroic 'cumulate-type' dykes in the Lower and Middle Zone, and this was followed upwards by injection of coeval basic melts into the partly crystallised Upper Zone.

The GIC was emplaced into previously deformed and metamorphosed volcanic and related intrusive rocks of the Skorovass Complex, and extensive partial melting took place along the margins of the intrusive complex. Intense shearing was localised along contact zones of the intrusions and much of this deformation was evidently contemporaneous with the magmatic events.

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Introduction

The Grøndalsfjell Intrusive Complex (GIC) is situated in the Grong District of the central Norwegian Caledonides, 250 km northeast of Trondheim (Fig. 1). The presence of volcanogenic massive sulphide ores has made the region attractive from an economic point of view, and regional and detailed geological investigations have been carried out throughout this century (see, e.g., Halls et al. 1977, Kollung 1979, Lutro 1979, Reinsbakken 1980, 1986, 1992, Reinsbakken & Halls 1987, Roberts 1979, 1997, Roberts & Tucker 1991). The present study forms part of a multidisciplinary programme of investigations by the Geological Survey of Norway with the aim of integrating and improving the geological basis for further exploration in the area. Based on detailed studies and remapping of a ca. 50 km^2 area at a scale of 1:10,000, the field relations and petrography of a cogenetic plutonic suite of ultramafic to acidic rocks in the Grøndalsfjell area are described. The complex is remarkably well exposed (>90-95%) and in general little affected by metamorphic recrystallisation and later deformation. At altitudes above ca. 700 m in the central and southern parts of the GIC, the intrusive rocks provide a unique record of primary magmatic relationships. Work is in progress on other aspects of the GIC. The result of investigations on the processes governing the evolution of the magma chambers, the chemical and isotopic characteristics of the magmas and the mechanism and time of emplacement will be published separately.

Regional setting

The Grong District is divided into two principal parts. The southeastern part includes the Orklump and Björkvatn Nappes of the Köli Nappe Complex in the Caledonian Upper Allochthon (Roberts 1997), and consists mainly of various metasedimentary rocks with local metavolcanic units. To the northwest, these nappes are tectonostratigraphically overlain by the Gjersvik Nappe which hosts the GIC and is also regarded as part of the Upper Allochthon (e.g., Stephens et al. 1985, Roberts 1997). The northwestern part of the Gjersvik Nappe borders on equivalents of the Helgeland Nappe Complex of the Uppermost Allochthon, which comprises migmatitic gneisses, mica schists, marbles and a variety of plutonic complexes, partly of batholithic dimensions (Nordgulen et al. 1993).

The Gjersvik Nappe is composed of volcanic and subvolcanic rocks of the Skorovass Complex (Roberts 1997; previously referred to as the Gjersvik Group) and the overlying, predominantly sedimentary, Limingen Group, in addition to a variety of plutonic rocks (Fig. 1). According to Reinsbakken (1992), the volcanic rocks of the Skorovass Complex can be

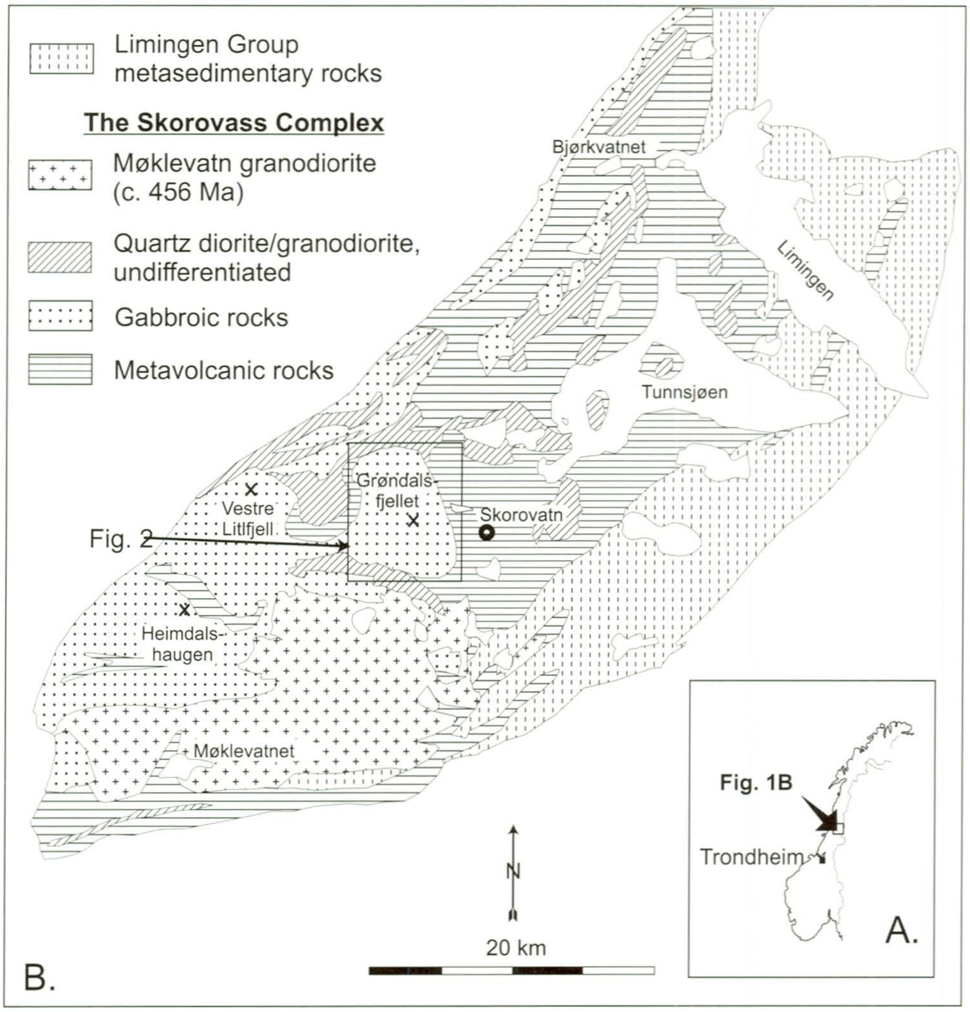


Fig. 1. Geological map of the Gjersvik Nappe showing the Skorovass Complex and the location of the GIC. The area covered by Fig. 2 is framed.

subdivided into three major stratigraphic units: 1) a lower unit comprising massive and pillowed lavas of tholeiitic basalt to basaltic andesite; 2) a very heterogeneous middle unit, composed of differentiated tholeiitic basalts, basaltic andesites and andesites forming massive to pillowed flows in addition to abundant feldspar-phyric rhyodacite flows and pyroclastites; and 3) an upper unit comprising primitive, pillowed and massive tholeiitic basalts and local boninites alternating with quartz-phyric rhyodacite flows and tuffites. The lower unit is assumed to have formed during the early stages of construction of an ensimatic island arc, whereas the middle and upper units developed later in response to rifting of the arc complex (Reinsbakken 1992).

Gabbroic to tonalitic bodies are abundant and are interpreted as subvolcanic intrusions related mainly to the middle volcanic unit. Parts of the Skorovass Complex contain metagabbros which pass upwards into sheeted dyke complexes reminiscent of ophiolite fragments (Heim 1992 and own observations). Preliminary interpretations of geochemical data suggest a link between these dyke complexes and the upper volcanic unit.

In addition to syn-volcanic intrusions, the metavolcanic rocks of the Skorovass Complex were intruded by a large number of plutonic bodies with areal extents of some 10 km^2 or more (Fig. 1) ranging in composition from ultramafic and gabbroic, to trondhjemitic and granodioritic (Halls et al. 1977, Lutro 1979). Field evidence and preliminary geochemical data imply that many of these intrusions were unrelated to the preserved, tholeiitic, metavolcanic sequence of the Skorovass Complex, whereas others which cut across only the lower to middle volcanic members may possibly be cogenetic with effusive rocks in the upper parts of the volcanic sequence. A trondhjemite belonging to the latter suite, near Bjørkvatnet in the northern part of the region (Fig. 1), has yielded a U-Pb zircon age of $483^{+5}/_{-3}$ Ma (Stephens et al. 1993).

The southern part of the region (Fig. 1) is dominated by the Møklevatnet granodiorite in addition to gabbro complexes such the GIC described in the present account and the Heimdalshaugen gabbro complex to the southwest (Reinsbakken & Halls 1987, Roberts 1997). The Møklevatnet granodiorite approaches dimensions of 20 x 14 km and has been dated (U-Pb, zircon) at 456 ± 2 Ma (Roberts & Tucker 1991). Recent mapping shows that parts of the Møklevatn granodiorite intruded sedimentary rocks which have been considered as belonging to the lower part of the Limingen Group, prior to a major uplift event with subsequent deposition of arkoses and conglomerates largely derived from the granodiorite complex. Furthermore, the Møklevatn granodiorite shows intrusive relationships to the Heimdalshaugen gabbro complex which appears to be similar in age to the GIC, implying that a minimum age for the latter would be 456 Ma.

The rocks of the Gjersvik Nappe are regionally inverted, so that the Limingen metasedimentary rocks are located at the structural base along a marked thrust contact to the underlying southeastern nappes (Kollung 1979, Lutro 1979). To the northwest, there is a less distinct tectonic contact between the metavolcanites of the Skorovass Complex and equivalents of the tectonostratigraphically overlying Helgeland Nappe Complex. This contact is apparently older than the southeastern contact, being partly obliterated by abundant granitoid intrusions, some of which are deformed by early folds (Kollung 1979, M. Heim pers. comm. 1994). The rocks of the Gjersvik Nappe have been subjected to polyphase deformation under lower to upper greenschist-facies conditions, with the first two episodes of deformation being the most conspicuous (Halls et al. 1977, Lutro 1979, Roberts 1979). According to Lutro (1979), the early phase was related to coupling of the Gjersvik and Helgeland Nappes and was responsible for a regional inversion of the sequence, as well as the tight to isoclinal folding and development of the regional schistosity. In the Skorovass Complex, this stage is characterised by a very heterogeneous style of deformation which was controlled largely by contrast in rheology between different rock units. Later deformation led to more open folding accompanied by further movements along previously formed, low-angle shear zones. The heterogeneous patterns of deformation have typically left the plutonic complexes more or less intact with well-preserved original igneous fabrics and mineralogy, whereas penetrative tectonic fabrics are developed along their margins (Halls et al. 1977).

Geology of the Grøndalsfjell area

The GIC is situated in the south-central parts of the Skorovass Complex (Fig. 1). Other gabbroic rocks which resemble parts of the GIC are exposed to the west and southwest in the vicinity of the mountain Heimdalshaugen, and a similar, but smaller, complex occurs at Vestre Litlfjellet. The latter is separated from the GIC by a belt of moderately to strongly sheared metavolcanites and subvolcanic intrusions and local thrusts (Reinsbakken & Halls 1987). This shear-belt envelops the GIC and its shape was evidently controlled by the rigid behaviour of the gabbro complexes (Fig. 2). Similar, post-intrusive shear zones are observed locally near the eastern and southern contacts of the GIC, mainly affecting metavolcanic wall rocks but also deforming marginal parts of the intrusive complex. Despite this deformation, well-preserved intrusive contacts can be observed at several places along the eastern margin and in the Murfjellet area in the southwest (Fig. 2). In the area between the mountain Grøndalsfjellet and the river Grøndalselva the rocks are metamorphosed to a degree where xenoliths can no longer be mapped separately. In this area the zone boundaries are interpolated from areas with less metamorphosed rocks.

