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Proterozoic Geology and Scandian High-Pressure Overprinting in the Western Gneiss Region

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Summary:

The report is a guidebook for a four day excursion in connection to the COPENA meeting held at NGU 18.-22. Aug. 1997. The first day of the excursion will wisit localities in the Caledonian Nappes at Oppdal, and then continue over Sognefjell to Sogndal with stops along the contacts to the Jotun Nappe and in the nappe itself. The second day the excursion will continue through the Western Gneiss Region to Måløy with several stops in the Proterozoic gneisses. Many of the classic eclogite localities will be visited, eg. in Almklovdalen, at Selje and Verpeneset, and there will also be some stops in the Devonian sediments. The third day will also consentrate on the Western Gneiss Region with stops at the Fiskå anorthosite, the Ulsteinvik eclogite and then continue over to Nordøyane and visit the Haram gabbro and examine the structures in the gneisses. The last day will go from Lepsøy to Trondheim via Molde. Here the same nappe sequence as was seen at Oppdal will be visited at several localities, but the nappe sequences are in places only a few meters thick.

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COPENA CONFERENCE AT NGU, TRONDHEIM, NORWAY

Guidebook for Pre-meeting Field Trip A-3
August 14-17, 1997

Proterozoic Geology and Scandian High-Pressure Overprinting in the Western Gneiss Region

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INTRODUCTION

The Western Gneiss Region is the second largest exposure of Precambrian rocks in Norway, but understandably, has been less studied from a Precambrian point of view than other areas, because of the moderate to intense late Silurian-early Devonian (Scandian) tectonic-metamorphic overprinting. There are, nevertheless, superb exposures of variably reconstituted Proterozoic rocks and some modern radiometric ages pointing toward the details of Proterozoic history. The northern part of the region is dominated by granitic-tonalitic gneisses in the age range 1686-1657 Ma considered typical of the Transcandinavian Granite-Porphyry Belt, but there are extensive areas of deformed rapakivi granite best dated at 1508 Ma and well preserved gabbros, some dated with variable quality at 1462, 1289 and 926 Ma. Southwest of a line approximately from Ålesund to Dombås there is increased evidence of middle Proterozoic igneous activity, mainly in the form of granites in the range 1000-942 Ma, and, close to Sognefjord, limited evidence of middle Proterozoic deformation and medium-grade metamorphism. The autochthonous to para-authochthonous basement is overlain locally by autochthonous cover and by a variety of far-travelled Scandian thrust sheets. One of these, the Jotun Nappe, is exposed over an area 25% as large as the whole Western Gneiss Region, and internally shows only rare evidence of Scandian overprinting. It contains 1694 Ma syenites to monzonites, 1252 Ma gabbros and pyroxene granulites, and zircon and sphene evidence of a Sveco-norwegian amphibolite-facies overprint at 909 Ma as well as ~900 Ma granites. Other nappes derived from ancient Baltica northwest of the present exposure of the Western Gneiss Region contain Proterozoic rocks ranging from 1640 and 1190 Ma rapakivi granites to Late Proterozoic continental rift-facies sandstones cut by late Proterozoic diabase dikes. To develop a clear picture of late Proterozoic Baltica, it will be ultimately necessary to interpret the events in these various thrust segments and to place them back in their original locations before Scandian thrusting.

One of the exciting features of the Western Gneiss Region is to examine the details of Scandian continental subduction and eclogite-facies, including coesite-eclogite-facies, regional metamorphism on pre-existing Proterozoic rocks. Extreme gradients in strain and fluid conditions commonly allow study of the complete transition from undeformed Proterozoic igneous rocks through various stages of deformation to Scandian mylonitic gneiss and eclogite, all within a single large outcrop. Another significant feature of the Western Gneiss Region is the widespread occurrence of sheets and pods of garnet peridotite and garnet pyroxenite, containing petrologic and isotopic evidence both of Scandian high-P metamorphism and of Proterozoic garnet equilibration, with reported ages at 1703 Ma and 1040 Ma, indicating these may be layers of Proterozoic continental lithosphere imbricated with Baltica crust during the Scandian collision and continental subduction.

The following section provides a brief introduction to the geology of the region, with particular emphasis on Early to Middle Proterozoic rocks. Although the resources are at hand, the time is not available to provide a comprehensive summary, and what follows is only a guide to the details assembled for each of the stops.

PROTEROZOIC BASEMENT IN THE WESTERN GNEISS REGION

Proterozoic Supracrustal Rocks

Extensive previous studies have suggested the widespread occurrence of Early to Middle Proterozoic supracrustal rocks in the Western Gneiss Region (c. f. Carswell and Harvey, 1985; Bryhni, 1989), and this still may be the case. However, in a number of areas of detailed study, rocks previously so assigned can be proved or implied to be supracrustal rocks within complex infolds of thrust nappes (Tucker, 1986; Krill, 1987; Robinson, 1995, 1997; Tveten and Lutro, 1996). This implication may be applied successfully in particular to a variety feldpathic quartzites extending from Trollheimen through Møre og Romsdal to the Sunnfjord region. However, Øyvind Skår (abstract, this meeting) has demonstrated a much older derivation for some quartzites in the western part of Sognfjord. Obviously the widespread intrusive igneous rocks must have been intruded into something, but it will be quite challenging to demonstrate which rocks are in fact supracrustal rocks in the basement and which are actually rocks in nappes. A particularly tempting situation is where the extensive Rjukan rift volcanics disappear beneath the front of the Caledonides and the Jotun Nappe, and even appear in a window beneath the Jotun Nappe, but have not so far been located in the Western Gneiss Region. The comments about supracrustal rocks do not apply, of course, to late Proterozoic sequences, that are a key part of the sedimentary history of the Baltic margin that was later enveloped in the Caledonides.

Proterozoic Mantle

A special feature of the Western Gneiss Region is the widespread occurrence of garnet peridotite and garnet pyroxenite containing subcontinental mantle assemblages that formed at pressures near 30 kbar that have been reliably dated (Mearns, 1986) as having equilibrated in the Early and Middle Proterozoic (1703 Ma and 1040 Ma). In view of the subject of this field trip, it is interesting to speculate on where the garnet peridotite and pyroxenite was located during the Proterozoic and how it reached its present position in the Caledonides. The chrome-rich garnet-bearing ultramafic rocks that are probably sub-continental mantle rocks rather than metamorphosed ultramafic cumulates, are common in the moderately high-pressure to high-pressure parts of the Western Gneiss Region, and many bodies seem to occur as either discrete layers within gneisses or as horizons of boudins within gneisses. The ultramafic rocks do not bear any obvious relationship to the adjacent gneisses, and it is therefore realistic to believe that many of the contacts are tectonic. Since the western part of the Western Gneiss Region is a location in which continental crust was being subducted to mantle depths, two locations can be envisioned where continental crust and sub-continental mantle would become in contact. One (A) would be on the active subduction surface where descending Baltica continental crust, possibly upper crust, could come in contact with mantle, probably initally quite hot mantle, of the upper (Laurentian) plate. The other (B) would be where Baltica basement rested on its own sub-continental mantle, which was then incorporated in the base of a thrust sheet at a time of crustal imbrication. Thermally it would seem that scenario B would be more likely to preserve Proterozoic mineral assemblages as at Almklovdalen, but this would also require that the region expose true lower crust in the vicinity. Imaginative pursuit of the answers to these questions might be rewarding.

Trans-Scandinavian Igneous Belt (1686-1650 Ma)

To the extent of coverage of reliable radiometric ages, the most widespread gneisses in the Western Gneiss Region in the area of the trip are derived from tonalitic to granitic intrusions in the age range 1686-1650 (Tucker et al., 1991), which falls within the time span of the Transcandinavian igneous belt. Though dominantly highly deformed amphibolite-facies gneisses, there are locations where the amount of strain is low and simple igneous textures are preserved.

Augen Orthogneiss (±1500 Ma)

This rock, in its least deformed state, is a generally granulated rapakivi granite, and is widespread in parts of the Western Gneiss Region, where it has been most extensively studied near Molde and the islands of Midsund by Carswell and Harvey (1985). They obtained a Rb-Sr whole rock isochron for these rocks of 1506±22 Ma, and more recently the same rock has yielded a U-Pb zircon age of 1508 Ma (Tucker and Krogh, 1986). A similar porphyritic mangerite at Flatraket has yielded a U-Pb zircon age believed to indicate the time of igneous crystallization at 1520±10 Ma (Lappin et al., 1979).

Gabbros (±1450, ±1200, ±900 Ma)

Gabbros are widespread in the Western Gneiss Region. Limited radiometric dating indicates they they span a large age range and no clear groupings have been established. The best dated gabbro is at Selsnes west of Trondheim where baddeleyite has yielded an age of 1462±2 Ma (Tucker et al., 1991). Two gabbros in Nordøyane, at Flem and at Haram have yielded igneous mineral - whole rock Sm-Nd ages of 1289±48 and 926±70 Ma respectively (Mørk and Mearns, 1986), and an olivine gabbro at Kråkenes northwest of Måløy has yielded 1258 (Mearns, 1984).

Sveco-norwegian Granites (1000-900 Ma)

Beginning along a line approximately from Dombås to Ålesund the Western Gneiss Region contains a variety of fine-grained to porphyritic biotite granites which have been well dated bythe U-Pb zircon method (Tucker and Krogh, 1986, Schärer, 1980) in the range 1000 to 900 Ma. Interestingly these do not seem to be associated with significant deformation. They very closely resemble other late Sveco-Norwegian granites in south Norway, but there they are superimposed on rocks with a strong record of Sveco-norwegian deformation and metamorphism which seems to be lacking in the Western Gneiss Region. This leads one to speculate as to what happens to the Sveco-norwegian Protogine zone after it passes beneath the front of the Caledonides near the Norwegiam-Swedish border.

PROTEROZOIC BASEMENT ROCKS IN THRUST SHEETS

Risberget Nappe of the Lower Allochthon (1650-1642 Ma, 1190-1180 Ma)

Until recently the rapakivi granites of the Risberget Nappe were believed to be about 1500 Ma, based on the Rb-Sr isochron of Krill (1983) from Oppdal and the similarity of the rocks to the augen orthogneiss of the Western Gneiss Region discussed above. In 1995 Handke at al., completed U-Pb zircon ages on 9 different localities over a wide geographic area and came up with two different age groups. Five of these yielded ages of 1650-1642 Ma, just slightly younger than the TIB, and four yielded surprising ages of 1190-1180 Ma, just older than a cross-cutting pegmatite dated by Krill by the Rb-Sr method at 1163± 80 Ma. Thus the thrusting of this nappe seems to have sampled a section of Baltica not quite like the part now exposed in the Western Gneiss basement itself.

Jotun Nappe

The monzonitic-anorthositic-mafic complex of the Jotun Nappe is not thoroughly dated. The most important dates are U-Pb zircon and sphene ages from Schärer (1980), 1694± 20 Ma for crystallization of a syenitic to monzonitic magma, 1252+28-25 Ma for intrusion of gabbros which subsequently developed garnet coronas, and 909±16 Ma for an upper greenschist facies - lower amphibolite-facies dynamothermal metamorphism. The anorthosite is very calcic, a common feature of Archean anorthosites (Ashwal, 1993), but this anorthosite is generally considered to be Proterozoic. Uncertainties are discussed at some length under Stop 1-11 and need not be repeated here.

EVIDENCE FOR EARLY TO MIDDLE PROTEROZOIC METAMORPHISM

Clear evidence for the age or ages of Proterozoic metamorphism is difficult to come by despite widespread evidence for an early granulite-facies event, both in the western part of the Western Gneiss Region and in the Jotun Nappe. Tucker et al. (1991) make the point that there is no evidence for disturbance of the TIB rocks between their age of crystallization and the age of Scandian recrystallization. In the face of this type of evidence, it is not surprising to see granulite-facies corona formation ascribed to post-magmatic cooling. In the northern part of the Western Gneiss Region a case can be made for granulite-facies overprinting following eclogite-facies crystallization and before amphibolitization (Jamtveit, 1987), but in the vicinity of the Flatraket granulite body, Krabbendam and Wain (1997 and this guidebook) emphatically argue that the granulite-facies assemblages are earlier than the eclogite-facies overprint.

TECTONO-STRATIGRAPHY OF CALEDONIDE NAPPES

Understanding of the Scandinavian Caledonides is based on 1) the identification and mapping of a complex sequence of tectono-stratigraphic units and 2) the recognition that these represent rocks generated in a wide variety of settings that were later assembled in a major continental collision during which shortening and thrust translation over distances of 100's of kilometers was characteristic. For the non-specialist the array of units and unit names is challenging (Gee and Sturt, 1985), and the details of correlation, even for the area of this field trip, is beyond the scope of this introduction. Here we have adopted a general and very simplified sequence of units most easily understood both in local terms and in terms of orogen-wide correlations.

The lowest tectono-stratigraphic unit exposed in the field trip area is the Baltica basement, a segment of the former Baltic craton dominated by Proterozoic granitoid intrusive rocks of the Transcandinavian igneous belt ("TIB") in the age range 1686-1650 Ma (Tucker et al., 1986) that were locally intruded by rapakivi granites dated in one location at Molde at 1508 (Tucker et al., 1991) and by still younger gabbros dated in one location at Selsnes at 1462± 2 Ma (Tucker et al., 1991). The extent and intensity of Proterozoic metamorphism of these rocks is poorly understood, but there is limited evidence that some rocks may have reached pyroxene-granulite facies. The area is south of well recognized Sveco-fennian deformation and contains the outermost influences of the Sveco-norwegian orogenic belt first indicated by occurrences of 1000-900 Ma granites (Tucker et al., 1991).

The extent and intensity of metamorphic overprinting of Baltica basement during the Scandian continental collision is part of the subject of this field trip. Generally there is evidence of an early Scandian overprint ranging in intensity from low amphibolite facies to eclogite facies followed by a general late Scandian amphibolite-facies overprint. The best recent understanding is that the Baltica basement in the field trip area, although providing the basement for emplacement of the sequence of far-traveled thrust nappes, is not truly autochthonous with respect to the Baltic shield exposed in front of the Scandian orogen in Sweden and southern Norway. Evidence for this comes in two main forms. In the part of the Western Gneiss Region exposed in Trollheimen (see Fig. 1.3), maps clearly delineate two levels of basement, each capped by a quasi-continuous layer of variable deformed late Proterozoic quartzite and pebble conglomerate. It is inescapable that the upper level of basement forms a vast and highly folded thrust sheet emplaced above the lower level of basement and its autochthonous cover (Nilsen and Wolff, 1989). Robinson (1997) has deduced a similar situation within the anticlinal culmination centered on Rekdalshesten about 20km southwest of Molde (see Fig. 4.1) and there are various other indications of probable segmentation of Baltica basement within the northern part of the Western Gneiss Region. The second form of evidence is in the deep seismic seismic profile from Trøndelag across the orogen to the Baltic shield in Sweden (Huric, et al., 1988) clearly showing that the Baltica basement exposed in various tectonic windows near the Norwegian-Swedish border lies above a major shallowly dipping reflector that appears to correspond to the authochthon exposed at the front of the orogen.

Above the Early to middle Proterozoic Baltica basement in various parts of the map area are vestiges of a very thin authochthonous sedimentary cover sequence, usually consisting of probable late Proterozoic quartzites and conglomerates, and overlying pelites representing metamorphosed Cambrian alum shale. Within the field trip area, these units of the autochthon and Lower Allochthon are too thin to show, and in many parts of the area they are entirely absent or recognized with difficulty, and usually not distinguishable from each other. They are, however, reported locally, for example in the previously mentioned quartzites of Trollheimen, and in the Øyangen Formation (Tucker, 1986) of quartzite and overlying mica schist in an area west of Orkanger. In the unmetamorphosed lowest thrust allochthon in Sweden, these are overlain by a thicker sequence, which includes Baltica basement, late Proterozoic sandstones, a limestone-shale sequence of Cambrian-Ordovician age, and a thin Silurian sequence of sandstone and limestone grading upward into turbidites that may range into lowest Devonian.

Above the autochthonous cover and Lower Allochthon, and commonly in direct contact or close contact with Baltica basement, are the rocks of the Middle Allochthon. The lowest recognized unit is the Risberget Augen Gneiss Nappe correlated with the Tännäs Augen Gneiss Nappe in Sweden and its proposed correlative Jotun Nappe further south. The

Risberget Nappe is dominated by variously deformed middle Proterozoic rapakivi granites with various associated gabbros, anorthosites, and other granitoid rocks. Earlier assigned an age of 1500 Ma (Krill, 1983a), new concordant zircon ages (Handke et al., 1995) indicate that these distinctive rapakivi granites fall into two age groups, 1659-1642 Ma at 5 localities, and 1190-1180 Ma at four localities. Although of two different ages, neither age group corresponds to known igneous ages in the immediately underlying Baltica basement, not even to the 1500 Ma age of recognized augen gneisses derived from rapakivi granites. The other key part of the Middle Allochthon consists of feldspathic quartzites derived from late Proterozoic feldspathic sandstones, interlayered with amphibolites derived from later Proterozoic diabase dikes. This unit termed the Särv Nappe in Sweden is variously known in Norway as the Sætra, Songa, and Leksdal Nappes. A few areas of feldspathic gneisses, intricately interlayered with amphibolites, might be Baltica basement to the Särv Nappe heavily intruded by the same late Proterozoic dike swarm (see Stops 3-10, 4-6 and 4-7) Near the front of the Caledonides in Sweden, the late Proterozoic sandstones of the Särv Nappe are as much as 2 km thick. By contrast, in parts of the Western Gneiss Region, the equivalent quartzite-amphibolite sequence of the Sætra Nappe has been mapped where it is from 10 m (Robinson, 1995) to as thin as 1m (Terry and Robinson, 1996).

In Sweden the Upper Allochthon has traditionally been mapped as two major units, the lower Seve Nappe, characteristically containing medium- to high-grade metamorphic rocks, and the upper Köli Nappes containing medium- to low-grade metamorphic rocks, locally with Ordovician fossils. The traditional equivalent names in Norway have been the Skjøtingen and Støren = Meråker Nappes respectively. In the central part of the Caledonian sequence the high grade Gula Nappe has been regarded as a separate nappe between the Støren=Köli and Skjøtingen=Seve, but we regard the Gula Nappe as an equivalent of Seve. Geotectonically, the rocks of the Seve and Gula Nappes have been considered as the extreme outboard assemblage of the Baltica continental margin, and to have been subjected to high-grade, even locally high P metamorphism in pre-Scandian and/or early Scandian time. The Köli and Støren = Meråker Nappes are considered to have a largely exotic origin as Late Cambrian - Earliest Ordovician ophiolite sequences and Ordovician volcanic-arc sequences and their unconformable Late Ordovician to possibly Early Silurian cover from Iapetus Ocean. Ordovician fossil affinities in the Støren Nappe suggest deposition proximal to Laurentia, and possibly even that the strata were thrust or obducted onto Laurentia in the Ordovician Taconian orogeny, and then later transferred onto the Baltic margin in the Scandian collision.

In detailed subdivision of the Seve equivalents in the Trollheimen region of Norway, Krill (1987) identified a lower Surna Nappe characterized by higher grade metamorphism and abundant intrusions of Trondhjemite and pegmatite, and an upper Blåhø Nappe, usually slightly less metamorphosed and lacking such intrusions. Robinson (1995) did not attempt to carry this distinction in his correlation within the Moldefjord region and adapted the composite term Blåhø-Surna Nappe, but for the Ålesund and Ulsteinvik 1/250,000 sheets Tveten and Lutro (1996) simplified this to Blåhø Nappe which is also used in this guidebook.

Within the northern part of the Western Gneiss Region, it has been most practical to map two nappes. The lower nappe is characterized by medium- to high-grade mica schists, commonly with garnet±kyanite±sillimanite, and with variably distributed granitoid intrusions and pegmatites, by abundant coarse amphibolites, commonly with garnet and pyroxenes, and by fairly common layers of coarse-grained marble. The upper nappe is dominated by low- to medium-grade metamorphosed volcanic and related intrusive rocks including ophiolite fragments, by metamorphosed volcano-sedimentary sequences, and by metamorphosed black shale. An additional component of this nappe, recognized earlier (Tucker, 1988; Gautneb and Roberts, 1989) but receiving special emphasis recently (Robinson et al., 1996; Tucker et al. 1997; Robinson et al., 1997), is a variety of middle to late Ordovician medium- to coarse-grained calc-alkaline intrusive igneous rocks that were contemporary with the extrusion of the arc volcanics. A common distinction between the lower and upper nappes is that the lower one contains medium- to high-grade rocks with coarse garnet, whereas the upper one contains low- to medium-grade rocks with no more than 2-3mm garnets if any at all. For this guidebook we have used the name Blåhø for the lower nappe and the name Støren for the upper nappe.

LATE OROGENIC CLASTIC SEDIMENTS

At the top of the tectono-stratigraphic section, and indeed not really a part of it, are the moderately deformed and slightly metamorphosed conglomerates, sandstones, shales and rare limestones of the Devonian Old Red Sandstone basins. They are exposed on Smøla, Hitra, and Ørlandet (Trip B-1, this conference) and a large number of small islands near Trondheim, and in four major basins in west Norway, from north to south Hornelen (Stop 2-9), Håsteinen, Kvamshesten, and Solund. According to a structural study by Seranne (1992) and in agreement with studies of other Devonian basins in west Norway (Andersen and Jamtveit, 1990; Andersen, 1993), all of these strata lie on the upper plates of major top-to-west extensional detachment faults that carried both the Devonian strata and their immediately underlying igneous-metamorphic substrate for many kilometers southwestward or westward from their original sites of deposition. The rocks unconformably beneath the basins have escaped much of the deformation characteristic of the Western Gneiss Region and appear to belong to parts of the Caledonides normally exposed far to the east and also commonly rather low in the regional nappe stratigraphy.

EFFECTS OF SCANDIAN DEFORMATION AND METAMORPHISM ON PROTEROZOIC ROCKS

As will be seen on the field trip, in fact one of the main themes of it, is the great variation in the extent and nature of deformation and metamorphism of Proterozoic protolith rocks. Clearly the partitioning of strain was extreme, and even though rocks commonly went through more than one Scandian deformation, some parts were protected from major effects. Clearly also the access of fluids to the rocks was extremely variable. This had two effects: it limited the extent to which rocks could reach their equilibriun assemblages, and where secondary hydrous phases, particularly micas, did not form, it limited the amount of ductile strain. This being said, the extent of amphibolite-facies re-equilibration is remarkable in view of the seemingly water-poor igneous and older metamorphic protoliths, and must lead one to speculate on sources for hydrous fluids. Several workers have pointed out the complimentary relationship between mafic rocks, which lose H_2O upon the breakdown of amphibole under high pressures, and gneisses which lose biotite to phengite by hydration, and the reverse of these two processes during unloading. However, the volume of mafic rock overall is not sufficient to have had more than local effects.

It seems likely that speed of subduction and uplift were critical to preservation, both of old protoliths and high-pressure and ultra high-pressure assemblages. This could be most effectively accomplished by the imbrication of basement slabs which moved forward onto cooler Baltica basement, while at the same time being juxtaposed with cooled higher-level nappes moving away from the craton on extensional faults. Basement sphene in TIB basement studied in detail by Tucker et al., (1987, 1991 and in preparation) shows variable degrees of recrystallization from the igneous protolith age of around 1657 Ma toward the time when Scandian lead loss was terminated. The remarkable feature is not that there are variable degrees of lead loss, but that all samples, regardless of degree of lead loss, fall on the same chord at 395±2 Ma, implying cooling over a very broad region in a very short period of time. Furthermore, Ordovician intrusive rocks of the Støren Nappe, locally only 1 km from completely recrystallized basement, show little or no resetting of their Ordovician igneous sphene, implying a major early extensional detachment between the nappe and basement (Robinson et al., 1996; Tucker at al., 1997; Robinson et al., 1997). These data, combined with the limited U-Pb dating of new metamorphic zircon in eclogites at 402±2 Ma (see Fig. 3.1B) imply that many of these rocks may have been subducted and cooled below 600°C in a little as 10 m.y.! Furthermore, new time-scale data based on dating of tuffs in fossiliferous sections (Tucker et al., 1997) indicates that the Devonian began about 418 Ma, and thus that most of these Scandian events took place in Early Devonian rather than Silurian time.

A PRACTICAL NOTE TO PARTICIPANTS

Depending on information available it is expected to pick up participants either at NGU or at Hotels in Trondheim about 8 A. M. Thursday August 14, and proceed direct to Stop 1 at Støren. Particpants will be returned to the same locations on Sunday evening, August 17. Cost of $400 U. S. includes guidebook, all transportation including ferries, overnight accommodation for three nights, and all meals (excluding alcoholic beverages) except lunch on the first day to be bought on the road. Many stops are near the road, but others involve walks up to 1 km on boggy ground. Expected weather can be anything from hot sunshine to strong wind with horizontal rain. Waterproof boots, rain suit, and pack to carry them are highly recommended. Large wave-washed exposures can be enjoyed even in very bad weather. In addition to the rocks, this trip will cover some of the most spectacular fjord and mountain areas in Norway.

This field trip was designed to give participants the maximum amount of insight into the geology, particularly the Proterozoic geology, and the scenery of a significant part of western Norway within a limited number of days. Even in mid-August, field work is possible well into the evening. Emphasis is on "seeing the rocks", admittedly the most easily accessible rocks, and not on extended descriptions and discussions, which may nevertheless take place in unscheduled moments.

Distances to be travelled are quite long and some of the stops are quite short, so participants will have to acquire a certain degree of self-discipline to gain full benefit from the experience. A further degree of discipline is imposed by the schedule of ferries, which must be conformed to. These include 1 ferry on day 2 and 4 ferries each on days 3 and 4. Therefore, when leaders indicate that it is time to leave a stop, the intention is serious and your welfare is involved. In return the ferries do supply an opportunity for informal refreshments and abundant public toilets which **should not be missed**. The ferry fares of all participants will be paid by the leaders. During ferry trips it is always possible to climb to a sun deck for further enjoyment of scenery and geology, or, if you like, descend to the "salong" in the bowels of the ship to rest from it, as is the custom of many Norwegians.

The schedule each evening is different. On day 1 we hope to reach our hotel about 18:30 for dinner. Then from 20:00 to 21:45 there will be a short excursion to three spectacular exposures near Sognefjord. On day 2, due to the abundance of important rocks late in the day, we will not reach our hotel and dinner until about 20:15. On day 3 we will stop for dinner about 18:45, but then at 20:30 catch another ferry to our overnight location. Once there, there will be an informal field trip 21:00 to 22:00 to a lighthouse with huge pavement exposures. On day 4, the final 2 1/2 hour drive to Trondheim will last until around 21:00. Persons with hotel reservations should inform them of late arrival Sunday evening. Notice that Conference activity other than Registration does not begin on Monday until 10:00.

INTRODUCTION TO DAY 1 14/8/97

The entire route of the field trip is shown on Figure 1.1, including the locations of several stops not shown on local maps. The most important objective of day 1 is to travel south about 460 km from Trondheim to begin our traverse across the Western Gneiss Region near Sognfjord. The route will follow Route E-6 along the line of the railroad, partly above timber line, as far as Otta, and on a major highway west to Lom. Then we will climb over the Sognfjell Pass (1434m), the highest through highway in Norway, which is open only in summer, and down to Sognfjord. On the route to Otta we will visit several classic outcrops of Caledonian nappes, including Proterozoic rocks, that lie in the Trondheim Synclinorium or on the north-eastern margin of the Western Gneiss Region (Stops 1-1, 1-2, 1-3, 1-4). Crossing the Sognfjell Pass we will examine the northwest margin of the Jotun Nappe (Stops 1-5, 1-6), a far traveled allochthon of Proterozoic rocks with a somehwhat different history than the Western Gneiss Region. Near Sognfjord we will examine two Sveco-norwegian granites in the Western Gneiss Region (Stops 1-7, 1-8), and then, after dinner in the evening, we will drive 18 km to the southeast into the heart of Proterozoic rocks in the Jotun Nappe (Stops 1-9, 1-10, and 1-11).

ROAD LOG

Total Time	Time since prev.	Total Km	Km since prev.	
8:15				Trondheim, NGU
8:35	20			Klett Traffic Circle. Continue south on E-6. Small quarry in ultramafic rocks for Nidaros Cathedral near Øyesand to west.
9:00	25			Sedimentary rocks of Late Ordovician, possibly even Silurian Upper Hovin Group.
9:02	2			Lower Ordovician black shale near roadside park.
9:03	1			Lower Hovin Group. Green sandstone derived from volcanics. Conglomerate below this at base of Lower Hovin above Støren greenstone.
9:05	2			Right exit, then left to Krigsminne. Then north down bike path to 2nd "M" sign.

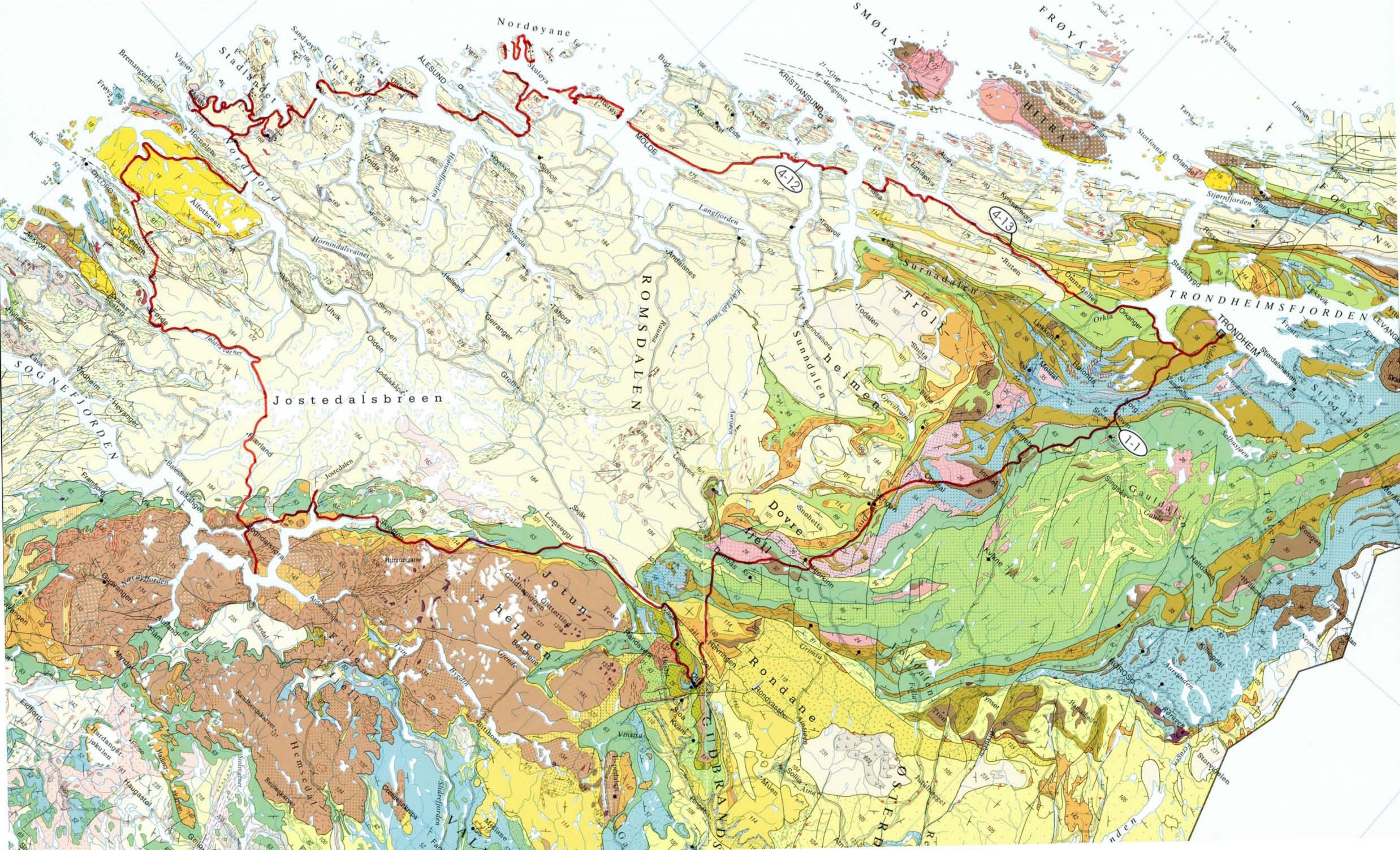
STOP 1-1: Støren Volcanics near Haga bridge. (15 minutes) Pillow breccia and pillow lava of the Støren Group in greenschist facies (See Fig. 1.2). The Lower Ordovician (?) Støren Group is here ca 2 km thick and it is overturned. The Støren Group is thought of as a fragment of ophiolite and is part of a large group of obducted ophiolites in the age range 500-480 Ma that are now located on the both the Baltic and Laurentian margins of the Atlantic. Walk from the pillow breccia near the light pole northwest through the zone of tuff with beds of jasper to the pillow lava.

9:20	**15**			At stop do U-turn. Return south and cross Haga Bridge and drive through Støren Village.
9:25	5			Village of Støren.
9:26	1	50		Junction. Turn onto E-6 for Oslo. Now in Gula Group. View back left to Trondhjemite quarry.
9:38	12	64.0	14	Soknedal Bakery. Possible emergency toilet.
9:54	16	82.5	18.5	Berkåk. Junction for Orkanger. Stay on E-6.
9:59	5	88.0	5.5	Cliff view spot in highway. Sedimentary rocks of Støren Group. Further on with felsic dikes.
10:04	5	94.0	6.0	Ulsberg. Junction with Route 3 for Tynset. Stay on E-6.
-	-	-	-	Smooth landscape with many boulders. "Innset massif" of dark gray intrusive Trondjhemite. At about this point we enter the area shown in Fig. 1.3, including the locations of Stops 1-2, 1-3, and 1-4.
10:24	20	118.6	24.6	Oppdal Junction. Turn right toward Sundalsøra. Park on right beyond Domus store and Vinmonopolet. 15 min. stop.
10:39	**15**	119.0	0.4	Leave Oppdal. Continue south on E-6.
10:43	4	122.0	3.0	View of Blåhø Mountain and gorge of Driva River.
-	-	130.4	8.4	Road cuts in Risberget augen gneiss. View of high flagstone quarries.
10:55	12	135.7	5.3	Skiferbrud. Entrance to flagstone quarries on right. Go under underpass, turn right, follow narrow road up hill.
10:58	3	136.8	1.1	Quarry building at top of rough road and northwest-facing cliffs.

STOP 1-2: (20 minutes) Eidsvoll Flagstone Quarry in the Sætra Nappe. Folded late Proterozoic feldspathic sandstone cut by dolerite dikes. (See Figure 1.4). The folds generally plunge southeast and may be typical of folds oriented quasi-parallel to the nappe transport direction during thrusting. The following description was adapted from Krill.and Röshoff (1981).

Dolerite dikes are abundant in the psammite of the Sætra Nappe, but they are not commonly seen in the quarries. The dikes represented structural heterogeneities in the psammite and prevented its uniform deformation into well foliated flagstones. Therefore the numerous flagstone quarries here mainly avoid the dikes, which are most common between the

Fig. 1.1. Part of the bedrock geologic map of Norway, 1/1,000,000, showing the route of Field Trip A-3 and the locations of Stops 1-1, 4-12 and 4-13.



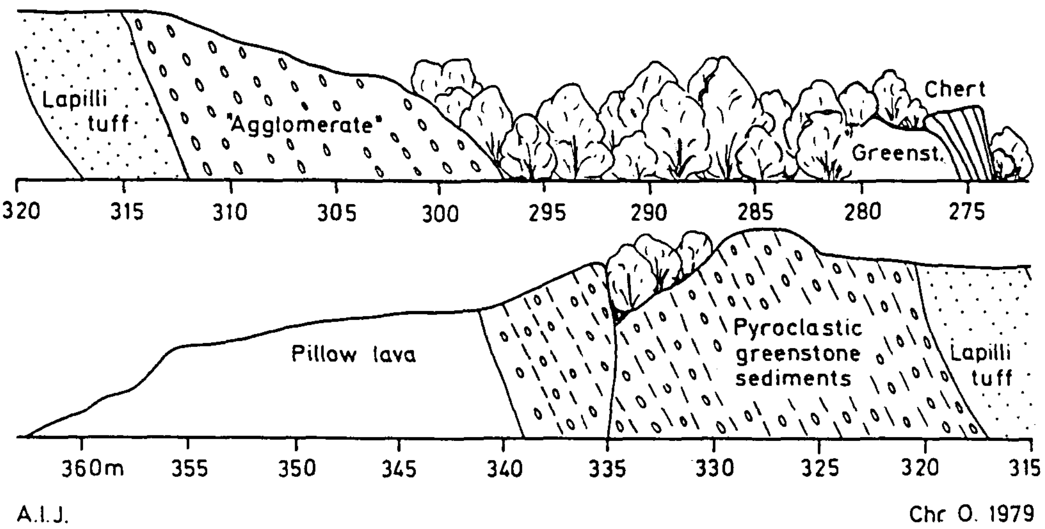


Fig 1.2. Road section along the highway at Haga bridge. The figure is part of a figure taken from Wolff et al. 1980. The road has since then been widened and the section we will be looking at is some tens of meters further back compared to the 1980 section.

quarries. Over a hundred dikes can be found among the quarries. The main dolerite at this locality is a very irregularly shaped, stepped intrusion, later deformed. Much of it is weakly foliated, but it is strongly deformed near the psammite wall-rock, which is tightly folded next to it. South of the three-pronged body of meta-dolerite, a well preserved part of the stepped intrusion shows that the dike originally truncated sedimentary layering in the arkose. The dike served to shield the psammite, which is progressively foliated and flattened a few meters away. Farther south, the center of the dike is completely unfoliated. Whole-rock Rb-Sr dating of samples taken from this dike gives an age of 738 ± 65 Ma. On basis of lithology, age and tectonostratigraphic position, the Sætra nappe is considered to be the extension of the Swedish Särv Nappe on the western side of the Trondheim Synclinorium.

