33 IGC excursion No 29, August 15 – 22nd, 2008

33 IGC, The Nordic Countries

The Caledonian infrastructure in the Fjord-region of Western Norway; with special emphasis on formation and exhumation of high- and ultrahigh-pressure rocks, late- to post-orogenic tectonic processes and basin formation.

Organizers:

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Kyanite veins in unaltered eclogte tectonite at Drøsdal, western Norway, details see Day 4, Stop 4.1

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PGP PHYSICS OF GEOLOGICAL PROCESSES

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Abstract
The present structure of the Scandinavian Caledonides is the product of the Silurian-Devonian collision between Baltica-Avalonia and Laurentia during the Scandian orogeny, subsequent extension and erosion of the orogen. The collision produced a ~2000 km long mountain belt comparable in size to present-day Himalayas between the eastern and western syntaxes. Similarly to the Himalayas, high-level extension commenced already during the collision. The extension continued after plate convergence had seized, and reached its most intense stage in the Devonian when the main supra-detachment basins were formed. The structure along the coast of western Norway is also strongly influenced by N-S shortening affecting the entire crustal section, including the Devonian 'Old-Red' basins. The giant E-W trending folds are Devonian to Early Carboniferous in age ('Variscan') and form regional structures such as the Bergen Arcs and the synclines in which the Devonian basins are preserved and antiforms in which the UHP-rocks are exposed. These folds are thus important in providing exposure of the deepest structural levels in the root zone of the orogen, as well as preserving evidence for the syn-tectonic surface topography in the Devonian basins. The Norwegian mainland was later affected by Permo-Triassic and Late-Jurassic to Early Cretaceous extension, tectonic events that were essential for formation of the petroleum-province in the adjacent North Sea and Norwegian Sea basins. The structure presently exposed in western Norway is therefore also important for understanding the deep structure and thermal history in the adjacent shelf areas. Some unique geological features perfectly exposed in western Norway will be in focus during this excursion:

- The petrology and structural history of high- and ultra-high-pressure complexes exposed in the Bergen Arcs and in the Western Gneiss Region.
- The tectonic elements responsible exhumation of deep crustal complexes, formation of large low-angle extensional detachments (Nordfjord-Sogn) and the Devonian 'Old-Red' sedimentary basins
- The geological processes responsible for sedimentary architecture, structure and alteration of the Devonian supra-detachment basins.

During this field excursion we shall demonstrate and discuss a number of phenomena of general importance for understanding tectonics during mountain building and orogenic extensional collapse that are extremely well illustrated in western Norway. Secondly, we shall give the participants an understanding of the tectonic evolution of Caledonides by examining a number of the key localities for understanding this evolution.

Logistics

Dates and location

***Timing*:**	**Friday 15/8 to Friday 22/8-2008**
***Start location*:**	**The excursion will start from outside the University of Bergen Science building "Realfagbygget", Allégaten 41, at 09 AM Friday August 15th.**
***End location*:**	**The excursion will end Friday 22/8 at ca 19.00 PM at Selje hotel. Overnight at Selje hotel will be arranged for departure with boat for Måløy, Florø or Bergen at 06.50AM Saturday 23/8. The final night not included in the excursion fee.**

Travel arrangements

START: Participants must arrange their own transport from Oslo to Bergen, for example the overnight train, or alternatively travel to Bergen Thursday evening (14th) and make their own accommodation reservation in Bergen 14-15/8. The Bergen railway station is within walking distance (ca 10 min, see below) from the University science building (Allégaten 41). The Bergen to Selje excursion is by bus and car ferries, and all accommodation and transport will be organized.

Map Bergen, showing railroad station (trains from/to Oslo) and the main bus terminal where busses from Bergen airport Flesland will stop. Easy 10-15 min. walk to the University Science building, (Realfagbygget) Allé gt. 41 where the excursion will start on 15th

END: The excursion will end at Selje hotel, Selje on the evening of August 22nd. You may chose to stay (extra cost) in Selje until Saturday (23rd) and travel by boat either to Måløy (bus to Oslo), to Florø (flights to Oslo or Bergen) or all the way to Bergen (also international departures) by the coastal express boat (5 hours Selje to Bergen on a spectacular boat trip). Travel from Selje is *not* included in the excursion fee.
An alternative is to return to Oslo by overnight bus from Måløy to Oslo Friday 22nd.

Accommodation

All accommodation will be in double room normal standard hotels. Breakfast and dinner will be at the hotels, also supplying lunch for the day excursions (included in fee). Notice that the accommodation (22-23rd) at Selje after the excursion is finished must be covered individually and is not included in the excursion fee.

Field logistics

All transport is by bus and car ferries. Walks during the day excursions are relatively easy and with maximum length/climbs of ca 2-3 km and ~150 m respectively. Some stops will last several hours and good grip footwear and solid wind/waterproof clothes are required. Bring a light 'back pack' for food-drink and extra clothes. August in western Norway may be anything from windy and rainy (10 to15°C) to very nice and warm (+20°C). Sampling of some spectacular rocks, granulites/eclogites will be possible in several localities. The leaders however, reserve their rights to stop sampling in some localities and we ask you to please *respect instructions concerning use of hammers to ensure preservation of localities where restrictions are obligatory or requested by us.*

2. Introduction to the Regional Geology

Geological setting and main topics of the excursions

The Scandinavian Caledonides (Fig. 1) are divided into five main tectono-stratigraphic units (Roberts and Gee 1985), which from base to top record increased transport distance with respect to Baltica:

- Autochthon-Parautochthon: The Archean (only northernmost Norway) to Proterozoic Fennoscandian basement of Baltica and the sedimentary cover of Late-Proterozoic to Lower-Palaeozoic age.
- Lower Allochthon: Dominated by sedimentary cover, but basement-cored nappes derived from the Baltican basement are involved some thrust sheets.
- Middle Allochthon: Dominated by Proterozoic crystalline complexes, thrust-stacked with and locally unconformably covered by Late Proterozoic to Lower Palaeozoic metasediments. Rift related latest Proterozoic dyke swarms and other magmatic rocks are locally common. Caledonian granitoids related to the Scandian collision have been identified in the Jotun nappe and in the Bergen arcs.
- Upper Allochthon: Dominated by Ordovician to Early Silurian ophiolite and island-arc complexes. Lower parts of the Upper Allochthon (the Seve Nappes and their lateral equivalents), also contain Precambrian gneisses, metasedimentary rocks, amphibolites and locally eclogitized mafic dikes and volcanics, parts of which are believed to have constituted transitional continental-oceanic crust segments of the rifted margin of Baltica.
- Uppermost Allochthon: Present in Nordland and Troms of northern Norway, and constitutes most likely also the Hitra-Smøla archipelago. This unit is a heterogeneous complex dominated by large batholitic composite intrusions mostly of Middle Ordovician age. In the Tromsø region, well-preserved Ordovician eclogites rocks are preserved.

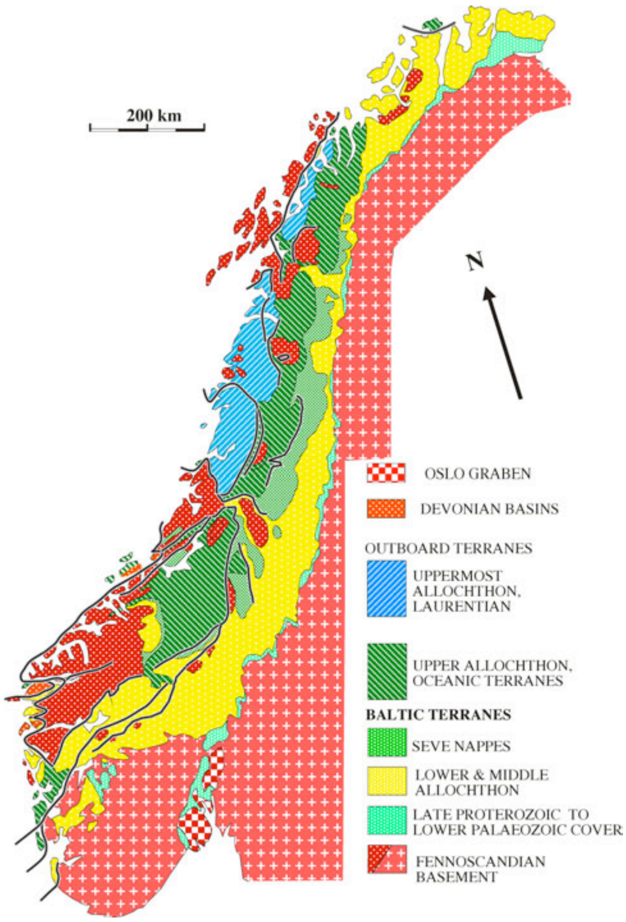
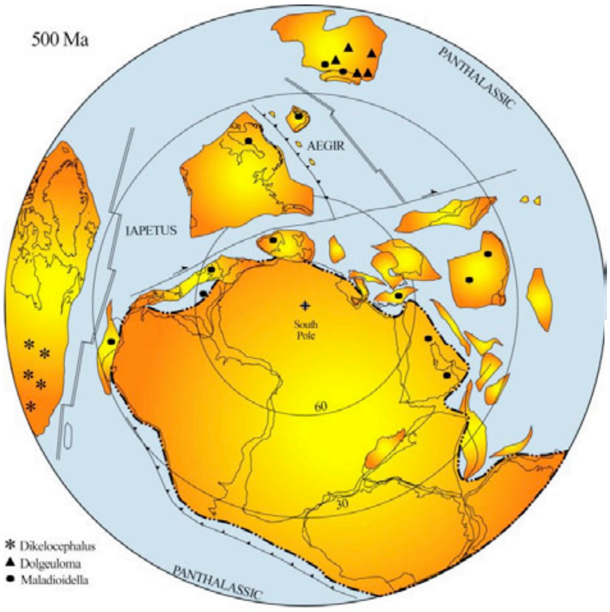


Fig. 1. The simplified tectono-stratigraphic map of the Scandinavian Caledonides indicates the tectonic affinity/terrane statuses of the main units. Notice also that major extensional shear zones and detachments, shear zones and faults are marked.

We emphasize that although the final assembly took place during the Scandian orogeny in the Silurian to Lower Devonian (Fig. 2); evidence of Pre-Scandian orogenic events is widespread, in the Middle, Upper and Uppermost Allochthons. The Pre-Scandian events include Ordovician eclogite facies deformation and metamorphic events in the Tromsø (Uppermost Allochthon) (Fig.1) and in the Seve Nappes (Upper Allochthon) (Corfu et al., 2003, Brueckner and Van Roermund, 2005, Root and Corfu, 2007), as well as widespread deformation and metamorphism in the Ordovician ophiolite/island-arc complexes of the Upper Allochthon (e.g. Andersen and Andresen 1994) and in the Middle Allochthon (Høyvik Group/Dalsfjord Suite, see below, Day 3, e.g. Brekke and Solberg, 1987, Andersen et al., 1999). It has been suggested that these early events in the Upper- and Uppermost Allochthons are 'Taconic' akin to the Laurentian margin and unrelated to the Caledonian margin of Baltica (Pedersen et al., 1988), which at the time of these events, in the early to middle Ordovician was facing the Ægir Sea separating Baltic and Siberia (Fig. 2a).



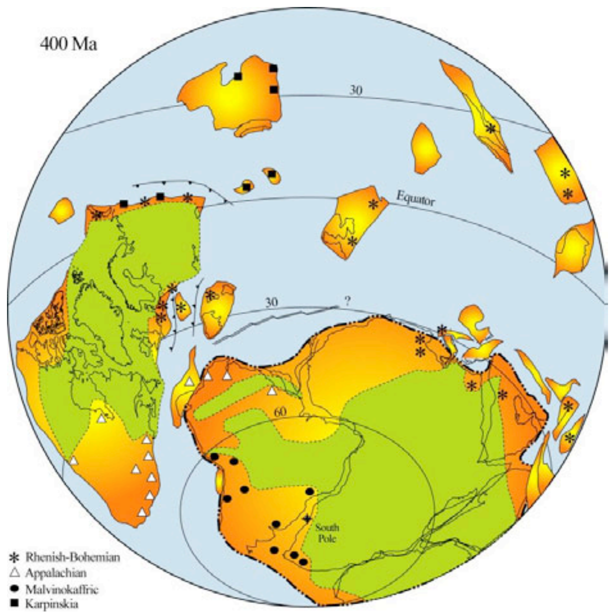


Fig. 2. Paleogeography reconstructions for times ~500 and 400 Ma. For details, see the web pages from the NGU geodynamics group http://www.geodynamics.no/platemotions/500-400/

During this fieldtrip we shall mainly focus on the tectonic processes related to the Scandian orogeny and how the large-scale continental collision and the subsequent extension is expressed in structures, mineralogy and fabrics in a crustal section from the deepest crust to the syn-tectonic surface.

2.1. High- and Ultra-High Pressure rocks.

The exhumed (ultra) high-pressure [(U)HP] rocks in western Norway [Bergen Arcs (HP) and WGC (UHP and HP)] provide one of the largest, best preserved and exposed deep crustal provinces in the world. Both areas are classical for studies in metamorphic petrology, exemplified by the ‘Landmark Papers’ by Eskola (1921) and Austrheim (1987) selected by the Mineralogical Society of London, and also from the first discovery and description of regional metamorphic coesite in eclogite by Smith (1984).

The (U)HP rocks visited in the excursion occur in two tectono-stratigraphic positions, within (1) the Western Gneiss Complex and (2) the Bergen Arc Complex.

1) High and ultra-high pressure rocks of the Western Gneiss Complex

(1) *The WGC* represents the westward continuation of the Fennoscandian basement of Baltica, and exposes the the deepest parts of the root zone of the Caledonian mountain belt. Along the southeastern margin of the vast WGC window, the structure and mineralogy of the rocks are dominated by their Proterozoic history, and they are affected by Caledonian overprint mostly adjacent to the overlying cover and nappes and in some localized zones. The north-westernmost parts of the WGC, containing ultra-high-pressure (UHP) rocks have a more complex structure, which probably involved a significant amount of crustal stacking during the Scandian collision as already proposed by Bryhni and Andreasson (1985). Consequently exhumation of some of the UHP-rocks must therefore be carefully reconsidered (Terry et al. 2004) and may be more complex than the (U)HP rocks further to the south and east.

The rocks of the WGC are highly heterogeneous in composition, comprising famous mantle-peridotites (e.g. Carswell and Van Roermund, 2005, Brueckner et al. 2002), large ultramafic to mafic and acid intrusive bodies variably modified to orthogneisses (e.g. Austrheim et al. 2003) and numerous bands and lenses of paragneisses of variable composition and probably also ages. The protolith ages of the WGC rocks are Middle Proterozoic, dominantly formed between ca 1660 and 930 Ma (e.g. Tucker et al. 1990, 2004), although some of the mantle peridotites apparently have Archean protoliths (Spengler et al. 2006). Infolded lenses and narrow bands of paragneisses and meta-supracrustal north of Stadtlandet (Fig. 7) have been interpreted as Caledonian nappes, and assigned to the Middle- and Upper Allochthons (Robinson, 1995, Terry and Robinson, 2004). Other areas with abundant paragneiss are clearly Proterozoic in age as they are truncated by granites and orthogneiss with U/Pb zircon intrusive ages up to 1640 Ma and overprinted by Sveconorwegian (Grenvillian) granulite facies metamorphic at 987±10 Ma (Rohr et al. 2004).

The Scandian metamorphic overprint shows an overall coherent pattern with a progressive regional increase in PT_{max} towards the northwest (e.g. Labrousse et al. 2004) as already suggested by Krogh (1977). The simple regional pattern is, however, strongly modified by lack of metamorphic equilibration locally, as well as late Devonian E-W to NE-SW trending folding of the gradient and younger isotherms defined by mineral cooling ages (e.g. Root et al. 2005). On sample to outcrop scale the metamorphic equilibration is highly heterogeneous as demonstrated by incomplete and fluid-limited reactions (see ‘the classic paper’ by Austrheim 1987). Preserved protoliths and non- to partially reacted mineral assemblages occur in a number of localities throughout the WGC (e.g. Straume and Austrheim 1999, Krabbendam et al. 2000, Engvik and Austrheim 2001, Røhr et al., 2004).

The UHP rocks occur in the NW-corner of the WGC between Nordfjord and the Molde area (Fig. 7). These rocks are exposed within 3 antiformal culminations and thus represent the deepest structural levels exposed in Norway. Their deep origin is demonstrated by systematically younger Ar-cooling ages towards deeper structural levels (Root et al. 2005). The UHP domains have the youngest $^{40}Ar/^{39}Ar$ muscovite ages (<380Ma), and the regional $^{40}Ar/^{39}Ar$ muscovite isochrones are fold together with the entire crustal section in western Norway (see map, figure xx). This is an extremely important observation because of its influence on the exhumation models that can be applied for the Norwegian (U)HP rocks; it is obvious that their principal exhumation cannot be ascribed to large-scale thrusting (see below).

The UHP index minerals in the WGC include coesite and polycrystalline quartz aggregates after coesite, micro-diamonds and majoritic garnet in garnet peridotite. In addition UHP conditions are indicated from orthopyroxene bearing eclogites (low Al in opx coexisting with gar) and from mineral-equilibrium PT-calculations in several localities (i.e. Vrijmoed et al. 2006, Young et al. 2007). UHP minerals have been found in felsic gneiss from 3 localities including the first diamond occurrence (Dobrinhetskaya et al 1995), but occur most abundantly within eclogites and peridotites. Majoritic garnet occurs in one peridotite body only (Van Roermund et al., 200x). In total UHP conditions have been identified from more than 50 localities, with diamond identified from 3 localities (recent overview by Vrijmoed et al., submitted, February 2008).

The age of the (U)HP metamorphism in the WGC is relatively well constrained and dated by a several methods (U/Pb, Sm/Nd, Lu/Hf, see Krogh et al. 2003, Root et al. 2004, Kylander-Clark et al., 2007, Young et al., 2007). The eclogite facies metamorphism is latest Silurian to lower Devonian and ranges from ca 420 to 398 Ma. In the Bergen Arcs the eclogites now positioned in the Middle Allochthon, is slightly older (425-430 Ma, see below). The ages obtained from several labs and methods indicate that (U)HP metamorphism during the Scandian continental collision lasted 25 to 30 million years. We suggest that fluid-limited metamorphism controlled intermittent eclogitization at different stages during both burial and decompression, and that near complete eclogitization of both mafic and intermediate rocks only occurred in the highest-grade parts of the WGC (Walsh et al., submitted, Tectonics)

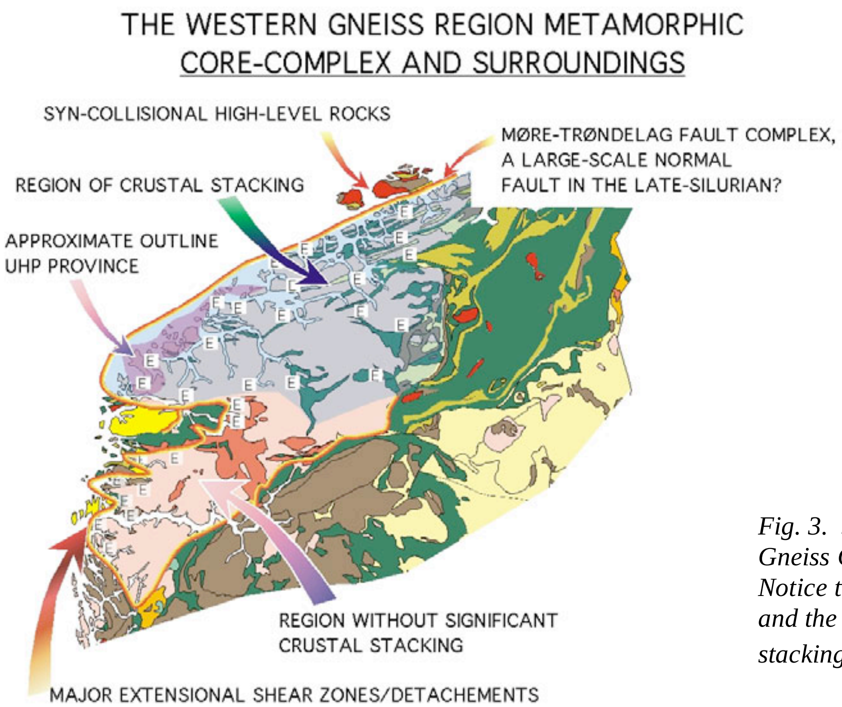


Fig. 3. Simlified map of the Western Gneiss Complex and the surroundings. Notice the distribution of UHP rocks and the area where significant crustal stacking have been identified.

PT-time paths suggest that decompression from peak pressure conditions in most places was adiabatic or associated with a minor temperature increase of less than 100^{o}C (e.g. Labrousse et al. 2004).

2) The high-pressure rocks of the Bergen Arcs (Lindås Nappe)

The Lindås Nappe in the Bergen Arcs is correlated with the Jotun Nappe and other parts of the Middle Allochthon. The Bergen Arc eclogites are positioned structurally higher than those of the WGC, and HP metamorphism should therefore be older than those of the WGC. U/Pb zircon ages from zircons produced by eclogitization reactions involving breakdown of the original ilmenite to rutile and Fe-oxides confirm an older age and gives a Middle/Late Silurian age of 424±4 Ma for the eclogites at Holsnøy (Bingen et al. 2004). In a recent geochronological study (Glodny et al. 2008) six multi-mineral eclogite facies veins have been datet at 429±3.5 Ma (Rb/Sr), an eclogite facies vein gave an U/Pb metamorphic zircon concordant age of 427±3 Ma, identical to an 427±0.9 Ma U/Pb zircon xenocryst from an amphibolite-facies vein. The amphibolite facies was dated by seven Rb/Sr mineral isochrones showing fluid infiltration at 414.2±2.8 Ma, which shows decompression but still deep crustal conditions lasting for at least 15 Myr (Glodny et al. 2008).

The Bergen Arcs are a series of arcuate Caledonian nappes centred on Bergen. The most important unit, from both a geological and volumetric standpoint, is the anorthosite-mangerite-charnokite-granite rocks (AMCG-suite) of the Lindås Nappe. They represent a Middle Proterozoic intrusive complex(s) metamorphosed to granulite facies at 800-900°C and 1.0 GPa during the Sveconorwegian orogeny (Austrheim and Griffin, 1985). Peak granulite-facies metamorphism occurred at ~945 Ma. This metamorphism produced mostly dry assemblages dominated by pyroxenes, garnet, feldspar, although scapolite and amphiboles are common in several of the granulites.

The Caledonian orogeny brought the granulite-facies rocks to eclogite-facies conditions at pressures of ~2 GPa and temperatures of about 650-700°C. Transformation to eclogite-facies assemblages was however incomplete, and granulites and eclogites occur together at all scales. Plagioclase- and pyroxene-rich granulitic assemblages are replaced by new garnet, omphacite, kyanite, rutile, and hydrous phases such as phengitic muscovite, amphiboles and zoisite/clinozoisite in the eclogites. The HP metamorphism is accompanied by a significant densification of 10 to 15 % depending on initial composition (Austrheim and Mørk 1988), which also is accompanied by increased seismic wave velocity (Fountain et al. 1994).

Austrheim (1987) concluded that infiltration of fluids during metamorphism was essential for the development and stabilization of the eclogites facies assemblages, and the associated introduction of fluids also change the mechanical properties of the rocks so that eclogitization is commonly associated with deformation. Outside of fractures, shear zones and veins in zones where fluid did not penetrate, granulite-facies rocks persisted in a non-reacted state at eclogite-facies conditions.

The Lindås Nappe complex was rapidly exhumed as it was emplaced as part of the trailing end of Middle Allochthon and attained amphibolite facies conditions at 410 to 415 Ma, during the Scandian phase of the Caledonian orogeny (e.g. Jolivet et al. 2005, Glodny et al. 2008), when the WGC underwent burial to (U)HP conditions. Arrest of eclogitization due to rapid exhumation and limited amount of fluids available allowed for preservation of a complex that provides the most excellent view into the processes associated with burial of old “dry” lower crust into the root zone of a continental collision zone.

Another remarkable feature of the Bergen Arc eclogites is the pseudotachylytes and other brittle deformation phenomena associated with the incipient eclogitization first described from this area (Austrheim & Boundy 1994, Lund et al. 2004). The conception of a brittle-ductile transition in the crust as presented in most textbooks and papers is perhaps too simplistic and based on unrealistic rheology and the conditions at which rocks may fracture. The occurrences of high-pressure brittle structures will also provide a pathway for understanding of the mechanisms of deep earthquakes, which will be discussed at several localities during this field excursion.

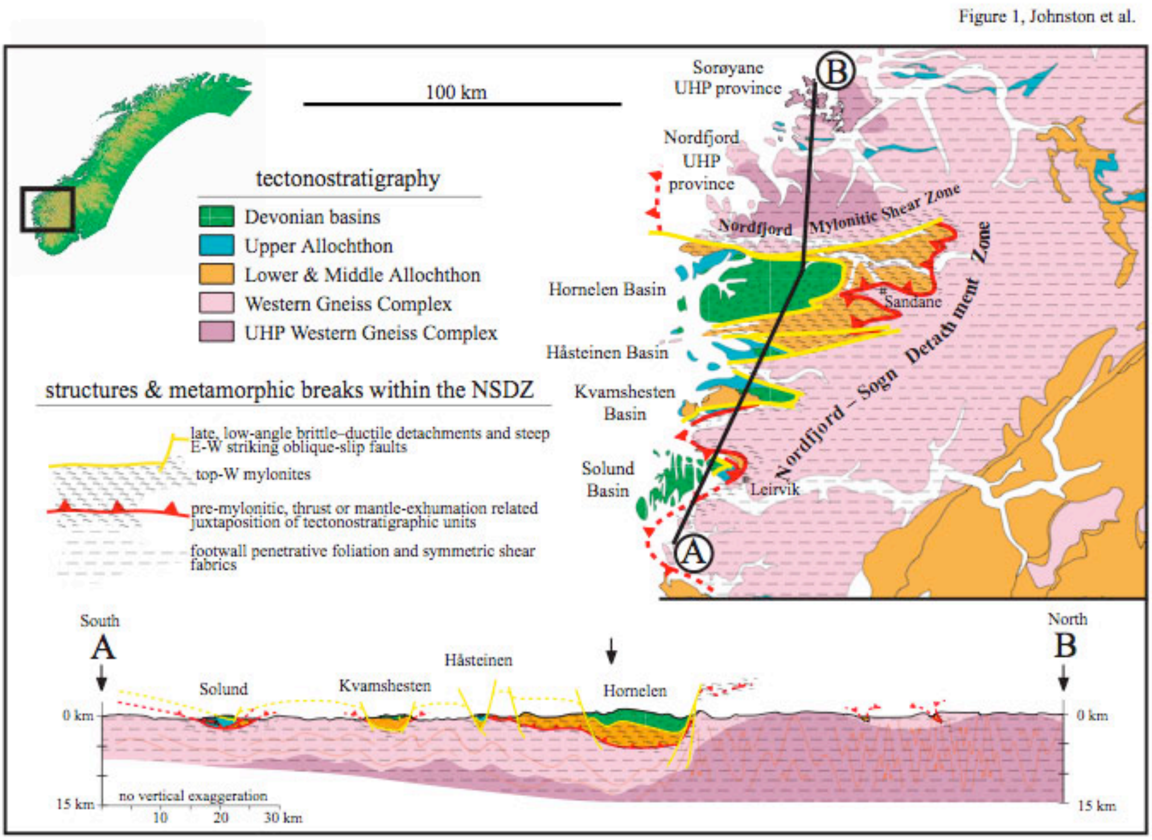
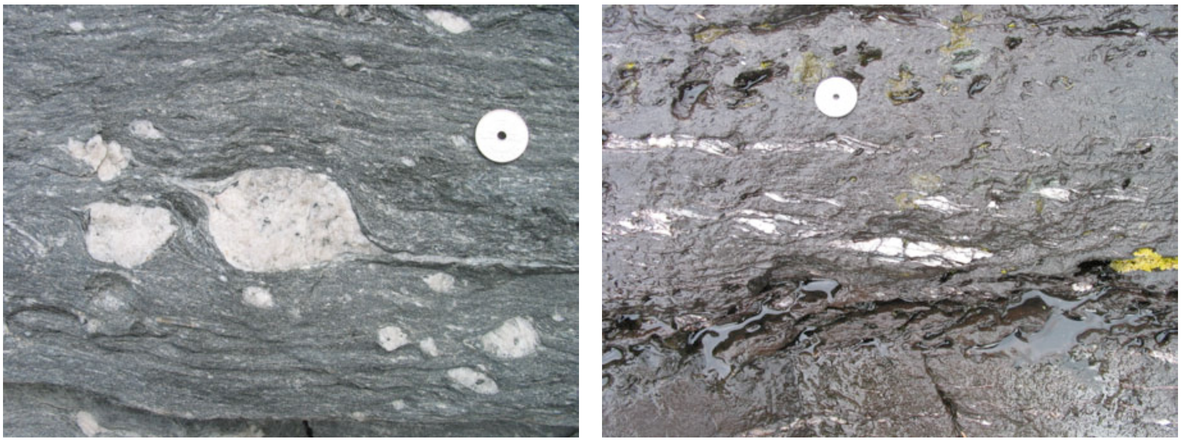


Fig. 4. Simplified map and N-S cross-section of showing the Nordfjord-Sogn Detachment Zone and its relationship to the footwall (U)HP province and the hanging wall with Caledonian Nappes and the supra-detachment Devonian basins (Johnston et al. 2007).

2.2. The Nordfjord - Sogn Detachment Zone (NSDZ)

Extensional faults and shear zones thin the crust and are important structures for exhuming deeply buried rocks. The NSDZ represents the most spectacular extensional detachment zone with the largest component of crustal excision found anywhere in the world. The NSDZ mylonites were first re-interpreted as extensional and named by Norton (1984). The mylonites achieve a structural thickness of up to ca 5 to 6 km and have recently been described in detail in several recent papers (e.g. Johnston et al., 2007, Marques et al. 2007, Young et al. 2007).

Minimum estimates of the normal displacement on the NSDZ based on strain calculations and/or crust excision is 60 to 100 km (see Andersen & Jamtveit, 1990, Hacker et al., 2003). More realistic estimate of the displacement is, however, probably in the order of 100 to 150 km because of the problems with quantification at very high strains. In the Nordfjord area crustal excision is dramatic as ~2 GPa eclogites are juxtaposed with upper crustal rocks and the Devonian sediments across the detachment (see figs. xx). As shown in the cross-section below, the progressive unroofing of deeper parts of the crust is well illustrated by the downward decrease in $^{40}Ar/^{39}Ar$ cooling ages across the detachment (Fig. 6).



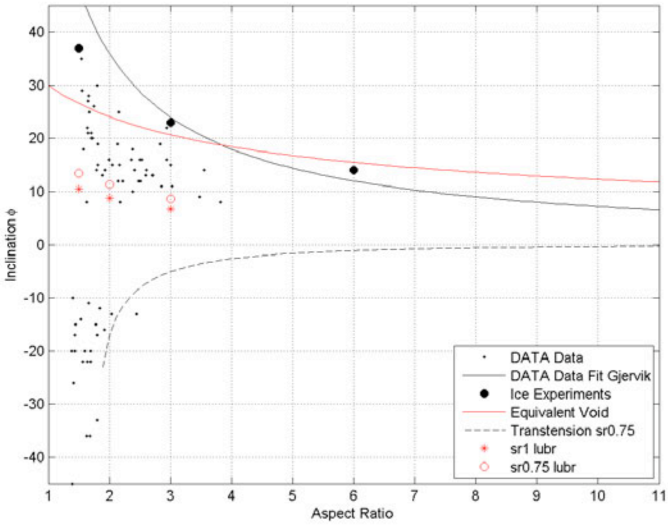


Figure 5.
Mylonites from the NSDZ, left at low levels (Sandane) and right from Gjervik on Atløy at the uppermost level. These two stations are characterized by Sr (ratio of simple to pure shear) of 1 and 0 respectively.

Diagram to the left shows Gjervik (solid line fit) and data points (dots) from Sandane compared with experiments and numerical modelling. Axis are aspect ration of the inclusions and the angle the long axis makes with the shear plane (Marques et al. 2007).

The exhumation of the lower-crustal rocks was also achieved by a considerable component of vertical shortening, particularly in the deepest parts (e.g. Andersen and Jamtveit, 1990, Engvik and Andersen, 2007). The vertical shortening adds several kilometres of exhumation to the simple shear component, which dominate the upper parts of the NSD mylonites ($Sr = \varepsilon/\gamma \approx 1$, where ε and γ are flattening- and shear strain respectively, see Marques et al., 2007). Extension of 100 to 150 km across the NSDZ and the additional vertical shortening of the lower crust (e.g. Andersen et al., 1994) is sufficient to explain exhumation of HP rocks from pressures up to ~2.5 GPa (assuming that the pressure is equal weight of overburden, $P = \rho gh$). Exhumation from deeper burial and UHP conditions is not explained by the observable structures in the exhumed rocks in western Norway. Geologists should therefore be open to other less conventional interpretations of how UHP conditions can be achieved, particularly in regions where crust and mantle lithosphere interacts during collision.

The very large strains and spectacular mylonites of NSDZ produced numerous and spectacular shear sense and other strain markers that can be used to quantify the flow in the shear zone by comparison with analogue and numerical experiments (see fig 5 above from Marques et al., 2007).

The main detachment of the NSDZ identified by the principal excision of the metamorphic gradient also controlled the geometry and distribution of second-order detachments and faults in its hanging wall. These in turn controlled the basin topography in the Devonian supra-detachment basins (Osmundsen et al., 1998, 2000).

Post-Devonian faulting reactivated some segments of the NSDZ, and both palaeomagnetic and radiometric dating of these fault rocks indicate that major reactivation in the Permian as well as in the late Jurassic/early Cretaceous (e.g. Torsvik et al., 1992, Eide et al., 1997, 1999).

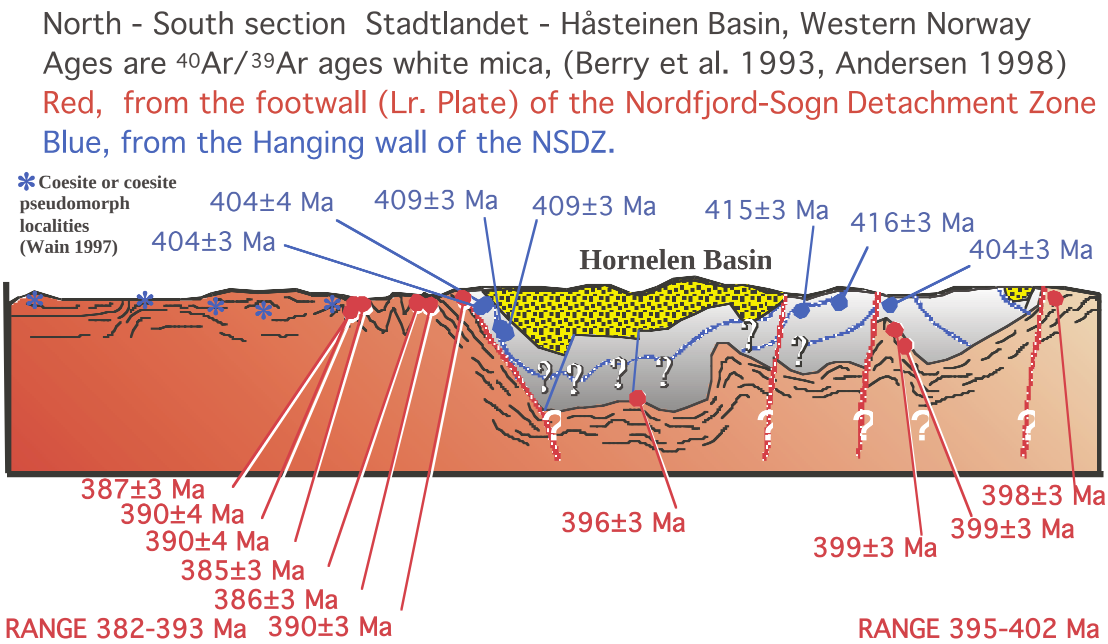


Figure 6. N-S cross-section from the UHP province in Nordfjord to the Håsteinen basin in the south. Caledonian nappes in grey and the Hornelen basin in dottet yellow ornament. The ages shown are all $^{40}Ar/^{39}Ar$ muscovite ages from Andersen (1998). Notice the downward decrease in ages.

2.3. Caledonian history and tectono-stratigraphy recorded in the hanging wall of the Nordfjord-Sogn Detachment Zone

The Caledonian rocks between Vilsnesfjorden and Stavfjorden near Atløy in Sunnfjord (Fig. 4) represent a key to understand the Scandian and as well as pre-Scandian history in the Caledonides. The geology of Atløy is remarkably well preserved in a regional low-strain domain, and preserves 3 major unconformities (see below) that are important for understanding Caledonian regional geology in Scandinavia (Brekke and Solberg 1987, Andersen et al. 1990). Contrary to rocks in the footwall of the NSDZ, the hanging wall preserves structures related to both contraction and extension of the orogen.