The Grøndalsfjell area was earlier described as a zoned complex in which a core of metagabbro containing xenoliths of layered olivine gabbro was enclosed by hornblende diorite (Halls et al. 1977). A new tripartite division of the GIC is proposed in this paper. The oldest part is found in xenoliths and large rafts of coarse-grained, massive to layered olivine gabbro. The olivine gabbro is entirely enclosed within a younger intrusion, here termed the *Layered Series* which constitutes the greater part of the GIC. On the basis of phase layering defined by the presence or absence of olivine, Ca-poor pyroxene and quartz, the Layered Series can be subdivided into three main zones: the *Lower Zone (LZ)* consisting of layered olivine gabbro in the central and northern part, grading southwards into the *Middle Zone (MZ)* consisting of partly-layered gabbronorite which in turn grades into quartz diorite of the *Upper Zone (UZ)*. The three zones are laterally persistent from the central part of the area towards the west and east. The layering in the LZ olivine gabbro and in parts of the MZ gabbronorite is approximately vertical in most of the area. A change in strike direction from E-W in the central northern and western parts, to ESE-WNW in the eastern and southern parts of the area (Fig. 2) is due to minor post-magmatic deformation, also revealed by a similar deflection of cross-cutting granodioritic dykes. The Layered Series is intruded by various mafic dykes, and it is argued here (see below) that these are related to a third intrusive phase represented by the hornblende-diorite-gabbro series which is particularly well exposed along the river Skorovasselva.

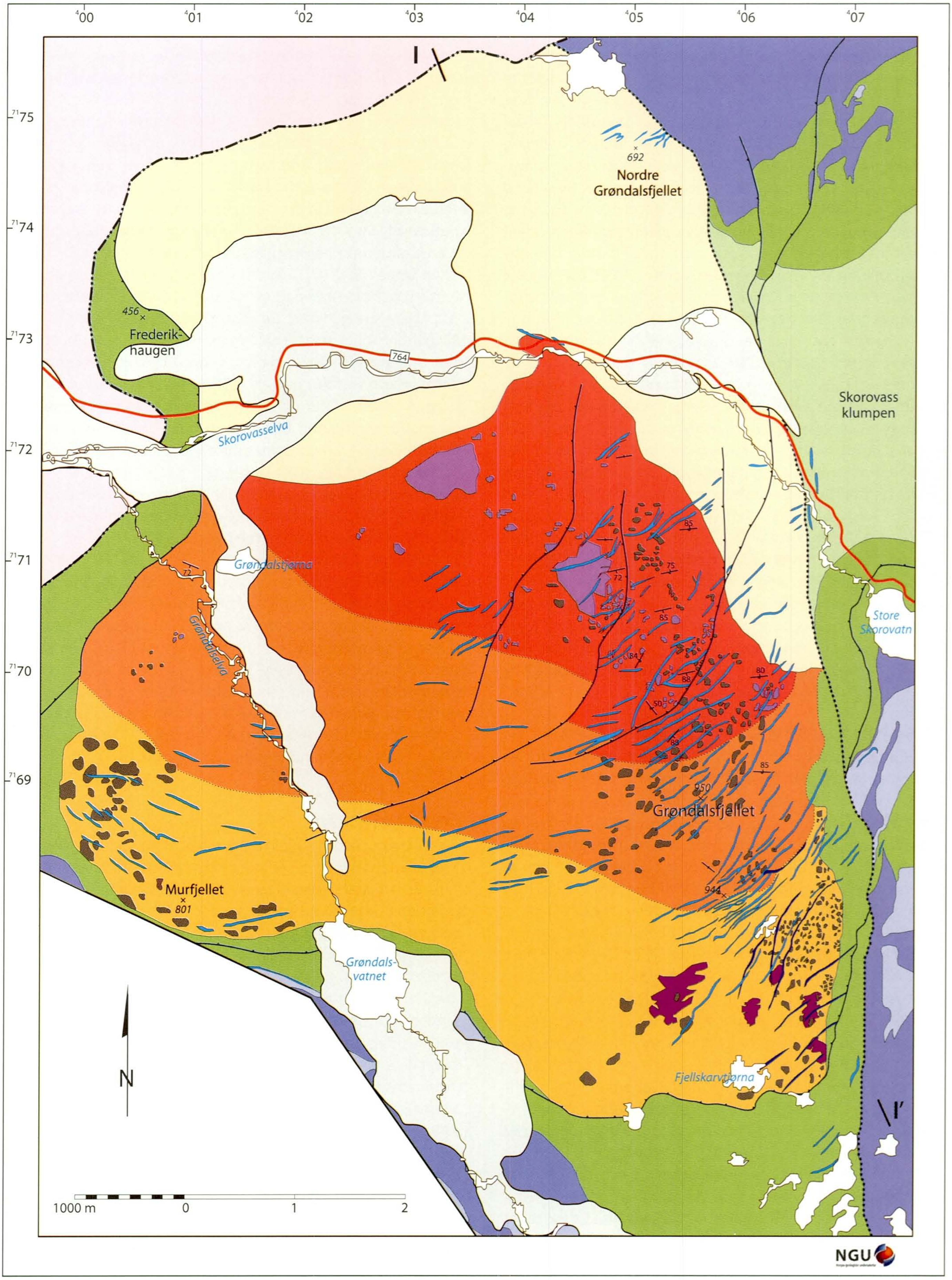
The entire GIC is intruded by numerous NE-SW striking, approximately vertical, granodiorite dykes (Fig. 2). Some of these can be followed continuously for more than 500 metres before they wedge out, jump or branch out in an en échelon pattern. The dykes vary in width from 15 cm (Fig. 3) to more than 10 m, but are typically 1.5 to 2 m wide. In addition to quartz, plagioclase and alkali feldspar they contain minor muscovite, garnet, sphene and accessory amounts of magnetite and sulphides. A few of these cross-cutting dykes comprise mingled mafic and granodioritic components (Fig. 2).

Field relations

The following descriptions of the rocks of the GIC are primarily based on mapping and detailed studies of key field relationships at well-exposed localities, together with evidence obtained from textural and mineralogical investigations (see below). The descriptive terms for primary magmatic structures, types of layering and cumulates are used in accordance with Irvine (1982). Terms such as adcumulate and orthocumulate are avoided, since a variety of different processes can lead to the development of similar cumulate textures, and the degree of post-cumulus overgrowth on cumulus minerals is often difficult to estimate. Accordingly, we have chosen to characterise the various rock types by the cumulus phases and clearly identifiable intercumulus phases they contain, as suggested by Hunter (1996). Pyroxenes are generally termed Ca-rich or Ca-poor because compositions cover fairly wide ranges.

Wall-rock xenoliths in the GIC

Xenoliths of metavolcanic wall rocks are very abundant in the Layered Series. The xenoliths are found mainly in the central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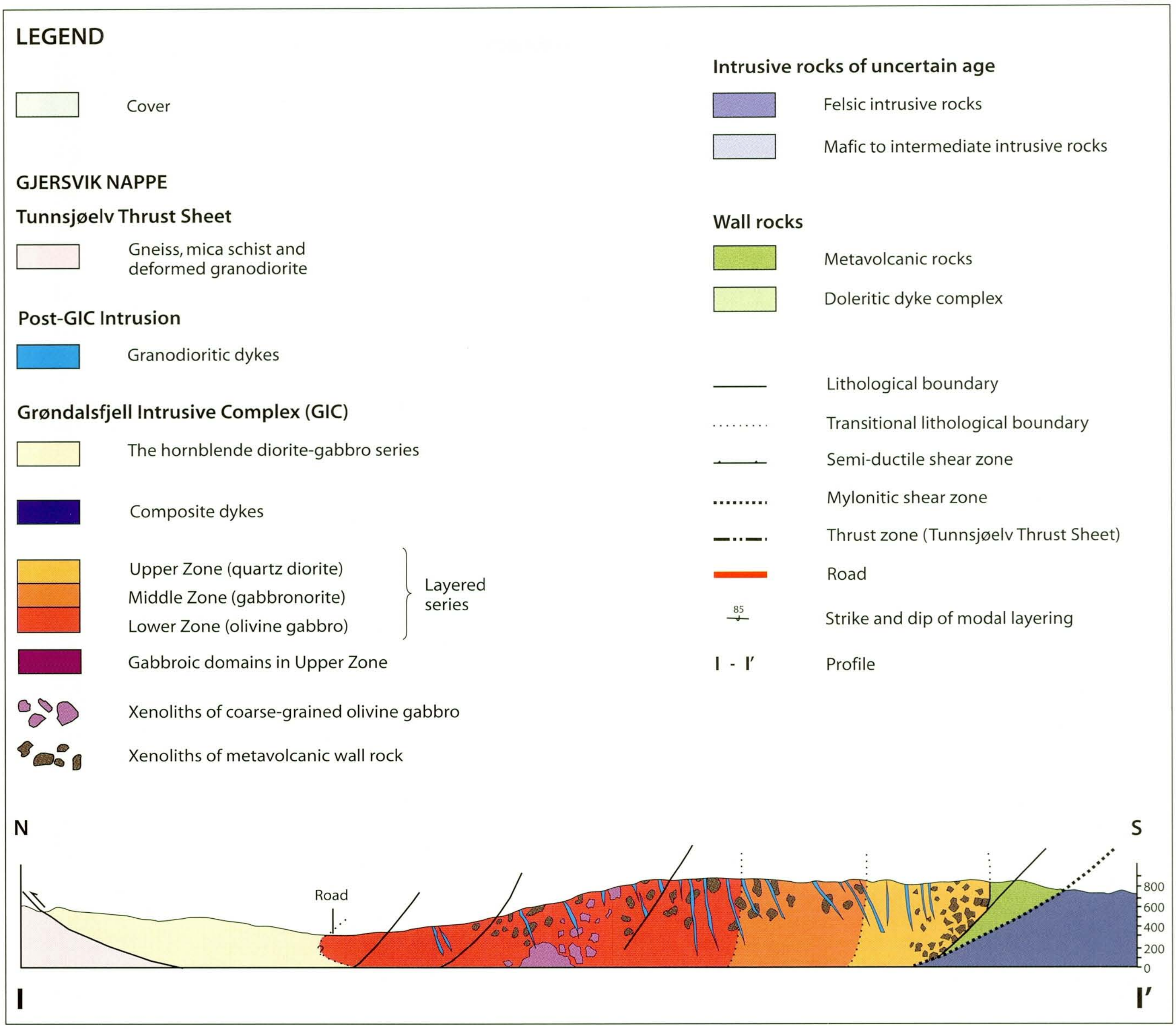

Fig. 2. Geological map of the Grøndalsfjell area and cross section A-A'. For location of map, see Fig. 1.

and easternmost parts of the olivine gabbro (LZ), in most of the gabbronorite (MZ) and in an area close the contact zone of the quartz diorite (UZ) in south east (Fig. 2). In the upper part of the MZ and the lower part of the UZ there is an interval with few or no xenoliths. In some parts of the LZ and MZ, xenoliths compose more than 60% of the volume of the rock.

