Tectonostratigraphy in the Velfjord-Tosen region, southwestern part of the Helgeland Nappe Complex, Central Norwegian Caledonides

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In the southwestern parts of the Helgeland Nappe Complex, dismembered ophiolites and their cover sequences are imbricated together with nappes consisting dominantly of continentally derived rock units. A local nappe sequence comprises three nappes, informally termed the Lower, Middle and Upper nappes. The Lower and Upper nappes consist of partly migmatitic mica gneisses and orthogneisses associated with marbles and calc-silicate gneisses. Between these nappes, the Middle nappe includes an igneous complex of mafic and ultramafic rocks of ophiolitic affinity, unconformably overlain by a cover sequence with material derived partly from the ophiolite substrate.
Plutonic rocks, ranging from hornblende gabbros to diorites and granites, were emplaced at several stages during the tectonometamorphic evolution of the region. Based on comparison with nearby areas, most of the regional metamorphism and deformation would seem to have occurred in the Ordovician, with a later phase of thrusting during the Mid Silurian to Early Devonian Scandian orogeny.

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Introduction

During the past decade, a number of detailed studies of the southwestern parts of the Helgeland Nappe Complex (HNC) have been made, in order to elucidate the complex tectonic, metamorphic and intrusive history of this part of the Uppermost Allochthon. The present paper focuses on the tectonostratigraphical development of the Velfjord-Tosen region (Fig. 1), situated in the southwestern part of the HNC, based mainly on work forming parts of cand.scient. theses (University of Bergen), concentrating on the Velfjord (Løseth 1985) and Sausvatn-Tosen areas (Thorsnes 1985).

Regional context

The HNC forms the southernmost part of the Uppermost Allochthon of the Scandinavian Caledonides in Central Norway (Gee et al. 1985). As the name suggests, it is composed of a series of nappes recording a complex tectonic evolution (Fig. 1). Towards the east and southeast, the HNC lies structurally above low grade rocks of the Köli Nappes (Foslie & Strand 1956, Ramberg 1967, Gustavson 1973, 1981, 1988, Lutro 1979, Dallmann 1986). In the southwestern part, the base of the HNC has been mapped between Grong and Bindal (Roberts et al. 1983, Nordgulen & Bering 1987, Husmo & Nordgulen 1988), where the Late Ordovician/Early Silurian Heilhornet Pluton (Nordgulen & Schouenborg 1990) intrudes both the underlying medium-grade supracrustal rocks (Kollung 1967, Schouenborg 1988) and the basal parts of the HNC (Fig. 1). Northwest of the Heilhornet Pluton, the continuation of the base of the HNC has not been identified with certainty (Nordgulen & Mitchell 1988).

Several authors (Prestvik 1972, Gustavson 1975, 1981, 1988, Nordgulen 1984, Bang 1985, Løseth 1985, Sturt et al. 1985, Thorsnes 1985, 1987, Tørudbakken & Mickelson 1986, Husmo & Nordgulen 1988) have shown that the constituent nappes of the HNC can be divided lithologically into two main groups: (1) nappes composed largely or entirely of high-grade gneisses, partly migmatitic, associated with calcareous metasedimentary rocks; (2) nappes characterised mainly by mafic and ultramafic igneous rocks of ophiolite/island arc affinity, unconformably overlain by a sequence of polymict conglomerates, schists, psammites and marbles. The latter rocks are found in a belt along the coast (Leka - Sauren - Rødøy - Skålvær), in the Tosen - Velfjord area, and in the Mosjø-

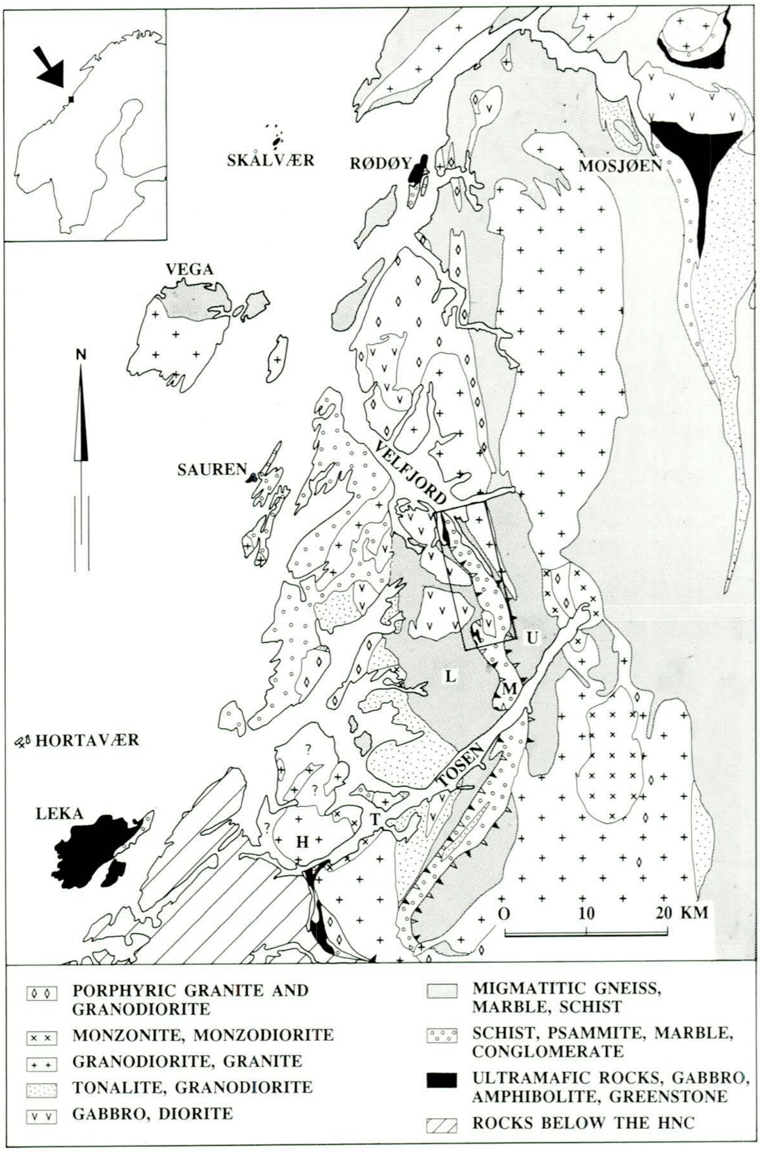


Fig. 1: Simplified geological map of the Helgeland area, Central Norwegian Caledonides, showing the main lithotectonic units and intrusions (compiled from Gustavson 1981, Nord-gulen 1984, Bang 1985, Løseth 1985, Sturt et al. 1985, Thorsnes 1985, Tørudbakken & Mickelson 1986, and Nordgulen & Bering 1987). L - Lower nappe, M - Middle nappe, U - Upper nappe, H - Heilhornet, T - Terråk.

en area (Fig. 1). The rocks found in the Sørfjord area possibly belong to the coastal belt.

On Leka, in the extreme southwestern part of the HNC, U/Pb dating of zircon in quartz keratophyres of the Leka Ophiolite Complex has yielded an age of 497 ± 2 Ma (Dunning & Pedersen 1988, Furnes et al. 1988) for an immature arc stage of the ophiolite.

