FIELD EXCURSION TO THE FOSEN PENINSULA AND TRONDHEIMSFJORD REGION

FIELD GUIDE
September 2-4, 1998

Excursion led by David Roberts and Arne Solli (NGU)
in conjunction with the BAT project affiliates:

Norwegian Petroleum Directorate

Norges forskningsråd

NGU Report 98.119

Geology of the Fosen Peninsula and Trondheimsfjord Region: a synopsis and excursion guide

NGU Norges geologiske undersøkelse
Geological Survey of Norway

Geological Survey of Norway
P.O.Box 3006 - Lade
N-7002 Trondheim, Norway
Tel.: 47 73 90 40 11
Telefax 47 73 92 16 20

REPORT

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Authors: David Roberts	Affiliates: Amoco, BP, Conoco, Mobil, Phillips, Saga, Shell, Statoil, NPD, Chevron & Hydro
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Summary:

In the *first part* of the report, a synopsis is presented of the general geology and tectonostratigraphy of this part of Central Norway, with a slightly more detailed account given of the geology of the Fosen Peninsula. The *second part* comprises an excursion guide, spanning 3 days, covering the southern district of Fosen from Rørvik to Ørlandet and to the outer coast near Sandnes; and then continuing along the Verran Fault (Møre-Trøndelag Fault Complex) via Verrabotn and Beitstadfjorden to Steinkjer. The last day of the excursion takes in selected localities along the southeastern side of Trondheimsfjorden, finishing at Storvika close to Trondheim Airport, Værnes. The excursion aims to show the variety of rock-types at different tectonostratigraphic levels in this part of the Caledonides, and demonstrates the significance of faulting and diversity of fault trends, fault rocks and vein systems of a variety of ages in this onshore region adjacent to the Mid-Norwegian continental shelf.

A preliminary version of this report and guide was distributed to participants during the actual excursion, 2-4 September 1998 – days blessed by warm, sunny weather. The excursion was the first in the project 'B*asin analysis and applied thermochronology on the Mid-Norwegian Shelf*', otherwise known as the 'BAT project'.

Keywords: Bedrock geology	Caledonides	Fosen Peninsula
Trondheimsfjord	Precambrian	Palaeozoic
Devonian	Møre-Trøndelag Fault Complex	Excursion guide

Geology of the Fosen Peninsula and Trondheimsfjord Region: a synopsis and excursion guide

DAVID ROBERTS

Synopsis of the regional and local geology

Introduction

The counties of Nord- and Sør-Trøndelag in Norway and Jämtland in Sweden have attracted the attention of geologists since the middle of the 19th century. It was in this part of the Scandinavian Caledonides that the now classical work of Törnebohm (1888, 1896) had laid the foundations for the concept of thrust tectonics as we know it today, not only here in Scandinavia but with subsequent application to other orogenic belts worldwide. Earlier mapping in this region had established the basic distribution of the principal rock units (Keilhau 1850, Kjerulf 1871, 1876, Törnebohm 1872), which included a package of unfossiliferous quartzites, garnet schists, amphibolites and gneisses lying directly above low-grade Cambro-Silurian successions quite close to the mountain front. It was this abnormal, 'gneiss-upon-shale' relationship that ultimately convinced Törnebohm that major thrust displacement of rock units was an integral element in the development of the Caledonian mountain chain.

As a consequence of this early attention, and the later realisation that parts of the lithological successions in western Trøndelag carried fossils in abundance, this tract of the Caledonides has been the locus of many geological excursions, commonly with international participation (including International Geological Congress excursions in 1960 and 1980). This activity has been particularly noteworthy over the last three to four decades, partly due to the fact that such excursions have only been properly documented for bibliographic reference since about 1960, but also in view of the fact that modern mapping at 1:50,000 scale by NGU during this period and concurrent active research have led to many new and exciting developments.

This particular excursion is designed to meet the general wishes of our colleagues in the oil companies that are contributing to the project '*Basin analysis and applied thermochronlogy on the Mid-Norwegian Shelf* ', otherwise known as the BAT project; i.e. to see as much as possible of Fosen Peninsula geology within just three days. As this inaugural project excursion also involves picking up certain people from early morning flights on the first day, catching a ferry, and driving several participants to the airport by the late afternoon of Day 3, then the time left for serious geology is already somewhat reduced. Because of these constraints, we have felt it necessary on this occasion to confine ourselves to the southern part of Fosen Peninsula; and the excursion itinerary has accordingly been designed with a restricted number of official stops, either along road-cuts or on easily accessible coastal sections. This does not mean that extra stops cannot be made. Indeed, the discussions en route, and during the evenings, may warrant our making brief detours and extra stops – as long as we keep to our basic schedules.

Several of the chosen stops have featured in one or other of our own earlier guides, or in guides prepared by colleagues – Wolff et al. (1980), Gee & Wolff (1981), Solli et al. (1997a). These are duly acknowledged in the appropriate stop descriptions. The area covered by the excursion route lies within the 1:250,000 bedrock geological map-sheets Trondheim (Wolff 1976) and Namsos (Solli et al. 1997b).

Regional geology: a synthesis

To understand the basic geology of Fosen (Fig. 1), it is necessary to consider just one or two of the principal elements, and stages of development, of the Caledonide orogen in Central Norway. In this region, the Caledonide orogen is composed of a series of east- to southeasterly transported nappes that were subsequently affected by regional-scale folds and extensional faults, or larger detachments, and also transected by one conspicuous, multiphase, strike-slip fault zone, the Møre-Trøndelag Fault Complex. The various nappes and thrust-sheets are composed of rocks which originated in diverse palaeogeographic settings and were ultimately juxtaposed during one or more episodes of intense lateral shortening, tectonic telescoping and thrust translation (in some cases over distances of hundreds of kilometres), and later extensional movements, in Early Palaeozoic time.

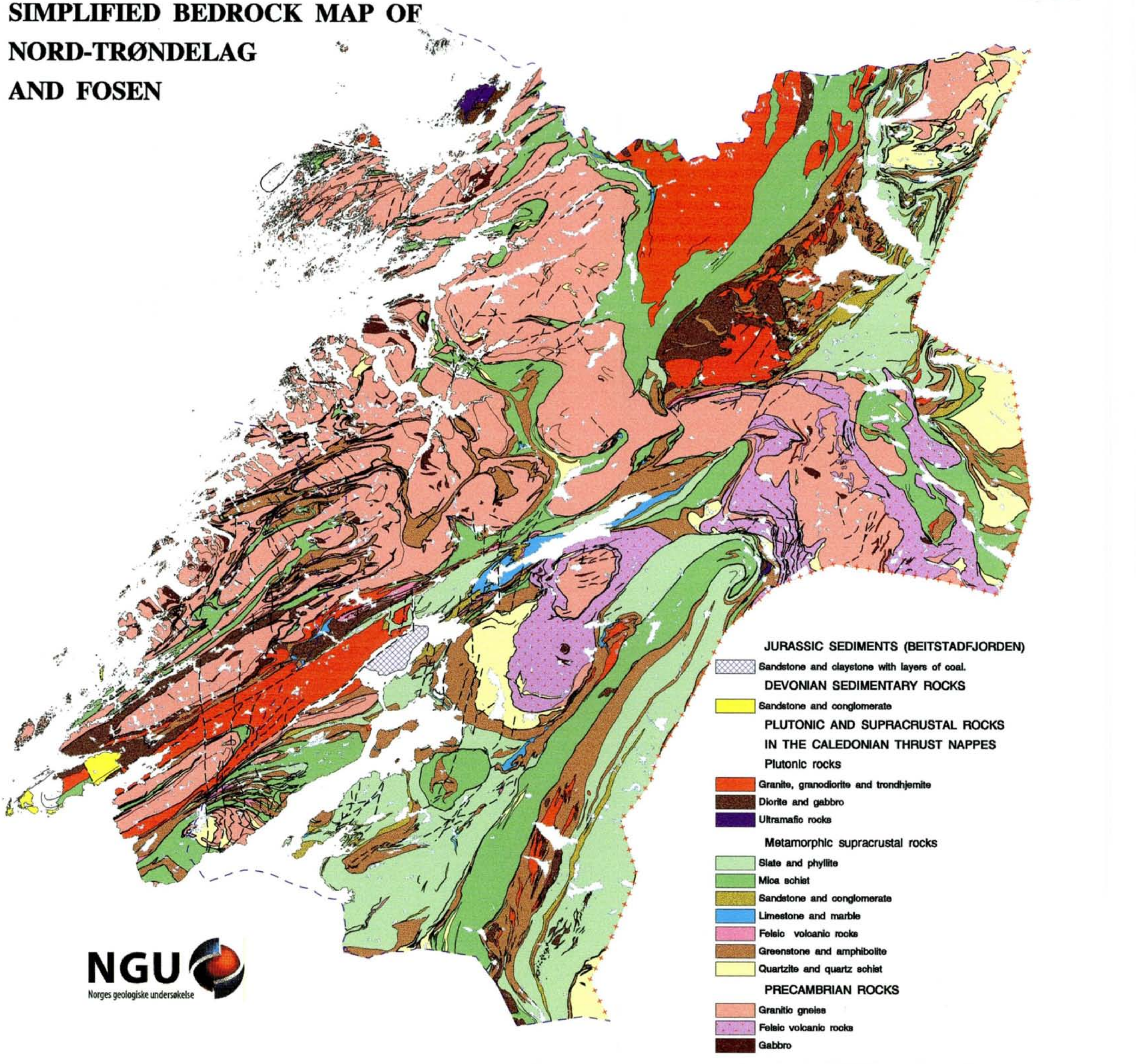
Tectonostratigraphy: The various nappes and thrust-sheets have been grouped into four major allochthonous complexes; the Lower, Middle, Upper and Uppermost Allochthons (Table 1) (Roberts & Gee 1985). This is a tectonostratigraphy that, to a large extent, reflects the original palaeogeography marginal to the palaeocontinent *Baltica*, and beyond -- moving outboard from the Baltoscandian platform and miogeocline (the 'sandstone nappes' of the Lower and Middle Allochthon levels) into the more exotic oceanic and arc terranes of the Upper Allochthon, and ultimately, in the highest allochthon, into rock complexes of probable Laurentian affinity.