On Atløy, the well-preserved basement-cover relationships give the best evidence for the polyphase nature of the Caledonian orogen recorded in Scandinavia. The depositional unconformity between the Late-Proterozoic or Cambro-Ordovician (age uncertain) Høyvik Group and the fossiliferous Silurian Herland Group can be mapped continuously along strike 5.5 km across the island. The Høyvik Group was deformed and metamorphosed in a pre-Scandian event (at ca 450 Ma). The geology of Atløy and the adjacent islands also provides the best-preserved relationships between continental and oceanic complexes in the Scandinavian Caledonides (Andersen et al., 1990, Skjerlie and Furnes, 1991). The timing of the obduction of the Solund-Stavfjord Ophiolite (U/Pb zircon age, 443±3 Ma) is recorded by the stratigraphy of the Herland Group, which has a shallow marine fauna including Pentamerid brachiopods of Wenlock age, and the unconformable overlying Sunnfjord Melange formed during the obduction.

The Dalsfjord Suite constitutes the lowermost unit in the hanging-wall of the NSDZ. The rocks are orthogneisses and intrusive rocks belonging to the AMCG suite. Mangerite syenite gneiss and a gabbro have been dated at 1634±3 Ma and 1464±6 Ma respectively, and titanite ages show Sveconorwegian reworking between 920 and 960 Ma (Corfu and Andersen, 2001). These rocks are correlated with the Lindås Nappe containing eclogites in the Bergen area, but there is no indication that these rocks have experienced Caledonian HP metamorphism. The Dalsfjord-Høyvik basement-cover pair was, however, affected by a Middle Ordovician greenschist facies metamorphism and deformation recorded as the principal fabric in the Høyvik Group (Brekke & Solberg 1987, Andersen et al. 1990, 1998).

The Høyvik Group (>1500 m), which overlies the Dalsfjord suite non-conformably is divided in four formations: the (basal) Granesund, Kvitanes, Atløy and (top) Laukeland Formations (Brekke & Soberg 1987). The primary depositional contact with the underlying Dalsfjord Suite is locally remarkably well preserved on Atløy (see below). Meta-igneous rocks in the Høyvik Group occur as mafic dikes and volcanics (greenschists and pillow lava). The igneous rocks can be correlated with the late-Proterozoic rift-magmatic rocks elsewhere in the Caledonides.

The Herland Group (ca 350m) consists of conglomerate, sandstone, limestone and shale in the (basal) Sjøralden and (top) Brurestakken Formations. The unconformity to the Høyvik Group is remarkably well preserved across the island for ca 6 km. Metamorphism and deformation that affected the Herland Group is low, hence its preservation is unique and most unusual in the hinterland of the Scandinavian Caledonides. Fossils are preserved at a number of localities and are Middle Silurian (Wenlock 428-425 Ma) in age. The stratigraphy of the Herland Group records progressive destabilization and destruction of the continental margin during the final closure of the Iapetus. The Herland Group is overlain stratigraphically by the Sunnfjord Melange with a low-angle depositional unconformity.

The Sunnfjord Melange (ca 400m) contains greenish quartz-chlorite schists, chlorite-rich, impure marbles, greenstones, vein-quartz conglomerates, scattered clasts of epidosite and characteristic jasper bearing, matrix supported conglomerates. The clasts reflect a bimodal source of both continental and oceanic affinity. The continental clasts are from both Høyvik and Dalsfjord lithologies including quartz-schists, marble and anorthosite. Some undeformed and mature sandstone pebbles and cobbles were probably eroded from the Herland Group prior to Late-Silurian deformation during obduction of the ophiolite. Clasts of oceanic affinity comprise greenstones, epidosite and characteristic red jasper; vein-quartz pebbles are conspicuous throughout the conglomerate. Large (>100m) greenstone lenses are believed to represent olistoliths derived from the ophiolite. The dominant lithology of the upper parts of the melange is a chlorite-bearing, calcareous meta-greywacke. Talc-schist lenses and serpentinites occur at middle and upper level of the melange. The contact between the melange and the Herland Group is commonly sheared, but locally the unconformable depositional contact is preserved on northern Atløy (see below Fig. 5-9).

The conglomerates with bimodal oceanic-continental source, in the lower part of the melange, formed in a rapidly subsiding foreland basin. The subsidence was probably a result of the loading on the continental margin by the advancing ophiolite nappe and its overlying cover. The upper parts of the melange are mainly a tectonic melange formed by both intra oceanic deformation in a transform fault environment and subsequent contractional and extensional deformation along the basal thrust of the ophiolite nappe (for additional detailed information, see Skjerlie and Furnes 1991, Osmundsen and Andersen 1994, Alsaker and Furnes 1994).

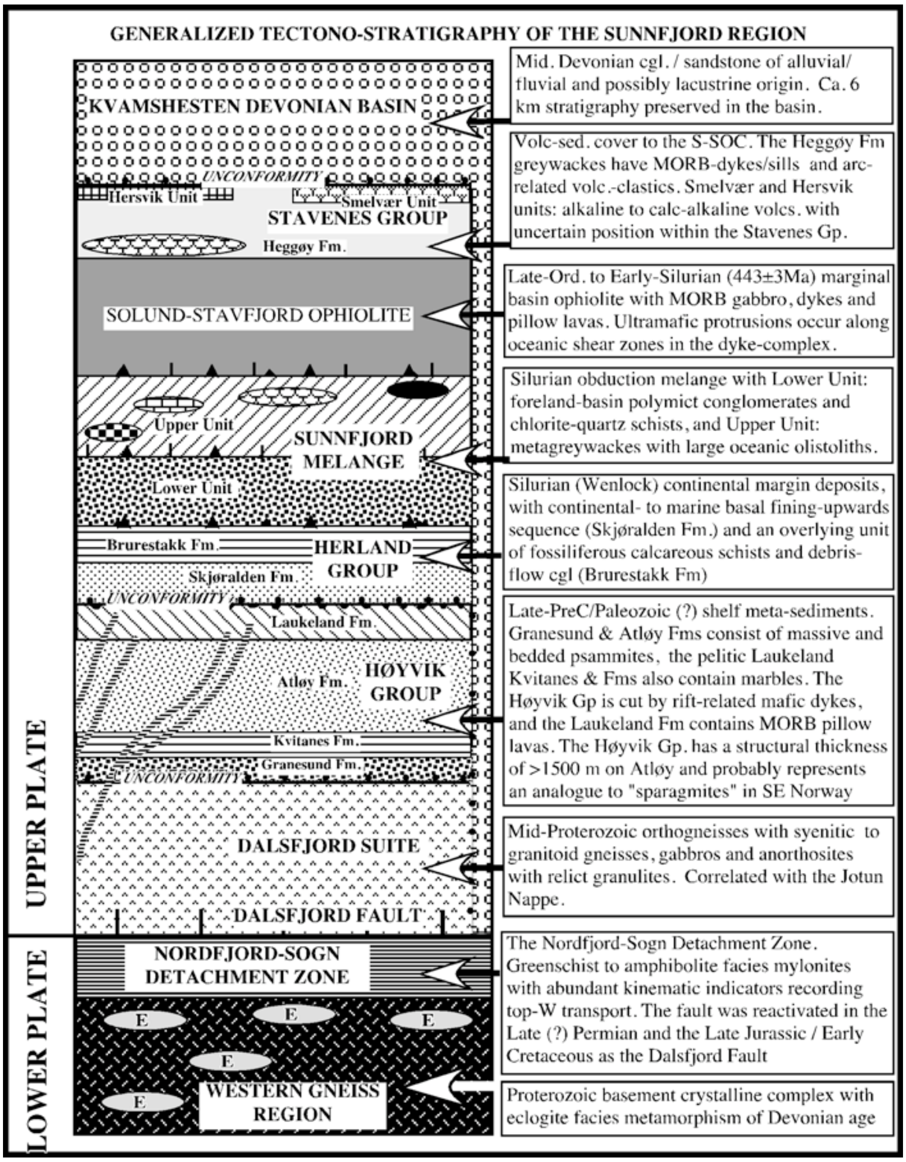


Fig. 7. Summary diagram showing all tectono-stratigraphic units, their age, structural and stratigraphic relationships in the key area between Stavfjorden and Vilnesfjorden, Sunnfjord.

2.4. The Devonian basins

The Lower- to Middle Devonian basins in western Norway are supra-detachment basins with respect to the NSD. C.F. Kolderup's pioneer work on the basins from the late 19th and early 20th-century resulted in a series of monographs on each of the basins published in the Bergen Museum Yearbook Series, and included reports on first discoveries of fossil fauna and flora. Kolderup was also aware and discussed the enigmatic vast stratigraphic thickness (>20 km) of the Hornelen basin. I. Bryhni also discussed this problem and suggested that migration of sedimentation rather than an unrealistic vertical thickness could explain the enigmatic thickness. Later work by Steel and co-workers concentrated on details of the alluvial- to fluvial sedimentology and explained the alluvial fan architecture by the migrating depo-centres. An important element in the recent studies of the basins has been to integrate relationships between the depositional systems in the basins with the detailed structural geology in drainage basins of the basins substrate (see papers by Osmundsen et al.). It can be demonstrated that the sedimentary architecture of the basins with abundant (~10 to100m scale) coarsening-up-fining-units (CUFU) and very thick (~km-scale) up-fining-units (UFU) was controlled by second- or third-order fault to the NSD, and the (S)E-ward shift in depocentre with time. The repeated CUFUs give rise to a spectacular step-topography in the basins (see: Google earth). Furthermore is has been demonstrated that shifts in basin floor tilt directions can be related to the large-scale tectonics, which involved progressive influence of contemporaneous extension and orogen-parallel sinistral strike-slip movements (transtension and transpression). Sequence stratigraphic methods have been applied to achieve a better understanding of the basin fill history and its detailed relationships to the active tectonics (Osmundsen et al., 2000).

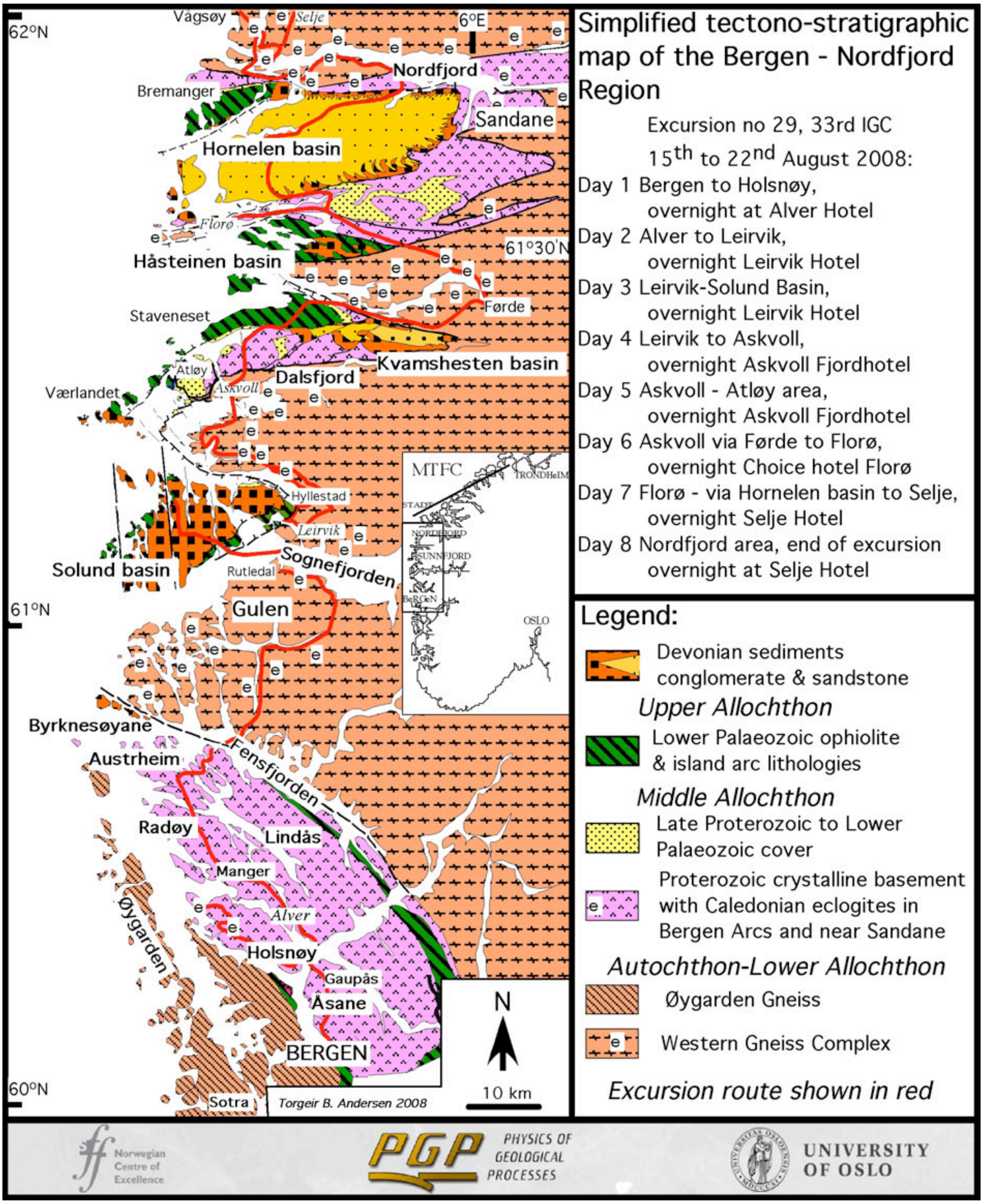
The Hornelen basin was characterised by a more eastward tilt direction and by W- to WSW paleocurrents in the sandy parts of the basin fill. The northern basin margin apparently constituted an E-W striking, dextral strike-slip fault whereas the southern and eastern margin faults were dominantly normal to normal-oblique slip and drained a much larger region in the provenance area. The provenance of the Hornelen basin is clearly dominated by the Middle Allochthon rock (similar to the Dalsfjord and Høyvik basement cover pair) and more locally along the northern margin by the ophiolite/island arc rocks of the Upper Allochthon. Ar-mineral ages from the WGC show that that the WGC was clearly not available to erosion when the Hornelen basin fill was deposited, and the basins were filled with sediments derived from the Caledonian nappes of the Middle- and Upper Allochthons.

The Kvamshesten basin is located between the Solund and Hornelen basins. Following intensive mapping and sedimentological studies in the 1990-ies, this is the best-studied basin in western Norway, but unfortunately mostly inaccessible for short field excursions. Sedimentological and structural data show evidence of an early SE-wards tilt direction followed by a more eastwards tilt and associated E-W flowing palaeo-drainage. The variations in tilt directions for the basins are interpreted as to reflect a regional variation in the direction of principal extension from SE-NW in the Solund basin, through SE-NW followed by E-W up-section in the Kvamshesten basin to mainly E-W or ENE-WSW in the Hornelen basin. The basins were shortened in a direction roughly normal to the direction of principal extension. Early folds and reverse faults in the Kvamshesten basin trend NW-SE, and are superposed by a set of E-W trending folds and reverse faults. In the Hornelen basin, contractional structures trend WSW-ENE. Shortening probably commenced during sedimentation, although the main phase of shortening appears to be post-depositional.

The observations and inferences presented above indicate that the Devonian basins in western Norway formed in a strain field dominated by regional transtension, accommodated by extension along the NSDZ and sinistral strike-slip along orogen-parallel shear zones and faults to the north of the basins. It is now firmly established that an important components of left-lateral transpressive and transtensive domains influenced basin architecture in western Norway and along Trondheimsleden into the Fosen peninsula during and after deposition (e.g. Osmundsen et al. 2006).

Details concerning geology of the Solund and Hornelen basins are described below (day 3 and 5) in connections with the excursions focussing on these basins.

Excursion Route Overview Map



Excursion Stops

Day 1

Day 1 excursion starts from the University of Bergen Realfagbygget (Science building) and takes the main road north through Åsane and towards Gaupås, stop 1.1 near Ytre Arna.
Stop 2 is at Holsnøy, the Ådnefjell locality stop 1.2.
Final stop is near Sætrevik, stop 1.3 where we shall be visit a number of localities on a ca 2.5 km walk.

We return to Alversund for accommodationa at Alver Hotel near Alversund shown on the map.

Introduction

The object of day 1 will be to demonstrate progressive eclogitization, the interdependence of metamorphism, deformation and fluid activity in the deep crust, and to demonstrate how metamorphic transitions control petrophysical and rheological characteristics and thus the geophysical signature of root zones of orogenic belts.
The Gaupås quarry outcrop may be worked and the details here depend on accessibility and instructions from the workers.
Please observe that some of the quarry and roadside exposures may have loose rocks. Many of the outcrops on Holsnøy are unique, much visited by geo-scientists and students and they should not be hammered unnecessarily! Stop 1.2 and 1.3 involves short walks and the ground may be wet and slippery, hence use proper shoes.

Stop No 1.1 Gaupås quarry, Granulite facies coronas and their hydration

This stop depends on the permission to drive into the quarry.
This locality is chosen to demonstrate the Precambrian mineralogy and structure of the anorthosite and associated rocks of the Lindås nappe and how the complex is hydrated with the development of new (Caledonian) foliations. This is one of the localities studied by Griffin (1972) in his classical paper on corona formation. Corona structures consisting of orthopyroxene, clinopyroxene and garnet separate the olivine core from plagioclase (Fig. 1-1).

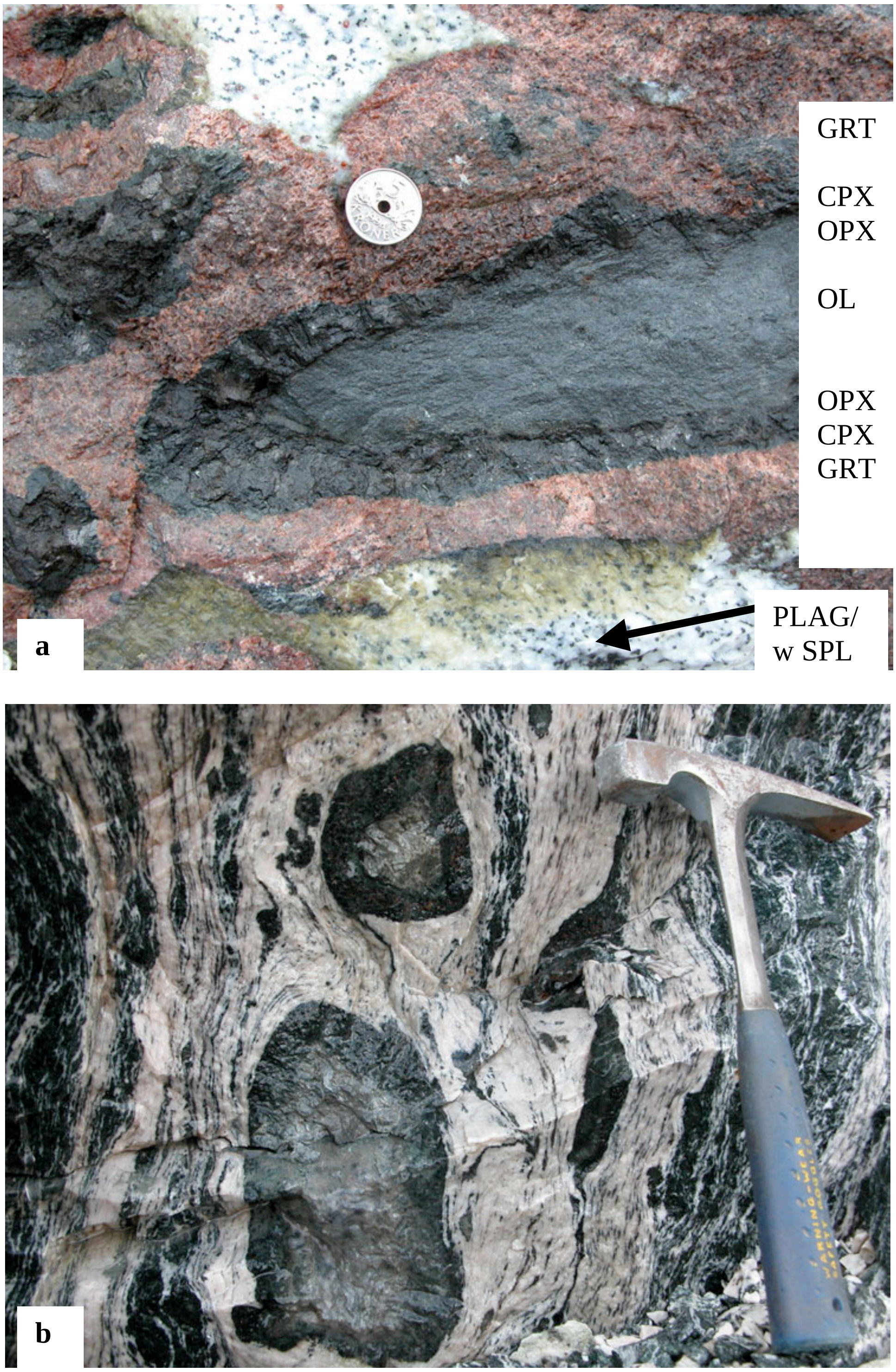


Fig. 1-1. a) Corona structure in anorthosite gabbro with olivine surrounded by orthopyroxene, clinopyroxene and garnet. The dark mineral inside the white plagioclase domains is spinel (pleonast). The corona formed during the HP granulite metamorphism in the Proterozoic Sveconorwegian orogeny at ca 950 Ma.
b) Hydrated and deformed equivalent of a). The former corona around olivine now consists of amphiboles, talc, serpentine and dolomite.

Earlier the coronas were interpreted to be formed by a reaction between plagioclase and olivine as the complex cooled from *magmatic* temperatures into the *granulite* facies. These granulite areas are found as lenses surrounded by sheared and hydrated parts where the coronas typically form augen in the gneiss structure (see fig 1-1b). Notice that the granulites form rigid blocks in the ductile deforming hydrated rocks. Several zones of eclogitization can also be found here but this is not the main topic of stop 1 and will be demonstrated in detail later today on Holsnøy.

Notice also the eclogites may form at the boundary between the granulite lenses and the amphibolites.

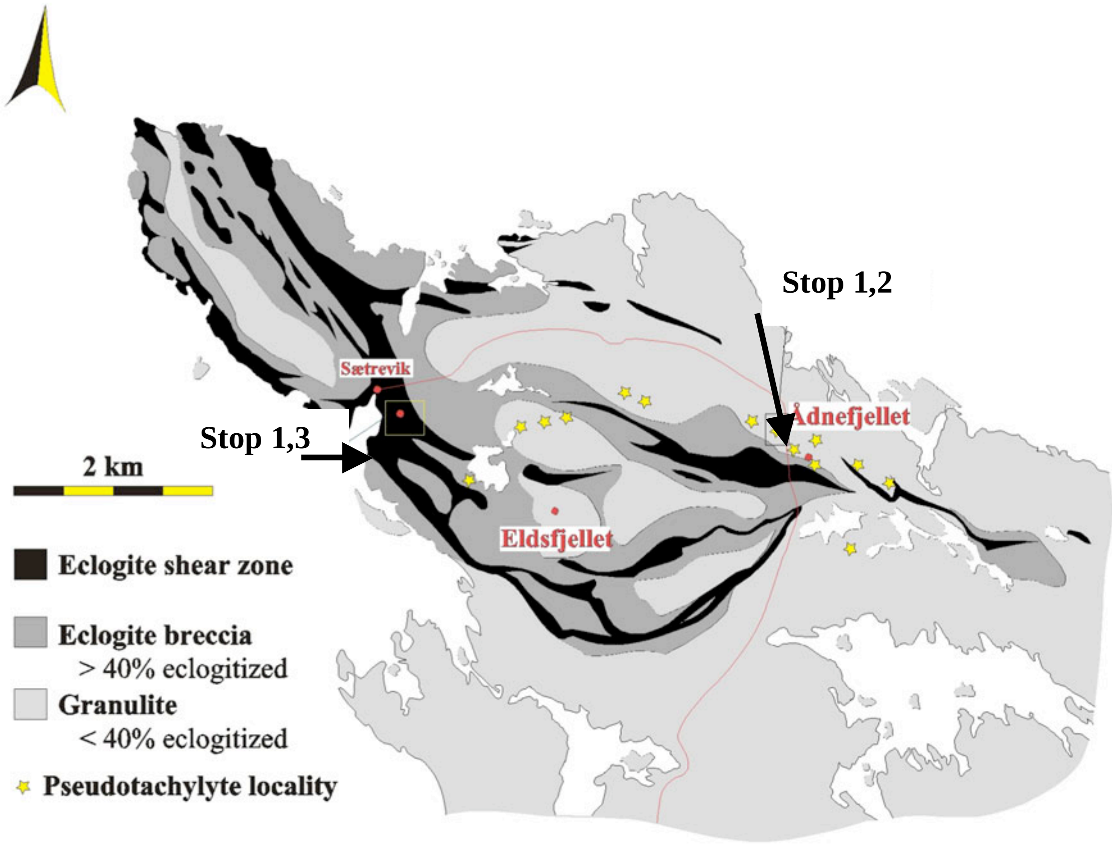


Fig. 1-2. Geological map of Holsnøy, after work by Austrheim & coworkes. Our stops at Sætrevik and Ådnefjell are marked.

Stop 1.2: Ådnefjell west, Holsnøy, Evidence for fluid-mediated eclogitization and deep crustal earthquakes

Drive across the Nordhordland floating bridge and continue to Holsnøy. Stop 2 involves a short walk, partly through bushy terrain, into an area displaying the incipient stages of eclogitization of the granulite-facies gabbroic anorthosite. We shall visit three localities in this area. The use of hammers is restricted here so please leave them in the bus!

Fig. 1-3. The famous and much photographed eclogitization vein and associated deformation at Ådnefjell. Approximately 10 cm wide, straight eclogitization fronts along both sides of an eclogite facies vein cutting the foliated granulite facies anorthosite. The colour change is due to the breakdown of the white plagioclase in the granulite and formation of the eclogites facies mineralogy (Ådnefjell, stop 1.2).

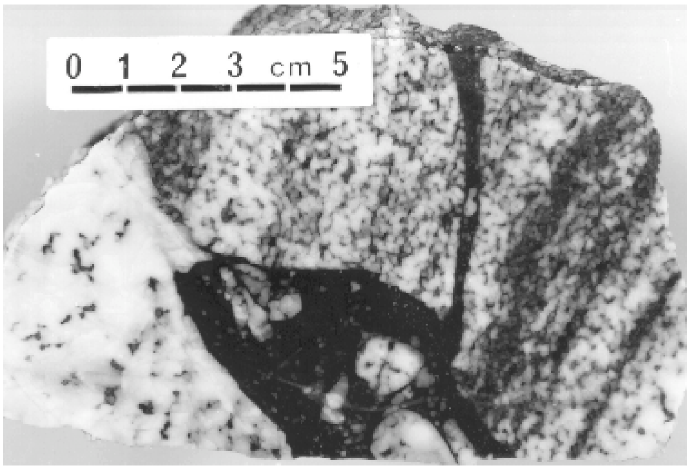


Fig 1-4. Pseudotachylyte vein with eclogite facies mineralogy, cutting granulite facies anorthosite. Note that the pseudotachylyte-decorated fault juxtaposes anorthosites of variable composition and the melt-accumulation (centre) and the intrusive relationships between veins and wall-rock.

1.2.1: Eclogite-facies veins and reaction fronts - the initiation of eclogitization

The low degree of eclogitization here permits observation of pre-Caledonian structures and mineralogy of the granulite-facies complex. A cm-scale foliation defined by alternating dark pyroxene/garnet and light plagioclase layers represent the old Precambrian structure. This structure is truncated by bands of eclogites (Fig. 1-3) containing omphacite, garnet, phengite, clinozoisite and locally kyanite. The eclogite bands are developed around central veins, which contain quartz, phengite, amphibole and locally omphacite. The transformation of granulites composed of mostly anhydrous minerals to eclogites with abundant hydrous phases requires addition of fluids. Except for hydration, the metamorphism is isochemical. The central veins in the eclogite band represent the fluid channels from which the fluid migrated into the granulite and triggered the metamorphic transformation. Note that the fronts between the dark eclogite and the light granulite are straight on outcrop scale. This contrasts with the relationships at Hundskjeften (see below stop 1.3) where eclogite forms pronounced finger-like structures into the granulite.

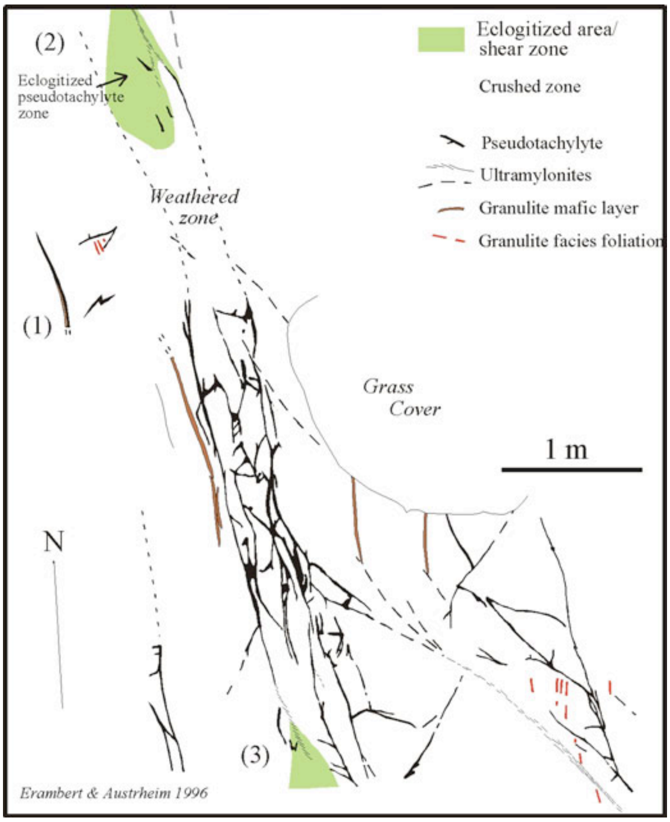


Fig. 1-5: Field outcrop map showing relationship between pseudotachylyte, cataclasite and eclogite-facies shear zone. A pseudotachylyte zone, about 0.5-1m thick, (central part) is bounded by pseudotachylyte veins and ultramylonites. It is oriented parallel to the granulite-facies layering, a common feature in this area. Veins often form at the contact of the mafic layers (1). Pseudotachylyte may pass into cataclasite or ultramylonite. The crushed zone is penetrated by a network of small pseudotachylyte veins, cataclasites and ultramylonites. Preferential eclogitization of pseudotachylyte zone is observed in (2), promoted by fluid infiltration along the fractures. (3) Tip of eclogite-facies shear zone.

1.2.2: Eclogite-facies pseudotachylytes, part 1 - evidence for deep earthquakes

The dry granulite is locally shattered by cm thick dark flinty veins (Fig. 1-4 and 1-5). At outcrop scale these veins have all the characteristics of pseudotachylytes: spatial relationships to faults, internal flow banding, and intrusive relationships with the wall rock. Note how small blocks of granulites are rotated and how the pseudotachylyte veins can be followed into the adjacent eclogite where their colour changes from black to green. Note also that displacement occurs along the thinner veins while the thicker veins commonly represent intrusive melt accumulations. Detailed photographs of these features can be found in Boundy and Austrheim (1998). The pseudotachylytes are precursor for more penetrative eclogites facies ductile shearing and at several localities at the Ådnefjell locality evidence for ductile overprint of the eclogites facies pseudotachylytes can be studied.

Eclogite-facies pseudotachylytes, part 2 - evidence for deep earthquakes

The pseudotachylyte veins on this outcrop are associated with both ultramylonites and cataclasites. What does this observation imply for our ideas about brittle ductile transition and how intermediate and deep earthquakes (>60 km) may take place in collision and subduction zones. The outcrops near Ådnefjell and many other in Holsnøy display areas where the granulite is crushed. A sketch of an outcrop is shown in Fig. 1-5 (be careful at this locality, there is a steep cliff!). Pseudotachylytes are typically interpreted as melts formed during seismic faulting. Austrheim and Boundy (1994) and Austrheim et al. (1996) demonstrated that these pseudotachylyte veins contain mineral assemblages and textures indicative of formation at eclogite-facies conditions. In addition to the Ådnefjell area, the same spatial relationship between pseudotachylytes and fluid-mediated eclogitization of granulites were observed on more than 50 outcrops. Single pseudotachylyte veins can be followed for at least 50 m and the measured displacement is up to 50 cm. The pseudotachylytes formed in mostly dry granulites enclosed by eclogite-facies shear zones. On a larger scale, the pseudotachylyte veins are found over at least 100 km^2 and preferentially associated with major eclogite-facies shear zones (see also stop 1.3). We observed that the shattering of the rocks enhanced reactions by allowing fluid to reach new volume of the granulites as discussed by Austrheim et al. (1996, 1997). Perhaps seismic faulting is an integral part of the eclogitization of dry strong rocks during subduction and collision?

Pseudotachylytes are useful rocks because we can use them to determine strength of the faulted material, assuming that most of the energy released by seismic faulting is transformed to heat. Since the work (W) done by the faulting is stored as heat we can use the simple equation: [$W = \Delta\sigma \times \gamma$] where the strain-averaged-stress ($\Delta\sigma$) and shear strain (γ) is associated with the melting of the rock along the fault vein. Since melting occurs and we assume that the ambient temperature is the same as that of the regional metamorphism we know the minimum temperature change ΔT required for the melting to take place. If the shear strain can be determined ($\gamma = d/t$; where d is displacement and t is the thickness of the fault) we can than use the heat capacity C; latent heat of fusion H; and determine the melt fraction (M) to estimate the energy released by a given single event fault episode and hence determine the stress released by the faulting (strain-averaged-stress) according to the equation:

$$\sigma_d = \rho[\, C_p(\Delta T) + H(1 - M_f)]\gamma^{-1}$$

The minimum strength of a faulted rock can be determined. This work is, however, not yet completed for the localities at Holsnøy.

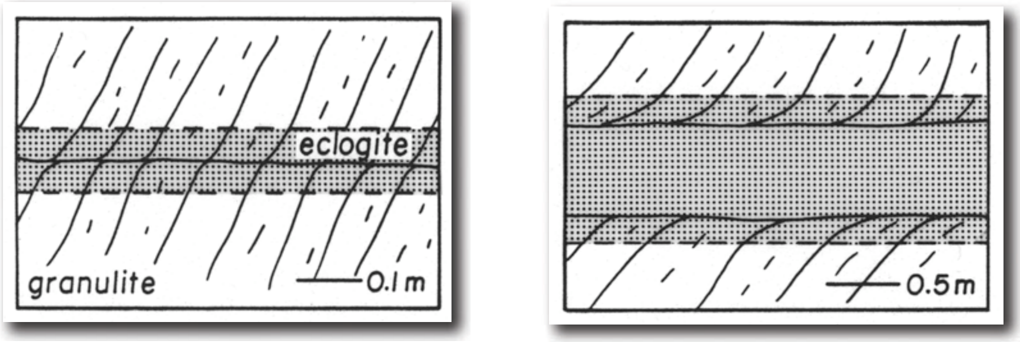
Stop 1.3: Eclogitization of the deep crust, Hundskjeften, Holsnøy

Drive to Sætrevik on northern Holsnøy. Parking by the shop and walk small road ca. 1 km along path towards Hundskjeften. If it is wet, boots are recommended. During this walk we shall study several localities and phenomena described in a number of papers from the past 2 decades.

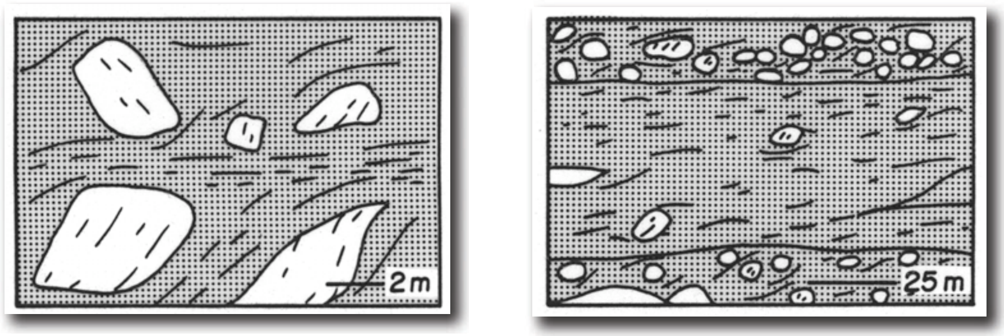
The eclogites on Holsnøy occur in three structural settings illustrated in simplified sketches below. All these modes of occurrences are well exposed in the Sætrevik area (Fig. 1-6).