A variety of Caledonian plutons collectively termed the Bindal Batholith are found in the HNC. The intrusions range in composition from gabbro to quartz diorite and granite, and were emplaced at various stages during the tectonometamorphic evolution (Kollung 1967, Nordgulen 1984, Nordgulen & Schouenborg 1990). In the southwestern parts of the HNC metamorphic rocks of continental origin were intruded by tonalites and granodiorites prior to c. 500 Ma (Nissen 1986). These intrusions are considered to have been emplaced in a foliation-forming orogenic phase in Late Cambrian time (Nissen 1986). Many of the large plutons collectively grouped as the Bindal Batholith appear to be essentially of Late Ordovician to Early Silurian age (Nordgulen & Schouenborg 1990), and a Silurian mineral age has been recorded

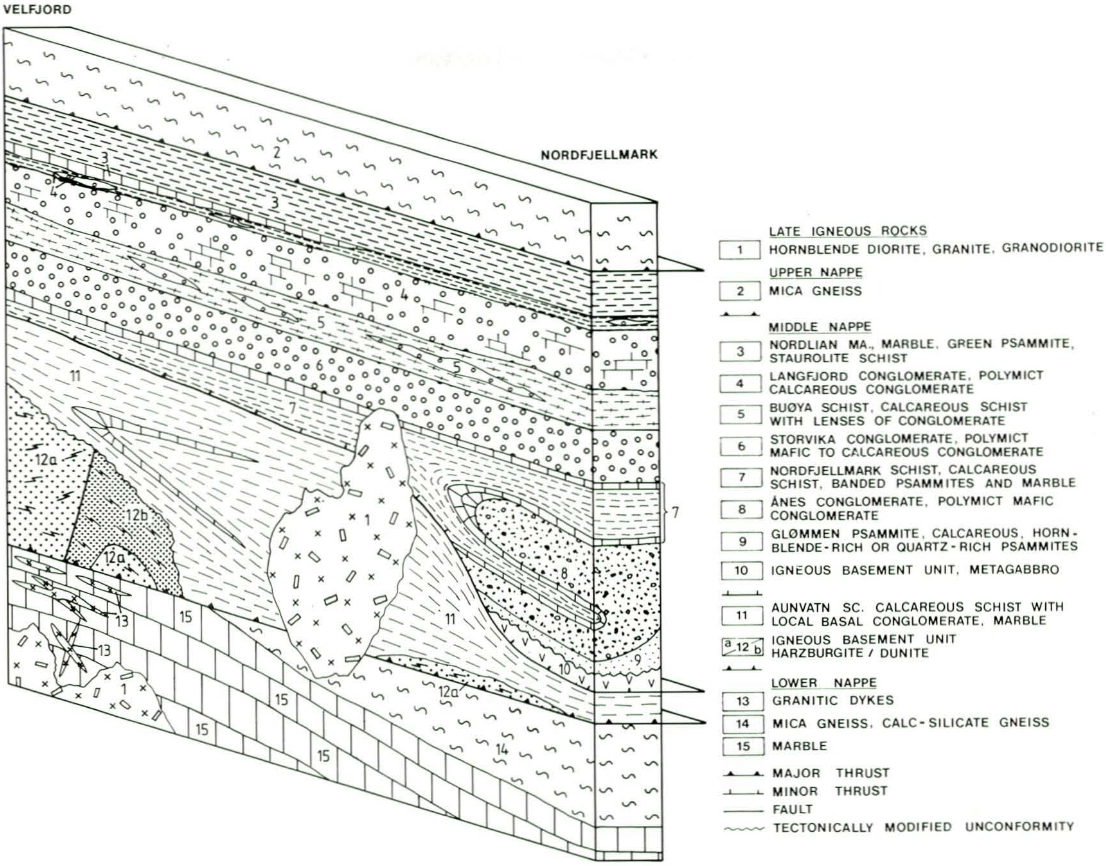


Fig. 2: Synoptic block diagram, showing the main lithotectonic and structural units in the Velfjord-Nordfjellmark area.

from the Mosjøen Gabbro (Tørudbakken & Mickelson 1986).

Most of the deformation and thrusting of the HNC has traditionally been considered to have occurred during the Mid-Late Silurian to Early Devonian Scandian phase of the Caledonian Orogeny, though in several stages (Roberts et al. 1983). In the Hattfjelldal area, along the eastern margin of the HNC, Dallmann (1986, 1987) considers that polyphase eastwards thrusting of the HNC took place in Middle Silurian times. This thrusting postdated thrust emplacement of the underlying Hattfjelldal Nappe, forming part of the Köli Nappes (Dallmann 1986). Radiometric datings by Nordgulen & Schouenborg (1990), however, indicate that the juxtaposition of the HNC with the structurally underlying medium-grade supracrustals in the Vestranden region along the southwestern margin of the HNC, and internal imbrication of at least parts of the HNC, took place prior to or during the Late Ordovician, while the final accretion of the HNC occurred during the Late Silurian/Early Devonian Scandian phase of the Caledonian Orogeny.

Tectonostratigraphy: a summary

In the Velfjord-Tosen region, the rocks can be assigned to three nappes, informally named the Lower, Middle and Upper nappes (Fig. 2) The Lower and Upper nappes comprise lithodemic complexes of gneisses and calcareous rocks.

The Middle nappe is the most extensively studied nappe unit in the present investigation. It can be divided into two units forming a basement-cover couplet. The basal unit consists of variably altered ultramafic rocks and metagabbros. In the Velfjord area, the Heggefjord ultramafite constitutes the major part of the igneous basement unit. The cover unit consists of schists, metaconglomerates, psammites and marbles.

The Heggefjord ultramafite shows evidence of several phases of deformation which occurred prior to deposition of the overlying metasedimentary cover rocks. In the latter unit, 4 phases of deformation have been established (D1-D4), with the peak of metamorphism (medium-grade) during D2. Structures associated with D1 are few and usually obliterated by the penetrative S2 foliation, formed as a result of isoclinal folding and thrusting during D2 (Fig. 3). Later deformation (D3 and D4) refolded the structures formed during D1-D2 and produced the present attitude of the rocks, dipping 40-60° towards the ENE (for a more detailed description of the deformation and metamorphism, see page 14).

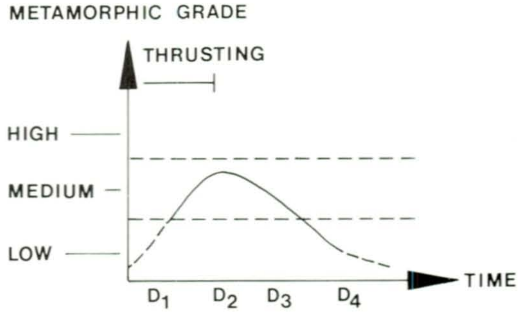


Fig. 3: Schematic presentation of timing of metamorphism and thrusting for the cover sequence within the Middle nappe.

Lower nappe

The Lower nappe comprises a heterogeneous assemblage of gneisses, schists, calc-silicate rocks and marbles (Fig. 1). It is intruded by a variety of igneous rocks along its base (Fig. 1). Towards the south, south of Tosen, the nappe becomes thinner as it is truncated by intrusions belonging to the Bindal Batholith. South of Terråk, the nappe is excised by these intrusions (Nordgulen et al. 1989). Northwest of Tosen the structural thickness of the nappe increases to several kilometres. Here it is intruded by the Kråkfjellet pluton along its southwestern margin (Nordgulen 1984).

In the northern parts of the area, south of Velfjord, the contact relationships are less clear. In the west, towards the Sauren-Torghatten-area, beneath the Lower nappe (Fig. 1), a sequence of medium-grade schists, marbles and metaconglomerates is seen to unconformably overlie a lower unit consisting of variably altered ultramafic rocks and metagabbros (Heldal 1987, Heldal & Hjelmeland 1988). Lithologically, the rocks bear several similarities to the Early Ordovician Leka Ophiolite Complex, positioned c. 50 km along strike southwest of Sauren (Fig. 1). The rocks appear to be less deformed and metamorphosed than the rocks of the Lower nappe. It therefore seems appropriate to assign the rocks to a separate tectonic unit beneath the Lower nappe, informally called the Sauren unit.

The precise nature of the contact between the Lower nappe and the Sauren unit is uncertain, not least because a number of variably sized plutons, producing widespread contact metamorphism in the area, intrude the contact (Ø. Nordgulen pers. comm. 1989). However, the present authors consider a thrust most likely, since the Lower nappe apparently structurally overlies the less deformed and metamorphosed Sauren unit. The internal structure of the Lower nappe has never been studied in detail, but from previous work it is clear that the rocks are polyphasally deformed, locally forming complex fold interference patterns (Kollung 1967, Myrland 1972). Parts of the mica gneisses are migmatitic (Nordgulen 1984), indicating that these rocks have experienced metamorphism at temperatures higher than the cover rocks of the Middle nappe. The gneisses of the Lower nappe may represent basement for the more evident supracrustal rocks of the nappe, but the generally high strains have probably obliterated any possible unconformable relationships.

The gneisses of the Lower nappe are dark grey, banded, coarse-grained, migmatitic biotite gneisses with abundant leucosome veins. They show a well-developed penetrative foliation, within which there are concordant leucosomes composed mainly of quartz + oligoclase/andesine + biotite + muscovite + garnet + (fibrolitic) sillimanite ± microcline ± hornblende ± chlorite. Accessory minerals are tourmaline, apatite, zircon, sphene, pyrite and pyrrhotite. With increasing content of biotite and decreasing grain size, the gneisses grade into commonly rusty biotite-garnet schists, locally with conspicuous mats of fibrolitic sillimanite.