The wall-rock xenoliths have an average size of about 5 x 5 m but can range from less than 1 m (Fig. 3) to more than 50 m across. They vary from angular to rounded, and are generally difficult to distinguish from the host olivine gabbro or gabbronorite because of strong recrystallisation and diffuse contacts. Strongly recrystallised metavolcanic xenoliths may only be recognisable by their lack of modal layering and their granular texture, together with the reactions rims of pegmatitic material between 10-50 cm thick which form locally along their margins (Fig. 3).

Xenoliths of variably altered anorthositic rocks (Fig. 3) have been observed at three localities in the Lower Zone of the Layered Series. The anorthosite is white or grey in colour due to saussuritisation of the plagioclase. The rock has a homogeneous appearance, but a weak magmatic lamination caused by a preferred orientation of tabular plagioclase crystals can be seen locally in less altered parts. The origin of the anorthosite is uncertain. It can be considered to represent either a part of the pre-GIC, wall-rock lithology, or an early phase of crystallisation of the coarse-grained olivine gabbro (se below) equivalent to the anorthositic blocks in the Skaergaard Intrusion (Irvine 1987).

Xenoliths of coarse-grained olivine gabbro

The oldest plutonic rocks of the GIC are coarse-grained olivine gabbros which occur exclusively as angular to slightly rounded inclusions in the Layered Series. There are two very

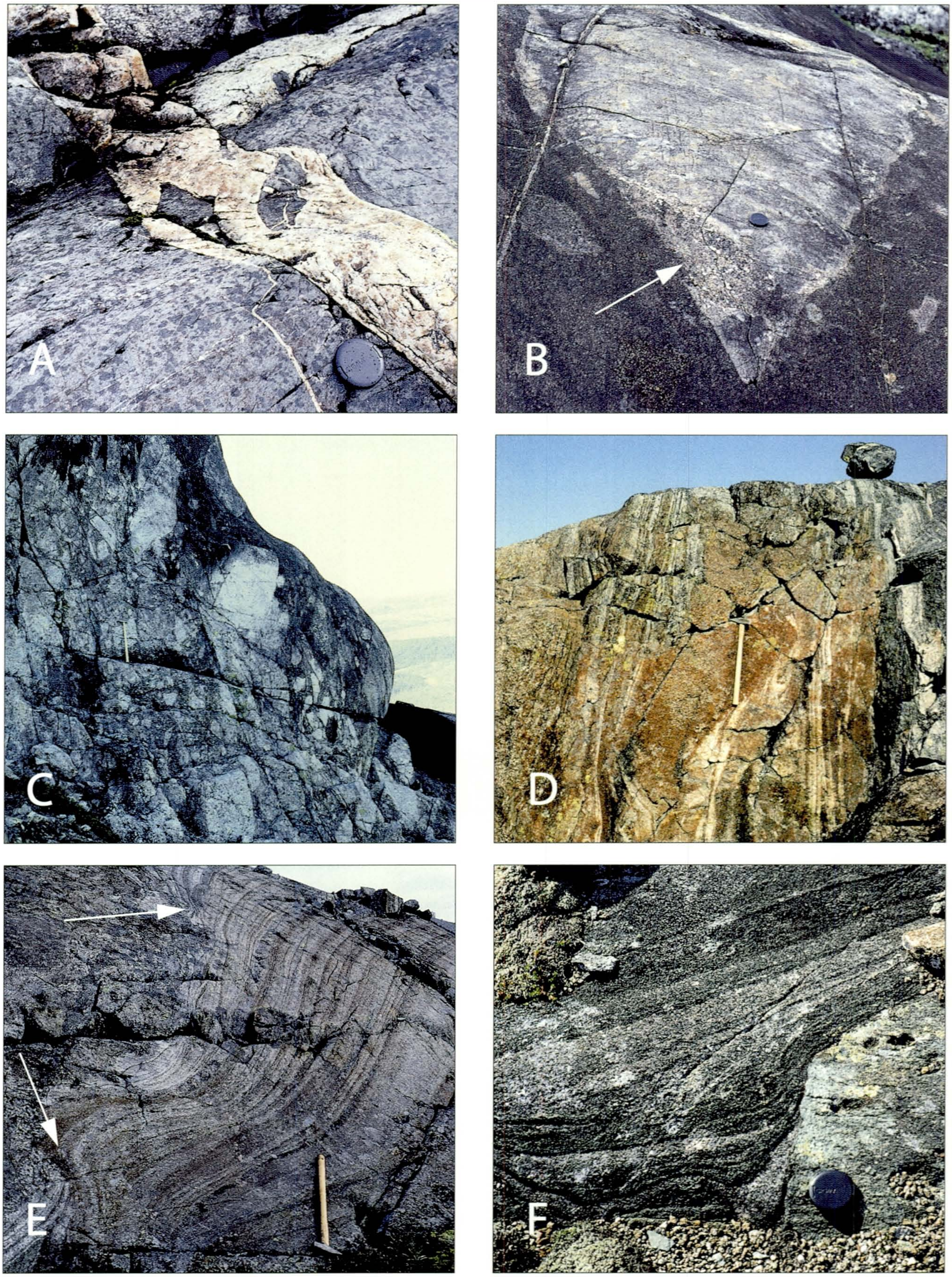

Fig. 3. A. Granodioritic dyke cutting deformed metavolcanic wall rocks and gabbro in the contact zone of the GIC. Located 2 km east of the 944 m peak (Fig. 2). B. Xenolith of metavolcanic wall rock in olivine gabbro located in the central northern part of the Lower Zone. A pegmatitic reaction rim is partly developed along the margin of the xenolith (marked with arrow). C. Xenoliths of anorthosite in Lower Zone olivine gabbro. Located in the central northern part of the Lower Zone. D. Xenolith of coarse-grained olivine gabbro in layered olivine gabbro in the central eastern part of the Lower Zone. Stratigraphic way up is to the right. E. Layered olivine gabbro in the central northern part of the Lower Zone. Stratigraphic way up is down to the right. A large xenolith of metavolcanic rock occupies the upper left part of the outcrop. Two minor unconformities are marked with arrows. F. Draping of modal layering along the flanks of a xenolith in the central northern part of the Lower Zone. Stratigraphic way up is to the top.

large blocks in the northwestern part of the area (Fig. 2) and numerous xenoliths (Fig. 3) and several large blocks further east. At one locality, an anorthosite xenolith is included in a block of coarse-grained olivine gabbro, the latter being itself enclosed by layered olivine gabbro of the LZ. Inclusions of other wall rocks, such as metavolcanic rocks which are very abundant as xenoliths in the layered olivine gabbro of the LZ, have not been found within the coarse-grained olivine gabbro.

Typically, the coarse-grained olivine gabbro is isotropic with a brownish-red, conspicuously knotty, weathering surface and numerous fractures along which the gabbro is altered for up to a distance of 50 cm. Layering is locally conspicuous, with normal layers 20-50 cm thick. The orientation of the layering in two xenolithic rafts is 116/60° S and 260/80° N, respectively. This is slightly different from that of the surrounding layered olivine gabbro which is about 090/90°, indicating that the blocks rotated during descent through the magma before impact with the contemporary floor of the magma chamber.

The Layered Series

The layered olivine gabbro of the Lower Zone (LZ), the gabbronorite of the Middle Zone (MZ) and the quartz diorite of the Upper Zone (UZ) constitute the Layered Series, which has been mapped as one large intrusive body composing 65% of the GIC. The preserved part of the LZ is up to 3 km thick and occupies more than 35% of the Layered Series, passing south-wards into gabbronoritic rocks of the MZ as Ca-poor pyroxene takes over from olivine as a cumulus phase. This compositional change is accompanied by increasing contents of oikocrystic magnetite/ ilmenite. The MZ is approximately 1.5 km thick and forms about 30% of the Layered Series. Farther south, around the 944 m peak (Fig. 2), quartz and biotite gradually appear and the ca. 2 km-thick UZ, which forms about 30% of the Layered Series in the south, consists predominantly of quartz diorite. Alkali feldspar is present in certain varieties of felsic veins and dykes in the contact zone, locally also in the central parts of the UZ (Fig. 2). It should be emphasised that the stratigraphy of the Layered Series given above is somewhat simplified; for example, olivine locally reappears in the MZ and quartz and biotite are present intermittently over fifty to a hundred metres in the uppermost part of the MZ.

Lower Zone

The LZ layered olivine gabbro is easily distinguished in the field by its reddish-brown weathering. It is characterised by alternating light and dark layers in which the modal proportions of plagioclase and olivine and partly also Ca-rich pyroxene vary (Fig. 3). Compositions range from pure anorthositic to peridotitic layers on the scale of a few millimetres to tens of centimetres. Primary magmatic features such as unconformities (Fig. 3), modally graded layering and draping of layers over xenoliths (Fig. 3) and depression under them are particularly common in the olivine gabbro. In addition to modal layering on the medium- to small-scale, other varieties such as uniform layers, micro-rhythmic layering and textural layering occur in the olivine gabbro. All these structures distinguish the layered olivine gabbro of the LZ from the xenoliths of massive or dm-scale layered, coarse-grained, olivine gabbro.

The modally graded layering, impact structures and slump structures in the LZ olivine gabbro provide consistent indicators of the way-up of the Layered Series which is towards the south. On the assumption that the modal layering was originally sub-horizontal, there is evidence that the Layered Series has been tilted approximately 80° towards the southeast. In some outcrops, however, the strike of the modal layering changes by up to 90° from the general E-W orientation, showing a chaotic folded pattern (Fig. 4). In most cases the presence of xenoliths adjacent to these deformed areas shows that the disturbance was due to plastic deformation when xenoliths settled into the partly consolidated cumulates residing on the floor of the magma chamber.

Locally, the LZ olivine gabbro has intruded into large rafts of the coarse-grained olivine gabbro in a manner reminiscent of stoping. Angular fragments of coarse-grained olivine gabbro have been broken apart slightly, evidently with little or no rotation, so that the melts of the Layered Series seem to have penetrated fractures in the solidified rafts to form small pockets and dykes of weakly layered, medium-grained, olivine gabbro.

Middle Zone

In little-metamorphosed parts of the Layered Series, the transition from LZ olivine gabbro to MZ gabbronorite is marked by a gradual change over 100m from layered, reddish-coloured rocks towards more massive, brownish-coloured rocks. This is accompanied by an increase in the amount of Fe-Ti oxides. The preferred orientation of plagioclase laths and partly also of prisms of Ca-poor pyroxene is common in the gabbronorite giving rise to a magmatic lamination. Modal layering is developed in some areas (Fig. 4) but is less common than in the LZ. Towards the south, the modal proportion of plagioclase gradually increases, and the colour of the rock changes to a light brownish-grey over 100 to 150m as quartz and biotite appears and form major phases at the base of the UZ.