Fig. 1-6 (next page)

- *1-6 a) cm to dm thick fractures and veins that contain coarse-grained euhedral eclogite facies minerals including abundant hydrous phases (phengite, clinozoisite, amphibole); granulites adjacent to the veins were converted to eclogite to varying degrees as fluids migrated from the veins into the protolith.*



- *High-strain zones that range in thickness from cm to hundreds of meters; the thicker zones can be traced laterally for several kilometers (Boundy et al., 1992; Boundy, 1995); eclogites exhibit pronounced mineral lineation and foliation. The lineation in these shear zones are dominantly E-W and unpublished kinematic analyses indicate that they are dominantly thrust-related and top-E.*



b)

- *Eclogite-facies breccias in which rotated angular blocks of granulite (dm to m across) are surrounded by foliated eclogites; breccias are often bound the major high-strain zones (below) and are composed of about 40% eclogite.*

Stop 1.3.1: Eclogite breccia - mixture of granulites and eclogites

The term eclogite breccia, as defined by Austrheim and Mørk (1998) and well displayed in the cliff in front of us, refers to zones of foliated eclogite that enclose and wrap around blocks of granulite-facies rocks, which occur as angular, lensoidal blocks typically less than 5 m across. Such mixtures of granulites and eclogites outcrop over an area of 1000 m^2 and are a characteristic and dominant unit on northern Holsnøy. Breccias, containing about 40% eclogite, are commonly developed adjacent to major eclogite-facies shear zones such as this locality where eclogite breccias bound the Hundkjeften shear zone. The presence of such lithologies in the deep crust is surprising and, unfortunately, gives us one more degree of freedom to interpret seismic velocities measured in present day deep crust and upper mantle. Austrheim and Mørk (1988) assumed that the velocity would be a linear function of the volumetric ratio of the two rock types. But it is possible that an abrupt change may occur at a certain percentage of eclogitization, which depends on the seismic wavelength and the spatial distribution of eclogites and granulites at depth. If a marked increase in velocity occurs at a low degree of eclogitization, the result will be a crust with a high velocity and a relatively low density.

Stop 1.3.2: Eclogite breccia, part 2 - rheology of deep crust

The rheology of the crust and upper mantle are generally regarded as functions of mineralogy and geothermal gradient. Most published lower crust/upper mantle depth–viscosity profiles are based on models where the rheology of the lower crust is controlled by feldspar and the upper mantle by olivine. The rheological properties of eclogite-facies rocks and the change in properties associated with the granulite–eclogite-facies transition is generally not considered. This outcrop and the next demonstrate that the eclogites have low viscosities compared to their granulite-facies protolith. Here one can observe rotated blocks of granulite floating in the eclogite matrix. The granulite-facies banding is completely disrupted in the eclogitized matrix. The remnants of the mafic bands are recognized as mafic boudins within the eclogite. The eclogite gives the impression of having flowed as a viscous fluid.

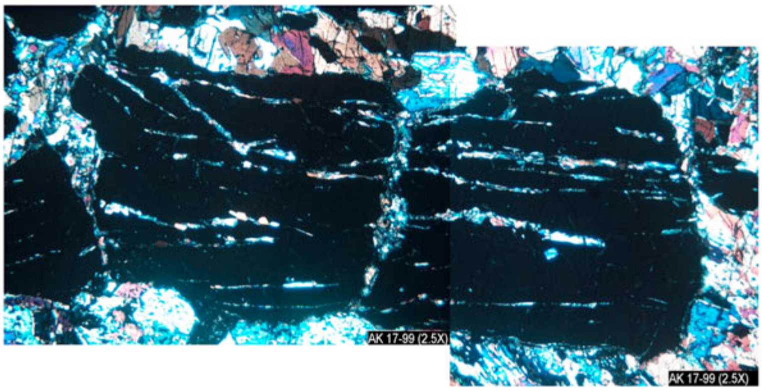


Fig. 1-7: Microphotograph of fractured garnet from an eclogite facies "finger". The fractures are oriented sub-parallel and are filled with eclogite facies minerals, omphacite, kyanite, phengite and amphibole.

Stop 1.3.3, Eclogite fingers outcrop - deep crust hydration processes

Introduction of fluids into dry granulites is a prerequisite for eclogitization in the Lindås Nappe. The mechanism by which dry impermeable deep crust is hydrated is controversial. On a large scale, fluid introduction requires the presence of permeable channels, such as faults or fractures. At Stop 1.2.1 and here we observed that eclogitization fronts are parallel to a central veins and extend only 5 cm into the wall rock. At this locality we observe that the front separating 'dry and wet' rock is morphologically unstable with the fingers extending several m into the granulites. Microtextures in the eclogite fingers demonstrate that relict granulite-facies garnet is fractured, suggesting that microfracturing allowed hydration (Fig. 1-7). Field relationships, microtextural data and a simple network model indicate that the volume change associated with the volatilization reaction led to fracturing and that transport of fluid into the initially dry rock was accelerated by perturbation of the local stress fields caused by the associated volatilization reactions (Jamtveit et al., 2000). Further, the morphology of the reaction fronts was found to depend on the anisotropy in the external stress field.

Stop 1.3.4, Hundskjeften shear zone - structure and petrophysical characteristics of eclogite-facies high strain zones

The Hundskjeften shear zone is one of several major shear zones transecting the granulites on Holsnøy (Fig. 1-8). Within the shear zones the eclogitization process is nearly complete and only remnants of granulite-facies garnets can be found. Shear zones are surrounded by eclogite breccias that consist of granulite- and eclogite-facies rocks in about equal proportion. Breccias are composed of zones of foliated eclogite that enclose and wrap around blocks of granulite-facies rocks, which occur as angular, lensoidal blocks typically less than 5 m across. These breccia zones are flanked above and below by granulite-facies anorthosites and anorthosite gabbro. The eclogite-facies shear zones exhibit pronounced mm-scale layering defined by alternating omphacite/garnet- and kyanite/zoisite-rich layers and a strong shape-fabric defined by aligned omphacite, kyanite, zoisite, and phengite. Shear zone foliations generally have a north to northeast dip of 10° to 30°. Lineation in the shear zones are defined by rod-shaped aggregates of omphacite and garnet, elongate relict corona structures, and mineral lineation. Rey et al. (1998) followed by Jolivet et al. (2005) identified a variety of macroscopic and microscopic kinematic indicators in the shear zones: sigmoid-shaped mineral clusters, S and C planes, asymmetric pressure shadows around garnets, tiling microstructures, asymmetric crystallization tails as evidence of top to the E shear for the Hundskjeften shear zone. Although these features indicate that the shear zones are normal in their present orientation, the orientation during metamorphism and deformation was probably reverse and thrust-related during the initial stages of the Scandian collision at 430 to 425 Ma as suggested by Jolivet et al. (2005), (Fig 1-10)

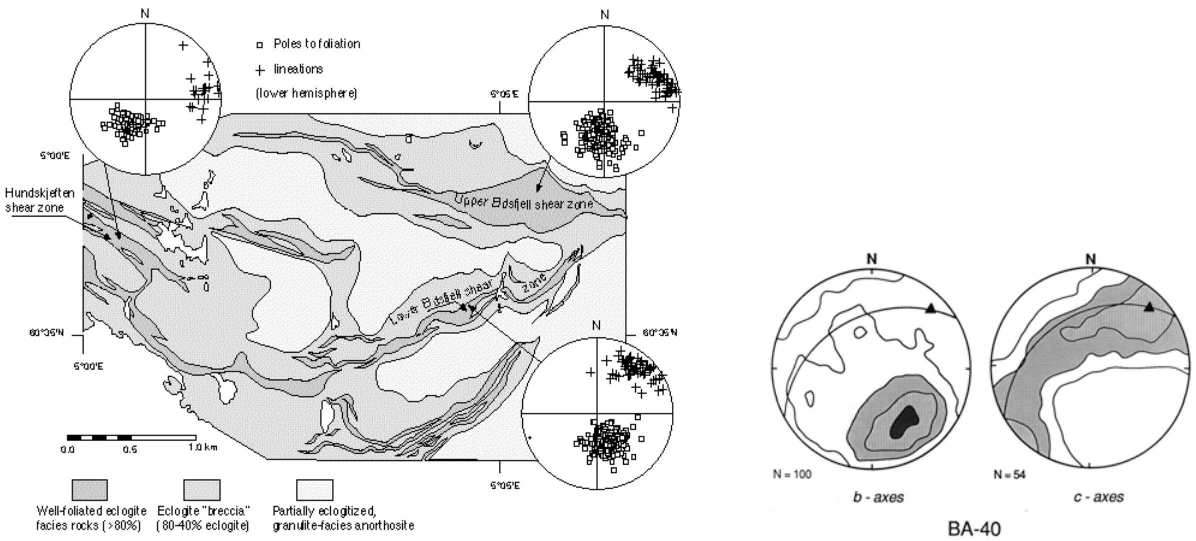


Fig. 1-8. Geologic map of a portion of Holsnøy (From Boundy and others, 1992; Fountain and others, 1994; Rey et al., 1998) showing eclogite-facies shear zones and structural data (squares; poles to foliation; + lineations). Outcrop widths are not indicative of true thickness because topography is not shown. To the right, CPO for omphacite from eclogite-facies shear zones at Holsnøy, lower hemisphere projection (From Boundy et al. 1992)

U-stage measurements of omphacite crystallographic preferred orientation (CPO) show that omphacite *b*-axis maxima are approximately normal to the foliation and *c*-axis girdles lie within the foliation plane (Boundy et al., 1992). Weak *c*-axis maxima within the girdles are approximately parallel to the lineation (Fig. 1-8).
The geometry of the shear zones and anticipated large contrast in physical properties across them led to the construction of seismic velocity profiles through structures structures. Compressional wave velocity measurements to 600 MPa for shear zone samples are reported in Fountain et al. (1994). It was found that V_p in shear zone samples ranges from 8.3 to 8.5 km/s, values generally higher than reported from reaction fronts presumably because shear zone eclogites tend to be more completely reacted. Velocities within shear zones are not uniform (Fig. 1-9) due to the effects of intra-shear zone compositional variations, degree of reaction and anisotropy. The velocity and density contrast between strained eclogites is large

as illustrated by one of our hypothetical profiles in which we show a one-dimensional profile through the two Eldsfjell shear zones bounded by granulite-facies rocks (Fig. 1-9). More realistically, because the shear zones are bounded by eclogite breccias, the velocity, density, and impedance contrasts across the shear zone boundaries may be less. However, the granulites within the breccias are matrix-supported blocks within a high-velocity matrix. How do P- and S-waves propagate through a unit like this?

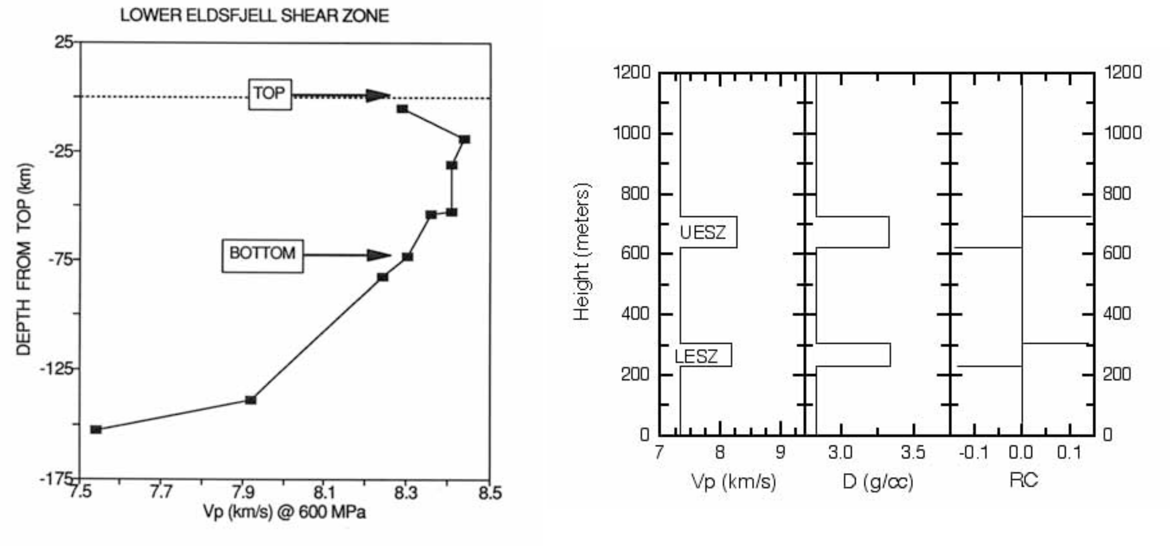


Fig. 1-9. Left: P-wave velocity profile for an eclogites facies shear zone. Right: Variation of Vp, density, and reflection coefficients (RC) through the two Eldsfjell shear zones for the case where the shear zones are bounded by granulite-facies rocks (From Fountain et al. 1994).

Deformed eclogites from high strain zones exhibit P- and S-wave anisotropy, anisotropy that, in some cases, are comparable to that reported from laboratory measurements on ultramafic rocks. P-wave anisotropy for Eldsfjell shear zone samples ranges from 1 to 7% (based on 3 minicores cut parallel to the main fabric elements) and, when present, generally exhibits a transversely isotropic pattern. Minimum V_p is generally normal to foliation and, for samples for which omphacite CPO is known, parallel to *b*-axis maxima. The fast propagation direction is parallel to foliation and, for samples for which omphacite CPO is known, lies within the *c*-axis girdles. Mauler et al. (2000) report similar P-wave anisotropy ranges and patterns are reported for non-retrogressed eclogites collected from the Monviso ophiolite complex, western Alps.

The kinematics of the eclogite facies shear zones in Holsnøy show a consistent top-E relative displacement, however most likely with a considerable flattening component (e.g Jolivet et al. 2005). The transition from coseismic deformation to major ductile shear zones is interpreted to represent the initial detachment of the leading edge of the crystalline basement of Baltica into major translation of nappes as indicated in figures below.

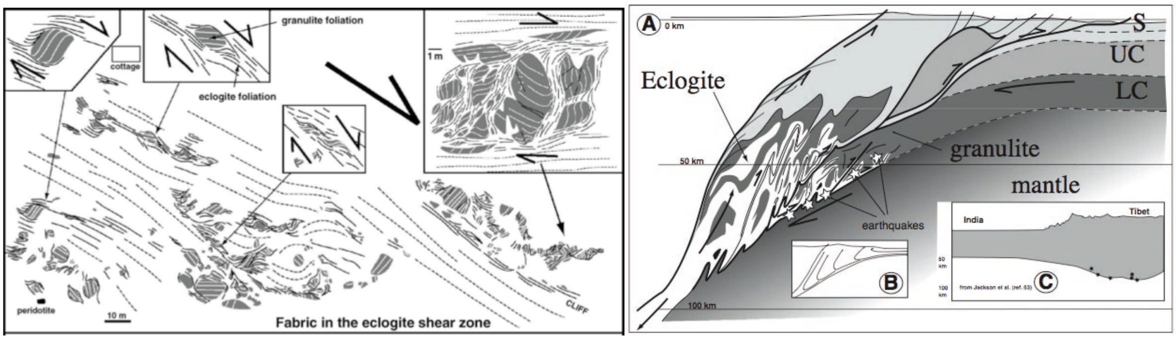


Figure 1-10. Detailed map from Hundkjeften (notice the location of a garnet peridotite) showing the asymmetrical pattern displayed by larger blocks and lenses of granulite preserved within the intense eclogite facies shear zone. Figure to the right conceptually indicates how the incorporation of deeply buried continental crust into a nappe stack may take place with initial coseismic deformation (stars for earthquakes) and later in major thrust shear zones. The model from Holsenøy is compared with interpretation of deep earthquakes under Himalaya. Figures are from Jolivet et al. (2005) and the Himalaya –Tibet section is after Jackson et al. (2004).

Additional geochemical and mineralogical information to the Holsnøy eclogites.

Geochemistry

Major and trace element geochemical analyses of cores were carried out by the geochemistry group at Washington University and published in Rockow et al. (1997). They compared chemical compositions of granulite and its undeformed eclogitized equivalent adjacent to veins in locations where a single band of granulite could be traced and sampled as it approached the vein (such as you see at this locality). Nine separate granulite-eclogite transition zones, including this locality, located at veins in anorthosite, jotunite and gabbro protoliths were analyzed. For each transition, no compositional difference between the average granulite and average eclogite composition was found at the 90% confidence level except for loss on ignition, which was consistently significantly higher in the eclogite samples. Although not significant at the 90% confidence level for any single traverse, the average eclogite concentrations of SiO_2, Na_2O, Cs, As, and Br exceed the average granulite concentrations for eight or all nine of the traverses. For most traverses, statistical analysis of the data limits any gain of SiO_2 in the eclogites to no more than a few relative percent. Other than the introduction of volatile substances, presumably an H_2O-rich fluid, eclogitization associated with vein formation was essentially isochemical.

Mineralogy

The metasomatic fronts reveal progressive mineralogical changes associated with the eclogitization process. Scanning electron microscope and electron microprobe techniques were used to quantify the detailed mineralogical changes across reaction fronts using the same cores used for the geochemical and petrophysical investigations. The granulite-facies protoliths are generally coarse-grained (1-3 mm) with granoblastic textures. They consist of diopside, plagioclase, and garnet. The more mafic granulites also contain Fe-Ti oxide (ilmenite-magnetite intergrowth) and orthopyroxene in the form of exsolved bands within clinopyroxene. Granulite samples taken nearest the eclogite overprint zone show signs of incipient eclogitization; e.g. very fine grained reaction rims around plagioclase and between pyroxene and opaque phases, and feldspar clouded with needles of mica, kyanite, and zoisite (see Austrheim and Griffin (1985) and Mattey et al. (1994) for detailed descriptions of progressive mineralogical changes associated with eclogitization). Plagioclase not only diminishes in abundance with increasing reaction progress, but the remaining plagioclase becomes increasingly sodic because calcium is taken up by clinozoisite. The samples from the eclogite overprint zones are fine grained (<1 mm) and consist of clusters of omphacite grains partially altered to symplectite (plagioclase, jadeite-poor clinopyroxene +/- opaques) and fine-granular regions of phengitic muscovite, zoisite, quartz, and kyanite. Proportions of these phases vary depending on the composition of the protolith and degree of reaction progress. Two generations of garnet are present. Granulite-facies relict garnet is coarse relative to the eclogite mineralogy and has corroded rims surrounded by amphibole. Second generation garnet is smaller, more euhedral, and enriched in Ca and Fe relative to the relict garnet (see Austrheim and Griffin, 1985). Eclogitization may not be complete in the eclogite-facies overprint zones as detailed traverses illustrate that the eclogite still contains plagioclase, diopside, and relict garnet.

Day 2, From the Bergen Arcs to the Western Gneiss Region

Day 2 will take us from Alver hotel in the Middle Allochthon of the Lindås nappe to Leirvik guesthouse situated in mylonitic gneisses the Nordfjord-Sogn-Detachment-Zone (NSDZ). We will cross the main contact between the Caledonian Nappes and the Western Gneiss Complex on the ferry across the major Fensfjorden lineament which coincide with the S-ward continuation of the main detachment (Fensfjorden shear zone).

The progressive involvement of the WGR orthogneisses into the detachment mylonites in the Leirvik region north of Sognefjorden will be the main topic of the day. However, before getting there we shall make a brief visit to a classical locality near Manger, where granulite facies monzonite was first described and named Mangerite, by C.F. Kolderup. We shall continue north and drive thorugh the village 'Austrheim', where Håkon grew up and first rubbed his nose on rocks.

The Fensfjorden lineament is sculptured along the main detachment zone separating the WGC from the Caledonian nappes, locally also referred to as the Bergen Arc Shear zone. From the ferry we will have a view NW wards towards the Byrknesøyane archipelago where the small Fensfjorden Devonian basin is exposed. Recent mapping in this area reveals that large eclogites are extremely common very close to the Devonian rocks, and that the basin sediments are separated from the eclogite bearing basement by a major detachment mylonites zone. Contacts between the basin and the mylonites are not exposed anywhere in the area. Unfortunately these rocks are not accessible without private boat transport, and have for logistic reasons chosen not to be included in our itinary.

Stop 2.1. The type locality of Mangerite near Manger, Radøy.

From the hotel take the main road across Alverstraumen bridge to Radøy and Manger

The rock-type Mangerite was first described from this locality by C.F. Kolderup in 1903. Compositionally the rock at the type locality is a mafic monzonite with the mineral assemblage: mesopertite, clino-pyroxene, ortho-pyroxene, hornblende, ilmenite/hematite scapolite and apatite. Where fresh, it has a dark colour and a massive 'igneous' appearance. The texture is typically polygonal suggesting recrystallization at granulite facies conditions. A banding defined by coarser-grained leucocratic layers can be seen. U/Pb geochronology on zircons from the granulite facies mangerite have given concordant ages of approximately 945 Ma. Notice the small zones where the mangerite takes on a slightly lighter colour apperance. This is associated with incipient hydration of the granulite. Around the Nordhordland region, the composition of the variably retrograded and hydrated mangerites form valleys and good soils and are consequently the main agricultural areas, whereas preserved the mangerites and anorthosites form hills, forrested areas with poor soils that are non-productive farmland.

Buss and ferry transport through Nordhordland into Sogn og Fjordane county

After the Mangerite type locality of we shall travel northward through the communities of Austrheim and Lindås. The ferry from Leirvåg to Sløvåg takes ca 20 minutes. We have view

to a number of the large industrial activities connected to the production of oil and gas from the Norwegian shelf, including the Mongstad oil refinery. The Fensfjorden ferry takes us from the allochthonous crystalline Lindås nappe into the autochthonous basement of the Western Gneiss Complex, the structurally lowest unit in the Caledonides. Fabrics along Fensfjorden are documents a major oblique (top-NW) extensional shear zone (Wennberg and Milnes 1994). It represents the southward continuation of the NSDZ.
From Sløvåg on the northeast side of the fjord, we continue north towards the Sognefjorden through the large-scale antiformal culmination of the WGC separating the Fensfjorden and Solund Devonian basins. Detailed mapping and geochronological work in selected areas in this region reveal an interesting evolution with Middle Proterozoic (~1640 Ma) gneisses and some partly well-preserved metasedimentary rocks affected by Sveconorwegian granulite faces metamorphism (Røhr et al. 2004). Although chiefly a Precambrian orthogneiss complex, the WGC have numerous lenses of eclogite and horizons of metasupracrustals. The WGC is dominantly amphibolite facies and has a weak retrograde greenschist-facies overprint, particularly along the extensional shear zones, but it also contains local but well-preserved Proterozoic protholits of magmatic and granulite facies rocks (e.g. Skår 1998, Engvik, 2000, Røhr et al. 2004, 2006).

The geochronology of the WGC along Sognefjorden was studied by Skår (1998), and the fabric development was summarized by Milnes et al. (1998). These rocks are mostly by granitoids and felsic migmatitic gneisses. The Lavik-Leirvik area, however, also comprises a large massif of meta-diorite and meta-gabbro, dated provisionally at ca 1540 Ma (Skår 1998). Eclogites were previously considered to be rare in the southern part of the WGC, but recently (2006) a large number of new eclogite occurrences have been identified both to the S and N of Sognefjorden, and particularly in the arkipelago between Eivindvik and Fensfjorden (in Gulen, see excursion itinary map above). Due to the logistics of the field trip we shall not visit these localities, but we may make an exception with stop 2.1 briefly described below if the ferry schedule and time allows.

Stop 2.1. Eclogitized gabbro at Botnen Camping.
Extra stop if waiting time for ferry across Sognefjorden permits
At the Botnen Camping on the south side of Sognefjorden near Rutledal ferry key, coastline outcrops of metagabbro which is partly preserved/partly reacted (?) area are exposed. This to eclogite is by no means spectacular, nevertheless it is quite typical of eclogites in WGC, which are mostly retrograde to amphibolite. The eclogite/retro-eclogites are commonly vein by quartz also a typical feature of many of the eclogites in the area. This particular outcrop has not been studied in detail and have no PT estimates have been carried out at this locality. Details of this particular body and many others in Gulen awaits further study.

The Hyllestad – Leirvik Area
The ferry across Sognefjorden comes in at Rysjedalsvika near Leirvik (Stop 2.4 Fig 2-1). The stops at the north side of the fjord will demonstrate the progressive reworking of the WGC rocks into the NSDZ. Structurally above the WGC is the Hyllestad Complex, subdivided by Tillung (1999, unpublished master thesis, UiB) into the Aksevatn psammite, Kleive mafic schist, Gåsetjørn pelite, Sæsol semipelite, and Nygård amphibolite. The lowest of these units, the Aksevatn psammite, is a quartzose metasandstone. The WGC contains structurally interleaved layers of similar-looking rocks with local pebbly layers, suggesting that this unit *may* have been deposited on the WGC (Tillung 1999). The Kleive mafic schist is characterized by hornblende + biotite + garnet + plagioclase assemblages, the Gåsetjørn pelite contains kyanite + staurolite + garnet + chloritoid, the Sæsol semipelite includes marble to calc-silicate layers, and the Nygård unit is an epidote + biotite amphibolite (Tillung 1999).

The Hyllestad Complex is ca 1 km thick and has been correlated with the Lower Allochthon (Chauvet et al., 1992; Swensson and Anderson, 1991) or the Høyvik Group of the Middle Allochthon (Tillung 1999). This is an important correlation in either case. The Lower Allochthon elsewhere contains sedimentary rocks as young as Wenlock, which would place an older limit on the metamorphic age of the Hyllestad Complex. The Høyvik Group lies depositionally on top of the Jotun-like Dalsfjord Suite, is depositionally overlain by the Wenlock-age Herland Group, and contains muscovites with ~448 Ma $^{40}Ar/^{39}Ar$ ages (see below day 5).

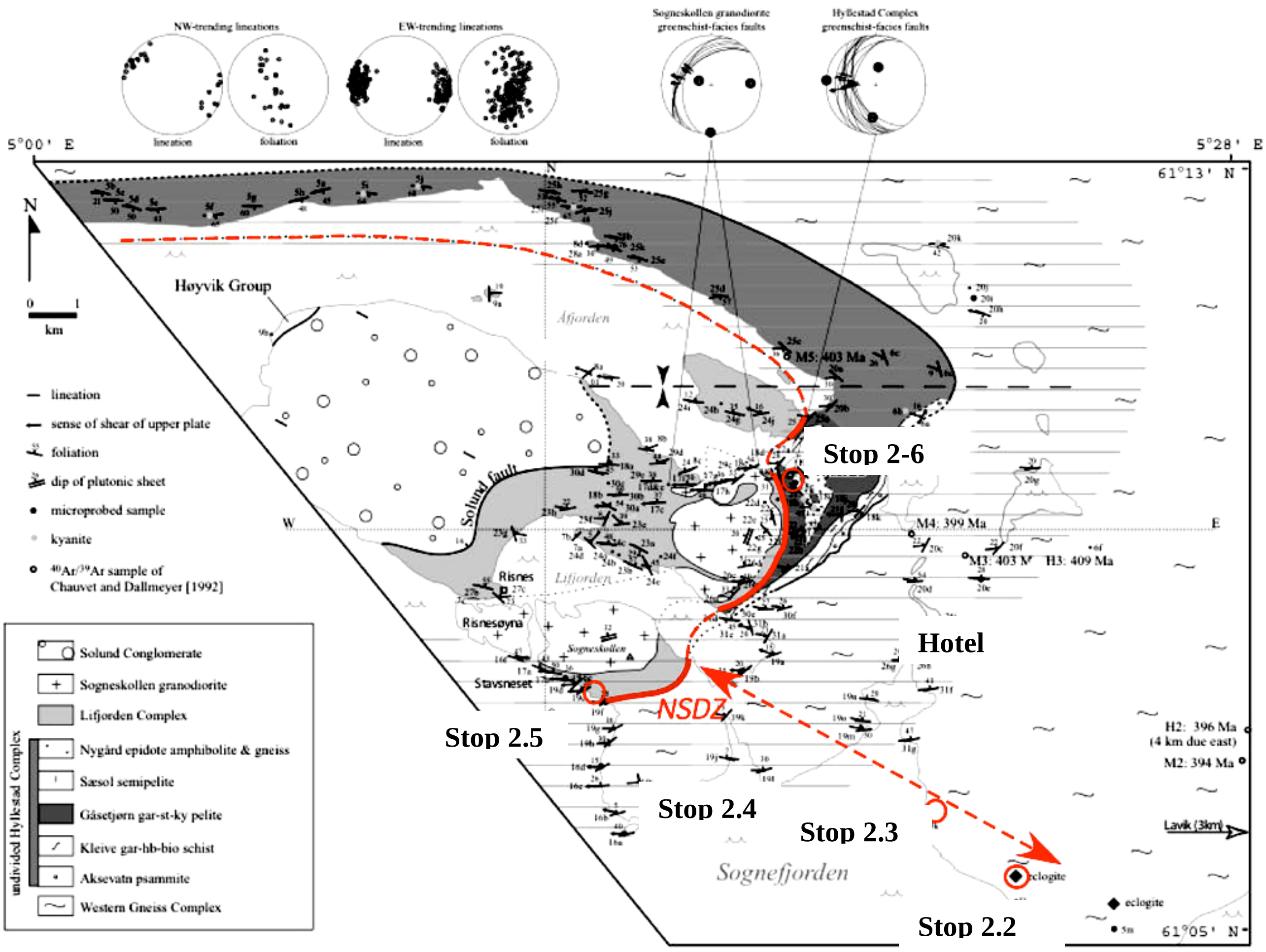


Fig. 2-1. Map of the Leirvik-Hyllestad area (modified from Tillung, 1999 by Hacker et al., 2003). Inset shows the orientations and geometry of the main structural elements. Notice the consistency in sense of shear. At the base of the Sogneskollen granodiorite however, well-preserved thrust-related structures are preserved. Red line marks the main metamorphic hiatus and the red arrow the approximate width of the NSD mylonites in the footwall of the detachment. Notice that also the hanging wall is strongly affected by extension and particularly along the Solund Fault below the Devonian basin.

The Lifjorden Complex

Structurally overlying the Hyllestad Complex is the Lifjorden Complex, which consists of ca 3 km structural thickness of mostly metagraywacke, greenschist, and greenstone, with serpentinite, metagabbro, chert, quartzose sandstones, marble, and volcanogenic conglomerate. The greenstone, serpentinite, and metagabbro occur chiefly toward the bottom of the section, whereas the top of the section is dominantly clastic (Tillung 1999). The volcanogenic conglomerates, which tend to occur in the middle of the section, include pebbles to cobbles of chiefly greenstone, plus sandstone, metagabbro, granodiorite, and quartzose rock in a volcanogenic matrix. The lithologies and deformation of the Lifjorden Complex are similar to, and probably correlative with, the Staveneset Group metagraywacke and metavolcanic rocks that overlie the Solund–Stavfjord Ophiolite (Furnes et al 1990, Skjerlie et al. 2000).

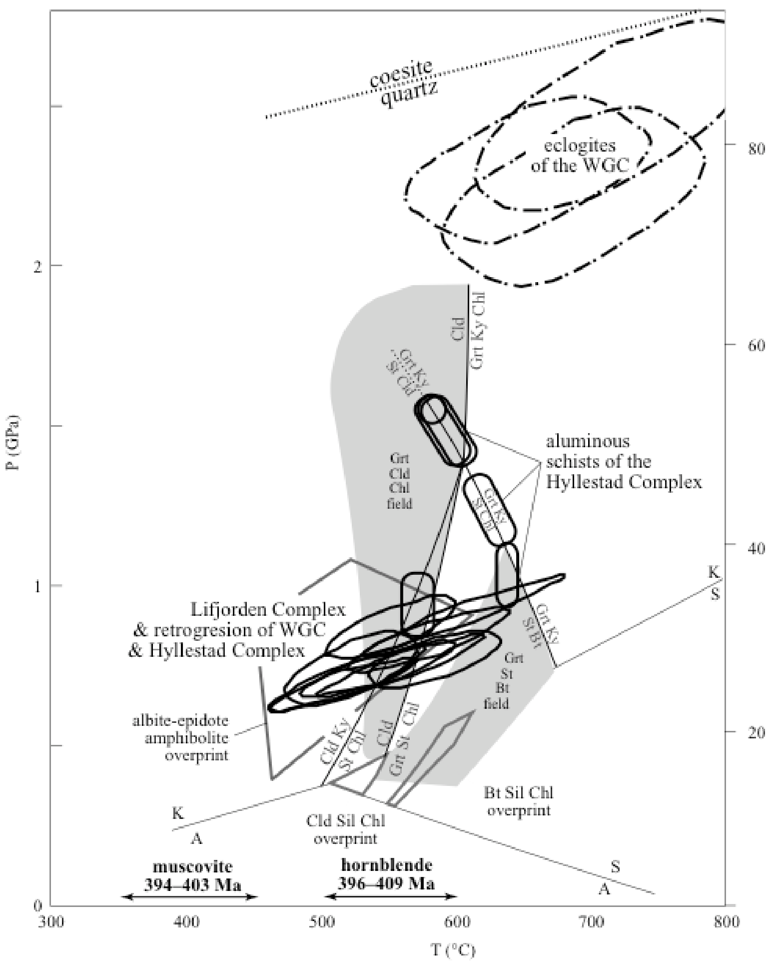


Fig. 2-2. Thermo-calc P-T estimates from the Hyllestad-Lavik area from Hacker et al. (2003). Notice that the Lifjorden Complex correlated with the Upper Allochthon and intruded by the Sogneskollen granodiorite (U/Pb zircon: 434±4Ma), show no record of HP conditions. The metamorphic hiatus occurs along the boundary between the Lifjorden and Hyllestad complexes, and there is a PT-gradient down into the gneisses of the WGC. Notice that approximate burial depth (assuming P ≈ ρgh) is shown on right hand side of diagram.

The Sogneskollen granodiorite

The Lifjorden Complex is intruded by the Sogneskollen granodiorite, which is a medium- to fine-grained leucocratic granodiorite to quartz monzonite with biotite and epidote. Epidote forms clusters of crystals commonly associated with biotite and is interpreted as magmatic (Skjerlie et al. 2000). The granodiorite is a sheetlike body that is at least 300 m thick and dips ~20° west near the axis of the synform. Skjerlie et al. (2000) interpreted the high Ba, Sr, and Na/K, and low Y, ε_{Nd}, $^{87}Sr/^{86}Sr$, and HREE concentrations to indicate formation of the Sogneskollen granodiorite by melting of hydrous sediments outside the stability field of calcic plagioclase and within the stability field of garnet. They proposed that greywackes like those of the Lifjorden Complex melted during thrusting beneath the rest of the Solund–Stavfjord Ophiolite. Recently Hacker et al. (2003) have dated the granodiorite (U/Pb zircons, TIMS and SHRIMP) to 434±4Ma. In general the pluton is strongly affected by the extension, but locally along its base the original intrusive relationships may be discerned. The granite cuts top-E contractional fabrics, and is strongly affected by extension.

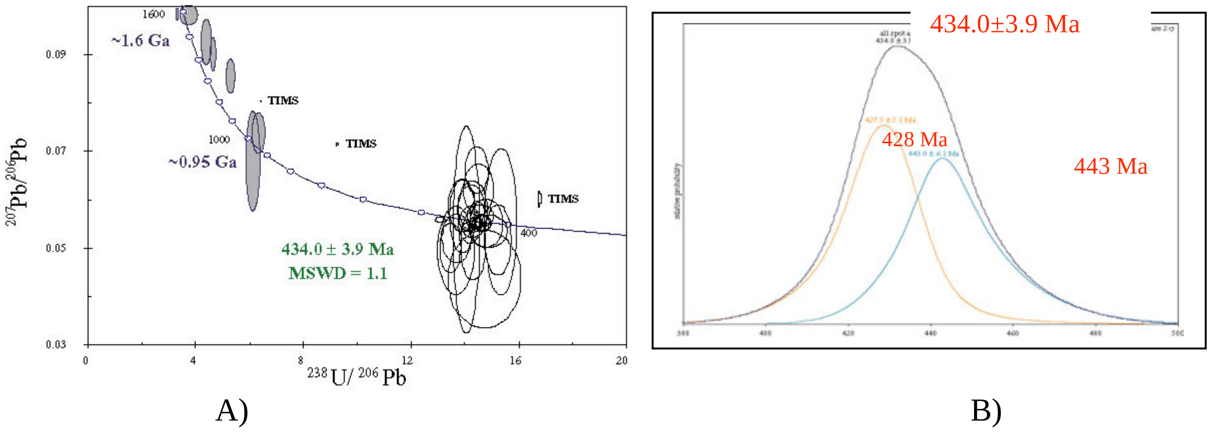


Fig. 2-3. A) Tera-Wasserburg diagram with U/Pb zircon data from the Sogneskollen granodiorite. B) Histogram of SHRIMP 238U206Pb spot ages showing that the data cannot be resolved to other than a single age. The example shown may indicate that the age distribution could be composed of two ages of 443 Ma and 428 Ma, but such populations are not statistically distinct. Both figures from Hacker et al. (2003)

Stop 2.2 Eclogite-facies boudins near Brensdal (UTM 0305001-6778022) (see Fig. 2-1). The Proterozoic history of the WGC is characterized by well-preserved intrusive relationships between various granitoid and mafic phases (c.f. Skår 1998). Eclogites are, however, locally developed and preserved, but the roadside exposures of eclogites in this area are not particularly spectacular. Nevertheless, presence of eclogites shows that also this part of the WGR was subjected to HP conditions. At a roadside locality near Brensdal, the garnet has plagioclase, hornblende, and epidote inclusions, indicating prograde epidote amphibolite facies. Phengite not included in garnet, has broken down to biotite + plagioclase symplectite. Omphacite is most commonly decomposed to plagioclase + hornblende with needlelike inclusions. Eclogites at the top of this hill (Fig. 2-1) are larger and better preserved. Thermo-calc estimates of pressure and temperature based on primary garnet, cpx (without SiO_2 rods), and phengite indicate equilibration at ~2.2-2.3 GPa and 700°C (Fig 2-2). The rocks at this locality are relatively little affected by the strains related to the Nordfjord-Sogn Detachment Zone. As we proceed westwards, however, this influence becomes very pronounced and the gneisses become progressively more foliated and eventually sheared by rotational top-to the west deformation as we enter the lower part of the NSDZ.