Precambrian crystalline rocks dominate the ***Lower Allochthon*** in this part of Norway (Fig. 2). In eastern areas, and in Sweden, there are comparatively pristine Late Palaeoproterozoic granitoid and volcanic rocks with a thin Vendian-Cambrian sedimentary cover, and only negligible signs of a Caledonian imprint. Towards the west, these rocks gradually become penetratively foliated, recrystallised and in places mylonitised as a result of the Siluro-Devonian *Scandian* deformation. Metamorphic grade reached amphibolite facies, and even locally

Fig. 1

s. 5a

SIMPLIFIED BEDROCK MAP OF NORD-TRØNDELAG AND FOSEN



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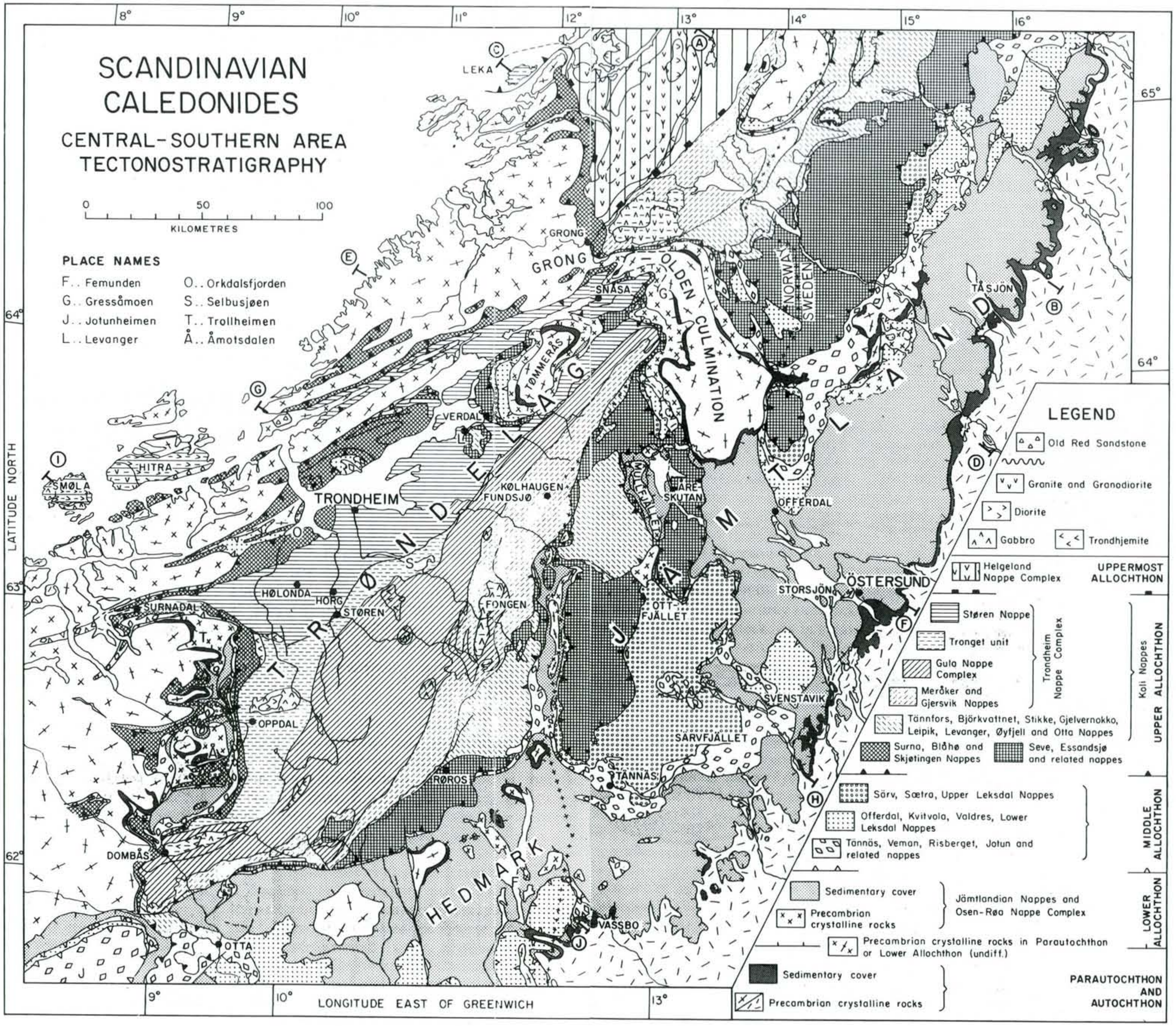


Fig. 2. **Tectonostratigraphy of the central southern part of the Scandinavian Caledonides.**

From Gee et al. (1985).

Table 1. Correlation of main tectonic and stratigraphic units in the central southern part of the Scandinavian Caledonides.

	Southwestern areas			Central areas			Eastern Areas
Tectonic units	Dombås (Guezou 1978)	Oppdal (Krill 1980)	Trollheimen (Gee 1980)	Trøndelag Western (Wolff and Roberts 1980; Roberts and Wolff 1981)	Trøndelag Eastern	North of Grong–Olden Culmination (Stephens *et al.* this volume)	Central and Southern Jämtland (Gee 1975a)
Late-orogenic sediments				Late Silurian(?) to Mid-Devonian	Early Devonian		
Uppermost Allochthon						Helgeland Nappe Complex	
Upper Allochthon	Trondheim Nappe Complex: Fokstua Group, Musadal group, Skåkåhøi Group	Tronget unit		Støren Nappe Meråker; Gula Nappe Complex; Levanger Nappe Øyfjell		Gjersvik Nappe, Leipik Nappe, Gelvanakko Nappe, Stikke Nappe, Björkvattnet Nappe	Köli Nappes (Tännfors district) — Seve–Köli Nappe Complex
	Bottheim Group	Blåhø Unit		Skjøtingen Nappe Essandjø		Seve Nappes	Seve Nappes — Seve–Köli Nappe Complex
Middle Allochthon	Andbergshøi Complex: Veslefjell Group	Sætra Nappe; Risberget Unit	Sætra Nappe; Indre Kam Formation (Hansen 1971) Augen gneiss	Leksdal Nappe: Dolerite-intruded Sandstone; Sandstone without dolerite; Hærvola Nappe	Remskleпp Nappe: For subdivision of this unit, see Sjöström (1983)	Särv Nappes (with Ottfjället Dolerites); Augen gneiss	Särv Nappes (with Ottfjället Dolerites); Offerdal Nappe; Tännäs Augen Gneiss Nappe
Lower Allochthon	Osen–Røa Nappe Complex (Nystuen 1981)	Not distinguished	Svarthammer unit (Hansen 1971) in part	Foliated granite and rhyolite; Bjørndalen Formation (Gee 1977)	Remskleпp Nappe	Jämtland Supergroup in Jämtlandian Nappes	Jämtland Supergroup in Jämtlandian Nappes
Parautochthon and Autochthon	'sparagmite'	Åmotsdal Unit	Gjevilvatnet Group	Bjørndalen Formation	Quartzites and black phyllites	Tåsjön and Sjoutälven Groups	Tåsjön and Sjoutälven Groups
	Precambrian gneiss and granite	Lønset Unit (gneiss)	Trollheimen Granite	Precambrian granite and rhyolite	Precambrian granite and rhyolite	Precambrian granite, gneiss, etc.	Precambrian granite, gneiss, etc.

From Gee et al. (1985).

granulite facies in the Roan district of Fosen Peninsula (Johansson & Möller 1986, Möller 1988); and original granites are now represented by migmatised, banded orthogneisses.

The ***Middle Allochthon*** is characterised by Neoproterozoic, low-grade metasandstones, locally with profuse mafic dykes, and with extensive sheets of strongly Caledonised Precambrian crystallines (Gee et al. 1985). These sandstone nappes are overlain by sedimentary and magmatic rocks of the lower division of the ***Upper Allochthon*** – the *Seve Nappes* – part of the ancient continent-to-ocean transition zone; and these, in turn, are superposed by ophiolitic, island arc and back-arc marginal basin elements of the *Köli Nappes,* derived largely from within and peripheral to the Iapetus Ocean (Gale & Roberts 1974, Grenne et al. 1980, Prestvik 1980, Roberts et al. 1984, Heim et al. 1987). All these units show evidence of more ductile, higher strains and higher metamorphic grade towards the west. The ***Uppermost Allochthon,*** present in Nord-Trøndelag and farther north, comprises abundant granitoid rocks of Ordovician to Silurian age (Nordgulen et al. 1993) cutting diverse Proterozoic gneisses. This is a granitoid magmatic association that is foreign to Baltica.

<u>Caledonian deformation and metamorphism</u>: The internal structures and principal metamorphic fabrics in all these nappes are largely the result of the process of oblique collision between Baltica and Laurentia, initiated in Mid to Late Silurian time and extending well into the Devonian – the *Scandian orogeny*. The polyphase nature of this event, involving subduction of the margin of Baltica beneath the Laurentian plate with metamorphism up to eglogite and granulite facies, and E to SE translation of the developing nappes over vast distances, has been described in many publications. One important aspect, already recognised over thirty years ago as a gravity-induced extensional collapse of the orogen (Roberts 1967, 1971), is that of a widespread, late-Scandian vertical shortening. This produced a ubiquitous, flat-lying crenulation cleavage in appropriate lithologies, and led to reverse-sense (top-west) reactivation along nappe-sole thrusts (Möller 1988, Sjöström et al. 1991) and the generation of thick zones of top-to-the-west or southwest, shear-banded mylonites along detachments beneath developing *Devonian basins* (Séranne 1992).

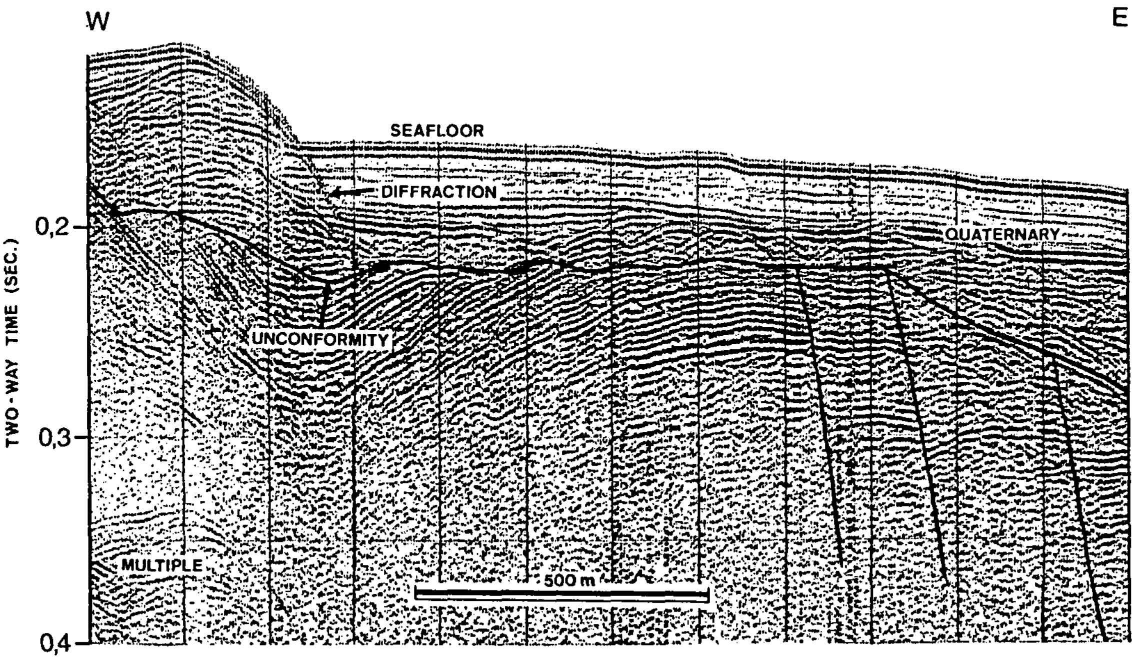
An additional, but no less important aspect of Caledonian deformation is that of earlier contractional orogenic events, notably in the Ordovician. An Early Ordovician orogeny, commonly termed the *Finnmarkian,* following continent-arc collision in a probable Baltica-Siberia scenario (Torsvik et al. 1995), involved the outermost margin of the Baltican miogeocline and thus mainly the Seve Nappes and higher part of the Middle Allochthon (Särv Nappes). Ophiolite obduction also occurred at this time (Sturt & Roberts 1991). Evidence from the island of Smøla, c. 100 km southwest of Fosen, also points to an important Mid Ordovician (Taconic equivalent) orogenic event, a deformation which has also been recognised in some of the higher Köli Nappes farther to the north, in Nordland, and in Sweden. From the complexities of these specific events, it follows that the rocks in some thrust-sheets have had a bi-orogenic and not just polyphase development (Lagerblad 1983, Tietzsch-Tyler 1989), whereas others have been affected only by the climactic Scandian deformation and metamorphism