The calc-silicate rocks are generally dark, banded and schistose consisting of hornblende + plagioclase ± diopside + biotite ± quartz and minor amounts of calcite, apatite, allanite, zircon and opaque minerals. With increasing contents of biotite and quartz + plagioclase, they grade into hornblende-biotite gneiss and psammitic biotite gneiss. Locally, thin layers of marble are present (Nordgulen 1984).

Marbles are prominent in the Lower nappe (Kollung 1967), typically in the form of white or grey, banded calcite marble. The marble is usually coarse-grained with occasional specks of pyrite oriented in rows parallel to the banding. The content of impurities, such as calcsilicate minerals, is variable.

Various plutonic rocks, generally termed the Velfjord Massifs, which range from hornblende gabbros to granites (Vogt 1897, Kollung 1967, Myrland 1972), constitute an important part of the Lower nappe (Fig. 1). On a regional scale, the large plutons are conformable with their metamorphic envelope, but on outcrop scale the relationships may be discordant, with apophyses cutting the penetrative foliation in the surrounding metasedimentary rocks. Contact metamorphic aureoles are present around these massifs (Vogt 1897, Kollung 1967). The Velfjord Massifs were therefore considered by Vogt (1897) to postdate the main phase of deformation and metamorphism in the investigated area, whereas Kollung (1967) interpreted them as synorogenic. In the Sausvatn-Markafjell area (Fig. 4) a dioritic to monzodioritic pluton (Kollung 1967) belonging to the Velfjord Massifs cuts the thrust contact (D2) between the Lower and Middle nappes (Thorsnes 1985), but the pluton is deformed by later deformation structures (D3 and D4). In our opinion, this shows that the Velfjord Massifs were emplaced at a comparatively late stage of the tectonometamorphic evolution, postdating the main stage of deformation and thrusting.

Contact relations between the Lower and Middle nappes

The Middle nappe is considered to have been thrusted over the Lower nappe on the basis of evidence presented below. On a local scale, the foliation and lithological banding of the rocks in the Lower nappe are concordant with the thrust plane. However, on a regional scale, the base of the Middle nappe truncates lithological contacts in the footwall, as e.g. the contacts between gneiss and marble in the Lower nappe (Fig. 5).

The contact relations between the Lower and Middle nappes are best seen along the shore areas in Velfjord (Fig. 5, loc. A). The Heggefjord ultramafite is here thrusted over the marbles of the Lower nappe (Fig. 5). The marbles beneath the thrust consist essentially of medium- to coarse-grained calcite with subordinate amounts of tremolite-actinolite, plagioclase, quartz and pyrite, and contain scattered boudins of rusty schists up to 5 m thick, and granitic dykes and veins. Approximately 50 m away below the thrust, cross-cutting relationships are found between granitic dykes and schist boudins, and between individual granitic dykes. Just below the contact, remains of the dykes are found only as boat-shaped boudins, with a strong foliation giving rise to a flaggy appearance. The cleavage is anastomosing, and the dyke material bears a well developed stretching lineation parallel to the L2-lineation found in the metasedimentary rocks of the Middle nappe; i.e. plunging 30-50° towards the ENE-ESE. At this level, cross-cutting relationships between dykes and schist boudins, or between individual dykes, can no longer be observed. Since no granitic dykes have been found in the ultramafite, this is clearly indicative of a pre-thrust age for the granitic dykes, and a thrust boundary between the marbles of the Lower nappe and the overlying ultramafic unit of the Middle nappe.

A similar relationship, but on a larger scale, is found along the northeastern side of the Tosen fjord. In a c. 400 m high cliff exposure, marbles of the Lower nappe are superposed by Middle nappe rocks; small lenses of serpentinite, mica schist, psammite and metaconglomerates (Fig. 6, UTM 925 317). Granitic dykes are nearly totally restricted to marbles of the Lower nappe. In the lower part of the section, well below the contact between the two, the granitic dykes are found to transect the banding in the marble. Towards the thrust contact with the Middle nappe, the granitic dykes gradually become sub-parallel to the banding. Since the dykes become highly deformed when approaching the thrust plane between the Lower and Middle nappes, this implies that the rocks of the Lower nappe were intruded by granitic dykes prior to the thrusting event. The few granitic dykes present in the Middle nappe are of unknown age, but are probably not related in time or space to the dykes in the Lower nappe.

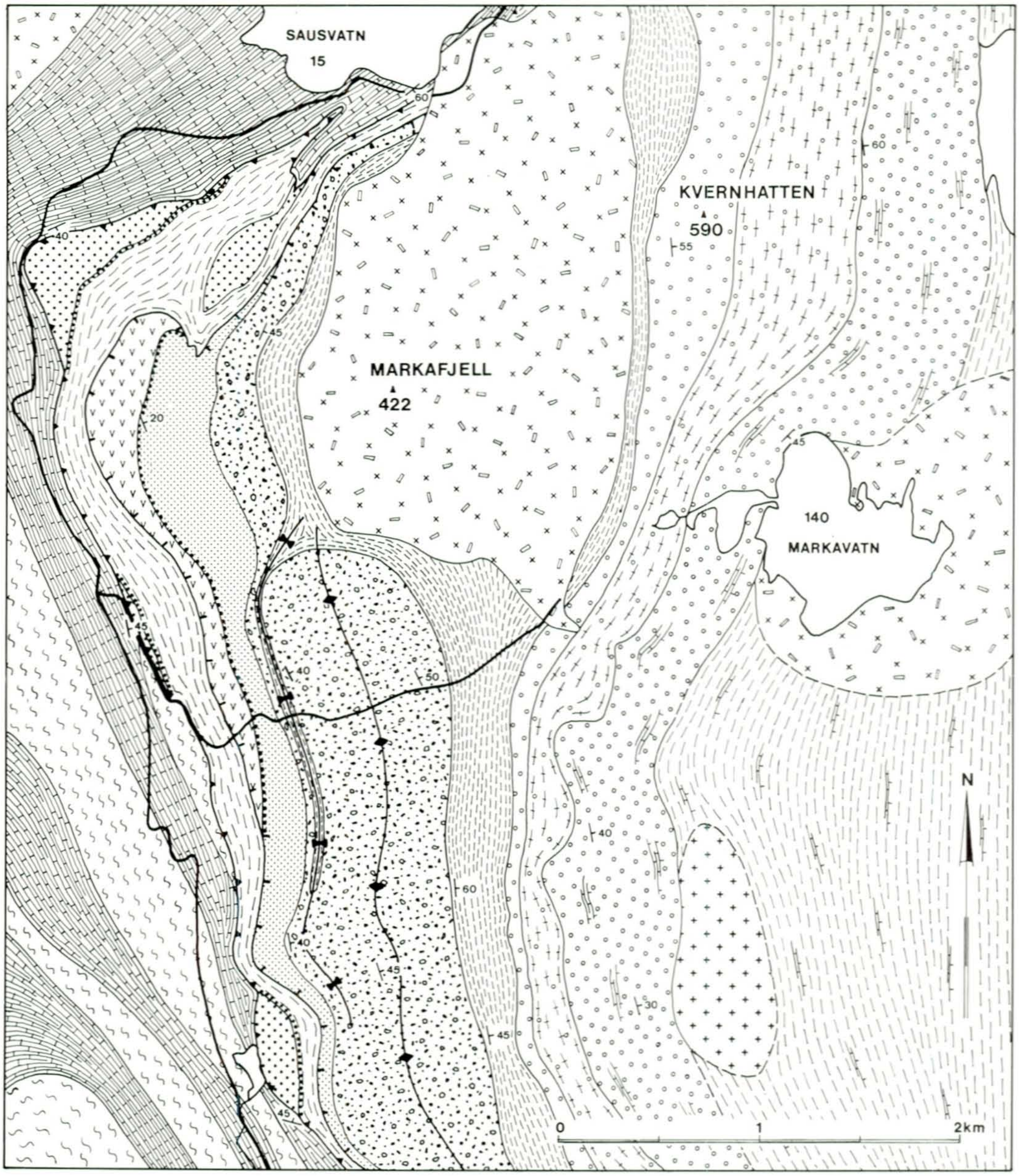
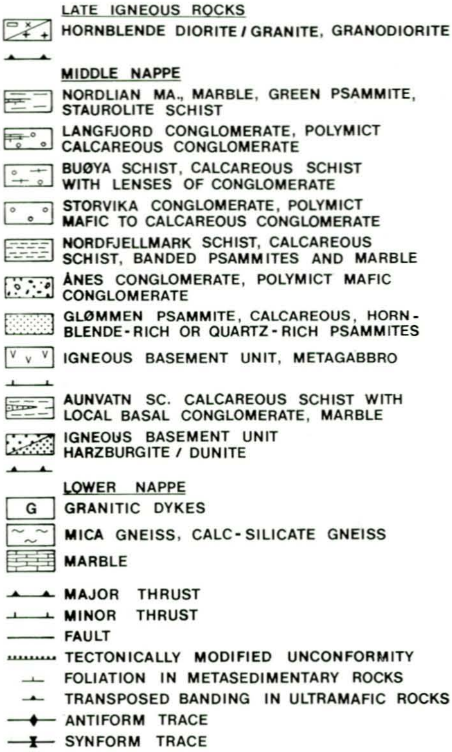


