Extension of Trollheimen tectono-stratigraphic sequence in deep synclines near Molde and Brattvåg, Western Gneiss Region, southern Norway

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A 70 km-long belt along Moldefjord contains a well-defined sequence of Caledonide thrust nappes infolded into Baltica basement, corresponding exactly to the sequence in the Surnadal syncline and Trollheimen, from base to top, the Risberget, Sætra, Blåhø-Surna, and Støren Nappes. Quartzites in areas of basement may correspond to Åmotsdal Quartzite tectonically sandwiched with basement in Trollheimen. The metamorphic discontinuity, previously described in the Surnadal area, between high amphibolite facies Surna Nappe and low amphibolite facies Støren Nappe, persists through the area, and newly discovered zoisite-phengite eclogite boudins in the Sætra Nappe and locally in the Risberget suggest discontinuities at lower levels. All levels are pervaded by subhorizontal lineation parallel to fold axes. Lineation is related to sinistral shear features including porphyroclast tails, S-C fabrics, shear bands, tilted boudins, mylonite, ultramylonite, and shear and tubular folds superimposed on earlier structural features and indicating a phase of late Scandian sinistral shear under low amphibolite conditions parallel to the length of the orogen.

Introduction

The status of medium- to low-grade supracrustal rocks exposed in the Western Gneiss Region of southern Norway (Fig. 1a) is recognized as a major problem (Bryhni 1989) that has been debated in the last several decades. In the eastern part of the Moldefjord area (Fig. 1b), Hernes (1955, 1956a, 1965) demonstrated and mapped a distinctive stratigraphic sequence in an apparent syncline between older gneisses, and suggested this might be either a deeply downfolded sequence of Caledonide cover rocks extending from the Surnadal syncline (Hernes 1956a), or a Proterozoic sequence. Gjelsvik (1951) described similar rocks near Brattvåg in the western part of the Moldefjord area. Gee (1980) showed that the nappes known in Sweden and eastern Norway could be identified in Trollheimen (Fig. 1a). This correlation was expanded through Trollheimen by Krill (Krill 1980; Krill & Roshoff 1981; Krill 1985), into the Surnadal syncline (Fig. 1b) by Krill (Krill & Roshoff 1981; Krill 1987), and into areas northwest of the Surnadal syncline by Tucker (1986). Krill & Sigmond (1986) suggested that the narrow zones of low- to medium-grade supracrustal rocks in the Molde area (Fig. 1b), and to the west near Brattvåg, do contain correlatives of the Trollheimen tectono-stratigraphy. Bryhni (1989) recognized this possibility, but seemed to favor the earlier view of Carswell and Harvey (1985), that the low- to medium-grade rocks in the Moldefjord area are merely high grade gneisses that have been retrograded by shearing and still contain relics of high grade minerals.

Present investigations began in 1990 along the southwestern trend from the Surnadal syncline near Molde and Brattvåg (Robinson & Krill 1991a, b, 1994). This paper presents the following preliminary conclusions:

1. The thrust nappes of western Trollheimen are superbly represented in terms of lithic characteristics and of detailed sequence both in the Molde area and near Brattvåg 120 km west of Surnadal and 20 km northeast of Ålesund.

2. Structural features associated with earlier thrust- and fold-nappe stages have been largely obliterated during a stage of late large-scale sinistral shear, characterized by development of subhorizontal folds and lineations, sinistral sheath folds, and mylonites produced under low amphibolite-facies conditions.

3. The metamorphic discontinuity first emphasized by Krill (Krill & Roshoff 1981) in the Surnadal area between the high amphibolite facies Blåhø-Surna Nappe and the low amphibolite facies Støren Nappe persists through the area. The locally migmatitic coarse-grained Blåhø-Surna rocks show extensive evidence of retrograde hydration close to Støren contacts. In the overlying Støren there is no evidence that the rocks were ever more highly metamorphosed than the low staurolite zone. Furthermore eclogite boudins abundant in parts of the Sætra Nappe and locally the Risberget Nappe contain
Fig. 1. Index maps. la) (right) Generalized geologic index map of southwestern Norway. Inset indicates area covered by Figure 1b. Key to patterns: dots—undisturbed Proterozoic crystalline basement; double-ticks—Caledonian nappes and cover; unpattemed—Western Gneiss Region, hachured line—late Caledonian normal fault. Modified from Andersen et al. (1991). lb) (above) Geologic index map showing the Moldefjord syncline of Caledonide nappes in relation to the Surnadal syncline and other areas of proved or probable nappes infolded into basement of the Western Gneiss Region. Moldefjord syncline is indicated in black and other areas are shaded. Sources of map information include Bryhni et al. (1989, 1990a, 1990b), Hernes (1955, 1956b), Krill (1987), Mørk (1989a, 1989b) and the present work.

evidence of low grade zoisite-eclogite-facies metamorphism including prograde growth zoning of garnet. This is in contrast to the high-grade eclogites common in the adjacent Baltica basement (Krogh 1977, 1980; Mørk 1985, 1986), suggesting another important metamorphic discontinuity.

The emphasis of this paper is on evidence concerning tectono-stratigraphy and secondarily on a newly recognized phase of Late Scandian sinistral shear, with lesser attention to other details of structural geology and metamorphism that are covered in other papers in progress. Emphasis is on the Moldefjord belt where I think the correlations of the Caledonide nappes are definite, and not on areas to north and south where correlations are more difficult and less certain (Robinson 1995a). The critical evidence for tectono-stratigraphy is in details of rock types and rock sequences. The description and field photographs provided here should help other geologists, not familiar with these tectono-stratigraphic units, to recognize them elsewhere in the Western Gneiss Region.