Devonian basins: In the Ørlandet area of SW Fosen, on Hitra, near Smøla and on many smaller islands in this district (Fig. 2), successions dominated by coarse conglomerates and sandstones of mainly fluvial origin occur either unconformably upon or in extensional-tectonic contact above the polyphasally deformed nappe rocks. A fundamental transtensional regime has been inferred to have existed during the period of deposition of these Devonian sedimentary rocks (Roberts 1983) -- rocks which are generally regarded as molasse deposits derived by erosion of the rapidly exhumed Scandian nappes.

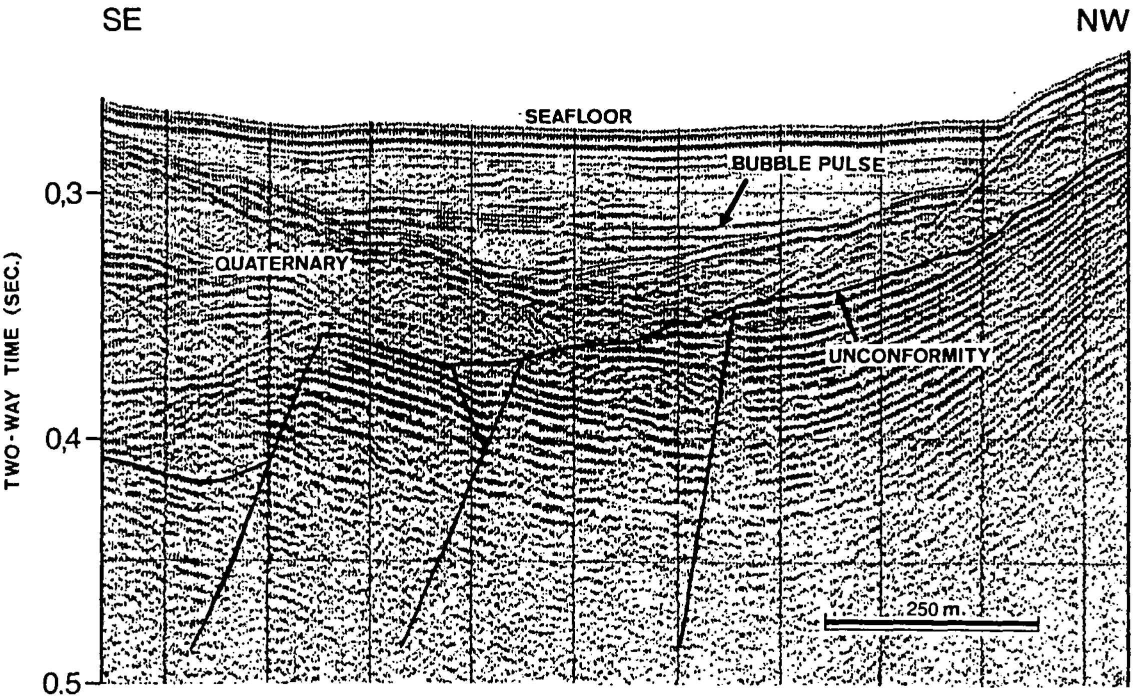
Plant remains testify to a mainly Early to Middle Devonian age for these late-orogenic sedimentary rocks (Vogt 1929, Høeg 1936, 1945, Allen 1976) although on Hitra the basal formation (Siedlecka & Siedlecki 1972), containing a *Dictyocaris* fauna, may be of Late Silurian (Pridoli) age (Størmer 1935). On Ørlandet and adjacent islands, stratigraphic subdivision of, and sedimentological studies on these Devonian, or Old Red Sandstone rocks have been carried out by Siedlecka (1975) and Bøe & Sturt (1991).

Deformation structures in the Devonian rocks on Hitra and Ørlandet have been described by Bøe et al. (1989), Bergfjord (1989) and Séranne (1992). A major extensional detachment beneath the Devonian rocks on Ørlandet carries evidence of top-SW shear (Séranne 1992), such that the original location of the basin – probably at some distance to the northeast -- is not known. Discrete, thin mylonites also occur within the Devonian succession (D.R. unpubl. data) which, as a whole, is deformed in a gentle ENE-WSW-trending syncline. A similar, but tighter syncline affects the Devonian rocks of Hitra (Bøe et al. 1989). In that succession, metamorphosed at the anchizone/greenschist-facies boundary, S-directed internal thrusting has also been reported by these same authors. The folding and very low-grade metamorphism of the Devonian rocks of this outer Trøndelag district are believed to be of Late Devonian to possibly earliest Carboniferous age (Steel et al. 1985, Bøe et al. 1989).

Mesozoic sedimentary rocks: Sedimentary rocks of this age are known to occur in Edøyfjord, south of Smøla, in Frohavet, and are almost certainly present in Beitstadfjord in the eastern part of Fosen (Bøe & Bjerkli 1989, Bøe 1991) (Fig. 1). They have also been described from the Griptarane area, on the margin of the Møre Basin, southwest of Smøla (Smelror et al 1994, Bøe & Skilbrei 1998). Rocks of this age have not yet been found *in situ* on land in Trøndelag. On our excursion we will pass along the northwestern shoreline of Beitstadfjord, from where Vigran (1970) described plant remains of Mid Jurassic age from fragments of coal and sideritic ironstone collected from a stream section. Shallow seismic profiling helped in determining the internal structure of the succession of inferred Jurassic age sedimentary rocks in the Beitstadfjord basin (Oftedahl 1975, Bøe & Bjerkli 1989) (Fig. 3), but as yet we are lacking the confirmatory shallow drilling in this innermost arm of Trondheimsfjord.



Part of profile 14 from Beitstadfjorden (Fig.2B) illustrating folding in the Mesozoic sequence close to the Verran Fault (situated to the left).



Part of profile 10 from Beitstadfjorden (Fig.2B) illustrating fault and fold pattern along the northwestern margin of the basin. The Verran Fault is situated to the right.

Fig. 3. Shallow seismic profiles from Beitstadfjorden, taken from Bøe & Bjerkli (1989). The cited Fig.2B refers to a figure in this article.

Fosen Peninsula

The Fosen Peninsula (Fig. 1) forms part of the Western Gneiss Region, exposing some of the deepest levels of the Caledonian orogen. The geology of the peninsula mainly comprises strongly reworked, Palaeoproterozoic crystalline complexes of the Lower Allochthon, and supracrustal rocks of higher, far-travelled, thrust sheets of the Middle and Upper Allochthons (Johansson 1986a, Roberts 1986, Möller 1988). These include parts of the Leksdal (Särv), Skjøtingen (Seve), Gula and Støren (Köli) Nappes (Table 1). Some thin supracrustal rock sequences in western areas are of uncertain origin and age. The youngest exposed rocks on the peninsula, as mentioned above, are the Devonian conglomerates and sandstones in the Ørlandet area.

It is interesting to look back into earlier interpretations of Fosen geology. Over a century ago, Kjerulf (1871) regarded the 'basement gneisses' of what he called 'Vestranden' as consisting mainly of Precambrian 'granites'. Holtedahl (1944), on the other hand, believed the foliated granitoid rocks to be products of Caledonian granitisation and migmatisation of older supracrustal rocks. Birkeland (1958) totally rejected the Caledonisation idea, noting that «there is no doubt that the rocks of the basement complex existed in their present state long before the beginning of the Cambrian». He also considered the ubiquitous foliation in the granitoids to be a primary igneous structure. Moreover, he favoured the notion that all the Lower Palaeozoic volcanosedimentary rocks in the 'nappes' were lying unconformably upon the Precambrian basement complex. This primary contact hypothesis was also supported by Oftedahl (1964).

Detailed mapping and structural studies in Trøndelag during the 1970s and 80s, partly systematic NGU work but also associated with IGCP Project 27 'The Caledonide Orogen', supported the idea that the intensity of Scandian deformation increases markedly from east to west at any one given tectonic level, not least in the Proterozoic rocks of the Lower Allochthon. Suprajacent nappes, easily identified in eastern districts, were also strongly affected, in some cases attenuated or even excised. The extent of Caledonisation in the Fosen district is such that protolith granitic to tonalitic, migmatitic orthogneisses and basic rocks have generally been thoroughly reworked and transposed into strongly banded, gneissic L-S tectonites (Johansson 1986a, Roberts 1986, 1998, Möller 1988, Solli et al. 1997b). Möller (1988), in fact, referred to the entire assmblage as the '*Banded Gneiss Complex*' (BGC). Here and there, however, there are lensoid bodies and structures present on scales ranging from a few metres to lenses up to 5-6 km in length. These commonly consist of coarsely foliate and migmatitic orthogneiss and basic rocks, some coronitic textured, which along their margins show rapid transpositions through high-strain zones into the ubiquitous, heterogeneous banded gneisses (Johansson 1986a, b, Roberts 1986).

In the Roan district of coastal central Fosen Peninsula, the banded gneisses overlie an antiformal, high-P granulite-facies terrane; the Roan Igneous Complex (Johansson & Möller

1986, Möller 1988, 1990). Along their mutual thrust contact, high-PT Scandian mylonites carry a NW-SE lineation with both top-SE ductile-contractional and later, top-NW extensional structures. Gilotti & Hull (1993) have suggested that Caledonian thrust movement here was directly entirely towards the WNW, a notion that gains little support from regional geological considerations. A more likely scenario is that there was significant, late-Scandian, extensional reactivation focused along this particular contact, carrying the hangingwall BGC rocks northwestwards across the Roan Igneous Complex at some stage during Devonian time.