11:18	**20**	-	-	Leave flagstone quarry.
11:21	3	137.4	0.6	Pause below quarry. View of cross-cutting dike on right. Turn left through underpass, then turn right.
11:22	1	137.9	0.5	Back on E-6 south. View of Mock Quartzite Factory!!!
11:25	3	140.3	2.4	Turn left on short segment of old E-6. Park and walk back to road cut.

STOP 1-3A: (10 minutes) Anorthosite, hornblende gabbro in Risberget Nappe. Lenses of metamorphosed anorthosite are associated with various gneisses of the Risberget nappe. The anorthosite lenses seen here are strongly deformed and fully recrystallized, but a massive anorthosite gabbro in Pineggbekken 4 km further south contains both ortho- and clinopyroxene. North of the metamorphosed anorthosite is the contact (unexposed) with the Sætra nappe. The Sætra nappe lies undeneath the Risberget nappe here, as they are inverted on the lower limb of the large-scale Holberget recumbent anticline.

11:35	**10**	140.5	0.2	Drive or walk to end of segment of old E-6 and examine road cut on left.

STOP 1-3B: (10 minutes) Risberget rapakivi granite. The rapakivi granite exposed here contains megacrysts of perthitic K-feldspar up to 15 cm long. The rapakivi texture, large K-feldspar megacrysts with thin plagioclase mantles, is considered to be an igneous texture, formed by crystallization from a potassium-rich magma (Tuttle and Bowen 1958, Stewart and Roseboom 1962). This exposure of some of the least deformed parts of the Risberget Nappe is similar to the material from which Handke et al. (1995) obtained a U-Pb zircon age of 1189.0±1.0 Ma (See Figure 1.5). This was surprising in view of the Rb-Sr whole rock isochron for this and adjacent outcrops obtained by Krill (1983, see discussion for stop 1-3C).

11:45	**10**	-	-	Walk 100m south along new E-6 to road cut on left.

STOP 1-3C: (10 minutes) Mylonite of Risberget Nappe. Krill (Krill and Röshoff, 1981) gave the following description of the this outcrop. "The roadcut south of the the rapakivi rock contains a common type of augen-gneiss ultramylonite. K-feldspar augen - some with rapakivi mantles are the only remaining porphyroclasts in the very fine-grained ultramylonitic matrix. Rb-Sr whole-rock analysis of the ultramylonite yielded an isochron: 1533 ± 65 Ma. (Krill, 1983). The ultramylonite may be Precambrian, but its foliation and lineation are parallel to Caledonian fabrics in the nearby Sætra Nappe. Alternatively, the Precambrian date may be the primary age of the rapakivi rock and not the age of the mylonitization."

In carrying out his Rb-Sr whole rock study, Krill (1983) noted that the scatter of coarse Rapakivi granite and augen gneiss samples gave a very poor "errorchron" of 1182±115 Ma. which he considered geologically meaningless. In contrast, the ultramylonite samples were much more radiogenic, and when combined with the other samples gave an errochron indicating an age of 1618±44 Ma. Now that we know from the zircons that the age of the rapakivi granite is actually 1189 Ma. it is tempting to speculate that the ultramylonites were produced from another rock in the Risberget Nappe which was not cogenetic with the rapakivi granite and was probably older, possibly the basement into which the rapakivi granite was intruded. This is consistent with the errochron of 1533±65 Ma obtained from the ultramylonite alone. It seems that this older rock suffered selective transformation to ultramylonite in these outcrops! Krill also obtained a five-point whole rock errorchron of 1163± 80 Ma. for a granitic pegmatite which intrudes the rapakivi granite and is foliated with it as well as sheared along its contacts. Krill's speculation that this pegmatite may reflect a Sveconorwegian thermal event, albeit an early one, seems to be born out by the new zircon data (see also discussion for Stop 3, B-1 field trip, this Conference).

11:55	**10**	-	-	Continue south on E-6.
12:10	15	158.0	17.5	Turn right to Kongsvoll Railway Station. Outcrops and loose blocks near west end of bridge over Driva River.

STOP 1-4: (10 minutes) Biotite-muscovite-hornblende schist and amphibolite of Blåhø Nappe.

The following note is from A. G. Krill, unpublished excursion guide, 1987. The Blåhø Nappe in this area consists of garnet- and hornblende-bearing pelite and amphibolite. In roadcuts about 500m north of here traces of staurolite occur in the schist, and kyanites are found in quartz-veins. The garnets here are retrogressed to chlorite. The thrust contact to the Tronget = Støren Nappe is located on the main road just south of Kongsvoll fjellstue, but is not exposed.

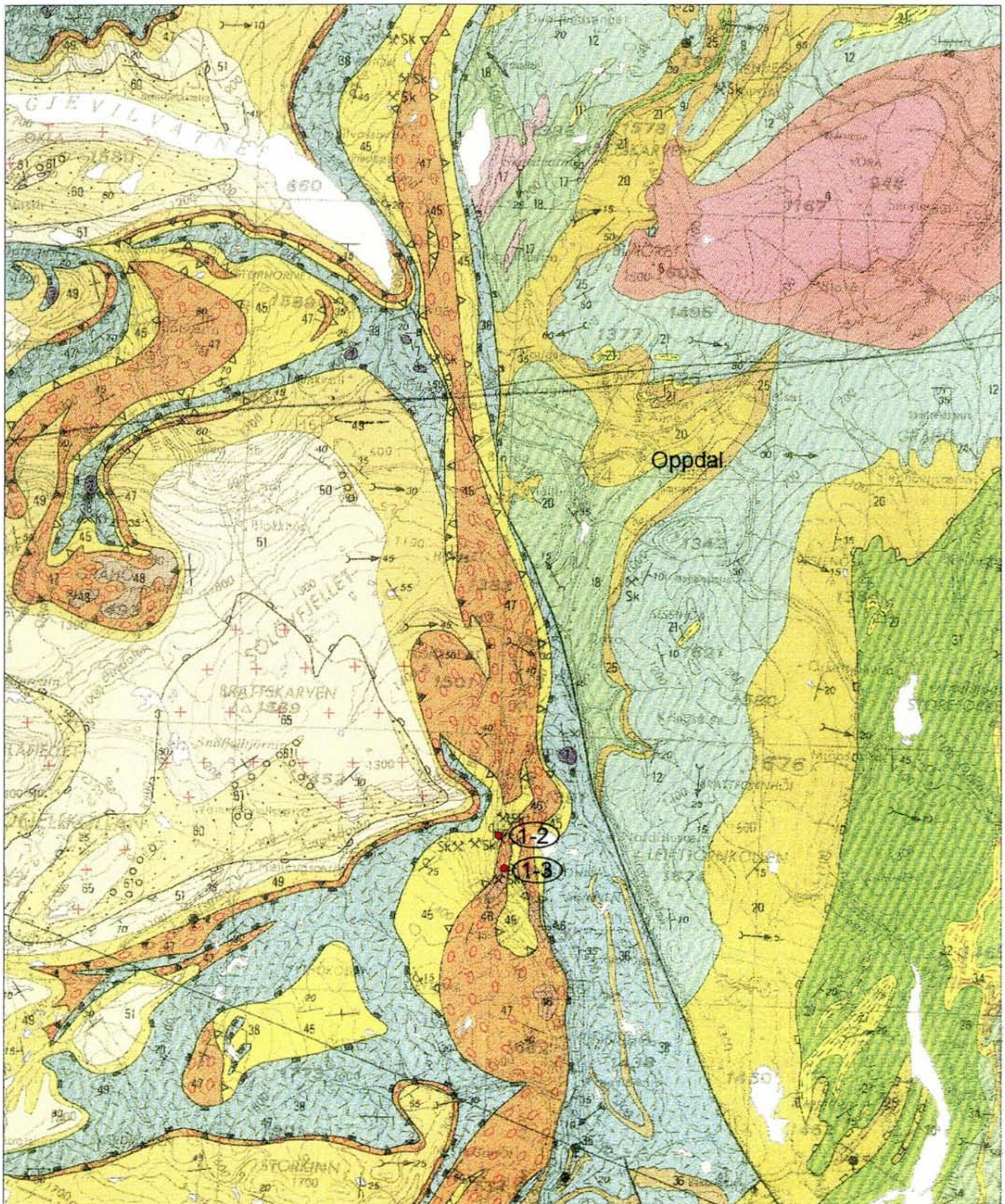


Fig 1.3. The stops in the Oppdal area. The map is copied from the 1:250.000 sheet Røros og Sveg (Nilsen & Wolff 1989).

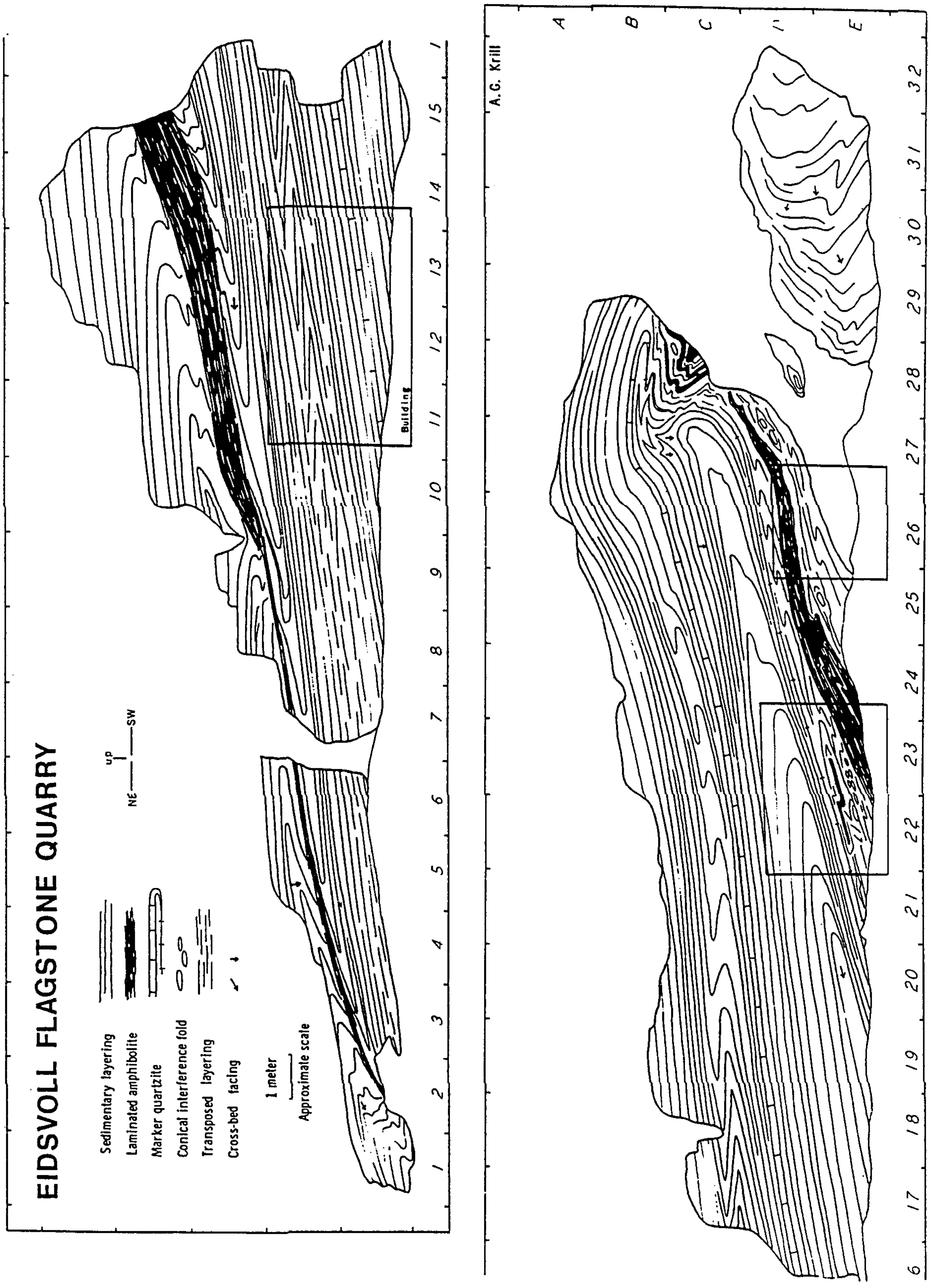


Fig. 1.4. Simplified drawing of a rock wall in the Eidsvoll quartzite quarry. Figur taken from Krill 1986.

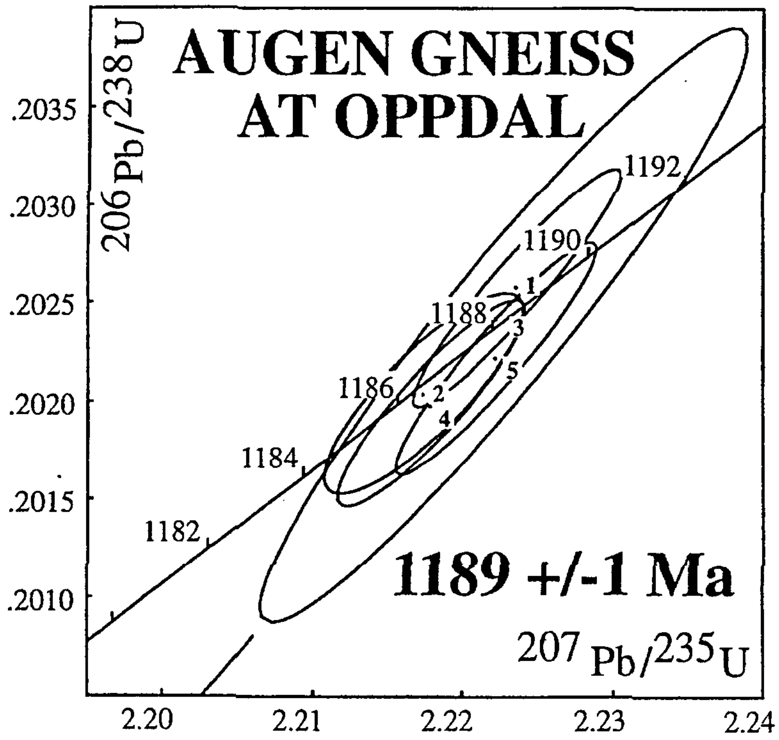


Fig. 1.5. Concordia diagram showing zircon U-Pb isotopic ratios and igneous crystallization age determined for augen gneiss/rapakivi granite in the Risberget Nappe exposed near Route E-6 south of Oppdal (Stop 1-3B), by R. D. Tucker.

12:20	**10**	-	-	Return to E-6 and south.
12:22	2	158.5	0.5	Kongsvoll Fjellstue. Rare plants.
12:29	7	168.5	10.0	Turn off on left to rest area with toilet. View of Snøhetta 2286 m composed of Åmotsdal Quartzite. Possible lunch spot.
12:44	**15**	-	-	Leave rest area.
12:45	1	170.0	1.5	Folldal junction. Stay on E-6.
13:07	22	201.4	31.4	Dombås Junction. Road cuts in mica schist of Gula Nappe. Stop for coffee.
13:22	15	-	-	Leave Dombås. Enter Gubrandsdalen. Pass by turn off for Høvringen, another location where Handke et al. (1995) obtained a U-Pb zircon age on augen gneiss of 1189 Ma.
13:48	26	235.8	34.4	Junction. Trun off for Sel. Stay on E-6.
13:59	11	248.0	12.2	Turn right in Otta toward Lom, Stryn on Route 15.
-	-	249.4	1.4	Road cuts on right, Ordovician schist of Sel Series.
14:05	6	254.0	4.6	Green rocks. Volcanics of Vågå ophiolite.
14:24	6	279.0	25.0	Vågåmo. Stay on Route 15.
14:46	22	304.0	25.0	Road cuts in basement of Western Gneiss Region above lake. Many folk musicians on approach to Lom.
14:50	4	310.2	6.2	Lom Junction. Turn right into parking lot for Stavkirke.
14:51	1	310.5	0.3	Park in front of Lom Stavkirke.
15:06	15	-	-	Leave Stavkirke.
15:07	1	310.8	0.3	Back to junction in Lom. Turn right toward Sogndal (143 km).
15:14	7	319.4	8.6	Flåklypa. Contact of Western Gneiss Region basement, then quartzite, then mica schist/ phyllite below the Jotun Nappe.
15:24	10	330.7	11.3	Bøverdalen. Near here we enter the area of Fig. 1.6 showing the locations of Stops 1-5 and 1-6.
15:36	12	343.0	12.3	Picnic table left.

STOP 1-5: (15 minutes) Foliated Valdres sparagmite, cover of the Jotun Nappe, in smooth pavement, Leirdalen. Spectacular views up valley to southeast. Light-colored, layered metamorphosed arkose. In the sediment, characteristic purple to blue and red feldspar clasts are found. The Valdres sparagmite is late Proterozoic in age and might be correlated with the Åmotsdals unit in the Trollheimen area. The layering is folded by steeply plunging SSE-oriented fold axes, and quartz veins are formed parallel to the axial plane. The Valdres sparagmite is found in rather thin layers within gneisses in this part of the Jotun Nappe Complex. They seem to lie in an inverted position, in many places with a conglomerate at the inverted top contact, and a thrust at the lower contact. Thus the Valdres spragmite is part of an imbricate structure in this lower part of the nappe complex.

15:51	**15**	-	-	Leave STOP 5. Resume climb toward Sognefjell Pass.
16:09	18	360.7	17.7	Sognefjell Pass, 1434m. Retrograded dioritic gneiss with foliated Proterozoic pegmatite in lower part of Jotun Nappe.
16:11	2	362.0	1.3	Picnic table on right. Park on left.

STOP 1-6: (10 minutes) Jotun Nappe Complex, Sygnefjellet. This stop is at the margin of the high grade Proterozoic rocks of the Jotun Nappe Complex. There is a long distance view to east of glaciers and peaks. In these mountains layering in pyroxene granulite can be seen cut by later structures. Near the northwest margin of the Complex lenses of less deformed intrusive rocks are preserved within strongly foliated and schistose rocks. Here we find a monzonitic rock with saussuritized plagioclase and reddish K-feldspar and also rare quartz. Thin-sections show relics of clinopyroxene and possibly orthopyroxene. To get to high-grade mesoperthite-bearing rocks drive further on the highway for another 5 or 6 km, turn to the left and take a small road down to the dam at Prestesteinsvatnet.

16:21	**10**	-	-	Leave Stop 6.
16:25	4	365.0	3.0	Enter Sogn og Fjordane Fylke.
16:36	11	374.8	9.8	Rest area on right. View of Store Skagasstølstind. Photostop 5 min.
16:41	**5**	-	-	Leave rest area. In this vicinity we enter the area of Fig. 1.7 showing the locations of Stops 1-7, 1-8, 1-9, 1-10, 1-11, 2-1, and 2-2.
16:46	5	378.5	3.7	Turtagrø Hostel. Center for alpine mountaineering in Norway.
16:55	9	-	-	View on steep cliff above and to right. Layered sparagmite of Jotun Nappe overlying phyllites.
17:02	7	391.3	12.8	Vassbakken Camping and waterfall.
17:06	4	393.0	1.7	Outcrops of western gneiss region basement near turnout by lake.
17:07	1	394.0	1.0	Lustrafjord shore. West along shore.
17:19	12	405.0	11.0	Luster.
17:34	15	420.2	15.2	Gaupne. Turn right toward Jostedalen.
17:38	4	423.7	3.5	Wide pull out on right by river. Road cuts on left.

STOP 1-7: (10 minutes) Homogeneous Sveco-norwegian granite, Jostedalen (pink on map) A homogeneous medium-grained porphyritic gray granite with slender K-feldspar phenocysts up to cm 2 cm long. This granite, informally called the Gaupne granite, is one of several similar granites found in this part of the Western Gneiss Region. They are undeformed to slightly deformed. The deformation is probably of late Sveco-norwegian age because the foliation is truncated by Caledonian deformation. A Rb-Sr whole rock age on this rock (Einar Tveten, unpublished data) is 1009 Ma.. The similar Hestbrepiggan granite was dated by Priem et al (1973) to be 975±35 Ma (recalculated to 1009±36 Ma).

17:48	**10**	-	-	U-turn. Leave Stop 7.
17:52	4	427.3	3.6	Return to main road at Gaupne.
17:55	3	430.0	2.7	Turn inland. Mica schist.
18:07	12	442.0	12.0	Hafslo. Junction toward Solvorn. Parking on right.

Stop 1-8: (10 minutes) Sveco-norwegian quartz monzonite in Western Gneiss Basement, Hafslo. This outcrop lies just below the main Jotun shear zone. It is a coarse-grained slightly deformed porphyritic quartz monzonite, informally called the Hafslo granite. It consists of up to 3.5 cm large red K-feldspar crystals, somewhat smaller green plagioclase, quartz and biotite. A U-Pb zircon age on this rock is 946 (Schärer, 1980). This rock type is found on both sides of the Jotun Nappe Complex and indicates that there is a continuation of the basement of Southern Norway underneath the Jotun Nappe Complex into this southern part of the Western Gneiss Region. At the stop the rock is transitional into a Caledonian shear zone. The next exposures down the highway are a finer-grained epidote-biotite granite.

18:17	**10**	-	-	Leave Stop 8.
18:30	13	455.3	13.3	Junction at bridge. Turn right into Sogndal.
18:32	1	455.9	0.6	Sogndal Sentrum.
18:33	1	460.0	0.1	Quality Sogndal Hotel. 1 1/2 hours dinner. Evening field program beginning 20:00.
20:00	-	460.0	-	Quality Sogndal Hotel. Return east through Sogndal.
20:02	2	460.7	0.7	Take bridge over fjord.
20:03	1	460.8	0.1	Big slabby outcrop at back of parking lot on left.

STOP 1-9: (10 minutes) Strongly foliated pink Jotun basement with deformed mafic dikes. Top SE Scandian sense of shear. This large new outcrop superbly illustrates the extreme Scandian strain in the lowest part of the basement of the Jotun Nappe, and will be in sharp contrast with Stops 1-10, 1-11 where Middle Proterozoic granites are only weakly deformed if at all.

20:13	**10**	-	-	Leave Stop 9 toward Kaupanger.
20:24	11	-	-	Kaupanger turn off. Stay on main road to Mannheller Ferry.
20:27	3	473.3	12.5	Bus stop on right opposite last of a series of huge road cuts. Go half way east, then back.

STOP 1-10: (15 minutes) Foliated anorthosite and gabbroic anorthosite gneiss cut by layered, possibly folded, but not foliated granodiorite of the type for which Koestler (1982) obtained an Rb-Sr whole rock age of 887± 100 Ma. If this is correct, then this part of the Jotun Nappe might have escaped the Sveco-Norwegian dynamothermal metamorphism at 909±16 Ma documented nearby by Shärer (1980) on the basis of U-Pb data on zircon and sphene (See discussion Stop 1-11).

20:42	**15**	-	-	Leave Stop 10, continue east onto Bomveg and tunnel (no payment).
20:47	5	477.6	4.3	Mannheller Ferry Terminal. At end of tunnel stay to right away from ferry line and park by terminal. Walk back to large road cut and shore exposures. This terminal went into operation in 1996 and we know of no publication describing the rocks in detail.

STOP 1-11: (40 minutes) Super coarse anorthositic gabbro, coronas, granulation, shearing, hydration. Original ophitic mafic minerals interstitial to plagioclase have been retrograded to hornblende and anthophyllite, whereas original calcic plagioclase megacrysts have been converted to a medium- to fine-granular matrix.. Relict garnet coronas between plagioclase and original pyroxenes and olivine are still locally preserved. These anorthositic rocks are intruded by the same granodiorite dikes as at Stop 10.

To our knowledge these particular rocks have not been studied in detailed by any geologist, but there is an excellent publication by Griffin (1971) describing the general character of the rocks in the district, with emphasis on the formation of corona structures during granulite-facies cooling of the coarse-grained olivine-bearing gabbroic anorthosites. According to Griffin the primary igneous cumulate minerals consisted of plagioclase An70, green spinel, dark green clinopyroxene, and olivine that crystallized at a pressure less than 9 kbar. This high anorthite content, more characteristic of Archean than Proterozoic anorthosites (Ashwal, 1993) is typical of most anorthosites of the Jotun Nappe in the Sognefjord region. During cooling there was a slight increase in pressure toward 10-12 kbar with formation of corona structures in several stages. The earliest reaction was between olivine and plagioclase to form aluminous orthopyroxene, aluminous clinopyroxene and spinel. Subsequent garnet formation began at mutual contacts of orthopyroxene, clinoyroxene and spinel, and further garnet growth was accompanied by formation of a second lower

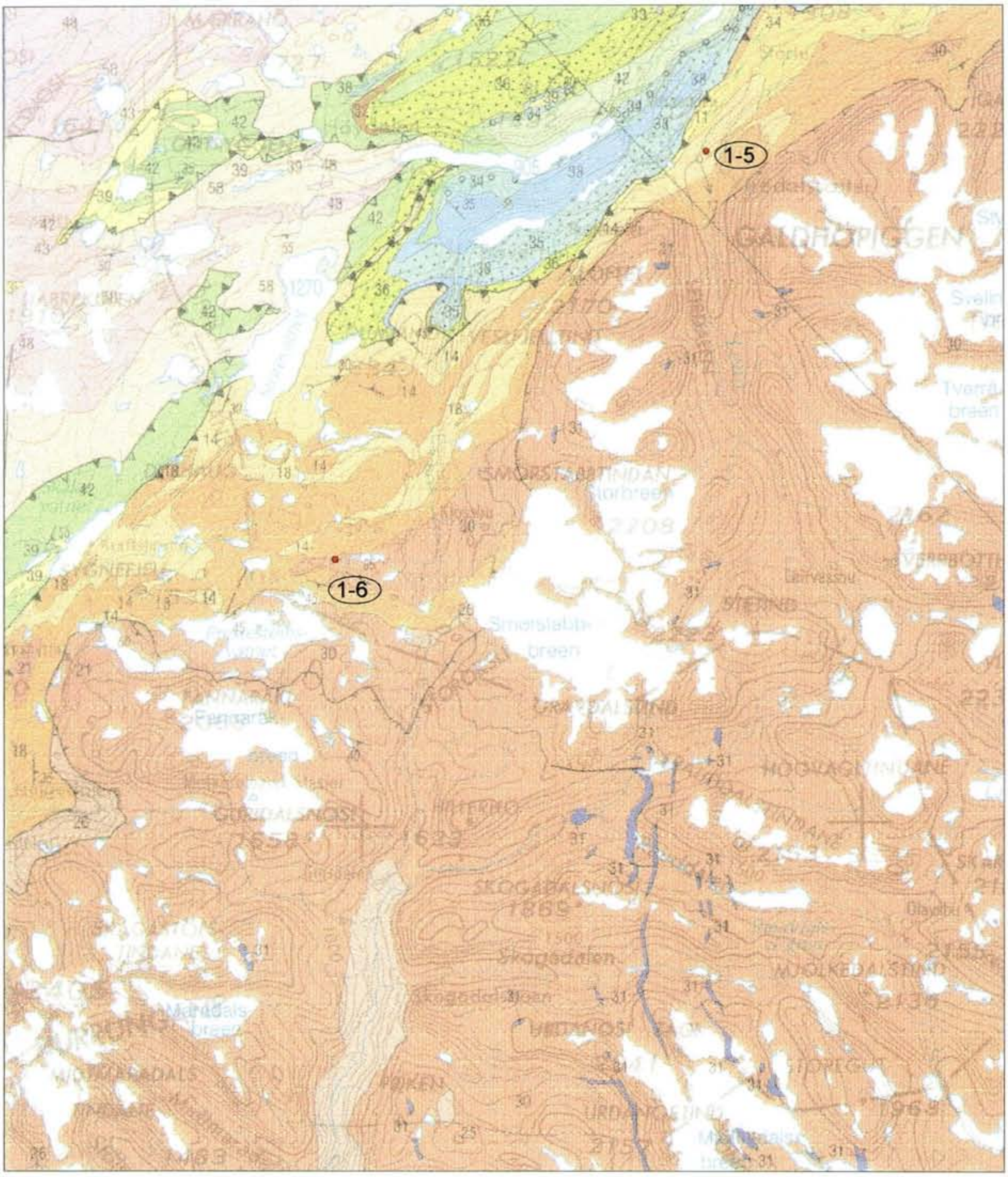


Fig 1.6. Map showing stops on Sygnefjellet, day 1. The map is copied from the 1:250.000 map sheet Årdal (Lutro & Tveten 1996)

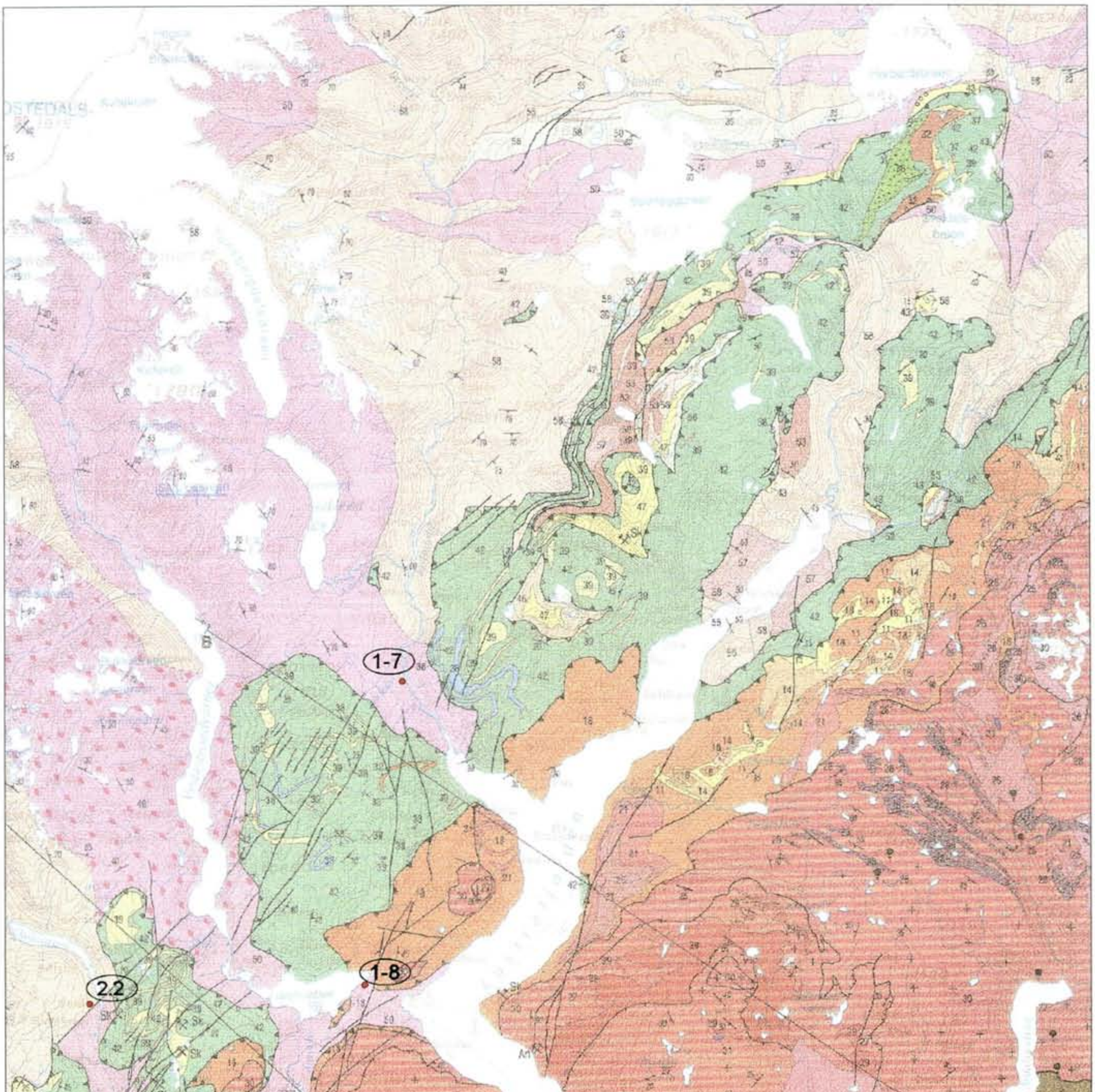


Fig 1.7. Map of the area around Sogndal showing stops of the first and the second day
The map is copied from the 1:250.000 map sheet Årdal (Lutro and Tveten 1996).

Al clinopyroxene at the expense of orthopyroxene, according to the overall reaction: Al orthopyroxene + Al clinopyroxene + spinel + anorthite = lower Al orthopyroxene + lower Al clinopyroxene + garnet. In these coronas the garnet is zoned with more calcic compositions closest to plagioclase, suggesting growth in a chemical gradient. Breakdown of olivine and garnet growth continued according to the reaction olivine + anorthite = orthopyroxene + clinopyroxene + garnet and probably corona growth stopped with the complete consumption of the olvine core and the intergrowths of clinpyroxene and spinel. In many locations corona formation was accompanied by or followed by formation of pargasitic amphibole of two kinds, early amphibole composing much of the corona and late, more Fe-rich amphibole replacing garnet rims. Locally the metamorphic orthopyroxene has been completely replaced by anthophyllite. Thus the rocks at Stop 11 were probably olivine-clinopyroxene anorthositic gabbros in which orthopyroxene and garnet were produced in corona formation. Subsequently the coronas were largely replace by hornblende, whereas orthopyroxene after olivine was replaced by anthophyllite. Griffin also describes fine-grained plagioclase symplectites between various primary granulite minerals and ascribes these to rapid decompression at the end of granulite facies metamorphism which he equates with emplacement of the Jotun Nappe. This is now highly improbable based on the geochronology discussed below.

The most complete geochronological study of the Jotun nappe is by Schärer (1980), who, however has not dated the anorthosites. He determined U-Pb ages on zircon of 1694± 20 Ma for crystallization of a syenitic to monzonitic magma, and 1252+28-25 Ma for intrusion of gabbros into syenites and monzonites. He also notes the growth of metamorphic garnet in the gabbro and ascribes it to post-magmatic cooling. Schärer also obtained a U-Pb age in zircon and sphene of 909±16 Ma. for an upper greenschist facies - lower amphibolite-facies dynamothermal metamorphism. The latter could have been the time of amphibolitization of the anorthosite at this stop, but the results give no definite clue as to the time of granulite-facies metamorphism. The weakly deformed granodiorites (see Stop 1-10) at 887±100 Ma.(Koestler, 1982) set a minimum age for all of these events, and there are very few effects of Scandian metamorphism in the Jotun Nappe basement. By contrast Schärer obtains excellent evidence, in U-Pb analyses of zircons in two samples, for intense Scandian recrystallization of the sparagmite cover beneath the Jotun Nappe at 415±21 Ma. and 395±6 Ma.

21:27	**40**	-	-	Leave Stop 11. Return through tunnel, back past Kaupanger and back to Sogndal Hotel.
21:49	22	495.2	17.6	Overnight at Quality Sogndal Hotel.