Upper Zone

The greater part of the UZ consists of medium-grained quartz diorite, with an increasing number of metavolcanic xenoliths towards the intrusive contacts. Neither layering nor lamination has been observed. Locally, there are transitions into gabbroic to dioritic domains up to 300 m across, apparently concentrated along a roughly E-W zone trending from the central to the eastern part of the UZ and locally along the wall-rock contact. Transitions into quartz monzodiorite or granodiorite are also seen. Mafic dykes and enclaves are volumetrically subordinate but form a significant component of parts of the UZ. Back-veining of the quartz dioritic or dioritic host by the mafic intrusions is common. Mafic dykes which locally pass into 'trains' of individual subcircular or complex-shaped individual bodies (Fig. 4), provide evidence

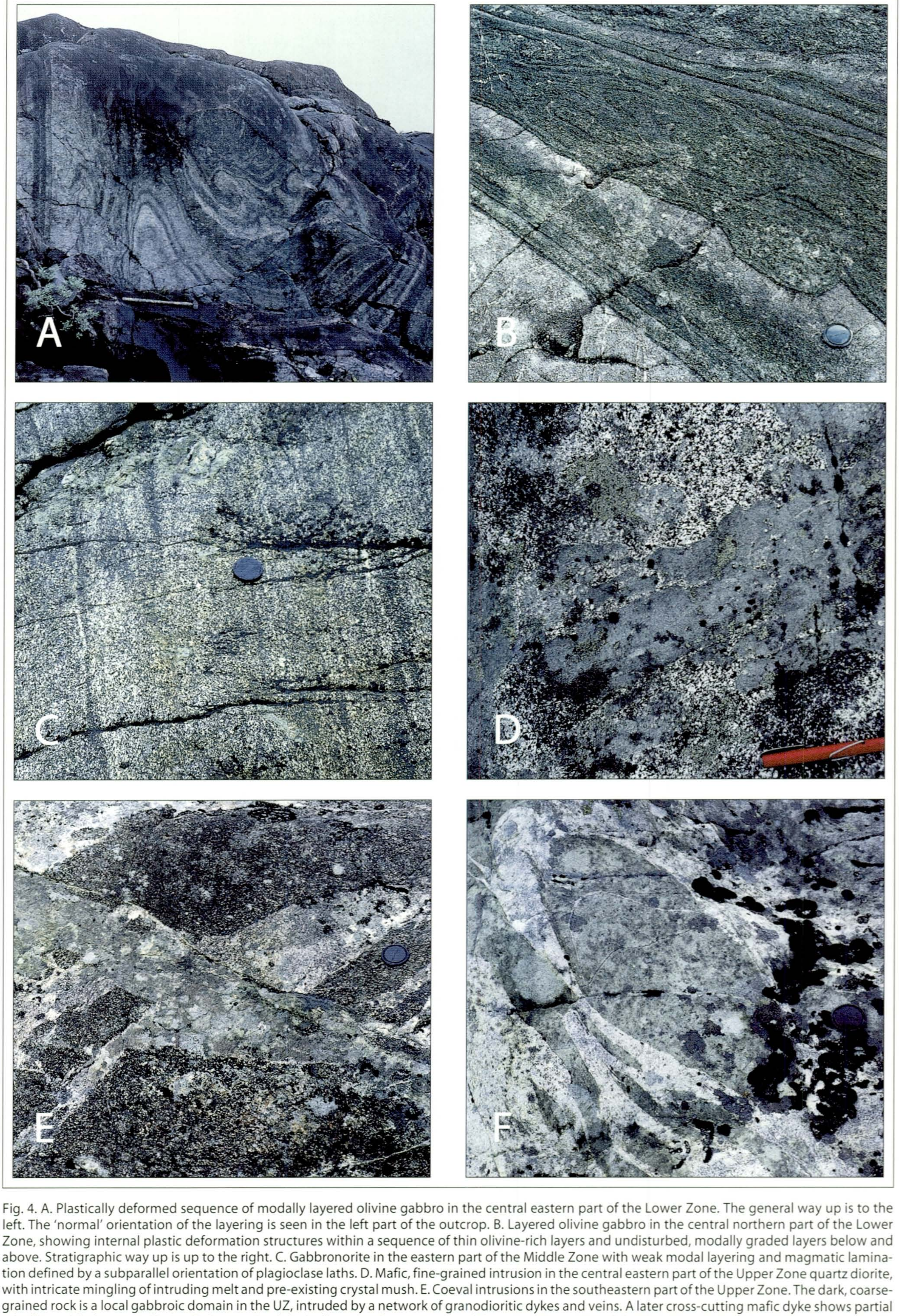

Fig. 4. A. Plastically deformed sequence of modally layered olivine gabbro in the central eastern part of the Lower Zone. The general way up is to the left. The 'normal' orientation of the layering is seen in the left part of the outcrop. B. Layered olivine gabbro in the central northern part of the Lower Zone, showing internal plastic deformation structures within a sequence of thin olivine-rich layers and undisturbed, modally graded layers below and above. Stratigraphic way up is up to the right. C. Gabbronorite in the eastern part of the Middle Zone with weak modal layering and magmatic lamination defined by a subparallel orientation of plagioclase laths. D. Mafic, fine-grained intrusion in the central eastern part of the Upper Zone quartz diorite, with intricate mingling of intruding melt and pre-existing crystal mush. E. Coeval intrusions in the southeastern part of the Upper Zone. The dark, coarse-grained rock is a local gabbroic domain in the UZ, intruded by a network of granodioritic dykes and veins. A later cross-cutting mafic dyke shows partial mingling with the granodiorite. F. Composite dyke in the central eastern part of the Upper Zone. Metadoleritic 'pillows' (dark) in a lighter granodioritic to quartz dioritic matrix. Weakly developed, chilled margins are present in the pillows, but are preserved only locally due to extensive fracturing of the mafic enclaves and back-veining of the granodioritic material.

that these dykes were emplaced into a melt or an unconsolidated crystal mush.

Rocks of quartz monzodioritic and granodioritic composition are particularly abundant in the central-eastern parts of the UZ, in places forming dyke-like bodies or veins with thicknesses ranging from a few millimetres to several metres (Fig. 4). Some of these are composite bodies in which evidently penecontemporaneous, fine-grained dykes, enclaves and pillow-like structures of mafic composition are contained in a leucocratic host (Fig. 4). The mafic rock usually shows a chilled, finer-grained margin against the felsic host. Many enclaves have been fractured, and back-veining of felsic material into the enclaves is quite common. Although the contacts are in general sharp, gradual transitions can be seen, showing that mixing of the mafic and the leucocratic components occurred, at least on a local scale. Some of these composite dykes extend through the contact zone between the UZ and the metavolcanic wall rocks (Fig. 2).

The hornblende-diorite-gabbro series

A suite of texturally varied, hornblende-rich, intrusive rocks ranging in composition from diorite to gabbro and subordinate quartz diorite, occurs in the northern part of the Grøndalsfjell area (Fig. 2). The areal extent of this complex has not been mapped in detail, but it covers at least 5 km^2 along the river Skorovasselva and apparently 9-10 km^2 of the Nordre Grøndalsfjell area (Reinsbakken & Halls 1987). In the field, the contact with the Layered Series is difficult to define in this area because of extensive metamorphism and the lack of good exposures, but in places the dioritic rocks form a network of relatively coarse-grained, partly pegmatitic veins in the LZ layered gabbro. Also, over a zone in the LZ approximately 100 metres wide towards the contact with the diorite, there seems to be a gradual increase in brown hornblende at the expense of olivine. Above (south of) the contact, a series of mafic dykes and associated pegmatites has intruded the Layered Series. These are described separately below. However, petrological data, including geochemical studies (in progress), lead to the conclusion that they are part of the hornblende-diorite-gabbro series.

The major body of the hornblende-diorite-gabbro series consists mainly of plagioclase and hornblende with varying, but generally minor, amounts of quartz, magnetite, apatite and sulphides. The texture in which hornblende crystals form subparallel prisms with interstitial plagioclase range widely from equigranular, medium- or coarse-grained to fine- or medium-grained inequigranular. Metamorphosed varieties of hornblende diorite can be recognised in the field by their yellowish-brown weathering surfaces, whereas the colour on unmetamorphosed rock surfaces is dark grey to brown.

Intrusive bodies of fine- to medium-grained hornblende gabbro of variable shape and size are abundant in the hornblende diorite. In general, these bodies intrude the diorite in very complex patterns (Fig. 5). Commonly the gabbro and hybrid enclaves are back-veined by the diorite. Hybridisation in which the dioritic host is present as tiny veins or as scattered remnant crystals or composite grains of plagioclase and hornblende along the contacts of the intruding gabbro or gabbro-dominated hybrid magma is common. These relationships demonstrate that the hornblende-gabbroic intrusions were emplaced into the hornblende diorite when a significant fraction of melt was still present in the latter. This led to mingling and hybridisation between the intruding gabbroic melt and the pre-existing crystal mush.

Mafic dykes in the Layered Series

Peridotite and olivine gabbro dykes

The olivine gabbros of the LZ have been intruded by an early generation of steeply dipping, N-S striking, peridotite dykes almost at right angles to the modal layering. These were closely followed in time by medium-grained olivine gabbro dykes (Fig. 5). These dykes have been observed only at a few localities in the central-northern part of the LZ and seem to be a relatively local feature of the GIC. (The dykes are not shown in Fig. 2). They have widths of 0.5-1 m and can be followed along strike for up to 100 m. Their margins show no evidence of chilling, but features such as bridging and offset of the layers in the olivine gabbro indicate that the host rock was sufficiently rigid to be fractured at the time of dyke emplacement. In places, the pattern of intrusion of the dykes is sinuous. There is also local fine interdigitation of veins of dyke material with the host rock. Locally, the peridotitic dykes appear to have replaced or mechanically eroded plagioclase-rich layers in the LZ olivine gabbro.

Hornblende-gabbroic dykes

Hornblende-gabbroic dykes are numerous in both the LZ and the MZ, but there is a gradual decrease in the frequency of dykes towards the upper part of the MZ (not shown in Fig. 2). Where cross-cutting relationships can be observed, the hornblende-gabbroic dykes are consistently younger than the peridotite and olivine gabbro dykes. However, close similarities in orientation and the intrusion pattern suggest that they have a common origin. This is particularly evident where olivine gabbro dykes and then hornblende-gabbroic dykes have followed along the same sinuous path as peridotite dykes (Fig. 5), and where all these dykes show the same, partly branching, pattern of intrusion in the enclosing layered olivine gabbro.

The composition of these rocks ranges from magnetite-bearing hornblendite through hornblende gabbro and locally into anorthositic varieties. The dykes are fine- to medium-grained, and generally have a laminated texture caused by the preferred orientation of hornblende and plagioclase parallel or sub-parallel to the contact. Commonly, these dykes have a fine lamination or banding parallel with their margins. Individual laminae/ bands of 1-2 mm thickness are commonly fluently folded into open structures. Locally, a banding reminiscent of modal layering occurs nearly at right angles to the dyke walls (Fig. 5).