Fig. 4: Simplified map over the Nordfjellmark area, Sausvatn, showing the main tectonostratigraphic units and structures. For legend, see facing page.

Other intrusive rocks evidently postdate the thrusting. At the Velfjord locality (Fig. 5, loc. A), one set of basic dykes showing chilled margins cross-cuts both the thrust between the Lower and Middle nappes, and the penetrative foliation in the marble-schist unit of the former. On a larger scale, entire plutons can be shown to cut the thrust. At Markafjell in the Nordfjellmark area, c. 10 km south of Velfjord (Fig. 4), a small (c. 4 km^2) dioritic to monzonitic pluton has been mapped by Kollung (1967). This pluton cuts both the basal



thrust and the internal imbrication of the Middle nappe (Figs. 2 & 4), and also postdates the penetrative S2 foliation in its metasedimentary cover unit.

Middle nappe

The lower part of the Middle nappe is composed of a unit of igneous rocks. It comprises variably altered ultramafic rocks and lenses of metagabbro, cropping out discontinuously along the base of the Middle nappe.

The largest and best preserved igneous complex is found at Nevernes, where there is an approximately 5 km long and up to 1 km wide body, the Heggefjord ultramafite (Fig. 5). The main lithologies in the ultramafite are harzburgite (dominant), dunite and minor amounts of clinopyroxenite and wehrlite. The mineralogy of these rocks has been extensively modified by both regional and contact metamorphic processes. Some relict primary minerals and textures are, however, preserved — particularly in the northern and central parts of the Heggefjord body. The harzburgite crops out in the northern and southwestern parts of the body, while the dunite occupies the central part. Wehrlite and pyroxenite occur in a small fault-bounded block in the southwestern parts.

The ultramafic rocks are interpreted to be of mantle affinity, and the structures and textures described below are considered to be related to early, non-orogenic deformation under upper mantle or lower crustal conditions (for a detailed description and discussion, see Løseth (1985)). The harzburgites show an imperfect foliation defined by zones or bands enriched and/or depleted in flattened grains of enstatite partly replaced by bastite. This harzburgite 'foliation' is parallel to pyroxenite veins and tabular bodies of dunite (partly veins, partly bodies of uncertain origin). In dunitic bodies, chromite bands form a distinct banding, and flattened chromite grains may form an axial planar cleavage in the fold hinges of open to isoclinally folded chromite layers. Cross-cutting relationships may be observed between individual pyroxenite veins, and between pyroxenite veins and sheet-like dunite bodies (Fig. 7). These planar structures appear to have formed during the same stage of early, non-orogenic deformation, and are normally parallel or subparallel.

Microstructures and textures indicative of upper mantle/lower crust deformation of the ultramafic rocks are also found. In the northern harzburgite, two types of relict coarse-grained olivine occur. The first type is that of 0.5-2 cm equant olivine crystals which have straight grain boundaries meeting in triple junctions at 120°. The second type is usually over 2 cm in size, with quite irregular grain boundaries and common kink bands, giving a porphyroclastic appearance. These textures correspond well with textures termed 'coarse equant' and 'coarse porphyroclastic' by Nicolas et al. (1980), who concluded that they developed during plastic deformation simultaneous with crystal slip and recrystallization at temperatures between 1000° and 1300° C, formed during asthenosphere flow at seafloor spreading sites.

A third type of olivine is represented by fine-grained, elongated and recrystallized olivine crystals or aggregates defining an LS fabric in the southwestern parts of the ultramafite. The fine-grained textures are associated with a strong and partly mylonitic foliation. This can to some extent be compared to textures ter-

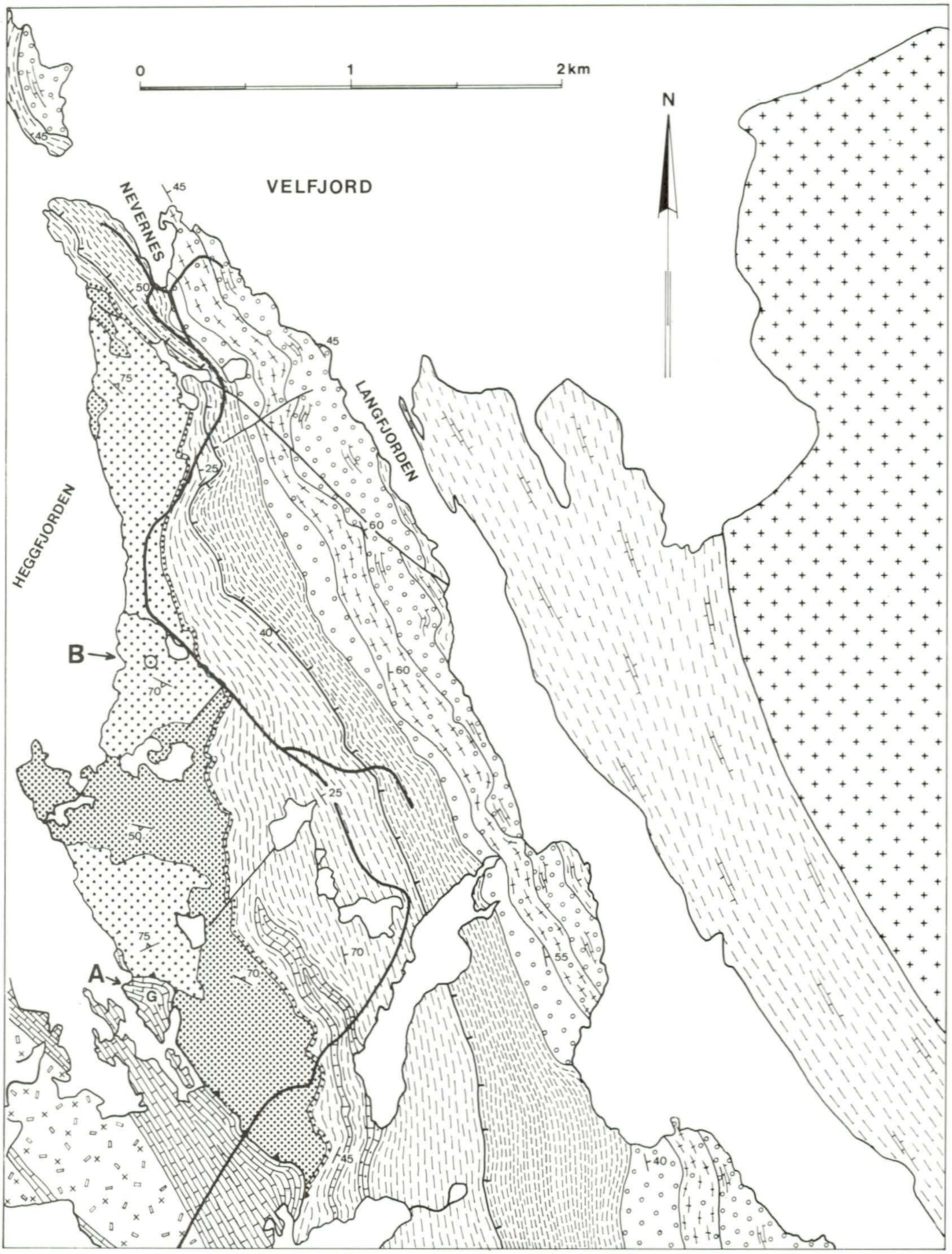


Fig. 5: Simplified map over the Nevernes area, Velfjord, showing the main tectonostratigraphic units and structures. For legend, see previous page.
A - locality with well exposed relations between the Lower and Middle nappes.
B - locality of fig. 7.