INTRODUCTION TO DAY 2 15/8/97

Day 2 will present a kaleidoscope of geologic provinces, rock types, processes, and scenery. In the first part we will take one more look at the mylonitic rocks at the base of the Jotun Nappe (Stop 2-1), more Proterozoic granites and granite gneisses in the center of the Western Gneiss region (Stops 2-2, 2-3, 2-4), and look at Boyabreen, one of the outlet glaciers of Jostedalsbreen, the largest icefield in Europe. In second part we will move to where the western gneiss region has been to eclogite facies (Stop 2-5), see some of the tectono-stratigraphy close to the detachments associated with the Devonian sandstone basins (Stops 2-6, 2-7, 2-8), and examine the Devonian sandstones themselves (Stop 2-9). The third part will be devoted to exposed Proterozoic mantle (Stop 2-10) and the region of relict high-pressure and ultra-high-pressure rocks (Stops 2-11, 2-12, 2-13, 2-14) in the Nordfjord-Stadlandet area. For this last part we present an introduction prepared by Alice Wain and further remarks prepared by Maarten Krabbendam and Alice Wain.

ROAD LOG

Total Time	Time since prev.	Total Km	Km since prev.	
8:00	-	0.0	-	Quality Sogndal Hotel.
8:01	1	0.2	0.2	Traffic circle. Turn right on main highway.
8:04	3	2.3	2.1	Road cuts. Complexly folded Jotun mylonites.
8:05	1	2.9	0.6	Yield sign at road for Bjelle. Turn vans around immediately and park.

STOP 2-1: (15 minutes) Deformed lower part of Jotun Nappe Complex, Sogndalsdalen. (See Fig. 1.7) Fine-grained layered mylonites of the lower part of the Jotun Nappe Complex, predominantly rocks of igneous derivation,.possibly with some supracrustal layers. The outcrop shows a strong southeast-plunging lineation and folds in the mylonitic layering with the same orientation. Locally top-to-NW shear indicators are found which may have developed during late Scandian extension..

Total Time	Time since prev.	Total Km	Km since prev.	
8:20	**15**	-	-	Leave Stop 1. Continue northwest on highway toward Fjaerland.
8:21	1	3.9	1.0	Big cuts in mica schist above Western Gneiss Basement.
-	-	4.4	0.5	Western Gneiss basement. Granite porphyry cut by fine gray granite.
-	-	5.5	1.1	Bridge across river to SW side.
8:29	8	10.0	4.4	Bus stop for Kollsete. Small cut on left.

STOP 2-2: (5 minutes) Granitic gneiss of Western Gneiss Region, Sogndalsdalen. (See Fig. 1.7) A granitic gneiss which is typical for this part of the Western Gneiss Region. It is usually deformed, either lineated or foliated or both and is migmatitic in some areas. The Sveco-norwegian granites intrude this granitic gneiss. The age of the granite complex is uncertain, but it is most probably pre-Sveco-norwegian.

Total Time	Time since prev.	Total Km	Km since prev.	
8:34	**5**	-	-	Leave Stop 2. Continue northwest toward Fjaerland.
-	-	11.1	1.1	Big road cut. Same gray granitic gneiss.
8:39	5	14.7	3.6	View up lake. High mountain views. Beyond this gravel-filled valley.
-	-	20.8	6.1	Bearing left (west) in side valley toward tunnel.
8:46	7	22.2	0.6	Enter tunnel. 7 km.
-	-	29.2	7.0	Exit tunnel.
8:53	7	29.8	0.6	Rest area for busses on left, Berge. View of Fjaerlandfjord.

STOP 2-3: (10 minutes) Granitic gneiss, Fjærland. Foliated porphyritic granite gneiss of similiar type to the last stop, cut by fine-grained granite and pegmatite of possibly Sveco-norwegian age.

Total Time	Time since prev.	Total Km	Km since prev.	
9:03	**10**	-	-	Leave Stop 3 and enter another tunnel.
9:06	3	32.7	2.9	Exit tunnel. View of Fjaerland.
9:08	2	34.4	1.7	Bomstasjon (120 kr per vehicle, no charge for passengers).
9:10	2	34.9	0.5	Glacier Museum. No stop. Scenery better beyond. Enter area of granite (pink on map).
9:18	8	42.1	7.2	Boyabreen Exit. Turn right.
9:19	1	42.7	0.6	Boyabreen parking

STOP 2-4: (30 minutes) Boyabreen ice fall, glacial lake with floating ice blocks. Boulders of typical Proterozoic granite and gneiss including gneissic porphyry (see red pattern unit 49 on map).

Total Time	Time since prev.	Total Km	Km since prev.	
9:49	**30**	-	-	Depart Boyabreen Parking.
9:51	2	43.4	0.7	Turn right on main highway. Fjaerland Tunnel 6380 m.
9:56	5	50.2	6.8	End of tunnel, rest area left, view of lake. Typical mountain terrain in massive granite. **Photostop**.

10:01	5	-	-	Depart photostop. Drive along north side of lake. Topography changes at northwest contact of granite.
10:16	15	64.1	13.9	Junction. Turn left on E39 toward Bergen, Førde.
10:36	20	87.6	23.5	End of lake - Vassenden.
10:45	9	96.8	9.2	Junction, road to Voss. Stay on E39.

Introduction to the Sunnfjord Area (see Fig. 2.1 showing location of Stops 2-5 to 2-9)

Western Gneiss Region granitic gneisses and granites (with local eclogite lenses, Stop 2-5) are overlain in this area by three units with rocks older than the Devonian. The youngest, the **Stavenes group**, located entirely above the extensional detachments associated with the Devonian basins, is considered to be of Cambro-Silurian age and consists mainly of pelitic schists and metavolcanic rocks and is part of the Solund Stavfjord Ophiolite complex and its cover (Andersen et al 1991). The **Lykkjebø group** consists of mainly feldspathic quartzites (Stops 2-6, 2-8) and feldspathic mica schist/gneiss with minor amphibolite and dolomitic to calcitic marble. This unit has been correlated with the Åmotsdalen unit (Bryhni 1989). At several places there is a quartzite conglomerate at the contact between the feldspathic quartzite and underlying gneiss in the Lykkjebø group suggesting that the gneisses of the Lykkjebø group are Proterozoic rocks. Structurally the Lykkjebø group is above the Eikefjord group. The **Eikefjord group** consists mainly of highly deformed and metamorphosed anorthosites (Stop 2-7) and orthogneisses of syenitic to monzonitic and granitic composition. The orthogneisses contain in places large mantled alkali-feldspar megacrysts and relics of granulite-facies mineral assemblages. These rocks are deformed to fine-grained, in places rather dark, finely laminated mylonitic gneisses. The Eikefjord group has been tentatively correlated with the Risberget unit of the Oppdal area (Bryhni 1989).

10:56	11	107.6	10.8	Førde. Junction with Route 5. Turn right on 5 toward Florø. Along this route there will be views of the Devonian Kvamshesten basin to the south.
11:07	11	119.8	12.2	Naustdal Junction. Turn inland in Route 5.
11:09	2	120.9	1.1	Turn off into parking on right near end of old steel bridge.

Stop 2-5: (20 minutes) Naustdal Eclogite, partly retrograded to amphibolite. To view pavement outcrops containing fresh eclogite with coarse omphacite as well as variably retrograded eclogite and an interesting post-metamorphic fault breccia, go through underpass at near end of bridge. To collect eclogite go to 1st road cut across bridge. Road cut on main road is only interesting to those who want to see badly retrograded eclogite. The following notes are adapted from Griffin and Mørk (1981), Bryhni et al. (1981) and Lutro (1992). The tough eclogite has given rise to a small waterfall below which there is an excellent pond for fishing. A total of 11,000 kg of salmon was caught here in 1979, most of it just below this old bridge.

The Naustdal eclogite body, one of several large bodies in the Sunnfjord region, is 2 km long and 400 m wide. Layering is mainly defined by modal variation of garnet, omphacite and barroisitic amphibole, but also layers of less common rock types such as garnet-paragonite-clinozoisite-quartz rock and carbonate-rich layers mainly consisting of ferrodolomite/ankerite-garnet-quartz-omphacite-barroisitic amphibole. Quartz-rich veins containing idioblastic to irregular grains of omphacite, garnet, rutile, and apatite are also present. Locally what appear to be relics of subophitic textured doleritic protolith are preserved. Dusty pseudomorphs after magmatic clinopyroxene now consist of omphacite (Jd 40-45) + barroisitic amphibole, which are also present in the fine-grained groundmass. Pseudomorphs after plagioclase are fine-grained aggregates of clinozoisite-paragonite-quartz-minor phengite. The retrogression of the eclogite leads to the formation of coarse-grained hornblendite and to veins with large hornblende crystals and potash feldspar. Phengite occurs locally as micaceous coatings on foliation surfaces, while paragonite seems so be the only mica present in the matrix. The Naustdal eclogite has formed at lower temperature and pressure than those further northwest and locally contains glaucophane. Estimates by Krogh (1977, 1980a,1982) give 630±30°C and 15±2.5 kbar.

Binns (1969) and Korneliussen (1980) give analyses showing the rocks are olivine tholeiites with high Ti, P, and Fe/Mg. A likely interpretation for the origin of this body is that it represents the transformation of an original gabbroic dike in the gneisses. The southern contact of the body, exposed in the road cuts appears to show intrusion of the eclogite by the surrounding tonalitic gneisses consisting of plagioclase, quartz, phengite, biotite, and garnet, but this may represent backveining produced in the cooling gabbro by melting of its surroundings. Sm-Nd dating of an omphacite-garnet eclogite and of the apatite + omphacite from a coarse-grained vein in this body gavcce a three-point isochron of 545±48 Ma (Griffin and Brueckner, in preparation). The date is tentatively interpreted as the time of back veining, hence the age of intrusion.

This eclogite is rutile-bearing and it has been investigated as a potential Ti-ore. It is estimated to contain at least 100 Mt of approximately 3 % rutile (Korneliussen & Foslie 1985). Because of its location on the river, rutile investigations are currently focussed elsewhere in the district.

11:29	**20**	-	-	Leave Stop 5 for tunnel.
-	-	121.4	0.5	Naustdal Tunnel 6950 m.
11:35	6	127.5	6.1	Exit tunnel.
-	-	132.1	4.6	View of Håsteinen Devonian basin to left.
-	-	134.7	2.6	Junction. Turn off route 5 onto route 615. See wild quartzite landscape up valley.
11:47	12	138.1	3.4	Turnout on right at end of point on lake shore to examine road cuts.

STOP 2-6: (20 minutes) Late Proterozoic quartzite, Endestadvatnet. The stop shows highly deformed quartzite of the Lykkjebø group. This quartzite is probably of the same age as the Åmotsdals unit in Trollheimen (cf. Snohetta, Day 1) and the Valdres sparagmite in Jotunheimen. A thin zone of carbonate-rich schist with dolomitic marble is found in the quartzite.Understanding of its situation here requires analysis both of original Caledonide thrust-related tectono-stratigraphy and late Scandian extensional detachments. The E-W trending folds are typical of ductile features formed during late Scandian extension earlier than the mylonite zones associated with discrete extensional detachments.

12:07	**20**	-	-	Leave Stop 6. Return toward Route 5.
12:10	3	140.9	2.8	Rejoin Route 5. Turn right at outcrop of white mylonitic anorthosite. Long road cuts in deformed anorthosite.
12:15	5	145.6	4.7	Eikefjord. Stay on Route 5.
12:23	8	153.9	8.3	Junction. Turn right off Route 5 toward Svelgen.
-	-	154.9	1.0	Big road cut. Foliated white anorthosite.
12:27	4	157.7	2.8	Nordalsfjord Bridge. Parking and picnic table on left. Road cut on right. Lunch stop.

STOP 2-7: (30 minutes with lunch) Mylonitic anorthosite, Eikefjord group, Nordalsfjorden. Layers of white metamorphosed anorthosite, a white needley rock with fuchsite (?), in blastomylonitic intermediate gneisses with biotite and garnet.. The rocks are folded in late folds with axes plunging east that deform an earlier lineation.

12:57	**30**	-	-	Depart Stop 7 and cross bridge.
13:04	7	163.3	4.6	Turnout with picnic table at waterfall over Devonian sandstone.

STOP 2-8: (10 minutes) Strongly deformed late Proterozoic micaceous quartzite of Lykkjebø group (not previously mapped) with late extensional veins. A normal fault in the lake marks the southern contact of the Hornelen Devonian basin. The fault dips ca 45 N. In the cliff north of the lake subsidiary faults are seen above the main fault. The rock just above the fault is conglomerate. The rocks in the footwall are thinned representatives of different tectonostratigraphic units of the Fjordane Complex, anorthosite and gneiss of the Eikefjord Group and quartzite of the Lykkjebø group.

13:14	**10**	-	-	Depart from Stop 8.

Hornelen Basin

The Hornelen basin is the largest of the Devonian basins of western Norway. It is 70 x 25 km and it lies in an elongated structure. It is fault-bounded on the northern and southern margins with steep normal faults dipping towards the center of the basin. The eastern margin is most probably a flat-lying normal fault, whereas the sediments have a depositional contact to the underlying rocks in the west. The rocks along the margins are conglomerates which are alluvial-fan and fan-delta deposits of mainly debris flow, stream-flood and sheet-flood origin (Larsen and Steel 1978, Steel and Gloppen 1980, Steel et al 1985). The dominant rock in the axial part of the basin is arkose or lithic arkose formed from a large, sandy, stream-dominated fan-delta system. A prominent feature of the Hornelen basin is the pronounced large scale layering seen in most parts of the basin. This layering is made by sedimentary cycles often with a coarsening upward sequence. These sedimentary cyles have been attributed to a tectonic translation of the basin during sedimentation. The migration of the depocenter with time has also helped in explaining the great thickness of the basin, 25,000 m. The movement of the basin during sedimentation has been attributed to a low-angle fault (Hossack 1984, Norton 1987 among others) or to detachment generated during the extensional collaps of the orogen. (Andersen and Jamtveit, 1990). The layering in the central parts of the basin dips generally between 10 to 25 E. In the northern part of the basin the layers are steeply dipping to vertical and along the southern margin the beds are folded in large-scale folds with axes plunging east.

13:16	2	163.9	1.6	Cross late fault into Devonian. Follow north side of the fault. Big fallen blocks of coarse conglomerate from near basin margin. View of Florø ahead.
13:22	6	168.4	4.5	Red sandstone cliffs to right show a broad syncline plunging east.
13:25	3	172.9	2.7	Mouth of tunnel below Magnhildskaret. Sandstone with isolated pebbles. View of barren sandstone landscape to southwest.
13:29	4	176.0	3.1	Exit from tunnel. Park on right. Walk back to outcrop at left of tunnel.

STOP 2-9: (10 minutes) Huge outcrop of cross-bedded Devonian sandstone with isolated pebbles. The following notes are from Bryhni et al. (1981). "Green pebbly mudstone with pebbles mainly of feldpathic quartzite and granitic rocks. The former is most abundant and shows less rounding than the granitic pebbles. The sandstone is trough cross-bedded where the symmetry indicates unimodal sedimentary transport west- or southwestwards. The sands were deposited from braided rivers flowing along the basin paleoslope toward the west. Most of the clastic material was derived froma terrain of feldspathic quartzite similar to that of the Lykkjebø Group."

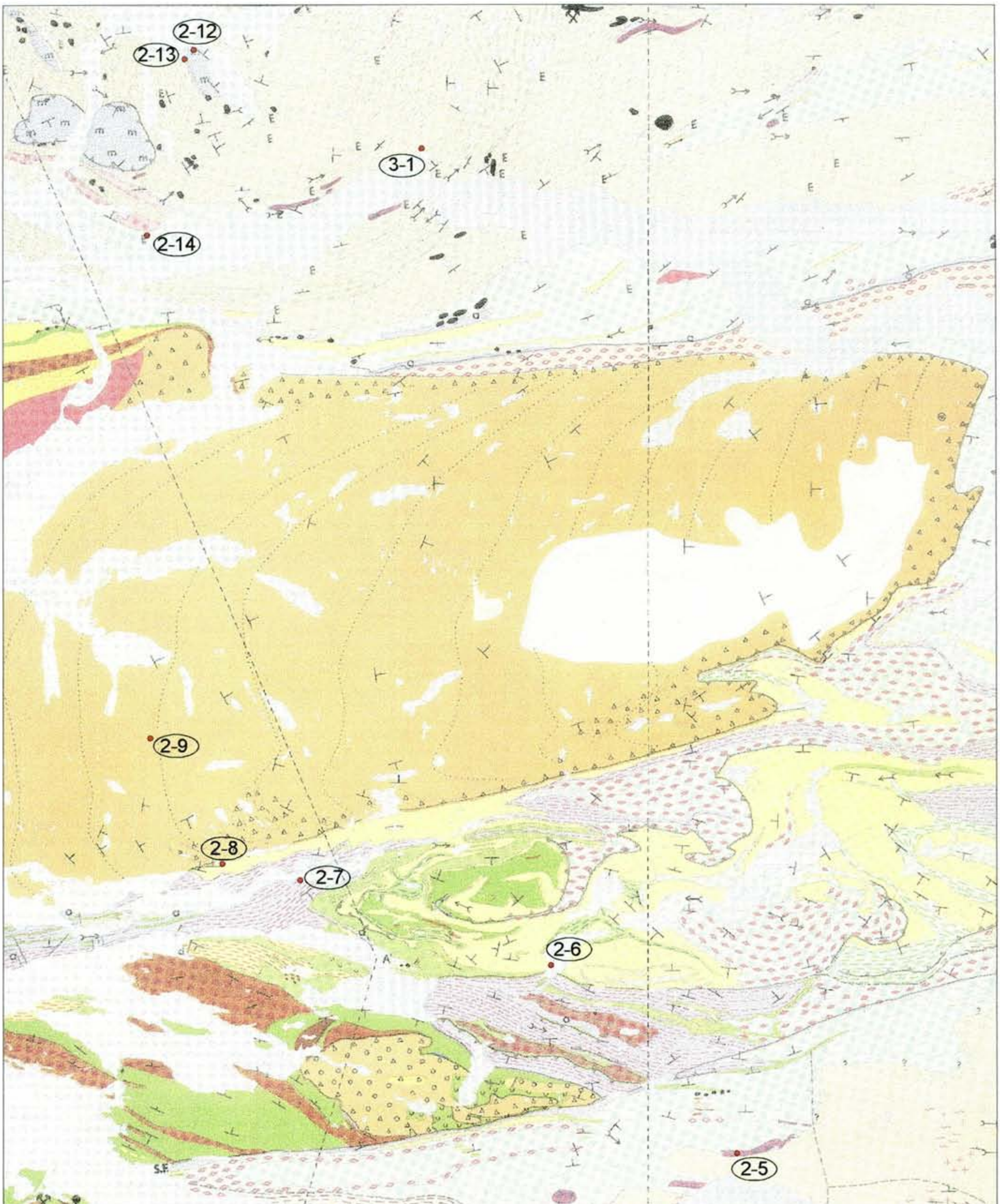


Fig. 2.1. Map showing stops in Sunnfjord and Nordfjord, days 2 and 3. The map is copied from the 1:250.000 map sheet Måløy (Kildal 1970)

13:39	**10**	-	-	Leave Stop 9.
14:00	21	196.3	20.3	Svelgen. Panorama of "industrial red" sandstone.
-	-	196.5	0.2	Sharp turn in Svelgen for Isane. This turn is not well marked. Spectacular sandstone scenery for next 20 km with little convenient parking. During this drive the bedding orientation changes gradually from gently dipping at Svelgen to steep to vertical dips near Isane. However, the detachment fault separating the Devonian strata from the Western Gneiss Region basement is quite gently dipping, indicating that the Devonian strata were folded before the development of the detachment.
14:08	8	202.3	5.8	Turnout on left. **Photo stop** for sandstone cliffs.
14:13	**5**	-	-	Depart photostop.
14:33	20	225.8	23.5	Enter Isane Tunnel in vertically dipping Devonian sandstone. The contact of the marginal breccia and the gneisses is in the tunnel. Bedding is lacking close to the contact, but bedding can be seen by the tunnel entrance in the finer-grained breccia and in erosional remnants of siltstone. The layering is steeply dipping or even overturned. The breccia consists of pebbles of gabbro/tonalitic to tonalitic clasts up to 50 cm in diameter and subordinate gneiss and feldspathic quartzite. The plutonic lithotypes are not represented in the basement north of the contact.
14:34	1	227.6	25.3	Exit from Isane Tunnel in western gneiss region basement.
14:37	3	229.9	2.3	Isane Ferry. Exposures of basement gneiss below the Devonian detachment fault. Views of the detachment surface may be had here or on the ferry to Stårheim.

Introduction to Ultrahigh-pressure Metamorphism in the Western Gneiss Region (Alice Wain)

Ultrahigh-pressure metamorphism (UHPM) refers to metamorphism in the coesite or diamond stability field. The first evidence of UHPM for crustal rocks was the discovery of coesite in pyrope quartzite from the Alps (Chopin, 1984), and eclogite from the Western Gneiss Region (Smith, 1984). Coesite from the WGR was preserved as microinclusions in clinopyroxene, indicating P>28 kbar at T800,C. Since this time Smith (1988) found one other coesite-eclogite pod, and five other eclgites in which polycrystalline quartz inclusions were interpreted as pseudomorphs after coesite. Microdiamons have recently been recovered from gneiss on the Isle of Fjørtoft (Dobrzhinetskaya et al., 1995), but these are yet to be found in-situ, and their signficance is thus unclear.

Ultrahigh-pressure metamorphism has remained controversial in the WGR due to scarcity of UHP eclogites, due to firm evidence only in metabasic rocks, and due to the uncertain relationship of UHP eclogites to other WGR eclogites and gneisses. The geographical area in the northwest WGR in which these eclogites were found Smith termed the "Coesite eclogite province", but he excluded all other eclogites and gneisses, believing the UHP eclogites to be foreign with respect to the rest of the WGR.

Recent work (Wain, in press) has attempted to delineate the extent of UHPM in the WGR, and determine the local and regional relationship of UHP rocks. A distinct UHP province has been identified in the Nordfjord-Stadlandet area, on the basis of widespread evidence for coesite in eclogites (Figure 2.2). Eclogite-facies gneisses have been found associated with some coesite eclogites, and are preserved in areas of low amphibolite-facies (late-orogenic) strain. At four localities polycrystlline quartz inclusions taken as evidence for former coesite are found in these gneisses. This is evidence for in-situ UHPM, which may have been regional in extent within the defined UHP province. The southern boundary to the UHP province is located in the Norfjord area, and is defined by a change from UHP to HP eclogites defined by the following. **HP quartz eclogites**, commonly preserve prograde zoning in larger euhedral garnets. These contain quartz inclusions throughout, with no textural evidence of former coesite. Garnet-omphacite-phengite thermobarometry (Waters 1996 method) yields P<24 kbar, T 700-800°C. **UHP coesite or polycrystalline-quartz pseudomorph-bearing eclogites**. Minerals are unzoned, with subhedral to anhedral textures. Garnet-omphacite-phengite thermobarometry yields P>27 kbar, T 750-850°C, consistent with minimum pressures for coesite stability.

Eclogite-facies rocks (metabasic and gneiss), as well as pre-eclogitic HP granulites are preserved in low strain enclaves in amphibolite-facies gneisses which have undergone pervasive late-orogenic deformation and recrystallization, obliterating most evidence for eclogite-facies metamorphism (Krabbendam and Wain, 1997). This late-orogenic deformation has obliterated regional eclogite-facies structural information, and obscured the tectonic relationship of UHP and HP eclogites.

In a 10 km-wide zone north of Nordfjord both types of eclogite are interleaved along different horizons in the gneisses, with a structural separation of <1 km (Figs. 2.2, 2.3). P-T results are bimodal in this mixed zone, with P jumps of >3 kbar and local inversions of isobars, rather than a smooth gradient in P. The precise tectonic relationship between UHP and HP eclogites is obscured by strong and pervasive late-orogenic deformation (Krabbendam and Wain, in press), and no discrete amphibolite-facies shear zones separate UHP from HP eclogites. Close juxtaposition of HP and UHP eclogites must have taken place prior to this late overprinting phase. This zone may represent a folded or imbricated tectonic break between the UHP unit and the rest of the terrane. This the evidence supports in-situ UHPM, but the relationship of the UHP provicne to the rest of the WGR is still controversial. An eclogite-facies P-T break suggests the possibility of a tectonic contact, but late-orogenic overprinting has obliterated any evidence for this.

Fig. 2.2 New coesite eclogites in Western Norway: outlining an ultrahigh-pressure province in the north-west WGR. Alice Wain 1997

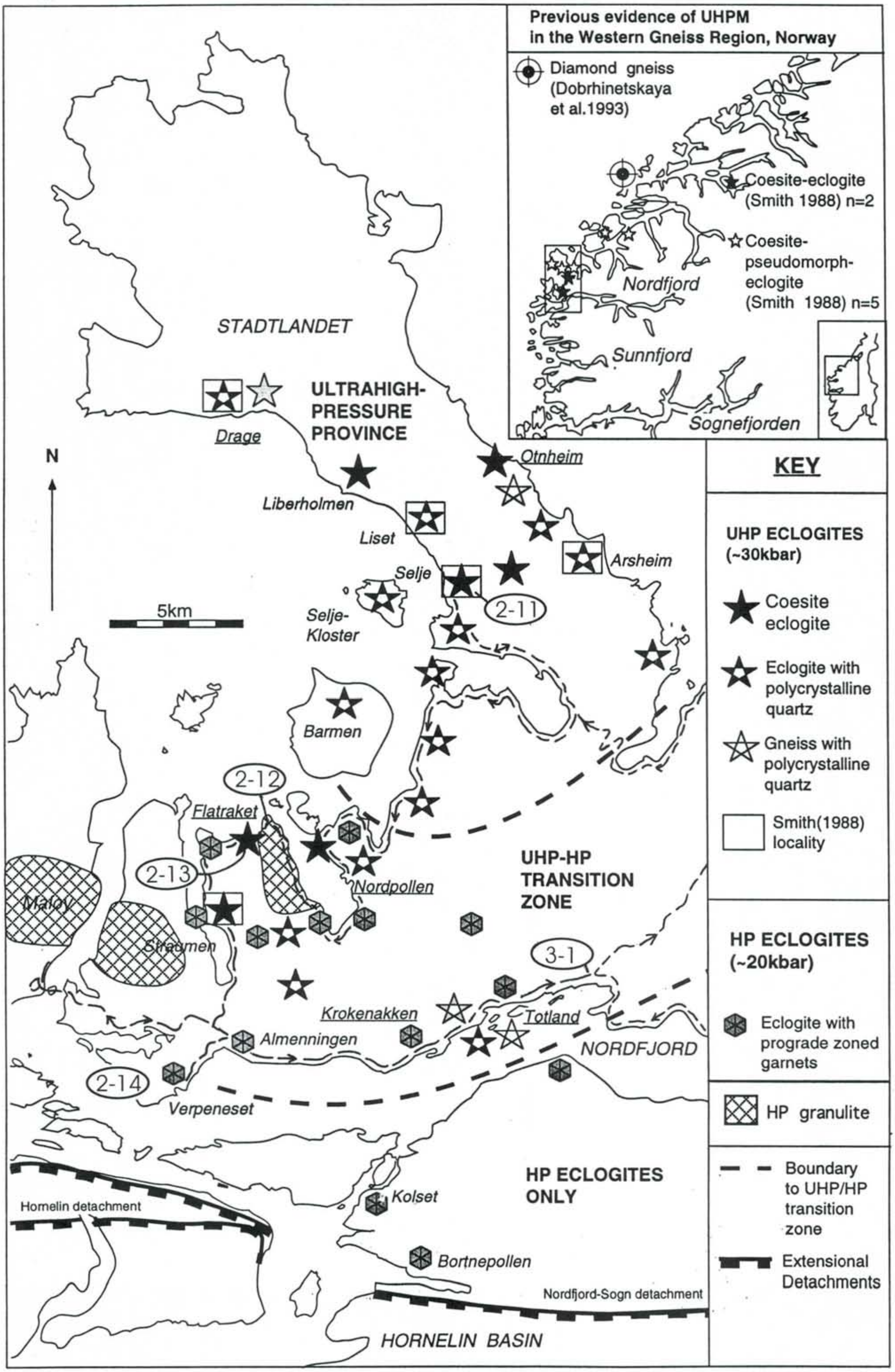
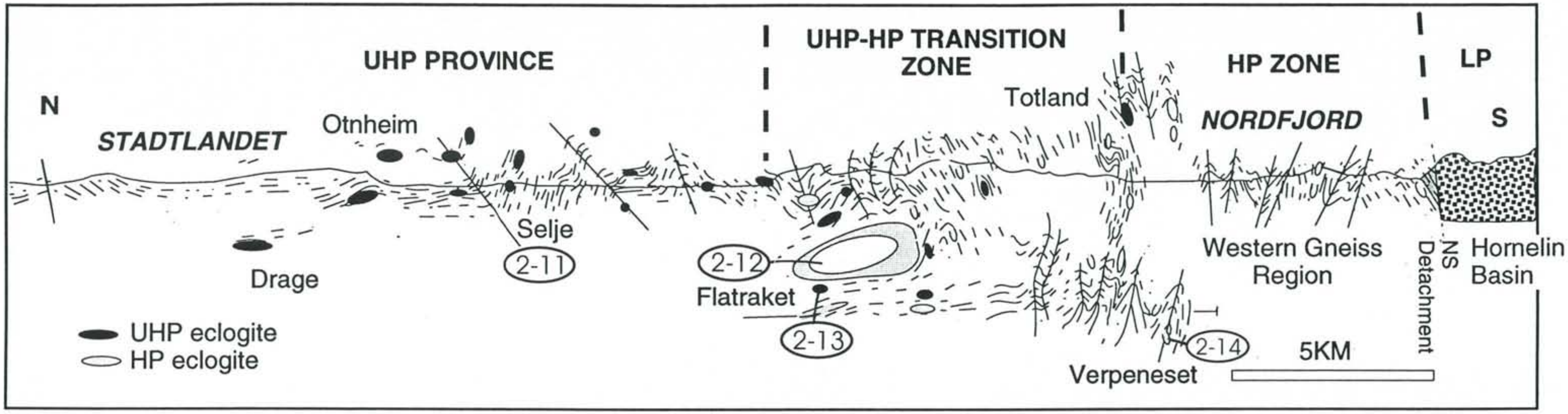
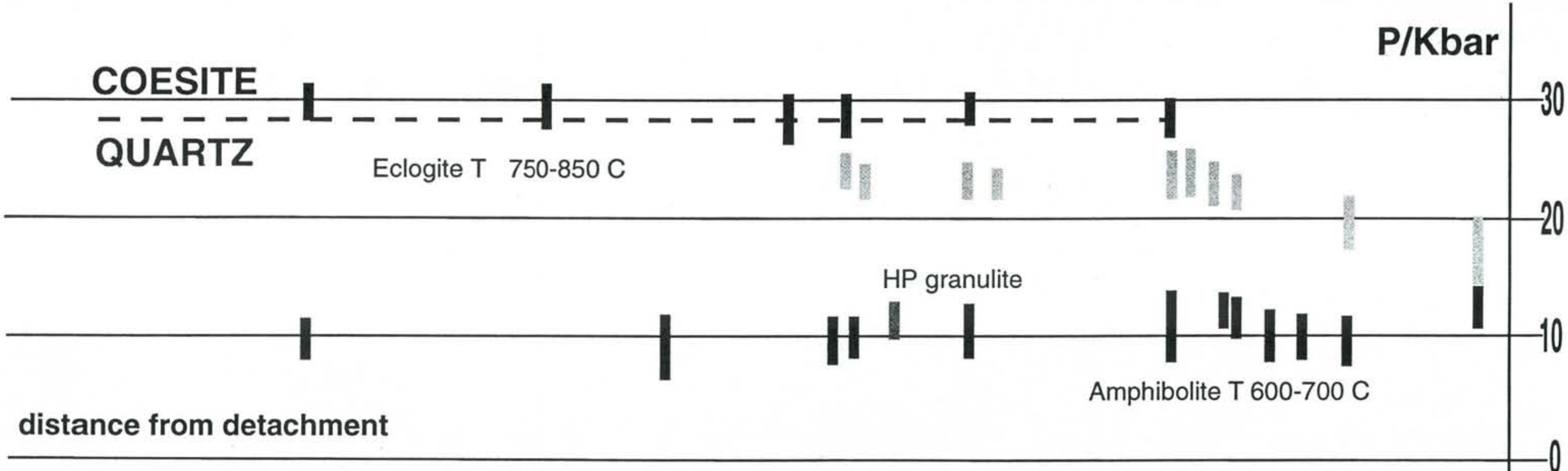


Fig. 2.3

Cross section from the Devonian Hornelin extensional basin through the HP and HP zones of the WGR (Krabbendam and Wain 1997) showing structural position of UHP and HP eclogites (Wain 1997)





P-T estimates by Alice Wain from coesite, Grt-Cpx-Phe thermobarometer (Waters 1996) and thermocalc/Amphibole-Plagioclase barometers (Holland and Powell 1990, Holland and Blundy 1994)

14:50	**13**			Drive onto ferry for Stårheim and 15-minute crossing of Nordfjord. Take advantage of toilets, and in good weather climb to the sun deck next to the pilot house. Your ferry fare will be paid by trip leaders.
15:05	**15**	-	-	Exit ferry from Isane.
15:06	1	230.3	0.4	Turn left (west) on Route 15 toward Måløy.
15:17	11	243.5	13.2	Underground olivine mine.
15:19	2	246.8	3.3	Olivine shipping.
15:21	2	248.7	1.9	Maurstad junction. Turn right on Route 61 toward Åheim.
15:26	5	254.4	5.7	Enter Møre og Romsdal Fylke. See Fig. 2.4 for locations of stops.

Introduction to Almklovdalen

The Almklovdalen area is a classic area for the study of garnetiferous ultramafic rocks; several large ultramafic outcrops occur in the valley (Fig. 2.5). Field mapping (Lappin 1966, 1967, Medaris 1980 1984, Cordellier et al., 1981) and gravity measure measurements (Grønlie & Rost 1974) suggest that all of these are connected in the subsurface, forming a bowl-shaped sheet around a central gneiss area (Fig 2.5). The major rock type are dunite (+ chromite) and peridotite with the mineral assemblage oliv + opx + chlor ± amph. Small areas of garnetiferous peridotite are clearly relics, and are replaced by the chlorite-bearing assemblage on all scales (Medaris 1980). The chlorite peridotites are intensely folded, and Medaris (1980) has shown that all fold phases in the chlorite peridotite are shared by the surrounding gneisses.

Detailed structural studies by Cordellier et al. (1981) suggest the following history:

a) Intrusion of a peridotite slice from the mantle into the crust; folding of garnet-rich S0 layers, inducing an S1 foliation and L1 lineation marked by flattening of garnet and olivine crystals
b) Hydration of peridotites, coinciding with pervasive deformation of both peridotites snd gneisses, producing isoclinal folding with S2 foliation and L2 lineation marked by chlorite and amphibole, respectively, in the peridotites.
c) Gravity sinking of the whole slice, relative to the gneisses, creating the present cup-shaped configuration, an S3 foliation of chlorite parallel to the contacts, and an L3 lineation of chlorite/spinel strings parallel to the geneatrix of the cone. This sinking is correlated with the amphibolite-facies metamorphism in the gneisses, which have a foliation and lineation parallel to those of the peridotites.

Cordellier et al. (1981), following O'Hara & Mercy (1963) and Lappin (1966, 1974) regarded the garnet peridotite assemblages as relict upper-mantle mineralogy. Griffin et al. (1985) and Griffin & Qvale (1985) suggest that the garnet peridotites were formed in the crust, by metamorphism of an alpinotype (serpentinitized?) spinel lherzolite, and correlated this metamorphism with the Caledonian eclogite-forming event. Ecogites occur within the Almklovdalen peridotites as integral parts of layered garnet-peridotite sequences (Lien/Helgehornsvatnet, Loc. 2), as discrete bands (Rødhaugen, Loc. 4) and as boudins (Raudkleivane Loc. 1). Typical 'external' eclogites are also abundant in the gneisses (Medaris 1984), and several large bodies of anorthosite occur in the valley as concordant layers in gneiss.

The dunite parts of the ultramafic rocks have been mined for olivine for several decades. Production is now about three million tons/year, with estimated reserves of 2,000 million tons, enough for production for about 1000 years. The dunite is crushed in A/S Olivine's plant at Åheim and exported, largely for the manufacture of refractory materials. Olivine "ore", essentially chlorite dunite, reaches coastal processing plant by conveyer belt in tunnel, because trucking of the large production would be too expensive. No beneficiation is needed.