Not all of the strongly deformed orthogneisses on Fosen are necessarily of Proterozoic age. The Ordovician to Early Silurian, dioritic, granodioritic and granitic rocks of the Smøla-Hitra Batholith have been showed to be traceable into the Stjørnfjord-Ørlandet district (Gautneb & Roberts 1989), and further to the northeast. The Lerberen Granite, on Ørlandet, has yielded a U-Pb zircon age of 442 $\pm$ 2 Ma (R.D.Tucker; in Solli et al. 1997a) and a highly sheared, foliate granodiorite near Hasselvika (indicated as a paragneiss on Wolff's 1976 map) is also of Ordovician age judging from unpublished U-Pb zircon data from an identical rock along strike just southwest of Trondheimsfjord (R.D.Tucker). Farther to the northeast, near Follafoss, a granodioritic gneiss has yielded a U-Pb zircon age of 460 $\pm$ 5 Ma (Thorsnes et al., manuscript).

The Precambrian granitoid orthogneisses of the Fosen Peninsula have yielded protolith ages (U-Pb, zircon) between c. 1830 and 1640 Ma (Johansson 1986a, Schouenborg et al. 1991, Johansson et al. 1993). Although there are few data actually published at present, the results are indicating that the oldest Palaeoproterozoic crust occurs in the northern part of Vestranden, whereas the granitoid orthogneisses in southwestern Fosen, where we will be concentrating our excursion, are appreciably younger and formed at around 1650 Ma (Tucker & Krogh 1988, Johansson et al. 1993). Surprisingly enough, there is no firm evidence of any major tectonothermal disturbance affecting these plutonic rocks until their major reworking during the Scandian orogeny (Tucker et al. 1991). A Sveconorwegian overprint, for example, is lacking in this region.

The age of the peak, high-P granulite-facies metamorphism in the Roan Window, based on Sm-Nd data, is c. 425 Ma (Johansson et al., in Möller 1988). This age is comparable to that reported (c. 420-430 Ma, also Sm-Nd) for the eclogite-facies metamorphism farther southwest in the Western Gneiss Region (Krogh et al, 1974, Griffin & Brueckner 1980). Large muscovites in pegmatites developed in contractional mylonites in one area on eastern Fosen have yielded a Rb-Sr age of c. 424 Ma (Piasecki & Cliff 1988). U-Pb ages on zircons from discordant pegmatite dykes developed after the peak Scandian event are generally around 400 Ma (Tucker et al. 1987, 1991, Schouenborg et al. 1991, Solli et al. 1997a). Cooling ages derived from $^{40}Ar/^{39}Ar$ analyses on biotite and muscovite generally fall in the range 410-395 Ma (Dallmeyer et al. 1985), while metamorphic sphenes in basement gneisses from southwest of Trondheimsfjord have given consistent U-Pb ages of c. 395 Ma (Solli et al. 1997a, Tucker et al. in prep.). Exhumation and cooling of these rocks, following subduction to great depths, must therefore have been extremely rapid, and occurred coevally with Devonian sedimentation and early extensional collapse. Rb-Sr dates on muscovites from strain-induced pegmatites developed along *SW-directed* mylonitic shear zones in the Jøssund district of SW Fosen, at 389 ± 6 and 386 ± 6 Ma (Piasecki & Cliff 1988), appear to provide a reasonable, Mid Devonian age for the regional, SW-directed, extensional detachment movements.

Møre-Trøndelag Fault Complex: A major feature of Fosen geology is its transection by the ENE-WSW-trending, multiply reactivated Møre-Trøndelag Fault Complex (MTFC), or Fault Zone, with its two principal faults, the Verran and Hitra-Snåsa Faults, and a third oblique structure, the Mosvik Fault (Grønlie & Roberts 1989) (Fig. 4). An inferred parallel fault along a steep escarpment beneath Trondheimsfjord may also belong to this system. These faults, which postdate the stacking of the Scandian nappes, can be followed southwestwards into the shelf area of offshore Nordvestlandet and further into the northern North Sea (Fossen 1989, Blystad et al. 1995, Doré et al. 1997). A number of principal stages of movement have been determined for the fault complex, based mainly on isotopic, fission-track and palaeomagnetic studies (Bøe & Bjerkli 1989, Grønlie & Torsvik 1989, Grønlie et al. 1991, 1994, Séranne 1992). These include ductile sinistral offset in Early/Mid Devonian time, and ductile-to-brittle (or more brittle at younger stages) dip-slip and mainly dextral strike-slip/oblique-slip displacements in Late Devonian, Permian-Triassic, Late Jurassic/Early Cretaceous and Late Cretaceous/Early Tertiary time. Details of the mesoscopic structures, fault rock products and vein-system mineralogies can be found in Grønlie et al. (1991).

During our excursion we will have the opportunity to examine fault lithologies and structures along part of the Verran Fault, and in adjacent gneisses, close to Verrabotn in innermost Beitstadfjorden.

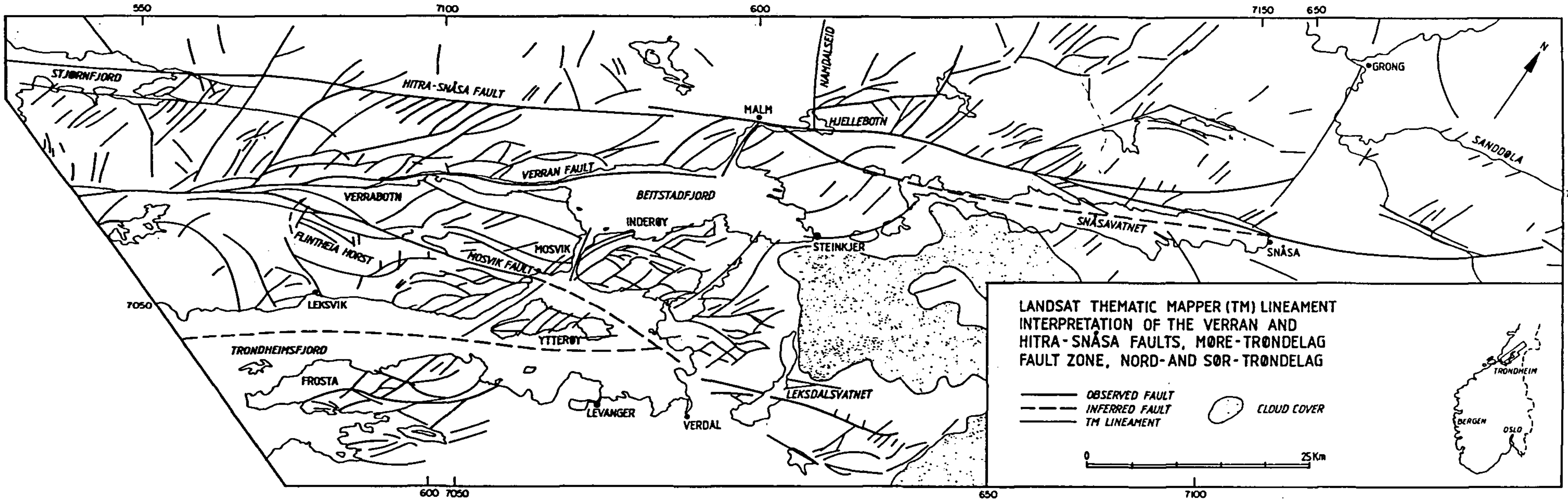
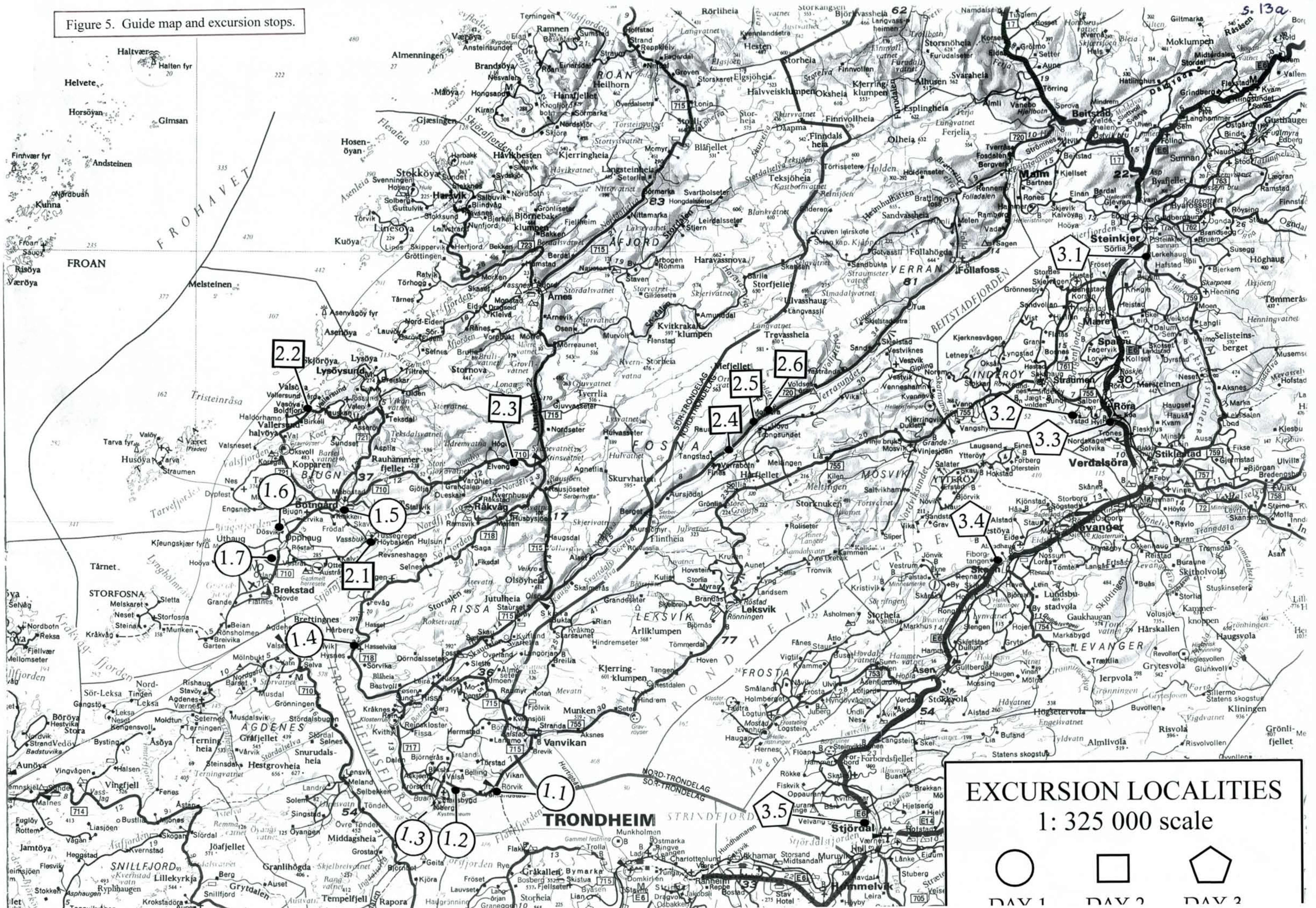


Fig. 4. Landsat Thematic Mapper (TM) lineament interpretation of the Verran and Hitra-Snåsa Faults, Møre-Trøndelag Fault Complex, Fosen Peninsula and innermost Trondheimsfjord, Central Norway. From Grønlie & Roberts (1989).