Because the outcrops are mostly easily accessible from roads, much of the text is organized as a travelogue of important localities. Structural measurements, equal area diagrams, cross sections, and analysis of overall structure, are emphasized elsewhere. Fig. 2 gives a generalized view of the Moldefjord area with a key to areas of more detailed maps.

Description of tectono-stratigraphic units

A definitive sequence of five tectono-stratigraphic units was identified that corresponds very closely with units in Trollheimen and elsewhere in the central Caledonides, as follows:

*Baltica basement.* – The basement consists of strongly deformed gneisses, gabbros, eclogites, amphibolites, and very minor supracrustal rocks, derived from Proterozoic intrusions with minor amounts of host rock. Locally gabbro boudins preserve primary igneous textures.

*Risberget Nappe.* – This thrust nappe consists of augen gneiss and amphibolite that represent deformed middle
Proterozoic rapakivi granite with subordinate gabbro, intruded by mafic dikes. Near Skår the rapakivi granite is preserved in a totally undeformed state with large microcline phenocrysts rimmed by plagioclase. Recognition of the Risberget Nappe is more difficult in the Moldefjord and Surnadal synclines than in eastern Trollheimen for two reasons. (1) In eastern Trollheimen the Risberget Nappe is consistently separated from the basement by Åmotsdal Quartzite and other autochthonous or parautochthonous supracrustal rocks that are absent in these western areas. (2) Augen gneiss of similar character appears to be a major component of the Baltica basement, especially to the north of the Moldefjord (Carswell & Harvey 1985). In practice the basement augen gneiss is usually fine grained and the microcline phenocrysts are flattened and polycrystalline as a result of relatively homogeneous deformation, whereas the typical gneiss of the Risberget Nappe contains large coarsely crystalline phenocrysts in a micaeous matrix interspersed with zones of obviously mylonitic character. The best argument that the Risberget unit is a nappe comes from its great lateral continuity and consistent stratigraphic position across the orogen from these areas to the Tannås Augen Gneiss Nappe in Sweden (Krill & Roshoff 1981).

Sætra Nappe. — This nappe is characterized by strongly laminated pure to feldspathic quartzite and amphibolite, locally garnetiferous, and locally eclogitic. These represent metamorphosed sandstone cut by diabase dikes corresponding to the Sårv Nappe near the front of the orogen in Sweden. Though locally discontinuous, this key unit occurs throughout the belt, but is commonly no more than 10 m thick.

Blåhø-Surna Nappe. — This nappe consists of porphyroblastic garnet-mica-feldspar schist, coarse gneissic garnet and pyroxene amphibolite, and pegmatite; interpreted as highly metamorphosed shales and volcanics. A distinctive zone of impure marble and calcareous schist lies near or at the upper contact of this nappe. Commonly there are also thin impure marbles or calcareous impure quartzites at or near the base. In its best preserved portions this nappe shows evidence of early high temperature metamorphism with extensive development of migmatites unlike anything in the other nappes. In this respect it corresponds to part of the Seve Nappe in Sweden.

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

In addition to these units, there are feldspathic quartzites, locally hematitic, within areas of basement that may correspond to the Åmotsdal Quartzite that is tectonically sandwiched with basement in Trollheimen. In 1994 and 1995 these were widely mapped in the mountainous area south of Rekdal.

Distribution of tectono-stratigraphic units

The tectono-stratigraphic units are exposed in two tight to isoclinal synclines overturned to the north-northwest,
with subhorizontal axes. The major Moldefjord syncline (Fig. 2) has been traced for 70 km and the narrower Helleneset syncline has so far been traced for 25 km. The structure in the inner Moldefjord is a synclinal fold, not fault controlled. This is shown by well exposed overturned north-facing sequences on Bolsøya and other islands near Molde, and on Grønnes Peninsula, and by less well exposed right-side-up south-facing sequences on the north side of Grønnes Peninsula and in the Fanefjord Tunnel. The west-plunging synclinal hinge is mapped on the Grønnes Peninsula near Kortgarden. Near Brattvåg on the south limb there are three tightly folded sequences separated by two fine-grained mylonite zones. Parts of the south limb are well exposed east of Brattvåg near Vatnefjord, near Rekdal, and on Tautra. The Helleneset syncline south of the Moldefjord syncline has been traced for 25 km from west of Brattvåg to southeast of Rekdal. Its limbs and axial surface have been refolded about late open folds with horizontal or gently south-dipping axial surfaces. Between these synclines is a complex anticline outlined particularly by a thick unit of feldspathic quartzite near Vatnefjorden and in mountains south of Rekdal that separates lower and upper layers of basement gneiss.

**Inner Moldefjord area**

The tectono-stratigraphic sequence in the inner Moldefjord area (Figs. 2, 3) is disposed in a narrow isoclinal syncline plunging gently west and overturned to the north like the Surnadal syncline. Above the heterogeneous Baltica basement is an apparently continuous and characteristic zone of augen gneiss assigned to the Risberget Nappe. While it might be argued that this is merely part of the basement, its narrowness and continuity argues that it is a thin thrust sheet. The Sætra Nappe of quartzite and amphibolite is poorly exposed, but was apparently traced in some detail by Hernes (1955, 1956b), and five special exposures, mentioned below, are critical to the syncline interpretation. Coarse migmatitic schists and amphibolites of the Blåhø-Surna Nappe form a zone about 400 m wide on the south limb, and a much narrower belt on the north limb. The center of the syncline is occupied by the Støren Nappe of low grade amphibolites and associated fine-grained garnet-biotite schists, as well as metamorphosed gabbros.