15:36	10	263.2	8.8	Junction in Åheim. Turn right (south) on road to Almklov.
15:40	4	267.1	3.9	Stay right toward Sunndal, not right toward Almklov.
15:42	2	268.6	1.5	Slope in ultramafic rocks and eclogites on left. This is the locality Raudkleivane (Locality 1 in Fig. 2.5) and there will probably not be time to visit it on this trip. It is described as follows (Mørk and Krogh, 1987). The locality shows numerous boudins of eclogite in chlorite peridotite with a very tight isoclinal folding. The axial plane foliation to these folds strikes N40E, dip 50SE on the average, and the associated lineation is essentialy down-dip. Local relics of garnet peridotite/eclogite show more open folding, and demonstrate the retrogression to chlorite peridotite with accompanying development of the foliation. Lappin (1974) described two of the boudins as layers in the garnet peridotite sequence. He regarded the compositional variations as primary magmatic variations, and treated the eclogites as high-P melts from the surrounding peridotite. Griffin and Qvale (1985) have shown that the Fe-rich rocks are compositionally analogous to amphibolitized basaltic dikes in other (Caledonian) peridotites and serpentinites. They therefore interpret the eclogite and garnet-peridotite assemblages at this locality as the result of crustal metamorphism of a serpentinized peridotite. The evidence includes a strong prograde zoning in the garnets of the Fe-rich eclogites, and inclusions in garnet of K-feldspar and an Al-, Ca-rich amphibole, distinct from the secondary amphibole outside the garnet.
15:43	1	269.4	0.8	Top of slope, view of lake. Turn sharp left on mine road and climb steep hill.
15:45	2	269.7	0.3	Park at top of mine road. Plan for 2 hour stop. From mine road follow dozer track and trail to pass, then trail on left (north) of lake (Helgahornvatnet) to National Scientific

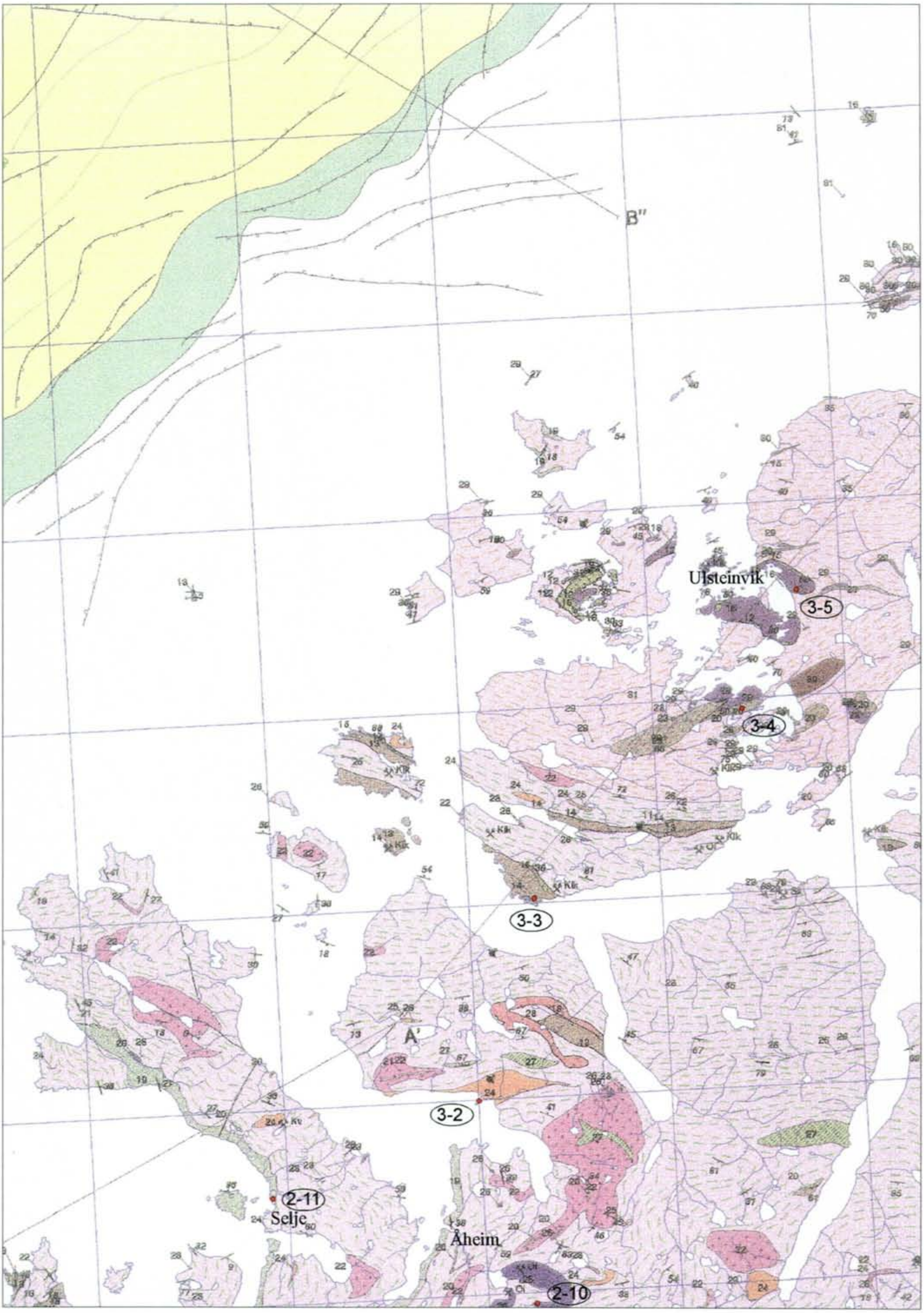


Fig 2.4. Map showing stops of day two and day three. The map is copied from the preliminary 1:250.000 map sheet Ulsteinvik (Tveten et al in prep)

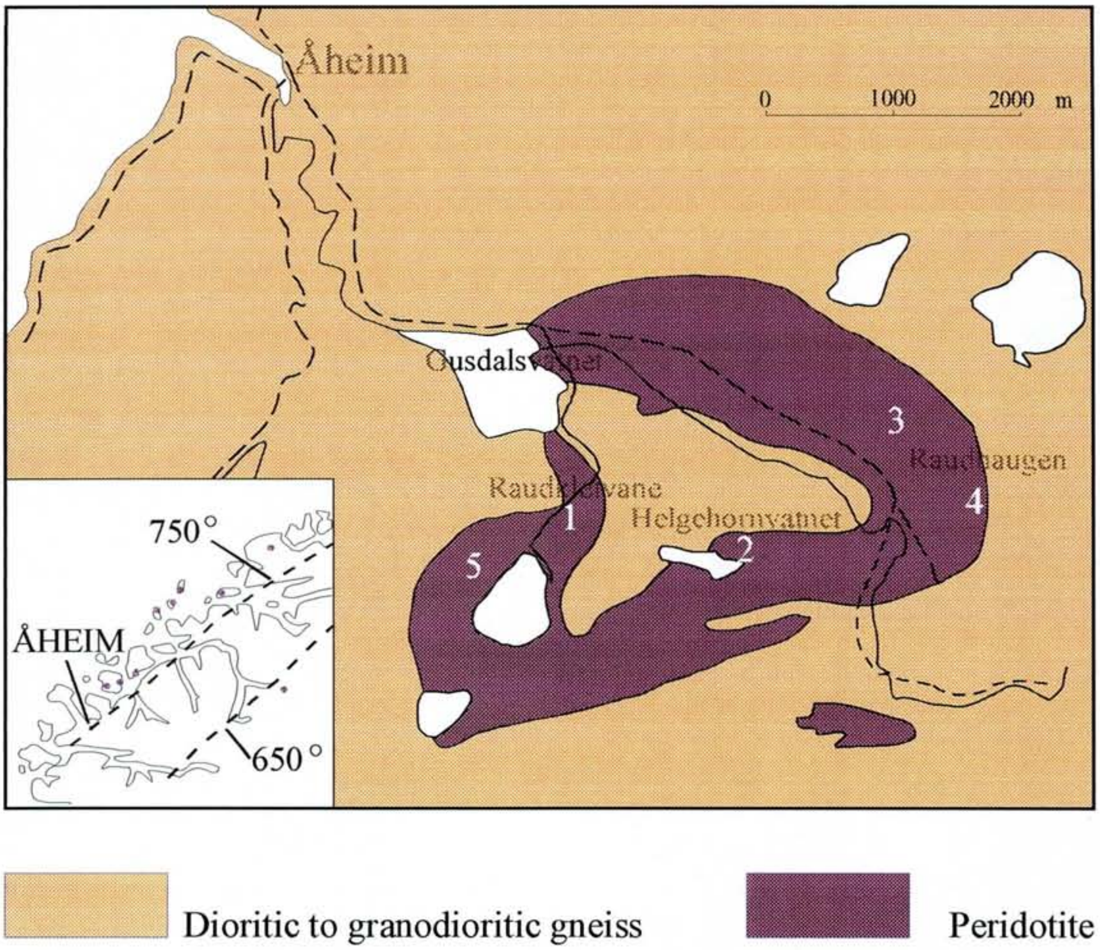


Fig. 2.5 Outline of the ultramafic bodies in Almklovdalen, based on mapping by Cordellier & BNoudier (1981) and gravity surveys (Grønlie & Rost 1974). Inset: garnet peridotite localities in W Norway.

Preserve at east end of lake. During this walk we pass through the basin of gneiss that overlies the peridotite.

STOP 2-10. (2 hours) Helgehornvatnet (Fig. 2.5, Locality 2). Proterozoic sub-continental mantle. Layered garnet peridotite and garnet pyroxenite. The following description was updated by Gordon Medaris in 1987 (Mørk and Krogh, 1987).

"The Almklovdalen ultramafic body consists largely of chlorite peridotite, in which subordinate amounts of relicts garnet peridotite and pyroxenite have been preserved. Sm-Nd ages of 1703±29 Ma and 1040±30 Ma have been obtained for garnet lherzolite at Raudkleivane and garnet websterite at Helgehornvatnet, respectively (Mearns, 1986). The Almklovdalen body most likely represents a fragment of Proterozoic garnetiferous mantle that was recrystallized and deformed under amphibolite facies metamorphism during the Caledonian Orogeny.

"Excellent outcrops of folded chlorite peridotite are exposed along the south side of Helgehornvatnet. Chlorite peridotite shares the same structural elements with surrounding quartzofeldspatic gneiss, andmineral assemblages in the two rock type are compatible. At the eastern end of the lake garnetiferous peridotite and garnet pyroxenite are interlayeredon a scale of centimeters to decimeters. This is the classic locality that was described by Eskola in 1921 and investigated in more detail by Medaris in 1980 and 1984. Chemical analyses of rocks and minerals indicate that the layering is not a primary magmatic feature. Porphyroclastic texture is common in the garnet ultramafites, in which large strained grains of garnet, clinopyroxen and orthpyroxene reside in a fine- to medium-grained mosaic matrix of olivine, orthopyroxene, clinopyroxene, pargasitic amphibole and chromiferous spinel. PT conditions estimated for cores (770°C, 28 kbar) and rims (560°C, 18 kbar) of porphyroclastic grains do not agree with the Caledonian Tzt (sic) path that has been calculated for the Western Gneiss Region (Medaris and Wang 1986). This discrepancy can be explained by the preservation of Proterozoic mantle PT conditions in the core compositions of porphyroclasts and metastable exchange of Fe and Mg between garnet and other phases during uplift and cooling."

N.B.! The locality at the east end of the lake is protected as a national monument, and collecting is forbidden. The outcrop has already been severely damaged by blasting for mineral collecting. Leave the hammers in the cars.

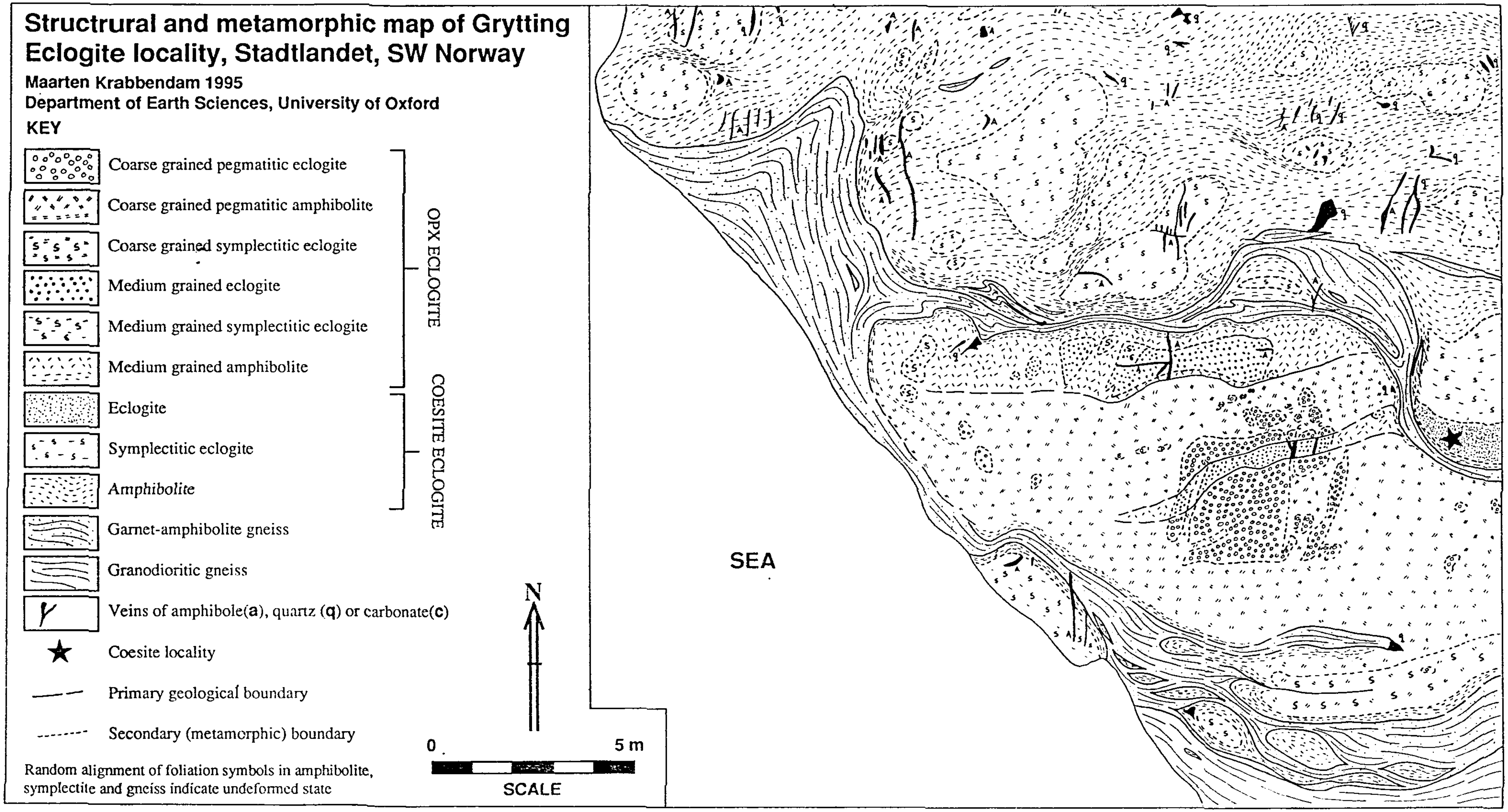
17:45	**2:00**	-	-	Return to top of olivine pit and leave for Selje. Near the pit there are available fresh specimens of chlorite dunite.
17:47	2	270.0	0.3	Main road. Turn north toward Åheim. If time permits there may be an opportunity for collecting in road exposures just below this turn, the locality Raudkleivane.
17:54	7	276.1	6.1	Junction in Åheim. Turn left on Route 61.
-	-	276.5	0.4	Second junction in Åheim. Turn right on Route 620 toward Selje.
17:58	4	280.0	3.5	Fylke boundary. Back to Sogn og Fjordane.
18:03	5	284.1	4.1	Left on Route 618 toward Selje. Begin steep climb.
18:06	3	286.1	2.0	Top of pass.
18:09	3	288.4	2.3	Junction. Bear right toward Selje.
18:13	4	293.2	4.8	Right to Skårbø. Selje Hotel.
18:15	2	293.8	0.6	Park by church. Walk 400m north along coast.

STOP 2-11. (30 minutes) Gryttingvåg orthopyroxene eclogite (Eskola, 1921) and Gryttingvåg coesite eclogite (Smith, 1984, 88) at Selje. Some details of this complex outcrop are shown in a map recently prepared by Maarten Krabbendam (Figure 2.6).

We give here part of a brief description from an earlier guidebook (Griffin and Mørk, 1981). 'Type locality (Eskola, 1921) for an especially coarse-grained "eclogite-pegmatite" of gryting type". The body is clearly layered, and many details are visible despite later amphibolitization. Mineral analyses are given by Green (1969), Lappin and Smith (1978) and Carswell et al. (1982). Lappin and Smith used averaged mineral analyses and calculated P/T to ca. 950°C, 40 kb. Carswell et al. showed that analyses of coexisting phases yield much less extreme conditons (800°C, 20-25 kb) which they regard as maximum values. The cpx+gnt of the coarse-grained eclogite yield a Sm-Nd age of 448±20 Ma (Griffin and Brueckner, 1980). The garnet and cpx both have high 87Sr/86Sr (0.719; Griffin and Brueckner, in prep.), suggesting extensive interaction with crustal material before/during eclogite crystallization.' The orthopyroxene eclogite with large crystals of orthopyroxene in a coarse matrix of garnet, omphacite and rutile ± magnesite, and with a thick rim of retrograde amphibolite, was described in detail by Eskola (1921) and newer mineral analytical data is presented by Carswell, Krogh and Griffin (1985). P-T estimates are further discussed by Cuthbert and Carswell (1990). The coesite eclogite, containing omphacite, garnet, kyanite, and dolomite with inclusions of partially retrograded coesite, was described by Smith (1984,88), and he also gives three pages of detailed description in an earlier guidebook (Mørk and Krogh, 1987). The two bodies are separated by about 25 cm of gneiss. **Note:This is a Norwegian National Scientific Preserve and collecting of any kind between the monuments is strictly forbidden.**

18:45	**30**	-	-	Back at church. Return south toward Måløy.
18:51	6	299.5	5.5	Junction. Right toward Måløy.
19:10	19	318.0	18.7	Nordpoll. Coesite eclogite has been located near here (Wain, in press).

Fig. 2.6



Structrural and metamorphic map of Grytting Eclogite locality, Stadtlandet, SW Norway

Maarten Krabbendam 1995

Department of Earth Sciences, University of Oxford

Introduction to the Flatraket HP-Granulite Body (Maarten Krabbendam and Alice Wain)

The Flatraket body is a 2 km^2 body (Figs. 2.7, 2.8), containing mainly felsic gneiss, with additional anorthosite, and several mafic to intermediate dikes. In the Flatraket body much of the felsic gneiss contains very coarse megacrystic K-felspar. The Måløy Body is very similar, except that the megacrystic granulite occurs more rarely.

HP-granulite assemblages (or relics thereof) can be found in several places in all three rock types, typically represented by garnet + clinopyroxene + plagioclase. Many mafic dikes which in the field appear to possess an eclogite-facies mineralogy actually do contain granulitic assemblages, including plagioclase with polygonal structure. Granulite-facies assemblages also occur if the rock has escaped subsequent Scandian deformation. Very locally eclogite-facies assemblages occur. These assemblages appear to occur either in undeformed mafic rocks (e. g. eclogites at Seljeneset) or in felsic rocks as eclogite-facies shear zones. Much of the rocks have wholly or partially retrogressed to amphibolite-facies assemblages. This retrogression is commonly associated with the strong late-orogenic deformation, for instance in the many distinct shear zones which occur within or bounding the Flatraket body. Much of the megacrystic granulite, however, has also been strongly retrogressed towards amphibolite facies in the absence of deformation.

The following evolution is envisaged for the Flatraket granulitic body: (1) Crystallization of melts with monzonitic and anorthositic composition (possibly dated by the 1520±10 Ma U-Pb upper intercept of Lappin et al., 1979). Intrusion of dikes. (2) HP-granulite metamorphism, probably pre-Caledonian. Minor deformation associated during this event. (3) Burial of the WGR and the Flatraket Body to eclogite-facies pressures ($P \leq 24$ kbar) during Scandian thrusting. The bulk of the body, however, behaves as a low strain zone and remains metastable at HP. Locally, equilibration occurs, associated with eclogite-facies shear. (4) Exhumation of the WGR and the Flatraket Body by late-Scandian extension, associated with strong late-orogenic extension and retrogression to amphibolite facies assemblages. The Flatraket Body, however, behaves as a low strain zone during the late-orogenic deformation and retrogression is not pervasive. Thus, the Flatraket Body is like a "window" through the Caledonian, preserving some pre-Caledonian structure and assemblages, and only locally affected by the Scandian contraction and late-Scandian extension. It is a good example of metastability at eclogite-facies conditions.

The occurrence of the UHP eclogite pod at Flatraket Harbor and several other UHP eclogites in the surroundings (Fig. 2.9) pose some problems. Metastability of plagioclase at pressures of 28+ kbar is much harder to explain than metastability of plagioclase at pressures of 22-24 kbar. It is, therefore, likely that the Flatraket body and UHP eclogite pods have been juxtaposed some time during the late-Scandian exhumation/extension phase.

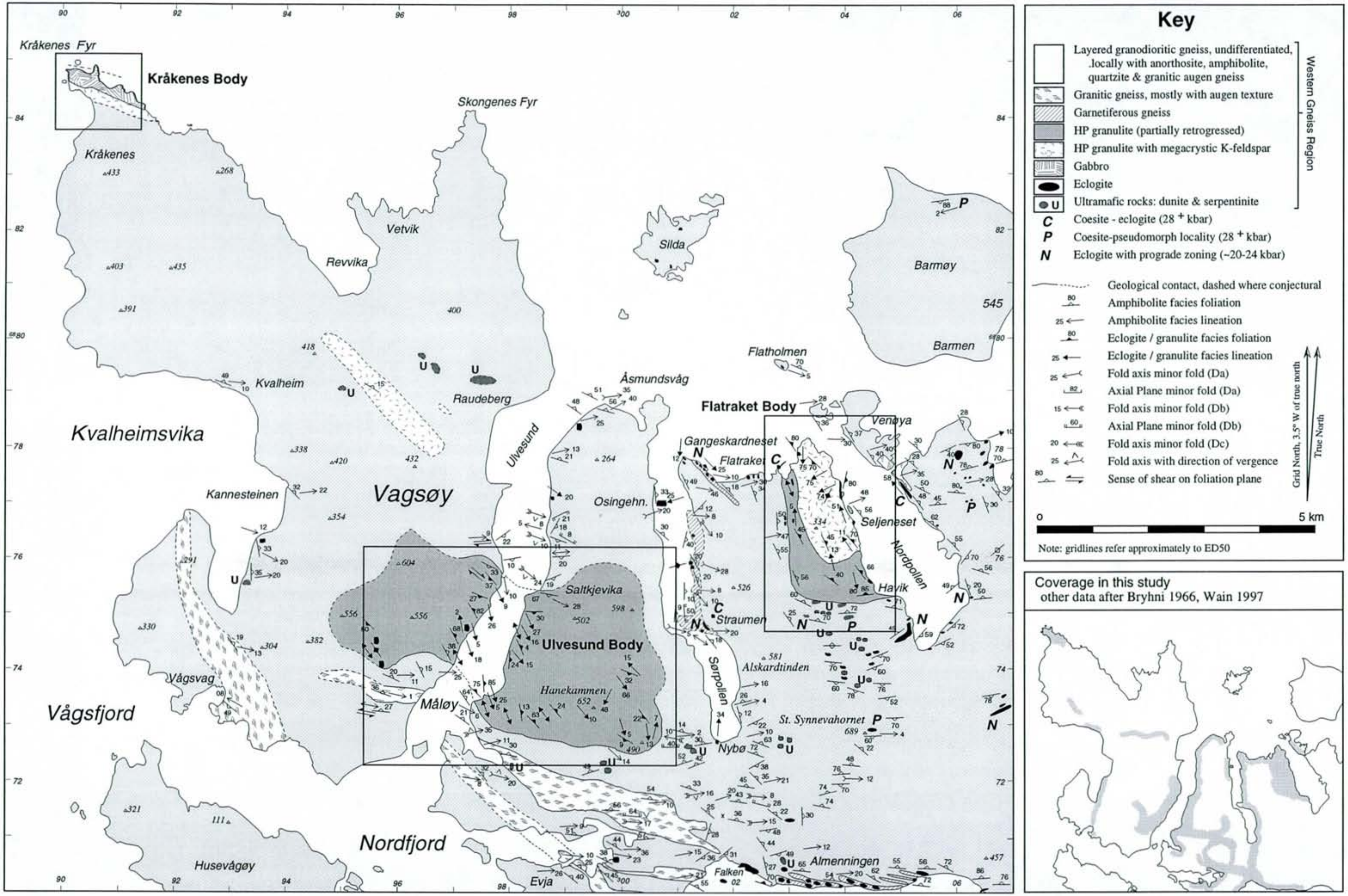
19:17	7	324.0	6.0	Park at picnic tables on right just beyond quarry on left. We will confine our attentions to the road cut east of the picnic tables.

STOP 2-12. (10 minutes) Flatraket Quarry. Megacrystic Quartz monzonite / augen gneiss with mafic dikes. (See Fig. 2.8) Undeformed quartz monzonite contains K-feldspar megacrysts, plagioclase, augite, garnet, with minor amphibole, biotite, rutile and Fe-Ti oxides. Relic orthopyroxene represents an earlier (igneous?) assemblage. The mafic dikes contain granoblastic garnet, plagioclase and augite. Granulites are variably hydrated to amphibolite assemblages with recrystallization of plagioclase and precipitation of clinozoisite, and breakdown of ferromagnesian minerals to secondary biotite and amphibole. Amphibolite facies mylonites occur in shear zones in the quarry. A U-Pb age on zircon in the mangerite yielded 1520 Ma (Lappin et al., 1979) considered to be the age of igneous crystallization. The age of granulite metamorphism is unknown, but older than local HP eclogite shear zones and still later amphibolite-facies shear zones that are both considered Scandian.

19:27	**10**	-	-	Leave Stop 12 and continue into Flatraket Village.
19:28	1	324.7	0.7	Turn sharp right on narrow road toward harbor.
19:30	2	325.2	0.5	Drive to parking space at end of harbor wall.

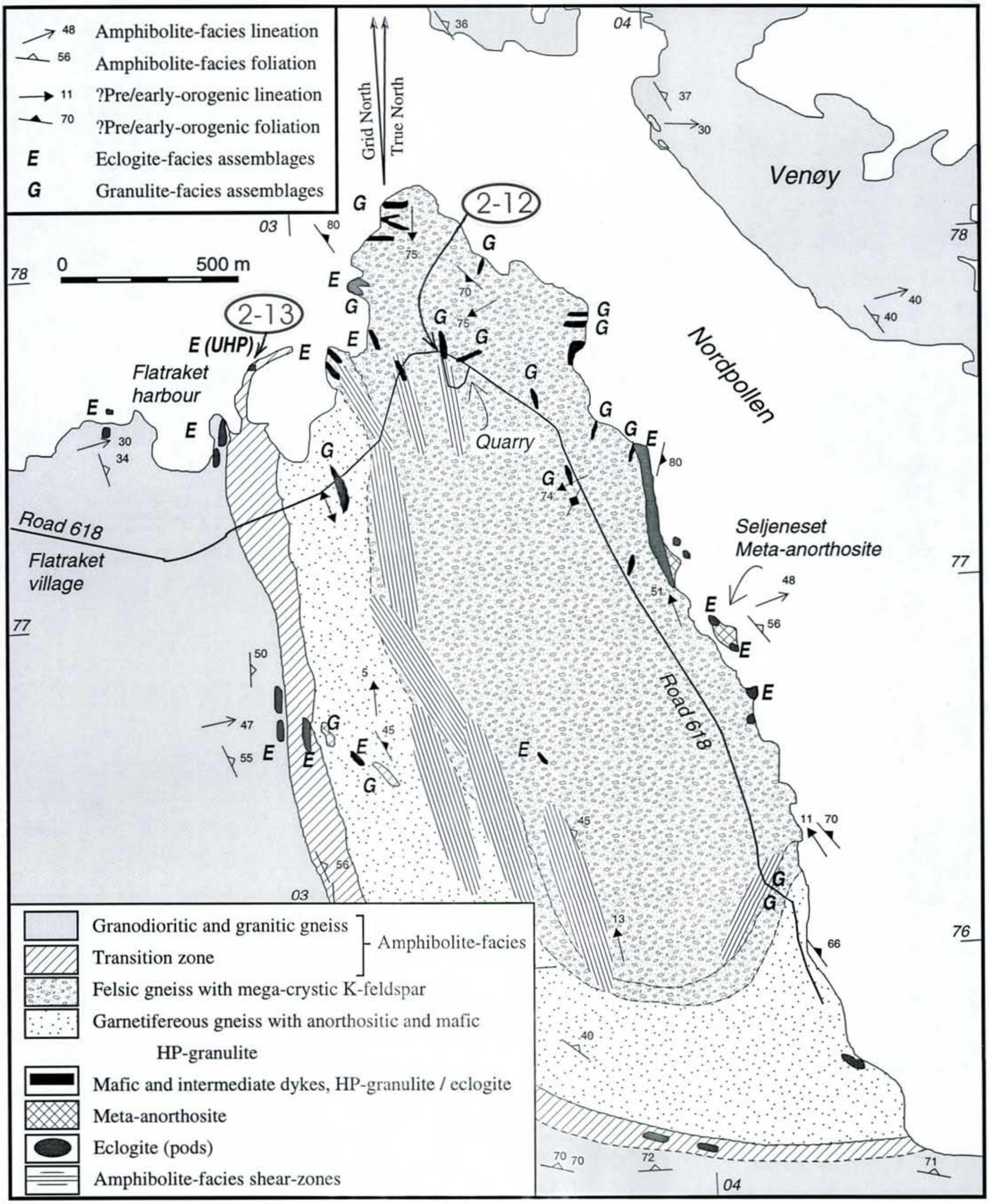
STOP 2-13: (20 minutes) Coesite-kyanite-phengite eclogite reported by Alice Wain (in press). (See Figs. 2.8, 2.9) This 5 m eclogite body occurs within amphibolite-facies gneisses. It is coarse-grained (2-20 mm), containing anhedral garnet, omphacite and quartz with accesory kyanite, phengite, rutile, and amphibole. Coesite is rarely observed in garnet, and polycrystalline radial and polygonal-textured quartz is observed in garnet and omphacite. Garnet-Omphacite-Phengite therobarometry (Waters 1996 method) gives P 29 kbar, T 750-820°C. Amphibolite-facies retrogression increases toward the rim of the pod, which is recrystllized to garnet amphibolite. Small pods of garnet amphibolite occur in garnetiferous gneisses within a meter of the pod. Garnets may be relics of an eclogite-facies assemblage, whilst the matrix is amphibolite-facies. External to these, strongly deformed amphibolite-faices gneisses and epidote amphibolite occur, relating to late-orogenic deformation (P 8-10 kabar, T 600-700°C. Due to close quarters and limited time, major collecting is not recommended on the trip, but the leaders plan to supply thin-section sized pieces from material previously collected at this outcrop. The harbor wall has a great variety of quarry blocks of the augen gneiss / rapakivi granite, with one containing part of mafic dike with HP-granulite mineralogy..

19:45	**20**	-	-	Head back toward 618. Back on 618. Head toward Måløy.
19:53	8	333.5	8.3	Pass and junction with Route 15. Turn left (away from Måløy).



Geological map of Vagsøy - Flatraket area, showing discordance of pre- or early-Scandian structures with respect to late-Scandian structures. Maarten Krabbendam, 1997. Localities of UHP / HP eclogites from Alice Wain (1997)

Fig. 2.7

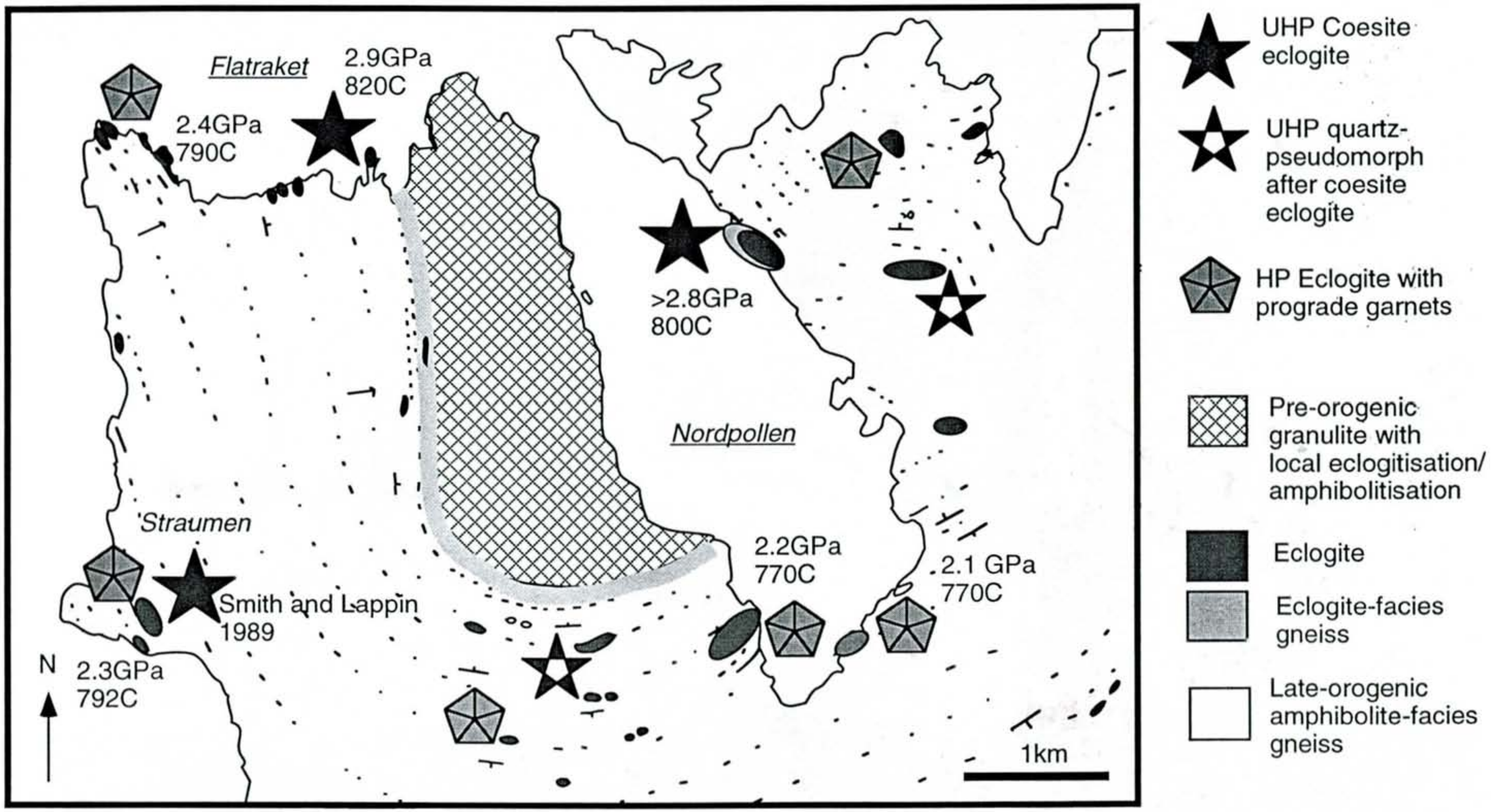


Geological map of the Flatraket body, indicating occurrence of different metamorphic assemblages.
Maarten Krabbendam & Alice Wain, 1997

Fig. 2.8

Fig. 2.9

Part of the HP-UHP transition zone in the Western Gneiss Region showing the Flatraket granulite complex: Alice Wain 1997



19:54	1	335.3	1.8	Turn right on narrow secondary road. Yellow sign for Vemelsvik. Travel southwest along coast.
20:00	6	338.5	3.2	Small road cut on both sides. Park on wider spot just beyond. Vehicles turn around 0.7 km down the road and return to the Stop.

STOP 2-14: (10 minutes) Verpeneset layered zoisite±kyanite eclogite. Garnets show prograde growth zoning. With bright green fresh omphacite, this locality epitomizes the most beautiful eclogites in Norway. We give here part of a description from an earlier guidebook (Griffin and Mørk, 1981).

" The locality is described by Bryhni and Griffin (1971), who give analyses of rocks and minerals. The eclogite is about 20 x 30 meters in outcrop, and consists of two types of layers: (1) coarse-grained omph (Jd 35) +gnt+kyan+zois, correponding to ca. 20% Al_2O_3. (2) Medium-grained gnt+cpx (Jd35)+qtz rock, in dm-thick layers. Phengite and talc are accessory phases in type (1), and "secondary" segregations of talc + phengite ± kyanite ± pale amphibole occur in both types.