Fig. 6: Cliff exposure of the contact between the Lower and Middle nappes (the contact runs between the two white markers, middle left to top right). Note the abundance of granitic dykes intruding marbles and calc-silicate rocks in the Lower nappe. In the lower part, discordant relationships are found, while close to the contact the dykes are concordant to the base of the Middle nappe. The Middle nappe is virtually free of granite dykes at this locality. The height of the cliff exposure is c. 400 m. The cliff is located on the southeastern side of Tosen (UTM 925 317).

med fine-grained porphyroclastic to mylonitic by Nicolas et al. (1980). Such textures are most common in the basal part of an ophiolite pseudostratigraphy, but can also be found in the transitional zone between mantle tectonites and cumulates in an ophiolite, where the majority of the structures relate to deformation under upper mantle or lower crustal conditions. Early, non-orogenic deformation has also been reported from the harzburgite tectonite of the Leka Ophiolite Complex (Furnes et al. 1988).

The early, non-orogenic deformation of the ultramafic rocks was followed by faulting under brittle conditions; i.e. at high levels in the crust, possibly related to a post-obduction event predating the deposition of the overlying metasedimentary sequence. The best example of these structures is the fault contact between the northern harzburgite and the central dunite which causes a discordant relationship between the chromite layering in the dunite and the pyroxenite veins in the harzburgite. These planar fabrics are normally parallel, belonging to the early tectonic structures (Fig. 8). This fault ends at the base of the overlying metasedimentary rocks, thus indicating that brittle deformation of the ultramafite occurred prior to deposition of the cover sequence. This is a similar situation to Leka, where the major movements on some of the faults in the LOC clearly predate the deposition of the unconformably overlying Skei Group (Furnes et al. 1988).

A number of minor faults and fractures having the same trend may also be related to this brittle deformation. During regional deformation and metamorphism, reactivation of these faults and fractures probably accommodated the regional strains and served as pathways for fluid migration. Extensive retrogression took place in these zones, and large porphyroblasts of serpentine and magnesite (up to 10 cm) are present. Spectacular ring growth structures also occur where faults intersect, leaving less altered peridotite fragments in a talc-antigorite matrix (Fig. 9). Locally, the retrogression zones are strongly deformed, producing talc-antigorite schists where the schistosity is parallel to the margins of the alteration zones, while porphyroclasts of magnesite and antigorite can be found in the central parts. Apparently, the alteration zones have had a great ability for accommodating

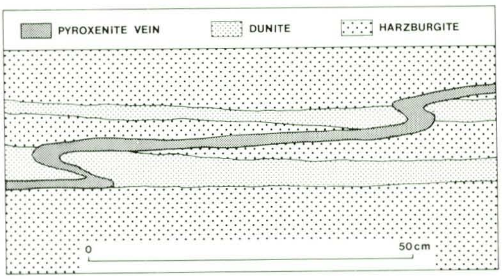


Fig. 7: Drawing of observed field relationships showing tabular dunite bodies in harzburgite cross-cut by a folded pyroxenite vein. For location, see fig. 5.

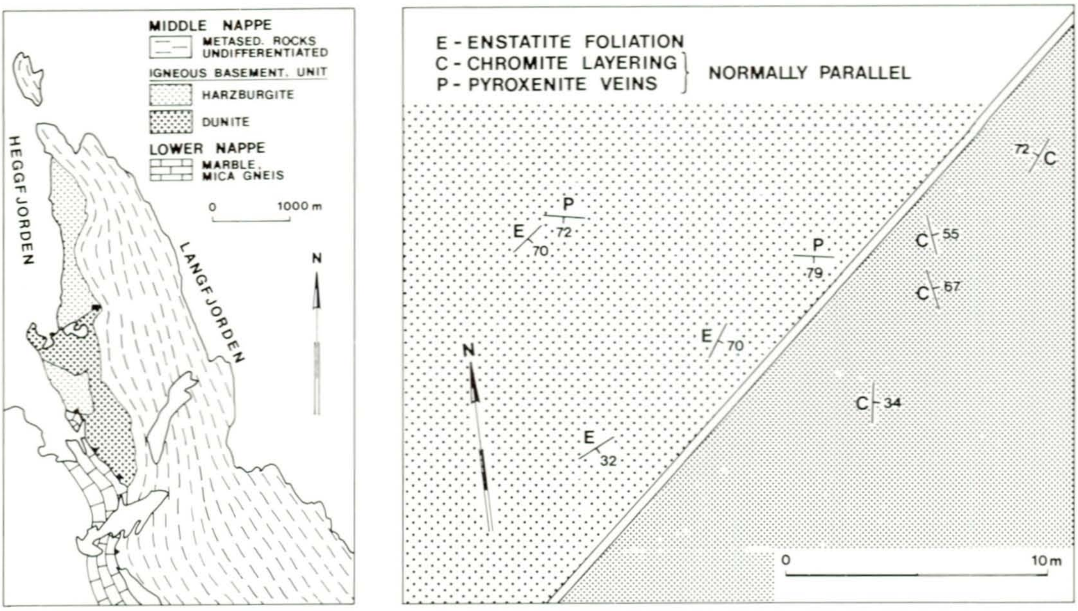


Fig. 8: Fault contact between harzburgite and dunite, truncated by the overlying metasedimentary rocks (left of arrow, map to the left. The black rectangle shows the outline of the map to the right). Chromite layering and pyroxenite veins are normally parallel, but show discordant relationships across the fault (map to the right).

most of the strain during regional deformation, leaving the less altered and more rigid parts of the ultramafite virtually undeformed.

Structures related to the translation of nappes and deformation of the entire sequence are found mainly in the marginal parts, or in shear zones within the ultramafite. In the marginal zones, particularly along the thrust between the ultramafite and the Lower nappe, but also locally along the contact with the overlying metasedimentary rocks, retrogression of the ultramafite has produced talc-antigorite schists with a strong foliation. However, these zones seldom exceed one metre in thickness. In the northernmost part of the ultramafite, shear zone structures are common. These are observed either as eyes or lenses of relatively fresh harzburgite set in a serpentine schist matrix, or as mega-augen where relatively fresh peridotite is separated by thinner zones of altered rocks. The structures range in size from a few centimetres up to 18 m in thickness and several hundred metres in length. A strongly developed serpentine foliation is usually associated with the zones. The trend of the foliation varies, but is normally parallel to the surfaces of unaltered harzburgite.

Contact-metamorphic microtextures within the ultramafic rocks have been described by Bakke & Korneliussen (1986). They found that while the northern part of the dunite contains primary olivine crystals with deformation lamellae, the olivines in the southern part were recrystallized into a microscopic jack-straw texture. This texture can be ascribed to contact metamorphism caused by the nearby dioritic to gabbroic plutons of the Velfjord Massif.

Another part of the basal igneous unit is found south of Sausvatn, at the western part of Markafjell (UTM 907 448). A lens of metagabbro (c. 1 x 3 km) lies between two of the lithological units within the lower part of the metasedimentary rocks. This is considered to represent a dismembered part of the basal igneous unit, whose present structural position is related to imbrication of the lower parts of the Middle nappe.

In the eastern, lithostratigraphically uppermost parts, the metagabbro is coarse- to very coarse-grained. It is weakly to moderately foliated, with the foliation expressed by elongated aggregates of hornblende, parallel to a banding defined by bands of dark hornblende, alternating with discontinuous, irregular laminae of greyish plagioclase. The hornblende may form individual crystals up to 1 cm long, and in places shows relict 'sub-ophitic' textures. Along strike, the metagabbro shows apparently primary textural and modal variation.