The best exposures of the Moldefjord syncline occur on Bolsøya, as shown in Fig. 3. An important feature of the regional sequence, on the west coast of Bolsøya, is a marble horizon, recognized by Hernes, that lies within the Blåhø-Surna Nappe near or exactly on the Støren contact (Fig. 4A). As recognized by Inge Bryhni (1989 and pers. comm. 1990) this marble is locally mylonitic with little evidence of subsequent recrystallization, suggesting very low grade conditions of deformation (Fig. 4B). The marble with mylonite is also recognized in a new set of highway exposures on the north coast of Bolsøya (Fig. 3) connected with the Fanefjord tunnel. Within the Støren amphibolites and south of a distinctive narrow belt of metamorphosed gabbros, both on the west coast and in

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![Geologic progress map of the Bolsøya area investigated 1990–1993, or based on Hernes (1955). Contacts: solid—accurately located, dashed—approximately located, dotted—location inferred, dash-dot—based on Hernes (1955) or extrapolated. Includes the south-facing sequence on the north limb of the Moldefjord syncline exposed in the Fanefjord Tunnel. The area of the Sætra Nappe on the southwest side of Bolsøya is based on quartzite shown by Hernes but not seen by this author.](image-url)
Fig. 4. Features of the contact region between the Blåhø-Surna and Støren Nappes on the west coast of Bolsøya. (A) Contact between Blåhø-Surna sulfidic mica schist and marble to the right and low grade Støren amphibolite to the left. There is late boudinage of amphibolite with white calcite flowing into neck areas. Note pocket knife, left center, for scale. (B) Thin section print of graphitic marble mylonite in the Blåhø-Surna Nappe close to the Støren contact. Section is cut parallel to the lineation and shows typical indicators of sinistral shear. Scale bar = 0.5 cm.

The highway exposures, there is a belt of garnet-mica schist fairly typical of the Blåhø-Surna Nappe. At first it was thought this might be just a local late anticline exposing rocks beneath the Støren, but there is no geometric evidence for this, and the marbles characteristic of this contact on Bolsøya are lacking. The schist belt could be a part of the Støren Nappe, but the best evidence, accumulated from field relations of similar schist belts near Brattvåg and on Taustra, is that it is an early thrust imbrication of the top of the Blåhø-Surna Nappe.

The Fannefjord tunnel itself was little studied during construction, but it was possible to observe and sample extensive spoil piles containing abundant blocks of Risberget augen gneiss, Sætra quartzite and amphibolite, and Blåhø-Surna garnet schists and amphibolites. Later the southern part of the tunnel was mapped with the results shown in Fig. 3. Based on engineering marks beginning near the Årø end of the tunnel, the contact of the Risberget augen gneiss with Baltica basement is at 1760 m, the base of the Sætra Nappe at 1806 m, the base of the Blåhø-Surna Nappe at 1821 m, and the base of the Støren Nappe at 1937 m. These observations show that the structure is a syncline with tectono-stratigraphic sequences on both north and south limbs, although the north limb sequence is much thinner.

The northern limb of the syncline is also well documented on the Grønnes Peninsula (Fig. 5) where Sætra quartzite and amphibolite in south-facing sequences are exposed in a new highway exposure near Talset, in a new hillside excavation east of Talset, and in low road exposures south of Kortgarden. The synclinal hinge was mapped in heavily vegetated cliffs near Kortgarden and superb tree-rip-up outcrops of the Sætra Nappe were found on the south limb southwest of Kortgarden.

Brattvåg area

The tectono-stratigraphic units in the vicinity of Brattvåg (Fig. 6) are much better exposed, but the structure is much more complex. The strata in the northern part of Fig. 6 all appear to belong to the main steep to northward overturned south limb of the Moldefjord

Fig. 5. Detailed geologic map of eastern hinge of Moldefjord syncline on Grønnes Peninsula. Contacts: solid — accurately located (contacts of Sætra Nappe are solid by graphical necessity), dashed—approximately located, dash-dot—based on Hernes (1956b) or extrapolated. Arrows indicate four areas of critical exposure of Sætra Nappe. For explanation of structure symbols see Fig. 3.
Fig. 6. Geologic map of the south limb of the Moldefjord syncline near Brattvåg, including the narrow Hellemeset syncline to the south. Illustrates three tectono-stratigraphic sequences separated by mylonite zones. Contacts: solid—accurately located (contacts of Sætra Nappe are solid by graphical necessity), dashed—approximately located, dash-dot—location inferred. For explanation of structure symbols see Fig. 3.
The mylonites are divided into three repeated sequences by two zones of fine-grained mylonite formed during sinistral shearing. The sequences are complicated by local subhorizontal folds that are en echelon to the mylonite zones and appear to be truncated by them. The southern sequence contains all units from basement up to Støren, including the marble-bearing upper part of the Blåhø-Surna as on Bolsøya. The narrow middle sequence between the mylonites consists only of Sætra, Blåhø-Surna, and Støren. The northern sequence begins with sheared gabbro in the middle of the Risberget Nappe and extends well up into the Støren. The interaction of these structures produces a bewildering outcrop pattern, but a consistency of stratigraphy makes reconstruction feasible.