The dykes are traceable along strike for 20 to 50 m before they wedge out or merge with other dykes of similar composition. Their width is generally between 2 and 20 cm, but can be less than a centimetre, extending along strike for several metres. Dykes wider than a metre only occur locally. Chilled contacts are never observed, but where dykes intrude larger

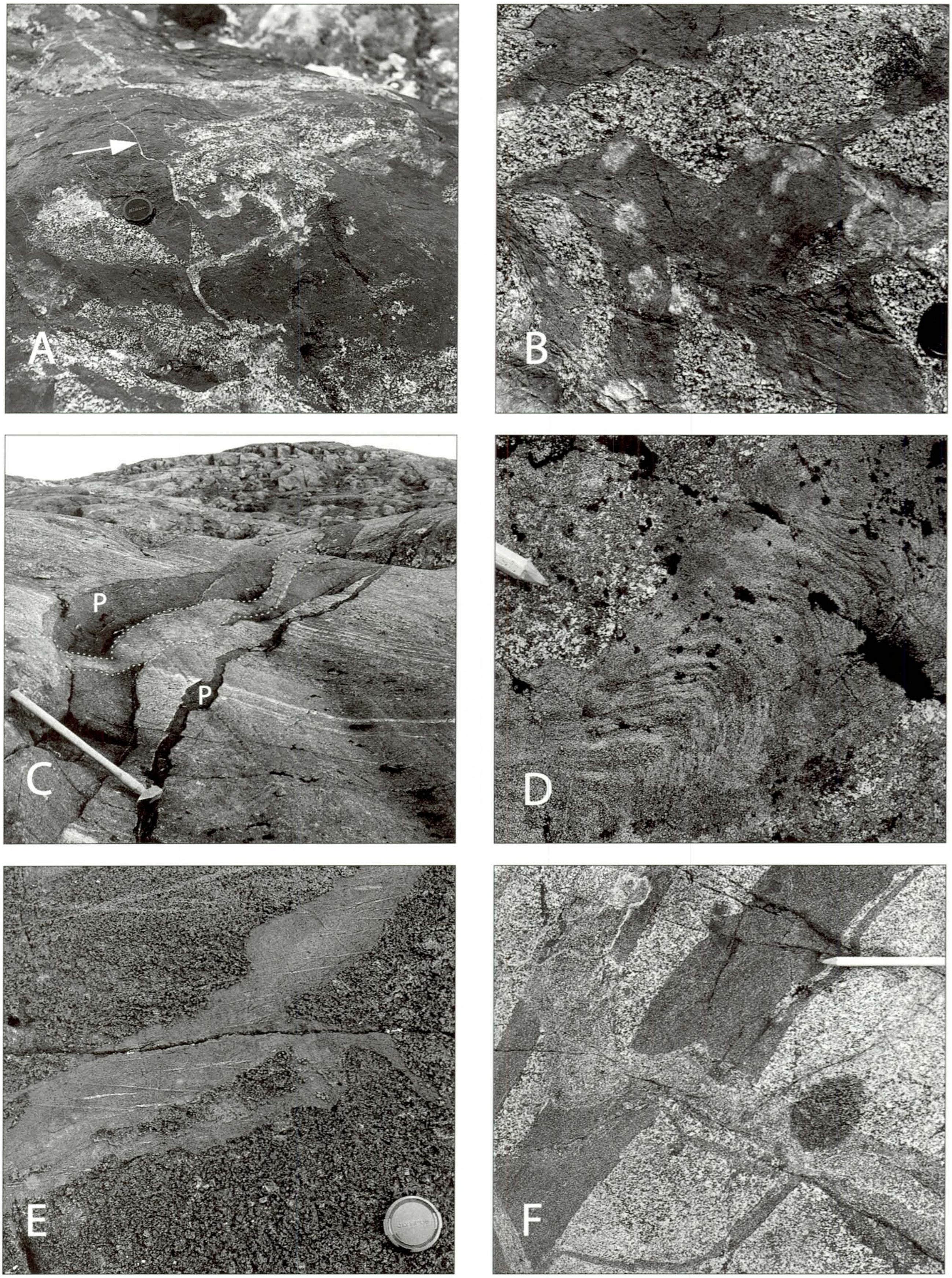

Fig. 5. A. Complex, mutual intrusive relationships between co-mingling hornblende diorite (light) and microgabbro (dark). Back-veining of the hornblende diorite into the microgabbro is marked with an arrow. Outcrop located along the river Skorovasselva. B. Close-up of hornblende microgabbro, forming complex bodies of variable thickness in hornblende diorite. Outcrop located along the river Skorovasselva. C. Coarse-grained peridotite dykes (dark brown, marked with P), succeeded and partly cut by a subparallel, thinner dyke of olivine gabbro (pale brownish-grey, weakly outlined in white). The dykes intrude layered olivine gabbro of the Lower Zone nearly at right angles. Located in the central part of the Lower Zone. D. Hornblende-gabbroic dyke in the eastern part of the Middle Zone gabbronorite. The dyke displays a weak plastic folding of the modal banding which may be due to lateral magma flow. E. Hornblende-gabbroic dyke in the Lower Zone, showing branching apophyses into the host olivine gabbro. Located in the central part of the Lower Zone. F. Dykes of hornblende gabbro (dark) and succeeding hybrid intrusions (medium grey) in gabbronorite (light grey) of the Middle Zone. Located in the eastern part of the Middle Zone. The circular dark area is a wet spot.

blocks of the coarse-grained olivine gabbro, they seem to follow angular fractures in the rock. In contrast, the pattern of intrusion into the layered olivine gabbro and the gabbronorite is complex (Fig. 5), and individual dykes commonly branch into a fine web of thin veins in the layered gabbro.

The contacts of the dykes in the MZ are locally well defined. However, mixing and mingling is also quite common and obviously related to intrusion of the dykes into the gabbronorite at a late-magmatic stage. This process has resulted in transitional boundaries between the hornblende-gabbroic dykes and the gabbronoritic host rock and a variety of complex, mutual, intrusive relationships (Fig. 5).

Pegmatitic dykes

The hornblende-gabbroic dykes in the Layered Series are commonly accompanied by pegmatitic dykes of a similar composition (Fig. 6). These are found mainly in the LZ, but dykes of this type are also observed more locally in the MZ gabbronorite. They usually show a more rectilinear pattern of intrusion than their finer grained counterparts, but the two varieties were evidently closely related in time and space since some of the hornblende-gabbroic dykes are cut by pegmatite whereas others cut the pegmatitic dykes themselves. In some cases transitional boundaries have been observed, providing further evidence of their close relationship.

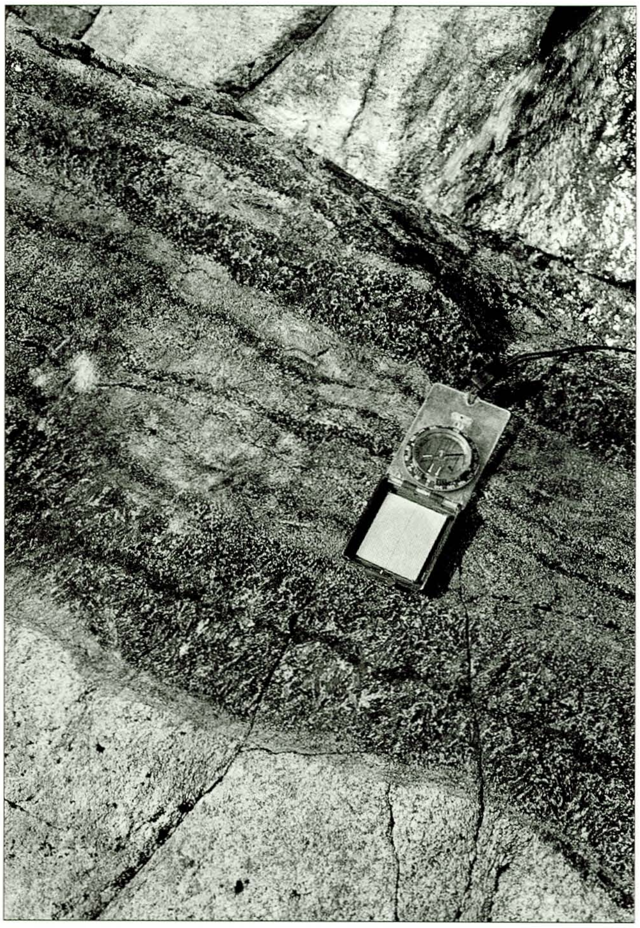

Fig. 6. Composite, pegmatitic to fine-grained, hornblende-gabbroic dykes intruding olivine gabbro. The preferred crystal growth of hornblende perpendicular to the contacts is well developed below the compass. Located in the easternmost part of the Lower Zone.

The width of hornblende-gabbroic pegmatite dykes varies from 20 cm to 1 m and individual dykes can be followed for up to 300 m along strike. The texture is striking, with crystals of hornblende up to 10 cm growing perpendicular to the walls. Commonly they show conspicuous bilateral banding parallel to their contacts in which hornblende-rich and plagioclase-rich, or fine- and coarse-grained layers alternate. The euhedral hornblende crystals have nucleated along the contacts with the host rock, along small xenoliths of host rock in the dykes or along the contacts to hornblende-gabbroic dykes (Fig. 6). In hornblende-rich bands, plagioclase and minor amounts of magnetite and sulphides occupy the interstitial matrix.

Relationships between the Layered Series and the wall rocks

The contact between the MZ gabbronorite, the UZ quartz diorite and the metavolcanic wall rocks is locally sharp and can be defined within centimetres. However, more commonly the contact is a transitional zone 10-50 m thick, in which either gabbronorite or quartz diorite form a network of veins along cracks and fractures in the wall rock (Fig. 7), the veins being thinner and more scarce outwards. On the map (Fig. 2) the contact is defined along a zone where intrusive rocks predominate over wall-rock material.

The metavolcanic wall rocks near the eastern contact of the Layered Series have a pronounced N-S to NW-SE foliation with westerly dips of 30-45°. The rocks vary from a strongly sheared state in which pillow structures and dyke contacts are still recognisable, to a completely penetrative mylonite. In places, this zone of deformation is cut by the intrusive network originating from the Layered Series (Fig. 7).

Locally, the net of gabbronoritic or quartz dioritic veins emanating from the intrusion is cut by, or has mingled with, very leucocratic quartz-feldspar-rich veins. Both at outcrop and in thin-section, these leucocratic veins show progressive transitions in composition towards that of the metavolcanic host rock. Compared with typical rocks of the Skorovass Complex, these metavolcanic wall rocks appear to be more recrystallised and depleted in felsic minerals, and it is likely that the leucocratic veins are leucosomes formed by partial melting of the metavolcanic rocks. Thick leucosome veins locally contain inclusions of gabbronorite and quartz diorite which appear to have been at least partly crystallised at the time of emplacement.

Along the contact zone, the foliation described above is locally overprinted by zones of super-ductile shearing in which migmatite-like rocks are developed. These migmatites consist of a chaotic mixture of highly sheared MZ gabbronorite or UZ quartz diorite and undeformed veins of similar composition, and variably deformed wall rocks which show transitions into sheared as well as undeformed leucosome veins (Fig. 7). In places, the leucosome veins clearly cut the zones of ductile deformation.