The metagabbro is cut by three types of dykes; amphibolitic, trondhjemitic and granitic. The amphibolitic dykes are dark, fine-grained and massive, with the margins transposed by the penetrative 'S2 foliation'. They contain dominantly dark hornblende and plagioclase, with locally abundant opaque minerals and minor epidote and quartz. The light-coloured trondhjemitic dykes are up to 1 m thick, and show a well developed foliation with elongated quartz grains set in a fine-grained matrix of quartz, plagioclase, hornblende and minor biotite and epidote. The amphibolitic and trondhjemitic dykes are found only in the metagabbro, and carry a similar imprint of deformation and metamorphism. We therefore consider them therefore to be genetically related to the metagabbro.

The granitic dykes in the metagabbro are medium- to coarse-grained, weakly foliated, and, composed of quartz, K-feldspar, plagioclase and biotite, with minor hornblende, sphene and epidote. Their width varies from 1 to 25 metres. The dykes are also found in the metasedimentary units surrounding the metagabbro, and they cross-cut the penetrative foliation. They thus postdate the penetrative foliation and the early deformation of the metagabbro. They are, however, affected by the later folding of the metagabbro.

Moving towards the tectonostratigraphically lower part of the metagabbro, there is a progressive mylonitization demonstrated by decreasing grain size and development of planar and linear fabrics. In the middle part of the metagabbro, anastomosing shear zones have isolated lenses of little deformed coarse-grained metagabbro in a matrix of fine-grained amphibolite. In thin-section, porphyroclasts of hornblende with recrystallized margins are commonly observed.

In the western, lowermost part, the original metagabbro is transformed into a fine-grained hornblende schist showing a well-developed LS fabric and is considered to be a mafic mylonite. Sporadic, light-coloured, concordant and isoclinally folded, quartzo-feldspathic bands exhibiting features indicative of large ductile strains are considered to be mylonitized trondhjemitic dykes.

The large strains recorded in the lowermost part of the metagabbro are probably the result of thrusting and imbrication of the lower parts of the Middle nappe during regional D2 deformation.

Fig. 9: Ring growth structure within the Heggefjord ultramafite, produced by alteration of peridotite to talc and antigorite along intersecting brittle faults. Pencil (14 cm) for scale.

Metasedimentary rocks in the Middle nappe

The metasedimentary rocks, which structurally overlie the basal igneous unit, comprise a series of psammites, schists, conglomerates, marbles and possible felsic volcanites. Despite high strains, various lines of evidence indicate that the contact between the igneous unit and the metasedimentary rocks is a primary unconformity, though modified during later regional deformation and metamorphism.

The contact between the basement unit and the metasedimentary rocks is sharp. Lithological banding in the metasediments, regarded as transposed bedding, is concordant with the contact on both outcrop and regional scale. Near the contact, however, the metasedimentary rocks exhibit comparatively low strains. This is shown by the presence of pebbles in a conglomerate and phenocrysts in crystal tuffs immediately overlying the Heggefjord ultramafite. Furthermore, in the same area, boudins of amphibole-rich layers in psammite formed during D1 are preserved within D2 fold cores. Such structures have not been observed away from the contact. In the Heggefjord ultramafite, no increase in strain is evident when approaching its upper contact, but a thin (generally c. 1 m thick) talc-antigorite schist is locally developed along the contact, possibly due to the difference in competence between the rocks. In the metagabbro in the western part of Markafjell, there is a distinct decrease in strain towards the contact with overlying metasedimentary rocks.

The lithology of the overlying metasedimentary rocks yields evidence for erosion of an assemblage of rocks partly comparable to the igneous basement unit. In the psammites immediately above the Heggefjord ultramafite, aggregates of tremolite-actinolite associated with chromite, together with pebbles of metagabbro, constitute part of the pebble population within pockets of a calcareous conglomerate. The tremolite-actinolite aggregates are considered to represent metamorphosed ultramafic clasts carrying chromite.

In the Nordfjellmark area (Fig. 4, UTM 910 435), similar psammites and schists overlie serpentinized ultramafic rocks. In the ultramafic rocks, pyrrhotite grains with pentlandite lamellae are present. Immediately overlying these rocks, there are biotite-quartz-feldspar schists with recrystallized pyrrhotite with pentlandite lamellae (L.P. Nilsson, pers.comm. 1991).

Further up in the sedimentary sequence, the pebble population of polymict conglomerates includes a high proportion of metagabbro, greenstones, felsic volcanites and scattered tremolite-actinolite aggregates. The combined evidence for low strain near the basement-cover contact, together with the lithology of the overlying metasedimentary rocks, the early ductile deformation in the basal igneous unit, and the brittle fault ending at the cover sequence, provide sufficient evidence to interpret the contact as a primary depositional unconformity. During regional deformation, some modification of the contact probably occurred, as shown by the talc-antigorite schist zones locally developed along the margin of the igneous complex. Similar primary stratigraphic unconformities have been described between cover sequences and ophiolitic rocks at a number of localities in the region (Bang 1985, Sturt et al. 1985, Heldal 1987, Husmo & Nordgulen 1988).

Due to D2 imbrication in the lower parts of the Middle nappe, the pattern of lithostratigraphy changes from north to south. In the Velfjord area, contact relations between the igneous basement unit and the overlying metasedimentary rocks are best preserved, while the most complete tectono- and lithostratigraphy is found in the Nordfjellmark area, midway between Velfjord and Tosen. A synoptic profile summarising the main structural features and tectonostratigraphic units is shown in Fig.2.

In the Velfjord area, the lowest unit is termed the Aunvatn schist (Fig. 5). It comprises a basal conglomerate, partly calcareous psammites, hornblende-bearing psammites, garnet-biotite-schists, thin marble horizons and subordinate amounts of fine-grained acidic igneous rocks (possibly extrusions or shallow intrusions). The structural thickness of this unit increases from c. 100 m to c. 200 m, from north to south. At the base of the unit, there is a calcareous banded psammite with a locally developed basal polymict conglomerate, up to 10 m thick, directly above the basal igneous unit (Figs. 2 & 4). The conglomerate is matrix-supported, with up to 70% calcite in the matrix. Locally, the matrix is green due to a relatively high content of tremolite-actinolite. Pebbles and clastic grains occur scattered in the matrix. The clast population is made up of gabbros, fine-grained quartz-plagioclase-calcite rocks, and aggregates of tremolite-actinolite associated with chromite grains. The clastic grains are of chromite and pyrrhotite together with thin bands rich in chromium probably representing altered, smeared-out chromite grains, and plagioclase partly recrystallized to a fine-grained granular texture. The Aunvatn schist appears to be separated from overlying mica schists and polymict conglomerates by a tectonic break, most probably a minor thrust (see p. 15).

This mica schist and polymict conglomerate unit can be traced for c. 15 km southwards to Nordfjellmark, c. 2 km south of Sausvatn, where similar lithologies overlie lenses of serpentinized ultramafic rocks included in the basal igneous unit. A lens of metagabbro structurally overlies the Aunvatn schist in the Nordfjell mark area. This lens is considered as a dismembered part of the basal igneous unit, which most probably was imbricated during thrusting of the Middle nappe. This is overlain by a thick metasedimentary sequence, starting with psammites.

The psammites have a structural thickness of c. 100 m, and are termed the Glømmen psammite. Three varieties occur; grey quartz-rich psammites, green calc-silicate-rich psammites, and dark hornblende-rich psammites. The mineralogical immaturity and locally high content of mafic minerals such as hornblende indicate erosion from a mafic source.

The psammites pass upwards into the Ånes conglomerate, which is an up to 200 m thick polymict 'mafic' conglomerate, with hornblende-rich matrix and a number of clasts reflecting erosion from a mafic to ultramafic source (Fig. 10). The matrix is dominated by hornblende, plagioclase and epidote, with possible clastic grains of chromite and plagioclase. The clast size normally ranges from 0.5 X 2 to 5 X 20 cm, though some clasts may reach up to 20 X 80 cm (in X-Z sections). In places, hornblende-rich psammites are found within the conglomerate.

The clast population is dominated by medium- to coarse-grained metagabbros, fine- to very fine-grained greenstones and greenschists, trondhjemite and altered ultramafic clasts (tremolite-actinolite aggregates). In addition, epidote nodules, quartzite, vein quartz, granite and possible chert or jasper is present, especially in the upper parts of the conglomerate. Many of the metagabbro pebbles are comparable to the metagabbro at the western part of Markafjell. The conglomerates are followed by c. 150 m of schists, marbles, and banded psammites, assigned to the Nordfjellmark schist. In the Velfjord area, clastic grains of pyrrhotite with pentlandite exsolution lamellae are found in the psammites. These are similar to those found in sediments immediately overlying the Heggefjord ultramafite. At the top of the unit, a laterally persistent marble horizon can be traced for at least 30 km, probably indicating stable depositional conditions.