So far the basement gneisses have received limited attention, but are dominated by pink biotite feldspar gneisses, locally cut by amphibolite dikes. The Risberget Nappe is dominated by augen gneiss derived from rapakivi granite, but has a distinctive mappable older unit of amphibolite derived from gabbro in which thin dikes of rapakivi granite have been recognized. The Sætra Nappe is a narrow, but extremely consistent unit, well exposed on the shore south of Hellland (Fig. 7A), and locally, as in the northern sequence west of Sunnaland (Fig. 6) is as thin as 7 m. Migmatitic features are particularly well shown in the lower part of the Blåhø-Surna Nappe (Fig. 7B), where there is a lesser amount of retrograde hydration. In the upper part of the Blåhø-Surna Nappe there is a bed of impure marble and calcareous schist about 6 m thick (Fig. 8) separated from the Støren contact by 15 m or less of mica-garnet schist. The position of marble near or at the top of the Blåhø-Surna Nappe is critical to several fold interpretations in the area west of Brattvåg (Fig. 6). Another, thinner marble appears to occur in the Blåhø-Surna Nappe, virtually at the Sætra contact. Near the upper Blåhø-Surna marble, the base of the Støren is a felsic schist (Fig. 9A) derived from felsic volcanics with thin interbeds of fine-grained garnet-biotite-muscovite-tourmaline schist. The lower part of the Støren is dominated by fine-grained hornblende-epidote amphibolites, and these are overlain by mappable units of massive to layered hornblende gabbros (Fig. 9B) locally with what appears to be relict cumulate layering. At one point north of Hellland there is a 1 m-thick layer of green amphibole that is probably a metamorphosed pyroxenite cumulative

Fig. 7. Outcrops on the southwest-facing shore south of Helland, opposite Brattvåg (see Fig. 6). (A) Pavement of Sætra laminated quartzite and amphibolite. The quartz-rich quartzite is typical of the uppermost meter of the Sætra nappe close to the Blåhø-Surna contact. By analogy with the Särv Nappe in Sweden and the Sætra Nappe at Oppdal, the amphibolite layers are believed to be highly strained diabase dikes. (B) Blåhø-Surna mica-garnet schist with pegmatitic layers produced by intrusion and/or partial melting. This is typical of the lower part of this nappe where there is abundant shearing, but less late metamorphic reconstitution than close to the Støren Nappe.

Fig. 8. Impure marble in upper part of Blåhø-Surna Nappe in the mapped bed along the coast west of Sunnaland (Fig. 6). This is separated from the Støren Nappe contact to the north by about 15 m of garnet-mica schist.
The southern part of Fig. 6 is dominated by a very narrow synclinal infold in basement, here named for Helleneset on Vatnefjord. The syncline is dominated by Risberget augen gneiss and a central core of Blåhø-Surna schist and amphibolite, with local layers of the Sætra Nappe on the north limb. Locally it is extremely narrow. For example, on the west shore of Brattvåg harbor, the Blåhø-Surna Nappe between Risberget outcrops can be no more than 41 m wide. At the Brattvåg School, the Blåhø-Surna schists in the core of the fold were seen in a temporary excavation. South of the syncline there are additional belts of augen gneiss in contact only with basement, which resemble but are not quite typical of the Risberget. These may be additional synclines of the Risberget Nappe in basement, or they may be merely extremely sheared porphyritic granite intrusions within the basement.

**Skår-Baraldnes-Tennøya area**

The Skår-Baraldnes-Tennøya area, east of Brattvåg (Fig. 10), is particularly important in showing details in the lower part of the tectono-stratigraphy that is a direct continuation from the central and southern parts of Fig. 6. Highlights include the outcrop at Skår, the major synclinal closure at Baraldnes, the wide belt of Sætra quartzite with retrograded eclogite boudins on the north coast of Tennøya, exposures of the Helleneset syncline at Helleneset and the south coast of Lauvøya, and probable Åmotsdal-type quartzites on Lauvøya, Medøya, and Langsetnakken.

The outcrop at Skår shows the upper part of the Risberget Nappe, the entire Sætra Nappe, and the base of the Blåhø-Surna Nappe in continuous exposure. In the bay at Skår, just above the poorly exposed basement contact there are small outcrops (Fig. 11A) of typical Risberget augen gneiss showing normal sinistral asymmetric tails on orthoclase phenocrysts, locally containing amphibolite layers believed to be metamorphosed diabase dikes. This is succeeded upward by more massive amphibolite, interpreted as metamorphosed gabbro, that occupies the first 44 m of the main outcrop. This is succeeded northward by an additional 15 m of Risberget rocks of which 10 m near the base is rather massive phenocryst-rich augen gneiss (Fig. 11B) in which the phenocrysts show strongly developed foliation and gently plunging lineation. The upper 5 m (Fig. 11C) is mylonitic with abundant relic phenocrysts and thin dark streaks that may represent mylonitized mafic dikes. North of the Risberget is 9 m of the Sætra Nappe, of which the lower 7.5 m (Fig. 11D) is metamorphosed feldspathic sandstone with minor amphibolite and with typical subhorizontal folds. In this lower part there are two boudins of retrograded eclogite less than 1 m north of the Risberget contact. The upper 1.5 m of the Sætra is cleaner, more quartz-rich metamorphosed sandstone (Fig. 11E) with more abundant amphibolite laminae in