Figure 5. Guide map and excursion stops.



Excursion itinerary

Excursion leaders – David Roberts & Arne Solli

The excursion route and the stops on the separate days are shown in Fig. 5. Grid references given for the various stops are taken from the latest M711, 1:50.000 topographic map series, 3-NOR edition, i.e. the *blue* WGS84 coordinate grid.

Day 1. Ferry from Flakk to Rørvik; then to Hasselvika, Botngård and Døsvika. Possible scenic stop at Lerberen. Overnighting at Brekstad Hotel.

Stop 1.1. *Garnet amphibolites and felsites, Seve (Skjøtingen) Nappe.*
Ferry plaza; road-cut immediately to the right on leaving the ferry.
1:50 000 map-sheet 'Rissa' – grid ref. c. 564 424.

At this stop we will introduce participants to the excursion itinerary, noting briefly what we will be seeing en route. Here we can examine garnetiferous amphibolites with intercalations of felsitic rocks. These rocks are fairly typical of the Seve Nappe, the lowermost part of the Upper Allochthon in Scandinavian Caledonide terminology, and are considered to derive from the Baltica-Iapetus transition zone.

The amphibolites are of variable grain size, and some are porphyritic. Garnets, with quartz envelopes, reach up to c. 1 cm in some layers. These mafic rocks are generally interpreted as strongly deformed and metamorphosed mafic volcanites or (where porphyritic) dyke rocks and microgabbros. The rocks show a prominent SE-plunging lineation. There are also NE-verging folds, and many transecting faults of NE-SW to N-S trend, some with breccias. Thin pegmatitic veins show evidence of strong flattening strains. Although shear sense indicators normal to the regional lineation are diffuse here, there is evidence within some layers of top-SE movement.

This stop, or one close to it, has been described earlier in Solli et al. (1997a).

Stop 1.2. *Garnet-mica schists, some amphibolites and ketatophyres: either Gula or Seve Nappe.*
Road-cut along the south side of road 717, near Fagerli.
1:50,000 map-sheet 'Rissa' – grid ref. 523 423.

Rusty brown weathering, garnet-mica schists with thin intercalations of amphibolite and keratophyre/fine-grained trondhjemite. The lithologies and sulphurous weathering are not untypical of the Gula Nappe, but the true affiliation of this lithology is uncertain.

There are several tight folds here to which the penetrative foliation is axial planar. Fold axes and pervasive lineation plunge southeast. Boudinage is conspicuous in some bands. In the lower part of the profile, some metres from the road, there is an interesting pattern of faulting along both NE-SW and N-S trends, locally with breccia or gouge. The NE-SW trend is broadly parallel to the orientation of the principal fault trend of the Møre-Trøndelag Fault Complex. The N-S alignment, as we will see at many localities on this excursion, also appears to be a major fault trend in this region.

<u>*Stop 1.3.*</u> *Palaeoproterozoic Ingdal granite gneiss.*
Shore locality, Røbergneset. 1:50,000 map-sheet 'Orkanger', grid ref. c.492 402.

The Ingdal granite gneiss, better known from the southwestern side of Trondheimsfjord where it was mapped by Tucker (1986), is excellently exposed at this shoreline locality and in a nearby quarry (described earlier in Solli et al. 1997a). Tucker distinguished three main types based on grain size. Here at Rødbergnes the rock is a pink-red, coarse-grained, microcline-rich metagranite with a NE-dipping penetrative foliation and c. ENE-plunging lineation. There is a prominent jointing, and incipient faulting here along a NNW-SSE to N-S trend, in places with protobrecciation.

In a geochronological and geochemical study in the type area, Tucker & Krogh (1988) reported a U-Pb zircon and sphene age of 1653 $\pm$ 2 Ma which they interpreted to represent the emplacement age of the granite. The lower intercept of 396 $\pm$ 5 Ma was ascribed to rapid cooling of the zircon and sphene below their blocking temperatures during later stages of the Scandian orogeny, in this case in Mid Devonian time (Tucker et al. in prep.).

<u>*Stop 1.4.*</u> *Proterozoic 'basement' gneiss with supracrustal nappe rocks.*
Hasselvika, coastal exposures and long road-cut. 1:50,000 map-sheet 'Rissa', grid ref. 412 565.

On the shoreline exposures below the picnic area the lithologies are strongly folded, boudinaged and lineated garnet-mica schists and gneisses, calc-silicate schists, quartzites and amphibolites which Wolff (1978) ascribed to the Leksdal (=Särv) Nappe of the Middle Allochthon (Fig. 6). In an alternative interpretation (Solli et al. 1997a), the schists and amphibolites closest to the sea, structually below but tectonostratigraphically above a thin marble horizon, have been tentatively correlated with the Skjøtingen (=Seve) Nappe of the Upper Allochthon. The prominent lineation plunges at c. 5-10° towards c. 050°. Shear sense indicators are not entirely consistent here, possibly due to the predominance of a flattening strain. Most indications favour dextral shear but there is also evidence in some layers of left-lateral shear.

The grey to pink-grey, banded gneisses and intercalated amphibolites to the south of the road are fairly typical of the 'banded gneisses' of the Fosen Peninsula (see p. 4). Some parts are migmatised, with the neosome carrying large clots and aggregates of hornblende. The protoliths to the amphibolites were probably either mafic dykes or thin sheets of gabbro. Along the gneiss/amphibolite contacts there are common indications of extensional or oblique-extensional slip.

Fig. 6. A lunchtime break on strongly banded and boudinaged schists, amphibolites and quartzites, Leksdal Nappe, Stop 1.4, Hasselvika.

Fig. 7. Devonian conglomerate and sandstone in the hanging-wall of a NE-SW fault (bottom left to top right). In the footwall, mylonitised and cataclased diorite is overlain by Devonian conglomerates and sandstones (contact approximately 2 metres above the base of the road-cut). Stop 1.5, looking southwest.

Fig. 8. Weakly sheared, polymict conglomerate close to the base of the Devonian succession. The extensional fault of Fig.7 is exposed in the bottom right of the photo. Stop 1.5, looking south-southwest.

Fig. 9. Botryoidal, geopetal calcite accreted to the wall of an open joint, now exposed at the southwestern end of the road-cut at Stop 1.5.

After the Hasselvika stop there will be a c. 60 km drive to Stop 1.5 -- our first taste of the Devonian rocks.

<u>Stop 1.5.</u> *Devonian conglomerates and sandstones above cataclased mylo-diorite, with several faults. Unusual occurrence of radiate calcite on joint surfaces. Road-cut along a comparatively new section of road 710, just south of Botngård. 1:50,000 map-sheet 'Bjugn', grid ref. 402 708.*

Along this c.100 m-long, high road-cut, Devonian conglomerates (*Bjugn Conglomerate* of Siedlecka 1975) are seen to lie with apparently comparatively little tectonic disturbance above mylonitised and later cataclased, Ordovician diorite (Fig. 7). This 'conglomerate above diorite' couplet is disrupted by c. NE-SW trending, SE-dipping extensional faults with locally strong brecciation/cataclasis.

The weakly sheared, Devonian sedimentary rocks comprise conglomerates and sandstones of a generally greenish-grey colour. They have not been studied in any detail in this comparatively new road-cut. For a good description of this formation the reader is referred to Siedlecka (1975). Descriptions of this and other formations in the Devonian *Fosen Group* (Siedlecka 1975) are also contained in Bergfjord (1989). According to Siedlecka, the original primary basal contact of the >2000 m-thick Bjugn Conglomerate is nowhere exposed; but this particular road-cut locality does, in fact, now appear to expose this important boundary, above which the clasts in the very basal conglomerate bed show only moderate signs of tectonic, shear deformation (Fig. 8).

The subjacent 'mylo-diorite' is pervaded by anastomosing shear surfaces and has a somewhat rubbly appearance, ascribed to subsequent cataclasis. From other parts of the Ørlandet area, Bergfjord (1989) has described several phases of ductile and brittle deformation in the metadiorite. The original protolith character of this greenish grey rock is almost impossible to recognise here, and on some older geological maps (e.g. Wolff 1978) the unit has been referred to as porphyritic greenstone or amphibolite.

At the northwestern end of this road-cut locality there is an interesting mineralogical curiosity in the form of a dark grey to black, botryoidal to organ pipe-like, void mineral infill along open joints (Fig. 9). The internal mineral structure is radiate-acicular. The mineral 'fizzes' when HCl is applied, and a XRD analysis has confirmed that it is calcite.

<u>Stop 1.6</u>. *Devonian conglomerates, sandstones, and mudstones with plant fossils. Døsvika, shore section. 1:50,000 map-sheet 'Ørlandet', grid ref. 334 686.*

Park in a small quarry, and stroll northwards along the track to extensive shoreline exposures of coarse, polymict conglomerates, sandstones (Fig. 10) and interbedded mudstones. The dark grey micaceous mudstones (easy to find at the end of the track) are a subordinate facies of the Bjugn Conglomerate, but are important because they contain plant

Fig. 10. Shoreline exposure of Devonian polymict conglomerates and sandstones, Døsvika, Stop 1.6. Here, a conglomerate appears to be cutting down into a thick bed of sandstone.

Fig. 11. Footwall exposure of red and orange fault breccias and green ultracataclasites in the Lerberen granite. The pencil is aligned parallel to the slip direction. Lerberen quarry, looking northeast.

fossils first described by Vogt (1929) and later by Høeg (1945). Naked branch systems of *Hostimella* (a few cm in length) are common here, and *Psilophyton rectissimum* has also been recorded. They indicate a Lower to possibly Middle Devonian age.

The polymict conglomerates are particularly spectacular here, interpreted by Siedlecka (1975) as alluvial fans. Cross-bedding can be seen in the sandstones, and ripple-cross stratification is noted at the transition into shales and mudstones. The locality has been described in earlier excursion guides (Wolff et al. (1980), Gee & Wolff (1981), Solli et al. (1997a).

In the quarry, there are several prominent faults along diverse trends (e.g. 355/60, 245/50, 315/55, 295/75), with slickenlines on surfaces showing both normal dip-slip and oblique-slip relative movement. Some of the faults carry breccia and/or gouge. Fault and joint patterns in the Devonian Fosen Group have been described by Siedlecka (1975) and Bergfjord (1989), but there are as yet no detailed descriptions of fault rocks or fault kinematics.

<u>*Stop 1.7.*</u> *Lerberen granite with fault breccias. Panoramic view from the hilltop Lerberen. Quarry in granite just south of the hill Lerberen. 1:50,000 map-sheet 'Ørlandet' grid ref. 333 655 (hill)*

The quarry is in a medium- to coarse-grained, non-foliate to very poorly foliated granite, which has yielded a U-Pb zircon age of 442 ± 2 Ma (Solli et al. 1997a), i.e. very early Silurian. The granite is transected by many faults (e.g. 225/60, 190/60, 205/50, 140/45, 060/35, 105/60), some of which carry red-coloured breccias in their footwalls (Fig. 11) and fine-grained, green ultracataclasites along their latest displacement surfaces. These have yet to be studied in detail. The petrography and microtextures in the granite have been described by Bergfjord (1989). Geochemical data indicate a high-K calc-alkaline signature (Gautneb & Roberts 1989); and the granite is considered to be part of the periphery of the Smøla-Hitra Batholith in which granites are a comparatively late phase.