A new period of tectonic instability is expressed by two conglomerate horizons, separated by a calcareous schist. The lowermost of these conglomerates, the Storvika conglomerate, is dark, polymict and matrix-supported with rather small clasts, seldom exceeding 2 x 5 cm. The clast population is basically similar to that of the Ånes conglomerate, but locally marble clasts form an important part. The matrix is generally rich in hornblende and plagioclase, though locally there is a higher quartz content, together with calcite and calc-silicate minerals. Clastic chromite grains occur sporadically in the matrix.

The Storvika conglomerate is overlain by the Buøya schist (Fig. 5), comprising mainly calcareous schists, with local development of quartz-rich psammites (fig. 11), conglomerate lenses and thin layers of quartz-keratophyres.

The upper conglomerate horizon, the Langfjord conglomerate, differs from the other conglomerates in being dominantly calcareous. The matrix may contain up to 80% calcite, and large marble clasts are common. The proportion of granitoid and quartzitic clasts is high in comparison with the Ånes conglomerate, while that of gabbro, greenstone and trondhjemite is correspondingly lower. Scattered clasts up to 10 x 25 cm (in X-Z section), of medium- to coarse-grained quartzo-feldspathic rocks exhibit a pre-pebble foliation, and were probably derived from acidic orthogneisses. Also quartzitic to psammitic pebbles may have a pre-pebble foliation. This indicates that metamorphic sialic crust must have been available for erosion, at the time of deposition. In the upper parts of the unit, psammites and schists with sporadic conglomerate lenses become increasingly important. The schists are either calc-silicate or biotite schists. Staurolite and

Fig. 10: Polymict mafic conglomerate (Ånes conglomerate), with clast population dominated by gabbro and greenstone (UTM 948 355). Pencil (14 cm) for scale.

Fig. 11: Isoclinally folded psammite within the Buøya schist, Nordfjellmark area. Bands rich in quartz and plagioclase alternate with bands rich in biotite and hornblende. Pencil (14 cm) for scale.

garnet may be important accessory minerals in the mica schists.

The uppermost lithological unit, the Nordlian schist, comprises marbles interbanded with green psammites in the lower part, and staurolite schists in the upper part. The marbles are green-grey and have occasional pebbly beds, dominated by rounded quartzite fragments. The staurolite schists are green-coloured, with staurolite porphyroblasts up to 1.5 cm in diameter. Bands of greenschist may represent metamorphosed and retrogressed basic lavas, sills or transposed dykes.

Contact relations between the Middle and Upper nappes

On the basis of regional considerations, the contact between the supracrustal rocks of the Middle nappe and the overlying, partly migmatitic gneisses and metasedimentary rocks, is interpreted to be a thrust. The contact, however, is concordant on the outcrop scale. No mylonites have been observed at the contact, only a well developed foliation. Considering that the thrust separates metasedimentary rocks rich in phyllosilicates, and that movement most probably occurred under medium-grade conditions, this is perhaps to be expected. On a regional scale, there are indications that some of the marble units within the Upper nappe become excised or at least attenuated along the base of the nappe (at Fuglvatn, east of Tosen (Nordgulen et al. 1989)).

South of Tosen, the contact between the Middle and Upper nappes is cut by granites and granodiorites of the Bindal Batholith (Ø. Nordgulen pers. comm. 1986).

Upper nappe

The Upper nappe comprises a heterogeneous assemblage of meta-sedimentary rocks and gneisses (Kollung 1967, Gustavson 1981, 1988). They are generally rather coarse-grained and partly migmatitic, with a penetrative foliation. The gneisses range from light-coloured, quartzo-feldspathic acidic gneisses, to dark varieties rich in biotite and calc-silicate minerals.

The metasedimentary rocks are dominated by calcareous psammites and schists, in which the content of calc-silicate minerals such as epidote, actinolite and diopside may be significant. Marbles form a locally prominent lithology, typically being grey, coarse-grained and intercalated with calc-silicate bands. In addition, there are variably abundant garnet-fibrolite-biotite schists and amphibolites.

The Upper nappe is cut by a number of acidic to intermediate intrusions. A large elongated pluton, termed granite by Kollung (1967) has intruded approximately along the contact of the Middle and Upper nappes east of Langfjorden (Figs. 1 & 4). Recent mapping and geochemical investigations (Ø. Nordgulen pers. comm. 1990) show that this is a light-coloured, medium- to fine-grained, strongly foliated tonalitic rock. In most areas the tonalite is cut by various pegmatites and granitic dykes.

Similar metamorphic and plutonic rocks outcrop extensively in the HNC outside the investigated area (Gustavson 1981, 1988), but it is not known whether these rocks belong to the same or a different tectonic unit.

Deformation and metamorphism in the metasedimentary rocks of the Middle nappe

The predominant stage in the tectono-metamorphic evolution of the metasedimentary rocks of the Middle nappe was D2, with the formation of a penetrative LS fabric nearly obliterating earlier structures. The following pre-D2 structures are collectively termed D1, even though they may possibly belong to different events.

Porphyroblasts of staurolite and garnet have overgrown a foliation defined by straight or weakly curved trails of very fine-grained to fine-grained quartz and opaque minerals, regarded as a S1 foliation. These porphyroblasts are deformed by D2 structures, and must have grown interkinematically D1-D2, or in the initial stages of D2.

In hinges of asymmetrical F2 folds, a foliation defined by tiny biotite flakes forms part of a composite S0/S1 foliation which is overgrown by somewhat larger biotite grains parallel to the axial surface of the F2 fold (S0 is a compositional banding, assumed to be represent bedding).

Close to the contact with the ultramafic rocks in Velfjord (Fig. 5), boudins of amphibole-rich layers in psammite are found, oriented perpendicular to the S2 foliation, in a F2 fold hinge. These must have formed by D1 boudinage prior to the development of S2 foliation.

The structures ascribed to D2 include isoclinal folds with associated penetrative axial planar schistosity (S 2, normally transposing bedding and earlier cleavage), strong flattening of pebbles, well developed mineral lineations and stretching of pebbles (L2), and boudinage parallel to S2. Most of the small-scale F2 fold axes and the L2 lineations plunge c. 20°-40° towards the E-ESE. However, due to later refolding (D3, D4), the direction and dip of these structures may vary considerably. The attitude of the S2 foliation is similarly governed by the later folding. In the Nordfjellmark area, a large isoclinal S-fold (Fig. 4) with a fold axis plunging c. 45° towards the ENE is a prominent structure. The amplitude and wavelength of this fold is estimated to 300 m and 700 m, respectively. Another large isoclinal fold is outlined by a marble horizon found within the Aunvatn schist in the Nevernes area (Fig. 5). This fold is somewhat strange since no complementary fold has been found. Most probably, the stratigraphy has been excised due to movements along the northeastern limb of this structure. This proposed tectonic break is placed at the top of the Aunvatn schist. However, it should be noted that the sediments above this tectonic break do not differ significantly in terms of metamorphism or structural style. This tectonic break, however, corresponds well with the minor thrust found at the base of the metagabbro in the Nordfjellmark area.

D2 was characterised by large ductile strains as recorded by the isoclinal folding, penetrative schistosity and a prominent stretching lineation; and the S2 foliation is parallel or sub-parallel to the thrust plane and the imbrication zone in the lower part of the Middle nappe. Consequently, the most likely interpretation is that the thrusting and imbrication of the nappes took place during D2. Provided this is correct, then the trend of the L2 lineation may be taken to indicate the direction of nappe transport.