Stop 2.3 Felsic to amphibolitic banded mylonites gneisses with amphibolite boudins are strongly affected by the extensional fabrics related to the NSDZ; we are still located in the lower part of the detachment zone (Fig. 2-1). Most of the rocks at structurally higher levels in the detachment zone (except some gabbro of the Leirvik-Lavik gabbro) are strongly influenced by the extension and the rocks are mostly proto-mylonites to ultra-mylonites. Kinematic indicators are spectacular and show top-to-the-west movement. Kinematic indicators are invariably present in the banded protomylonitic to ultramylonitic gneisses.

Notice also the medium to large scale tight to open overturned folds with to SW vergence. These demonstrate the progressive nature of the deformation in the detachment zone and represent the latest stages of top-W to NW shearing at this structural level in the detachment. At higher levels, semi-ductile to brittle top-NW shear bands and normal faults are commonly present (see stereograms in Fig 2-1).

Continue on main road passed Leirvik towards Rysjedalsvika

Stop 2.4 Small quarry behind Rysjedalsvika ferry quay parking area

Here, in the lower middle part of the NSDZ detachment mylonites we see spectacularly folded mylonites derived from the WGC granitoid gneisses. Notice that the fold axes in these outcrops are parallel to the E-W stretching lineation. Notice also the large-scale folds exposed in the cliff-face behind the quay. The progressive, multi-stage folding of the mylonites is a good illustration of the continuous shearing and perturbation of the flow in the shear zone during its progressive evolution. Detailed strain measurements have not been carried out here but by correlation with other similar localities a shear strain of ≥20 can be indicated, implying more than 60 km displacement across the 2-3 km thick mylonites sequence in the detachment zone.

Continue towards Nesje on the narrow small road

Stop 2.5 Coast exposures NW of Nesje fort (UTM 6781953-296662)**.**

At these outcrop we are near the top of the detachment zone developed from WGC granodioritic to gabbroic protoliths. The Hyllestad Complex (P 1.5-1.6 GPa, see Fig 2-2 and below) is mostly excised between the WGC mylonites and the Lifjorden complex (Fig. 2-1). The main object of the stop is to illustrate the intense shear fabric, which is particularly well displayed by the folding and boudinage of some leucocratic intrusive veins. At the northern end of the coast section the westernmost tip of the Lavik-Leirvik gabbro forms the protolith of the mylonites. The metagabbro here is seen as coarse-grained amphibolites, locally with large garnets. There are however, no remains of eclogite facies minerals/symplectites at this outcrop. Return to bus and drive back to the main road in Leirvik and continue to Hyllestad.

Beware of slippery outcrops along the coast, particularly if surfaces are wet! Return to Leirvik and continue main road towards Hyllestad.

Stop 2.6; The Hyllestad schists

The Caledonian rocks comprise two major units, the Hyllestad and Lifjorden Complexes (see Fig. 2-1). The Hyllestad Complex may include a cover sequence (?) to the WGR as well as metamorphosed sedimentary and igneous rocks belonging to the Lower and/or Middle Allochthons. The lowermost unit comprise a metapsammite/schist sequence (Aksevatn Unit) with local pebbly (?) horizons mapped by Tillung (1999). This unit is structurally overlain by a heterogeneous sequence of mylonitic schist dominated by metapelitic rocks and also containing marble, calc-schists (Gåsetjern Unit) and mafic gneiss and amphibolite (Nygård Unit); the latter may correlate with rocks of the Middle Allochthon. The Hyllestad Complex has been affected by HP-metamorphism as shown in Fig. 2-2.

The overlying Lifjorden Complex is dominantly greenschist facies and shows no record of HP metamorphism (Fig. 2-2). The (434±4 Ma) Sogneskollen Granodiorite (Fig. 2-3) intrudes the Lifjorden Complex. There is a pronounced structural discontinuity between the Lifjorden and the Hyllestad complexes (Fig. 2-1) coinciding with the metamorphic break along the NSDZ (Andersen & Jamtveit 1990). The Hyllestad complex is excised towards the south along this structure (Fig. 2-1), which shows a transition from ductile to semi-brittle deformation.

The rocks of the structurally overlying Lifjorden are correlated with the Upper Allochthon and include highly dismembered ophiolite/island-arc complex and its volcano-sedimentary cover, intruded by the Sogneskollen granodiorite (Skjerlie et al. 2000). Although more pervasively deformed in the footwall of the Solund Fault, the Lifjorden lithologies can be correlated with the Sunnfjord Melange, the Solund-Stavfjord Ophiolite Complex (SSOC) and its cover, the Stavenes Group, in Sunnfjord. The Sogneskollen Granodiorite has been studied petrologically by Skjerlie et al. (2000), who concluded that the granite formed from partial melting of wet metasediments containing detritus from a long-time Rb-depleted source, outside the stability field of calcic plagioclase in an island-arc during obduction of the ophiolite. Minor granitoid intrusions with similar compositions and petrology intrude the SSOC and its associated rocks in the type localities in Sunnfjord (Skjerlie et al. 2000). The final emplacement of the ophiolite occurred in the Middle Silurian since the emplacement-related deformation affects fossiliferous Silurian sediments (Herland Group) at Atløy (Andersen et al 1990).

Recent U/Pb geochronology on zircons (SHRIMP) give a weighted mean age of the 434.7±3.9 Ma, which suggest that the subduction-related melting and crystallization of down-going metasediments commenced already in the Llandovery (See Fig. 2-2 from Hacker et al. 2003).

Our **Stop 2.6** will be in the road section immediately to the east of Hyllestad community centre. The road sections provide spectacular outcrops of the coarse-grained and shiny HP-micaschists carrying the peak pressure assemblage: garnet + staurolite + kyanite + chloritoid + paragonite + muscovite + quartz without biotite or talc. Fibrolite overgrow rims of staurolite and kyanite. Garnet cores contain ilmenite whereas rims contain rutile, indication up-pressure crystallization (Chauvet et al. 1992). Recent thermo-calc estimates of pressure and temperature conditions of these highly aluminous and ferric schists suggest that they have been subjected to 575-600^{O}C and 14 to16 kbars (Hacker et al. 2003), i.e. similar to the minimum pressure estimates of some WGR eclogites (se above).

The fabrics in these schists are presently dominated by the extension and the most conspicuous texture is normal-slip crenulations that can be discerned on all surfaces in the area.

An important cultural aspect of the HP-micaschist is that it was subject to extensive quarrying from the early middle ages and later. The rocks were primarily used as millstones in Norway as well as exported to other parts of NW Europe. Several large quarries have been identified in the Hyllestad area, and a museum area illustrates the production.

From Hyllestad centre we shall also have a spectacular view to the Solund Fault, which bounds the eastern and southeastern margin of the Solund Devonian Basin. This fault is activated at a late stage, probably in the Permian and possibly later. The original basin-bounding fault was however, close to the present fault as witnessed by intense cataclastic and partly ductile deformation of conglomerates adjacent to fault in the hanging-wall. The prograde metamorphism and local intense deformation of the basin is documented by work by Sturt and Braathen (2001) and by fluid-inclusion and mineralogical studies on veins cutting the conglomerates (Svensen, 2001, PhD).

Day 3 The Solund Devonian basin; 1) Basin sedimentary architecture, (2) Reaction between peridotite clasts and basin brine - a natural example of CO_2 sequestration and (3) Large-scale landslides

Day 3 itinary goes with ferry and bus from Leirvik (return) to the Solund basin where the entire day will be spent. We shall get a view of the Solund fault, seen best on the island of Losna at the south entrance to the Krakehella sound. We start the day in the basin near the depositional unconformity to the Solund-Stavfjord Ophiolite Complex (SSOC)

Introduction

The Solund basin is an extensional supra-detachment basin situated in the hanging wall of the Nordfjord-Sogn Detachment Zone (NSDZ). The SE margin is presently formed by the Solund fault, a secondary low-angle normal fault in the NSDZ-system. The basin is entirely continental in origin and deposition of the basin fill was largely controlled by tectonics. The basin was filled by alluvial and minor fluvial deposits and some very large landslides belonging to a very large fan system apparently fed by erosion from the Caledonian nappes, which constitute the depositional basement in the west and the footwall rocks of the Solund fault in the southeast. The occurrence of major landslides at low and high stratigraphic levels, together with the coarseness, thickness and basin-wide distribution of major conglomerate units supports a model where footwall catchments collapsed by land sliding following major phases of uplift. The rhythmicity of sedimentation was most likely tectonically induced and the large-scale units may be several hundred meters in thickness. The resulting topography is very pronounced with steep NW facing cliffs and large dip-slope surfaces towards the SE. Five continental Devonian basins are situated along the coast of western Norway between Fensfjorden and Nordfjord (see excursion map page 16). We will spend day 3 in the Solund basin and drive through the Hornelen basin on day 6.

The basin is unconformable on the Solund-Stavfjord Ophiolite Complex (Fig. 3-1). The 5 to 6 km thick conglomerate fan-deposits of the basin contain numerous (locally up to 20%) ultramafic boulders and pebbles probably derived from the ophiolite, and the other clasts in the basin are also derived from the Caledonian nappes. The ultramafic boulders display concentric, mm- to 10 cm thick zones of varying red to black colour shades and show a clear, alteration-related textural evolution. (Fig. 3-2 and 3-3). The least altered parts of the clasts are partly serpentinized peridotite with a typical mesh texture, where veins of serpentine and Ni-rich magnetite surround compartments of olivine (Fo_{90}) and its Mg-depleted alteration product (iddingsite, Fig. 3-4). In the more evolved stages of alteration (ophicarbonate stage), compartments are filled with calcite, silica (opal) and talc (Fig. 3-4). In the final, 'jasper-like' stage, quartz, calcite and hematite dominate the mineralogy and occur together with minor amounts of chromite, talc and a chlorite. In tandem with this textural evolution is a decrease in MgO from 40 to 2 wt % (Fig. 3-4) and a CaO increase from 1 to 35 wt %. All clasts are characterized by low Na_2O and K_2O and high Cr and Ni (1000-4000 and 500-3000 ppm, respectively). Ni is constant or increases with decreasing MgO content (Fig. 5). The chemistry and the textural evolution show that the ophicarbonate and jasper-like rocks formed by an extreme Mg-leaching of peridotite, with development of secondary porosity and infilling of calcite. Calculated apparent $^{87}Sr/^{86}Sr$ ratios of the clasts at 385 Ma, corresponding to the inferred age of sediment deposition and incipient clast alteration, range between 0.7124 and 0.7139, respectively. These values are compatible with alteration by diagenetic to anchi-metamorphic basin brines and rule out simple interaction with seawater. For basins where peridotite represents an important source rock the process outlined will have an important influence on the CO_2 and MgO budget. We will make two stops where we focus in on the alteration process that affect the ultramafics and that convert them to calcite, silica (opal) hematite. The process we see is a natural analog to the many experiments presently carried out in labs around the world attempting to sequestrate CO_2 through reaction between olivine and fluid. Reconnaissance work in the Fensfjorden basin (Fig. 1) has revealed similar red ultramafic clasts as those encountered in Solund.

Stop 3.1: Ferry trip Rysjedalsvika to Krakhella

The ca 1 hour ferry-trip from Rysjedalsvika to Krakhella (via Rutledal) provide us with some (hopefully) spectacular views of fjord and landscape. On the south side of the fjord the extensional detachment fabrics intensifies westward and create large-scale dip-slopes in the banded gneisses. On the north side, the Solund fault and basin is well exposed in Lifjell, Losna and on the islands of Solund. We shall pass by the island Losna quite closely with the ferry and will the get a good dip-section view of the fault. Notice the low-angle (~15-20^o dip) and the hanging-wall cut-off of the stratification in the large conglomerate fans, which may be more than 100 m thick. Notice also the mylonitic fabrics in the footwall and the regionally folded fabrics in the metasedimentary rocks of the Lifjorden Complex. Boudins (white) of granitoid dykes, which are similar to the Sogneskollen granodiorite, can locally be seen in the footwall.

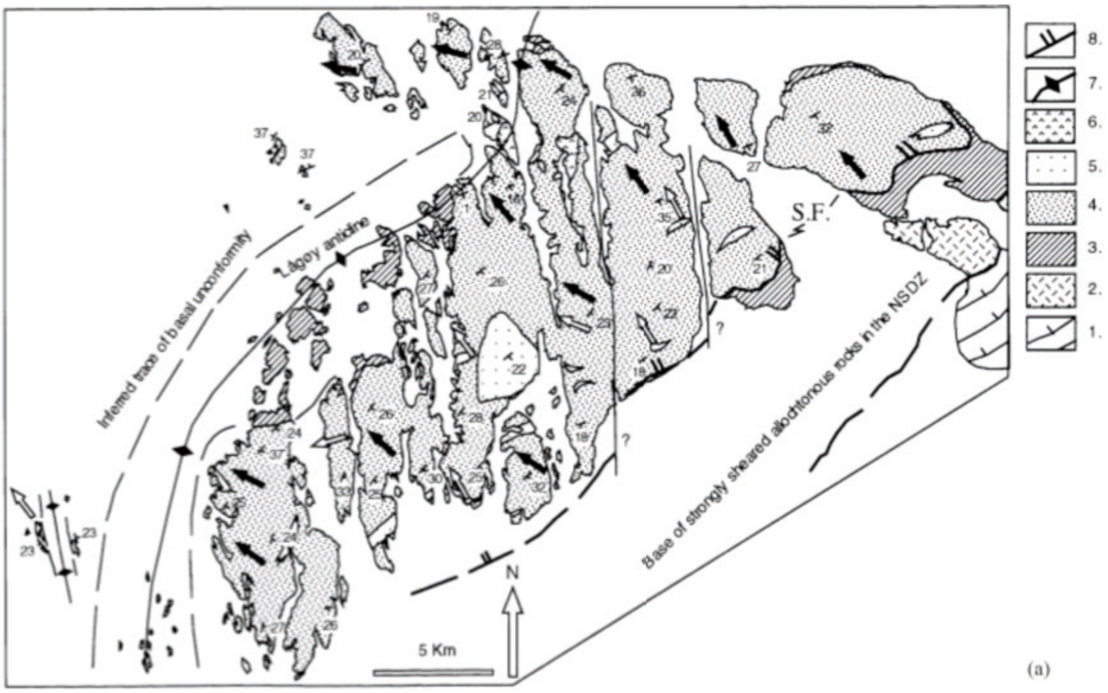


Figure 3-1, Simplified map of the Solund basin. 1) Mylonites WGC, 2) Sogneskollen granodiorite, 3) Strongly deformed, mostly ophiolite/arc rocks Lifjorden complex, 4) Solund basin conglomerates, 5) Solund basin sandstone, 6) Solund basin landslide deposits, 7) Lågøy anticline, 8) Solund Fault.

After landing at Krakhella quay we shall drive right through the basin and start the excursion at the depositional unconformity and the basin substrate. En route we call the attention to the large-scale coarsening-up-fining fans that build the basin fill and forms the characteristic topography.

Stop 3.2 East Strandavågen, Contact between Devonian sediments and varied-textured (coarse to fine) gabbro with dykes belonging to the Solund-Stavfjord Ophiolite Complex

The locality illustrates the undulating, irregular surface sculptured in the substrate of the basin. Several of such small valleys in the basin-floor topography of the Devonian basins in western Norway are filled with fine-grained red silt- to sand deposits, such as those seen in the cliff by the farm at this particular locality. Notice also numerous striated faults in the ophiolite basement illustrating the very common faulting in the depositional substrate of the basin, which on a large scale controlled the basin evolution. The Caledonian metamorphism in the ophiolite in the Solund area is relatively low greenschist facies, and garnet is not found in the metamorphic rocks of Scandian (Middle Silurian to Lower Devonian age) in this area. Some metamorphic schists found as clasts in the basin, however, contain garnet, and these may represent older Caledonian or even Pre-Caledonian metamorphic rocks derived from the Middle Allochthon in the nappes.

Stop 3.3 Lauvvika, road section between Avløypet and Hardbakke

In this locality we find conglomerate with 1-2 modal % of ultramafic clasts. The clasts display a concentric zonation typically with an outer red zone. The thickness of the red zone is variable and some of the clasts are completely altered to a red hematite stained calcite rich rock (see Fig. 3-2). Most of the clasts belong to the ophicarbonate stage, but some clasts have cores with relict olivine (Fig. 3-2) and others are altered to calcite, opal and hematite (the jasper stage). A special type of clasts has cores where with small andradite grains in a matrix of calcite and serpentine.

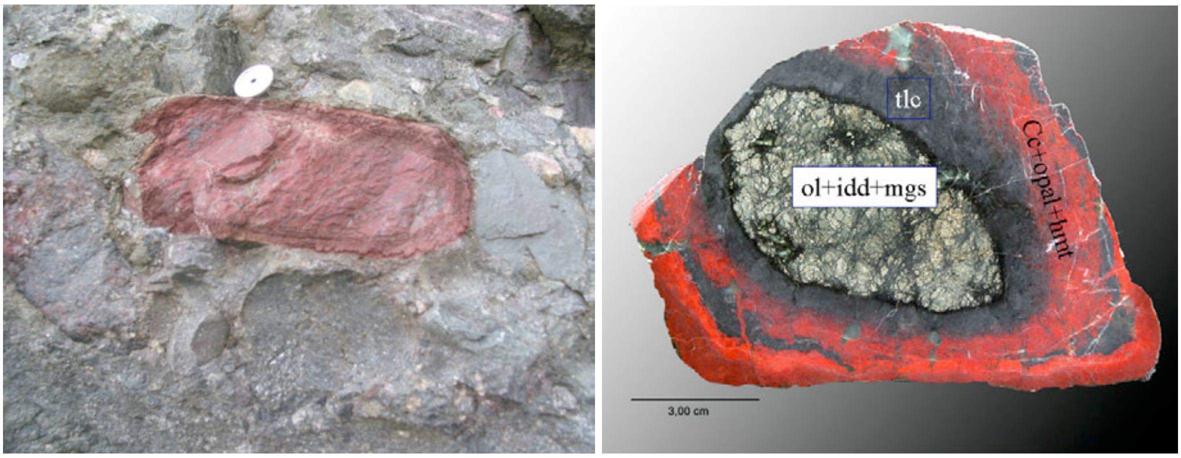
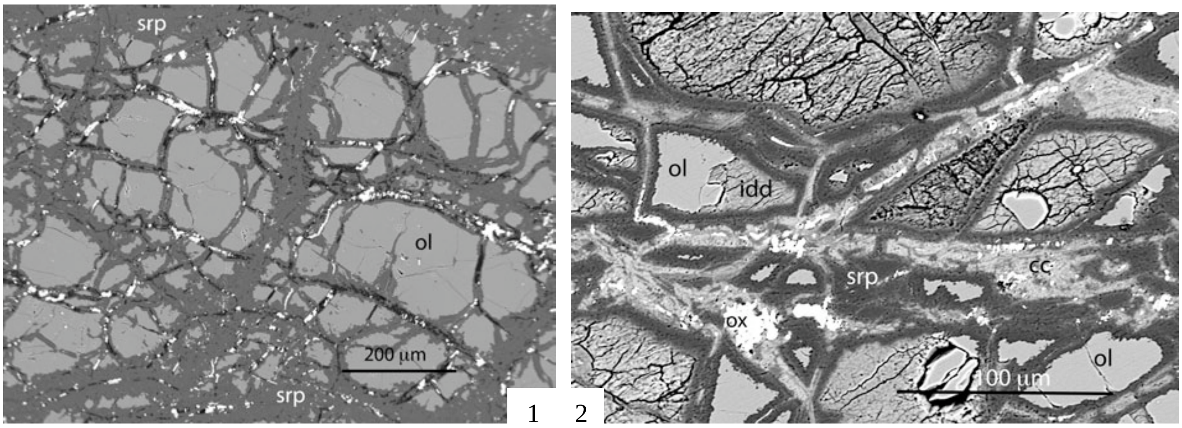


Fig. 3-2 Left: Conglomerate with a hematite stained red clast of altered peridotite. Note the concentric zoning of the clast, which suggests that the alteration occurred after the clast was emplaced in the basin. The altered peridotite is dominated by calcite and opal and belongs to the ophicarbonate group. Right: Ultramafic clast from Solund with a red outer zone of dominated by opal, calcite and hematite. The next zone inward is dominated by talc and the central zone consists mainly of olivine, iddingsite and serpentine.

Stop 3.4 Vaulen, along road from Gylta to Vaulen

In this area the red clasts are more frequent and makes up between 10-15 modal % of the total clast population. The clasts are on average larger than those at Lauvvika. Many of clasts have a core dominated by olivine and iddingsite. We will investigate in detail the concentric build up of the clasts in a road section. Then we will trace a peridotite rich layer towards the west in a short walk that also gives us a good impression of the strike-continuity of the fan units. This will give us an impression of the amount of ultramafic clasts and their influence on the present day topography. The short walk will also give us a good impression of the fan-architecture and clast population in the basin fill. Note that the layer rich on peridotite casts is more susceptible to weathering and form a steep cliff that can be followed for several km along strike. It raises the question to what extent the topography normally controlled by coarsening-up-fining-units also is influenced by composition of the sediments in individual fans.



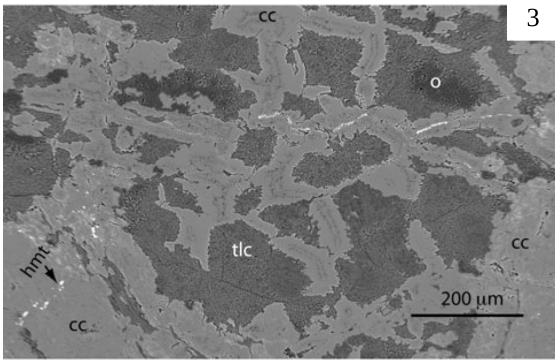


Fig 3-3. Top-left and clockwise:
1) BSE image from core of peridotite clast. Olivine (ol) is serpentinized along veins and with the development of mesh texture. Minor amount of magnesite (dark) is present together with oxides (bright) along the serpentine veins. Srp: serpentine 2) BSE image of altered peridotite clast. Olivine is serpeninized along veins and forms a mesh texture. In some of the compartments olivine is altered to iddingsite, while others are unaltered. Veins consist of serpentine(srp) and calcite (cc). 3) BSE image of peridotite altered to ophicarbonate. The mesh texture after olivine is still preserved but the rock consists of calcite, Mg-silicate and opal.

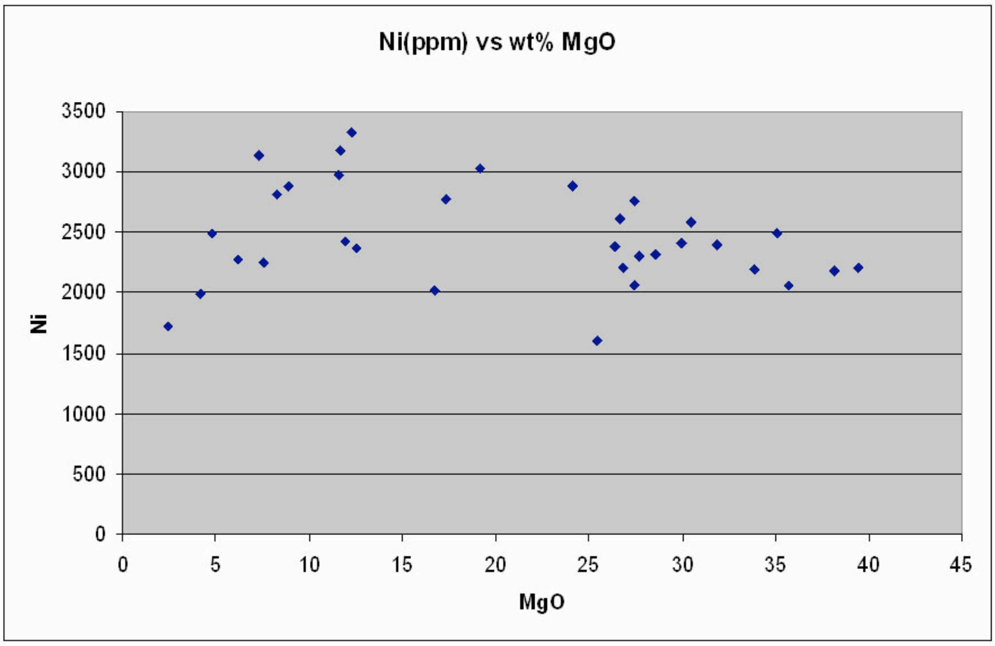


Figure 3-4. Ni (ppm) vs MGO (wt%) for altered peridotite clasts in the Solund basin. Note the elevated Ni contents, which remains high even for low MgO values in strongly altered clasts (From Austrheim et al. in prep).

Stop 3.5 Top of landslide on the road towards Hersvik, south of Husfjellet

At this stop we are near the top of the Hersvik landslide, where Devonian conglomerates are unconformable on the landslide. Fractures filled with fine-grained sand are common near the top of the landslide. The large hill, Husfjellet, to the north is all formed by the landslide body mostly gabbro. The landslide also comprises diorite and granitoid intrusives and various highly deformed metavolcanics, mylonites and schists. Ages from the landslide rocks give late Ordovician to early Silurian (U/Pb dating of zircons). Their origin have been debated and variably interpreted as Devonian lavas and intrusive rocks, Devonian thrust sheet and as landslides. In most parts of the body brecciation is intense. Recent work suggests that the fragmentation was mostly of pre-sliding origin as the breccias are also found as small clasts in the conglomerates. The hydrothermal alteration is also intense, partly pre-basin and partly post-basin in age, and most likely related to the hydrothermal activity that altered the ultramafic clasts (see above).

Stop 3.6 Road towards Leknes short walk to Skognipa, basal contact Hersvik landslide and conglomerates *(UTM 6789640-280245)*

At this stop the contact between the landslide and the underlying conglomerate is exposed. The base of the landslide is sharp and strongly deformed with local shear fabric. It can be demonstrated that the energy released as heat during emplacement of such a body may be enough to melt rocks near the contact if the energy is not disseminated to quickly. Locally pseudotachylyte has been found in the Hersvik landslide, but it is uncertain if they are related to the emplacement or older deformation. Another feature of the lower contact is that pockets of silt and sandstone are locally preserved under the sharp landslide contact (Fig. 3-6). From the Skognipa locality it is obvious that the lower contact of the landslide is planar and mostly parallel to the layering in the basin, and at this locality the thickness of the landslide reaches its maximum of 350 m. Transport direction of the landslide has not been worked out, hence the transport distance is unknown.

Return to the bus and drive back to Krakhella for ferry to Rysjedalsvika and hotel in Leirvik.

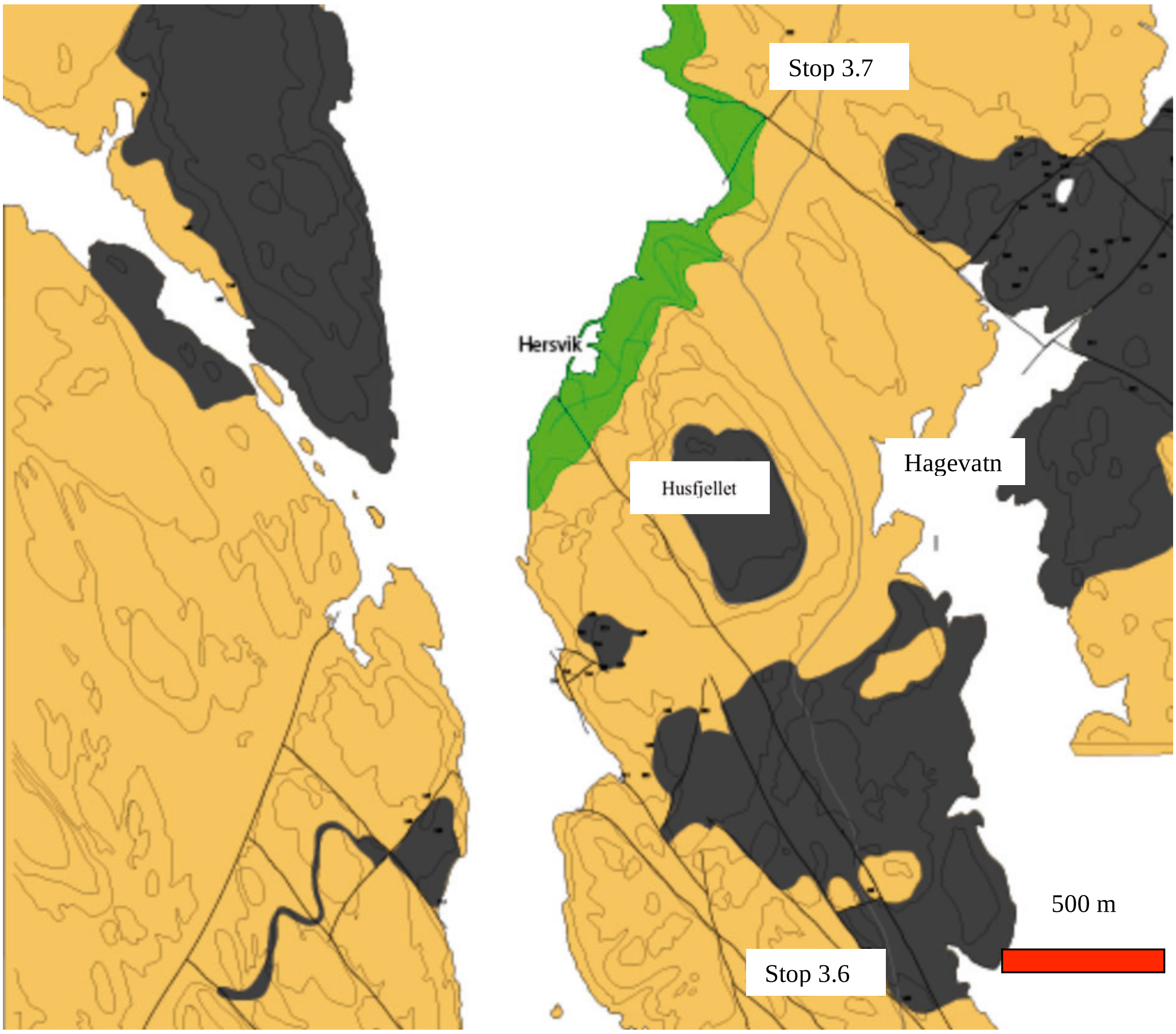


Fig. 3-5 Simplified map of the Hersvik landslide. Caledonian substrate (greenschist and metasediments/volcanics) is exposed at Hersvik (Green) and is overlain unconformably by the Devonian conglomerates. The landslide shown in dark is up to 350 m thick and extends ca 3 km laterally

Day 4 Eclogites in the Sogn to Sunnfjord region
(4.1) Drøsdal eclogite,
(4.2) Holt gabbro and eclogite
(4.3) Vårdalsneset eclogite

Bus/ferry from Leirvik to Askvoll via the coast road around Våge. The time available for the Drøsdal and Holt localities is dependent on the ferry schedule across from Fure to Askvoll, alternatively we may have to go via Dale and take the ferry to Eikenes. Several of these localities are very spectacular and we ask participants to use hammers with care and intelligence! Stop 4.2 is a more scenic stop for an overview of the geology and landscape, but also illustrates the structure in the felsic gneisses in this case the ~950 Ma Våge granite

Introduction

Eclogites in the Sunnfjord region are among the largest and most spectacular in the WGC. Because they have lower-pressure than those of Nordfjord, UHP petrologists have mostly neglected these rocks. Nevertheless, the outcrops in this region are the most important for understanding the burial and exhumation stage of the WGC, because of the proximity with the NSDZ and the Caledonian nappes. We shall visit 3 relatively large bodies.

The Drøsdal body is one of the largest and best-preserved mafic eclogites in the WGC. Eclogite facies rocks are exposed over ca 3 km^2, displaying many different types of structures related to eclogite facies deformation at a minimum depth of minimum ca 60 km and at peak temperatures of ca 630°C. The Drøsdal body does not preserve UHP assemblages, but its size and excellent state of preservation allow detailed examination of fabric development during the HP-event and subsequent exhumation. The Drøsdal body contains excellent examples of eclogite tectonite with garnet, clinopyroxene, quartz, amphibole, zoisite, phengite, kyanite and rutile present in variable amounts to define mm-scale layers, which mimic the striking cm and m-scale layers seen in the field. E-W trending isoclinal folds, boudinage, hinge-parallel lineation and meter scale kyanite-dominated veins are among the eclogite facies structures characteristic of these rocks. The best examples of folds are exposed on hills ca 2 km to the east of stop 4.1 (see Fig. 4-2); nonetheless, good examples of folding and hinge-parallel lineation can also be observed at stop 4.1. The Drøsdal body is interpreted to be a mega boudin. Although pervasively deformed during eclogite facies metamorphism, it was exhumed as a low-strain 'island' within amphibolite facies granodioritic gneisses. These show pervasive amphibolite facies deformation. The eastern and western ends of the Drøsdal body terminate by pinching out. Numerous <1m scale amphibolite facies shear zones occur at the western end of the body, and these appear to have accommodated the east-west stretching responsible for the boudinage seen at the km scale. Amphibolite facies overprinting of the Drøsdal body itself is largely confined to a narrow zone at its margins. However, structural evidence and greater exposure of the amphibolitised margin in key areas indicates that the Drøsdal body was pervasively folded on the kilometre scale during residence at eclogite facies, possibly during the earliest phase of exhumation. The amphibolite facies shear zones accommodated km scale boudinage of the body during exhumation through the eclogite to amphibolite transition.

The Holt gabbro preserves all stages of metamorphic and structural transformation from mostly pristine gabbro to mylonitic eclogites and amphibolites, recently described in detail by Engvik et al. (2007). The PT history is the same as in the Drøsdal body (~2.3GPa and 635°C). We shall focus on the most spectacular parts of the body where gabbro and gabbro pegmatite is partially to completely transformed to eclogite.

Finally we stop at the spectacular coast exposure of the Vårdalsneset eclogite (~2.3 GPa and 615°C) on the north side of Dalsfjorden. This body is particularly important because it makes contact with the detachment mylonites of the NSDZ and because we can trace all structures belonging to the exhumation of the body. It has been described in several papers and has significance for the large-scale understanding of the WGC.