layer in the gabbro. These features suggest the possibility that these gabbros represent sheared fragments of an ophiolite like the Lokken and Vassfjell units of the Støren Nappe near Trondheim (Grenne 1989). They also closely resemble in character and setting the gabbro slices studied by Boyd (1983) near Narvik, which he considers, on lithic and geochemical grounds, to be sheared fragments of the Lyngen Ophiolite. At Myrakaia within Støren amphibolites there is a narrow and poorly exposed lens of talc-anthophyllite-carbonate rock that would agree with the ophiolite hypothesis. North of the gabbro on the coasts north of Helland and Sunnaland there is an extremely narrow belt of garnet-mica schist closely resembling in character and position the narrow northern mica schist belt on Bolsøya, although here it lies north rather than south of the gabbro. In coastal exposures northwest of Sunnaland this narrow belt contains garnets up to 3 cm in diameter, relic migmatisitic features, and calcareous schists, all suggesting that this is a very thin tectonic slice of Blåhø-Surna rocks.
Fig. 10. Geologic map of Skår-Baraldnes-Tennøya area. The map shows the critical exposure at Skår, the synclinal hinge at Baraldnes, and the eclogite-bearing Sætra quartzites on the north coast of Tennøya, all on the south limb of the Moldefjord syncline. It also shows the Helleneset syncline at Helleneset, on the south coast of Lauvøya, and in the mountains to east and west. Between these, in the Rekdalhøsten anticline, Åmotdal-type quartzites are exposed in a zone between lower and upper layers of Baltica basement on Lauvøya, Medøya and Langsetnakken. Contacts: solid—accurately located (contacts of Sætra Nappe are solid by graphical necessity), dashed—approximately located, dash-dot—location inferred. For explanation of structure symbols see Fig. 3.
contact with the basal garnet-mica schist of the Blåhø-Surna Nappe. The base of the Blåhø-Surna (Fig. 11F) against the Sætra consists of garnet-mica schist and amphibolite, some in boudins. Exactly on the contact in an eroded groove is 5–15 cm of calcite marble and diopside calc-silicate that commonly occurs in this position. A second more impure marble occurs about 1.5 m above the contact.

A remarkable pavement outcrop occurs quite close to the road about 1 km east of Skår, and within the Risberget augen gneiss layer illustrated in Fig. 11B. This outcrop exposes 63.8 m of the upper augen gneiss of the Risberget Nappe as compared to the total thickness of 15 m at Skår, as well as 7.6 m of the overlying Sætra Nappe with eclogite boudins. Within the augen gneiss exposure there is a lens, 24.3 m thick, of completely...
undeformed rapakivi granite with round pale red-brown microcline phenocrysts with preserved internal igneous zoning and with plagioclase mantles. Such a preservation is unusual across the Caledonides in the Risberget and Tannås Nappes generally (Krill & Røshoff 1981), and is particularly surprising for this region where there have been many intense deformations.

A stratigraphic sequence identical to that at Skår (Fig. 10) has been mapped in detail around a major fold hinge at Baraldnes, and from there has been tentatively connected below sea level to the sequence on the north coast of Tennøya. The Risberget Nappe in the sequence on Tennøya is complicated by a narrow slice of felsic gneiss that most closely resembles basement. The Sætra Nappe on Tennøya is thicker than at Baraldnes with the lower part filled with boudins of fine-grained retrograded eclogite, apparently derived from the diabase dikes in an early phase of metamorphism. Similar retrograded eclogite occurs in the Sætra near Baraldnes, in the outcrop at Skår, in the hill southeast of Helland (Fig. 6), and in near exposures east of Alvestad (Fig. 6). North of the Sætra on Tennøya there are no definite Blåhø-Surna rocks, but a mappable mylonite with subhorizontal linear fabric is succeeded northward by a south-facing sequence of Risberget augen gneiss and then basement gneiss. This south-facing sequence apparently represents a severely attenuated or sheared-off north limb of a syncline, probably the Moldefjord syncline itself. If correct, then the outcrop at the northeastern tip of the island shows north-facing Risberget and Sætra of the south limb facing south-facing Risberget of the north limb across a mylonite zone.

The Helleneset syncline is shown in the southern part of Fig. 10 with important exposures on cliffs above Skåradalen, near Skåradalen and Gronhornet, on the south shore of Lauvøya, and at Helleneset. At Helleneset the combined width of Sætra and Blåhø-Surna between Risberget contacts on both limbs is 100 m. A detailed section within a single outcrop on the north limb includes from north to south 10.8 m of classic Risberget augen gneiss with fine-grained mafic sheets; 0.6 m of sheared biotite gneiss; 1.5 m of hornblende gneiss that could be sheared gabbro with a trace of augen gneiss; 11.7 m of stripy gray gneiss that appears to be sheared Risberget with minor amphibolite; 1.2 m of Sætra amphibolite with 5% quartzite, within which there is a retrograded eclogite boudin 0.9 m thick; 2.5 m of highly characteristic Sætra with 70% quartzite and 30% amphibolite; and 3 m of Blåhø-Surna garnet schist and amphibolite. Within this outcrop the Sætra pinches out completely to the east. In another outcrop the Risberget-Sætra contact can be observed continuously for 62 m. A special feature of the north limb of the Helleneset syncline is a narrow belt of muscovite-garnet quartzite and amphibolite with superficial resemblance to the Sætra that is assigned to the Blåhø-Surna Nappe.

On the southern part of Medøya, on the north end of Lauvøya, in a road cut southeast of Ørsnes, and in cliffs on the west and east faces of Langsetnakken, in areas dominated by basement, are layers of white to buff feldspathic quartzite up to 60 m thick, locally with specular hematite and feldspathic pebble beds. Lithically these closely resemble the Åmotsdal Quartzite of Trollheimen that is commonly exposed there in a layer above lower basement overthrust by an upper layer of basement. These quartzites outline a very gently west plunging anticline between the Moldefjord syncline and the Helleneset syncline. Quartzites are not present along the top of the high rocky ridge from Hellenakken through Langsetnakken to the vicinity of Ørsnes, but pass eastward beneath the ridge to cliffs on the east side and then are exposed voluminously in an eastward extension of the anticline beneath Rekdalshesten (765 m), to be described elsewhere.