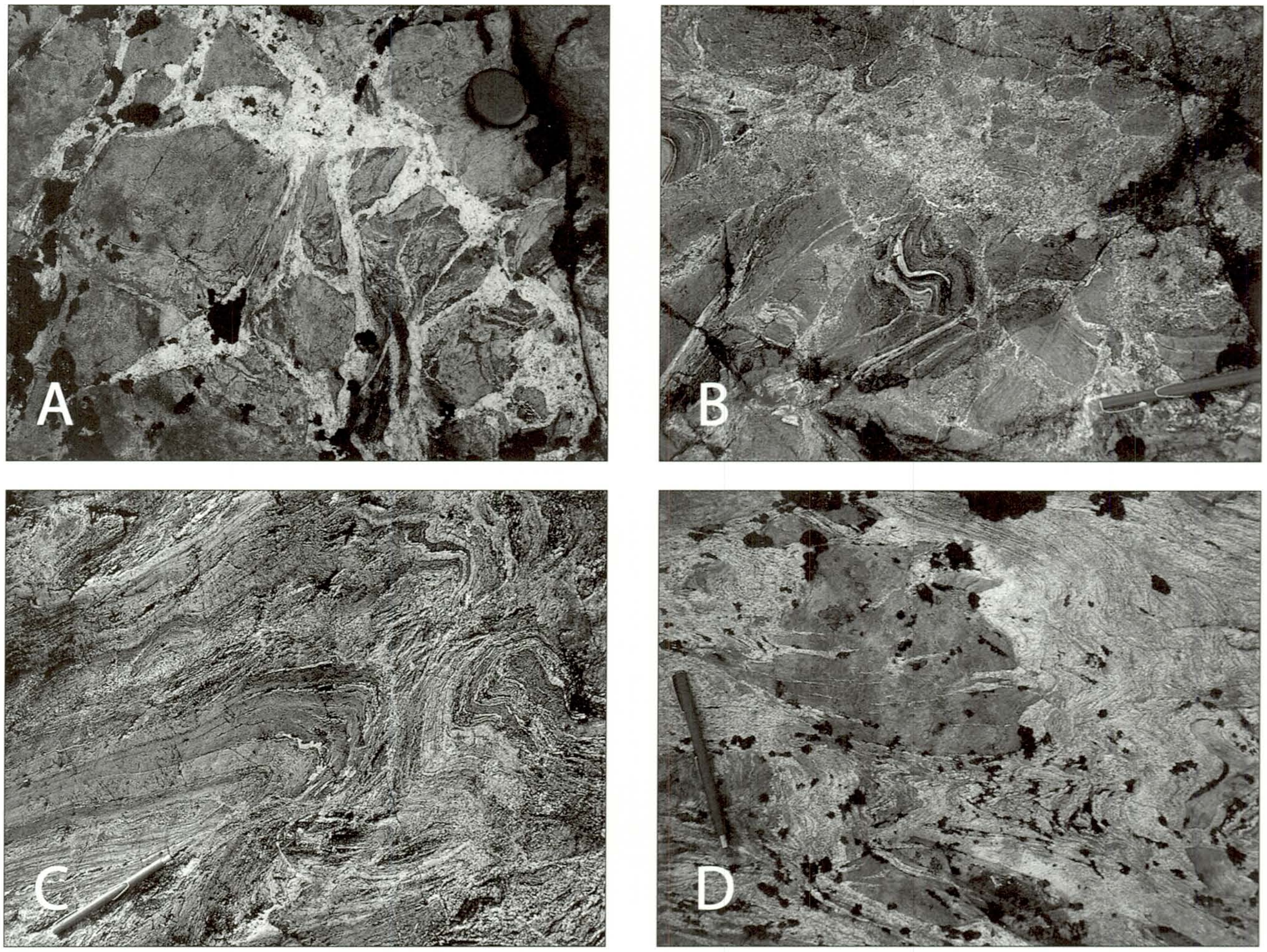

Fig. 7. A. Net-veining of metavolcanic wall rock by quartz diorite at the southeastern wall-rock contact of the Layered Series. B. Fragments of partly sheared metavolcanic rocks in a matrix of undeformed quartz diorite. Eastern part of the contact zone of the Layered Series. C. Ductile deformation of sheared metavolcanic wall rocks in the contact zone of the Layered Series. The outcrop is located 10 m from that of B. D. Leucosome and relics of metavolcanic rocks in the eastern contact zone of the Layered Series. A marked deformation fabric is present in both the leucosome and the metavolcanic rocks; however, this is locally cut by undeformed leucosome veins.

In the area southeast of the lake Fjellskarvtjørna (Fig. 2), the highly ductile shear zone along the intrusive contact is cut by a semi-ductile shear zone 2-3 m wide. This separates the Layered Series and its contact zone from moderately deformed metavolcanic rocks. This later shear zone continues westwards along the southern margin of the GIC to the area of Murfjellet. It is cut by an even later, 3-5 m wide, sinistral shear zone with a mylonitic fabric running N-S along the eastern contact of the Layered Series (Fig. 2). To the northwest, a 20 to 30 m-wide thrust zone separates the rocks of the Skorovass Complex from a sheet of biotite-bearing gneiss, mica schist and deformed granodiorite which forms a distinct subdivision within the Gjersvik Nappe. This was termed the Tunnsjøelv Thrust Sheet by Reinsbakken & Halls (1987).

Petrography

Wall-rock xenoliths

In the metavolcanic xenoliths, the original wall rocks have been recrystallised so that they have a marked granular texture (Fig. 8). The texture and mineralogy of the reaction rims mimic the mineralogy of the surrounding rocks of either olivine gabbro or gabbronorite. The mineralogy is made up by plagioclase (50-60%), Ca-rich pyroxene (10-20%) and Ca-poor pyroxene (15-25%), magnetite (1-3%), minor ilmenite and pyrite (<1%), brown hornblende (2-10%, in places >30%) and locally 10-20 mm-large poikilitic olivines (1-5%).

The anorthositic xenoliths consist chiefly of strongly saussuritised plagioclase. Some plagioclase crystals show slight bending of albite twin lamellae. This type of deformation is not observed in the surrounding layered olivine gabbro and was apparently imposed prior to emplacement of the GIC.

Xenoliths of coarse-grained olivine gabbro

The coarse-grained olivine gabbro consists mainly of euhedral to rounded olivine (1-4 mm), which forms an adjoining network of grains (Fig. 8). However, at both the outcrop and the thin-section scale, euhedral phenocrysts of plagioclase from 2 to 10 mm in diameter form the most obvious component of the texture. A few small grains of plagioclase may be

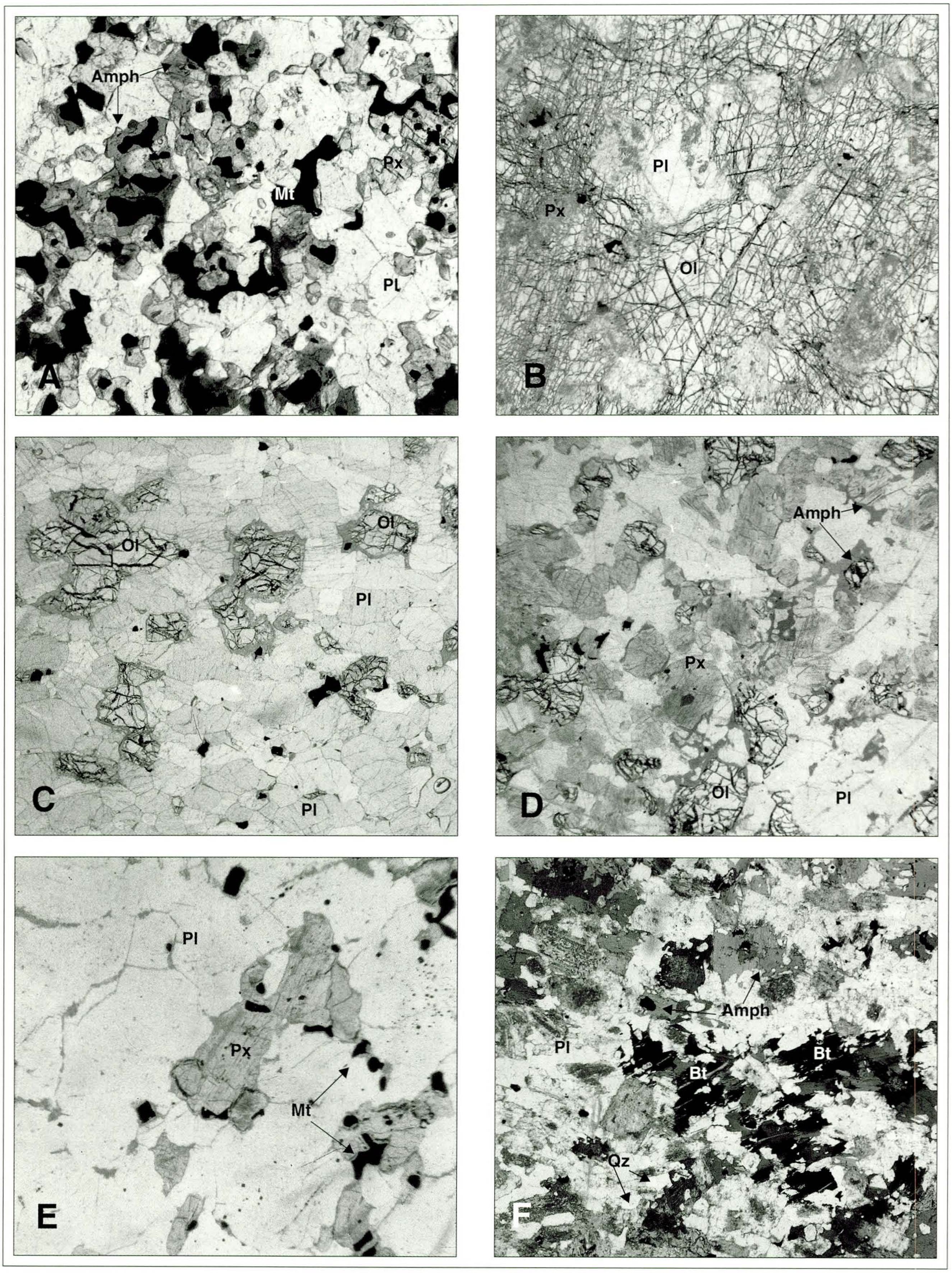

Fig. 8. Photomicrographs of the textures in thin sections. All photos are 8mm in width and height. A. Metavolcanic wall rock xenolith in Lower Zone. B. Coarse-grained olivine gabbro in xenolith in Lower Zone. C. Troctolite in Lower Zone. D. Olivine gabbro in Lower Zone. E. Gabbronorite from Middle Zone. F. Quartz diorite from Upper Zone. Abbreviations: pl = plagioclase, px = pyroxene, mt = magnetite ± minor ilmenite, amph = amphibole, ol = olivine, qz = quartz and bt = biotite.

enclosed in the cores of larger olivines. The modal proportions of olivine and plagioclase are typically 45-60% and 25-40% respectively, but more dunitic and anorthositic layers occur. Ca-rich pyroxene and locally brown hornblende form oikocrysts 1-10 cm in size which occupy 10-15% of the modal volume. In addition, 0.5 to 1% of magnetite with lamellae of ilmenite occurs as interstitial, partly oikocrystic grains. Ca-poor pyroxene is present as coronas around olivine.