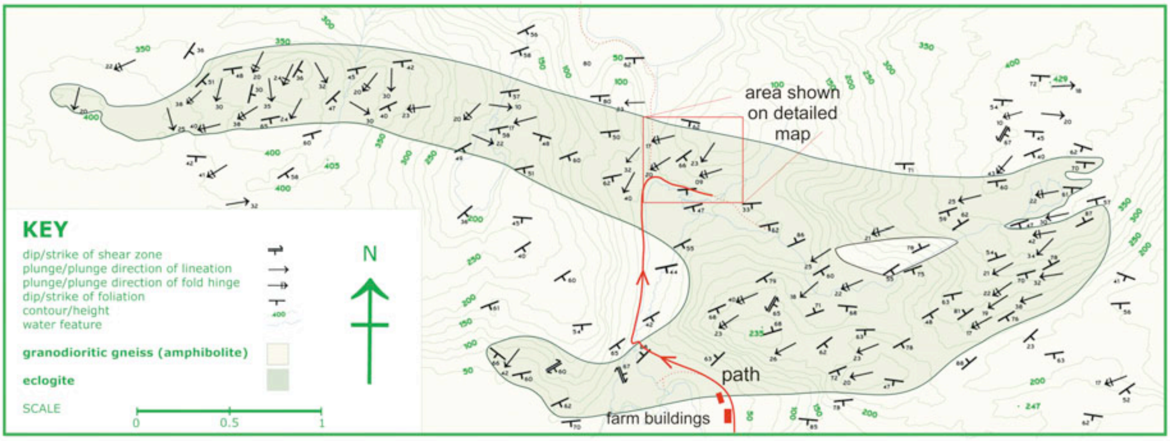
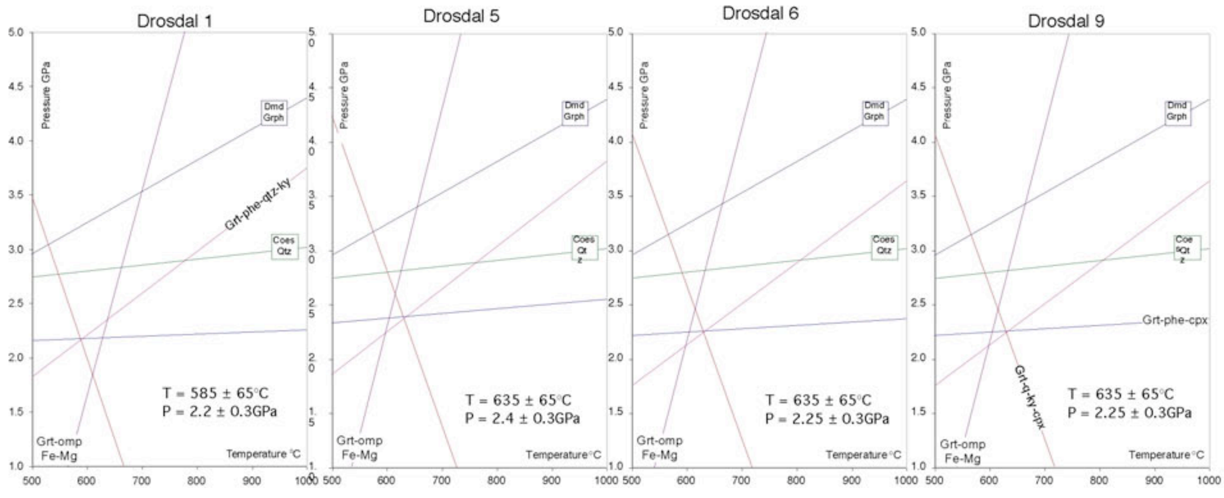


Fig. 4-2. Geological/structural overview map of the Drøsdal eclogite in the Hyllestad area. The eclogite constitutes a large and mostly well-preserved eclogite, and as such represents one of the largest coherent eclogite bodies of the WGC. We shall concentrate on the area shown in detailed map below. From Foreman et al. (2005)

Stop 4.1 The Drøsdal eclogite

Drive to Drøsdal and park cars at the farm, 1.5 km walk along farm and forest road to north side of small lake. Ask for permission to park at the farm and make sure to close the gates along the forest road. This locality show unique eclogite facies phenomenon and should only be hammered for scientific purposes. Please do not destroy the outcrops – the kyanite-rich veins are spectacular and should be left as they are. We anticipate that the stop at this locality will take ca 2-3 hours.

The most spectacular feature of this locality is that it hosts some of the largest kyanite veins found at Drøsdal and probably the largest in the WGC. The largest observed vein is several meter in length (not measurable due to lack of outcrop) and up to 0.7 m thick, and contains aligned kyanite crystals >10-20 cm in length. The veins may contain variable amounts of quartz, garnet, omphacite, phengite and rutile. A spectacular example a vein is shown on the front page of the guide. This locality is also interesting because it contains two types of lineation. The dominant lineation is penetrative and often lies parallel to eclogite facies fold hinges. It typically has a NE to SW trend and plunges range from around 15-40°. This is the main eclogite facies lineation and is found throughout the Drøsdal body in varying orientations (Fig. 2-4). The second type of lineation found locally is confined to foliation surfaces and is not penetrative. Its orientation is broadly E-W at this locality, and plunges are much shallower than those of the penetrative lineation. Rocks containing this lineation are often visibly more retrogressed than those containing only the penetrative lineation. The origin of the surface lineation is still poorly understood, but it may represent a later deformation event, perhaps related to E-W stretching during the earliest phase of exhumation.



Locality	Sample no.	Mineral assemblage	P (GPa)	T (°C)
Vårdalsneset	V5B	Grt-Omp-Ky-phengite-Qtz	2.30	635
Loc. 1 - Instetjern	FJ2BI	Grt-Omp-Ky-Qtz	2.33	629
Loc. 3 - Sørdal	FJ10	Grt-Omp-phengite-Qtz	2.25	556
Bårdsholmen	B8	Grt-Omp-phengite-Qtz	1.98	512

Fig. 4-3; Above PT estimates from Drøsdal, and (Table) from other localities, Holt (Instetjern and Sørdal), Vårdalsneset and Bårdsholmen in Sunnfjord (Engvik et al 2007, T.B.Andersen, unpublished).

Eclogite facies folds are present in abundance. In addition to the harmonic folds there are numerous disharmonically folded layers where flow has been more irregular. Partial melting as well as polyphase eclogite facies deformation can be observed in many localities at this stop. It is possible that segregations of partial melts may have been important in lowering the strength as diffuse veins, pockets and sometimes discrete dykes of quartz-rich garnetiferous and mica-rich leucosome are commonly present in the area.

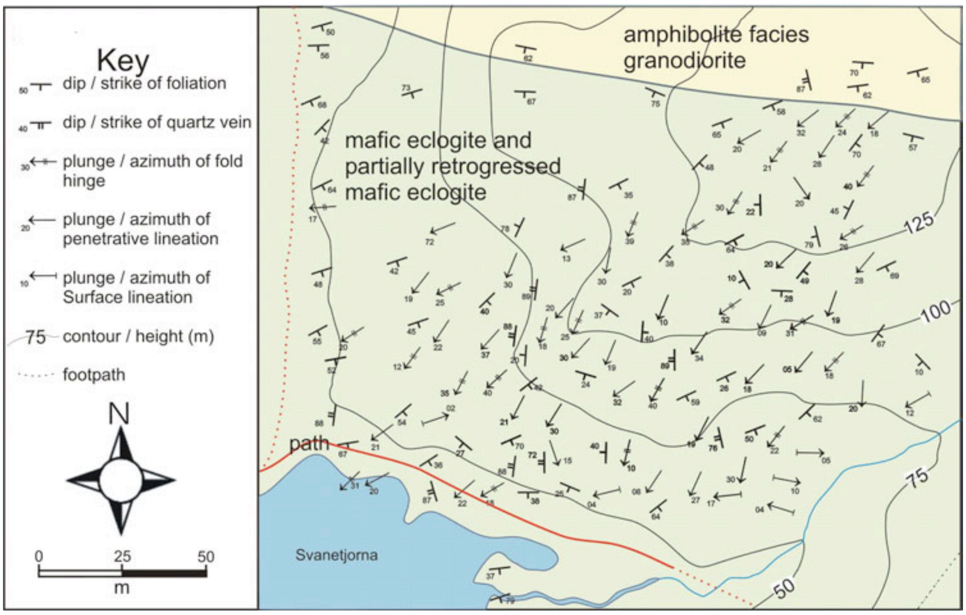


Fig. 4-4. Detailed structural map showing fabric orientation at Stop 4.1 in the Drøsdal eclogite. We shall examine in detail the eclogite facies structures exposed in the hillside between Svanetjørna and the hilltop. Notice the variable orientation in eclogite foliation and lineation at this locality. From Foreman et al. 2005

Return to the bus at Drøsdal farm and continue on the local road around headland towards Våge and Fure.

Stop 4.2 Roadside stop, mylonitic granite south of Våge *(UTM 6796552-286473)*

The rocks at this stop illustrate the typical detachment fabrics in the augen granite commonly found in the area. The Våge granite is Sveconorwegian, ca 980 Ma (Kober dating of zircon) in age. The asymmetry of the L>S shear fabric gives top-W displacement. To the SW we have view to the Solund basin. Our location is near the hinge of an E-W trending large-scale anticline.

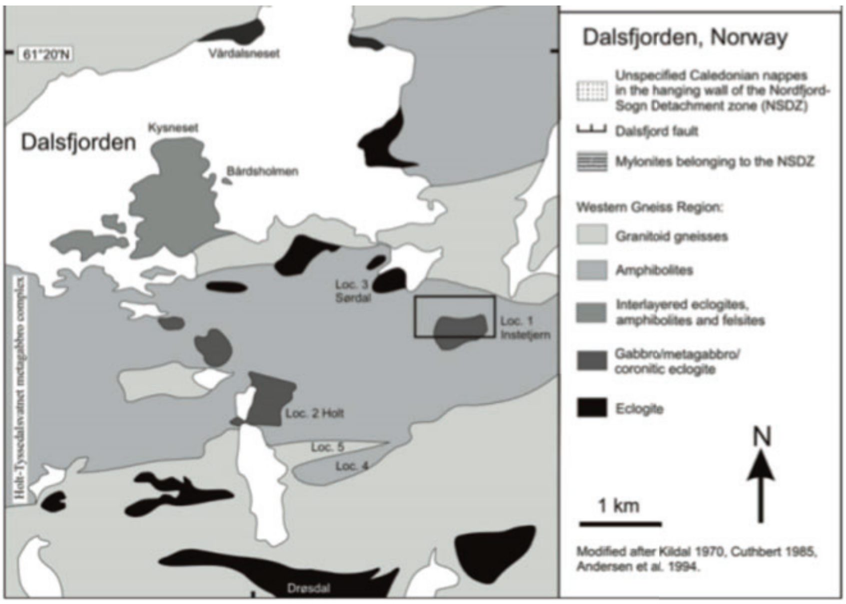


Fig. 4-4 Geological map showing main distribution of gabbro, large eclogites, amphibolite and felsic gneisses between Dalsfjord and Drøsdal. From Engvik et al. 2007.

Our stop is at locality shown as Loc 2, Holt on the map. Notice also locations Bårdholmen and Vårdalsneset shown on this map.

Stop 4.3 Holt gabbro and eclogite

Stop at Holt Farm (ask for permission at farm) and walk along forest road ca 1 km.
The Holt locality is located within a large mafic body with heterogeneous fabrics and mineralogy provisionally referred to as the Holt gabbro. The gabbro is ca 1550 Ma intruded by granites at ca 985 Ma and metamorphosed to granulite faces at ca 950 Ma (Skår, 1997, Glodny et al. 2008). It varies from mostly undeformed and metamorphosed layered to non-layered gabbro lenses, up to 1 km^2 in size, but is mostly overprinted by eclogite and

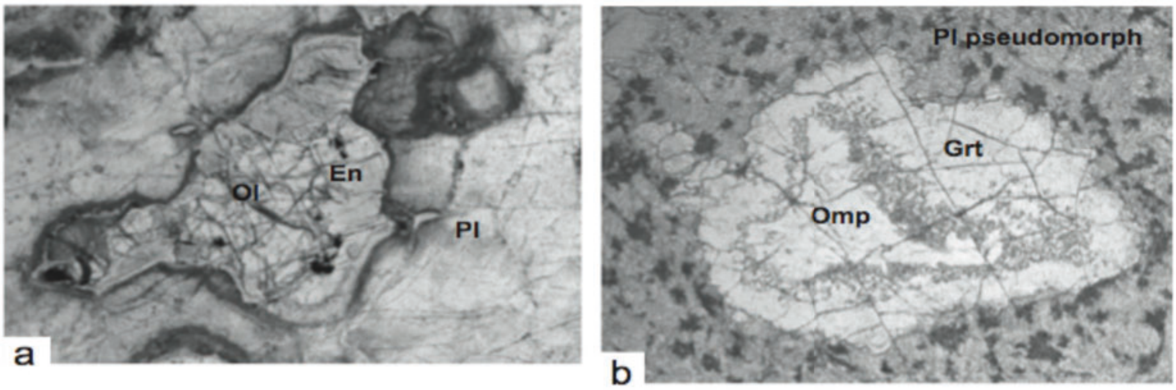


Fig. 4-5 Coronite microtextures from Holt area, a) olivine surrounded by enstatite and plagioclase in gabbro and b) omphacite surrounded by garnet corona in plagioclase pseudomorphs (from Engvik et al. 2007).

amphibolite facies fabrics/minerals. Details of the fabric evolution in this large body are described in a recent paper by Engvik et al. (2007). Eclogites are formed by static recrystallization of gabbro and gabbro pegmatite, producing coronitic eclogites and spectacular eclogitized pegmatites (Fig. 4-5). The eclogite tectonites vary from foliated and banded to localized mylonitic zones to larger L-S eclogite lenses. Amphibolitization is common throughout the area as shown by fig. 4.2.

Fig. 4-6 Eclogitized gabbro pegmatite from Holt. Left large pseudomorphosed crystals of pyroxene and plagiclase, now omphacite (perhaps symplectitic?) and garnet respectively. To the right magmatically zoned plagioclase crystals partly replaced by corona garnet (red) in contact with original olivine and pyroxene crystals.

Return to the bus and drive to take the ferry either at Fure or Dale (depends on timing).

Stop 4.4 The Vårdalsneset eclogite

At this stop (see Fig. 4-4 for location) we shall examine a well-preserved late-Caledonian eclogite, which evolved by prograde metamorphism to an eclogite tectonite with composite fabric. The remarkable feature of this locality is that enable us to study in detail the fabrics, mineral assemblages and structures associated with the syn-deformational decompression of the high-P rocks. The eclogite was mapped initially by Andersen et al. (1994) and described in detail by Engevik & Andersen (2000). Because of its position at the base the detachment zone, excellent exposures and the well preserved relationships between fabrics, mineral assemblages and structural elements of different generations, it is suggest that this eclogite represents one of the key outcrops where it is possible to work out the deformation-regimes affecting the high-P rocks from near P_{max} and during the decompression. Protoliths are not preserved at Vårdalsneset. The eclogite is structurally positioned near the base of the NSDZ. The rocks above are characterised by simple-shear and the 2 to 3 km thick zone of mylonites and fault rocks have accommodated a crustal thinning in the order of at least 60 km. The eclogite occur only a few kilometres structurally below the Devonian sediments in the hanging wall of the detachment. The map (Fig.4-7) gives an overview of the internal structure and distribution of lithologies within the Vårdalsneset eclogite.

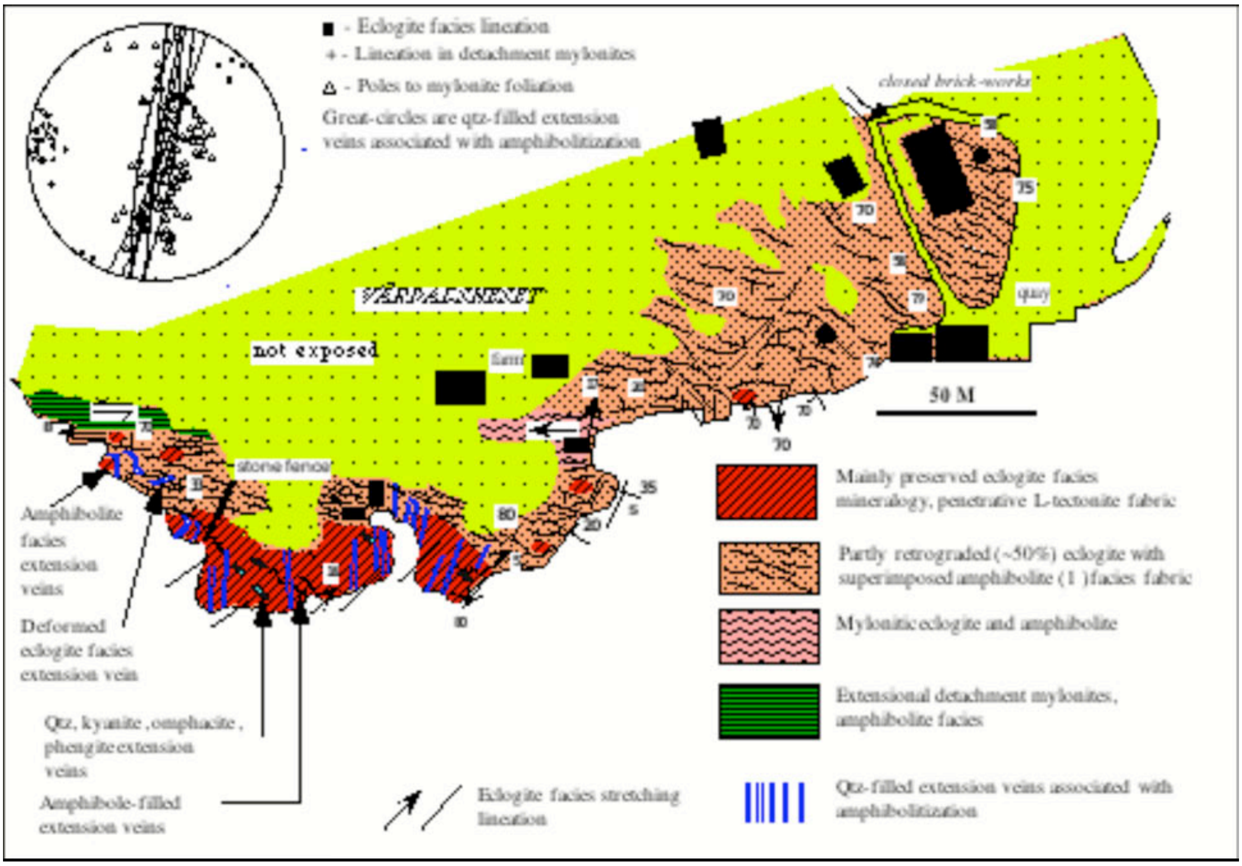


Fig. 4-7. Geological map of the Vårdalsnestet eclogite, Sunnfjord from Andersen et al. (1994).

The assemblage in coarse-grained eclogite includes garnet, omphacite$_{Jd48-49}$, kyanite, phengite, clinozoisite, amphibole, quartz and rutile. Talc and paragonite identified by microprobe analyses, occur locally and tourmaline is commonly found in quartz-rich eclogite-facies veins. A conspicuous feature of the eclogite is the occurrence of extensional veins of various generations, formed during both eclogite facies and later deformation events. The formation, relative chronology and deformation of the veins are of critical importance for models of exhumation suggested for the WGR.

The early eclogite tectonite fabrics record constriction. Andersen et al. (1994) suggested that these fabrics originally formed by bulk sub-horizontal shortening and vertical stretching of the deep crust during continental collision and subduction of Baltic crust. Eclogites with a high content of kyanite, quartz, phengite and clinozoisite often display strong linear fabrics. These fabrics commonly have a high angle to the later decompression-related structures, which were subhorizontal prior to the late E-W trending regional folds. The fabrics that developed during decompression are of two main types. Planar fabrics dominate the deepest sections, and kinematic analyses indicate that the strain was dominantly non-rotational. The orientation of this fabric with respect to the way-up direction in the crust suggests that it was formed by vertical shortening and sub-horizontal E-W stretching. PT characterizing the second-generation eclogite facies fabric cannot be distinguished from the first generation constriction within the analytical uncertainty. The eclogite fabrics are, however, reworked by progressive amphibolite facies deformation; the deformation is apparently co-axial with the earlier eclogite facies (see Fig. 4-3, table).

The eclogite- to amphibolite facies coaxial fabrics are overprinted by non-coaxial, shear fabrics related to deformation in the NSDZ. Detachment mylonite fabrics with abundant top-W kinematic indicators are present in the shore section at the western end of the eclogite. The detachment in Sunnfjord separates exhumed deep-crustal rocks from rocks characterised by medium- to low-grade Caledonian metamorphism. Unfortunately a boathouse has recently (2005) been built on the outcrops showing the contact of the eclogite and the felsic gneiss at the western end of the eclogite. Several outcrop of partly to completely retrograded eclogite are found to the west of the outcrops visited, and the Vårdalsneset eclogite also continues across the fjord to the east (Fig. 4-4) and makes it one of the large eclogites in the WGC.

Return to the bus and drive to Askvoll fjordhotell

Day 5, The Caledonian infrastructure in the Sunnfjord region and its significance for understanding regional evolution of the Caledonides

Bus and ferry from Askvoll via Atløy, Førde to Florø. The main object of the day is the Caledonian nappes of the hanging wall of the NSD particularly well displayed on Atløy and Stongfjorden area. En route to Florø we shall return to the WGC make some stops mostly for view of the regional structure

Main object of day 5 will be to study in detail, fabrics related to mylonitization and fault reactivation of the NSDZ in the Sunnfjord area, the Dalsfjord Fault, which presently mark the top of the detachment. The Caledonian stratigraphy and tectono-stratigraphy in the hanging wall detachment is particularly well illustrated on Atløy. At the end of the day we will proceed to Florø for overnight at hotel. A summary of the stratigraphy, teconostratigraphy and age determination in Sunnfjord is given in Fig. 7.

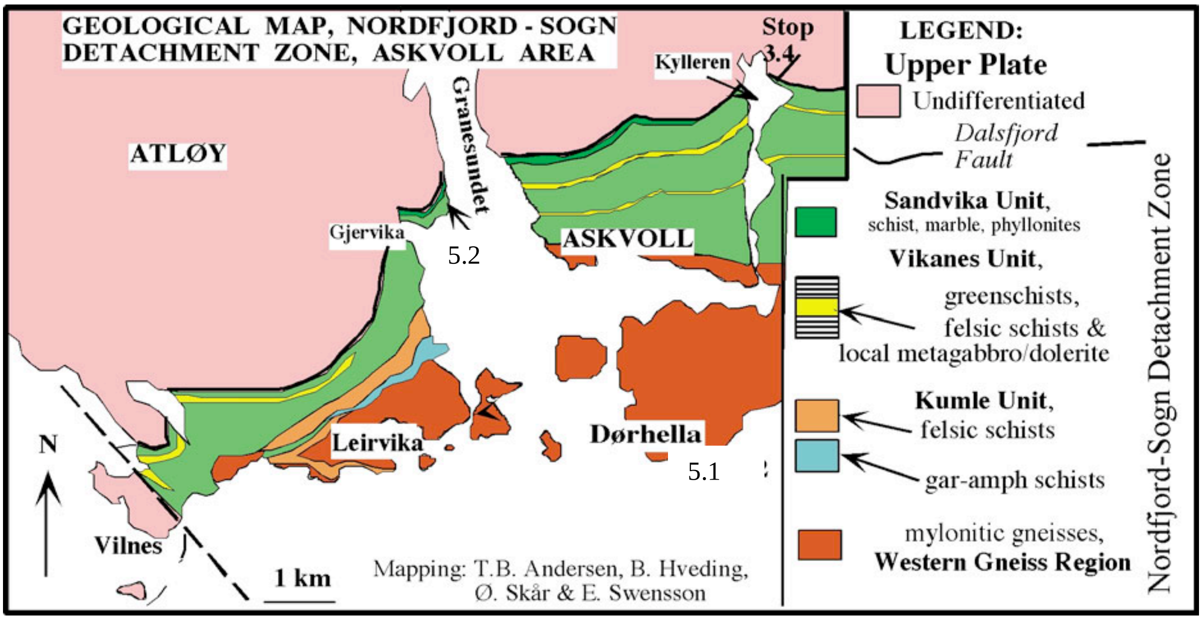


Fig. 5-1. Simplified map with stops in the Askvoll area; at mylonitic banded gneiss at Dørhella and at the top of the mylonites near Gjervik and the Dalsfjord fault plane.

Stop 5.1 Detachment mylonites at Dørhella coast section SE of Askvoll

Stops 5.1 and 5.2 will take us up through parts of the detachment mylonites in the NSDZ (see also the introduction and Marques et al. 2007 for details). An U/Pb zircon age of 1640 ± 2 Ma from a highly deformed quartz-dioritic rock at stop 5.2 on Atløy indicates that these are highly deformed WGR lithologies (Skår et al. 1994). The locality at Dørhella comprises spectacular banded WGR gneisses with a proto- to ultra-mylonitic texture. The section along the coast is on average parallel to the E-W stretching lineation in the mylonites, hence ideal for observing the kinematic indicators in the mylonites. The progressive deformation, i.e. folding, re-folding and formation and transposition of already formed structures in a mylonite zone is particularly well displayed in these outcrops. The outcrops have a range of spectacular kinematic indicators.

Stop 5.2 Detachment mylonites and fault-rocks in the NSDZ and the Dalsfjord Fault, the coast section and road north of Gjervik, Atløy

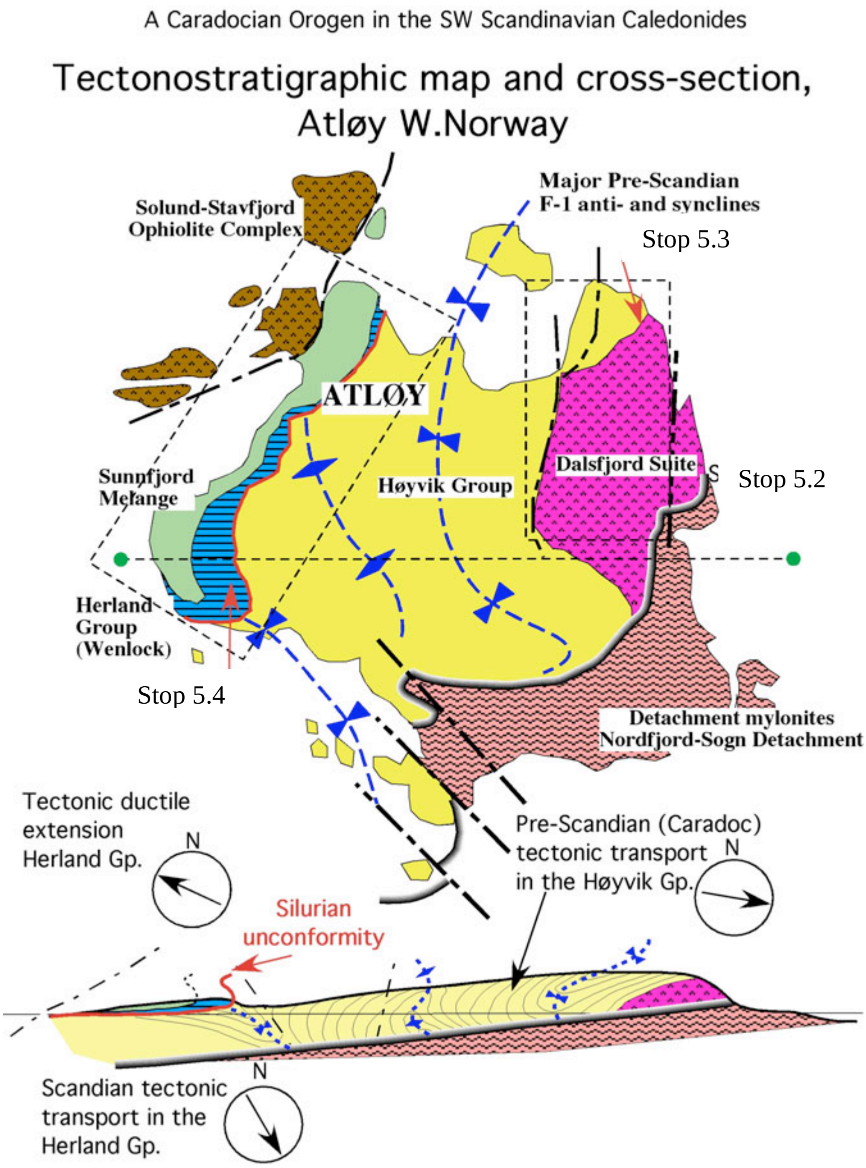


Fig. 5-2. Simplified geological map with excursion localities in the hanging wall of the NSDZ on Atløy. Axial traces of large-scale folds (overturned to recumbent, in blue) are pre-Herland Group unconformity. Notice also that the Sunnfjord Melange is directly on the Høyvik Group on northern Atløy. This contact is a low-angle angular unconformity, thus 3 major unconformities are preserved on Atløy; the Dalsfjord Suite - Høyvik Gp contact; the Høyvik-Herland Gp contact and the Herland Gp-Sunnfjord Melange contact.

The section north of Gjervik (Fig. 5-1, 5-2) allows examination of amphibolite to greenschist facies mylonites in the uppermost parts of the NDSZ, and the brittle fault rocks marking the boundary to the hanging wall of the detachment. Structurally above the mylonitic gneisses studied at locality 5.1, the detachment zone comprises a tectonostratigraphic sequence described by Swensson & Andersen (1991). From base upwards: The *Kumle Unit* (max thickness 200 m) comprising inter-banded felsic schists and phyllonitic garnet-amphibole mica-schists with lenses of coarse-grained garnet amphibolite. The *Vikanes Unit* (max. thickness 1500 m) dominated by mafic to intermediate mylonites (now mostly greenschists) and also containing laterally persistent, horizons of felsic schists and lenses of gabbro, locally with preserved igneous textures (Skår et al. 1994). The *Sandvika Unit* (max thickness 300 m) dominated by grey and green phyllonites, locally with massive sulphide mineralization, quartz schists and thin marble horizons. The mylonites above the banded gneisses (Stop 3.2) thus have a structural thickness in the order of 2 km.

A)

B)

Green breccia (Permian)
Red Breccia (Late Jurassic)
Fault Gauge (Age unknown)
Fractured greenschist facies mylonites

Fig. 5-3. A) The Dalsfjord Fault marking the top of the NSDZ on Atløy. H. Austrheim is pointing to the late fault plane shown in (B) decorated by red fault breccia (Jurassic) and a weakly consolidated fault-gauge, which are truncating green breccias (Permian) in the hanging-wall and brecciated green mylonites (Devonian) of the footwall.

The spectacular green (Vikanes Unit) to grey (Sandvika Units) mylonites on the headland south of the road tunnel, displays a variety of textbook kinematic indicator examples, which demonstrate the top-W shear sense on the detachment. Late N-S trending joints and breccias cutting the mylonites are probably Late-Mesozoic fractures. A small chalcopyrite/pyrite mine was worked (late l9. century) on massive sulphide in the greenschist mylonites.

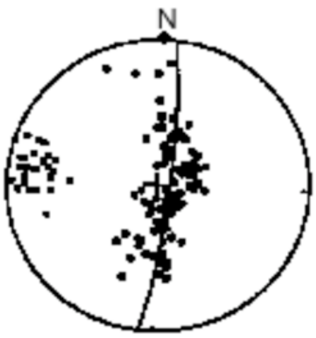
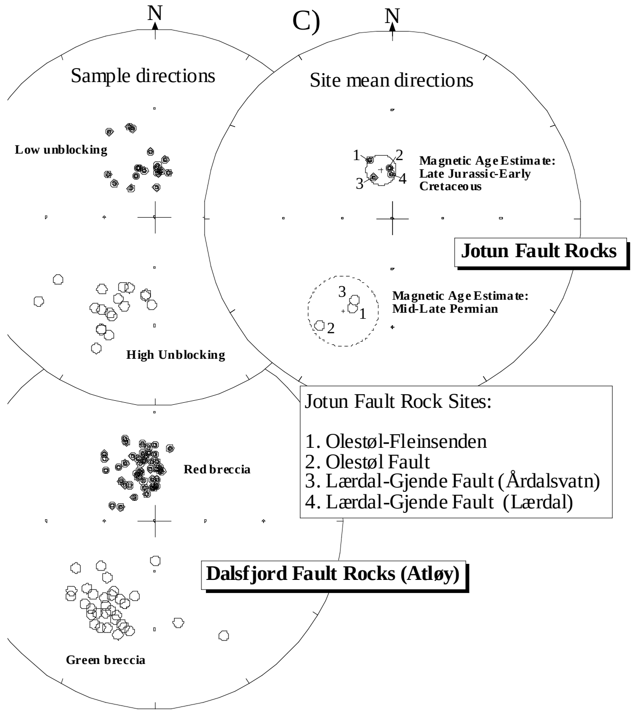


Fig 5-4. Stereographic projection of folded detachment mylonite foliation and E-W stretching lineation in the area around Gjervik (stop 3.3) and on the mainland of Granesundet. The measured field structural field data coincide with the magnetic fabrics from the mylonite zone (Swensson and Andersen 1990, Torsvik et al. 1990)

Near the top of the detachment zone the mylonites are brecciated. The contact to the hanging-wall is located along a sharp, well-defined fault plane, the Dalsfjord fault, which is exposed in the road-section near the tunnel on the road towards Høyvik (Fig. 5-3). The fault is decorated by green and younger red-stained breccias and a weakly consolidated fault-gauge. Geological, palaeomagnetic and radiometric work of the breccias all indicate multistage reactivation of the fault, a Late Permian age from the green breccias, (248-260 Ma), the red breccias younger than 162 Ma (Upper Jurassic) and fault gauges younger than 96 Ma (Torsvik et al. 1992, Eide et al. 1997). It is particularly interesting that these ages correspond with major stages of extension in the North Sea, and that these events also affected major parts of southern Norway (see Fig. 5-5). Modelling of Ar-spectra from K-feldspar in the area also suggest an important rapid cooling event of late Devonian to early Carboniferous age, not recorded in the palaeomagnetic data. The cooling event may be correlated with final stages of the folding affecting the entire crustal sequence in western Norway including the Devonian basins (Eide et al. 1999).

Fig. 5-5. Magnetic poles from fault breccias, showing two-stage magnetic remanences from major post-Caledonian faults in Western Norway (Dalsfjord) and from Jotunheimen in central south Norway.
Notice a close fit between the remanence poles of the 3 faults from which data have been collected. This demonstrates that major fault breccias were formed and (re)magnetization in a wide area at a broadly similar time in the Late Permian and Late Jurassic/early Cretaceous
(Data from Torsvik et al. 1990 and Andersen et al. 1999).



The protolith of the green and red breccias in the hanging wall of the fault are derived from the allochtonous, Middle Proterozoic Dalsfjord Suite recently dated (see Fig. 5-6) by Corfu and Andersen (2003). Large fragments of the protolith are preserved in the breccias a few meters above the fault plane at the tunnel entrance. A traverse along the road through the tunnel shows that the zone of brecciation is several tens of meters wide.

Stop 5.3 Non-conformity between the Dalsfjord Suite orthogneisses and the Høyvik Group at Kvitaneset.

The contact between the Høyvik Group and Dalsfjord Suite lithologies is locally preserved as a nearly undeformed primary non-conformity on northern Atløy (Fig. 5-2 & 5-7). The contact relationships exposed by the road is somewhat disputable due to strong foliation developed during the Middle Ordovician (ca 450 Ma) pre-Scandian orogeny. Near the top of the hill to the west, however, the depositional contact including a basal conglomerate is remarkably well preserved (Fig. 5-7). The Dalsfjord Suite comprises banded felsic gneisses, less deformed gabbro, monzonites and alkaline mangeritic rocks. Monzonitic rocks of the Dalsfjord Suite contain abundant mesoperthite, which is commonly found as typical clastic grains in the psammites of the Høyvik Group. Regionally the Dalsfjord Suite rocks have been correlated with similar rocks in Jotun and Lindås Nappe and the recent age data support this interpretation (Corfu & Andersen 2003).

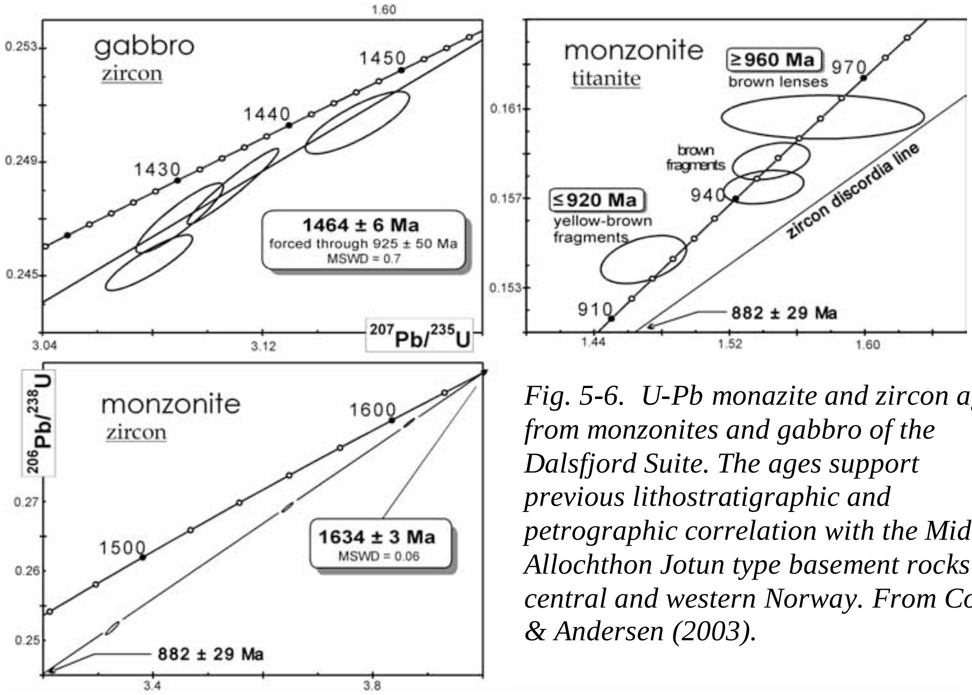


Fig. 5-6. U-Pb monazite and zircon ages from monzonites and gabbro of the Dalsfjord Suite. The ages support previous lithostratigraphic and petrographic correlation with the Middle Allochthon Jotun type basement rocks in central and western Norway. From Corfu & Andersen (2003).