Rekdal area

Eastward from Tenøya the strata of the Moldefjord syncline are completely submerged for a distance of 4 km until the Risberget augen gneiss with minor gabbro emerges at Øygardsneset (Fig. 12), in an outcrop with large augen, sinistral shear features, and apparent tubular folds with subhorizontal axes. From Øygardsneset eastward to Rekdal coastal exposure is sparse, but sufficient to locate the position of the Sætra Nappe. Several exposures of the lower part of the Blåhø-Surna Nappe contain conspicuous folded beds of calcareous impure quartzite. At the football field southeast of Rekdal, a measured section was made from south to north in layers dipping 40–50° south. This gave the following: 12.3 m fine-grained gray basement gneiss, 26.2 m covered interval, 41.5 m typical Risberget augen gneiss with minor mafic sheets, 10.8 m covered interval, 27.7 m wildly folded sheared gabbro with 0.3 m of augen gneiss, 4.6 m complexly sheared augen gneiss, 13.9 m fine-grained slably gneiss. On the coast east of Rekdal there are numerous outcrops of fine-grained Støren amphibolites, but there are no exposures close to Blåhø-Surna contacts. The offshore islet at Rekdal is Støren gabbro. The coastal outcrops at Dragneset are key ones in the region. A measured section shows from south to north: 34.6 m of Sætra quartzite and amphibolite (lower 14.6 m is 71% amphibolite, some with relic porphyritic texture; upper 20 m is only 23% amphibolite, again the uppermost quartzite is the most quartz-rich), a 10.8 m covered interval, and 38.9 m of Blåhø-Surna garnet-mica schist, interbedded calcareous impure quartzite and one 4.6 m bed of laminated amphibolite (33% of outcrop is calcareous rock in seven different beds ranging in thickness from 0.03 to 3.7 m). The Sætra Nappe is also less well exposed in a road cut near Dragneset. The contacts between Sætra and Risberget, and Risberget and basement are controlled by small outcrops south of Dragneset including one coastal exposure showing the exact base of the
Risberget. The Sætra outcrops at Dragneset are the last I have identified on the south limb of the syncline until those identified southwest of Kortgarden (Fig. 5), over 40 km to the east, although Hernes (1955) indicates quartzite near the southwest shore of Bolsøya (Fig. 3) that has not been confirmed.

Tautra

The isolated island of Tautra and adjacent islets (Figs. 2, 13) contain large exposures of the upper part of the Blåhø-Surna Nappe and the lower part of the Støren Nappe. As elsewhere, the Blåhø-Surna is dominated by...
gray- and rusty-weathering garnet-mica schist and amphibolite. There is a mappable unit of calcareous schist and marble close to, but not at the top, as near Brattvåg (Fig. 6). In exposures near the eastern tip of the island there is one pure marble bed 1 m thick. The base of the Støren, not generally well exposed, is fine-grained amphibolite, and this is succeeded upward in the western part of the map by sheared gabbro as at Brattvåg. Within the Støren amphibolite north of the gabbro and extending to the eastern tip of the island is a thin layer of garnet-mica schist resembling the Blåhø-Surna Nappe that is in an identical position to the thin garnet schist layers north of Brattvåg and on Bolsøya. On Storholmen, where it is 100% exposed and is 30 m wide, it contains amphibolite including garnet amphibolite and also some gneissic rocks. Between 1.2 and 3 m from the north contact there is a layer of sheared gneiss that looks like basement. A similar gneissic rock is exposed in this schist belt on a knob southwest of the fault near the eastern end of the Tautra, and Ole Lutro reports a similar gneiss inland from the south coast midway along the island (pers. comm. 1993). These features are evidence that this narrow schist belt is involved in an early thrust sheet, possibly even involving basement, and is not an integral part of the Støren stratigraphy. The prominent dextral fault at the eastern end of Tautra as well as dextral offsets of gabbro contact on Storholmen were probably produced by rigid block rotations related to late stages of sinistral ductile shear.

**Structural geology**

Broader structural patterns including the Moldefjord and Helleneset synclines and younger sinistral shear zones are illustrated in maps. Current observations suggest that these synclines are unrelated to the original processes that produced the tectono-stratigraphy and juxtaposition of tectono-stratigraphic nappes, but were produced just before or during an episode of strong sinistral shear for which evidence is given below. In keeping with this, minor structural features related to the phase of sinistral shearing pervade the outcrops, and few have been identified that can be related to early phases of deformation, including nappe emplacement. However, the synclines are older and tighter than the broader open northwest overturned folds with gently south-dipping axial surfaces, such as the great northwest-overturned anticline above the east limb of the Surnadal syncline (Fig. 1b) and the north-facing open anticlines and synclines that occur on Rekdalshesten and in the cliffs southeast of Skår, where the axial surface and both limbs of the Helleneset syncline wobble up the cliff following the later folds. Possibly the broad overturned folds were developed during the sinistral shearing process, but their development certainly post-dated the formation of the main, tectono-stratigraphically defined, synclines.