Serpentinisation and formation of magnetite from olivine is common along thin fractures running across grain boundaries. Coronas due to reaction between plagioclase and olivine and alteration of Ca-rich pyroxene and brown hornblende to green amphibole are common along mafic dykes.

The Layered Series

The Lower Zone

The LZ olivine gabbro consists dominantly of plagioclase (60-70%) and olivine (15-25%), with variable amounts of Ca-rich pyroxene and minor magnetite (Fig. 8). Compared with the xenolithic coarse-grained olivine gabbro, the texture of the rock is finer-grained and less poikilitic. Plagioclase is tabular with grain boundaries partly controlled by adjacent olivine, and there is a tendency for plagioclase to form laminated aggregates. The grain size varies from 1 to 3 mm; however, smaller grains (<0.5 mm) are enclosed in the cores of single olivine grains. Olivine (0.5-1 mm) is anhedral to rounded and locally has a reaction rim of Ca-poor pyroxene.

Ca-rich pyroxene is rare in the lower part of the LZ, but becomes more abundant upwards where it forms subhedral grains of 1 to 2 mm in size (Fig. 8). Locally, this pyroxene forms oikocrysts enclosing small rounded chadacrysts of plagioclase. The Ca-rich pyroxene contains thin, densely spaced lamellae of Ca-poor pyroxene, in addition to hair-like lamellae of exsolved magnetite. Brown hornblende occurs as small, interstitial grains (<2 %), but near metavolcanic xenoliths, bigger, oikocrystic hornblende grains (1-5 mm) are abundant. Magnetite with exsolved ilmenite occurs as small oikocrysts, generally closely associated with Ca-rich pyroxene.

Coronas are formed locally around olivine in contact with plagioclase, especially along mafic dykes in the gabbro. The coronas consist of an inner rim of Ca-poor pyroxene and an outer rim of green amphibole with symplectitic spinel towards the plagioclase. Along dyke contacts, olivine may be partly to completely replaced by a symplectic intergrowth of Fe-Ti oxide and Ca-poor pyroxene.

The Middle Zone

The gabbronorite of the MZ contains variable amounts of plagioclase (60-65%), Ca-rich pyroxene (20-25%) and Ca-poor pyroxene (15-20%) in addition to magnetite (2-4%), brown hornblende (0-4%) and locally apatite (<0.5 %) (Fig. 8). Plagioclase and Ca-poor pyroxene are commonly tabular and display a clear magmatic lamination which is subparallel to modal layering in the gabbronorite. The Ca-poor pyroxene contains small plates of more strongly pleochroic brown amphibole arranged along crystallographic planes. Ca-rich pyroxene occurs either as tabular grains or as medium-sized (2-4 mm) oikocrysts which include rounded grains of plagioclase. The Ca-rich pyroxene is locally associated with a rim of pleochroic brown hornblende, probably representing a late-magmatic overgrowth on the pyroxene. Brown hornblende forms oikocrysts with inclusions of Ca-poor pyroxene and magnetite, particularly near metavolcanic xenoliths. Interstitial magnetite, partly with smaller grains of ilmenite, is closely connected with Ca-rich pyroxene. Apatite forms small euhedral grains (<0.2 mm) which are partly or completely enclosed in plagioclase.

The Upper Zone

The quartz diorite of the UZ consists mainly of plagioclase (40-55 %), brown hornblende (15-29 %), biotite (10-15 %), Ca-rich and Ca-poor pyroxene (5-15 %), quartz (5-10 %) and minor amounts of magnetite (1-2 %), apatite and sulphides (Fig. 8). From north to south, there is a general increase in the quartz and biotite contents at the expense of pyroxene. The plagioclase is mostly euhedral, forming laths and tabular grains of 0.5 to 3 mm in size. Hornblende forms large oikocrysts (1.5 cm) with chadacrysts of plagioclase and pyroxene. Biotite is finer grained but otherwise shows a similar texture. Ca-rich and Ca-poor pyroxene both form clusters of subhedral tabular or prismatic grains of relatively small size (0.2-1 mm). Ca-rich pyroxene is present throughout the UZ, whereas the occurrence of Ca-poor pyroxene is restricted to the lower part of the UZ. Quartz is clearly interstitial to all other mineral phases. Magnetite is present as small, rounded to oikocrystic grains.

The gabbroic to dioritic domains in the UZ are texturally variable but generally coarser grained compared to the 'normal' UZ quartz diorite. The amounts of both Ca-rich and Ca-poor pyroxene are higher, whereas quartz, brown hornblende and biotite are less abundant (0-5 %). The granodioritic to quartz monzodioritic veins and dyke-like bodies in the UZ are fine- to medium-grained and equigranular, and are characterised by subhedral to euhedral grains of alkali feldspar (~10%) and plagioclase (25-30%). The content of quartz as interstitial grains varies between 40 and 50%. Minor amounts of calcite and biotite are present locally.

The fine-grained doleritic intrusions, present both as individual dykes in the UZ quartz diorite and in the composite dykes together with the granodioritic to quartz monzodioritic material, consist mainly of partly saussuritised plagioclase and brown hornblende (variably altered to green amphibole) together with minor amounts of clinopyroxene and biotite. Highly porphyritic, plagioclase-rich varieties can be seen locally, and some dykes contain conspicuous clots or glomerocrysts composed mainly of hornblende. Up to 10% quartz can be present in the mafic portions of composite dykes. Interstitial grains of opaque minerals, mainly magnetite, make up from 1 to 5% of the rock.

The hornblende-diorite-gabbro series

The hornblende-diorite-gabbro series is, in general, more altered by metamorphism than the Layered Series. Locally, unaltered or moderately altered parts composed mainly of plagioclase and brown hornblende with subordinate magnetite and apatite are preserved. Quartz is present as a minor phase locally in the central to northern parts of the intrusion. The textures, grain size (0.5-5 mm) and the modal proportions are highly variable. Plagioclase and primary brown hornblende are mostly subhedral. Rims of hornblende around cores of Ca-rich pyroxene were formed by syn- or late-magmatic overgrowth on the pyroxene. Parts of the diorite show a conspicuous texture defined by growth of long, euhedral, hornblende crystals with interstitial plagioclase. The grain size varies from pegmatitic (1-5 cm) to fine-grained (<1 mm). Quartz is present as small interstitial grains (<0.2 mm). Magnetite is present as rounded individual grains and as small poikilitic grains, whereas apatite forms small euhedral grains mainly included in hornblende.

The hornblende-gabbroic intrusions in the diorite have mineralogies and textures similar to those of the hornblende-gabbroic dykes described below.

Mafic dykes in the Layered Series

Peridotite and olivine gabbro dykes

The peridotite and olivine gabbro dykes both have equigranular, cumulate-like textures. The peridotite dykes are composed of olivine with interstitial plagioclase and minor Ca-rich pyroxene, the olivine gabbro dykes of plagioclase, olivine and Ca-rich pyroxene. Ca-poor pyroxene occurs as reaction products around grains of olivine in both types of rock, and oikocrysts of brown hornblende are common in the olivine gabbro dykes.

The peridotite dykes are coarse-grained with a grain size of 5-10 mm. Partly serpentinised olivine forms a densely granular matrix in which subhedral plagioclase phenocrysts and oikocrystic Ca-rich pyroxene are scattered. Magnetite occurs exclusively as a reaction product of the serpentinisation of olivine. The olivine gabbro dykes are fine-grained (0.1 to 1 mm) and have a partly granular texture in which are combined rounded grains of olivine, rounded to subhedral grains of plagioclase, oikocrystic Ca-rich pyroxene (1-2 mm), and interstitial brown hornblende which coexists with varying amounts of subhedral magnetite and ilmenite. Plagioclase forms a continuous network and is the dominant phase.

Hornblende-gabbroic dykes

These dykes consist of hornblende, plagioclase and magnetite in variable modal proportions. In general, hornblende is the dominant mineral and a few dykes are purely hornblenditic. Hornblende and plagioclase have a grain size of 0.1 to 0.5 mm and are largely euhedral. Magnetite is generally smaller than 0.1 mm and is almost exclusively associated with brown hornblende. In most dykes there is a marked preferred orientation of elongate plagioclase and hornblende grains subparallel to the contacts.

Contacts between the dykes and the olivine gabbro are characterised by symplectitic intergrowths of Fe-Ti-oxide and Ca-poor pyroxene, as well as corona structures between plagioclase and olivine (see also above) in the host olivine gabbro. These features are common over an interval of a few centimetres along the contact. Single grains of plagioclase from the host rock are enclosed and evenly distributed within the hornblende-gabbroic dykes. Grains of olivine also occur in the dykes, but only along the contacts and always partly or completely altered to a symplectitic intergrowth of Fe-Ti oxide and Ca-poor pyroxene.

Discussion

For descriptive purposes, the Grøndalsfjell Intrusive Complex and surroundings have been subdivided into nine distinct geological units that have been mapped on the basis of field observations, petrography and mineralogy. The magmatic relationships and modes of emplacement of these units are described below.

Wall rocks

The oldest rocks recognised in the Grøndalsfjell area are the metamorphic volcanic and intrusive rocks of the Skorovass Complex, forming both the wall rocks to the GIC and xenoliths within the GIC. The general absence of primary textures in the xenoliths implies that they recrystallised and reacted with the gabbroic melt to a completely new mineralogy and texture. The presence of a reaction zone around most xenoliths in the olivine gabbro and gabbronorite is further evidence of interaction with the enclosing melt. The origin of the anorthositic xenoliths is more ambiguous and from the present observations it is not possible to deduce their origin in any detail. They may be a part of the assemblages of pre-GIC subvolcanic intrusive rock, because they locally form inclusions within xenoliths of the coarse-grained olivine gabbro, but they could also represent an early crystallisation phase from the same magma from which the coarse-grained olivine gabbro crystallised.

A penetrative foliation is observed throughout the metavolcanic sequence. This is not seen in the GIC, and there is little doubt that the metavolcanic rocks of the Skorovass Complex were affected by regional deformation and associated metamorphism prior to emplacement of the GIC. Close to the contact zone of the Layered Series, this early, regional foliation is transposed into a complex, ductile and partly mylonitic shear zone which is sub-parallel to the intrusive contact. Along this intrusive contact, there is compelling evidence of extensive partial melting of the metavolcanic wall rocks. Within the temperature regime of at least the UZ, significant melting of basaltic rocks with formation of strongly quartzo-feldspathic melts, can be interpreted only in terms of melting of a hydrous mineral assemblage such as greenstone or amphibolite (Helz 1976). The observed complex relationships between leucosomes, intrusive rocks and shearing implies that the ductile deformation was penecontemporaneous with the intrusive emplacement of the GIC. It is not clear, however, whether the deformation was a result of the intrusive event or if it was related to a tectonic event of more regional significance.