The third deformation event, D3, is characterised by a number of open to isoclinal, small- to medium-scale folds (wavelengths in the order 0.1 to 20 m), with associated L3 lineation and a S3 crenulation cleavage. The trend of the fold axes is difficult to distinguish from the F2 folds, while the axial planes and the S3 crenulation cleavage have more of an E-W orientation. The D3 deformation can, in most places, easily be separated from D2 on the basis of refolding of F2 folds, and/or folding of the L2 lineation, and/or the formation of a S3 crenulation cleavage from the S2 foliation.
The regional extent of this deformation is uncertain, but the folds have the same orientation as the major, open, map-scale folds which can be seen in the Velfjord-Tosen area (Fig. 1). A locally developed stretching lineation can be seen in the Markafjell pluton (Fig. 4), defined by the preferred orientation of hornblende and plagioclase laths. This lineation has broadly the same trend as the L2 lineation, but can be separated from it because the pluton clearly transects the D2 fabrics in its envelope, and thus predates them. However, this coincidence of trends may indicate that D2 and D3 are coaxial.

The last deformation event observed in the investigated area is termed D4, and includes gentle to close folds, in many places of chevron-type, with fold axes plunging shallowly towards the N-NE or the S-SW, and with axial planes dipping towards the W-NW. A locally prominent crenulation cleavage, S4, can be found. The folds are found only as local, small-scale structures, and probably have little regional importance.

The metamorphism accompanying the deformation is characterised by prograde metamorphism which reached medium-grade conditions during D2, followed by post-D2 retrogression. Metamorphism prior to D2 is poorly constrained, but growth of biotite and plastic deformation of quartz during D1 tend to indicate low-grade conditions during this early event. Porphyroblasts of staurolite and garnet, growing interkinematically (D1-D2) or in the initial stage of D2, indicate that medium-grade conditions were reached prior to or in the initial stage of D2. These conditions persisted throughout D2, as shown by the growth and recrystallization of minerals such as biotite, garnet, fibrolitic sillimanite and hornblende along the S2 foliation. Retrogression of the medium-grade parageneses occurred during D3, as shown by the growth of chlorite, chloritoid and white mica. No metamorphic reactions have been observed in association with D4 structures.

Summary and discussion

Regional and local studies (Kollung 1967, Myrland 1972, Nordgulen 1984, Thorsnes 1985, Nissen 1986) show that the lithologies of both the Lower and the Upper nappes are part of a metamorphic complex comprising both para- and orthogneisses, which together with huge volumes of plutonic rocks constitute the bulk of the HNC. In the southern part of the HNC, fine-grained granodioritic dykes (526 ± 10 Ma) and dark, medium-grained tonalitic dykes (503 ± 26 Ma) intruding paragneiss and marble, have been dated by whole-rock Rb-Sr methods (Nissen 1986). Based on field relations, Nissen (1986) concluded that the dykes were syn-tectonic, and that the tonalite is older than the granodiorite. Consequently, the sequence was Cambrian or older, and presumably deformed in Late Cambrian to Early Ordovician times. The dykes are considered to have intruded during a foliation-forming orogenic phase in Late Cambrian time (Nissen 1986).

These findings have important implications for the understanding of the tectono-metamorphic history of the HNC. Based on lithological similarities, the ophiolitic basement unit of the Middle nappe seems to correlate with the Leka Ophiolite Complex (LOC) (Prestvik 1972, Sturt et al. 1984) in the western parts of the HNC. Radiometric dating (U/Pb zircon) by Dunning & Pedersen (1988) of a quartz keratophyre dyke in the LOC has yielded 497 ± 2 Ma, and this implies an Early Ordovician age for the formation of the primitive arc stage of the LOC. Hence, if the correlation is valid, regional deformation (D1-D4) and metamorphism in the igneous basement unit and the metasedimentary rocks of the Middle nappe must be younger than the Early Ordovician.

In summary, the metasedimentary rocks of the Middle nappe are dominated by schists and conglomerates, with minor amounts of marbles. The bulk of the clasts in the conglomerates, particularly in the lower parts, reflects erosion of an assemblage of rocks corresponding to an ophiolite pseudostratigraphy. In the upper conglomerates, a relatively high proportion of clasts such as quartzite, granite, tonalite, marble and possible acidic orthogneiss reflects derivation from a different assemblage of rocks, of probable continental affinity. The lithodemic complexes in the Lower and Upper nappes have lithologies in part comparable to these pebbles, but the significance of this is uncertain. The sequence of metasedimentary units in the Middle nappe is broadly equivalent to the stratigraphical pattern in Lyngen, where Minsaas & Sturt (1985) describe a cover sequence unconformably overlying the Lyngen Gabbro — considered to be part of an ophiolite complex. In the lower parts of this sedimentary sequence, rocks derived from the ophiolite dominate, while in the upper parts there is a significant contribution from metamorphic continental rocks. This influx of continental pebbles is interpreted by Sturt & Roberts (1991) to be associated with the obduction of the Lyngen ophiolite onto the westward extension of the continent Baltica, followed by uplift, erosion and subsequent deposition of a sedimentary sequence reflecting erosion from both continental and ophiolitic sources. Such far-reaching conclusions cannot be drawn from the present study, but the occurrence of probable continental rocks in the upper metasedimentary units of the Middle nappe indicates that the ophiolite was emplaced on to some sort of metamorphic, sialic crust of pre-obduction age, prior to the deposition of the metasedimentary rocks.

The poorly sorted nature and mineralogical immaturity of the matrix of the conglomerates indicate rapid deposition, possibly due to synsedimentary faulting. The recognition of the basement-cover contact as a modified depositional unconformity implies that the sequence in the lower parts youngs towards the east. Except for a large F2 fold in the Nordfjellmark area, and the invoked tectonic discontinuity in the Velfjord area, the sequence seems generally to have a younging towards the east, particularly when the change of clast populations in the conglomerates is taken into consideration. However, the generally high strains, general lack of reliable way-up criteria and lack of faunal evidence precludes any definite statements regarding the true stratigraphy of these rocks. Consequently, no formal lithostratigraphic division has been applied.

Timing of the thrusting of the Middle nappe can be constrained by a comparison with the tectonostratigraphic pattern in the Sørfjord area, in the southern part of the HNC (Fig. 1). An imbricated sequence of metagabbro and greenstones with island arc affinity unconformably overlain by polymict conglomerates, psammites, marbles, schists and minor felsic volcanites (Husmo & Nordgulen 1988) is cut by the large Heilhornet pluton. Granodiorites from the latter also intrude the medium-grade supracrustals structurally overlying the Vestranden orthogneisses, and have been dated by U/Pb in zircons, yielding a Late Ordovician-

Early Silurian age of 444 ± 11 Ma (Nordgulen & Schouenborg 1990). Based on combined field and isotope data, Nordgulen & Schouenborg (1990) conclude that an important part of the tectonometamorphic development, including nappe imbrication and emplacement of the HNC over the Vestranden orthogneiss/ supracrustal complex, took place in the Ordovician. Even though the imbricated sequence in Sørfjorden belongs to a lower tectonostratigraphic level within the HNC, the overall similarities in terms of the 'ophiolitic' basement and cover sequence indicates that this dating is relevant for the Middle nappe, too. Hence, it is inferred that regional deformation, initial thrusting of the Middle nappe, and its imbrication with the Lower and Upper nappes took place during the Ordovician. The final accretion of the HNC and parts of the underlying supracrustal rocks of the Vestranden sequence onto the Baltoscandian continent probably occurred during the Middle Silurian to Early Devonian Scandian phase of the Caledonian orogeny (Nordgulen & Schouenborg 1990). One should, however, note that there are indications for Middle Silurian eastward thrusting of the HNC from the Hattfjelldal area, along the eastern boundary of the HNC (Dallmann 1987).

Conclusions

The tectonostratigraphy in the southwestern parts of the HNC involves nappes of dominantly continental material, imbricated with nappes carrying ophiolite fragments. The ultramafic rocks in the ophiolite fragments contain indications of early, non-orogenic deformation under upper mantle/lower crustal conditions, and faulting under shallow crustal conditions, prior to uplift, erosion and deposition of an unconformable cover sequence. The metasedimentary rocks in the cover sequence dominantly reflect erosion of an ophiolite pseudostratigraphy in the lower parts, while the clast population in the upper conglomerates reflects an increasing influx of pebbles of continental affinity.

Most of the regional deformation and metamorphism seems to have occurred after the Early Ordovician, but prior to Late Ordovician/ Early Silurian times, with modification during the Late Silurian/Early Devonian Scandian phase of the Caledonian Orogeny. Radiometric dating from other parts of the region and structural relations indicate that the nappes with dominantly continental material have experienced a more protracted tectono-metamorphic history than the nappes comprising ophiolite detritus.

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