"The large garnets of type (1) layers show strong prograde zoning, which is complemented by the opposite zoning in the clinopyroxene. Cores of these garnets contain amphibolite-facies phases (magnesio-hornblende, paragonite) not present in the matrix (Bryhni and Griffin, 1971, Bryhni at al., 1977, Krogh, 1982). This eclogite thus shows clear evidence of a metamorphic origin from a lower grade amphibolitic protolith. Krogh has estimated P/T conditions at various stages of the metamoprhic evolution, from < 9 kb, 500°C to 17.6 kb, 720°C. Quartz-monzonite layers in the gneiss adjacent to the eclogite contain almandine garnets with ca. 40% grossular, another indication of high metamorphic pressures.

"A type (1) layer has yielded a Rb-Sr mineral isochron (zoisite + cpx + whole rock + kyanite + phengite) of 398±2 Ma. with initial 87Sr/86Sr = 0.7033 (Griffin and Brueckner, in prep.). Oxygen-isotope analyses (Vogel and Garlick, 1970) yield an unusually low $\partial^{18}O$ of 3.0 for the whole rock. Qtz-rutile fractionation gives a temperature of 585°C, which may reflect postmetamoprhic cooling."

For eclogites like this with prograde growth zoning Alice Wain suggests conditions of 700-800°C and < 24 kbar based on garnet-omphacite-phengite thermobarometry (Watters 1996 method).

20:10	10	-	-	Leave Stop 13. Return toward Route 15.
20:16	6	341.7	3.2	Junction Route 15 in Allmening. Turn sharp left on 15 toward Måløy.
20:18	2	343.5	1.8	Junction with Route 618. Stay straight toward Måløy.
20:24	6	349.4	5.9	Måløy Bridge. Proceed to Norlandia Måløy Hotell in downtown Måløy, reached by turning left at end of bridge and then beneath the bridge.

INTRODUCTION TO DAY 3 16/8/97

The day will begin with a drive from Måløy east along the north shore of Nordfjord to Maurstad, then north over the same pass to Åheim as on Day 2 and north to a ferry at Koparneset at 10:10 (Note Saturday schedule). En route there will be time to visit the coarse eclogite at Maurstad (Stop 3-1) and the spectacularly preserved anorthosite at Fiskå (Stop 3-2). From Koparneset we take the ferry to Årvik and drive across Gurskøya and Hareidlandet to a ferry at Hareid at 12:00. En route we will visit marble and amphibolite in probable Blåhø Nappe at Larsnes (Stop 3-3), the nodular sillimanite gneiss near Dragsund (Stop 3-4), and the Ulsteinvik eclogite (Stop 3-5). The ferry from Hareid goes to Sulasundet from which we drive through mostly wooded country to Brattvåg and then to a ferry at Skjeltene at 14:05. From Skjeltene we go by ferry to Haramsøya which is connected by bridge to Ullaholmen and Flemsøya. Here we will visit the Proterozoic Haram Gabbro with superbly preserved primary igneous features and early Scandian eclogite-facies shear zones (Stop 3-6), Ullaholmen with its late Scandian tubular folds superimposed on earlier fabrics (Stop 3-7), the Kvalvika garnet peridotite / pyroxenite with early Scandian subduction fabric and the Flem olivine gabbro and its conversion to eclogite (Stop 3-8), and the Nogva kyanite eclogite with retrograde sapphirine (Stop 3-9). We will have dinner at Longva on Flemsøya and then take a ferry at 20:30 to our overnight location at the Lepsøya Misjonsenter. Just before dark there will be a short trip to pavement exposures of infolded Sætra and Blåhø Nappes in "Sausage Rock" basement near Hellevik lighthouse on Lepsøya (Stop 3-10).

Morning Stops (3-1 to 3-5)

The morning of Day 3 will continue the theme of the previous afternoon in a region where there has been extensive petrologic work, but only limited tectono-stratigraphic mapping. Eclogites (Stops 1, 5) and pre-eclogite rocks (Stops 2, 4) occur in variable states of recrystallization and preservation, but there are also a few belts that may be infolded Caledonide nappes (Stop 3). See Fig. 2.4.

ROAD LOG

Total Time	Time since prev.	Total Km	Km since prev.	
8:00	-	0.0	-	Junction, center of Måløy. Proceed east across bridge on Route 15.
8:09	9	7.7	7.7	Junction with Route 618. Stay on Route 15.
8:10	1	9.5	1.8	Turn off for Verpeneset. Stay on Route 15.
8:21	11	21.7	12.2	Maurstad. Junction with Route 61. Park in school lot on left just before junction and walk back 50 meters to eclogite.

STOP 3-1: (10 minutes) Coarse eclogite with fresh omphacite behind road sign "Måløy". (SeeFigs. 2.1, 2.2) Following notes adapted from Mørk and Griffin (1981). A distinctive body of strongly foliated and layered zoisite-phengite eclogite and garnet quartzite. A metasedimentary origin seems likely. The adjacent gneisses contain highly calcic almandine garnets as at Verpneset. Green and Mysen (1972) give analyses of rocks and minerals. K_D (gnt/cpx) in the eclogite, and the apparent coexistence of calcic garnet (Gr25-27) with sodic plagioclase (An10) + kyanite + quartz in the gneisses , implies P≥20 Kbar at 650-700°C, conditions well over the Ab to Jad + Qtz transition. Kyan + gnt + Ab form complex intergowths in some of the quartz-rich gneisses; these could represent breakdown of high-P assemblages. Note also east-west trending folds typical of ductile extension fabric.

Total Time	Time since prev.	Total Km	Km since prev.	
8:31	**10**			Leave Stop 1. Turn north on Route 61 toward Åheim.
8:36	5	27.4	5.7	Enter Møre og Romsdal Fylke.
8:47	11	36.3	8.9	Åheim. Pass by Almklovdalen turn off. Stay on Route 61.
9:03	16	54.2	17.9	Turn left off Route 61 toward Fiskå.
9:04	1	55.0	0.8	Left toward Åram.
		55.5	0.5	Left toward Fiskå, then immediately right in front of food market and down road toward factory.
9:07	3	56.7	1.2	At factory parking lot bear left and park in extreme SW corner. Walk around end of fence (locked on Saturday) and walk west 0.2 km to quarry and shore exposure.

STOP 3-2: (30 minutes) Gabbroic anorthosite with coarse ophitic texture, Fiskåholmen. (See Fig. 2.4) A coarse to pegmatitic rock with grains in rare cases up to 50 cm. The plagioclase has a composition of An40-50. It also contains black orthopyroxene and titaniferous magnetite. The orthopyroxene has exsolved garnet and garnets are also seen in coronas around the magnetite. Preserved igneous textures indicate that this rock is an intrusion which was metamorphosed in the granulite facies and to only a small extent is retrograded in the amphibolite facies. The other anorthosites found in the WGR are retrograded fine-grained rocks (see Stop 2-7). This shows little or no effects of the eclogite-facies metamorphism that influenced the surroundings.

Total Time	Time since prev.	Total Km	Km since prev.	
9:37	**30**	-	-	Leave Stop 2.
9:40	3	57.9	1.2	Back to main road through center by food store.

9:41	1	59.1	1.2	Junction Route 61. Turn left.
9:45	4	63.3	4.2	Pass to Syvdsfjorden.
9:47	2	65.1	1.8	Junction. Stay on Route 61 toward Koparneset.
9:53	6	71.7	6.6	Koparneset Ferry. Outcrops of basement gneiss, typical E-W trending folds, evidence of partial melting.
10:10	**17**			Drive onto ferry for Årvik on Gurskøya.
10:25	**15**	71.8	0.1	Drive off ferry at Årvik. Turn left on Route 61. 42 km to Hareid.
10:28	3	73.5	1.7	Turn off, left, for Breivik Kalkverk.
10:29	1	74.0	0.5	Park by lower quarry and crusher.

STOP 3-3: (10 minutes) Amphibolite with coarse pure marble. Spectacular flat lineation. Probably part of Blåhø Nappe in a synclinal fold. (See Fig. 2.4).

10:39	**10**			Leave Stop 3.
10:40	1	74.5	0.5	Return to Route 61. Big road cut in amphibolite with flat lineation. Beyond this several cuts of Blåhø rusty rocks, marbles, amphibolites. Basement around bend.
10:43	3	77.3	2.8	Larsnes harbor. Laminated felsic-mafic gneisses. Probably basement.
10:44	1	77.8	0.5	Sharp turn right up hill on Route 61 toward Hareid. Up onto mountain. Stringey migmatites.
10:47	3	80.5	2.7	Top of pass.
10:50	3	83.3	2.8	Gurskebotn. Small exposures on bike path 1-2 minutes walk beyond left turn of garnet peridotite and hornblende migmatitic gneiss. Continue straight on Route 61.
11:02	12	95.4	12.1	Junction T, turn right.
		-	-	Left turn off 61 toward Dragsund factory.
11:03	1	96.5	1.1	Road swings back to left to road cut and small quarry on right. This lies between industrial site and private homes along the old road to Fosnavåg.

STOP 3-4: (15 minutes) Sillimanite-feldspar gneiss, Dragsund. (See Fig. 2.4)

Quartz-biotite-feldspar gneiss with big quartz-sillimanite nodules. Examine top of outcrop where nodules stand out on weathering surface. In addition to the nodular sillimanite gneiss, a retrograded eclogite lens is found and a thin-banded gneiss. The sillimanite is probably after kyanite, and may be typical of a granulite-facies cooling path that has bee identified in this district (Jamtveit, 1987). The origin of the nodules is world-class problem with diverse opinions. Such rocks occur in a major mapped unit in the Western Gneiss Region (Tveten and Lutro, 1996), in the Bamble area of south Norway, on Baffin Island, in Saskatchewan, in the Adirondacks, and in altered Ordovician volcanics in Massachusetts. Is the protolith intrusive, volcanic, or sedimentary? Were the nodules already present in a protolith, or are they strictly the result of a metamorphic or igneous process?

11:18	**15**	-	-	Leave Stop 4. Continue west to turn around.
11:19	1	96.7	0.2	Turn around. Return toward Route 61.
11:20	1	97.2	0.5	Left on Route 61 toward Hareid.
11:21	1	97.7	0.5	Over bridge, Dragsund.
11:22	1	99.3	1.6	Stop. Turn left toward Hareid (17 km).
11:26	4	103.3	4.0	Junction for Dimna. Stay straight on 61.
11:27	1	104.9	1.6	Rotary and exit for Ulsteinvik. Continue on Route 61.
11:28	1	105.3	0.4	Park on right. Outcrop on left side of road. Watch for traffic on this busy highway.

STOP 3-5: (10 minutes) Ulsteinvik eclogite. (See Figs. 2.4, 3.1) Layered eclogite, partly with hornblende. Elsewhere little hornblende but typical Ca-pyroxene - plagioclase symplectite.

The following information is modified slightly from Mørk and Krogh (1987). The Ulsteinvik eclogite body forms a sheet about 6x4km in area (Fig 3.1), but only ca 300m thick, folded in an E-W synform running through Ullsteinvik (Grønlie et al. 1972). It is internally layered, and locally shows clearly transgressive contacts to the country rocks, without the obvious tectonization common around smaller bodies. The chemical composition is transitional alkali olivine basalt - olivine tholeiite, but may have been modified by alkali loss during dehydration/metamorphism (Mysen and Heier, 1972, Griffin and Garman, in prep.). Detailed petrographic data are given by Mysen (1972a,b). The metamorphic peak has been estimated at ca. 800°C, 18 Kb by Griffin et al. (1982). The pelitic gneisses around the north limb of the body contain relict high-P granulite facies assemblages (gnt+omph+bio+plag+qtz) compatible with these conditions (Mysen & Heier 1972).

The surrounding dioritic gneisses have yielded a Rb-Sr whole-rock 'scatterchrone' date of 1646±70 with IR = 0.708 (Mysen & Heier 1972). The minerals of the eclogite give a Sm-Nd age of 423±30 Ma (Griffin & Brueckner 1980) and zircons from the eclogite provided by Mysen give U-Pb ages of ca. 410 Ma. (Krogh et al. 1974). R. D. Tucker (pers. comm. 1997, see Fig. 3.1B) reports a more refined age on the same sample of 402±2 Ma. The 87Sr/86Sr of the eclogite clinopyroxenes is relatively high (0.706), suggesting some contamination with crustal material prior to eclogite metamorphism.

The outcrop shows 0.5-1 meter layers of cpx-rich eclogite alternating with garnet-rich gnt-rich eclogite. The chemical variation is explained by Mysen and Heier (1972) as a low-P (< 8 Kb) sorting of olivine, clinopyroxene and plagioclase. The eclogite is retrograded extensively to amphibolite along late pegmatitic veins.Large inclusions of felsic gneisses have diffuse borders, suggesting partial assimilation, and retrograde granulite-facies mineral assemblages (gnt + opx +plag + qtz, gnt + ky + cpx + plag + qtz). Schlieren of quartz ± rutile ± kyanite ± omph ± gnt suggests the presence of a fluid garnet phase during metamorphism. Small patchy pegmatites with garnet and hbl have apparently formed at relatively high P (<12 Kb) as a part of the metamorphic episode (Green and Mysen 1972). Later pegmatites, clearly cross-cutting the eclogite and gneiss, are accompanied by extensive amphibolitization.

11:38	**10**	-	-	Leave Stop 5. Continue on Route 61.
11:41	3	108.2	2.9	High point of pass.
11:48	7	115.8	7.6	Ferry at Hareid.
12:00	**12**	116.0	0.2	Drive onto Ferry for Sulasundet.
12:25	**25**	-	-	Drive off ferry at Sulasundet. For stop locations beyond here see Fig. 3.2.
12:32	7	125.0	9.0	Junction for Bergen E39 (former Route 1). Stay straight for Ålesund.
12:36	4	129.3	4.3	Junction for Magerholm. Stay left toward Ålesund on E39.
-	-	-	-	Spjelkavik roundabout. Stay on E39.
12:40	4	132.8	3.5	Junction. Turn on E39 toward Trondheim.
12:51	11	147.0	14.2	Turn off on Route 661 to Brattvåg.
12:54	3	149.1	2.1	Twin bridges. One way.
12:56	2	149.9	0.8	Junction. Stay on Route 661 to Vatne, Brattvåg.
12:58	2	152.9	3.0	Junction to Vigra. Stay straight on 661.
13:02	4	156.9	4.0	T Junction. Left to Brattvåg. Route runs west on south side of Brattvåg Peninsula gradually climbing to tunnel which pierces the ridge allowing access to Brattvåg on the west side of a N-S trending harbor.
13:13	11	170.1	13.2	Center of Brattvåg. Possibilities for groceries and beer. From here it is about 12 minutes drive to Skjeltene Ferry.
13:14	1	171.7	1.6	Turn off to Brattvåg Ferry (Dryna, Fjortoft, etc.). Stay straight.
13:24	10	181.7	10.0	Turn right for Skjeltene and waiting line for ferry to Haramsøya.

Afternoon Stops (3-6 to 3-10)

The afternoon will devoted entirely to three of the Nordøyane (literally THE NORTH ISLANDS) Haramsøya, Flemsøya, and Lepsøya (Fig. 3.2, 3.3) which are being studied in detail by Michael P. Terry for his Ph. D. thesis at the University of Massachusetts. The context of Nordøyane would be better understood if we could view the rocks of the Moldefjord syncline near Brattvåg first, but logistics requires that to be postponed to day 4. Nordøyane are the westernmost exposures of the belt of basement rocks with high-pressure high-temperature eclogites that lies to the north of the Moldefjord and Surnadal synclines with their exposures of low amphibolite-grade rocks. Fjørtoft is the site of recent reports of crustal microdiamonds (Dobrzhinetskaya et al., 1995) in a narrow belt we believe can be assigned to the Blåhø Nappe.

Terry has divided the geology of these islands into three belts (Fig. 3.3), **southern**, **central** and **northern**, based on the character of basement and nappe units in each. The **southern belt** (not to be seen on this trip) is dominated by granitoid Proterozoic basement gneiss with abundant boudins of eclogite and bodies of garnet-corona gabbro. Within this there are six narrow belts of mica-garnet±kyanite schist and garnet amphibolite that are interpreted as early isoclinal infolds of the Blåhø Nappe. Although eclogites have not been surely identified in this Blåhø on Lepsøya, eclogite has been found in a correlative synclinal belt on nearby Vigra. The belts of Blåhø provide markers that outline the late subhorizontal open folds superimposed on the early isoclines and also isoclinal refolds. These consist of an open anticline located in southwest Lepsøya and a broad syncline centered on Goaldet, the high peak of Lepsøya, which is well displayed in views from Haramsøya or the ferry to Haramsøya. Asymmetric shear fabrics in the southern belt give a consistent top-to-west shear sense along the lineation that is parallel to these late folds, and is thus much like the features observed in ductile fabrics beneath the Devonian basins south of Nordfjord (Day 2).

The **central belt** is dominated by two basement types, granitoid gneiss and gray granitoid gneiss with amphibolites interpreted as deformed mafic dikes (Stop 3-10; for more about this see Stops 4-6 and 4-7). There is also a zone of relatively undeformed diorite with hornblende coronas and only minor garnet coronas. Throughout there is no evidence that these rocks ever went through eclogite-facies metamorphism, though that cannot be proved. The central belt also contains three extremely narrow isoclinal synclines dominated by mica-garnet±kyanite schists and garnet amphibolites of the Blåhø Nappe. The north limb of one of these synclines, at the basement-Blåhø contact, shows a consistent layer about 1 m thick of interbedded quartzite and amphibolite that is assigned to the Sætra Nappe (Stop 3-10). Commonly at the Blåhø-Sætra contact there a few centimeters of marble and calc-silicate rock, a common feature at this contact as will be seen at Stops 4-3 and 4-4. On Haramsøya limited outcrop of the central belt suggests it may be in a tight syncline so that gneiss of the southern belt lies to the north of it, close to the Haram Gabbro. The apparent metamorphic discontinuity between the southern and central belts must be an early feature because the contact shows no obvious fault features and is also complexly folded. Like the southern belt, the central belt is dominated by late Scandian features involving longitudinal extension, lateral constriction, and top-west shear, probably in a field of sinistral transtension.

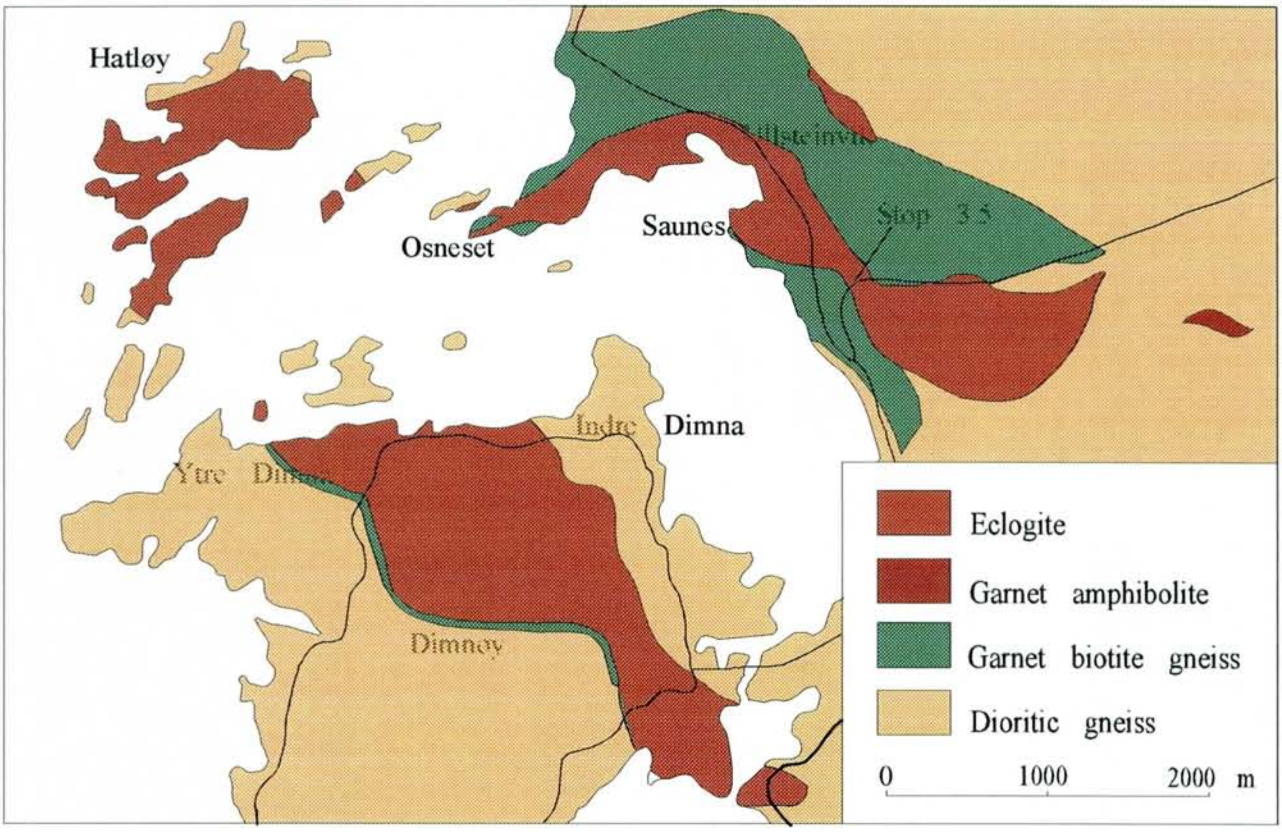


Fig 3.1a. Geological map of the Ulsteinvik area, after Mysen & Heier (1972)

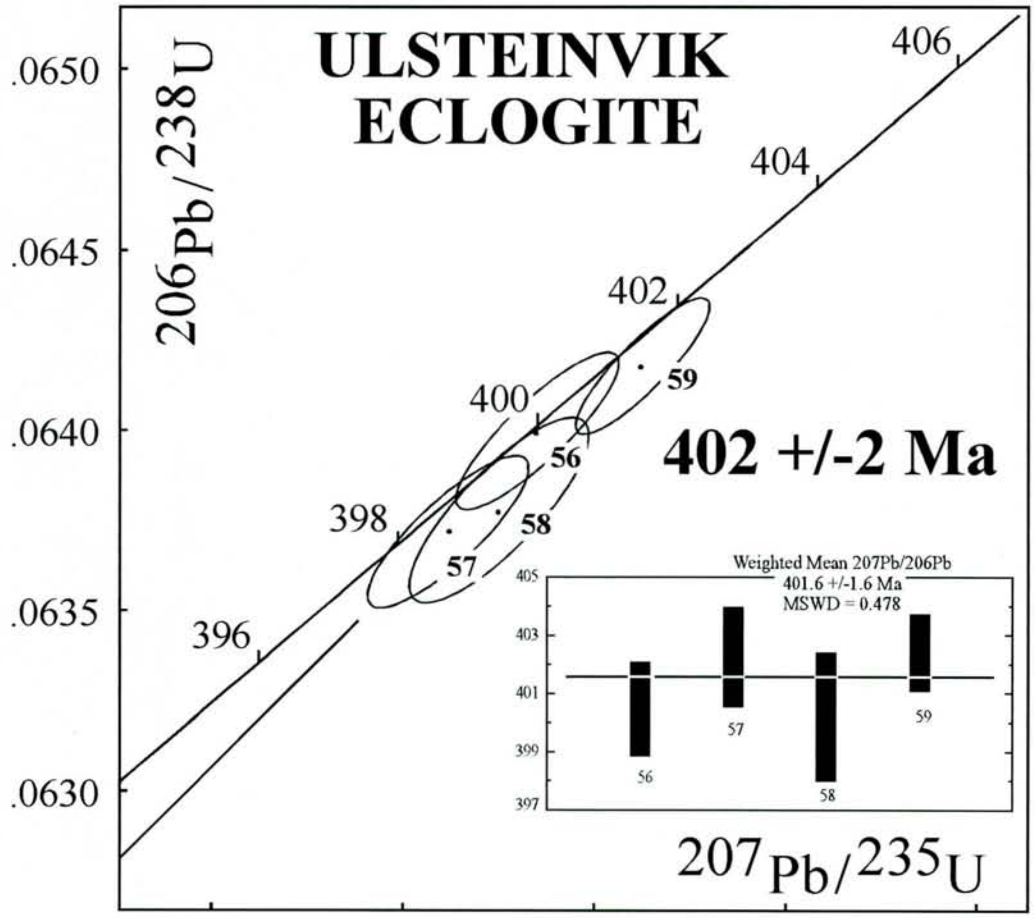


Fig 3.1b Concordia diagram showing zircon U-Pb isotopic ratios and metamorphic crystallization age for the Ulsteinvik eclogite. R.D. Tucker, T. Krogh and A. Råheim, unpublished data.

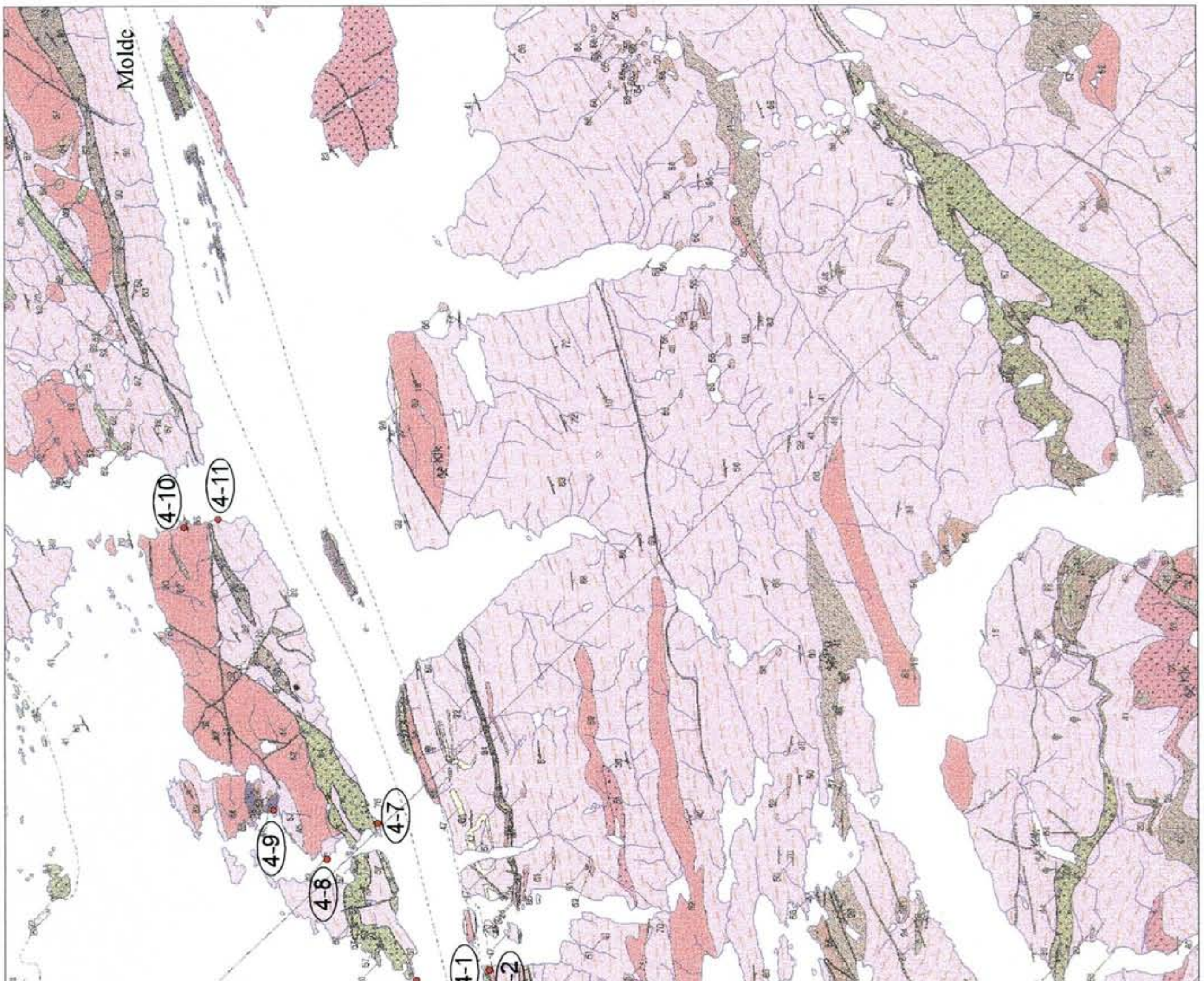


Fig. 3.2. Map showing stops of day three and four. The map is copied from the preliminary version of the 1:250.000 map sheet Ålesund (Tveten & Lutro in prep).

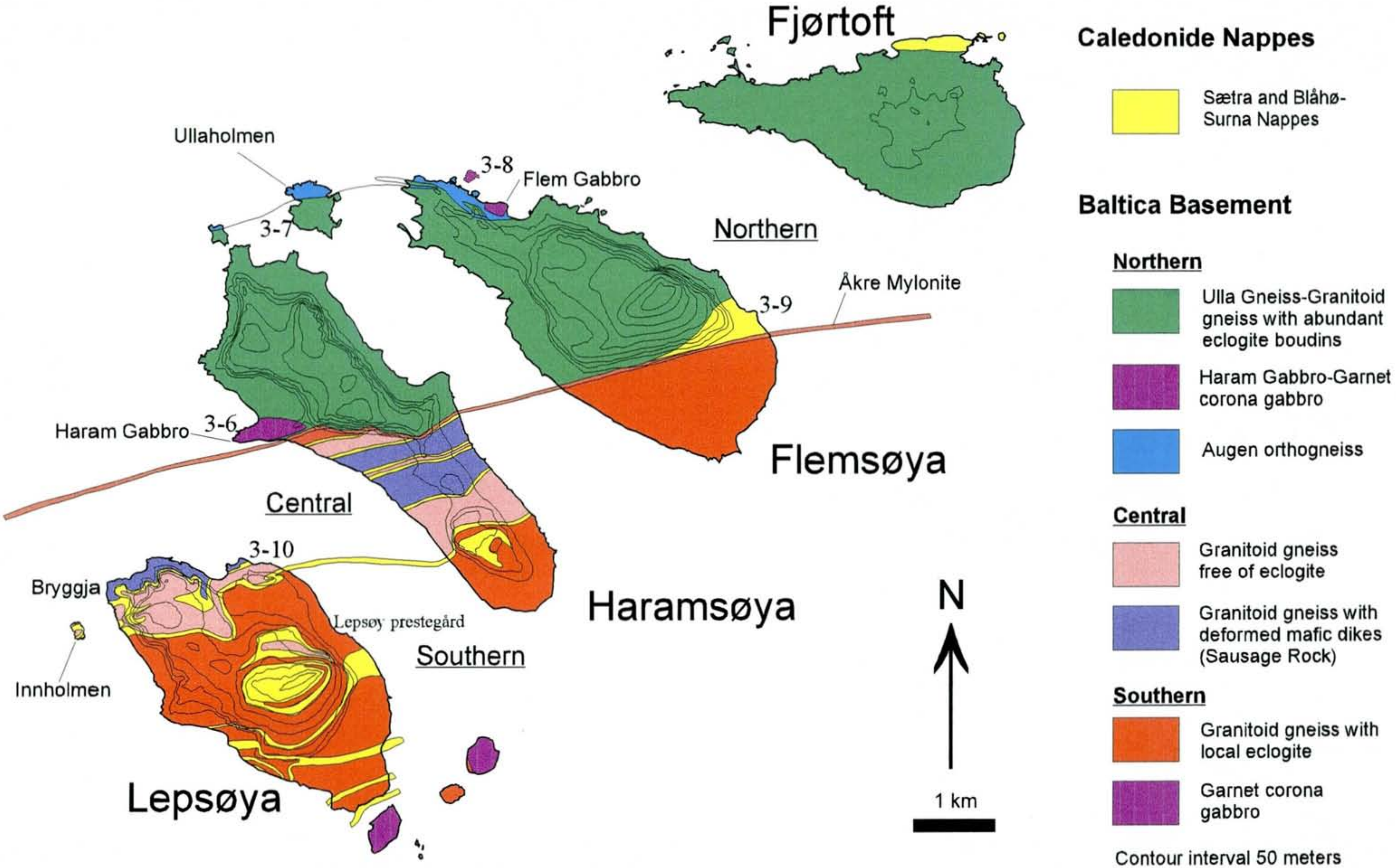


Fig. 3.3. Generalized geologic map of Nordøyane prepared by Michael P. Terry, based on field work through 1996.

The **northern belt** is dominated by the Ulla Gneiss, a complex granitoid to tonalitic gneiss with very abundant boudins of eclogite and retrograded eclogite, which we affectionately call the "dog's breakfast" (Stop 3-7). Subordinate rock types include augen orthogneiss (see Stop 4-10), garnet corona gabbro (Stops 3-6 and 3-8), garnet peridote and garnet pyroxenite, and two belts of garnet and biotite gneiss and garnet amphibolite with eclogite, that we tentatively assign to the Blåhø Nappe, on the north coast of Fjørtoft and on eastern Flemsøya, the later poorly exposed. Prelminary mapping of the ultramafic rocks (not shown in Fig. 3-0B) suggest they may be aligned along ancient shear zones and may separate different slabs of basement that were brought into tectonic contact with sub-continental mantle within the subduction zone, before being ejected by later thrusting. Like the southern and central belts, the northern belt is also dominated by late subhorizontal lineation and top-west shear fabrics, including subhorizontal tubular folds (Stop 3-7), however, it also preserves a variety of early transverse folds and lineations, even vertical tubular folds, which we interpret as remanents of fabrics produced under eclogite-facies conditions during the subduction process. These fabrics are widely preserved in Ulla Gneiss, even where it is dominated by later subhorizontal folds and lineation. It also appears in the "diamond-bearing" kyanite-garnet gneiss on Fjørtoft and in some of the garnet peridotites (Stop 3-8). It is best displayed in and near the Haram Gabbro (Terry and Robinson, 1996). where early shearing has produced an essentially vertical lineation in mylonitic gneissic gabbro and fine-grained mylonite produced either from gabbro or from granitic gneiss (Stop 3-6). The gradual conversion of gabbro toward eclogite in the fine-grained gabbro mylonite implies this shearing was taking place under eclogite-facies conditions. Sense of shear observed in thin sections cut perpendicular to foliation and parallel to lineation indicate north-side-up consistent with formation during northwestward subduction of Baltica. The boundary between the northern and central belts is unequivocally a zone of late subhorizontal sinistral shear with the development of about 100 meters of fine-grained mylonite including small boudins of eclogite. This Åkre mylonite, is superbly exposed in road cuts near the peak of Haramsøya, but obscures the original nature of this important tectonic contact.

14:05	**41**	181.8	0.1	Drive onto ferry for Haramsøya.
14:20	**15**	-	-	Ferry stops at Løvsøya. Stay on ferry.
14:40	**20**	-	-	Leave ferry at Haramsøya in village of Austnes. Turn left for Haram on main road.
14:50	10	188.7	6.9	At Haramneset take driveways to outermost house and park. Ask owner permission to visit coastal outcrops.

STOP 3-6: (1 hour 45 minutes) Haram Gabbro (Terry and Robinson)

The Haram Gabbro (Fig. 3.3) lies in the northern belt dominated by Ulla Gneiss very close to the bounding late Scandian Åkre mylonite zone with its low amphibolite-facies mineralogy, subhorizontal lineation, and sinistral shear features. The gabbro (Fig. 3.4) appears to be surrounded by zones of fine-grained eclogite-facies mylonite consisting mainly of gabbroic protolith, but also smaller amounts of granitoid country rock. The eclogite-facies mylonite also cuts through parts of the gabbro. Even though very fine grained, the eclogite-facies mylonite still contains relics of original igneous orthopyroxene, plagioclase and ilmenite in a matrix of omphacite (up toJd 29) plagioclase, garnet, quartz, and minor rutile. Preliminary estimated P-T conditions for the mineral assemblage in the mylonite are 840 ±40°C and 17 ±3 kbar. The unusual feature of the eclogite-facies mylonite is that it contains a vertical or near vertical foliation, a steep lineation, and indicators of north-side-up shear (Terry and Robinson, 1996; Terry and Robinson, 1997). When the foliation is rotated back to a subhorizontal position to cancel the effects of later folding, this gives a top-southeast sense of shear which chould be compatible with fabrics produced during northwestward subduction of Baltica crust. Within the gabbro adjacent to the eclogite-facies mylonite and in some broader zones there are zones of mylonitic gabbro gneiss with the same kind of early shear features. In most mylonite samples garnet growth seems to have outlasted shearing as shown by finely zoned garnet coronas between plagioclase and pyroxenes or ilmenite (Figs. 3.5, 3.6). Preservation of these fine early deformational features is thought to be related to little access of fluids during any later stages of deformation, and contrasts greatly with regions next to late pegmatite dikes where any of the mafic rock types in the complex may be converted completely to amphibolite.