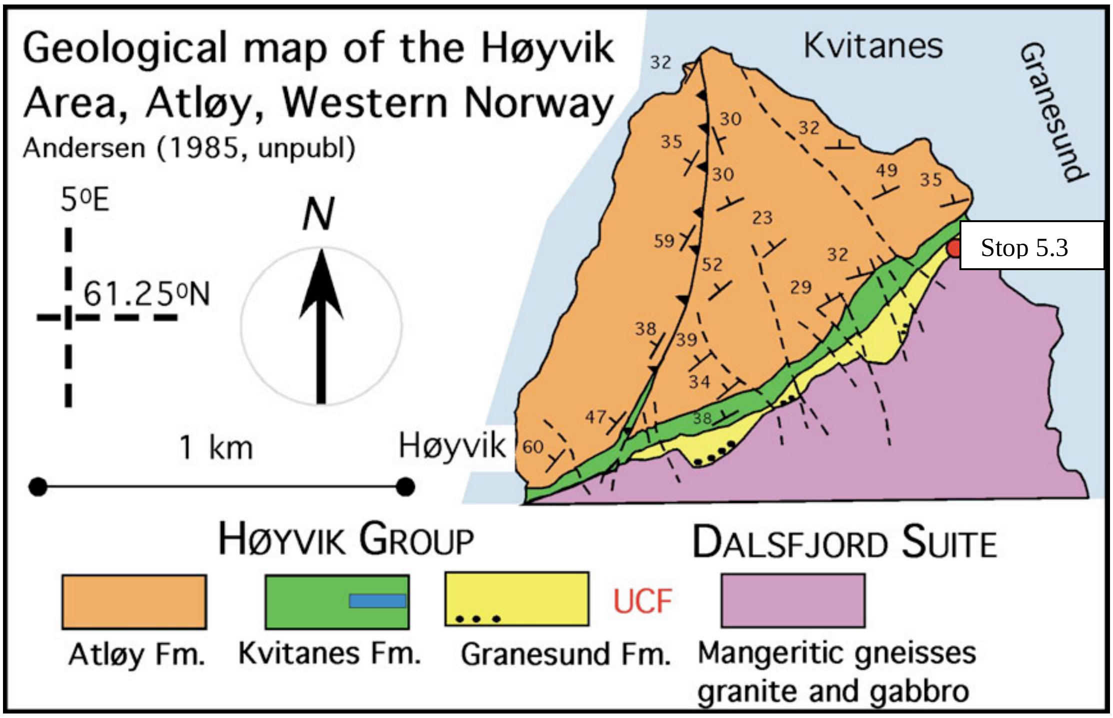


Fig. 5-7. Geological map of the Kvitanes area, Atløy showing the non-conformity between the Dalsfjord Suite and the Høyvik Gp. The best-preserved localities are along the top and just over on the SW side of the hill between Granesund and Høyvik (near cgl symbols).

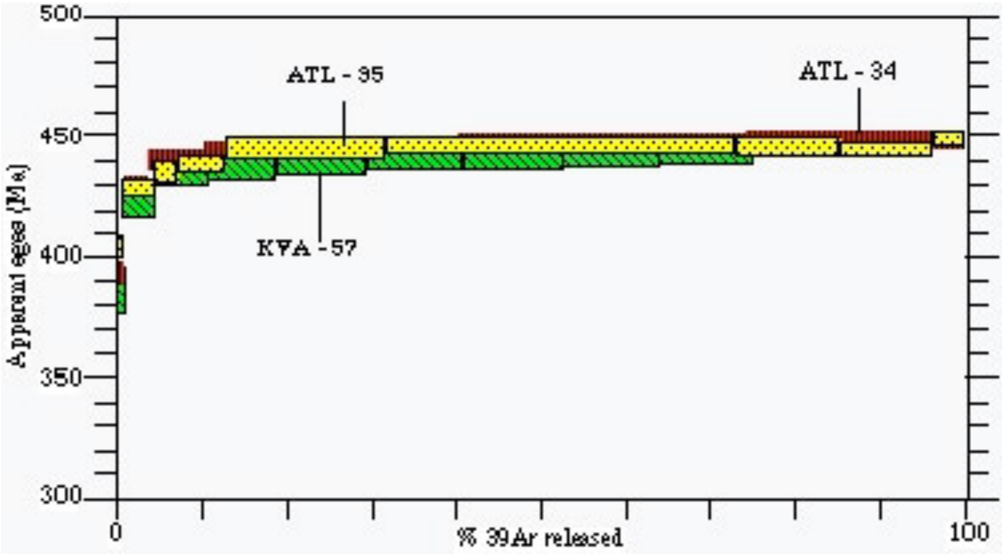


Fig 5-8. $^{40}Ar/^{39}Ar$ spectra of phengitic muscovite from the Høyvik Group at Atløy (ATL 34, 35) and Kvammen (KVA-57) yield ages of 446.1 ± 3 .0, 449.1 ± 2.2 and 447.5 ± 4.0 Ma, respectively, identical within experimental error. ATL-35 from Kvitaneset gives a plateau over 72% of the gas analysed, whereas the other are slightly disturbed, as indicated by lower apparent ages at low experimental extraction temperatures. Minor ^{40}Ar loss probably occurred during subsequent Scandian deformation and late- to post-orogenic extension (Andersen et al. 1998).

Locally, an up to 10 m thick zone, highly enriched in Fe-oxides and muscovite, possibly representing a palaeo-lateritic weathering zone in the Dalsfjord gneisses, is present along the unconformity. The basal deposits consist of deformed pebbly conglomerates and a massive bluish sub-arkosic meta-sandstone (Granesund Fm). This is succeeded quartz-rich mica schists, locally with layers of dolomitic marble (Kvitanes Fm.) and meta-psammites and schists (Atløy Fm.). The Høyvik Group were deformed and metamorphosed in a pre-Scandian, Ordovician (ca 450 Ma) orogenic event. The main greenschist facies foliation at this locality is of this age as dated muscovite (ferri-phengite) gives a reasonably well-defined Ar-plateau age of ~449 Ma (Fig. 5-8). The depositional age of the Høyvik Group is unknown, but by lithostratigraphic correlation it is thought to be of late-Precambrian to possibly early Ordovician age

Stop 5.4 Angular unconformity between the Høyvik Group and the Silurian Herland Group near Brurestakken, western Atløy.

The unconformity between the Herland and Høyvik Groups as well as the entire stratigraphy of the Herland Group, are spectacularly exposed at and around this stop on western Atløy (Fig. 5-2 and 5-9). With today's time-schedule we will only allow a very brief examination of these rocks. For those who have an opportunity to come back, it is well worth spending it here; hence a more detailed description and interpretation is presented.
The Herland Group consists of the Sjøralden- and Brurestakken Formations. The lower part of the Sjøralden Fm. consists of fluvial conglomerates deposited in several small palaeo-valleys (see Fig. 5-10). In section the valleys are from some tens to some hundred meters wide and less than a hundred metres deep. The basal conglomerates are interpreted as valley-fill alluvium. Sandstones with abundant plane-parallel lamination and wave-ripple cross-lamination overlay the conglomerates. Many trough-shaped cross-lamina are of dune scale and a few examples of hummocky cross-stratification has also been recognized. The sandstones are shallow-marine, deposited in a wave-dominated shore face paleao-environment. The marine sandstones are locally intercalated with conglomerates interpreted

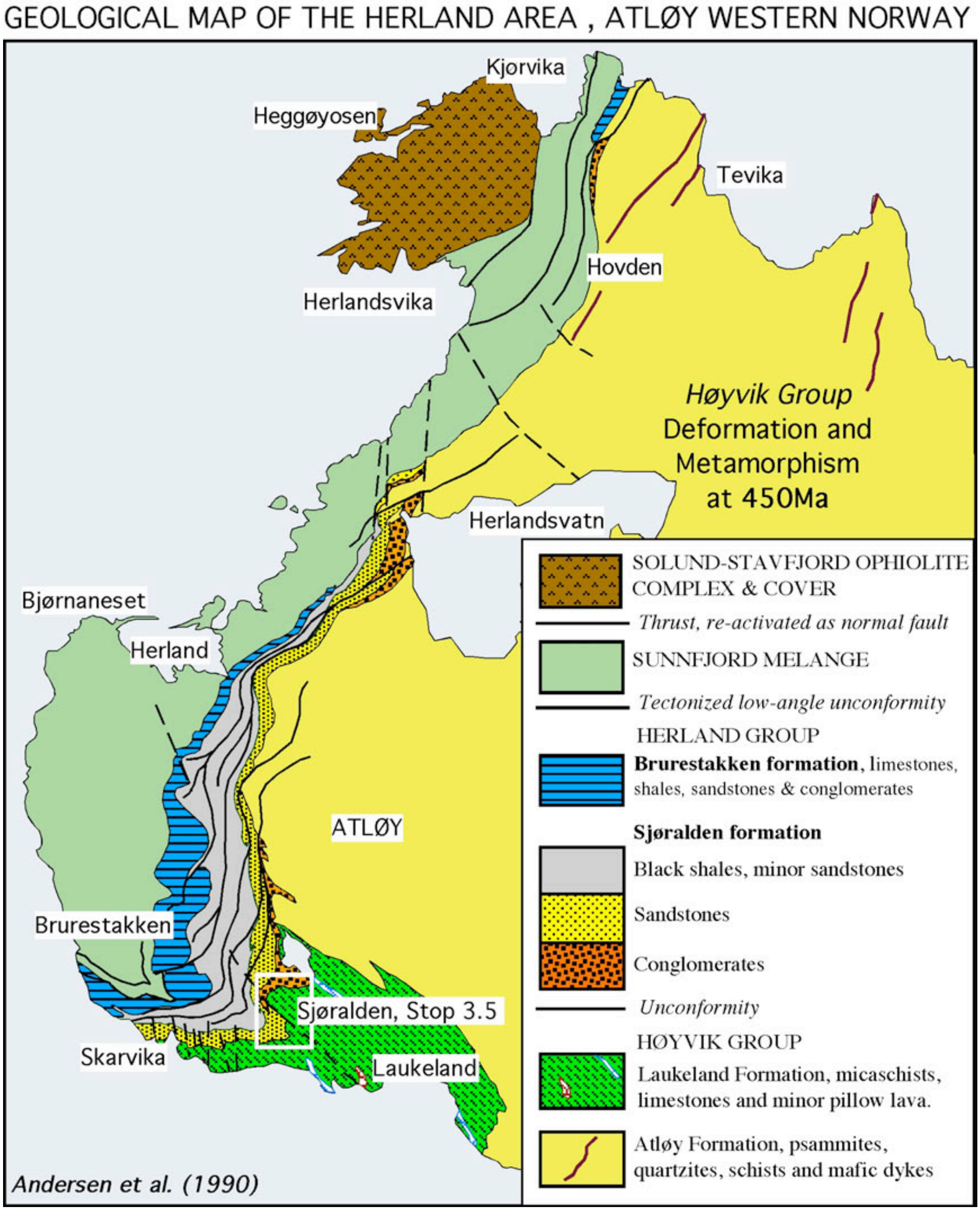


Fig. 5-9. Geological map of the Herland area, western Atløy, with stop 5.4 at Sjøralden marked (Andersen et al. 1990).

as debris-/sheet flood deposits, suggesting that the valley-dominated alluvial systems were still active at the time of the marine transgression. At a higher level some well-sorted monomictic vein-quartz conglomerates occur, and these probably represents redeposited (storm) beach zone material. The sandstones are overlain by finer-grained wackes or mud-richer sandstones that probably represent offshore storm deposits, accumulated below the fair-weather wave-base. The wacke succession passes into a black mudshale sequence, and a calcareous unit characterizes the transitional zone, which locally contains a Middle Silurian shelly fauna, the diagnostic fossils being Pentamerus sp.

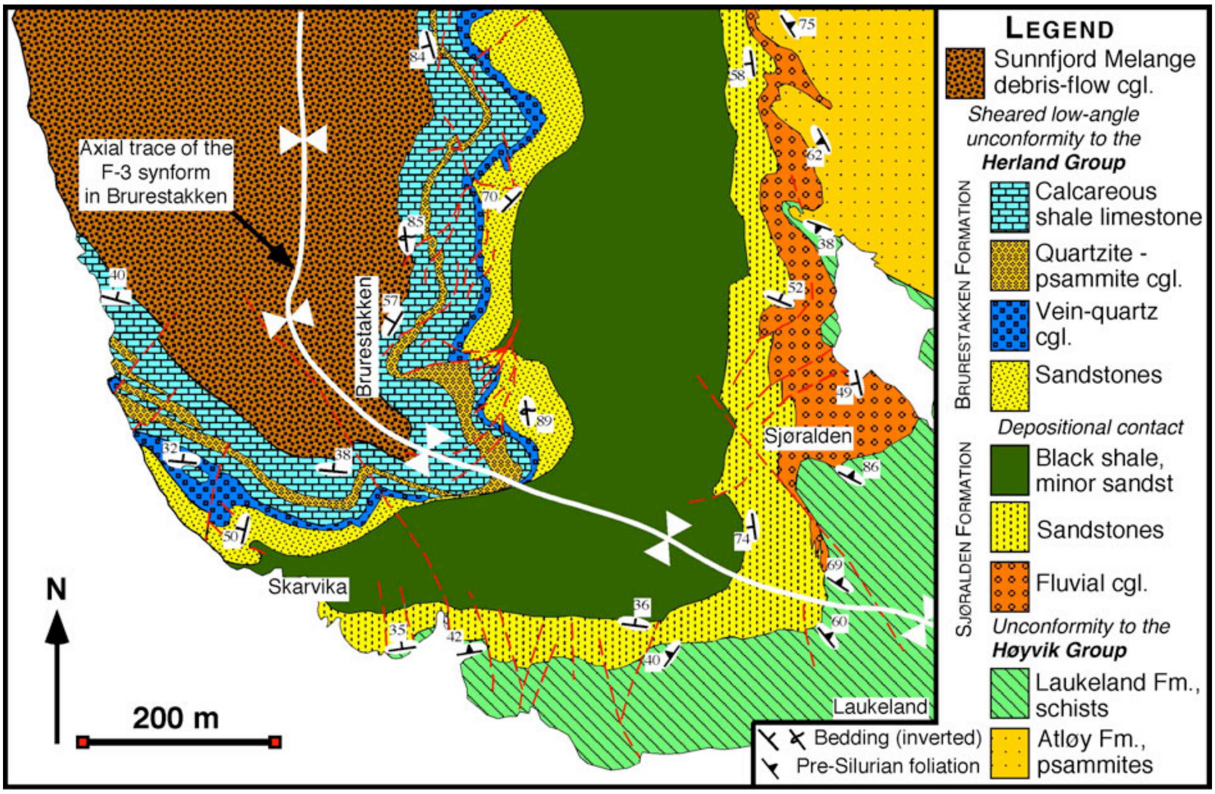


Fig. 5-10. Detailed geological map of the Herland Group at Brurestakken, western Atløy, with stop 5.4 at Sjøralden marked (Andersen 1985, unpublished).

The Brurestakken Fm. is approximately 140 m thick and comprises three coarse clastic units sandwiched between sandstone/shale and fossiliferous calcareous horizons. The basal contact is sharp and although black shales in the upper part of the Sjøralden Fm. are highly deformed, interpreted as a depositional contact. The lower (ca10 m) of the Brurestakken Fm. comprises turbiditic sandstones. The sand is thought to represent erosional products of the underlying Høyvik Gp. and possibly also redeposition of Sjøralden sandstones. The turbiditic sandstones are overlain by wave-dominated shore face arenites, which in turn are overlain by a succession indicating rapid deepening of water characterized by storm deposits and mudshales. The mudshales are overlain by the second coarse clastic unit of monomict vein-quartz conglomerates and turbidite sandstones, deposited by debris-flows to high-density turbidity currents. These coarse clastics are thought to represent a second pulse of resedimentation of the landward part of the Sjøralden Fm. The top of this unit indicates rapid deepening of the water, and the mudshales have clearly been deposited below the wave-base. This fine-grained unit also contain limestones in which a shelly fauna including pentamerids and crinoids locally are common. The third coarse-clastic units comprises immature polymict conglomerate and sandstones deposited by debris-flows and turbidity currents, overlain by wave-worked sandstones, and successively by approximately 20 m of variably calcareous mudshales deposited well below the storm wave-base. The coarse-grained units within the Brurestakken Fm. are thought to represent tectonically controlled re-deposition of the landward part of the Sjøralden Fm probably controlled by the collapse of the continental margin during the final stages of the obduction and emplacement of the Solund-Stavfjord Ophiolite Complex.

The structure of the Herland Group

The deformation of the Herland Group is related to layer-parallel shortening associated with the obduction and emplacement of the ophiolite and emplacement of nappes during the Scandian orogeny, and the W-vergent, asymmetrical back-fold related to the extension of the orogen. The western Atløy section was positioned at a high-level in the syn-orogenic crust, characterized by low greenschist facies metamorphism. A reconstruction of the structural geometry prior to the late folding shows a typical fold- and thrust belt geometry (Fig. 5-11) related to the SE-directed tectonic transport during the Scandian orogeny. Fine-grained sandstones and shaly horizons have acted as flats, and decollement thrusting and the flat-ramp geometry occur on both on the scale of individual outcrops and on map scale. In less competent calcareous shales and in the black shales, the cleavage is locally intense.

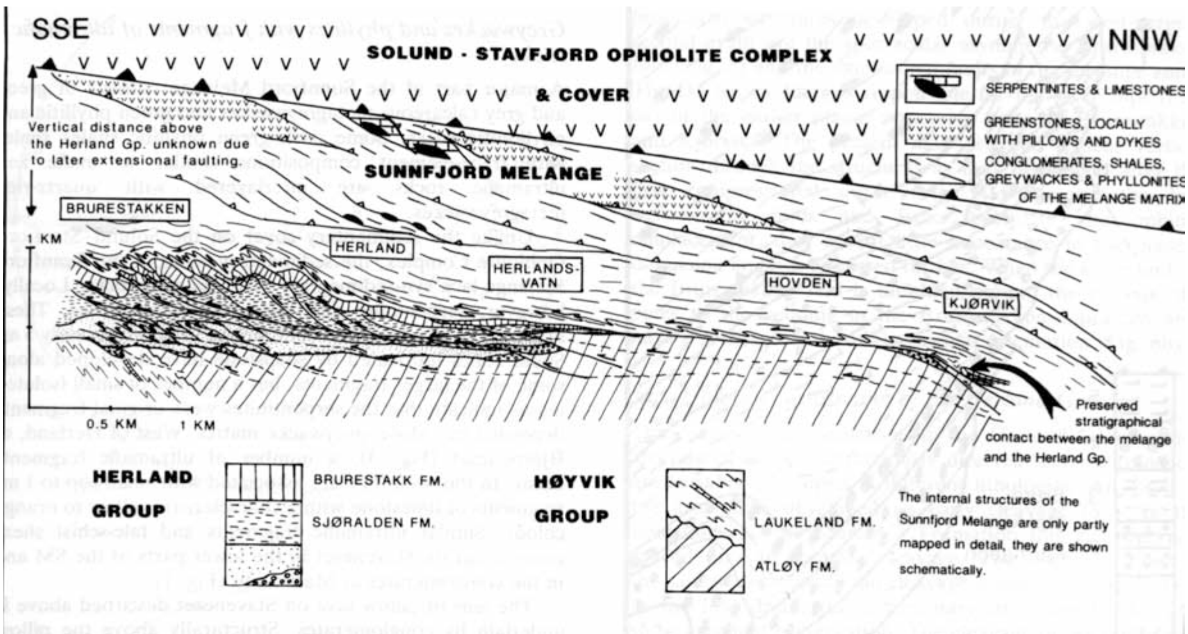


Fig. 5-11. Cross-section reconstruction (pre-extension)of western Atløy (Andersen et al. 1990). Notice the fold-thrust geometry and that the Herland Gp is excised by erosion and subsequent deformation below the melange in the NW.

A significant decollement zone is located in the upper parts of the Sjøralden Fm, and a number of small-scale duplexes and fault-propagation-folds have formed associated with ramps cutting up into the lower coarse-grained sandstones of the Brurestakken Fm. The competent sandstones and conglomerates, which are interlayered with shaly limestones in the Brurestakken Fm, experienced layer-parallel shortening by folding. Originally concentric folds with geometry controlled by the competent layers were formed as a result of shortening above the decollement horizons, and fault-propagation folds at variable scales are very common within the Brurestakken Fm. Additional shortening later modified some concentric folds. These folds were developed with originally gently plunging to sub-horizontal fold axes with a WSW-ENE orientation prior to the W-vergent back-folding. There is a progressive increase in strain towards the higher parts of the Herland Group and the Sunnfjord Melange, and this indicate that a dynamic accretion of material in the lower part of the melange may have taken place with time as the ophiolite progressively was thrust over its substrate. The geometric constraints for balancing the shortening of the Herland Group is not entirely satisfied. However, a very rough estimate based on the shortening of the basal layer of the Brurestakken Fm indicate a shortening of some 30 to 40% in the profile between

Brurestakken and Herlandsvatn (Fig. 5-9). The large-scale overturned syncline in the mountain of Brurestakken (Fig. 5-10) is a secondary structure folding the contractional fabrics. It is a W-vergent fold related to the earliest extension of the orogen.

The Sunnfjord Melange formed during obduction and emplacement of the Solund-Stavfjord-Ophiolite Complex, links the oceanic and continental rocks in the Sunnfjord region. The contact between the melange and the Herland Group is highly sheared, locally however, an unconformable depositional contact is preserved between Tevika and Kjørvika on northern Atløy (Fig. 5-9). The melange contains greenish quartz-chlorite schists, chlorite-rich, impure marbles, greenstones, vein-quartz conglomerates, scattered clasts of epidosite and characteristic jasper bearing, matrix supported, polymict conglomerates. The clasts in the conglomerates reflect a bimodal source of both continental and oceanic affinity. The clasts of continental affinity include metamorphosed Høyvik-type quartz-schists, marble, and anorthosite and commonly undeformed mature sandstone clasts. The unmetamorphosed sandstone clasts may have been eroded from the Herland Group prior to Late-Silurian deformation during obduction of the ophiolite. Clasts of oceanic affinity comprise greenstones, epidosite and characteristic red jasper; vein-quartz pebbles are conspicuous throughout the conglomerate. Large (>100m) greenstone lenses are believed to represent olistoliths derived from the ophiolite. The matrix is mostly green quartz-mica-schists with variable amounts of chlorite (up to 30%) and plagioclase.

In its upper parts, the dominant lithology of is a chlorite-bearing, calcareous meta-greywacke. Talc-schist lenses and serpentinites occur at middle and upper levels of the melange. The conglomerates with bimodal oceanic-continental source, in the lower part of the melange, formed in a rapidly deepening foreland basin. The rapid subsidence was probably as a result of the loading on the continental margin by the advancing ophiolite nappe and its overlying cover. The upper part of the melange is mainly a tectonic melange formed by intra oceanic deformation along in an oceanic shear zone and along the basal thrust of the ophiolite nappe.

Return for to Gjervika, ferry to Askvoll and continue main road towards Førde.

Stop 5.5 Ductile to brittle extension in the hanging wall of the NSDZ at Oslandsbotn east of Stongfjorden.

At the Oslandsbotn locality (Fig. 5-12, 5-13) along and in the river, we shall examine (if water level permits) the fault rocks and the extensional geometry of a major fault in the hanging wall of the NSD. Furthermore, we shall discuss the evidence for pre, syn and post-depositional faulting with respect to the deposition of the Devonian sediments. The fault zone exposed in the Oslandsbotn area (Fig. 5-13) is the easternmost of the main faults in this system truncating the pre-Devonian rocks. The Høyvik and Herland Groups with a structural thickness of more ca 2 km on Atløy, is dramatically thinned, and locally the Sunnfjord Melange rests directly upon strongly brecciated Dalsfjord Suite rocks (Fig. 5-13). The faulted contact between the Høyvik and the Dalsfjord lithologies is defined by a several tenths of meters thick strongly deformed zone. Semi-ductile, oblique-slip listric faults with NE-SW strike thin the Høyvik quartzites abruptly and sole out along the contact between the

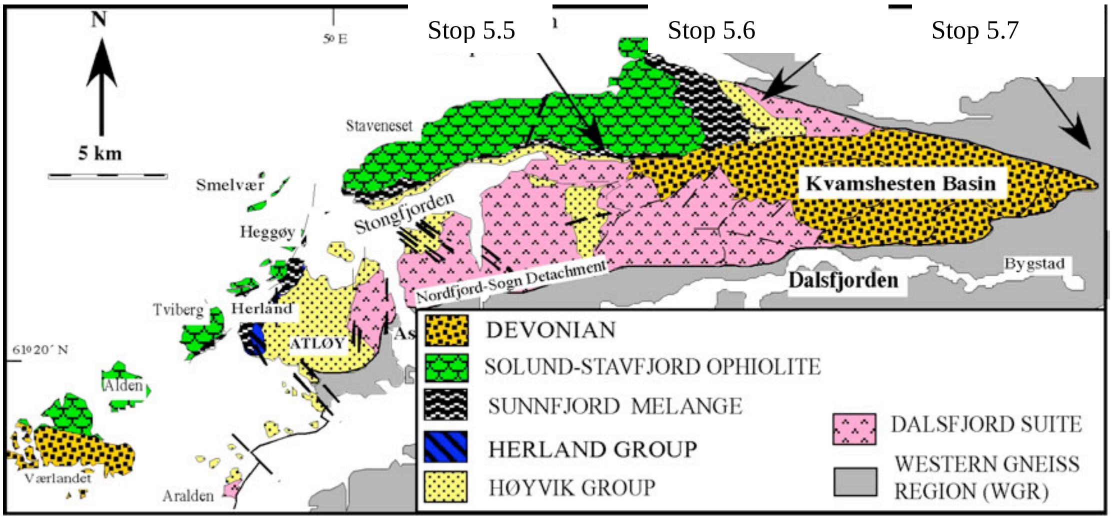


Fig. 5-12. Geological overview map of the hanging-wall of the Nordfjord-Sogn Detachment Zone in Sunnfjord, showing location of excursion stops on the south side of Førdefjorden.

Høyvik and the Dalsfjord rocks (Fig. 5-13). Asymmetrical lenses or fault blocks of Høyvik quartzites occur as map- and outcrop-scale extensional allochtons along the fault plane. Structures along the fault comprise shear bands with northeast-southwest strike, asymmetric, m-scale boudinage of Høyvik lithologies similar to the mappable features, and small-scale (meter-scale) thin 'extensional allochthons' of brecciated Høyvik quartzite along the fault plane.

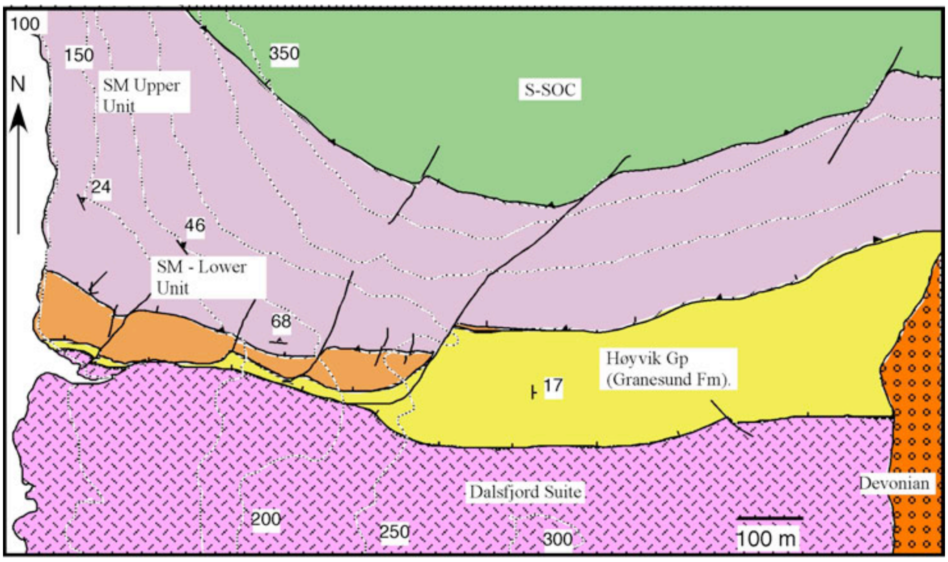


Fig. 5-13. Detailed map of the Oslandsbotn fault zone, for location see Fig. 3-12. Notice that the Høyvik rocks, which are ca 2 km thick at Atløy (Fig. 5-2) have been excised along the fault plane (From Osmundsen & Andersen, unpubl manuscript).

Mappable semi-ductile faults as well as small-scale shear bands dip northwest, the movement directions inferred for individual shear bands is oblique to dip direction. SW-directed, transtensional shear can be inferred from both map pattern and drag superimposed on the main foliation adjacent to the shear bands. This corresponds to a top-to-the W sense of shear along the main fault. The contact between the Høyvik and the Dalsfjord rocks has thus served as a detachment for the semi-ductile transtensional faults. Slickenside lineation (027/27) occur patchily on the fault plane. Minor, SW dipping shear bands are locally observed in fault rocks along the fault plane.

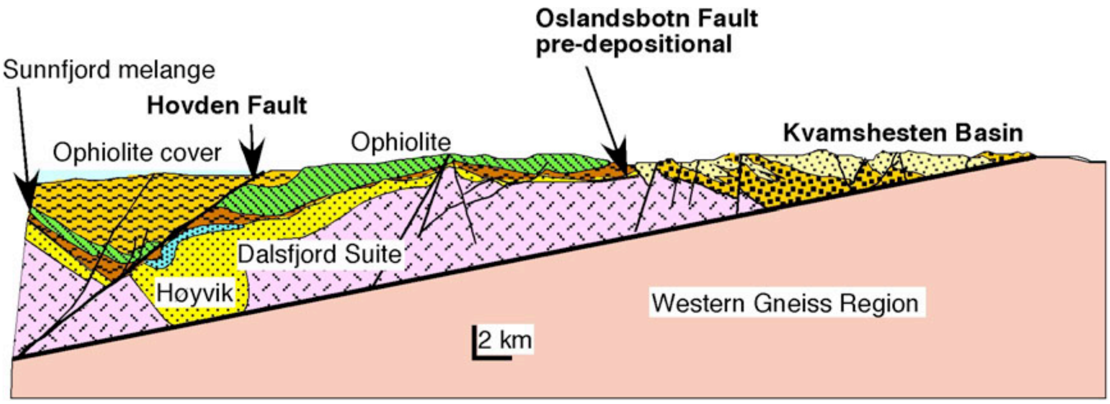


Fig. 5-14. W-E section across the Kvamshesten basin and substrate in Sunnfjord. Notice the major extensional faults in the hanging wall of the NSD and location of the pre-depositional fault zone in Oslandsbotn (From Osmundsen & Andersen unpubl manuscript).

Several generations of fault rocks occur in Oslandsbotn. Breccias are developed from both Dalsfjord- and Høyvik protoliths. The Dalsfjord protolith in the Oslandsbotn area is syenitic gneiss, locally with mafic dykes. The Høyvik protoliths are bluish to white massive quartzites. A chlorite-rich, semi-ductile breccia carrying sub-rounded fragments of the syenitic gneiss as well as scattered fragments of Høyvik quartzite is exposed for tenths of meters along the fault plane. This breccia is itself cut by a large number of high-strain zones, dismembering it into angular fragments. Up to 5 cm thick sheets of flow-banded and flow-folded pseudotachylyte occur on the fault plane. The northeast-plunging lineation mentioned above is superimposed upon these fault rocks.

Kinematic interpretation and age relationships
The northeast-plunging lineation described above is not consistent with the movement directions inferred from semi-ductile faults and shear bands. Thus, at least two stages of movement are inferred from the observations. Firstly, a top-west movement is inferred from the northwest-dipping shear bands and semi-ductile faults. Secondly, a top-southwest displacement is deduced from the northeast-plunging lineation together with the southwest-dipping shear bands. The southwest-directed displacement represents the youngest recorded deformation along the Oslandsbotn fault. The movement directions are given in the present frame of reference for orientation of the structural elements. The near-by contact between the Devonian sediments and its substrate dips approximately 30-45^0 towards the northeast due to Devonian block rotation and the folding. Because the faulted contact between the Høyvik and the Dalsfjord lithologies is unconformable overlain by the Devonian sediments, the structural elements along the Oslandsbotn Fault are unlikely to have their original orientations. Restoring of the Devonian unconformity to the sub-horizontal, the Oslandsbotn Fault becomes steeper. The displacement directions inferred from semi-ductile faults and northeast-plunging lineation change from left lateral to oblique normal, and from oblique reverse to left lateral, respectively.

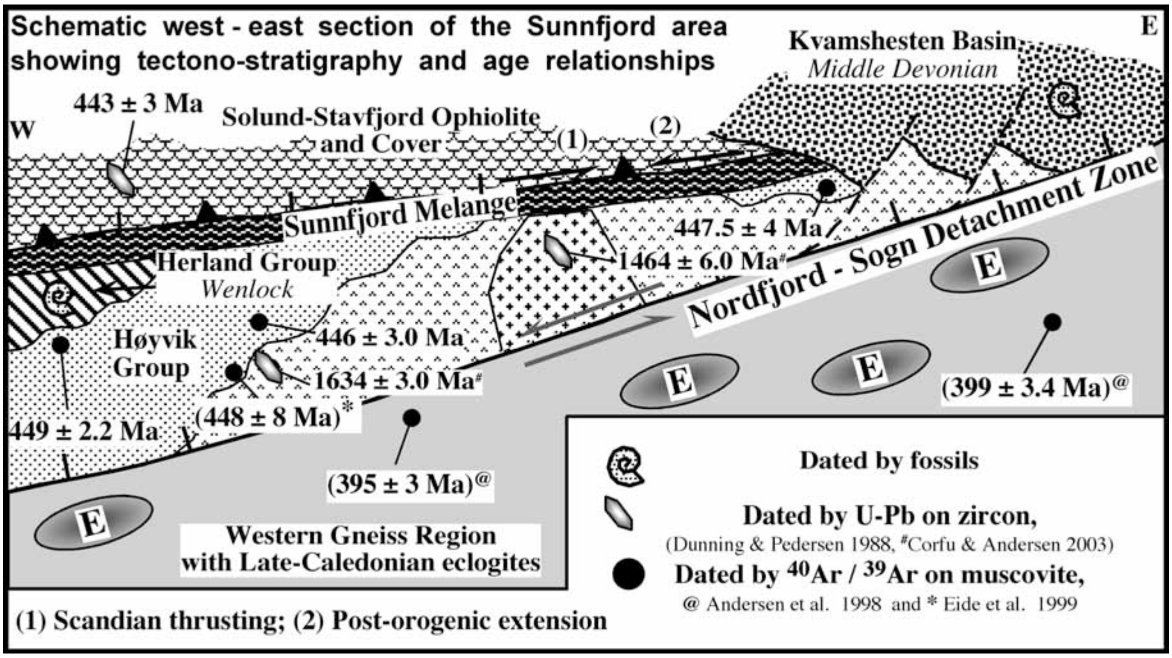


Fig. 5-15. Schematic E-W profile with summary of the stratigraphy, radiometric ages and tectono-stratigraphy in Sunnfjord (modified from Andersen et al. 1998, Corfu & Andersen 2003).

The Devonian unconformity can be studied after a walk up the hills east of Oslandsbotn. The thick and massive Devonian fanglomerates at this locality represents the stratigraphically lowermost and oldest deposits in the Kvamshesten Basin. Detailed mapping of the unconformity and its substrate in this area shows that the extensional structures studied at Oslandsbotn are unconformable overlain by the conglomerates (Fig. 5-15).
Drive back to the main road and continue towards Førde.

Stop 5.6 Detachment mylonites on the north side of the Kvamshesten Basin, Gjelsvika

On the main road towards Førde (Fig. 5-12) we cross the Caledonian tectono-stratigraphy in reverse order, from the ophiolite and the melange the Høyvik Group and across the massive Dalsfjord Suite gneisses making a prominent topographic feature to the south of the main road. The NSDZ makes a spectacular topographic feature along Førdefjorden, because the phyllonitic mylonites are less resistant to erosion. The road section near Gjelsvik provides excellent exposures of the mylonites along the northern part of the Kvamshesten basin. The mylonites at this particular locality have anorthositic protoliths. Note that the mylonites now are steeply south dipping, however, the stretching lineation and kinematic indicators in this section also show extensional top-west sense of motion. Eclogites are common immediately to the north of the road, again demonstrating the proximity of the high-pressure rocks to the low-grade Caledonian rocks and the Devonian supracrustals. There is little doubt that erosional exhumation had a minor role in their exhumation as they are positioned immediately below the detachment fault.
In areas little affected by the extension in the hanging wall of the NSDZ, the Ar-system of white mica is relatively undisturbed and show old Scandian or even pre-Scandian ages (see Ar-spectra in Fig. 5-8). A summary of stratigraphic relationships and radiometric ages are shown in Fig. 5-15.