If the weather is fine, drive up to the parking level just below the hilltop -- 99 m a.s.l., the highest point on the plain of Ørlandet -- which presents a spectacular panoramic view in all directions.

We then proceed to our hotel at Brekstad.

Day 2. Brekstad to Høybakken, then to Jøssund, followed by a long drive to Verrabotn (Verran Fault) and Beitstadfjord. Overnighting at the Grand Hotel, Steinkjer.

<u>*Stop 2.1.*</u> *Platy mylonites (mylonitised diorite) in the Høybakken detachment with later faulting.*
Coast section just south of the Høybakken molo. 1:50,000 map-sheet 'Rissa', grid ref. c.435 673.

From the parking area close to the molo, walk south along a narrow path a few metres above the shoreline until one comes to the first small cove.

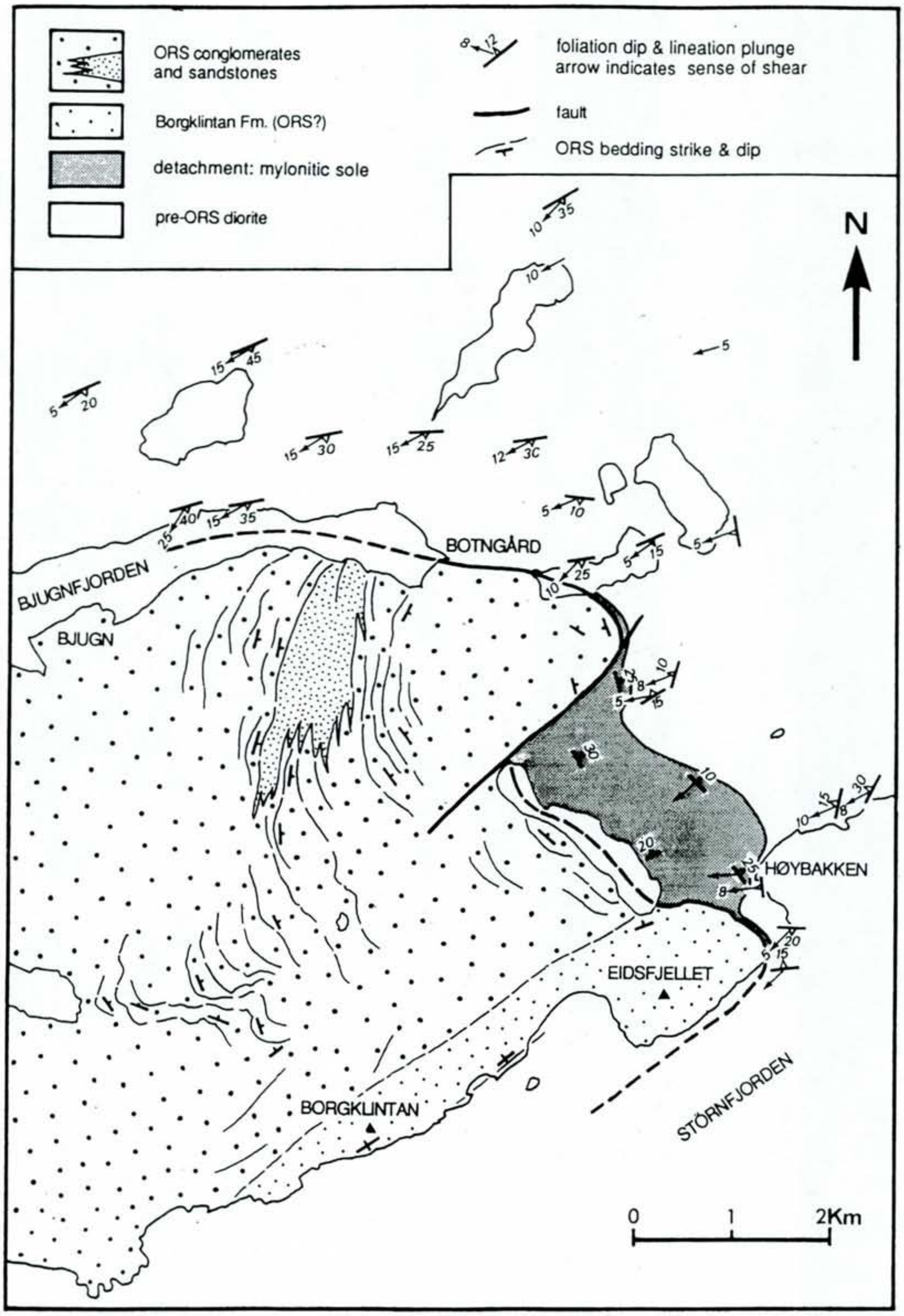


Fig. 12. Structural map of the eastern part of the Bjugn Basin showing ORS bedding, and the basal detachment parallel to basement foliation. The arrows on the stretching lineations indicate the sense of shear. The angle of plunge is also indicated. From Séranne (1992).

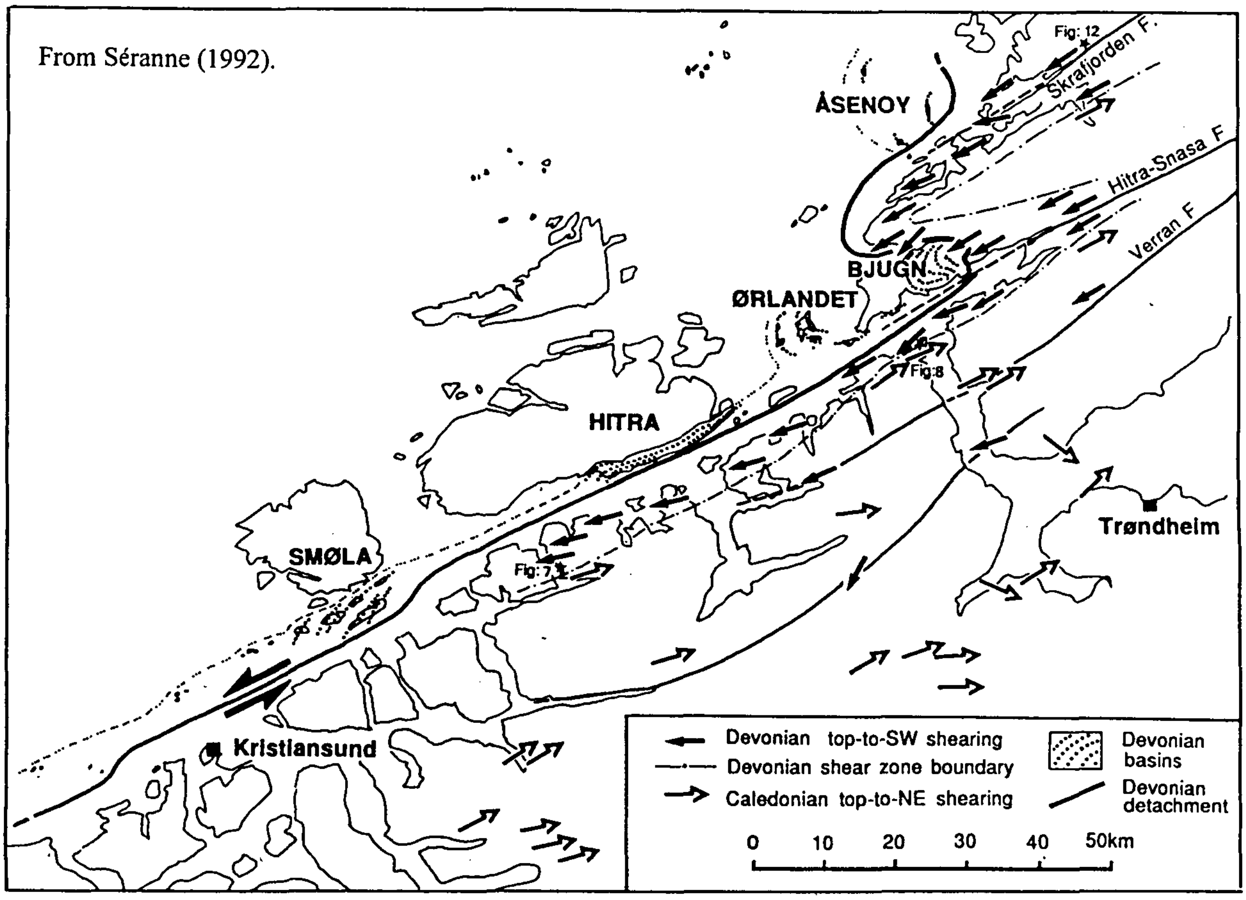


Fig. 13. Interpretative structural map of the Bjugn-Hitra-Smøla district, from Séranne (1992). The inferred top-to-SW shear zone, parallel to the Devonian basins, is marked by the dot-dash line. Shear criteria are indicated by arrows representing the 'top to...' sense of movement in sheared rocks in order to eliminate dip effects in NE-SW folds. Each arrow represents several consistent readings in a single outcrop. As observed in the Bjugn Basin, the most highly strained part of the shear zone is the Høybakken detachment (bold line). The top-to-NE kinematic indicators outside the boundaries of the shear zone correspond to preserved older fabrics.

The outcrops along this c. 400 m-long coastal section are situated in the mylonitic sole beneath the *Høybakken detachment* of Séranne (1992), i.e. the extensional detachment which is believed to underlie the Devonian sedimentary rocks (Figs. 12 & 13). The protolith to these rather platy mylonitic rocks is the Ordovician diorite that we saw at Stop 1.5. The westerly dipping mylonitic foliation carries a prominent lineation plunging gently towards southwest or west-southwest. Shear bands, though poorly developed, indicate a top-SW shear sense. Full details can be found in the paper by Michel Séranne (1992). The actual inferred detachment surface, directly below hangingwall Devonian rocks, does not appear to be exposed here.

Walking south and southwest along the shore we will encounter several anastomosing, extensional shear joints of NW-SE trend as well as many small normal faults trending NNW-SSE with most downsteps to the west. Finally, we will reach a steeply SW-dipping normal fault carrying breccia and gouge, with rocks of the Borgklintan Formation in the hangingwall.

Return to the vehicles. We then have an approximately 25 km drive to the outer coast near Sandnes.

<u>***Stop 2.2***</u> *Supracrustal rocks infolded in the 'basement' Proterozoic gneisses.*
Road-cut and shoreline exposures at the NW end of the bridge across Sandnesvågen, near Sandnes.
1:50,000 map-sheet 'Bjugn', grid ref. 368 807.