**Evidence for late Scandian sinistral shear**

Minor structural features in all rock units are dominated by subhorizontal folds in foliation, commonly variably plunging, especially as shown in migmatitic garnet-schist and amphibolite of the lower part of the Blåhø-Surna Nappe. The folds are accompanied by a strong subhorizontal mineral lineation well developed in all rock types (structure symbols, Figs 3, 5, 6, 10, 12, 13). Surfaces parallel to lineation and perpendicular to foliation commonly show small sheath-like folds, all indicating sinistral shear along the lineation. Coarse porphyroclastic schists and amphibolites of the Blåhø-Surna show consistent evidence of late metamorphic sinistral shear both in outcrop and in thin sections cut parallel to the lineation. This is well illustrated in observations from Bolsøya and Grennes in asymmetric feldspar porphyroclasts in mica schists (Fig. 14) and migmatites, in asymmetric tails on garnet porphyroclasts, and in asymmetric hornblende porphyroclasts in coarse hornblende gneiss. The same sinistral shear indicators occur both on north-facing south limbs of synclines, and on south-facing north limbs as confirmed in detail in the extensive north limb highway exposure near Talset (Fig. 5). Similar shear indicators are observed in Støren rocks in the middle of the synclines, as for example in the coarse metamorphosed Støren gabbro on Bolsøya. Larger-scale shear indicators include asymmetrical tails on pegmatite boudins, and nests of sheath-like folds in the lowermost Støren northwest of Brattvåg that show highly variable orientation within the dominant foliation plane, but a consistent asymmetry related to sinistral shear along the dominant lineation. The combination of sinistral shearing and folding is illustrated in an outcrop of mylonitic Risberget augen gneiss with sheath-like asymmetric folds on Tennesøya (Fig. 15).

Although many of the rocks in normal stratigraphic sequences are locally mylonitic in aspect, there are zones of more severe mylonitization near Brattvåg (Fig. 6) and on Tennesøya (Fig. 10) that are from a few cm to 160 m

![Fig. 14. Plagioclase porphyroclasts showing sinistral shear in mylonitic Blåhø-Surna schist. West coast of Bolsøya, a few hundred meters north of Risberget contact (see Fig. 3). Lineation is sub-horizontal parallel to surface of outcrop.](image-url)
Fig. 15. Complex of sheath-like asymmetric folds on pavement outcrop in variably mylonitized Risberget augen gneiss near west end of Tennøya (see Fig. 10). South is at the top. Dominant lineation is subhorizontal. Note variable plunge but consistent sinistral shear sense of folds. Dark layers may be mylonitized amphibolite. The rock south of the folds is medium-grained augen gneiss. Rock north of the folds is fine-grained mylonitic gneiss.

wide. The mapped zones appear to cut obliquely across the folded tectono-stratigraphic units in a manner consistent with sinistral shear. Furthermore, limited observations indicate that the mylonites themselves are filled with sinistral shear indicators, including tails on porphyroclasts, and asymmetric folds including sheath folds and tubular folds. Several outcrops suggest the mylonites are composed of rocks from several different nappes, consistent with the truncations on the map. In an outcrop near Sunnaland (Fig. 16) mylonitized Risberget augen gneiss and Risberget amphibolitized gabbro appear to be tectonically interleaved on an intricate scale. The extremely flattened heart-shape pattern in the right of Fig. 16 is that of a refolded fold. All of the fold axes could be observed and measured and all are subhorizontal parallel to the mylonitic lineation in the outcrop. Development of the features in this outcrop is viewed as a five-stage process: (1) Shearing of Risberget rock types into a mylonite zone dominated by Støren and Blåhø-Surna rock types. The nearest major area of Risberget now lies on the north side of the zone, while Støren appears nearby on both sides. (2) Multiple shearing and/or folding of the original contact between Risberget augen gneiss and gabbro so that it is now repeated in the outcrop. (3) Development of isoclinal folds in one of these contacts. (4) Refolding of the isoclinal by a later fold at a high angle to the first folding. (5) Further shearing of all fold hinges until all have been rotated parallel to the shear direction. The implication is that the amount of shearing is large, consistent with the broad distribution of mylonitic features, sub-horizontal lineation and sinistral shear indicators through the region. Despite the extreme deformation, Risberget augen are still well preserved in this outcrop and asymmetric tails indicate a sinistral sense of movement.

Thin-section observations of the mylonites indicate they are thoroughly recrystallized metamorphic rocks without evidence for significant retrograde hydration. The sample shown in Fig. 17 contains well crystallized biotite and tiny euhedral garnet porphyroblasts as well as abundant porphyroclasts of many minerals including tourmaline that is characteristic of Støren schists. It appears that this mylonite was formed and recrystallized under garnet- or low staurolite-zone conditions, the highest grade for which there is good evidence in the Støren Nappe. There is no evidence of retrograding below the ambient conditions in the surrounding rocks. There are asymmetric folds and asymmetric porphyroclasts of many minerals indicating sinistral shear. A few meters away there are anticlines of Blåhø schists and marbles that are shown schematically in Fig. 6. In a sample from the main mylonite zone 1 km west from this locality, there is a tubular fold in mylonite layering. A reconstructed 3D view of the tubular fold shows a sinistral shear sense like all other features in the mylonite zones.