Fig. 3-16. View from Karlstad, Solheimsdalen towards Litlehesten and the NSDZ zone. The rocks in the entire section up to base of the step cliffs made by the Devonian sandstones and conglomerates are detachment mylonites. Eclogites of the WGR are preserved close to this locality; hence the ca 40 km of crustal section has been excised across the present structural thickness of ca 2 km.

Stop 5.7 View of the Kvamshesten Basin and the NSDZ, Solheimdalen
The northern margin of the Kvamshesten Basins is spectacularly exposed in this area, undoubtedly one of the finest views in Scandinavian geology! Hopefully the weather permit visibility to the 1100 m high cliffs in the basin, exposed above the NSDZ, illustrated in Fig.5-16. Note the steep dips, partly inverted, of the bedding in the conglomerates and sandstones of the basin. This is due to folding and reverse-faulting within the basin related to N-S shortening during and subsequent to the basin formation. Note also how the bedding is truncated by the brittle fault along the top of the detachment. If the light is favourable one may observe a major reverse fault in the lower part of the highest peaks (Hellevangstaurene).
Continue on the main road to Førde and continue the road towards Florø.

Day 6, Topic: A Traverse of the Hornelen basin across the NSDZ into the WGC of Nordfjord.

Day 6 will take us from Florø thorough the Middle Devonian Hornelen basin, into the deepest (U)HP part of Caledonian orogen in Nordfjord. The main objectives will be:
1) the architecture of the Hornelen supra-detachment basin, the faulted margins and the relationship between the basin and the (U)HP rocks in Nordfjord;
2) the (U)HP rocks along Nordfjord.
We plan to end day 6 near the famous Verpeneset eclogite at the base of the thick package of extensional mylonites of the NSDZ.
We shall cross Nordfjord from Oldeide to Måløy and at the end of the day we will drive to Selje hotel.

The most remarkable feature of the geology of the region is the crustal excision that occurred during the post-Caledonian extension. This brought rocks that had been buried to great depths and UHP-conditions during the Caledonian orogeny at approximately 405 Ma, to middle and upper crust level already by the Middle Devonian at ca 385 Ma. This corresponds in time with the Early to Middle Devonian (Givetian 387-382 Ma), which is the time for deposition of the youngest parts of the Hornelen basin. It is however, important to note that the eclogite bearing WGC was not available to erosion when the Devonian basins were formed, and the UHP rocks did not cool down below blocking for Ar-diffusion in white mica until after 380Ma. The eclogite bearing rocks were not exposed to erosion until Pemo-Triassic time, as shown by heavy mineral studies from wells in the adjacent North-Sea basins.
Contemporaneously with decompression and cooling in the WGC, large steep to low-angle normal and oblique-slip faults broke the surface and controlled formation of sedimentary basins and the drainage in the mountain belt. These listric faults were rooted in the NSDZ. The famous Hornelen basin is one of the best examples of super-detachment basins in the world. Its formidable stratigraphic thickness of ca 25 km have puzzled geologist since its discovery. Today we know that migrating depo-centres related to strike-slip and normal faults in the hanging wall of the detachment gives the best explanation of the enigmatic stratigraphic thicknesses and the sedimentary architecture of the basins. Fossils of fish and plants are preserved at the highest stratigraphic levels, east in the basin. The stratigraphic age is Middle Devonian (Givetian) and suggests that the basin evolved contemporaneous with cooling below the nominal Ar-blocking temperature for muscovite in the Nordfjord region (see Introduction, Fig. 6).

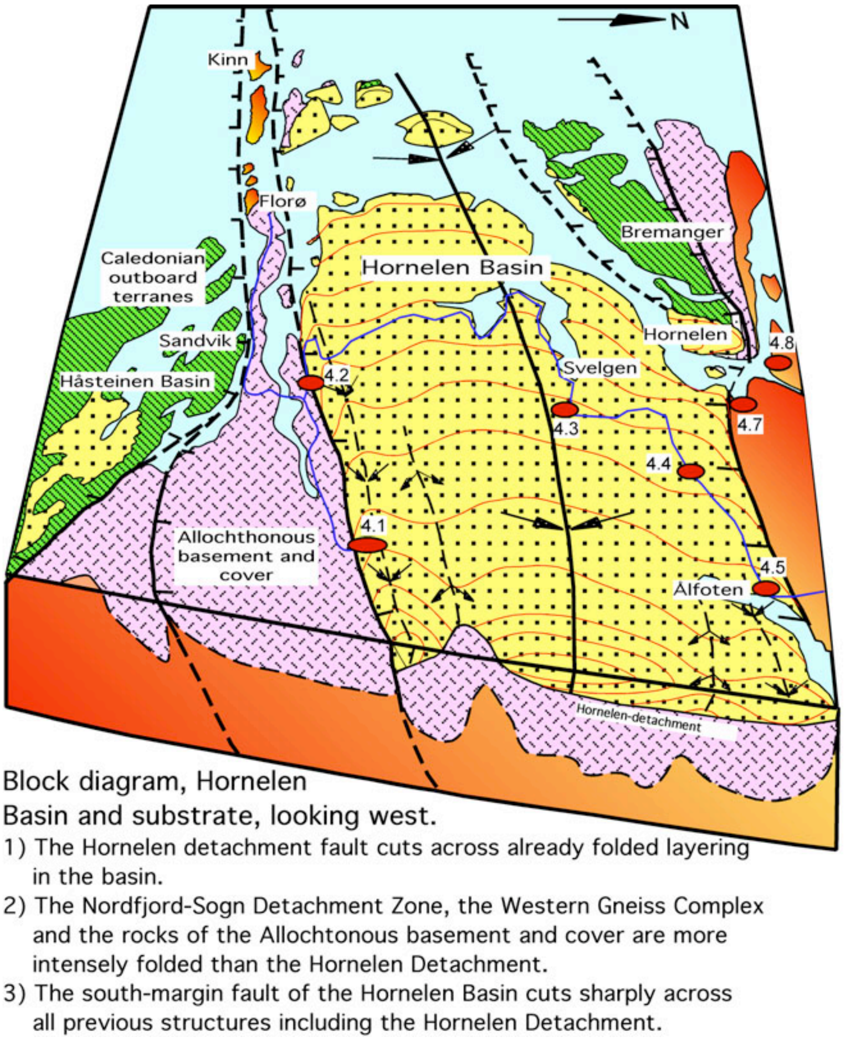


Fig. 6-1 Figure (from an older guide) illustrates the Hornelen basin and surrounding main geological units. The stops marked 4.2. 4.3, 4.4, 4.5 4.7 and 4.8 corresponds to our stops 6.1, 6.2 6.3, 6.4, 6.6, and 6.7 respectively. Notice that the present north and south margin faults are reactivated and truncate the extensional mylonites that are pervasively developed in the substrate of the basin. Notice also the large-scale folds in the basin. These are truncated by the Hornelen detachment, which bounds the basin in the east. The folds are also truncated by the marginal faults.

Stop 6.1 South margin fault of the Hornelen basin at Haukåvatn (UTM-6839812-3033398)

The parking place on the south side of the Haukåvatn provides a spectacular view of the south margin alluvial fan complex truncated by the south margin fault. The alluvial fans are represented by numerous coarsening to-fining upward units (CUPF, see examples of logs below). Differential weathering and erosion of the CUPF-units controls the topography of the basin and other areas underlain by the Devonian rocks in western Norway. Notice that the rocks in the footwall to the south of the fault-line scarp (where we are standing), are strongly foliated schists, heavily overprinted by brittle faults and joints, which are related to the young movement on the fault (palaeomagnetic data suggest Mesozoic faulting). These schists comprise both ortho- and paragneisses, belonging to the Middle Allochthon and are probably correlatives of the Jotun, Lindås and Dalsfjord granulite facies protoliths. The basin fill along the south margin fault is dominated by these rocks and the associated quartzites.

Stop 6.2 River section east of Svelgen (UTM 6854157-304770)

As shown in Fig. 6-2 the main part of the Hornelen basin fill comprises fluvial sandstones (Fig. 6-3). The sandstones were formed by a dominantly west-flowing river-system, forming a broad alluvial plain flood-basin dominated by braided rivers transport directions are shown by arrows in Fig. 6-2. The sandstones at this stop preserve a variety of spectacular sedimentary structures and structures related to their dewatering.
Logs of typical axial sandstone facies are shown below in Fig. 6-3.

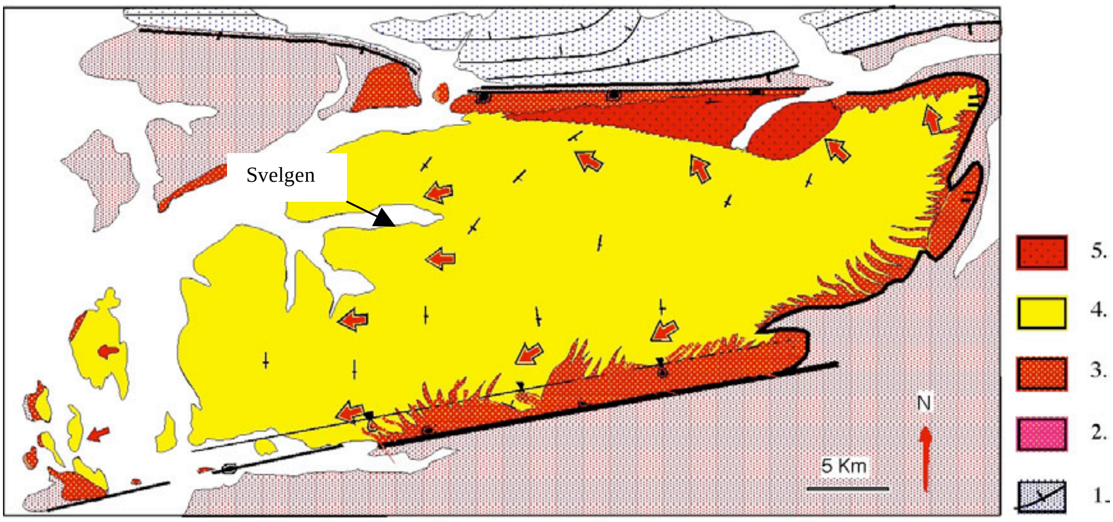


Fig. 6-2. Geological map of the Hornelen basin (based on mapping by Bryhni and sedimentological work by Steel and coworkers). 1) WGR; 2) Caledonian nappes; 3) Fan conglomerates; 4) Fluvial sandstones; 5) Flood-basin red fines (sand/siltstones), partly lacustrine sediments.

Stop 6.3 Langevatn car parking on the Svelgen - Ålfoten road, view to north margin fan complex and axial sandstones (UTM 6859961-311778)

The view from the parking place at Langevatn illustrates the large-scale sedimentary architecture and structure of the Hornelen basin. To the north and northeast, we have a view of the steeply SE-dipping north margin fan complex. According to Steel and co-workers, the alluvial fans here are shorter and more dominated by debris-flow deposits than the stream-flow dominated south margin fans. It is likely that the north margin fan complex originated from a relatively restricted drainage basin and that the larger more fluvial dominated south margin fans drained a much large area. Fans along the north margin fan complex in parts form fan-deltas where they interfinger with the flood-basin deposits along Myklebustdalen (see Figs. 6-3, 6-4). To the south we have a view to the more gently east-dipping axial sandstones of the basin. The transition from steep- to more gently dipping strata, illustrate the northern limb of the Hornelen synclinorium.

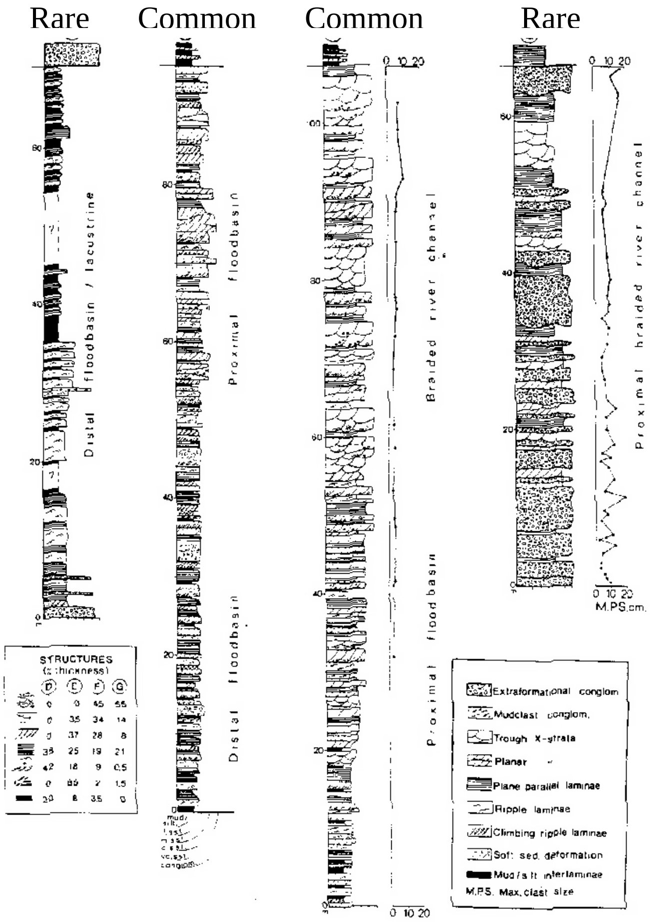


Fig. 6-3. Logs from Steel & coworkers showing 4 alluvial-plaine sandstone associations. Notice the CUP and CUPF sequences.

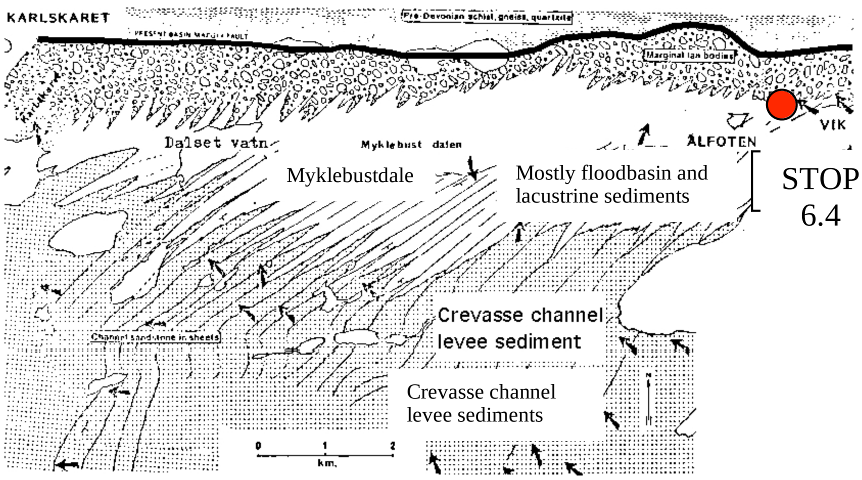


Fig. 6-4. Geological map showing sedimentary facies and palaeocurrent (arrows) distribution in the Ålfoten area (open arrow: Palaeo-wind direction). Notice the short debris-flow dominated fans interfingering with the floodbasin to lacustrine deposits. (From Steel & Nemec 1987).

Stop 6.4 Ålfoten, fanglomerates and red floodbasin sand- and siltstones along the north margin (UTM 6861206-326370)

Steeply dipping fluvial to lacustrine flood-basin sediments dominated by red sand- and siltstones interfingering with fan-conglomerates of the north-margin fan complex (Fig. 6-5). Notice that conglomerates frequently contain igneous granitoid clasts, suggesting that the basin deposits had provenance from Caledonian nappes including arc-type magmatic rocks similar to those found at Bremangerlandet. Presently all the Caledonian nappes are excised along the northern margin of the basin. Floodbasin deposits in Myklebustdalen probably represent the area of maximum subsidence in the basin, also indicated by preservation of "single-story" sedimentary events (see Fig. 6-6). The north margin (Botnen) fault of the Hornelen basin is also reactivated. We pass into detachment mylonites from WGC in the long tunnel shortly after stop 6.4. The fault is not exposed.

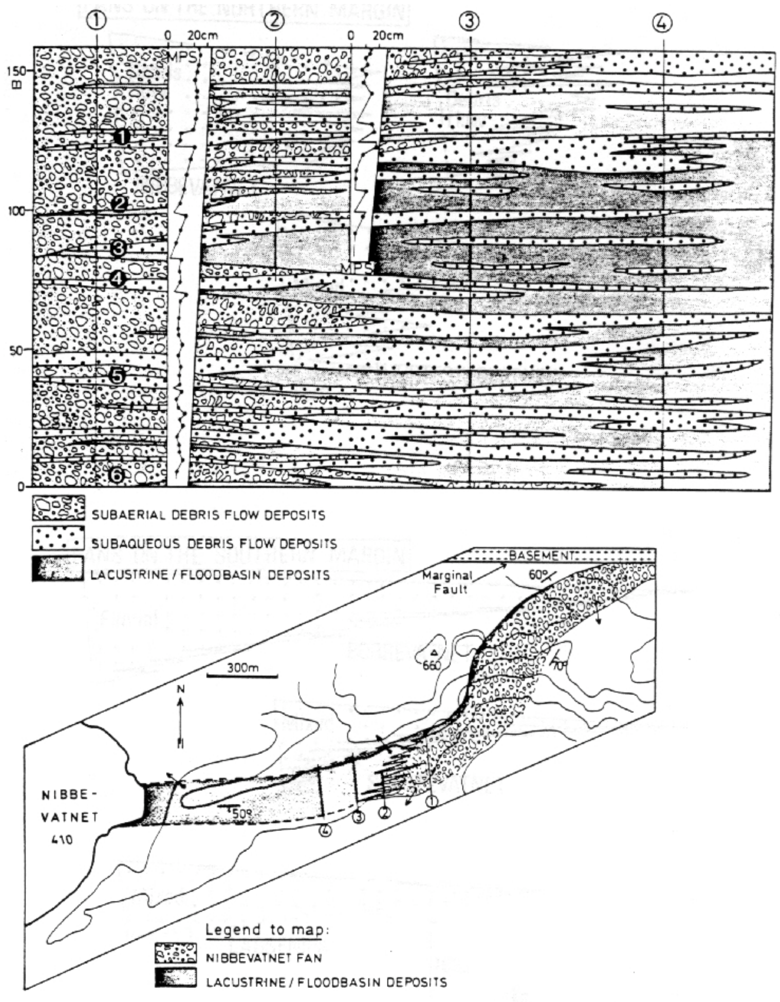


Fig. 6-5. Map and reconstructed facies distribution (after Steel & Nemec) illustrating the relationships between the debris-flow and lacustrine/flood-basin to the south, across the Nibbevatn fan delta near Stop 4.4.

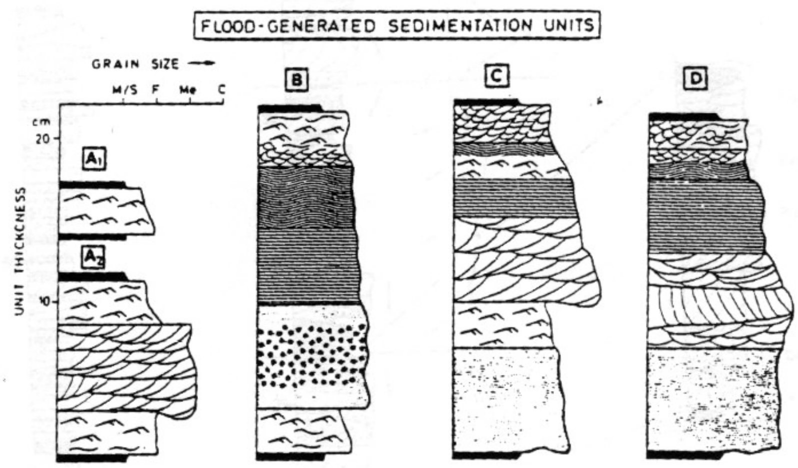


Fig. 6-6. Idealized "single-story" floodbasin / lacustrine sequences (after Steel & Aasheim). A) Distal sheetflow units, B) Density flow, C) Crevasse-splay/levee unit, D) Crevasse channel unit.

Stop 6.5   Eclogites in the Western Gneiss Complex basement north of the Hornelen basin (UTM 6869854-311714)

The steeply dipping north margin fault of the Hornelen Basin makes a spectacular topographic feature between Bortnepollen (Stop 6.6) and Ålfoten (Fig. 6-4). To the east of Ålfoten the fault becomes the more gently dipping Hornelen Detachment. The fault is not exposed in the road or coast section along Ålfoten but can be viewed at a distance to the SE from the coast near Isane ferry quay. From Isane towards Rugsundet we drive on the narrow road along the south coast of Nordfjord. There are numerous eclogites along this section. We will make one stop (6.5) at the headland between between Davik and Rugsundet (Fig. 6-8). Eclogites along this section give P-T estimate ranging from 2.7 to 1.9 GPa, at 660 to 700^{o}C (Young et al. 2007). The eclogite here preserves spectacular eclogite facies folds and a compositional variation of the eclogite facies rocks from felsites to mafic. Notice amphibolite facies retrogression along fractures, veins and more penetratively along the foliation around the preserved eclogite facies rocks.
Most of the sections between stop 6.5 and the N-margin fault of the Hornelen basin is strongly affected by the deformation related to the extension and the horizontal distance to the fault is approximately 6.5 km.

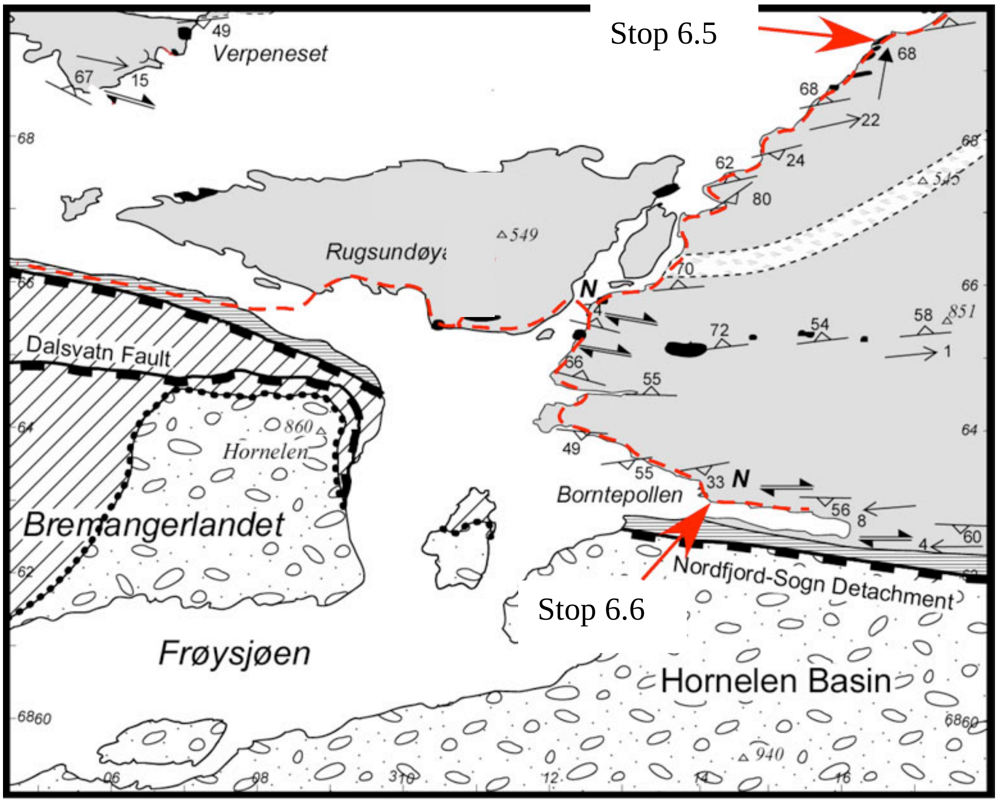


Fig. 6-7. Map showing geology and day 4 stops on the south shore of Nordfjord. Major eclogites are marked in black and N denotes "normal pressure" eclogites. Striped symbol denotes highly mylonitic to phyllonitic rocks along the detachment (From Krabbendam et al. 2000)

Stop 6.6 Eclogites and detachment mylonites between "Gloføykje" (bridge to Rugsundøya) and Bortnepollen (UTM 6865235-306137 to 6862896-307685)

The rocks along this section varies from mafic and felsic eclogite facies rocks to highly deformed banded gneisses and of both igneous (partly anorthositic) and possibly sedimentary origin (phyllonitic micaschists and quartz-feldspatic schists). Migmatitic gneisses at Bortnepollen are positioned within the upper part of the several km thick detachment zone separating eclogite-bearing rocks from lower grade rocks. Locally eclogites are preserved at this structural level demonstrating that the extensional shear zones were cutting deeply into the lower crust in the direction of the hinterland. Very large (>100 km) relative movements between the upper and lower crustal rocks took place across this zone and major excision of crustal section can be indicated. Some of the phyllonitic and mylonitic gneisses at this point have been suggested to be of supra-crustal origin and possibly represent the Caledonian nappes originally emplaced on top of the WGC. We cannot determine the origin of these rocks with certainty, however, we can observe the eclogites their retrogression and the kinematic indicators, which are invariably, present here and document large-scale extensional movements below the Hornelen basin. The upper parts of the mylonites are partly ultra-mylonites indicated on figure 6-7.

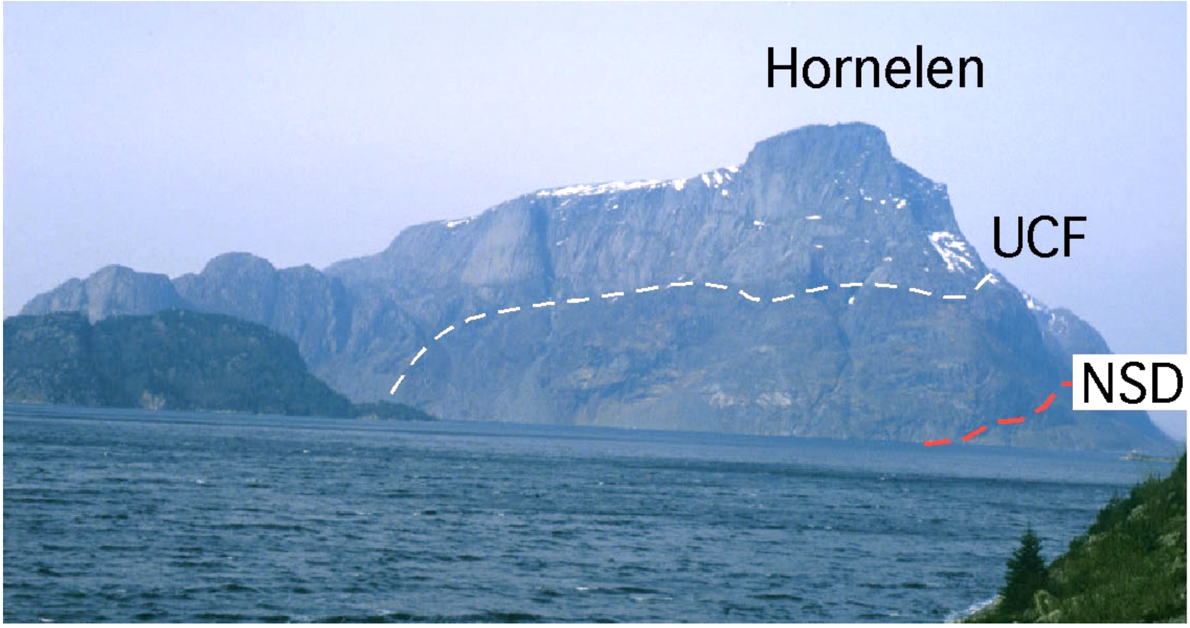


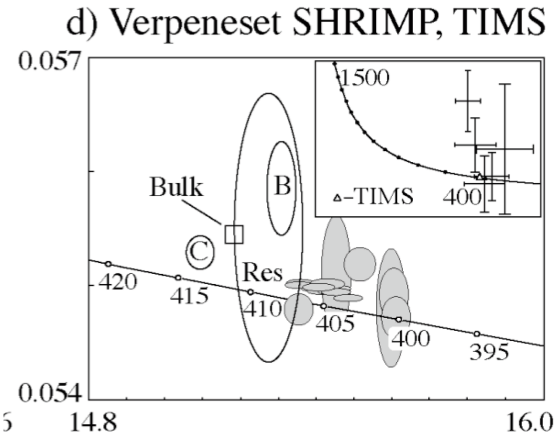
Fig. 6-8. Photo looking west from Leirgulen, near Bortnepollen. Notice the unconformity below the Devonian sediments in the cliff-face of Hornelen mountain. Notice also the normal faults outlined by light-coloured layers at the base of the cliff. The Nordfjord-Sogn Detachment zone continues and defines the north coast of Bremanger shown in the right-hand side of the photo. The Hornelen mountain is also famous for its historical/mythological significance. The old Viking King Olav Trygvasson climbed the mountain from the seaside ca 1000 years ago, and the mountain is also renowned in the mythology for the midsummer witches´sabbath!

If the weather is good we have a spectacular view to the Hornelen mountain on the island of Bremanger (Fig 6-8). Across the fjord to the south we can (hopefully) see the 860 m high mountain cliff made up by the north-margin fan complex of the Hornelen basin (light coloured top part); the underlying Caledonian nappes of the Upper and Middle Allochthons, and at the very base of the cliff, in the footwall of a brittle fault, a large thickness of mylonites derived from the WGC. Inge Bryhni described the basal deposits as sedimentary breccias. These are partly unconformable and partly in faulted contact with deformed ortho- and paragneisses as well as the outboard oceanic rocks of the Upper Allochthon. The youngest dated rock in the depositional substrate is the Early Silurian (440 ± 5 Ma) Bremanger granodiorite (Hansen et al. 2002). Large-scale, extensional top-W shear characterizes all the rocks between the brittle fault and stop 4.4, as well as for several km across the mylonite foliation to the north-shore of Nordfjord. This shear zone must have accommodated more than 100 km top-to-the-W movement. The exact magnitude of this displacement is, however, not possible to quantify. The amphibolite facies mylonites display a number of kinematic indicators.

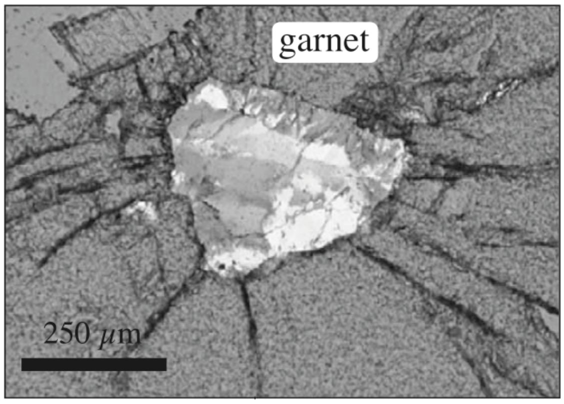
Stop 6.7 Eclogites and mylonite gneisses at Verpeneset, Nordfjord (UTM 6869228-300608) **and Biskjelsneset** (UTM 6868454-299320)

The Verpeneset eclogite is famous for its beauty and also protected so <u>*sampling is not allowed without permission from landowner*</u>!
The roadside outcrop has two eclogites, the spectacular aluminous eclogite L>S tectonite and the finer grained dark eclogite next to it. Both have polycrystalline quartz-palisade-like pseudomorphs after coesite, but the spectacular eclogite was formerly assigned to the “normal” eclogites and contains prograde zoned garnet with abundant amphibole and

pargonite inclusions. Conventional thermo-barometry gives 700C and 2.5 GPa, and thermocalc by Labrousse et al (2004) gives 3.1 GPa and 580C for this locality. Notice that the eclogite facies fabric of this locality as commonly observed in Nordfjord is oblique to the dominant E-W amphibolite facies fabrics in Nordfjord. The post-eclogite fabric is dominated by coaxial flattening to top-W shear fabrics. The large-scale E-W trending regional folds fold the dominant foliation and the present orientation of the foliation is locally overturned with respect to the way up in the crustal section (towards the Devonian basins). The eclogite is engulfed in banded gneisses. The eclogites have omphacite (Jd-35) + garnet + kyanite + clinozoisite + phengite and quartz + accessory talc and sulphide. Cuthbert and Carswell have described polycrystalline quartz inclusions from the foliated darker eclogite with a strong S>L fabric with omphacite and garnet overgrown by poikiliblastic hornblende.



a)



b)

Fig. 6-9 a) U/Pb data from zircons in Verpeneset and b) polycrystalline quartz inclusion from the alumina-rich eclogite at Verpeneset. Both figs for Root et al. (2005)

We continue along the narrow road to have our final stop of the day in the typical banded mylonitic gneisses of Nordfjord region. This locality at Bikjelsneset was site 3 of Marques et al. (2007) in the attempt to quantify the strain field in the detachment mylonites of the NSDZ. Confined flow of the late stage mylonitization suggest a large component of flattening across the mylonitic foliation. Notice that the outcrop has spectacular asymmetrical fabrics and that the eclogite boudins here are mostly amphibolitized.

Day 7, The (U)HP rocks in Nordfjord; topics: protoliths, eclogitization and retrogression, eclogite facies earthquakes and mantle peridotites.

The area between Nordfjord and Stadlandet is the classical eclogite-mantle peridotite terrain in Norway and indeed in the world. A large number of studies have been carried out over the years; nevertheless there are still many unanswered questions and much to be learned from these rocks. A variety of observations suggest that this region is one of the deepest exhumed parts of the Baltican basement after the continental collision between Baltica and Laurentia. Our hotel at Selje is situated very close to the protected Grytting eclogite where David Smith made his milestone identification of coesite in an eclogite of assumed crustal origin in 1983 (published 1984). We have reserved this *protected* locality, which is within walking distance of the hotel as the final stop of the field trip. Another remarkable occurrence is the mantle peridotite of Almklovdalen, where the company 'North Cape Minerals' have a large and efficient olivine mine. We shall visit two localities in this body, one dunite quarry locality and one *protected* garnet peridotite locality after a short walk to Rødhaugen. An enigmatic feature of the area is the proximity of well-preserved coesite eclogites and un-reacted Proterozoic HP-granulites as seen at Flatraket (stop 7.1). We shall also visit the Proterozoic Kråkeneset gabbro, where the igneous texture and mineralogy is well preserved in the gabbro and where the dynamics related to eclogite facies pseudotachylytes and shear zone during incipient eclogitization may be investigated in detail.

Stops 7.1 Flatraket: a) Megacrystic granulite protoliths and b) coesite eclogite.

The Flatraket granulite (Fig. 7-1) was last mapped in detail by M. Krabbendam and A. Wain in conjunction with their PhD studies (Univ Oxford) in the mid 1990-ies (see Krabbendam et al. 2001). The body is sandwiched between UHP-bearing rocks structurally below (1 km) and above (150 m). It contains quartz-monzonitic gneisses, with additional anorthosite and mafic to intermediate dykes which are partly to completely eclogitized. Much of the gneiss is characterized by coarse brown to purplish mega-crystic K-feldspar. White rims around the mega-crysts are recrystallised K-feldspar and the texture is therefore not strictly a rapakivi texture.

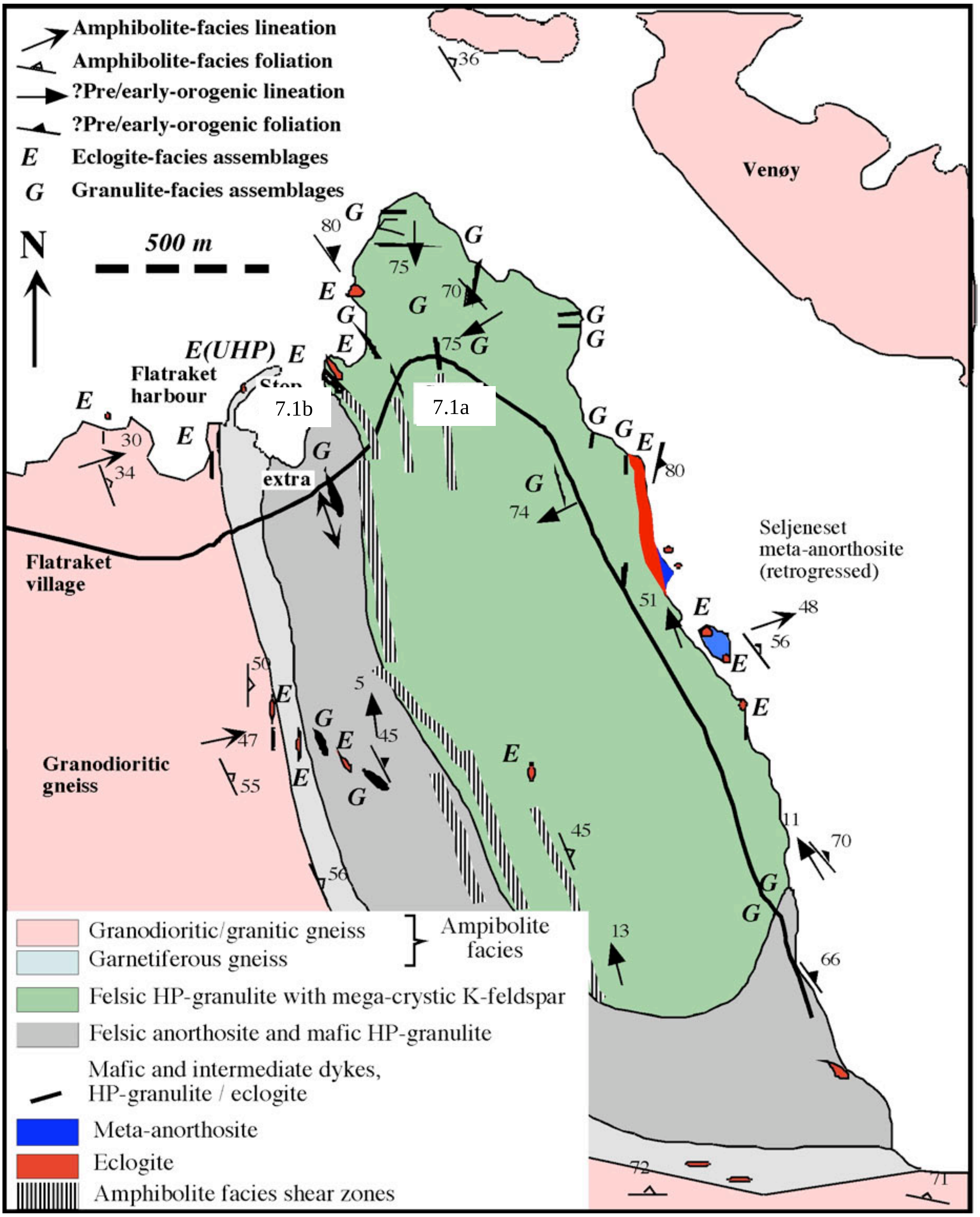


Fig. 7-1. Geological map of the Flatraket body and surroundings. Notice that granulite, HP-eclogite and UHP eclogites occurr in close proximity of each other. Modified from Krabbendam et al. (2000).