Xenoliths of coarse-grained olivine gabbro

The presence of coarse-grained olivine gabbro only as xenoliths implies that they had crystallised prior to the generation of the Layered Series. However, no coarse-grained olivine gabbro has been observed in the wall rocks in areas adjacent to the GIC, and xenoliths of metavolcanic wall rocks have not been observed in the coarse-grained olivine gabbro, even though xenoliths of coarse-grained olivine gabbro and metavolcanic rocks occur close to each other in the LZ of the Layered Series. From the present distribution of xenoliths it is suggested that the coarse-grained olivine gabbro intruded the metavolcanic sequence in the form of a macro-dyke or a body of uncertain dimensions. This was subsequently engulfed and incorporated into the Layered Series which may have intruded along the same general path in the crust. A relationship between the two, where the coarse-grained olivine gabbro represents an early magmatic stage of the GIC, is strongly supported by the many textural and mineralogical similarities to the Layered Series. Trace element geochemistry, isotopic data and mineral chemistry, now under investigation, are in accordance with a model in which the coarse-grained olivine gabbro crystallised from a precursor, more primitive magma than the cogenetic Layered Series. If so, the coarse-grained olivine gabbro must have been in a sufficiently crystalline state prior to intrusion of the Layered Series to allow fracturing, which produced the observed angular form of the xenoliths and dykes-filled fractures.

The Layered Series

The subdivision of the Layered Series is based on phase layering. Olivine is present in the LZ and is replaced by Ca-poor pyroxene in the MZ. Quartz and biotite are the minerals diagnostic of the UZ. The general sequence of the cumulate stratigraphy leads to the conclusion that the three zones of the Layered Series evolved by fractional crystallisation within a single magma chamber. Although a more detailed reconstruction of the intrusion history is beyond the scope of the present account, the field relationships and petrographical data provide several constraints on the magmatic evolution. One important parameter is the distribution of xenoliths, which are concentrated within the LZ, MZ and the uppermost part of the UZ. The high density of xenoliths in these parts indicates that local stoping of the roof was an important and continuous process during crystallisation of the Layered Series. Large-scale, continuous stoping would certainly indicate the repeated or continuous injection of magma into the chamber. This is in accordance with the character of the LZ, which consists of a rather monotonous pile of fairly primitive cumulates, up to 3 km thick, which would have formed by the more or less continuous influx of parental magma. The upward transition into somewhat more differentiated cumulates, still with abundant xenoliths in the MZ, suggests that magma replenishment gradually decreased over this interval. The absence of xenoliths in the lower part of the UZ, on the other hand, implies a break in the stoping activity at the time when this part of the intrusion was crystallising. This is consistent with the appearance of the relatively evolved rocks in this part of the Layered Series, indicating a period of fractional crystallisation without injection of new magma into the system.

Peridotite and olivine gabbro dykes in the Lower Zone

The peridotite and the olivine gabbro dykes intrude and obviously post-date the layered olivine gabbro of the LZ. It is not clear whether the apparent lack of such dykes higher up in the Layered Series is a real feature or is related to a lack of observations due to their general scarcity. The pattern of intrusion of these dykes suggests that the physical properties of the cumulate pile controlled the vertical ascent of the parental melts. They must have intruded at a stage when the surrounding cumulates were sufficiently solidified to sustain fracturing and channel the vertical flow of the magma. However, the branching and web-like veining shown by these and the succeeding hornblende-gabbroic dykes, shows that crystallisation of the host cumulates was not complete. Absence of chilled margins and evidence of replacement also suggest that the hot host rocks were still hot. The mineralogy and textures of the dykes suggest that they were not emplaced as normal melts, but rather as cumulate mush formed by crystal fractionation processes within the magma conduit. If so, the crystals were transported in suspension, not crystallised in situ. This process of hybrid cumulate emplacement is also supported by geochemical studies now in progress.

There are two possible explanations for the emplacement of the dykes. Either they were dykes feeding the more or less continuous magma influx required to form the thick LZ, or they were a new generation of primitive melt injection into the GIC. The first alternative would be consistent with the apparently restricted occurrence of the peridotite and olivine gabbro dykes within the LZ, but their more primitive mineral compositions as compared to the LZ olivine gabbro contradicts this (Meyer et al., in prep.). The second possibility is considered more likely in view of the intimate relationships between these dykes and the succeeding hornblende-gabbroic dykes which undoubtedly post-date the LZ as well as the MZ. In this case, subsequent differentiation of this new generation of magma would be necessary to produce more evolved mineral compositions in the dykes of the hornblende gabbro generation. This would imply that the parental magmas of the Layered Series on the one hand, and of the peridotite, olivine gabbro and hornblende-gabbroic dykes on the other, were supplied from separate magma chambers or, alternatively, from a zoned magma chamber at depth.

Hornblende-gabbroic dykes in the Lower and Middle Zone

The nature of the intrusion pattern of hornblende-gabbroic dykes into the LZ shows that these dykes, like in the case of the dykes of peridotite and olivine gabbro, were emplaced at a time when the surrounding cumulate pile was not completely solidified. Furthermore, their compositions, ranging from that of almost pure hornblendite to anorthosite, imply crystal-melt separation within the magmatic conduits, but it is uncertain whether this took place by fractional crystallisation in situ or by emplacement of suspended crystals that had grown at greater depth. The cumulate nature of the dykes is also shown by their locally 'layered' appearance and by geochemical studies in progress. Crystal separation within the conduit would be favoured by very slow rates of cooling and crystallisation within the high-temperature regime of the enclosing cumulates, allowing in situ fractionation of melt from an ascending crystal-melt suspension or crystal mush.

Similar dykes are found at higher levels in the MZ. Here, however, there is also evidence of extensive mingling and hybridisation of gabbronorite and the hornblende-gabbroic dykes, implying that, when the latter were emplaced, parts of the MZ was an incoherent crystal mush in which the two members were able to form a new, hybrid mixture.

Composite dykes in the Upper Zone

The abundant evidence of magma mingling in the composite dykes, as well as between mafic intrusions and normal UZ quartz diorite, clearly shows that the mafic melts were injected into this part of the magma chamber at a stage when it was only partly crystallised. Physical mixing of the mafic and felsic components, with formation of hybrid, intermediate melts, has taken place only on a minor scale, probably due to rapid cooling of the intruding mafic magma by the enclosing, cooler, SiO_2-rich melts. The presence of chilled margins locally in mafic enclaves shows this to have been the case. The occurrence of these mafic intrusions in the UZ and the mineralogically comparable, 'cumulate-type' dykes at lower levels in the Layered Series, suggests that there is a genetic link; however, additional data are required to confirm such a relationship.

The hornblende-diorite-gabbro series

Work in progress shows that the fine-grained, hornblende-gabbroic intrusions in the hornblende-diorite-gabbro series and the hornblende-gabbroic dykes in the Layered Series have similar, distinctive mineralogical and geochemical compositions. This suggests that they are both products of the same magmatic event. In the Layered Series, the dykes have intruded host rocks which were obviously in a more or less coherent crystalline state. In contrast, the equivalent rocks intruding the hornblende-diorite-gabbro series show complex patterns in which mingling with a pre-existing crystal mush is common. Also, the high contents of magmatic hornblende and partly magnetite, which characterise the hornblende-gabbroic intrusions, indicate a close relationship with the diorite. Thus, there is little doubt that the dioritic complex post-dates the Layered Series, although exposures of intrusive contacts are difficult to find. The lack of a chilled contact may be due to the short gap in time separating the intrusion of the two magma series. The evidence for intrusion of hornblende-gabbroic dykes into hot rocks of the LZ and crystal mush of the MZ in the Layered Series supports this conclusion. It is possible, although speculative, that processes such as post-cumulus hydration and/or infiltration metasomatism may have further obliterated the intrusive contact between the hornblende-diorite-gabbro series, which evidently was hydrous in view of its extremely hornblende-rich character, and the Layered Series which may still have contained a certain proportion of intercumulus melt. This would explain the apparent gradual increase of hornblende in the LZ olivine gabbro over an interval of 50-100 m from the inferred contact.

Granodioritic dykes

The latest magmatic event represented in the Grøndalsfjell area is the emplacement of a swarm of cross-cutting, granodioritic dykes. Compositional similarity with the Møklevatn granodiorite (456 ± 2 Ma) suggests that there is a close relationship between these intrusions. This is supported by the intrusive nature of the Møklevatn complex against GIC equivalents to the west-southwest (Heimdalshaugen, Fig. 1), implying that 456 Ma is a minimum age for the GIC. The tectonic phase responsible for the tilting of the GIC as well as of the granodiorite complex into their present position was probably related to nappe movements during the later, Scandian phase of the Caledonian orogeny. A reflection of this is seen in the local shear zones enveloping the GIC and other intrusive bodies in the Gjersvik Nappe (Halls et al. 1977) and similar deformation localised along granodiorite dykes in the GIC.

Conclusions

Field relationships and petrography suggest the following magmatic evolution of the pre-456 Ma Grøndalsfjell Intrusive Complex:

1. Intrusion of relatively primitive basic magma with crystallisation of coarse-grained olivine gabbro in a macro-dyke or smaller intrusive body.
2. Subsequent intrusion of more evolved basaltic melts to form a large magma chamber in which the Layered Series eventually crystallised. Active stoping in response to a continuous influx of magma led to incorporation of abundant xenoliths and formation of the layered olivine gabbro in the LZ as a thick cumulate pile.
3. Decrease or interruption of the supply of magma led to fractional crystallisation and the gradual evolution from olivine gabbro in the LZ to variably crystallised gabbronorite in the MZ, and quartz dioritic crystal mush with coexisting residual melts in the UZ.
4. New influx of magma from deeper crustal levels led to emplacement of a large intrusive body - the hornblende-diorite-gabbro series - in the lower part of the Layered Series. The magmas were hydrous and hornblende formed the predominant mafic cumulus phase. Continuous or intermittent replenishment by comparable mafic magma was accompanied by mingling of dioritic crystal mush.
5. Penecontemporaneous injection of basic magma or crystal-melt suspension along dykes in the Layered Series followed. Crystal-melt fractionation took place within conduits and led to formation of peridotite, olivine gabbro and hornblende-gabbroic 'cumulate-type' dykes in the LZ and UZ. Coeval mafic magma, supposedly representing the melt counterparts of the 'cumulate-type' dykes, was injected into crystal mush and residual melts in the UZ of the Layered Series.

6. Emplacement of granodioritic dykes possibly related to the 456 Ma Møklevatn granodiorite terminated the magmatic history.

The rocks of the Grøndalsfjell area were affected by shearing both before and after intrusion of the GIC. Particularly intense ductile shearing was localised along the contact zone of the intrusion and much of this deformation was evidently contemporaneous with the intrusive event.

The GIC intruded into previously deformed and metamorphosed volcanic and related intrusive rocks of the Skorovass Complex. Along the walls of the intrusion, these rocks were partially melted. Similar processes must have affected the metavolcanic xenoliths in the Layered Series, although the only evidence of this is pervasive recrystallisation and the formation of pegmatitic reaction rims. The effects of this melting on the overall magmatic evolution of the GIC cannot be resolved on the basis of field relationships and petrography alone. However, the large amounts of leucosome generated along the walls, and the very high density of wall-rock xenoliths in parts of the magma chamber, obviously point to the possibility of wall rock/magma interaction being an important process. It is the intention to investigate this phenomenon in the future.

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