The superb coastal exposures allow the original gabbro to be divided into three primary types: Coarse-grained mafic gabbro, anorthositic gabbro, and cumulate layered gabbro. These distinctions have not yet been successfully carried to the areas of smaller inland outcrops. The coarse-grained mafic gabbro occurs along the north margin of the complex and contacts with adjacent gabbros are mylonite zones. Of all the igneous types, this seems to have been most susceptible to deformation and formation of mylonitic gneiss with subvertical lineation. The anorthositic gabbro seems to have been least influenced by deformation and it is also host to the most spectacular gabbro pegmatites. Its contact with the cumulate-layered gabbro is locally primary. The cumulate layered gabbro contain sharp "inch-scale layering" of pyroxenes and plagioclase, which can be interpreted to indicate that the original top of the compex was to the south. From the overall aspect of the map, it seems likely that an unknown portion of the original complex may have been removed by early shearing. The fact that the total mass is so large gives some confidence that the early shear fabrics are in their approximately original orientation except for late folding, unlike the early fabrics in small eclogite boudins which commonly show highly diverse orientations (see Stop 3-7).

From the house walk west into the pasture and then north and northeast across a fence to north-facing coastal exposures. The first rock that you will see approaching the coast is a coarse mylonitic gabbro gneiss with striking steeply plunging lineation. The fine-grained smooth outcrops near the waterline (we expect to be there at low tide) are fine-grained gabbro mylonite with a minor amount of felsic mylonite. These appear to form a carapace all along the north coast of Haramneset. Travel east a short distance (much slippery rock) to a location with unusual overhanging gabbro scenery and a gully where one can walk south a short distance . Here one can see several shear zones, small gabbro pegmatites in various stages of deformation, and a zone of cumulate layered gabbro. Bending of foliation into mylonitic zones gives conflicting shear senses. To the east of the north end of the gully there is a zone of mylonitic gneiss where there is extensive development of garnet and green omphacitic pyroxene. North-side-up shear sense has been observed in hand specimen here. Follow coast west observing mylonite where possible, passing first small headland on the shore side, to north side of last headland of coarse-grained mafic gabbro. Here one can observe the contact between eclogite-facies mylonite and gabbro and a curious mylonite zone that curves into the main mass of the gabbro. In this one can seen original garnet-rich eclogite and secondary amphibolite related to later fractures.

Cross over headland of coarse mafic gabbro (several routes possible) to southwest edge of coarse gabbro where it grades into coase mylonitic gneiss with steep rodding and then into fine-grained mylonite. Across the gully is a large exposure of anorthositic gabbro. From here the contrast between the two gabbros is striking. Walk west across anorthositc gabbro to an area where there appears to be a relict diabase dike and then climb onto the top surface of the headland northwest of the lighthouse. Here a pavement exposure shows spectacular zoned gabbro pegmatite pods with crystals of plagioclase, pyroxenes, and magnetite 10-20 cm long. The only sign of the regional eclogite and amphibolite-facies metamorphisms are tiny garnet coronas between mafic minerals and plagioclase. In the broad gully north of the pegmatites is an eclogite-facies mylonite zone (not shown on Fig. 3.4) and then the contact with cumulate layered gabbro.

After observing the layering walk southeast toward the lighthouse over quite rough ground to a large west-facing wall with a great display of inch-scale layering. Beyond this descend steeply down toward the waterline (big boulders nearby). Here is a special example of a late pegmatite cutting through the inch-scale layered gabbro with complete transformation to amphibolite, perfectly preserving the layering but non of the original mineralogy. Near here are outcrops and lose pieces where layering is very photogenic. From here we proceed east through a boulder field with many outcrops. These show the approximate contact between gabbro and gabbro-mylonite and examples of granitic mylonitic gneiss and one bit of calc-silicate rock with steep mylonite lineation. Among the boulders are boudins of eclogite probably derived from outside the gabbro. Walk back northeast over raised beach gravels to house and vehicles.

According to Mørk (Mørk and Krogh, 1987) the chemical composition and the Sm-Nd isotopic composition distinguish the normally plagioclase-rich Haram gabbro from the more extensively studied Flem olivine gabbro (Stop 3-8), and it also appears to be younger. Sm-Nd dating of relict augite + orthopyroxene + 2 whole rocks gives an age of 926±70 Ma (Mørk and Mearns, 1986). Her report that metamorphic reactions involve only formation of garnet-hornblende coronas is not borne out by the present study, although the production of complete eclogite is much less extensive than at Flem. It is speculated that the driving force for corona development and transformation to eclogite is much stronger in olivine-plagioclase contact regions than in marginally quartz-bearing gabbro such as that at Haram (see Figure 3.5, Si map).

15:35	**105**	-	-	Leave STOP 6 and return toward Austnes.
-	-	195.5	6.8	Austnes. Proceed north through Ulla and Ulla Bridge.
-	-	203.0	7.5	East end of Ulla Bridge. Turn sharp left onto rough causeway to Ullholmen
15:55	10	203.7	0.7	Drive to field at the high point of the island. From there walk through fields to prominent rocks on west coast.

STOP 3-7: (45 minutes) Tubular and complex folding in Ulla Gneiss. (See detailed map by Michael Terry in Fig. 3.7) (Terry and Robinson)

The dominant fabric in Ulla Gneiss is subhorizontal lineation and folds parallel to the east-northeast trending "stretching" direction during late Scandian sinstral transtension. However, the structure is somewhat chaotic because of the lumpy character of the rocks with abundant large and small eclogite and retrograded eclogite boudins. Furthermore there is abundant evidence of one or more earlier fold and lineation-forming episodes that may have originally been formed parallel to the eclogite-facies mylonites near the Haram Gabbro.

Walk directly west along north edge of the field to the first knob on the coast. Here the folds in layered gneiss are not dominantly tubular, but they show spectacular examples of folded lineations and refolded early fold systems, in some of which the early fold asymmetry is graphically dispayed.

From here walk north around a broad inlet toward the most prominent coastal knob. En route you will encounter a large layered eclogite boudin and a curious intrusive gneiss, which Ole Lutro calls "ovalite" and which is widespread in the Romsdal near Trollvegen. Are the ovals deformed giant phenocrysts or are they oval xenoliths of another rock type?

The south slope of the main knob shows many places where early folds and lineations are seen to be bent in great circles around late folds with a transport direction that is only a few degrees away from the late fold axes. The northern part of the main knob is the location of the detailed pavement map, structural measurements, and interpreted cross section in Figure 3.7. The best tubular folds are to be seen on west-facing joint surfaces that do not show very well on the map. The nature of the outcrop makes it just possible to identify which of the closures are tubular "basins" and which are "domes" on the near vertical surfaces. The tube axes along with most lineation and fold axes trend east-northeast and plunge gently east. On the nose of one "dome" (viewed from the east) it is possible to see earlier lineation bending in a great circle around the dome axis. According to Terry every layer which he traced in detail in the outcrop turned out to be an isoclinal fold if traced far enough. Based on these observations, an important question is the extent of earlier tubular folding, and the extent to which tight isoclinal synclines idientified in the region are actually only earlier manifestations of a prolonged episofe of tubular folding. The best overall evaluation of these folds, as illustrated in the cross section, is that the tubes themselves reflect a sense of top-west and northside-west (i.e. sinistral) shear during fold development.

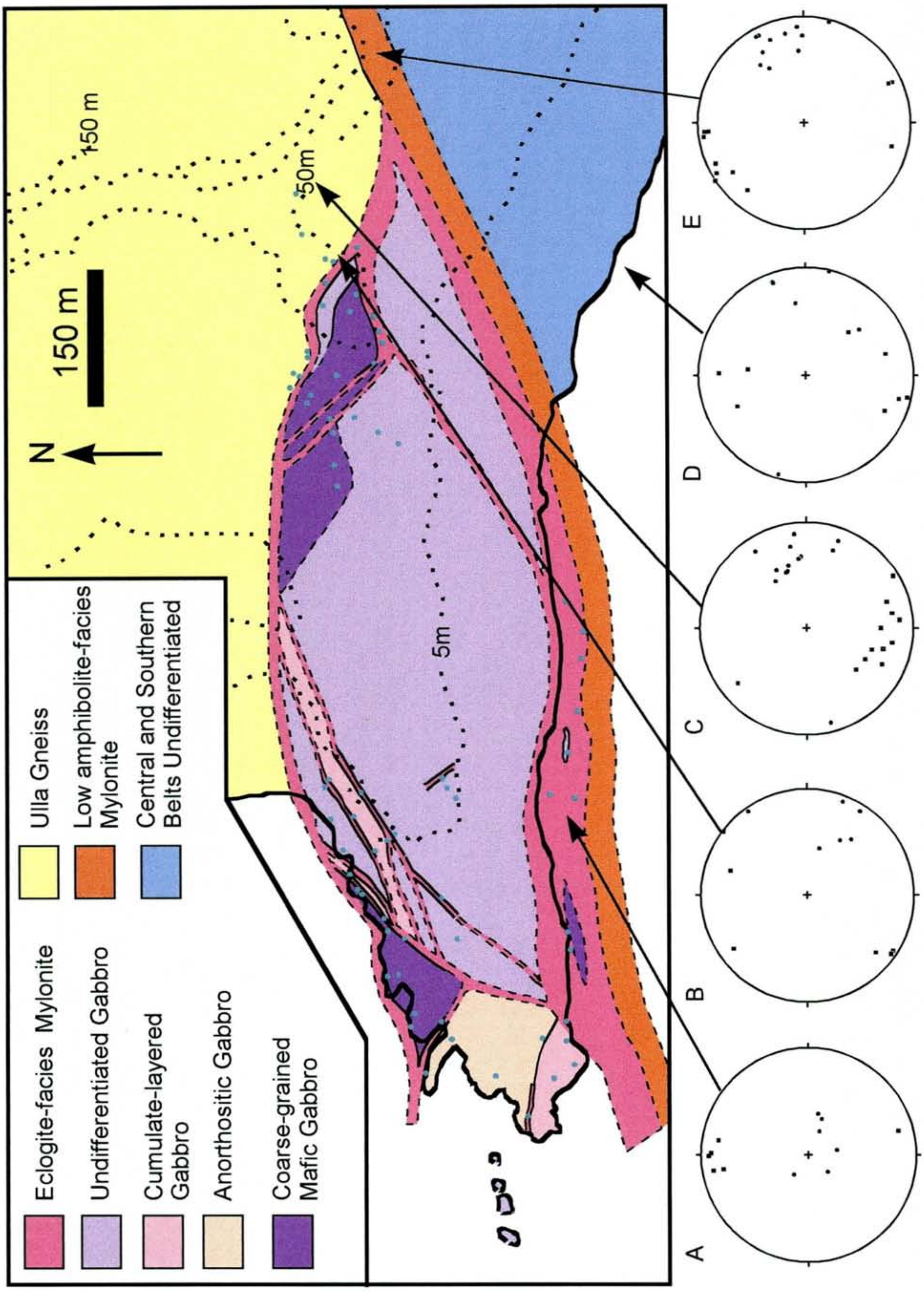


Fig 3.4. Detailed geologic map of Haram Gabbro and vicinity (Stop 3-6) prepared by Michael P. Terry, based on field work through 1996. Green dots indicate locations of detailed structural measurements. Equal area diagrams show selected measurements of minor structural features.

Squares = foliation; dots = lineation. Areas outside the gabbro and eclogite-facies mylonite (B,C,D,E) show typical gentle lineation trending approximately E-W. Gabbro shear zones and eclogite-facies mylonite (A) show near vertical lineation, and, in detail, a north-side-up sense of shear consistent with early northwestward subduction.

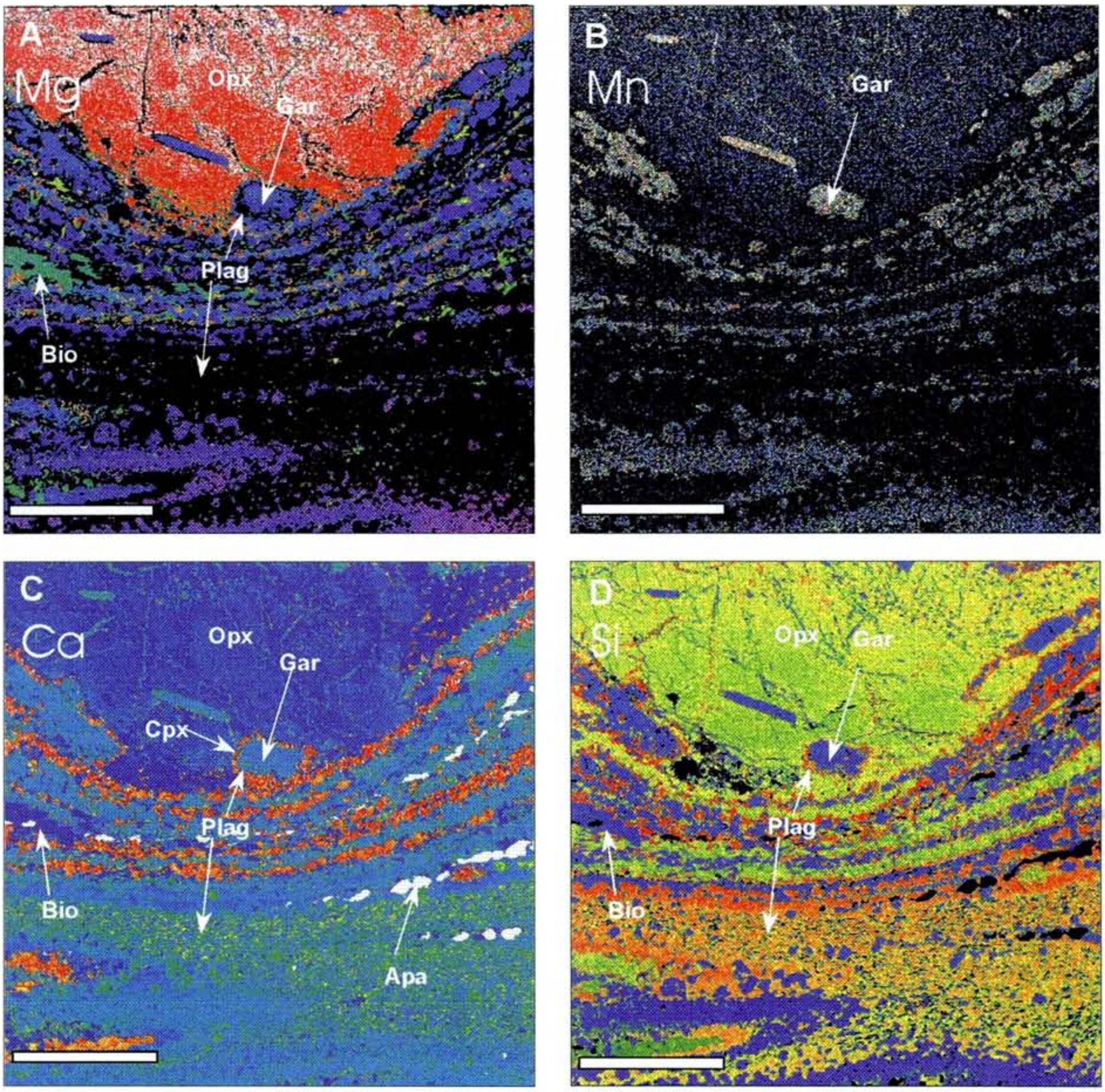


Fig. 3.5. Electron probe scanned element images of eclogite-facies mylonite zone in northern part of Haram Gabbro, Stop 3-6. Scale bar is 0.1 mm. The color scheme relates directly to element abundance from abundant preserved. The dominant feature is a porphyroclast of igneous orthopyroxene. The four elements which were scanned automatically and simultaneously in one overnight run are: A) Mg -Most abundant in orthopyroxene and biotite but significant present in garnet. B) Mn -Indicates locations of metamorphic garnet, also present to a lesser extent in orthopyroxene. C) Ca -Most abundant in apatite (white), clinopyroxene (red), and plagioclase, of which two varieties are seen, Ca-rich (red) in areas of local retrograde reactions and more sodic (green) in large areas. D) Si -Most abundant in quartz (red) and plagioclase (red), less abundant in orthopyroxene and clinopyroxene (yellow, green), scarce in garnet and biotite, and absent in apatite.

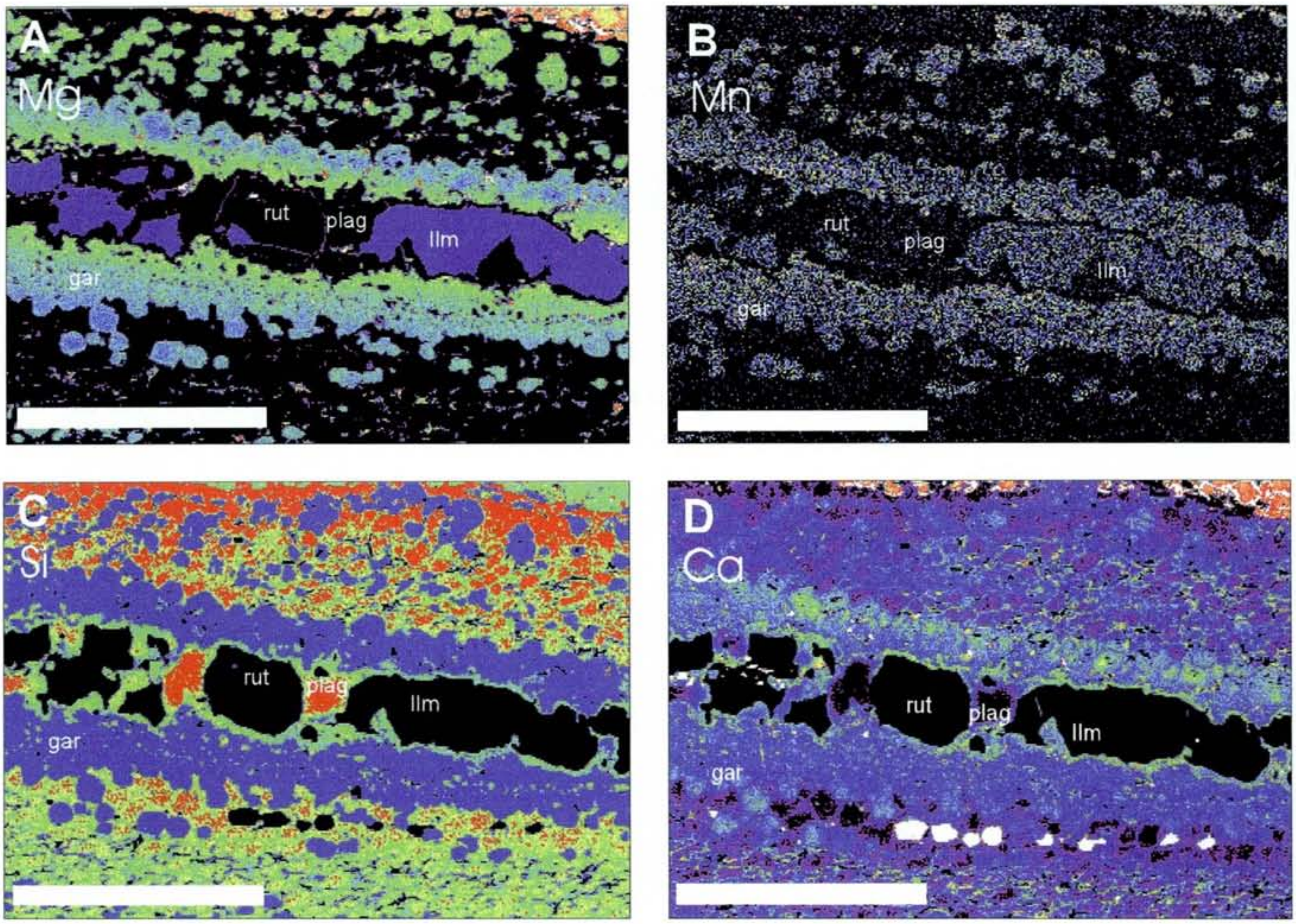
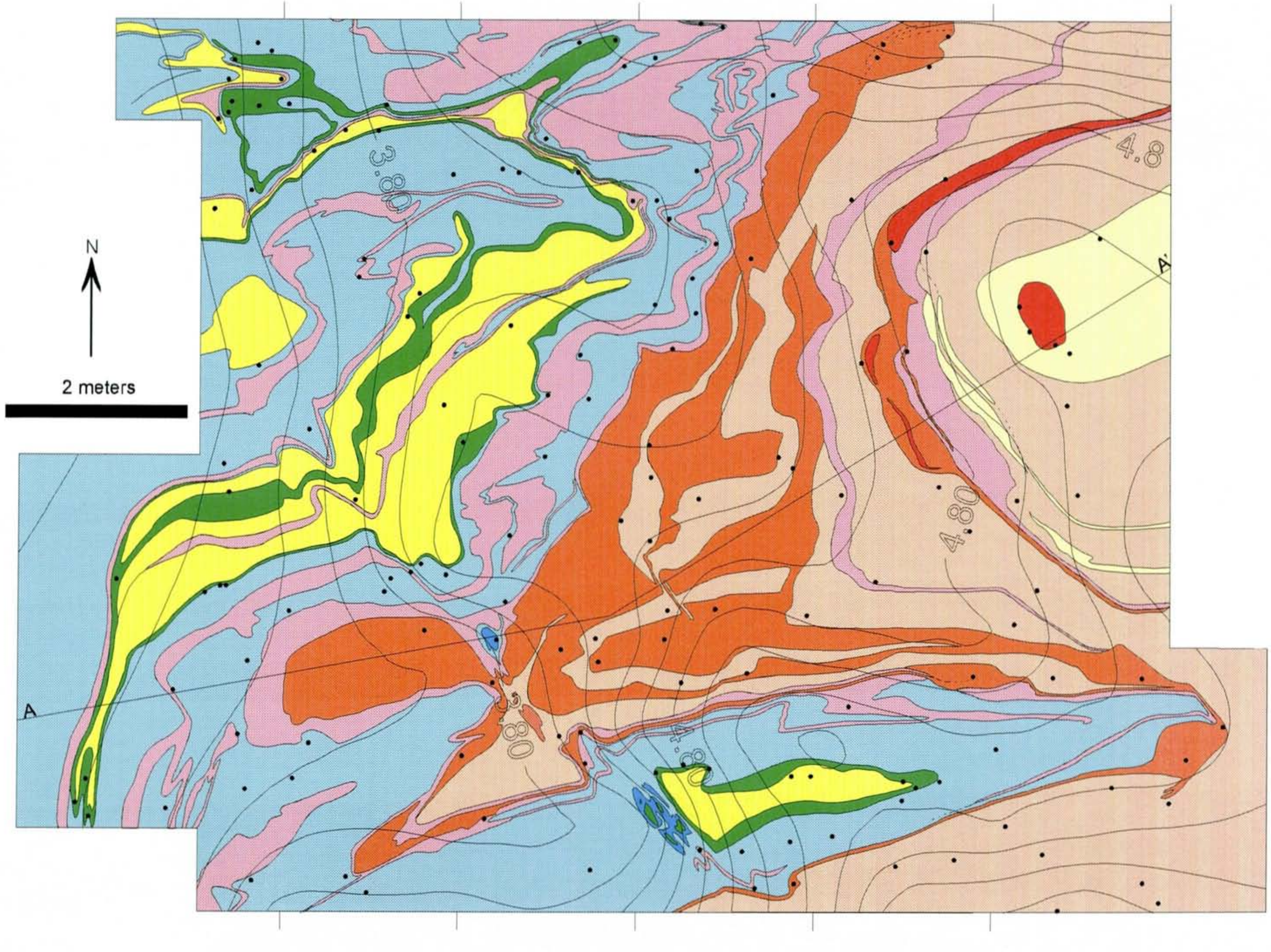


Fig. 3.6. Electron probe scanned element images in vicinity of sheared ilmenite ribbons in mylonitized gabbro with coronas of euhedral garnet, Scale bar is 0.1 mm. The color scheme relates directly to element abundance from abundant (white or red) to scarce or absent (violet or black). Rutile has formed in an ilmenite boudin neck zone with quartz in two adjacent pressure shadows. Quartz is rimmed by secondary plagioclase, which also forms a rim between garnet and ilmenite/rutile. The four elements which were scanned automatically and simultaneously in one overnight run are: A) Mg -Most abundant in garnet (green to blue) close to ilmenite (violet) and decreasing toward plagioclase-rich matrix. B) Mn -Present in garnet, also ilmenite. C) Si - Greatest in quartz in neck zone and in plagioclase in matrix and neck zone (red), less in garnet (violet), none (black) in apatite, rutile, ilmenite. D) Ca - Most abundant in apatite (white), variable in garnet (green to blue), low in plagioclase (violet).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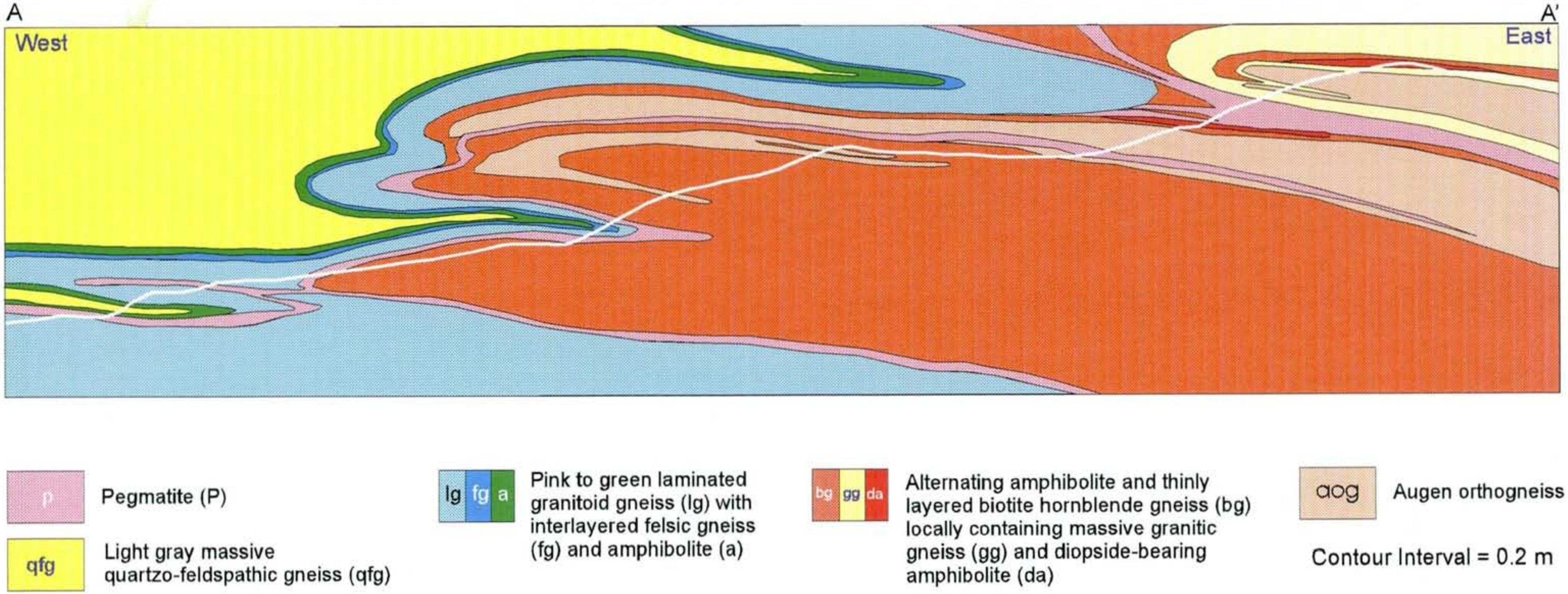

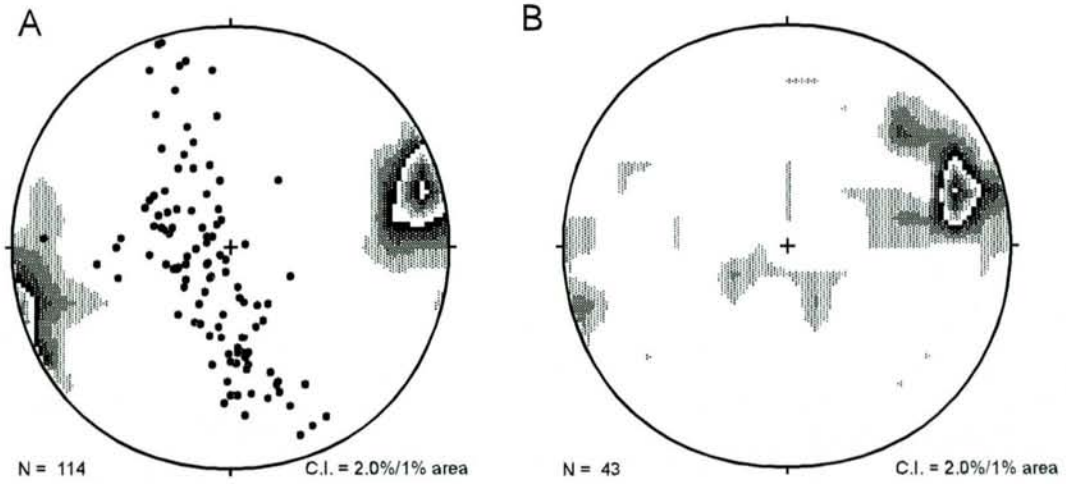

Summary of structural data for the Ullaholmen exposure. **A**. Contours of lineations and poles to foliation. **B**. Contours of fold axes.

Fig. 3.7. Detailed geologic map, cross section and equal area diagrams for part of a pavement exposure at Ullaholmen, Nordøyane, prepared by Michael Terry, Stop 3-7.

Persons with an additional half hour may wish to examine the large coastal exposures of complexly deformed augen-orthogneiss on the north point of Ullholmen 250 m away. After the stop walk back to the field over boddy ground.

16:40	**45**	-	-	Leave STOP 7 and Ullaholmen.
-	-	204.4	0.7	Turn left onto main causeway to Flemsøya.
-	-	206.4	2.0	At T junction at end of causeway turn left toward Flem. Follow narrow road around NW corner of Flemsøya.
16:50	10	208.3	1.9	Small parking area at Sandvik sand beach.

STOP 3-8: (1 hour 15 minutes) Kvalvika garnet-peridotite and Flem (Sandvikhaugane) Gabbro.

These two localities within a short walk of the beach at Sandvik were both described by Mai Britt Mørk (Mørk and Krogh, 1987), and a study of the gabbro was part of her Ph. D. thesis at Oslo University (Mørk, 1985; Mork, 1986, Mork and Mearns, 1986).

Depending on tide and sand conditions walk east along the beach or along the road about 150 meters to a peculiar hollow in the gneissic rocks. This is eroded in a body of yellow-brown-weathering garnet peridotite with thin folded layers of garnet websterite consisting of garnet, Cr diopside, enstatite and rutile. The body is surrounded by typical Ulla Gneiss as mapped by Terry, which appears to contain omphacite adjacent to the garnet peridotite. In summer 1993 and 1996 the body was 90% covered by sand, whereas in spring 1997 storms had excavated most of the sand leaving about 90% exposure of ultramafic rock. The folds in garnet websterite are steeply plunging and probably parallel to an early subduction fabric. So far the outcrops have yielded no information on the mode of emplacement of the body, but may upon closer study.

Walk back beyond the beach and out onto the point at Sandvikhaugene. At the east end of the big outcrop at low tide the original igneous intrusive contact of the gabbro with the augen orthogneiss can be seen, as well as a steep subduction related (?) linear fabric in the augen gneiss. Rare sugary textured granitic veins locally with coarse garnet and tourmaline in the gabbro may be backveins that went through eclogite-facies conditions. These contrast with coarse cross-cutting late pegmatite dikes that came in late in the Scandian exhumation and usually caused extensive amphibolitization in adjacent gabbro or eclogite. Walk northwest from the contact about 75 m to the northeast-facing point where the full transition from layered gabbro to eclogite can be examine in clean outcrop.

According to Mørk (Mørk and Krogh, 1987) the gabbro is a layered olivine gabbro with relict igneous mineralogy including olivine, plagioclase, augite, ilmenite and biotite. It shows all stages of transformation to an eclogite consisting of garnet, omphacite, biotite, amphibole and ilmenite. Three stages of tranformation are recognized in the field: 1) Massive corona gabbro dominated by relict igneous mineralogy and cumulate textures. 2) Transitional gabbro-eclogite with relict igneous textures and some relict minerals but with garnet and omphacite clearly visible in the field. 3) Completely eclogitized gabbro, either with pseudomorphic igneous textures or as recrystallized and foliated eclogites. Pseudomorphic replacements involve formation of garnet and orthopyroxene coronas between plagioclase and olivine, replacement of igneous plagioclase by more sodic plagioclase with thin spinel needles, increase of Na content of intercumulus augite and exsolution of an opaque phase. With increasing degree of reaction omphacite forms both by continuous reactions with the original augite and by nucleation within olivine and transient orthopyroxene, while garnet always seems to replace plagioclase. (For element images of this transition stage see Figure 3.8) As modal % of pyroxene climbs from about 15% in the gabbro to about 40% in the eclogite, the composition changes from Acmite 14 Jadeite 0 to around Acmite 10 Jadeite 25-30, and the garnet composition from pyrope 29 to 42-45, almandine nearly constant at 44-48, grossular 27 to 8, and spessartine 1.2 to 0.8. With increasing degree of reaction the transient phases disappear and garnet becomes more homogeneous with lower Ca and slightly higher Mg/Fe than in the corona stage. It appears that complete eclogitization and mineral-chemical as well as isotopic homogenization are enhanced by factors like oxidation, fluid availability, and deformation, while the transient stages reflect restricted element exchange between the mafic and felsic original domains (Mørk, 1985; Mørk and Mearns, 1986). Plagioclase-rich pegmatite dikes within the gabbro about 75 meters more to the west containing plagioclase, augite, orthopyroxene, and ilmenite have developed coronas with garnet and amphibole between plagioclase and pyroxene. A late Scandian pegmatite dike has introduced aqueous fluid that produced bordering zones of hornblende-rich amphibolite after either gabbro or eclogite about 0.5 m thick.

The gabbro is interpreted to have intruded into the augen orthogneiss (see above). Whole-rocks and relict igneous augite give a Sm-Nd isochron of 1289±48 Ma (Mørk and Mearns, 1986). This is interpreted as the age of the intrusion and similar to the age of other olivine gabbros from the Western Gneiss Region (Mearns, 1984) (By a strange quirk of fate this was also Robinson's field locality 1289 in July 1993!)

18:05	**75**			Leave Stop 8.
		210.2	1.9	Return to junction near causeway. Continue south toward Longva. Bear left at Longva and follow inland road around south end of Flemsøya.
18:15	10	217.0	6.8	Parking by bus garage at Nogva. Walk down driveway to small wharf and then north to large outcrop.

STOP 3-9: (25 minutes) Nogva kyanite-zoisite eclogite with retrograde sapphirine and corundum. (Robinson and Terry)

There are two moderately large eclogite boudins in this coastal outcrop that are currently under study. They have compositional layering that is truncated by the boudin margins, and also lineation that is transverse to the normal northeast trend. There are two dominant kinds of layers. The first are striking bright orange garnet-rich layers with very fresh omphacite partially replaced by fine plagioclase+pyroxene symplectite. According to D. A. Carswell, pers. comm. 1996, such a color usually denotes a high Ca content in garnet. The other layers are lighter colored and dominated by plagioclase-pyroxene symplectite after omphacite and lesser garnet. However in different places they contain abundant quartz, zoisite, plagioclase (probably as replacement of zoisite), hornblende, biotite, rutile, biotite+feldspar symplectite after phengite (?), and kyanite. At one point there is a boudin neck zone containing crystals of zoisite up to about 8 cm long. Commonly surrounding kyanite or replacing it completely are symplectites involving calcic plagioclase and one or two of the phases sapphirine (a very pale green variety), corundum, or spinel. Textural and rimming relationships suggest a variety of reactions indicative of decompression under relatively high temperature conditions. Locally secondary calcic pyroxene is concentrated as a rim between quartz and pyroxene-plagioclase symplectite. The latter as well as garnet is commonly replaced partially by hornblende, but some samples have no hornblende. Large zoisite grains may contain plagioclase or zoisite-plagioclase symplectite and may be a partial result of the reaction quartz + kyanite + zoisite = anorthite. The symplectic rims on kyanite denote decompression reactions between kyanite and omphacite producing calcic plagioclase plus one or more of the aluminous phases sapphirine, corundum and spinel, dependent on the local Fe/Mg ratio. Although we have not found any completely fresh kyanite eclogite in this outcrop, a boudin on nearby Fjørtoft contains a completely fresh core, with no symplectite and with only traces of secondary plagioclase, showing all mutual contacts among the phases garnet, omphacite, zoisite, kyanite, quartz, hornblende, pale brown biotite and rutile. The coexistense of quartz, kyanite and zoisite indicate the instability of anorthite and minimum pressure of about 11 kbar at an assumed temperature of 700°C (Harley and Carswell, 1990)

18:40	**25**	-	-	Leave STOP 9 and follow coast road back around south end of Flemsøya.
18:45	5	222.4	5.4	Arrive Sjøbuda Restaurant and dinner.
20:10	**85**			Leave Sjøbuda.
-	-	225.6	3.2	Back to Flem Junction.
-	-	227.6	2.0	East end of Ulla Bridge and Austnes.
20:25	15	235.2	7.6	Arrive Austnes Ferry.
20:30	**5**			**Back** onto ferry at Austnes for trip to Løvsøya (Kjerstad).
20:45	**15**			Leave ferry at Løvsøya (Kjerstad).
		235.6	0.4	Turn right on main road above ferry pier toward Hellevik.
20:50	5	237.0	1.4	Pass by Lepsøya Misjonsenter, our overnight location. Continue for 2.6 km drive over plateau and down to Hellevik.
20:54	4	239.6	2.6	Small parking place before driveway to the big lighthouse.