Parts of the body is meta-anorthosite with a granulite mineralogy (cpx + plag + grt +qtz), for which 750C and 1GPa was calculated by A. Wain. Other granulites in the area are very similar, except that megacrystic granulite is more rare. HP-granulite assemblages can be found several places at Flatraket, typically represented by grt + cpx + plag. Some mafic dykes, which in the field appear to have eclogite-facies mineralogy, and previously have been described as such, actually contain granulitic assemblages, including plagioclase with polygonal texture. Eclogite-facies assemblages occur locally (ca 5% of the body), either in undeformed mafic rocks or in the felsic rocks as eclogite-facies shear zones. Much of these rocks have been wholly or partially retrogressed to amphibolite-facies assemblages commonly associated with the strong exhumation-related deformation. Many distinct amphibolite facies shear-zones, one of which is nicely displayed at stop 7.1a, occur within or along the margin of the Flatraket body. Much of the mega-crystic granulite has, however, been strongly retrogressed towards amphibolite facies in the absence of deformation. Mafic inclusions in the retrograded granulite commonly have large (up to 3-4 cm) scapolite crystals indicating the importance of fluid activity during the retrogression. The following evolution is suggested for the Flatraket Granulite:

a) Crystallisation of melts with monzonitic and anorthositic composition (dated by the 1520 ± 10 Ma U/Pb upper insect of Lappin et al. 1979). Intrusion of mafic dykes.
b) HP-granulite metamorphism and minor deformation of Pre-Caledonian age.
c) Burial to eclogite-facies pressures (2.2-2.4 GPa) during the Scandian collision. The bulk of the body, however, behaved as a low strain zone and remained unreacted at HP. Equilibration occurred locally, associated with eclogite-facies shear zones.
d) Exhumation by late- to post-orogenic extension, associated with retrogression to amphibolite-facies assemblages.

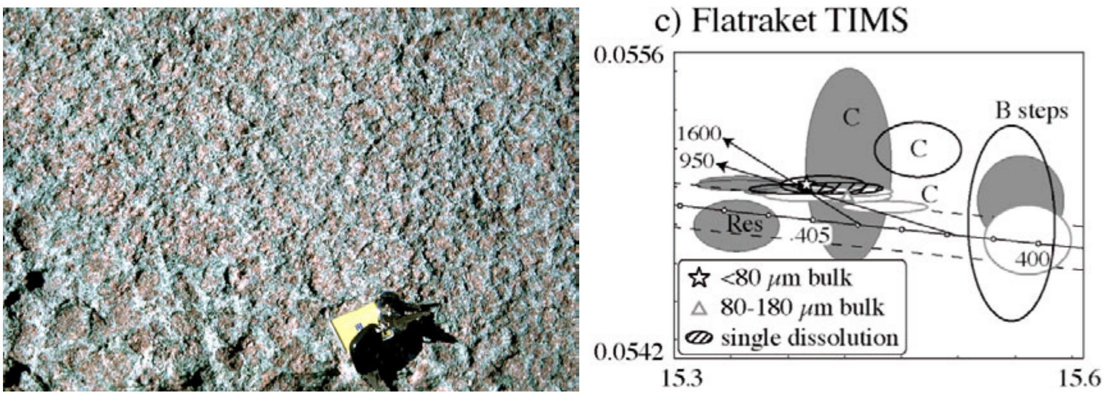


Fig. 7-2. Coesite eclogite and U/Pb dating on zircons (Root et al. 2005) from the Flatraket harbour locality.

Stop 7.1a. Mega-crystic, monzonitic gneiss, mafic dyke and retrogressed HP-granulite in shear zone at quarry and the bend of road, 1 km east of Flatraket village. In the eastern part of the quarry and in outcrops across the road on the NE-side of the quarry, undeformed to poorly deformed felsic gneiss with K-feldspar of 5-8 cm diameter occurs. The white rims around the brown to purplish mega-crysts are recrystallised K-feldspar and the texture is therefore not strictly a rapakivi texture. The mafic minerals within the matrix are biotite, epidote/zoisite and garnet, so some static retrogression to amphibolite-facies has taken place. Shear zones contain amphibolite-facies assemblages and are probably related to the late-Scandian extension. In the road cut opposite the quarry a sub-vertical mafic dyke occurs. This dyke contains a HP-granulite assemblage (grt + cpx + plag), although some up-pressure equilibration may have taken place, as much of the plagioclase is very cloudy.

Stop 7.1b: The occurrence of the UHP eclogites structurally below (Flatraket harbour) as well as above the main body pose some problems. The beautiful coesite eclogite (grt, omph, kya, pheng, qtz/coe) experienced pressure of ca 2.8 GPa (Fig. 7.3). Meta-stability of plagioclase at pressures of 2.8 GPa is harder to explain than meta-stability of plagioclase at pressures of 2.2-2.4 GPa. It has, therefore, been suggested that the adjacent Flatraket granulite and the UHP eclogites may have been juxtaposed sometime during the collision or the late-Scandian exhumation-extension phase, but no structural evidence for this is available and there is no distinct structural dislocation identified or structural model suggested that satisfactorily explains the close spatial association of the pre-Caledonian protoliths, UHP and HP rocks.

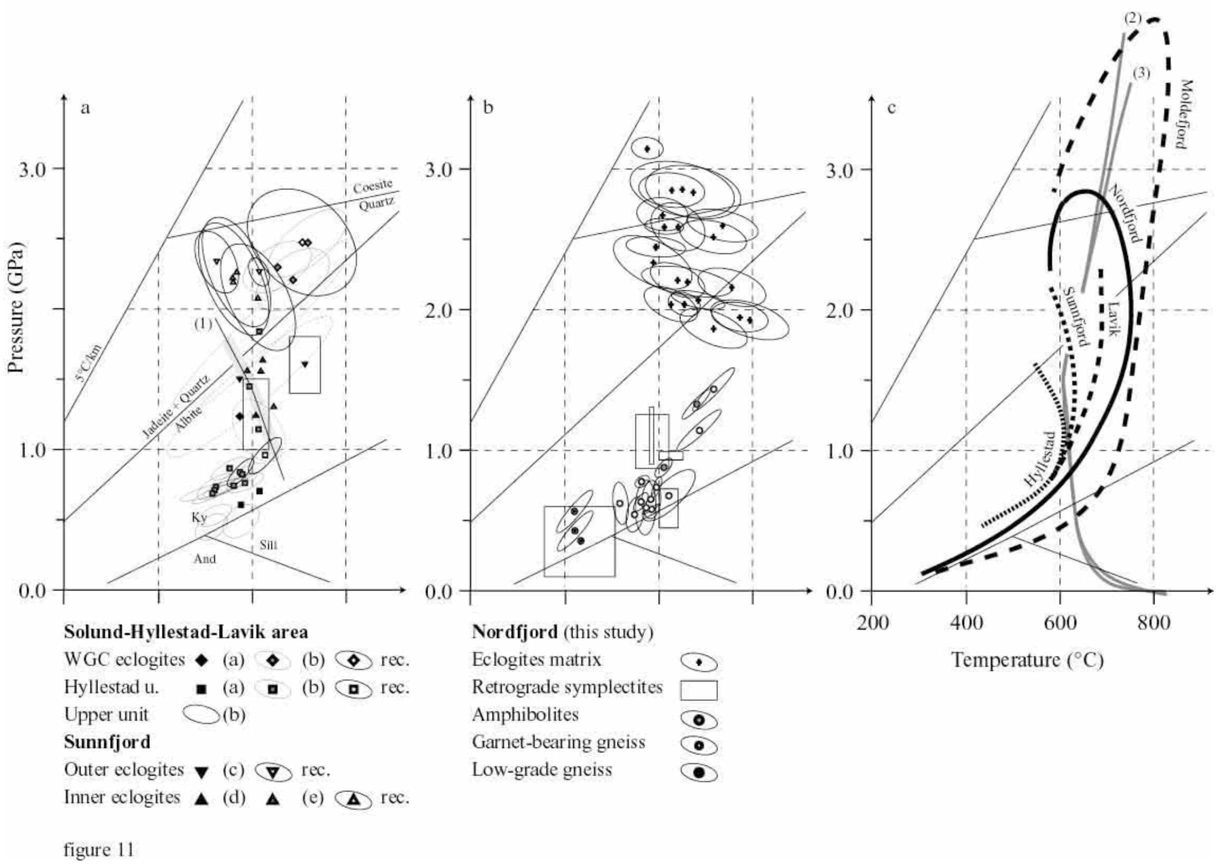


Fig. 7-3. Summary figure of P-T estimates from Western Gneiss Region in Sunnfjord, Nordfjord and the Moldefjord areas compiled by Labrousse et al. (2004)

Stops 7.2: Kråkeneset gabbro, Vågsøy: Topics
a) Gabbro with primary structure and mineralogy and incipient alteration
b) Co-facial eclogite pseudotachylytes and shear zones
c) Amphibolitization, hydration and retrogression

The Kråkeneset locality is a spectacular site on the margin of the Norwegian Sea. Exposures are accordingly good and well washed. The object of the stop is to demonstrate the incipient influence of collision and burial in the WGR proterozoic rocks. The gabbro constitutes a large-scale and low strain boudin within the highly deformed WGC gneisses generally found in the area.

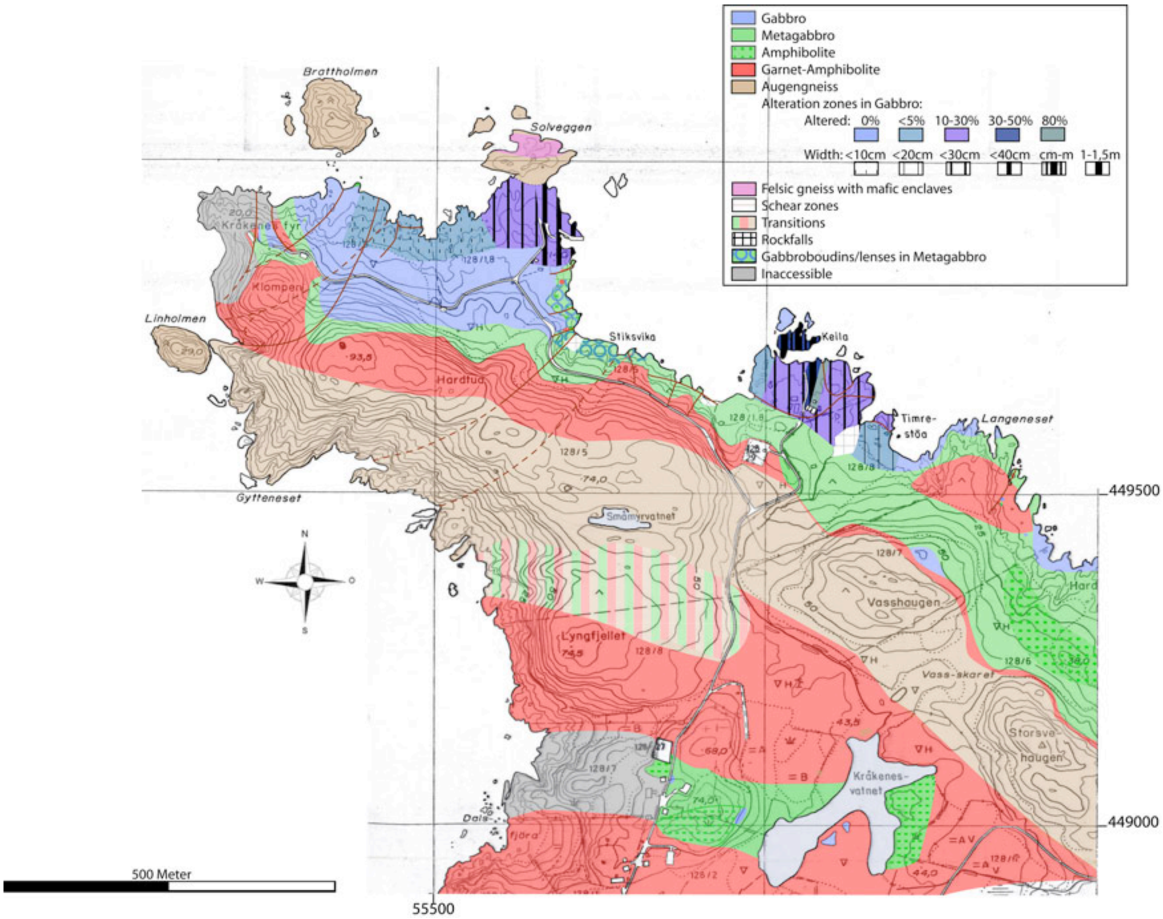


Fig. 7-4. Geological map of Kråkeneset, Vågsøy. (from a student field report, University of Kiel, 2007)

The Kråkeneset gabbro is well preserved both mineralogically and structurally at our first stop (parking area). Notice that cumulate layering is present and that alteration here is confined to fractures. In other areas the alteration is more pervasive (see Fig. 7-4). We shall make a traverse from the best-preserved gabbro westwards where good examples of pseudotachylyte and shear zones are preserved. Lund and Austrheim (2003) described textures from this site in detail and documented eclogite facies quenching of pseudotachylytes. Recently John et al. (2008) discussed and explained the coexistence of parallel co-facial pseudotachylytes and shear zones in the same area. This can be explained as a function of a deformation mechanism referred to as self-localized-thermal-runaway. Modeling shows that very minor differences in viscosities (less than 1%) of the visco-elastic gabbro controls whether deformation localizes as co-seismic failure and produces pseudotachylyte or if the deformation is characterized by ductile shear only. If pseudotachylytes are produced the stress is suddenly relaxed and adjacent creeping shear zones will terminate as the driving stress is released. A model run with viscosity contrast of less than 1% from John et al (2008) is presented in Fig 7-5, and illustrates the scenario. The advantage of this deformation mechanism is that the stresses required for explaining earthquakes at high confining pressure is greatly reduced compared to the stresses required for Byerlee-law fracturing at the same burial depth. It is therefore suggested that self-localized-thermal-runaway may be a viable mechanism for intermediate-depth and deep earthquakes in both collision and subduction tectonic settings.

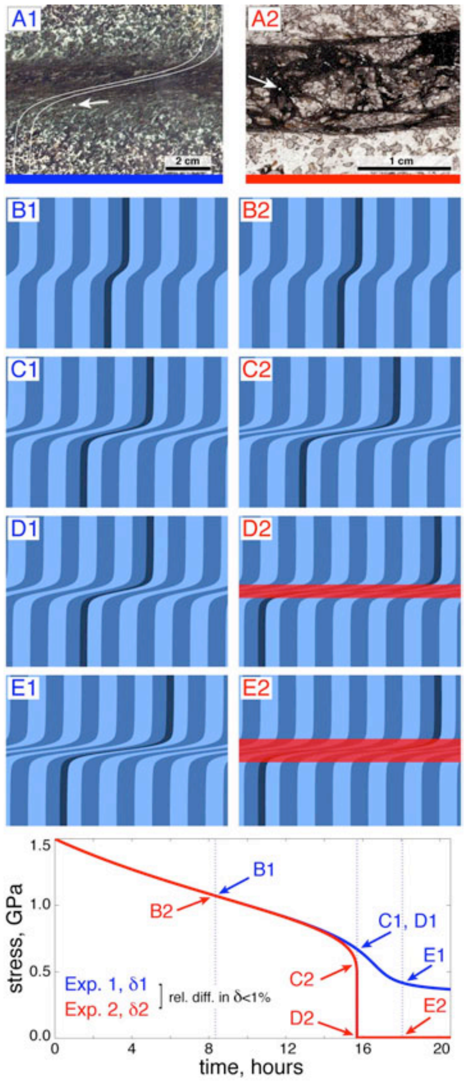


Fig. 7-5. Typical shear zone (A1) & pseudotachylyte (A2) from the Kråkenes gabbro. The shear zone shows no signs of melting, whereas pseudotachylytes have a molten core and limited deformation at the margins. Rows B-E show the results of numerical experiments that reproduce the observed structures. The left column illustrates a shear zone forming simulation and the right illustrates a pseudotachylyte forming simulation. The two simulations differ only by a slightly (1%) larger initial viscosity ratio (δ)in the pseudotachylyte simulation. The two columns show the evolution of passive markers (blue) together with regions of melting (red) for the two simulations at the model times shown in the lower plot, where the time dependence of the stress is illustrated. During the first stage (rows B and C) the behavior is similar for both simulations. However, shortly after the end of this stage (row C) the differential stress is catastrophically released in simulation 2, and no further deformation occurs. The rapid stress drop is accompanied by highly localized deformation and extensive shear heating that melts the deformation zone (D2). The thermal field in simulation 2 continues to evolve after the initial melting (D2-E2), and this is consistent with the observed microstructures that indicate stress free crystallization in the natural examples (Fig. 2b). In contrast, simulation 1 shows no melt formation, limited localization of deformation and a less pronounced stress drop. The similarities in the early stage stress evolution (bottom) and the small difference in the initial conditions favor co-existence of the two deformation processes at time C. However, the catastrophic stress drop in process 2 at time D would unload the system and preclude further deformation. The predicted unloading of simulation 1 (D1) and the thermal relaxation in simulation 2 (E2) are fully consistent with the strain marker patterns recorded in the field. The white curves in A1 are initially vertical lines with the deformation field from D1

The Kråkenest gabbro has been variably hydrated and deformed during exhumation. This is particularly well illustrated immediately east of the parking area (see Fig. 7-6 below). Notice also the abundant presence of large dendrite-like crystals of scapolite that can be observed within the amphibolite inclusion in the megacrystic augen gneiss at Solveggen (Fig. 7-4).

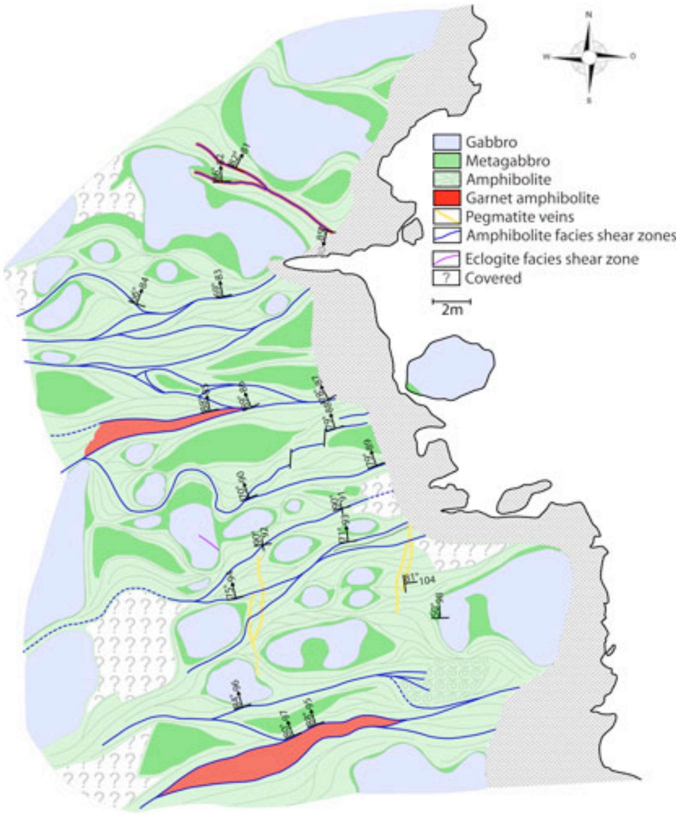


Fig- 7-6. Stikvika Kråkenes. The detailed map shows the progressive reworking of the Kråkenes gabbro into shear zones. The outcrop illustrates in an excellent manner the transitions from prestine gabbro to completely hydrated amphibolite. Notice also locally preserved eclogite facies pseudotachylyte or shear zone (not studied in thinsection) in the northern part of the section.

The mapping was carried out by master students from Kiel university during a field course during the summer 2007.

Return to the mainland and take the fastest route towards Åheim and Almklovdalen (main road along Nordfjord (Rd-15) and then across the mountain to Åheim (Rd-61)

Stop 7.3 Almklovdalen peridotite, near Åheim. Two stops:
a) Dunite with internal eclogites in one of the quarries.
b) Garnet peridotite dunite at Raudhaugen.

Ultramafic inclusions of variably sizes are characteristic and important rock types in the WGR. We have already observed several of these lenses on the road to Kråkeneset, near Raudeberg and near Almklovdalen hosts several large ultramafic bodies and is a classical area for the study of garnetifereous ultramafic rocks. The major rock types are dunite and peridotite. The peridotites typically carry the mineral assemblages oliv + opx + chlor + amph with small areas of garnet peridotite, which are interpreted as relicts and the precursor to the chlorite bearing assemblages. These rocks have been taken to represent fragments of the mantle and the outcrops in Almklovdalen has strongly coloured the existing view of the composition, mineralogy and deformation of the upper mantle. Recently it has been suggested (van Roermund et al. 2000) that garnet peridotites form Oterøy outside Molde, which are closely related mineralogical and compositional to those in Almklovdalen, have been derived from a depth of more than 185 km. If correct these rocks may provide insight into processes in deeper parts of the mantle and certainly put constraints on the geodynamic models proposed for the WGR. The mechanism by which large dense fragments of the mantle become part of the crust is presently not understood although several suggestions have been made. The ultramafites and in particular the garnet peridotites have been extensively studied and Carswell (1986) who developed a seven stage metamorphic evolution for the Oterøy peridotite. These are all interpreted in terms of changing P-T conditions.

The dunitic parts of the ultramafic rocks have been mined for olivine for several decades initiated by the pionering work of V.M. Goldschmidt. A.S. Olivin carries out production in two large quarries (Fig. 68, Gusdal and Sunndalen). In 1995 the annual production was 3 mill. tonns to a value of 400 mill n.kr. In 1995 the company had near 250 employees.

We will make two stops in Almklovdalen.

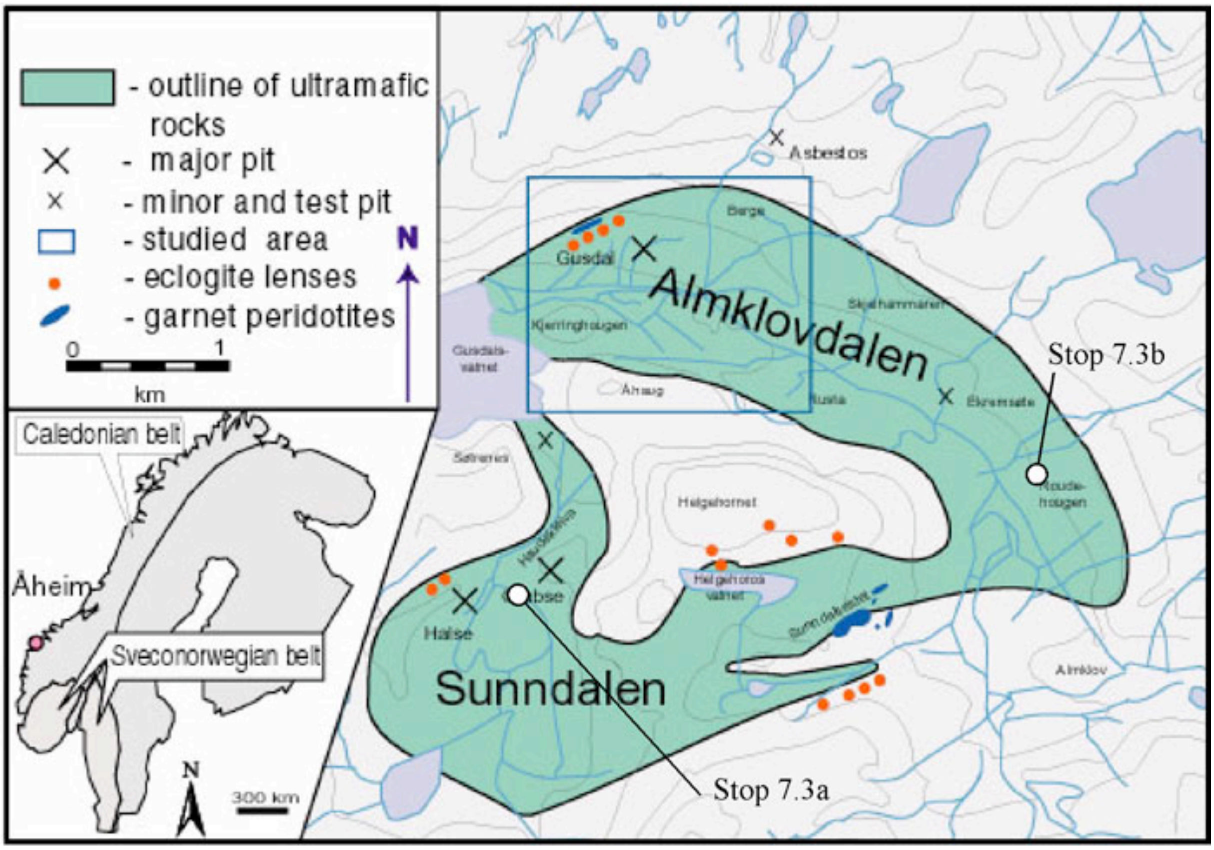


Fig. 7-7, Overview map of the Almklovdalen peridotite, showing the location of stops in the peridotite.

Stop 7.3a The quarry.

The quarry stops at Almklovdalen always presents some uncertainty of what can be seen and where we have access due to the very active working of the pits. Most likely we shall visit the southern quarrys towards Sunndalen. The major rock type is the dunite which normally have layers of harzburgite and some internal eclogites. Chlorite defines a foliation in the dunite. The dunite alternates between a grey and various shades of a green sugary type. Field observations reveal sharp transitions from grey-coloured to green coloured dunite, suggesting the green type is formed from the grey type by fluid infiltration. Locally the dunite is serpentinised, and it is observed that the green type tend to form around veinlets filled with serpentinite. Large ovoid olivine megacrysts may represent porfyroblasts or clasts. At present is uncertain if the colour-change from green to grey represents a fluid event in the mantle or if it occurred after the complex was introduced within the gneisses. Kostenko et al. (2002) discussed this fluid event, which adds considerable complexity to already complex P-T evolution outlined by Carswell (1986). Kostenko et al. (2002) concluded that following metamorphism in the garnet-peridotite stability field the peridotite was pervasively infiltrated by fluids from fractures, and that this event occurred in the chlorite-peridotite stability field, most likely associated with the exhumation of the WGC. The infiltration have increased the grainboundary diffusion rates and caused extensive recrystallization and grain coarsening in the dunite. The grain boundary migration associated with this recrystallization caused the the colour change from grey to green during this fluid-assisted recrystallization event.

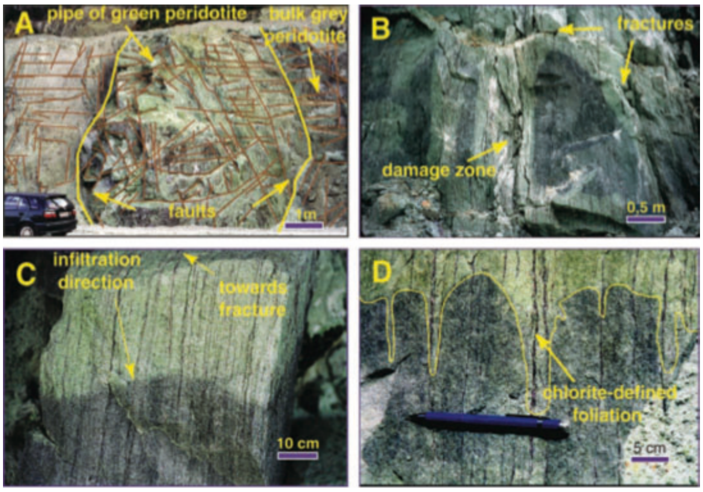


Fig. 7-8, Quarry wall photographs illustrating the front- and finger-like relationships between the grey and the coarser grained green sugary dunite caused by recrystallization associated with fluid alteration along discrete zones or pipes in the dunite.
From Kostenko et al. 2002.

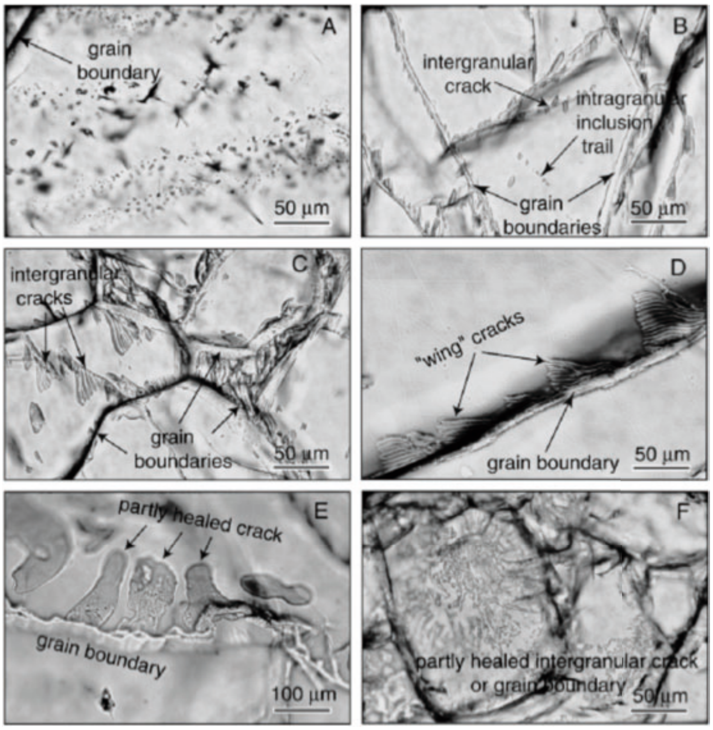


Fig. 7-9 Fluid inclusion trails and microfractures in a) grey peridotite, b) along grain boundaries in green dunite,
c) and d) wing fractures in olivines from the green dunite,
e) and f) partly healed cracks along grain boundaries in olivine grains from

Stop 7.3 b. Rødhaugen. Layers of garnet-clinopyroxenites, dunite and garnet peridotite
Path from Eikremseter towards south (ca 10 min. walk). The path starts at a stone bridge over a ditch.
Rødhaugen is protected as a national monument; collecting is stricktly forbidden.
The Rødhaugen locality is a classic site in geology, described by Eskola (1921) as one of his type examples of eclogites (Rødhaugen type). The outcrop is characterized by 0.5 to 1 m thick layers of garnet clinopyroxenites interlayered with dunites and garnetiferous peridotite. The

layer defines a large open fold in the garentiferous peridotite of variable mineralogy and stages of retrogression. On the track towards Rødhaugen we pass a small waterfall to the left of the path about 200 m from the road. This river exposes a thick layer of eclogite (or garnet pyroxenite) in dunite. The eclogite lacks olivine and orthopyroxene, and in colour and texture is typical of the internal eclogites (eclogites found inside ultramafites). *Continue along path to Rødhaugen.* The Rødhaugen site is an isolated knob in an open forrest/boggy area with a distinctive red weathering colour. On the NE side, eclogite occurs as a distinct meter-thick layering defining a large open fold in garnetifereous peridotite.
Return on the path to the bus and drive the shortest route Selje hotel.

Stop 7.4 Grytting eclogite, Selje.

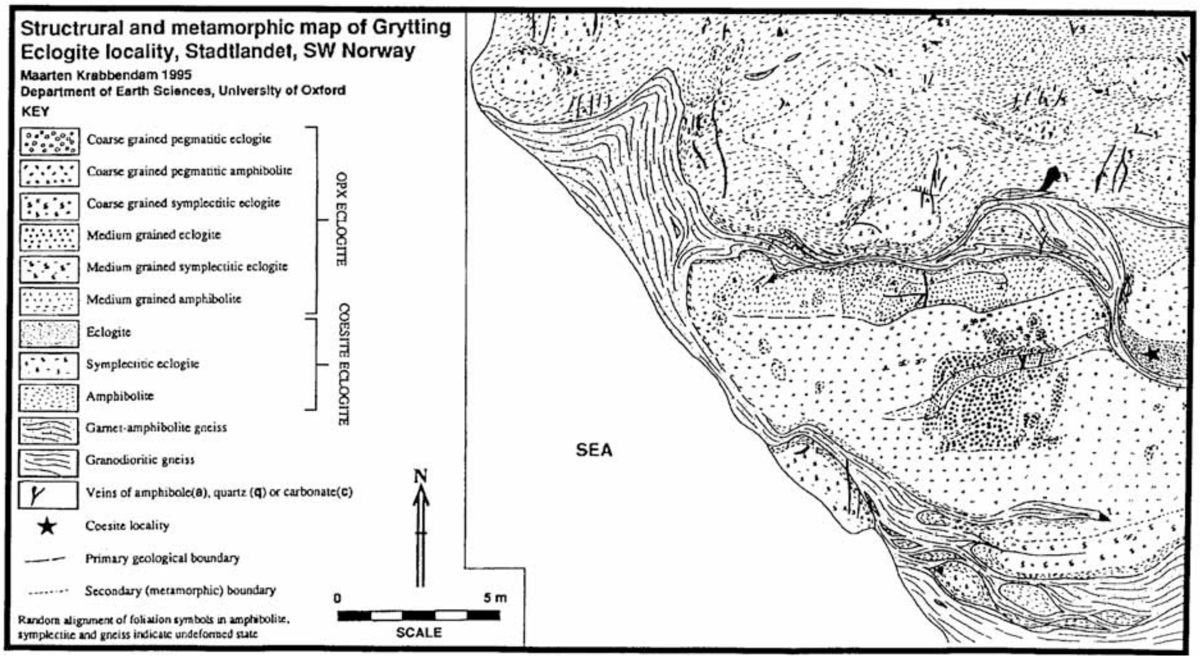


Fig 7-10. Detailed outcrop map of the Grytting UHP eclogite and immediate surroundings at Selje (mapping by M. Krabbendam). Notice that the first coesite locality is from a finer grained less attractive eclogite next to the pegmatitic opx-eclogite. This site is protected and sampling of any kind (also loose material) is strictly forbidden!

The Grytting UHP eclogite and country rock gneisses is accessible by a short walk along the beach from the hotel towards the Selje and walk passed the boat houses north to the locality marked by signs showing that the locality it is protect by law. Fig.7-10 by M. Krabbendam, shows the Grytting locality, one of the classical eclogite localities that Eskola used when defining the eclogite facies in his classical work from 1921. The beautiful pegmatitic opx-bearing eclogite is only locally fresh, but it was in a rather 'insignificantly' looking eclogite next to it (see star mark on map) that Smith found the coesite. This locality and the map clearly illustrate the problems with tectonic juxtaposition of the UHP rock into the lower pressure gneissic envelope. It is also worth noting that recent work on Fe-Ti rich peridotite and opx-bearing eclogites may indicate that pervasive metasomatic alteration has taken place in the ultramafic inclusions within the gneisses and that original hypothesis that we have widely different origin (mantle peridotite vs. peridotites of cumulate origin) must be viewed with much caution (see PhD work by Vrijmoed in progress).

Selected references to Excursion Guide IGC no 29

"Caledonian infrastructure between Bergen and Nordfjord;with special emphasis on the formation and exhumation of high and ultrahigh-pressure rocks, late to post orogenic tectonic processes and basin formation"

(with apologizes to those forgotten)

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