A supracrustal sequence consisting of garnet-mica schists ($\pm$ kyanite), calc-silicate schists and gneisses, marble and garnet amphibolites occurs at several places in the outer Fosen district, infolded into the Proterozoic gneisses and in tectonic contact with the latter. Such rocks are nicely exposed here at Sandnesvågen. Some layers are quite rich in large garnets. Foliation dips steeply to the NNE and the main lineation plunges at a low angle to ESE. Both sinistral and dextral strike-slip, shear sense microstructures may be seen here.

In the new road-cut there is a fascinating array of faults on a variety of scales, some showing near-horizontal slickenlines. One small-scale, graben-like form with many internal small faults is seen to be bounded by strike-slip faults and has a pattern not unlike that of a flower structure (Fig. 14). Other more ductile shear zones have moderate to steep dips to the northwest.

We then have a c. 40 km drive to the next locality, via Botngård. Along the way we will pass road-cuts at Jøssund exposing thin pegmatites. Muscovites from similar pegmatites generated along top-SW mylonitic shear zones in this same area have given Rb-Sr ages of 389 $\pm$ 6 and 386 $\pm$ 6 Ma (Piasecki & Cliff 1988).

<u>***Stop 2.3.***</u> *Strongly foliated, protomylonitic Ordovician granodiorite, close to the Hitra-Snåsa Fault.*
Southwestern end of a long road-cut at Øvre Høgsetvatnet. 1:50,000 map-sheet 'Bjugn', grid ref. 579 757.

Just a short stop here to examine a strongly deformed granodiorite, originally regarded as a Proterozoic pluton but now almost certainly Ordovician (based on a U-Pb zircon dating on a

Fig. 14. Graben-like fault structure with several, small internal faults bounded by two slightly larger, strike-slip faults; multilayered schists and amphibolites, Sandnesvågen, looking c. north-northeast.

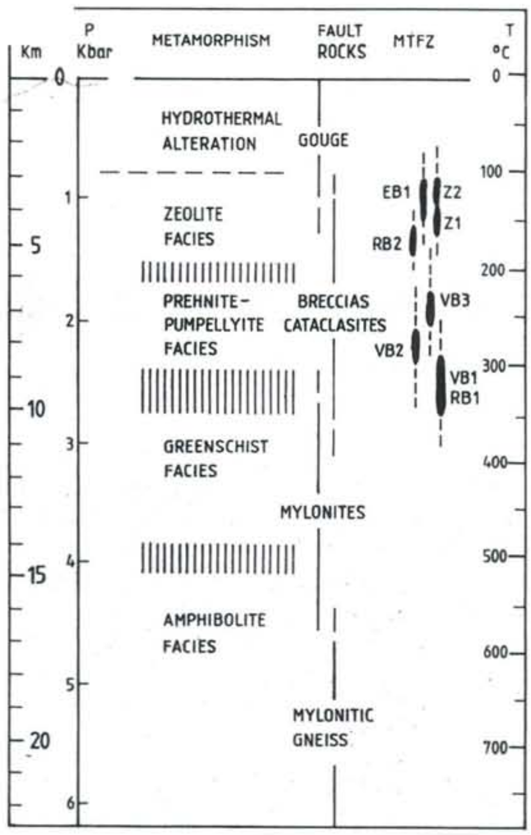


Fig. 15. Depth of formation of brittle fault rocks along the Verran Fault System, from Grønlie et al. (1991). The figure has been adapted from Sibson (1983). The geothermal gradient in this particular case is assumed to have been c. 35°C/km. VB1, VB2 and VB3 refer to the three main breccias/cataclasites along the Verran Fault. Other breccias are from the Rautingdal (R) and Elvdal (E) Faults. The letter Z refers to vein mineralisations, where Z1 is laumontite-calcite and Z2 stilbite.

comparable rock near Follafoss -- 460 ± 5 Ma). Shear bands (S-C structure) point to a sinistral shear sense for the ductile fabric. The c. NE-SW-trending Hitra-Snåsa Fault (HSF -- one of the main faults of the MTFC) passes through the lake Øvre Høgsetvatnet. Unfortunately, the mylonites and breccias of the HSF are not exposed, or very poorly accessible, in this particular part of Fosen. For information on the fault rocks and internal microstructures and textures along the HSF, see Grønlie et al. (1991).

Well developed, sinistral shear bands and small faults can also be seen in the rapidly disappearing face of a small aggregate quarry some 200 m northeast of the northeastern end of this same long road-cut.

We then drive to Verrabotn, along the Verran Fault – a distance of about 45 km.

Stop 2.4. *Photo stop, Verran Fault breccias, hydrothermal mineralisations, etc.*
Melan, on the 720 road. 1:50,000 map-sheet 'Åfjord', grid ref. 792 768.

This is really meant to be just a 5-minute photo stop, at the southwestern end of a c. 10 kilometre stretch of almost continuous road-cut exposures along the strike of the Verran Fault (VF). Because of the obvious danger involved in having so many people ramble along these outcrops, along the very narrow 720 road with its frequent rock falls, we would rather take our Norwegian oil company colleagues to safer exposures, i.e., Stops 2.5 and 2.6. The internal mesofaults, shear zones, breccias, gouges and hydrothermal vein mineralisations are available for inspection at the next stop.

Stop 2.5. *Oblique profile through the Verran Fault crush breccias, cataclasites, gouges, mesofaults and vein mineralisations.*
Track branching NNE from road 720 at Trongsundet. 1.50,000 map-sheet 'Åfjord', grid ref. c. 825 805.

This c. 200-m cutting along a tractor track (and an exposure on the main road 50 metres SW of the track/road junction) provides an excellent oblique section through the multiphasal VF, exposing a plethora of breccias, gouges, small folds, anastomosing mesofaults and vein mineralisations, as well as comparatively late faults (mostly N-S to NW-SE trends), some of which carry breccias or microbreccias. Visible slickenlines and fault surface steps and fibres show that most of this comparatively late generation (or generations) of VF-internal faults show oblique-slip to dip-slip offsets. This is not untypical of the innermost part of the fault zone proper. Towards the margins of this wide fault zone, and in the immediately adjacent country rock, strike-slip to oblique-slip fabrics dominate.

Three main generations of crush breccias and cataclasites overprinting retrograde mylonites have been distinguished in this area. Details are too voluminous to be reproduced here (see Grønlie et al. 1991), but Fig. 15 provides some information on the depth and temperature conditions of breccia generation based on the mineral parageneses. The oldest albite-chlorite-epidote-prehnite-haematite breccias accord with the transition from prehnite-pumpellyite to greenschist facies at depths of 9-11 km, whereas the latest prehnite-matrix breccias were developed in the upper parts of the elastico-frictional regime in zeolite facies (Grønlie et al. 1991). A fission track date on apatite from the VF at this Trongsund locality gave an age of 144 $\pm$ 22 Ma, indicating cooling of apatite through its closure temperature near the Jurassic-Cretaceous boundary. This phase of fault movement, coeval with pervasive stilbite hydrothermal mineralisation, is broadly coincident with the development of the Beitstadfjord Basin (Bøe & Bjerkli 1989).

Stop 2.6. *Ductilely deformed granodiorite immediately NW of the Verran Fault. Lowermost part of the gravel road to Ormsetvatnet. 1:50,000 map-sheet 'Åfjord', grid ref. 839 814.*

At the southernmost part of this long road-cut, Ordovician granodioritic gneiss shows good evidence of sinistral strike-slip ductile shear. There is also overprinting of this early, presumed Devonian, ductile fabric by dextral shear bands, and these are particularly prominent in thin biotite rocks (biotitites) which probably represent retrograded mafic dykes. This excellent road section, almost orthogonal to the VF, is currently being studied in great detail by two Ph.D. students from the University of Durham, UK.

A comparable road profile on the SE side of the VF, c. 15 km southwest of Verrabotn, has also provided convincing examples of dextral shear bands and small folds overprinting the earlier ductile, sinistral fabrics (work by the same students - in progress).

In situ stress measurements carried out near Ormsetvatn, employing the overcoring technique, show that $\sigma 1$ here is nearly horizontal and oriented E-W. Although no neotectonic faulting has yet been reported from this area, a drillhole displaced in a reverse sense along a mesofault surface in a road-cut near Roan (western Fosen) has indicated a circa E-W orientation of $\sigma 1$ (in situ remanent stress release) in that area (D.R., unpubl. data).

From this locality we have a long drive (c. 70 km) to Steinkjer. There are no further stops planned, but we may stop close to Tun, on the shores of Beitstadfjord – where Jurassic coal and shale has been found in local glaciomarine deposits and in one particular stream – for a brief discussion of the Jurassic basin development. If time is short, we can postpone this discussion until the evening.

Day 3. Steinkjer to Storvika near Trondheim Airport, Værnes. Nappe rocks and structures, lamprophyre dykes.

Stop 3.1. *Arkosic metasandstones, lamprophyre dykes, Leksdal (=Särv) Nappe. Lerkehaug aggregate quarry. 1:50,000 map-sheet 'Stiklestad', grid ref. 223 979 to 228 978.*

At the Lerkehaug quarry just south of Steinkjer, arkosic metasandstones of the Leksdal Nappe (Middle Allochthon) are worked for aggregate production. The gently NW-dipping,

Fig. 16. Lamprophyre dykes cutting arkosic metasandstones of the Leksdal Nappe. Lerkehaug quarry, looking southwest.

low greenschist-facies metasandstones show cross bedding and convolute lamination. They are cut by moderately to steeply dipping, partly schistose lamprophyre dykes (Fig. 16), which are also the loci of extensional faulting. Some dykes show internal, extensional shear bands. There are two principal dyke trends, at c. 215/70 and c. 260/60. Some of the thinner, retrogressed dykes are curviplanar and follow cleavage refraction trajectories in the metasedimentary rocks. Some of the extensional faults in the upper parts of this quarry are also curviplanar, with some segments following bedding over short distances.

The lamprophyres show alkaline-ultrabasic geochemical features (Andreasson et al. 1979 and D.R., unpubl. data). An attempt to date phlogopite phenocrysts from the lamprophyres using the $^{40}Ar/^{39}Ar$ method was not in any way definitive, but tended to favour a possible latest Proterozoic age (Mitchell & Roberts 1986). Palaeomagnetic data, on the other hand, has revealed evidence of a Late Carboniferous/Permian event, but it is not certain if this is primary or an overprint (Torsvik et al., unpubl.).

Stop 3.2. *Fault breccias with spectacular hydrothermal alteration, and young fluorite-calcite veins, Støren Nappe.*
Coastal exposures between Høsholmen and Ystad bay, west of Hylla.
1:50,000 map-sheet 'Stiklestad', grid ref. 144 809 to 148 810.

Park at the end of a gravel road and walk eastwards across a cobble beach to a promontory exposing mainly greenschists of the Støren Nappe (locality 1 in Fig. 17). The main lineation plunges at a low angle towards c. 280°. Younger crenulations and small folds plunge WSW and there is a steep crenulation cleavage.