STOP 3-10: (45 minutes) Isoclinal infolds of Blåhø and Sætra Nappes in "sausage rock" basement. (Robinson and Terry) (See Fig. 3.9)

The pavement exposure at Hellevik gives a superb taste of the geology of the central belt of Nordøyane (Fig. 3.9). The basement here is gray gneiss with amphibolite boudins interpreted as mafic dikes ("gray sausage rock"). The dominant cover nappe unit is the Blåhø Nappe dominated by mica schist and garnet amphibolite which occurs in three isoclinal synclinal belts on Lepsøya, of which we will see the northern two. The southern schist belt is in direct contact with eclogite-bearing basement of the southern belt. At the north margin of the northern Blåhø belt there is a layer of Sætra quartzite and amphibolite about 1 m thick, which has been traced all along the north end of Lepsøya to Bryggja. There it is exposed on west-facing cliffs in the core of a large south-verging recumbent refold, itself refolded by upright folds.

From the parking place walk east down a grassy path to the edge of the pavement. The first rock is kyanite-bearing schist in the middle belt of Blåhø. Walk north between large boulders a short distance to a high spot. This rusty schist consists of quartz, biotite, plagioclase, garnet, pleochroic gray gedrite and sulfides. It is considered to be a metamorphosed hydrothermally altered basalt (see Stop 4-6). Walk a few meters north to contact between amphibolite and very narrow belt of basement, here usefully termed "schredded sausage rock". This belt and this rock extends all the way across the north end of Lepsøya. To the north the basement is in contact with the northern Blåhø belt. About half way across this schist-amphibolite belt there is an isoclinal infold of quartzite and amphibolite that we believe is a tight infold of the Sætra Nappe. There is a 10 cm bed of marble along the south contact, as is common elsewhere in the region (see Stops 4-3 and 4-4). At the north edge of the Blåhø belt there is about 1m of folded quartzite-amphibolite and then more "schredded sausage rock". A dip slope in this quartzite forms the south wall of the low bluff on which the small lighthouse is located. Traverse northwestward through the zone of schredded sausage rock to more substantial sausage rock. Here one gets the idea that the mafic layers may be dikes though the evidence is much weaker than in an outcrop on Oterøya (see Stop 4-7). If one walks south on the east side of the small lighthouse there is a pavement exposure in the middle of an area of pools and grass where one can see the Sætra overlying basement in a series of late west-plunging open folds. Here the Sætra has a bed of glassy quartzite 40 cm thick. From this point one may walk direct to the parking place in boggy ground or retrace the route around the point. With luck we will see the sun dip below the waves of the open Atlantic!!

21:39	**45**			Leave Stop 10 and return toward Kjerstad.
21.43	4	242.2	2.6	Turn left to Misjonsenter (Prestegård) for overnight. Unload baggage and select sleeping location in one of five bunk rooms in the main building or one of three in the small cabin (alcohol consumption permitted here only).

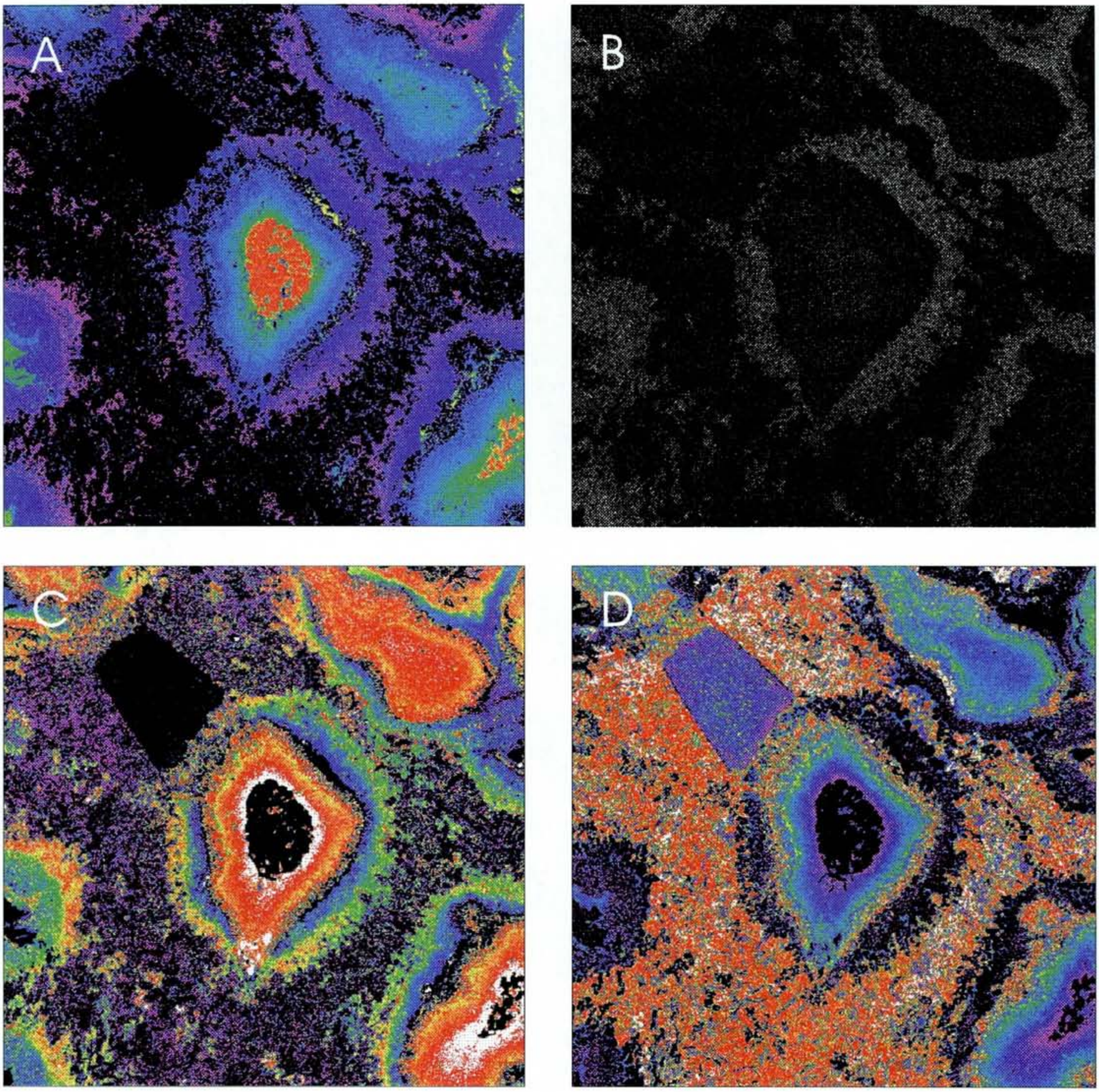

Fig. 3.8. Electron probe scanned element images of transitional olivine corona gabbro from Flem, Stop 3-8. The colorscheme relates directly to element abundance from abundant (white or red) to scarce or absent (violet or black). Relict igneous phases as well as metamorphic minerals are preserved in this transitional stage as studied by Mørk (1985). The dominant feature in the center is a former igneous olivine, now completely replaced by orthopyroxene, rimmed by clinopyroxene and finally by garnet against matrix plagioclase The four elements which were scanned automatically and simultaneously in one overnight run and processed by Dr. Peter T. Panish at the University of Massachusetts are: Mg - Most abundant in orthopyroxene (red) , then in zoned clinopyroxene which is most magnesian toward orthopyroxene (green) and less magnesian outward (blue), then in zoned garnet which is most magnesian toward clinopyroxene (dark blue) and less magnesian outward (violet). The high Mg phase (yelow along the garnet-clinopyroxene boundary is not yet identified. Mn - Present in metamorphic garnet, also detectable in orthopyroxene. Ca - Most abundant in inner edge of clinopyroxene(white)and decreasing irregularly outward (reds and yellows), also present in garnet, lowest (blue) against clinopyroxene and increasing outward (green - yellow-red) against plagioclase (violet), and absent (black in orthopyroxene and orthoclase in upper left. Na - Most abundant in plagioclase (red), strong zoning in clinopyroxene from low (violet) through intermediate (blue, green) to high (yellow, red) against garnet, small amount (blue, violet) in orthoclase, absent in garnet and orthopyroxene (black). The reality of growth in a chemical potential gradient produced by disequilibrium between olivine and plagioclase, with production of jadeite-bearing clinopyroxene is illustrated. These scenes encapsulate the dominant story of the Western Gneiss Region: pre-Cambrian rock resisting reconstitution during Scandian high-pressure overprinting.

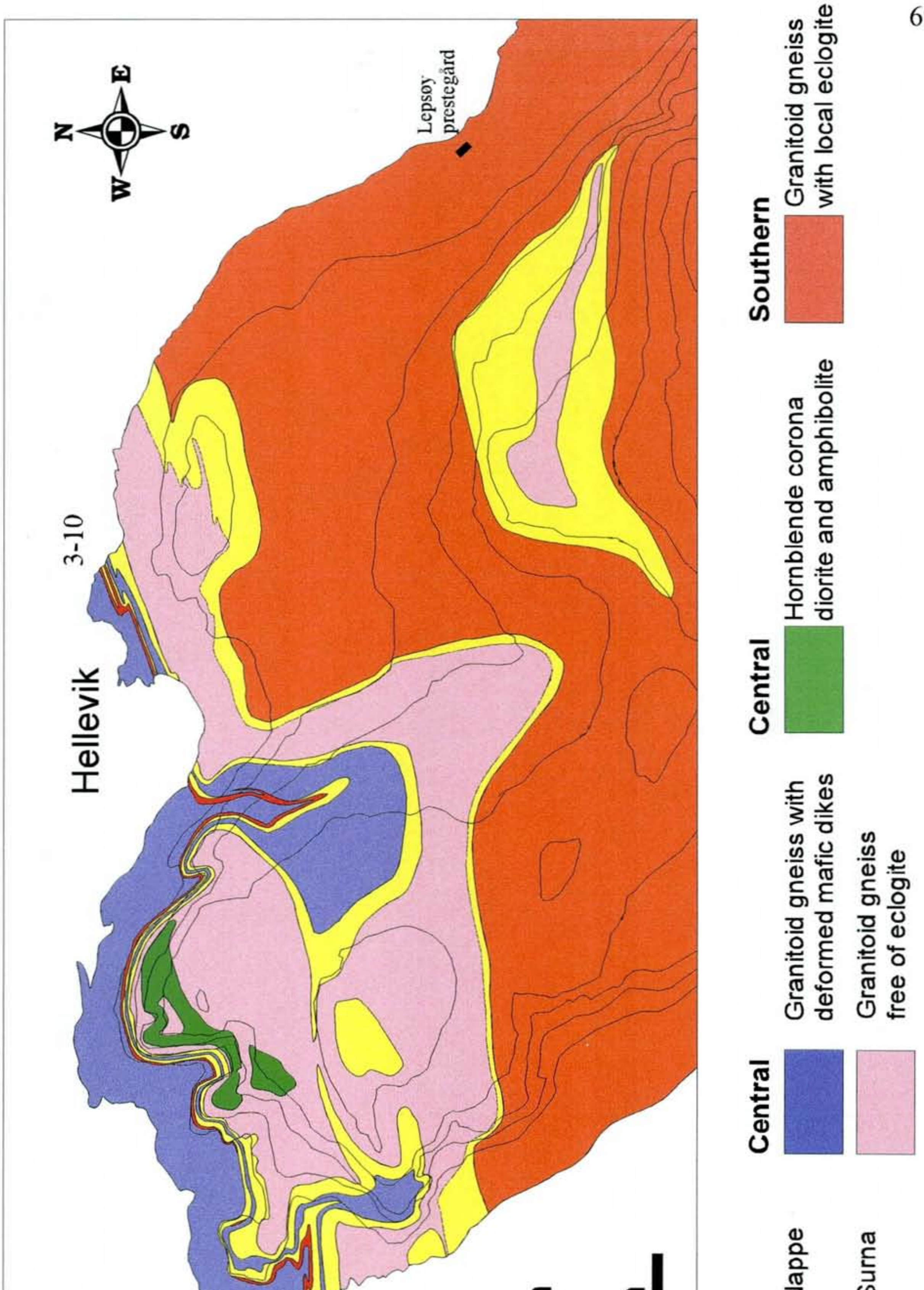

Fig. 3.9. Detailed geologic map of the northern part of Lepsøya, Nordøyane prepared by Michael P. Terry, Stop 3-10.

INTRODUCTION TO DAY 4 17/8/97

The day will begin with an early morning ferry ride from Lepsøya to the mainland (Fig. 3.2, 4.1). The first part of the day will be devoted to the features of Caledonide nappes on the south limb of the Moldefjord syncline near Brattvåg. These will be compared to similar rocks seen on the morning of day 1 near Oppdal. Their structural and metamorphic relations with the underlying Proterozoic basement will be considered. After a ferry ride from Brattvåg to Dryna, some features of the geology of Midsund Kommune will be examined, including eclogite-free basement and Blåhø Nappe rocks along the south coast and then eclogites, garnet peridotite, and 1500 Ma. augen orthogneiss in basement in the northern part. Following the ferry Solhomen-Mordalvågen we will need to proceed quickly with only one outcrop through Molde, Batnfjordsøra, and the Krifast Bridges to catch the ferry Kanestraum-Halsa before the final run, with one additional outcrop, into Trondheim, .

Tectono-stratigraphic Units in the Moldefjord Syncline near Brattvåg

A sequence of seven tectono-stratigraphic units was identified that corresponds very closely with units in Trollheimen and elsewhere in the central Caledonides, although some of the units observed elsewhere are absent.

Baltica basement - This basement consists of strongly deformed gneisses, gabbros, eclogites, amphibolites, and trace amounts of supracrustal rocks, derived from Proterozoic intrusions with very minor amounts of host rock. Locally gabbro boudins preserve primary igneous textures. The basement is locally separated into **lower basement** and **upper basement** by Åmotsdal Quartzite. By analogy with Trollheimen, the quartzite is probably unconformable on the lower basement and is overthrust by the upper basement. As in Trollheimen, eclogite is found in upper basement (see Stop 4-1), but not in lower basement.

Åmotsdal Quartzite - Feldspathic quartzites, locally hematitic and locally with feldspathic pebbles, exposed in an anticline in Vatnefjord and to the east. Locally up to 100 m thick, the quartzite has been mapped in areas where it is only 1 m thick (Robinson, 1997).

Risberget Nappe - This thrust nappe consists of augen gneiss and amphibolite that represent deformed middle Proterozoic rapakivi granite with subordinate gabbro, intruded by mafic dikes. Near Brattvåg the Risberget Nappe contains a distinctive mappable unit of amphibolite derived from gabbro in which thin dikes of rapakivi granite have been recognized. In a boudin near Skår the rapakivi granite is preserved in a totally undeformed state with large orthoclase phenocrysts rimmed by plagioclase (see Stop 4-2). Recognition of the Risberget Nappe is more difficult in the Moldefjord and Surnadal synclines than in eastern Trollheimen. In eastern Trollheimen the Risberget Nappe is consistently separated from upper basement by Åmotsdal Quartzite and other autochthonous or paraautochthonous supracrustal rocks that are absent in these western areas. Augen gneiss of similar character is a major component of the Baltica basement, especially to the north of the Moldefjord (Carswell & Harvey 1985) (see Stop 4-10) where it has yielded a U-Pb zircon age of 1508 Ma (Tucker et al., 1991), similar to the Rb-Sr whole rock age obtained by Krill at Oppdal (see stop 1-3) and to the U-Pb zircon age obtained on the porphyritic mangerite at Flatraket (see stop 2-12). In practice the basement augen gneiss is usually fine grained and the microcline phenocrysts are flattened and polycrystalline as a result of relatively homogeneous deformation, whereas the typical gneiss of the Risberget Nappe contains large coarsely crystalline phenocrysts in a micaceous matrix interspersed with zones of obviously mylonitic character. A recent development comes from the U-Pb zircon dating of augen gneisses in the Risberget and Tännäs Augen Gneiss Nappes (Handke at al., 1995) at nine different locations in Norway. Of these 5 yielded ages of 1650-1642 Ma., four yielded surprising ages of 1190-1180 Ma. including the rocks exposed at Skår (see Stop 3-2) and Oppdal (see Stop 1-3) and none yielded the "expected" age of 1500 Ma. The best argument that the Risberget unit is a nappe comes from its great lateral continuity and consistent stratigraphic position across the orogen from these areas to the Tännäs Augen Gneiss Nappe in Sweden (Krill and Röshoff 1981). The new ages lend further support to this interpretation.

Sætra Nappe - This nappe is characterized by strongly laminated pure to feldspathic biotite quartzite and amphibolite, locally garnetiferous, and locally eclogitic. These represent metamorphosed sandstone cut by diabase dikes corresponding to the Särv Nappe near the front of the orogen in Sweden. Though locally discontinuous, this key unit occurs throughout the belt, but is commonly no more than 10 meters thick. Near Brattvåg, the unit, especially its lower part, contains boudins of zoisite±phengite eclogite up to 10 m thick. Outcrop relationships demonstrate that the eclogite-facies metamorphism took place before the dike rocks where deformed into very thin amphibolites.

Blåhø Nappe - This nappe consists of porphyroblastic garnet-mica-feldspar schist, pyroxene-biotite schist, coarse gneissic garnet and pyroxene amphibolite, diopside calc-silicate rock, and pegmatite; interpreted as highly metamorphosed shales and volcanics. In the upper part of the Blåhø Nappe there is a bed of impure marble and calcareous schist about 6m thick separated from the Støren contact by 15m or less of mica-garnet schist. The position of marble near or at the top of the Blåhø Nappe is critical to several fold interpretations in the area west of Brattvåg. Commonly there are also thin impure marbles or calcareous impure quartzites at or near the base. In its best preserved portions, this nappe shows evidence of early high temperature metamorphism with extensive development of migmatites unlike anything in the other nappes. In this respect it corresponds to part of the Seve Nappe in Sweden. Migmatitic features are particularly well shown in the lower part of the Blåhø-Surna Nappe, where there is a lesser amount of retrograde hydration. R. D. Tucker has obtained U-Pb zircon ages from two pegmatites in similar rocks near

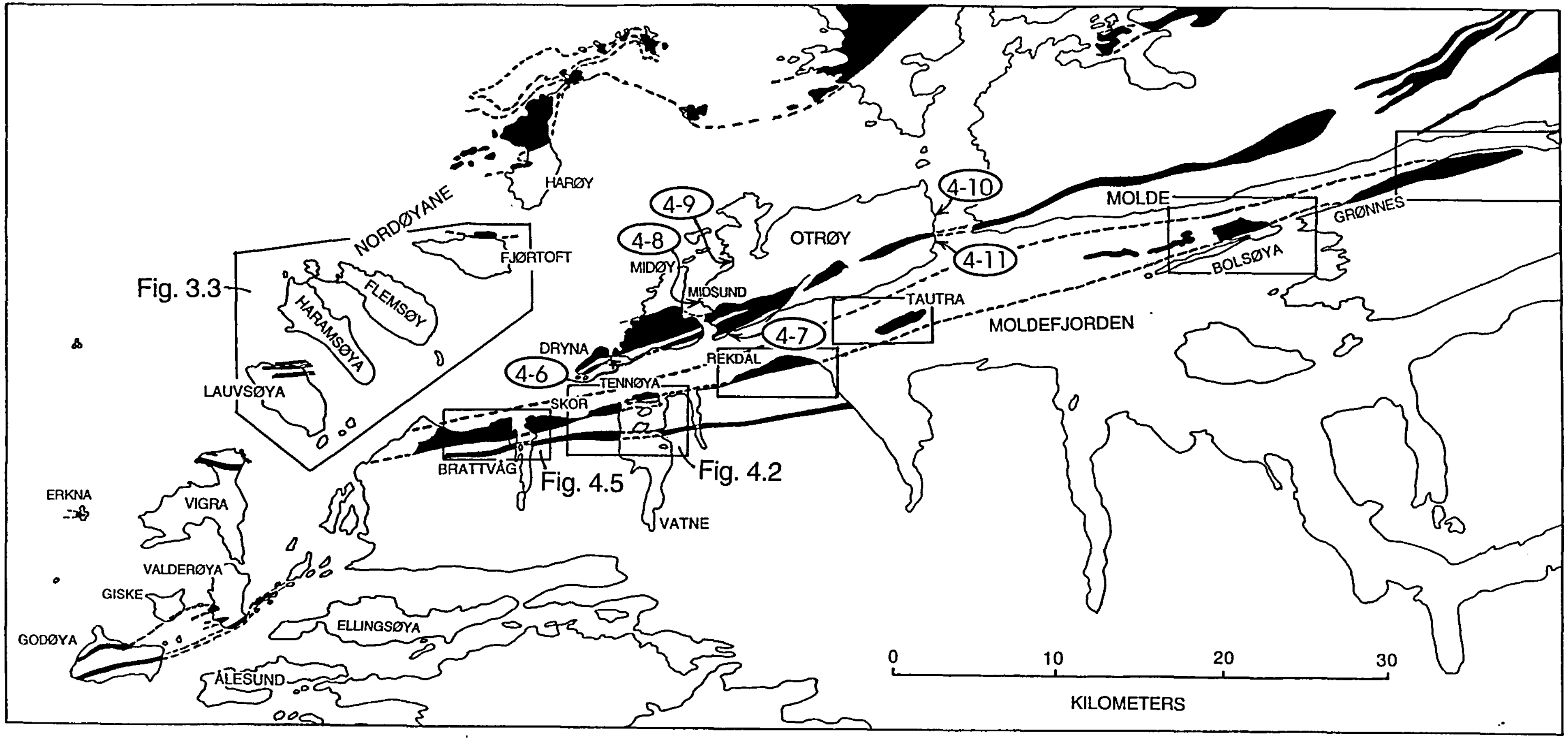

Fig. 4.1. Geologic index map of the Moldefjord region modified from Robinson (1995) showing the Moldefjord syncline and other areas of probable Caledonide nappes infolded into Baltica basement. Insets show areas covered in detailed maps. Sources of map information include Bryhni et al. (1989, 1990a, 1990b), Hernes (1955, 1956b), Krill (1987), Mørk (1989a, 1989b) and the present work.

Orkanger that cut an older metamorphic fabric but are themselves deformed in the late stages. These have yielded ages of 430 and 422.7 Ma, considerably older than pegmatites in adjacent basement (see Guidebook for Trip B-1, this conference).

Støren Nappe - This is composed of strongly laminated, fine-grained epidote amphibolite derived from metamorphosed basaltic volcanics, minor felsic schist derived from felsic volcanics with thin interbeds of fine-grained garnet-biotite-muscovite-tourmaline schist, and subordinate biotite-garnet-tourmaline schist representing intercalated sediments. Major layers of very coarse amphibolite and hornblendite, locally with relict cumulate textures, are metamorphosed massive to layered gabbro. There is also a lens of talc-anthophyllite-carbonate schist. These mafic and ultramafic rocks may be dismembered fragments of ophiolite such as those found in the Støren Nappe near Trondheim.

General Structure

The tectono-stratigraphic units are exposed in two tight to isoclinal synclines overturned to the north-northwest, with subhorizontal axes. The major Moldefjord syncline (Fig. 4.1) has been traced for 70 km and the narrower Helleneset syncline has so far been traced for 25 km. The structure east of Molde is a syncline, not fault controlled. This is shown by well exposed overturned north-facing sequences on Bolsøya and other islands near Molde, and on Grønnes Peninsula, and by less well exposed right-side-up south-facing sequences on the north side of Grønnes Peninsula and in the Fannefjord Tunnel. The west-plunging synclinal hinge is mapped on the Grønnes Peninsula near Kortgarden. Near Brattvåg, on the south limb, there are three tightly folded north-facing sequences separated by two fine-grained mylonite zones. Parts of the south limb are well exposed east of Brattvåg near Vatnefjord, near Rekdal, and on Tautra. The Helleneset syncline south of the Moldefjord syncline has been traced for 25 km from west of Brattvåg to southeast of Rekdal. Its limbs and axial surface have been refolded about late open folds with horizontal or gently south-dipping axial surfaces. Between these synclines is a complex anticline outlined by a thick unit of Åmotsdal feldspathic quartzite separating layers of lower and upper basement near Vatnefjorden and in mountains to the east (Robinson, 1997).

Sequence of Structural Development

Although various nappes probably contain older structural features the earliest recognizable event was the progressive development and emplacement of thrust nappes for several hundred km onto the Baltica margin in the **early part of the Scandian** orogeny. We believe (Robinson et al., 1996; Tucker at al., 1997, and in preparation; Robinson et al., 1997) that this carried rocks of the Storen Nappe far onto the then cool Baltica foreland, while contemporaneously there was subduction of the Baltica margin with its heating and high pressure metamorphism, locally to eclogite facies, producing early transverse top-to-SE shear fabrics (see Stop 3-6), new metamorphic zircon at 401±2 Ma, and progressive Pb loss in Proterozoic igneous sphene. The **middle part of the Scandian** involved basement imbrication at deep levels, with contemporaneous extensional collapse at higher levels. Features of the middle Scandian included the following: Thrust imbrication of the subducted heated basement slab or slabs onto cooler basement toward the foreland. We suggest this accounts for the repetition of basements separated by quartzite in Trollheimen and in the Rekdakshesten anticline, where eclogite is found only in the upper basement. Contemporaneously there was backsliding and extensional emplacement of the cool high level nappes against the cooling basement. Cooling of the basement slab or slabs from above and below abruptly terminated the short period of Pb loss in basement sphene at 395±2 Ma, while sphenes in overlying Ordovician igneous rocks of the Støren Nappe were never warm enough to be reset. This first extensional collapse was the main event that brought deep metamorphic rocks relatively close to the surface. The **late Scandian** was characterized by further extensional deformation in a field of sinistral transtension. Early in the late Scandian there was development of northeast-trending ductile folds and stretching lineations within the previously thrust and extensionally juxtaposed package. During this deformation subhorizontal layers developed top-west shear features, whereas steep to overturned layers developed predominantly sinistral shear features that pervade the region. The later part of the late Scandian brought ductilely deformed rocks into contact with more brittle rocks associated with Devonian sandstone basins deposited in the period 395-392 Ma.

Note in the above scenario that we show no place for the eclogite-facies metamorphism of the Sætra Nappe near Brattvåg, nor for the early high T metamorphism of the Blåhø Nappe. This is partly because we do not know the ages of these metamorphisms. The eclogites in the Sætra Nappe bear a very close resemblance to eclogites in the Seve Nappe of Arctic Sweden (Andréasson et al., 1985), also in late Proterozoic sandstone, what were metamorphosed at about 500 Ma, (Mørk et al., 1988) in an uncertain setting. The high grade metamorphism and deformation of the Blåhø nappes seems to have begun earlier but terminated at about the same time as intrusion of pegmatites dated at 430 and 422.7 Ma near Orkanger (see Trip B-1, this meeting). These events might be ascribed to subduction of rocks on the Baltica margin that came earlier than the subduction of the presently exposed basement.

How do the details of the geology near Brattvåg and on Nordøyane fit into this picture? We suggest that most of the contacts between nappes and between nappes and basement are original thrust contacts on which there has been a major amount of extensional backsliding and thinning during the middle Scandian. Once these contacts had been developed they were folded, first into a series of tight to recumbent anticlines and synclines, and then in a series of more open folds with northeast-trending axes, strong lineation, and sinistral and top-west shear features. At this point it is not easy to tell whether the earliest isoclinal folds were produced during late stages of the first extensional collapse or early stages of the sinistral transtension (recall features at Stop 3-7). This ductile transtension gradually evolved into a more focussed and more brittle deformation which produced the major sinistral mylonite zones, including those at Brattvåg and at Åkre on Nordoyane. It seems likely that these were forming at the same time as the extensional emplacement of the Devonian basins.

ROAD LOG

Total Time	Time since prev.	Total Km	Km since prev.	
8:00	-	0.0	-	Lepsøya Misjonsenter. Depart with all possessions for ferry.
8:05	5	1.8	1.8	Kjerstad ferry terminal.
8:15	**10**	-	-	Drive onto ferry for Skjeltene.
8:35	**20**	-	-	Leave ferry at Skjeltene.
8:36	1	2.0	0.2	Turn left on Route 659 toward Brattvåg.
8:38	2	5.7	3.7	Hildre Kyrke and coastal light.
8:44	6	11.9	6.2	Exit for Brattvåg ferry (to Dryna) Stay straight through Brattvåg.
8:51	7	16.1	4.2	Junction near base of mountain. Turn left for Hellandhamn.
8:56	5	22.2	6.1	Big curve at Hellandhamn. Direction of road changes from northward to eastward.
9:01	5	27.7	5.5	Park by entrance to private driveway to Baraldsnes. Do not block driveway.

STOP 4-1: (45 minutes) Traverse from Baltica basement with eclogite across Risberget and Sætra Nappes to Blåhø Nappe, south limb of Moldefjord syncline. (See Figure 4.2) Walk northeast on Baraldsnes Road then right (east) to prominent mound 75m east of road. Pavement exposures of biotite eclogite with 4 cm omphacite porphyroblasts, now mostly plagioclase - Ca-pyroxene symplectite. This eclogite also contains hornblende-plagioclase partially replacing garnet, and abundant plates of phengite rimmed by a coarse intergrowth of biotite and feldspar, the classic dehydration product of phengite. No probe analyses yet completed.

Walk north to road and further northeast observing typical stripey gneiss of Baltica basement with thin amphibolite layers, eventually reaching sharp contact with base of Risberget augen gneiss. Contact with basement is perfectly exposed on southeast side of road. Leave road and walk west across pavement exposures of Risberget augen gneiss to contact with gabbro/amphibolite, observing abundant west plunging folds that are sympathetic to the Baraldnes syncline. Cross grassy area near west fence of Baraldsnes farm with exposures of Risberget amphibolite and turn northwest toward crest of highest ridge. Observe upper augen gneiss member of Risberget Nappe just below ridge crest, then strongly sheared feldspathic gneiss in contact with interlayered impure quartzite-amphibolite-eclogite of the Sætra Nappe. At ridge crest are two eclogite boudins. Peeled off area displays folds in quartzite that apparently nucleated on walls of mafic dikes, now eclogite. Just west of crest are outcrops of Blåhø mica schist and amphibolite that lies close to the hinge of the Baraldsnes syncline. To the northeast as sea level it is possible to see large outcrops of the Risberget Nappe, particularly the gabbro/amphibolite member, on the northeast limb of the Baraldsnes syncline.

The eclogites found in the Sætra Nappe, as well as one found in the Risberget Nappe, have the following characteristics (Robinson and Panish, 1994). (1) All of the former omphacite is now a fine-grained reaction symplectite of pyroxene plus sodic plagioclase An_{9-17} produced by unloading. The most sodic pyroxene in the symplectites, clearly modified from the original omphacite has the composition indicating a minimum 15% jadeite component (2) Chemical zoning in the eclogite garnets shows high Mn cores and low Mn rims suggesting prograde eclogite-facies growth zoning with only minimal retrograde resorption. This is also demonstrated by abundant hornblende and zoisite inclusions in garnet, whereas relict omphacite occurs only in the matrix. Garnets in several samples show complex growth zoning with an abrupt increase in grossular content from $Gr_{17}Py_{18}Sp_{3}Alm_{61}$ to $Gr_{31}Py_{15}Sp_{2}Alm_{52}$ all with progressively decreasing spessartine and increasing ratio of Mg/(Mg+Fe). Preserved prograde growth zoning suggests these cover eclogites probably never reached the temperatures of 750°C and expected high diffusion rates reported for basement eclogites north of Moldefjord (Krogh, 1980; Griffin and Carswell, 1985; Mørk, 1986), a fact to be included in any tectonic reconstruction. 3) These eclogites contain relict coarse phengite with Si=3.25 comparable to phengites in eclogites from elsewhere in Norway. Phengite is always rimmed by biotite, even where included in garnet. Detailed study of a garnet-phengite contact zone shows the biotite formed by an important fluid-conservative reaction: garnet + phengite = biotite + more anorthitic plagioclase, that can be calibrated for quantitative estimates of pressure. A critical problem in reconstructing the tectonic evolution of these eclogites and their enclosing rocks is to learn their age, but that will not be easy.

Return to cars by same route.

9:46	**45**	-	-	Leave Stop 1, return west toward Brattvåg.
9:49	3	28.6	0.9	Parking on gravel patch to left. Cross into field on right and walk northwest to pavement exposures.

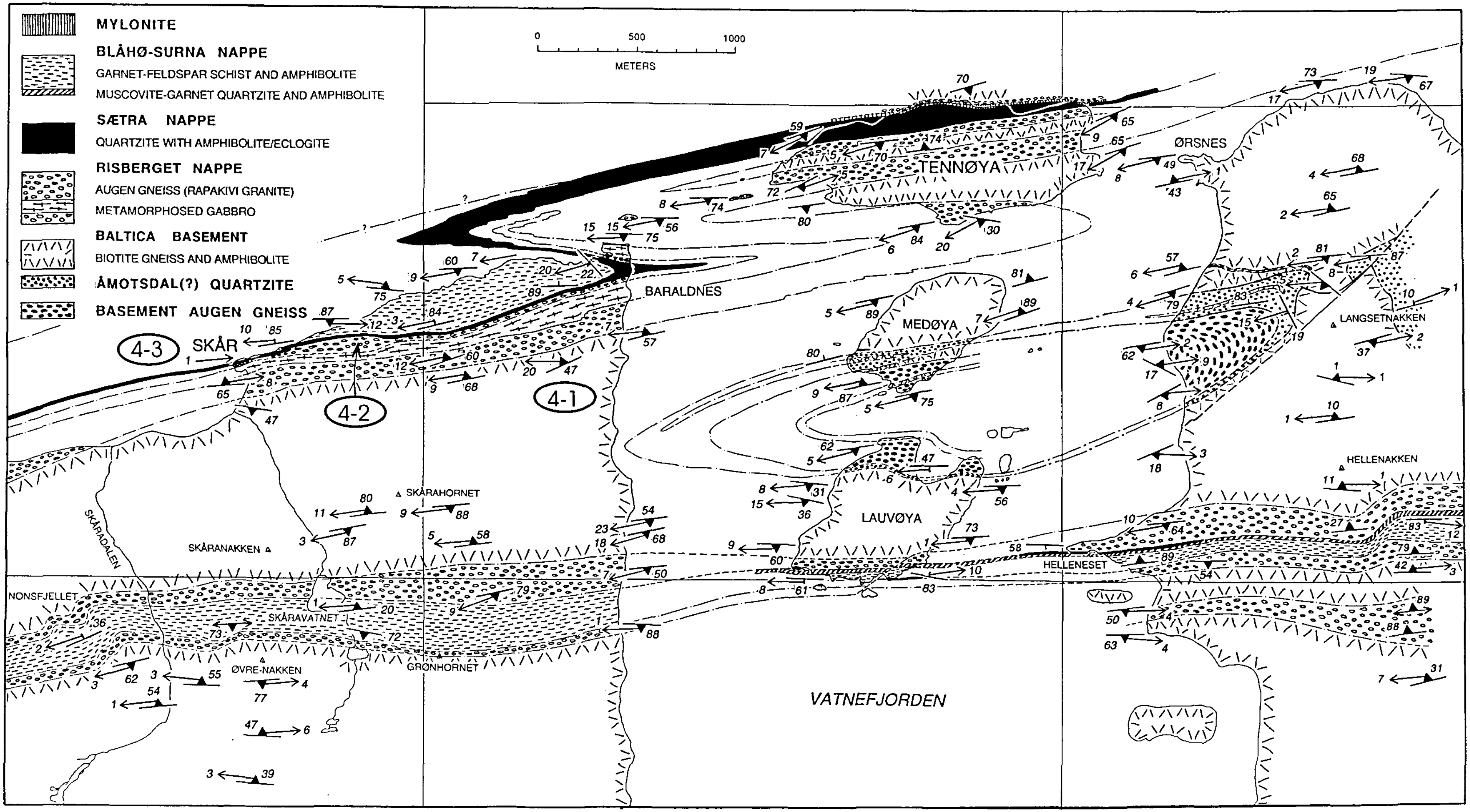

Fig. 4.2. Geologic map of Skår-Baraldnes-Tennøya area from Robinson (1995) with locations of Stops 4-1, 4-2, and 4-3. The map shows the critical exposure at Skår, the synclinal hinge at Baraldnes, and the eclogite-bearing Sætra quartzites on the north coast of Tennøya, all on the south limb of the Moldefjord syncline. It also shows the Helleneset syncline at Helleneset, on the south coast of Lauvøya, and in the mountains to east and west. Between these, in the Rekdalshesten anticline, Åmotsdal quartzites are exposed in a zone between lower and upper layers of Baltica basement on Lauvøya, Medøya and Langsetnakken. Contacts: solid - accurately located (contacts of Sætra Nappe are solid by graphical necessity), dashed - approximately located, dash-dot - location inferred.