The main purpose of this stop is to examine the faults, breccias, thorium-enriched veins and breccias, and fluorite-calcite(±quartz) veinlets. The principal fault and breccia set trends NE-SW, and some of the faults and breccias have spectacular orange-red hydrothermal alteration colours (Fig. 18). The best ones are a few tens of metres farther to the east/northeast (take the path at the top of the outcrop), close to the Ystad Fault (locality 2 in Fig. 17). Cores for palaeomagnetic analysis have been taken, but the results are not yet available.

The fluorite-calcite veins transect the older thorium-enriched breccias. They trend both NE-SW and c. N-S. A preliminary fission-track study on the fluorites gave ages of around 60 Ma, though with large error-bars (Grønlie et al. 1990). Although caution must be exercised in view of the large error-bars, the dating provides a minimum age of Late Cretaceous/Early Tertiary for this particular fluorine-bearing hydrothermal activity.

Stop 3.3. *Mylonites and phyllonites at the interface between the Skjøtingen (Seve) and Støren Nappes, Upper Allochthon.*
Koabjørga, tunnel area and adjacent shoreline exposures. 1:50,000 map-sheet 'Stiklestad', grid ref. 189 809 to 188 810.

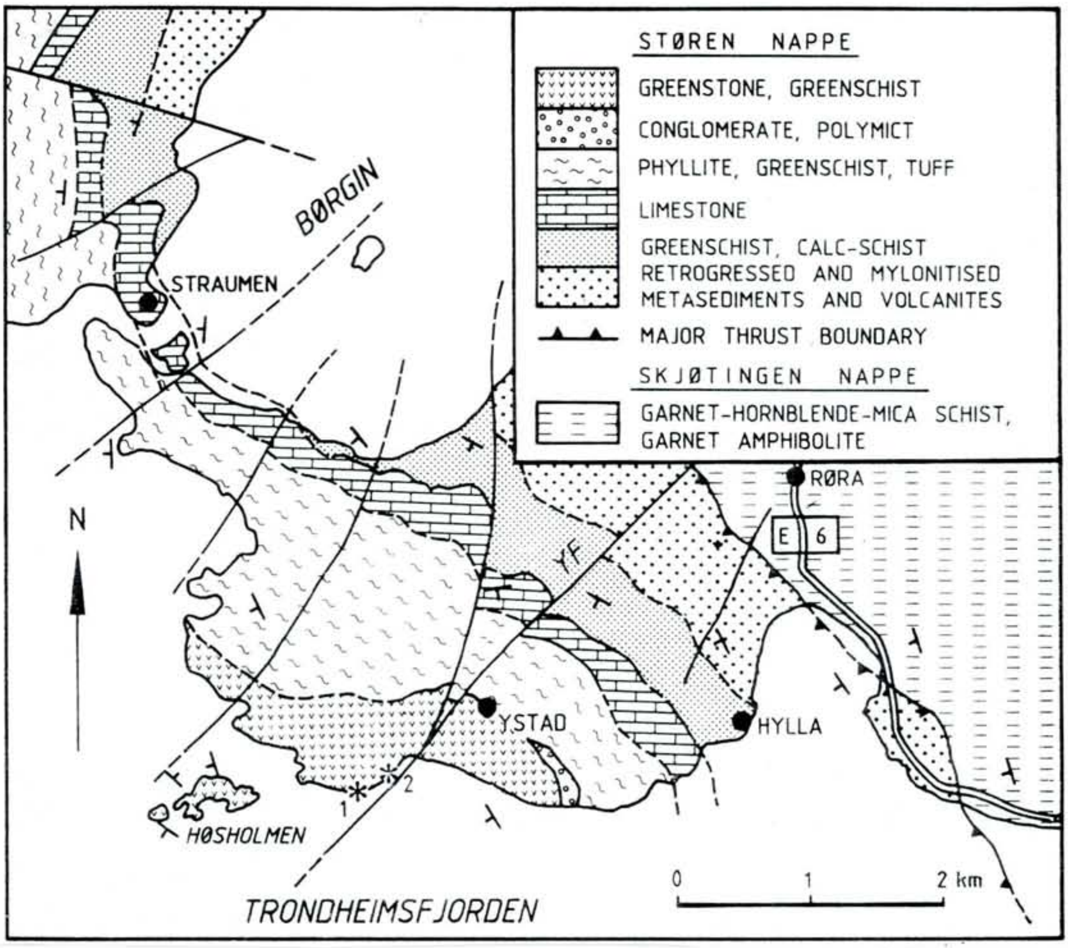


Fig. 17. Simplified bedrock geological map in the environs of the Ystad Fault (YF), inner Trondheimsfjord. From Grønlie et al. (1990). The numbers 1 and 2 southwest of Ystad indicate fluorite sampling localities.

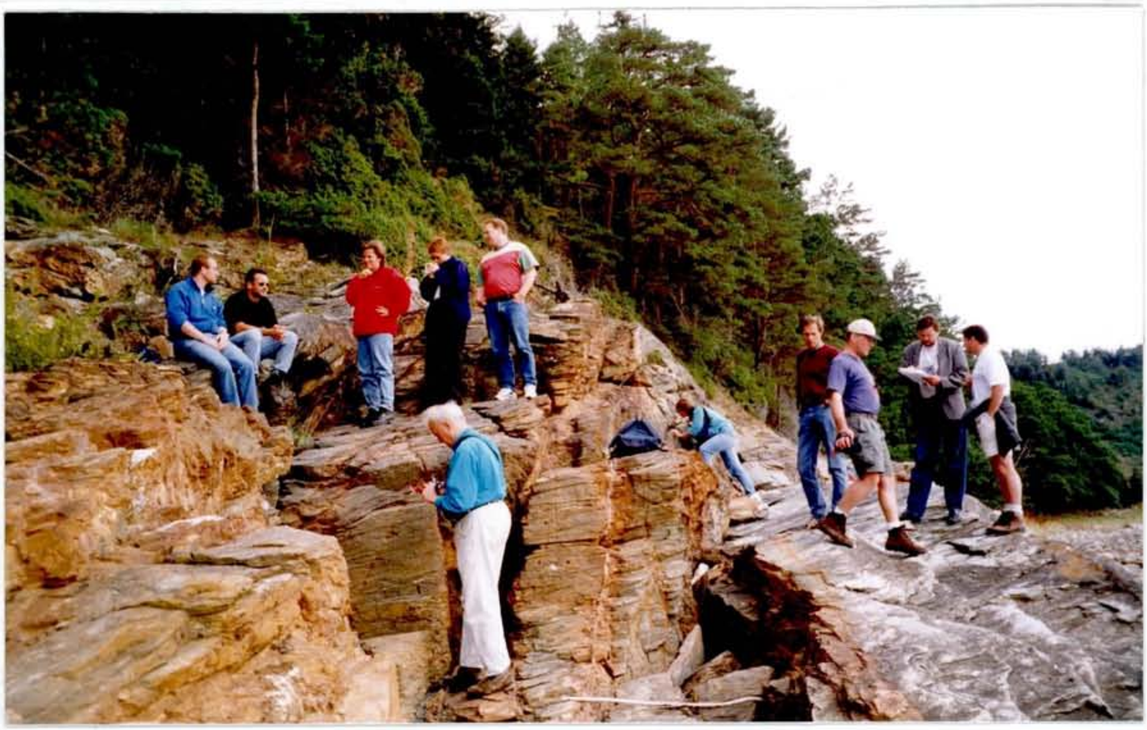


Fig. 18. Orange-red, hydrothermal alteration coloration along a NE-SW fault at locality 2, Fig. 17 (Stop 3.2). Fluorite-calcite veins are common at this locality.

There is a parking recess c. 100 metres south of the short tunnel at Koabjørga on the west side of the E6 highway. Before walking down to the shoreline outcrop at this point, note the predominance of amphibolites to the east of the road. In the shore outcrops west of the road, banded garnet amphibolites and gneisses of the uppermost part of the Skjøtingen Nappe are well exposed here, and boudinage is common. An old foliation and isoclinal folds are preserved in the boudins, wrapped around by the main foliation in the garnetiferous gneisses (Gee & Wolff 1981). A small ultramafite lens is also present. The west-dipping foliation becomes less sinuous northwards and retrogression is more pervasive.

If time permits, walk to near the southern entrance to the tunnel where there are retrogressed amphibolites, gneisses and schists. These pass westwards into phyllonites and mylonites at the Skjøtingen/Støren thrust contact. To the west there are west-dipping, thin-banded, protomylonitic, lower grade psammites and phyllites, inferred to constitute part of the Støren Nappe. These carry sporadic, early isoclinal folds, late tight to open folds, and diverse evidence of later extensional shear.

Stop 3.4. *Extensional faults, shear bands and gouge, Støren Nappe.*
Road-cut, east of the Norske Skog paper factory, Fiborgtangen, Skogn.
1.50,000 map-sheet 'Frosta', grid ref. c. 075 668.

At this road-cut locality there is a west-dipping extensional fault with a particularly impressive development of chloritic/illitic gouge and mesoscale shear bands (S-C structure) (Fig. 19), and some small folds, which clearly show down-to-the-west displacement of the hangingwall. Smaller examples of such dip-slip normal faults are seen nearby. Such faults are common in this general district, but little has yet been written on the late- to post-Scandian fault system. N-S oriented kink bands are also present.

Stop 3.5. *Ordovician Upper Hovin Group turbiditic metasediments with primary and tectonic structures.*
Storvika, NW of Stjørdal; and shoreline exposures to the southeast.
1:50,000 map-sheet 'Stjørdal', grid ref. 937 395 to 941 393.

Along this entire coastal section there are thin- to medium-bedded, turbiditic greywackes, shales and polymict conglomerates (both clast-supported conglomerates and matrix-supported pebbly sandstones). Graded bedding is common and there are penecontemporaneous deformation structures and slump folds. This facies association is suggestive of accumulation on a large submarine fan. More regularly banded turbidites a few kilometres to the northeast have yielded a deep-water *Nereites* trace fossil association (Roberts 1969a).

Tectonic folds of three generations can be demonstrated along this 400 m stretch of shoreline. At the sandy beach area of Storvika the late-Scandian F3 folds with their flat-lying crenulation cleavage are particularly well developed (Fig. 20). These folds are common over extensive areas of Central and southern Norway and also in Sweden, and were originally

Fig. 19. *(Upper photo)* Extensional fault with gouge, Stop 3.4, Skogn, looking south. *(Lower photo)* Close-up of part of the fault zone gouge showing shear-band structures, indicating top-to-the-west (right) shear.

Fig. 20. Ordovician, multilayered greywacke and phyllite with mesoscopic, late-Scandian (F3), gravitational collapse fold with flat-lying, axial planar, crenulation cleavage; Storvika, looking northwest.

interpreted by one of us as gravitational collapse folds related to vertical shortening (=horizontal extension) at a late stage in the development of the Caledonide orogen (Roberts 1969b, 1971). Quartz-calcite vein arrays are locally very common in these turbiditic lithologies, but little work has yet been done on these hydrothermal features.

This is the last stop of the excursion. Thank you for coming! We hope that you have found the brief excursion useful, and we look forward to forthcoming collaboration in the 'BAT' project.

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