STOP 4-2: (20 minutes) Pavement outcrops of Rapakivi granite, augen gneiss. (See Fig. 4.2).

Traverse begins in the gabbro/amphibolite member of the Risberget Nappe and proceeds north into strongly sheared augen gneiss of the upper member the same as in the outcrop at Skår. The outcrop exposes 63.8 meters of this upper augen gneiss as compared to the total thickness of 15 m at Skår, as well as 7.6 m of the overlying Sætra Nappe with eclogite boudins. Follow foliation northwest and then walk southwest onto large red pavement. Within these exposures there is a lens, 24.3 m thick, of completely undeformed rapakivi granite with round pale red-brown orthoclase phenocrysts with preserved internal igneous zoning and with plagioclase mantles. Such a preservation in granitoid rocks is unusual across the Caledonides in the Risberget and Tännäs Nappes generally (Krill and Röshoff 1981), and is particularly surprising for this region where there have been many intense deformations. Although the rapakivi granite is undeformed, it is metamorphosed, with fine-grained matrix garnet, clinopyroxene and biotite. In thin section, the white "wiborgite" rims are composed of twinned plagioclase crammed with fine white needles that may be zoisite. Detailed petrographic examination of this rock will require electron microscopy. Does the matrix assemblage reflect an old granulite facies metamorphism as implied at Flatraket (see Stop 2-12) or a partial eclogite-facies overprint reflected within the adjacent Sætra Nappe?

Observe the extreme strain gradient with evidence of sinistral shear at the north edge of the granite boudin. You may also wish to walk to the north edge of the outcrops to see retrograded eclogite boudins in the lower part of the Sætra Nappe.

Return to vehicles by the same route.

10:09	**20**			Leave Stop 2. Continue west to Skår.
10:11	2	29.2	0.6	Very tight parking on both sides. Do not block driveways.

STOP 4-3: (40 minutes) Outcrop at Verpholmen, Skår. Upper part of the Risberget Nappe, the entire Sætra Nappe, and base of the Blåhø-Surna Nappe in continuous exposure. (See Fig. 4.2)

The beach outcrop in the bay at Skår, lies in the lower part of the Risberget augen gneiss just north of the poorly exposed basement contact. The outcrop surface is eroded perpendicular to steep foliation and parallel to subhorizontal mineral lineation, and shows asymmetric tails on rounded relict orthoclase phenocrysts indicating sinistral shear parallel to the lineation. Thin and less common thick amphibolite layers are interpreted as deformed metamorphosed diabase dikes, possibly like those in the Sætra Nappe. In the high mountain valley directly east of Skår, a single boudin of fine-grained eclogite has been found on the south limb of the Helleneset syncline similar to the eclogites in the Sætra Nappe.

The southern part of the main outcrop consists of 44m of massive amphibolite, interpreted as metamorphosed gabbro, part of a continuous layer that was seen previously at Stops 4-1 and 4-2. This is succeeded northward by an additional 15m of Risberget rocks of which 10m near the base is rather massive phenocryst-rich augen gneiss in boudins in which the shear-elongated phenocrysts show strongly developed steep foliation and a lineation plunging 15° west.. This is the layer from which Handke et al. (1995) obtained a U-Pb zircon age indicative of igneous crystallization at 1190.3±2.8 Ma (Fig. 4.3). The upper 5m is fine-grained mylonitic gneiss with a variable abundance of relict phenocrysts and thin dark streaks that may represent mylonitized mafic dikes. North of the Risberget is 9-10m of the Sætra Nappe, of which the lower 7.5m is metamorphosed feldspathic sandstone with minor amphibolite and with typical subhorizontal folds. This lower part of the Saetra Nappe is typically more feldspathic than the upper part and is typically the host for retrograded eclogite boudins, two of which are exposed here, less than 1m north of the Risberget contact. The upper 1.5m of the Sætra is cleaner, more quartz-rich metamorphosed sandstone with more abundant amphibolite laminae near the base of the Blåhø Nappe. The base of the Blåhø Nappe against the Sætra consists of garnet-mica schist and amphibolite, some in boudins. Exactly on the contact in an eroded groove is 5-15 cm of calcite marble and diopside calc-silicate that commonly occurs in this position. A second calcareous layer is a thin, pitted, impure marble north of amphibolite boudins about 1.5 m above the contact.

Walk a short distance north to a "nest" of late steeply plunging sinistral folds that deform earlier subhorizontal folds and lineations. This exposure "freezes" a moment in the continuous process of fold development in a regime of extreme sinistral transtension. From the outer end of the point at Skår under good lighting conditions view the cliff of Skåradalen (Fig. 4.4) with its exposure of the refolded Helleneset Syncline. Return to vehicles by walking back around the point.

10:51	**40**	-	-	Leave Stop 3. Drive west to Hellandhamn.
10:55	4	33.0	3.8	Big curve at Hellandhamn. Direction of road changes from westward to southward.
10:56	1	33.6	0.6	Turn sharp right on paved road by mail boxes. Drive north on coast.
10:57	1	34.3	0.7	Park in lot for public beach. Walk south along shore over outcrops of Blåhø Nappe to low pavement outcrop of Sætra Nappe.

STOP 4-4: (30 minutes) Helland Traverse: Sætra, Blåhø and Støren Nappes and southern ultramylonite belt. (See Fig. 4.5)

The strata in the northern part of the figure belong to the main steep to northward overturned south limb of the Moldefjord syncline, divided into three repeated sequences by two zones of ultramylonite formed during sinistral shearing. The sequences are complicated by local subhorizontal folds that are *en echelon* to the mylonite zones and truncated by them. The southern sequence contains all units from basement up to Støren, including the marble-bearing upper part of the Blåhø Nappe. The narrow middle sequence between the mylonites consists only of Sætra, Blåhø-

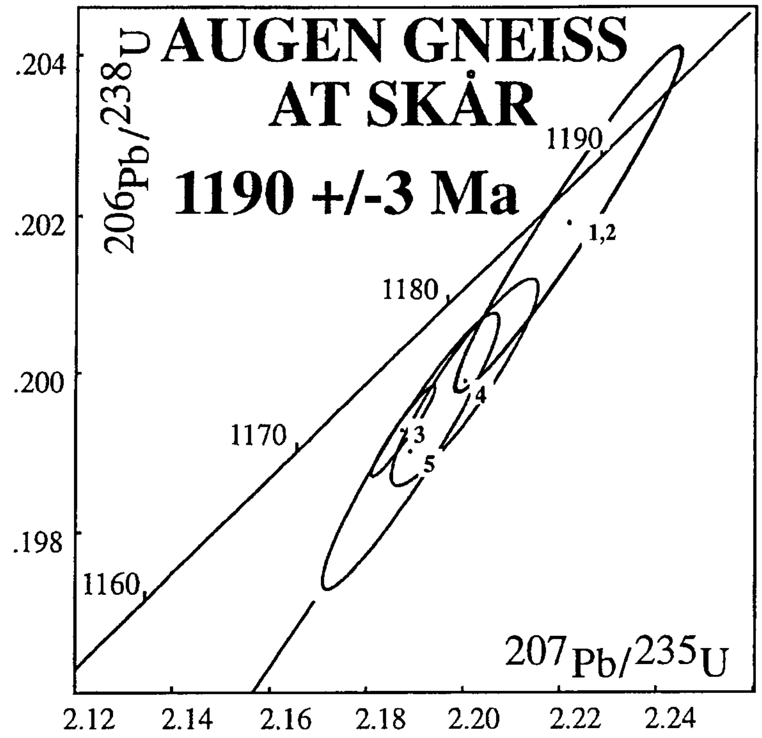

Fig. 4.3. Concordia diagram showing zircon U-Pb isotopic ratios and igneous crystallization age determined for augen gneiss in the upper part of the Risberget Nappe exposed in the outcrop at Verpholmen point (Stop 4-3) Skår, by R. D. Tucker.

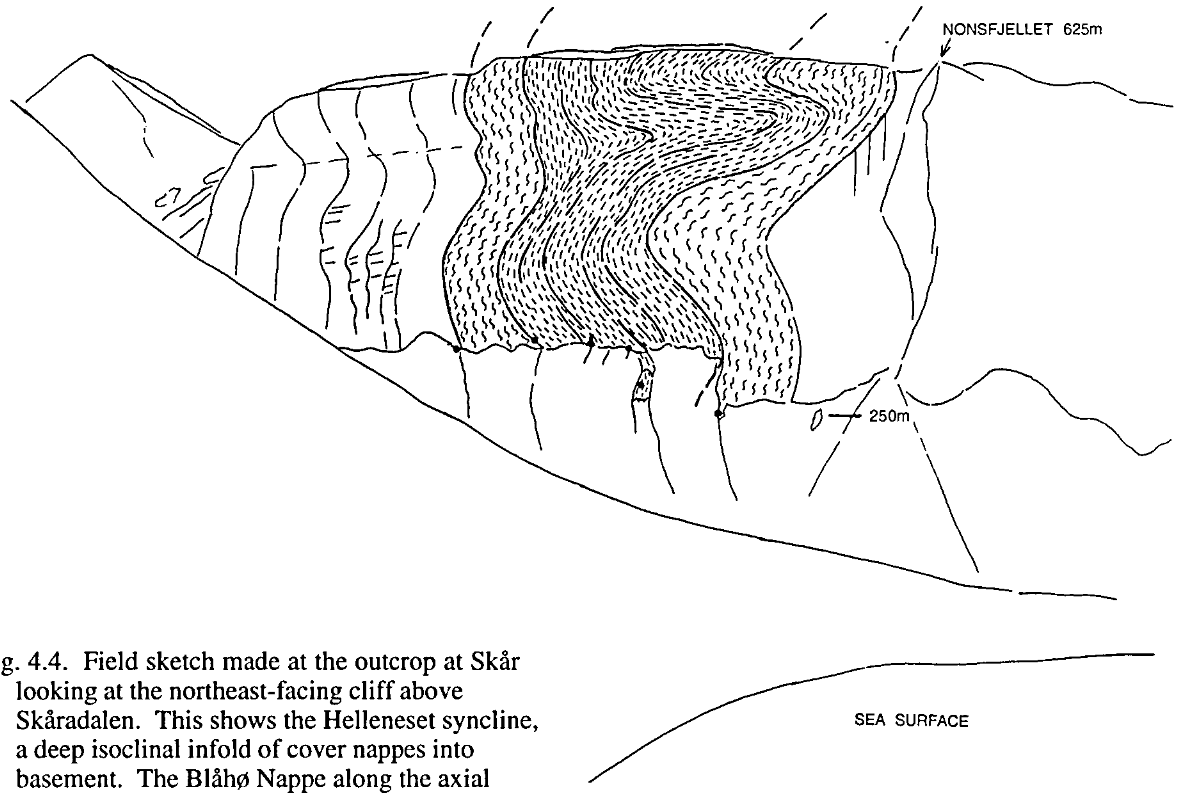

Fig. 4.4. Field sketch made at the outcrop at Skår looking at the northeast-facing cliff above Skåradalen. This shows the Helleneset syncline, a deep isoclinal infold of cover nappes into basement. The Blåhø Nappe along the axial surface of the fold is flanked by the Risberget Nappe. Elsewhere a very thin Sætra Nappe is present between. The axial surface of the syncline is refolded about sub-horizontal axes and axial surfaces. Dots indicate locations that could be reached for structural measurements at the top of steep talus below the cliff.

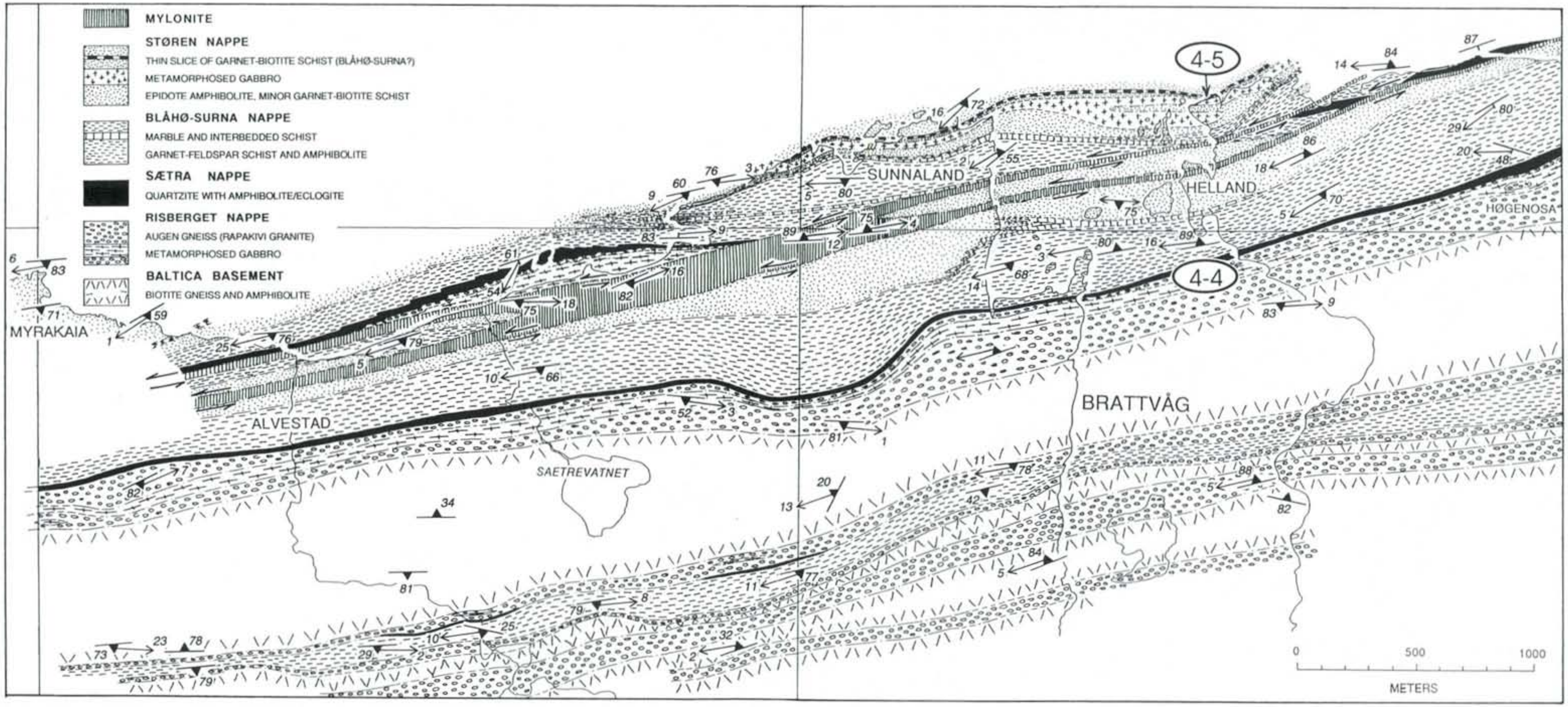

Fig. 4.5. Geologic map of the south limb of the Moldefjord syncline near Brattvåg, including the narrow Helleneset syncline to the south. From Robinson (1995). Shows locations of Stops 4-4 and 4-5. Illustrates three north-facing tectono-stratigraphic sequences separated by mylonite zones. Contacts: solid - accurately located (contacts of Sætra Nappe are solid by graphical necessity), dashed - approximately located, dash-dot - location inferred.

Surna, and Støren. The northern sequence begins with sheared gabbro in the middle of the Risberget Nappe and extends well up into the Støren Nappe. In this traverse we will begin with a pavement exposure of the Sætra Nappe and walk across the Blåhø and Støren Nappes to the southern ultramylonite belt.

From the parking lot walk south along the coast to pavement exposure of Sætra Nappe consisting of laminated quartzite and amphibolite. The quartz-rich quartzite is typical of the uppermost meter of the Sætra nappe close to the Blåhø-Surna contact. A thin layer of marble is exposed at the north edge of the outcrop and is typical of the contact region between the Sætra and Blåhø nappes.

Walk back north past public beach to large exposures on peninsula. These are Blåhø mica-garnet schist and amphibolite with pegmatitic layers produced by intrusion and/or partial melting. This is typical of the lower part of this nappe where there is abundant shearing, but less late metamorphic reconstitution than close to the Støren Nappe.

Continue north along steep rock slope to complex contact with epidote amphibolites of the Støren Nappe. The last exposed parts of the Blåhø Nappe consist of mica schist and marble. The complexity of this folded contact zone is illustrated by the following measured section beginning with the first marble in the continuous outcrop from the peninsula: marble 1.8m, garnet schist 4.5 m, low-grade amphibolite 6m, schist 0.9m, marble with wild folds 2.4m, mica schist 4.5m, impure marble 1.5m, low-grade amphibolite10.6m, garnet schist 3.6m and then low-grade amphibolite 7.6m to end of outcrop. The islet to the northwest appears to be all low-grade amphibolite of the Støren Nappe.

There is a gap in the outcrop of about 100 meters. Then walk east through industrial area with an artificial exposure of the full 27 m width of the southern belt of ultramylonite. Ultramylonite protoliths are impossible to determine without thin sections. Rock south of the ultramylonite is low grade amphibolite. The rock to the north appears to be retrograded Blåhø mica schist and impure marble for about 5 m, then also low grade amphibolite.

From this point walk south along industrail road back toward cars. At road junction walk northeast to another large man-made exposure showing Støren amphibolite to the south in contact with ultramylonite to the north with folds in mylonitic foliation. Elsewhere mylonites show tubular folds.

Drivers will pick up participants at this location for the drive to Stop 5.

11:27	**30**	-	-	Leave Stop 4.Drive north on narrow road.
11:28	1	34.7	0.4	Stop near east end of jetty and find parking. Walk short distance east along north-facing coast.

STOP 4-5: (20 minutes) Layered cumulate gabbro and epidote amphibolite of the Støren Nappe north of ultramylonite belts. (See Fig. 4.5)

The lower part of the Støren Nappe near Brattvåg is dominated by fine-grained hornblende-epidote amphibolites, and these are overlain by mappable units of massive to layered hornblende gabbros locally with what appears to be relict cumulate layering. At one point 200 m east of Stop 5 there is a 1 m-thick layer of green amphibole that is probably a metamorphosed pyroxenite cumulate layer in the gabbro. These features suggest the possibility that these gabbros represent sheared fragments of an ophiolite like the Løkken and Vassfjell units of the Støren Nappe near Trondheim (Grenne 1989a, 1989b). They also closely resemble in character and setting the gabbro slices studied by Boyd (1983) near Narvik, which he considers, on lithic and geochemical grounds, to be sheared fragments of the Lyngen Ophiolite. At Myrakaia within Støren amphibolites there is a narrow and poorly exposed lens of talc-anthophyllite-carbonate rock that would agree with the ophiolite hypothesis. North of the gabbro on the coasts north of Helland and Sunnaland there is an extremely narrow belt of garnet-mica schist. In coastal exposures northwest of Sunnaland this narrow belt contains garnets up to 3 cm in diameter, relict migmatite features, and calcareous schists, all suggesting that this is a very thin tectonic slice of Blåhø rocks.

From parking at end of jetty walk east across boulders to pavement exposure of layered but strongly sheared metamorphosed gabbro. Northeast beyond this is typical Støren epidote amphibolite, commonly with minor calcite. The extreme northernmost outcrops, accessible mainly at low tide, contain the narrow belt of garnet-mica schist interpreted as an early thrust slice of Blåhø rocks.

11:48	**20**	-	-	Leave Stop 5. Drive south.
11:51	3	35.7	1.0	Junction with main road, turn right.
11:56	5	41.3	5.6	Junction with Route 659. Sharp right turn toward Brattvåg.
12:03	7	45.5	4.2	Turn off for Brattvåg ferry terminal.
12:04	1	46.2	0.7	Arrive at Brattvåg Ferry. Depending on available time,.stops at Brattvåg mylonite zone, Sunnaland coast, "the final exam", Blåhø at ferry, may be added.
13:20	**76**	-	-	Drive onto ferry for Dryna.
13:40	**20**	-	-	Drive off ferry at Dryna and proceed east along main road.
13:42	2	48.4	2.2	Turn out at bend within sight of small bridge to Midøya. Walk back short distance to coastal exposure southeast side of road.

STOP 4-6: (15 minutes) Contact of Blåhø Nappe and "Sausage Rock" Basement. (See Figs. 3.2, 4.1)

"Sausage rock" (Norwegian= pølsestein) is an informally named rock unit that dominates the south coasts of Dryna, Midøya and western Oterøya. It consists of thinly laminated, highly foliated granitoid gneiss with thick and thin highly boudinaged layers of even-grained, locally porphyritic hornblende amphibolite. Because of the very high ductility contrast between enclosing gneiss and amphibolite, the amphibolite deformed into complex sausage shapes parallel to the late Scandian extensional lineation. When viewed in vertical outcrops cut normal to the lineation, the pattern is commonly chaotic, and contrasts sharply with the "straight" fabric observed in adjacent belts of schist and amphibolite of the Blåhø Nappe. When viewed on horizontal surfaces perpendicular to foliation and parallel to lineation, the boudins commonly show "bookshelf" style boudinage indicating late sinistral shear. There is abundant evidence that the mafic layers were invaded locally by late felsic melts presumably derived from the felsic matrix.

The purpose of this stop is to examine contact relations on both sides of a narrow belt of sausage rock that extends the entire length of Dryna. The first coastal exposure shows the south contact of this belt with mica schist and amphibolite assigned to the Blåhø Nappe. The contact zone 1 m thick is characterized by a thin bed of marble and diopside calc-silicate and also feldspathic schist zones that are unusually quartz-rich. The majority of well exposed contract zones on Midsund contain such marble and calc-silicate layers. The rusty-weathering schist several meters into the Blåhø Nappe is rich in gedrite, suggesting it is likely to be a metamorphosed hydrothermally altered mafic volcanic rock. Gedrite rocks have been found in similar locations on Oterøya as well as on Lepsøya (see Stop 3-10).

After observing this exposure walk north on the road past vehicles to another pavement of sausage rock which also lies on the coast just before the bus stop. From the pavement walk along the west side of a knob close to the road to a small northwest facing outcrop at the water line which is beyond the bus stop. Here there is a thin layer of marble and calc-silicate which is on the north contact of the belt of sausage rock. The marble occurs in a steep groove on the facing cliff of Middøya about 50m away, showing that there is no appreciable horizontal falut offset in the narrow gut between the islands.

Drivers will pick up participants near the bus stop.

13:57	**15**	-	-	Leave Stop 6.
-	-	48.5	0.1	Dryna-Middøya bridge. Pegmatites in Blåhø mica schist / amphibolite.
-	-	48.7	0.2	View ahead of huge cliffs. Mostly biotite schist and amphibolite of the Blåhø Nappe with pegmatite. There appear to be a few thin layers of basement gneiss.
14:00	3	49.5	0.8	View to left. Drynasund lighthouse resting on gabbro with eclogite-facies shear zones (Griffin and Råheim, 1973).
14:01	1	51.1	1.6	Junction. Left toward Midsund.
14:02	1	52.0	0.9	Below cliffs. On coast to south of here mica schist contains kyanite, amphibolite contains garnet-clinopyroxene-rutile assemblages with hornblende-plagioclase pseudomorphs after garnet, and there is minor eclogite.
14:03	3	49.5	0.8	View of Litle Digerneset to southwest. Here, Griffin and Carswell (1985) found eclogite-facies assemblages in both mafic rocks and in original igneous "back veins" of melted country rock. Dominant pink rocks are augen orthogneiss of Carswell and Harvey (1985) dated at 1506 ±22 Ma by whole rock RB-Sr, and more recently at 1508 by Tucker et al. (1991) using U-Pb zircon.
14:04	1	53.4	1.0	Riksgrense. This was the E-W international border between Sweden to the north and Denmark/Norway to the south between 1658 and 1660.
14:06	2	55.3	1.9	Junction to Vølen. Stay on 668 at north corner of Middøya.
14:10	4	58.8	3.5	Junction for Ramsvik. Turn left toward Midsund.
14:11	1	59.1	0.3	Bridge to Oterøya.
14:13	2	60.2	1.1	Junction in Midsund. Turn sharp right toward Heggdal. At big curve in road note cuts in Blåhø mica schist and cross-cutting but strongly deformed Scandian pegmatites.
14:15	2	61.7	1.5	Large parking place on right. Climb down through rocks, including Blåhø mica schist and pegmatite and heather to coast and walk west a short distance on continuous outcrop.

STOP 4-7: (35 minutes) "Sausage rock" basement gneiss intruded by mafic dikes, now amphibolite. (See Figs. 3.2, 4.1)

The purpose of this stop is to show some very fine contact relations in a coastal pavement between strongly foliated pink basement gneiss and amphibolite. The outcrops give convincing evidence that the amphibolites are dikes cutting a previously highly deformed gneiss. The dikes may be the same as those intruding the quartzites of the Sætra Nappe, ands if so are Late Proterozoic. It is hoped to test this hypothesis with major- and trace-element analyses of dike samples. If correct then the basement may be that of the Sætra Nappe itself and not directly related to the adjacent Western Gneiss Region. The dikes clearly truncate a strong deformational and metamorphic fabric, the age of which is quite uncertain, but presumable mid- to early Proterozoic. The scarcity, but not total absence of garnets in these dikes suggests, but does not prove that they never went though eclogite facies, like the amphibolites of the Sætra Nappe on the south shore of the fjord as well as the basement to the north. In fact no bonafide eclogites have been identified in any unit on the south coast of Midsund, although very fresh eclogites are well known only 1-2 km to the north (see Stops 4-8 and 4-11).

14:50	**35**	-	-	Leave Stop 7. Return toward Midsund.
14:52	2	63.2	1.5	Junction with Route 668. Stay straight (east) on 668.
14:53	1	64.4	1.2	Sign for Midsund Bruk. Turn left and drive to factory on coast.
14:54	1	65.0	0.6	Park in front of factory office and walk to south facing artificial exposure on north side of factory.

STOP 4-8: (10 minutes) Very fresh eclogite within big heavily amphibolitized body. (See Figs. 3.2, 4.1) This represents a very easy opportunity to collect very fresh eclogite in which the omphacite shows very minor but spectaular plagioclase symplectite and little or no secondary amphibole provided zones of secondary hydration are avoided. The occurrence illustrates the apparent sharp difference in metamorphism between the south and north coasts of Midsund.

15:04	**10**	-	-	Leave Stop 8 and return toward Route 668.
15:05	1	65.5	0.5	Back to Route 668. Turn left.
15:08	3	68.2	2.7	Turn left off 668 toward Ugelvik Quarry.
15:09	1	68.4	0.2	Park at quarry.

STOP 4-9: (10 minutes) Ugelvik garnet peridotite and garnet pyroxenite. (See Figs. 3.2, 4.1)

The following comments are from Griffin and Mørk (1981). "Note the contrast here between the extremely narrow fine-grained eclogitic (garnet and clinopyroxene rich) layers in the heavily serpentinized garnet-poor dunite and the very much coarser-grained tectonically bound lens of garnet websterite. The websterite shows clear textural evidence of stress-induced exsolution of garnet and clinopyroxene from what is interpreted to have been originally a high temperature aluminous orthopyroxene. This suggests that these peridotite bodies may have originally contained a higher-temperature, coarser-grained mineral assemblage of olivine + aluminous pyroxenes. The present mineralogical layering, shown mostly by variations in garnet content, may not reflect original igneous layering. It may rather, at least in part, represent tectono-metamorphic segregation layering developed in a lower-temperature olivine-low Al pyroxenes-garnet assemblage following stress-induced exsolution and recrystallization."

This is one of two bodies in the vicinity, completely enclosed in basement gneiss. Purplish chrome garnet appears throughout the strongly deformed layered peridotite in both weathered and fresh exposures and locally has near gem quality, although the olivine is somewhat serpentinized. Pyroxenite appears as thin streaks with bright green chrome diopside, also as large one mass of orthopyroxene with veins of purplish chrome garnet and chrome diopside (collecting is nearly impossible and to be discourage just here). Krogh and Carswell (1995) using complex textural and composition criteria estimate conditions of 725°±30C and 28±3 kbar kbar for the original Proterozoic (?) equilibration of this mass of sub-continental mantle, and 680° ± 30C and 18±2 kbar for the later Caledonian eclogite-facies re-equilibration. Implied high original Al content of coarse orthopyroxene, implies a still earlier low pressure protolith. Medaris and Carswell (1990) cite the coarse exsolved orthopyroxene megacryst at Ugelvik as one of the best pieces of evidence for a high-temperature low-pressure history in garnet peridotites before the initial Proterozoic high-pressure equilibration.

15:19	**10**	-	-	Leave Stop 9 and return toward Route 668.
15:20	1	68.6	0.2	Back on Route 668. Turn left toward Solholmen. Pass road cuts in garnet peridotite.
15:21	1	69.7	1.1	Raknes Fire Station on left. Beyond this is quarry in Raknes garnet peridotite and garnet pyroxenite.
15:22	1	70.5	0.8	Sign. Solholmen 10 km.
15:31	9	82.8	12.3	Road bends around northeast corner of Oterøya.
15:33	2	84.7	1.9	Park at right opposite factory road entrance. Examine road cut on right.

STOP 4-10: (10 minutes) Augen orthogneiss. (See Figs. 3.2, 4.1)

This rock and its highly deformed equivalents, which dominates the exposure on northern Midsund and part of the Molde peninsula, was studied extensively by Carswell and Harvey (1985). It is interpreted as an early mid-Proterozoic rapakivi granite that can be followed through progressive deformation and recrystallization until it can scarcely be differentiated from other more normal basement gneisses. Carswell and Harvey obtained a Rb-Sr whole rock isochron for these rocks of 1506±22 Ma., and more recently the same rock at Fanghol across Julneset, within sight of this stop has yielded a U-Pb zircon age of 1508 Ma (Tucker et al., 1991) similar to the U-Pb zircon age obtained on the porphyritic mangerite at Flatraket (see stop 2-12). In practice this basement augen gneiss is usually fine grained and the microcline phenocrysts are flattened and polycrystalline as a result of relatively homogeneous deformation, (Carswell and Harvey, 1985). Within this small road cut it is possible to see nearly every phase of progressive deformation of this porphyritic rock until the phenocrysts are no longer recognizable.

15:43	**10**	-	-	Leave Stop 10 and drive quickly to Solhomen Ferry.
15:45	2	86.3	1.6	Arrive Solhomen ferry. Coarse relict eclogite behind no-parking sign.

STOP 4-11: (15 minutes??) Coarse orthopyroxene eclogite with thick amphibolite rim. (See Figs. 3.2, 4.1)

Most of this eclogite, surrounded by augen orthogneiss, was destroyed during construction of the ferry terminal, but a small remanent remains. Carswell, et al. (1985) completed detailed mineral analyses on this rock and Cuthbert and Carswell (1990) list estimated conditions of formation at 760°C and 18-20 kbar. Several other small eclogites occur several hundred meters south of the ferry terminal, but no eclogites have been found by Robinson anywhere on the south coast of Oterøya and one gabbro shows only very slight garnet coronas. The implication is that there is a major metamorphic break running the length of the islands of Midsund.

On the next point to the north is a narrow belt of amphibolite, schist, calc-silicate and one 20 cm layer buff weathering pure marble here interpreted as an infold of the Blåhø Nappe. The same belt is exposed at Mordalvågen ferry terminal and the same buff marble appears in a road cut about 1 km to the east.

16:00	**15**			Drive onto ferry from Solholmen to Mordalvågen.
16:15	**15**			Exit ferry at Mordalvågen. Note large road cuts of garnet-biotite schist and amphibolite of Blåhø Nappe on right.
16:17	2	87.7	1.4	Junction with Route 662. Turn right toward Molde. From this point driving time to Kanestraum Ferry is about 1:20. In passing through Molde you may use by-pass to Sunndalsøra. Rejoin Route E39 in Molde and follow it all the way to Trondheim. The target from here is the ferry from Kanestraum to Halsa at 18:05 (Note last day of summer schedule is 17/8/97). **Note**: If Stop 10 cannot be made an alternative is to view the same rock at Hollingsholmen Ferry Terminal which lies approximately 9 km north of this junction. However, the time consumed would prevent reaching Kanestraum Ferry for 18:05.
16:26	9	95.3	7.6	Junction, Molde by-pass for Sunndalsøra. Stay straight to see Molde.
16:29	3	96.7	1.4	Molde ferry terminal. Rejoin E39.
16:30	1	97.4	0.7	Traffic circle. Stay right on E39.
16:48	18	115.7	18.3	Junction. Turn left on E39 toward Kristiansund.
17:01	13	131.1	15.4	Batnfjordsøra. Left on E39.
17:13	12	142.2	11.1	Right turn on E39 toward Gjemnes Bridge.
17:16	3	144.3	2.1	Traffic circle after turning right toward Trondheim at toll station.
17:22	6	149.9	5.6	East end of floating bridge. Turn right into rest area and kiosk. Time permitting, walk east to giant road cut.

STOP 4-12: (15 minutes) Foliated granitic gneiss with a "train wreck" of eclogite boudins. (See Fig. 1.1) (no detailed studies done here). The north wall of the cut shows eclogite mainly in section. On the south wall there are huge foliation surface showing the effects of boudinage on the sub-horizontal extensional lineation.

17:37	**15**	-	-	Leave Stop 11 and continue toward Kanestraum.
17:42	5	155.5	5.6	Straumsund Bridge
17:43	1	156.4	0.9	Junction. Turn left on E39 toward Trondheim.
17:50	7	165.0	8.6	Kanestraum ferry terminal and kiosk. (Excellent polser!!)
18:05	**15**	165.2	0.2	Drive onto ferry for Halsa.
18:25	**20**	-	-	Drive off ferry at Halsa. Standard driving time from here to Trondheim is 2.5 hours. There will be two short intermediate stops.
18:32	7	172.4	7.2	T-Junction at Betna. Turn left toward Trondheim on E39.
18:50	18	190.9	18.5	Rest stop with facilities on Valsøya.
19:00	**10**	-	-	Leave Valsøya rest stop.
19:02	2	192.2	1.3	Cross Valsøy Bridge.
19:14	12	205.6	13.4	Fylke boundary. Enter Sør-Trondelag.
19:25	11	217.6	12.0	Vinjeøra at end of fjord.
19:27	2	219.6	2.0	Junction with yield sign. Turn right on E39 toward Trondheim.
19:29	2	222.3	2.7	Gravel driveway on left before white outcrop on left.

STOP 4-13: (10 minutes) Songa (=Sætra) Nappe of Tucker (1986). (See Fig. 1.1) This outcrop lies in the extreme southwest part of the Snillfjord 1/50,000 map sheet (Tucker, preliminary map). It consists of very feldspathic layered quartz-mica gneiss. Is this a metamorphosed sedimentary unit such as a late Proterozoic feldspathic sandstone or is it a foliated igneous rock? The first choice is ultimately favored by most observers, though the rock has only a remote resemblance to the feldpathic quartzites of the Sætra Nappe near Oppdal and Brattvåg.

19:39	**10**	-	-	Leave Stop 12. Continue toward Trondheim.
20:14	35	262.9	40.6	Junction at Fannrem. Yield sign with very bad visibility. Stay on E39. Drive past Orkanger and east along coast of Trondheimsfjord.
20:42	28	292.2	29.3	Øysand. End of coastal section.
20:46	4	297.4	5.2	Klett traffic circle. Rejoin E6. Straight for Trondheim.
21:02	16	316.4	19.0	Trondheim, Lade. On field trip, participants will be delivered to hotels.

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