Fig. 16. Outcrop within the Brattvåg mylonite zone west of Sunnaland (see Fig. 6), looking west along axial direction of subhorizontal folds exposed on a steep east-facing surface. Shows repeated tectonically interleaved mylonites derived from Risberget augen gneiss (light gray) and from Risberget amphibolitized gabbro (medium gray). Derivation from Risberget augen gneiss is demonstrated by numerous small and a few large microcline porphyroclasts particularly well exposed on the flat top of the outcrop and in a blasted driveway exposure beyond. Note extremely flattened heart-shaped pattern in lower right of outcrop, which is a refolded fold. Orientations of the two primary hinges, upper right from the hammer, and the secondary hinge, lower right from the hammer are all subhorizontal parallel to mylonite lineation (for genetic interpretation see text.).
Metamorphism

Quantitative metamorphic studies in progress suggest there are discontinuities in early conditions of metamorphism between most of the nappes and between the lower nappes and basement, even though all probably converged in the low amphibolite facies during late Scandian sinistral shearing. Although all available evidence indicates that the age of the eclogites in Baltica basement is Scandian (Griffin et al. 1985), there is presently no proof against, and some circumstantial evidence in favor of, pre-Scandian metamorphism for the migmatitic rocks of the Blåhø-Surna Nappe, and for the low grade eclogites of the Sætra and Risberget Nappes. For example, eclogites produced from diabase dikes in a Sætra-like unit of the Seve Nappe in northern Sweden (Andréasson et al. 1985) have been dated at about 500 Ma (Mørk et al. 1988). The metamorphic differences between the thrust nappes must be taken into account in any kinematic model of their assembly (Robinson 1995b). This cannot be done with assurance until the ages of metamorphism are known, and these will not be easy to determine. Nevertheless, the dramatic metamorphic contrast between Baltica basement and the Støren Nappe only about 600 m higher requires major extensional faulting to have taken place after original nappe stacking and peak Scandian eclogite-facies metamorphism of the basement and before folding and sinistral shearing.

Metamorphic discontinuity between Blåhø-Surna and Støren nappes

The metamorphic discontinuity between the Blåhø-Surna and the overlying Støren rocks persists through the area. The Blåhø-Surna rocks contain very coarse garnet both in schists and amphibolites, commonly 1–3 mm in diameter, and extensive evidence that they once underwent local partial melting. Some of the schists contain very fine kyanite and staurolite that seem to have developed late in the metamorphic sequence and don’t appear relict, as suggested by Carswell & Harvey (1985). High-grade features are best preserved in the lower part of the nappe, well away from the contact with the overlying Støren. Here quantitative studies using garnet-biotite and garnet-hornblende geothermometry have given temperature estimates of about 700°C (Robinson & Peterson, in prep.). Closer to this contact retrograde hydration and deformation have caused major reconstitution including growth of new euhedral garnet as well as muscovite, staurolite and kyanite, as compared to irregular garnet porphyroclasts away from the contact. Particularly intriguing are garnets with concentric zoning, sectoral distribution of inclusions, and asymmetric tails in a staurolite-kyanite-bearing schist completely enclosed in marble mylonite on Bolsøya. This and another schist close to the Støren contact on Bolsøya suggest reconstitution during mylonitization and yield no garnet-biotite temperature estimate above 500°C. In the overlying Støren there is no evidence that the rocks were ever more highly metamorphosed than the low staurolite zone as shown by one staurolite-bearing feldspathic schist on Bolsøya, although some of the amphibolites appear exceedingly coarse grained because they are derived from coarse-grained gabbros. The garnets are typically very small, commonly 1–3 mm in diameter, and poikilitic, and show prograde growth zoning. Garnet-biotite geothermometry on the staurolite-kyanite-bearing sample and a garnet schist suggest maximum temperatures of 600°C, higher than in the contact zone. Possibly fluids for retrograding the upper part of the Blåhø-Surna Nappe were derived by simultaneous dehydration of the Støren. Mineralogical features of the mylonites suggest that mylonitization may have taken place under conditions only about 100°C cooler than those of peak metamorphism in the Støren Nappe. Structural and metamorphic features that may have formed when the two nappes were first juxtaposed appear to have been largely obliterated during sinistral shearing.

Zoisite ± phengite eclogite in Sætra and Risberget Nappes

The Sætra and Risberget Nappes contain features that suggest they were once lower grade than either the overlying Blåhø-Surna, with its migmatitic schists and amphibolites, or the Baltica basement, with its high-grade eclogites that apparently reached 750°C and 18 kbar during the early Scandian (Krogh 1977, 1980; Griffin et al. 1985; Mørk 1985, 1986). However, one should be aware that the basement immediately adjacent to the Moldefjord syncline, although it does contain some eclogites, contains none of the ones that have yielded these high temperature and pressure estimates. The eclogites in the Sætra Nappe and the one sample from the Risberget Nappe all occur in resistant boudins surrounded by highly sheared and recrystallized matrix
either of amphibolite, or of feldspathic quartzite. Former omphacite is entirely represented by clinopyroxene-plagioclase symplectite in various states of replacement by hornblende. The most sodic preserved pyroxene contains 0.25 Na per 6 oxygens (Robinson & Panish, 1994). Phenogte (si = 3.25) commonly occurs as clear plates, both in matrix and as inclusions in garnet, invariably rimmed by biotite. Ubiquitous minerals, both in matrix and as inclusions in garnet, are zoisite, hornblende, and rutile, quite commonly rimmed by retrograde spheine. The garnets are small and moderately poikilitic with Mn-rich Mg-poor cores and Mn-poor Mg-rich rims indicating a preservation of prograde growth zoning and that these eclogites probably did not reach temperatures much in excess of 600°C for an extended time.

Summary

The present work demonstrates that a modified Trollheimen sequence of Caledonide nappes extends in a narrow syncline within Baltica basement of the Western Gneiss Region down the Moldefjord at least as far as Brattvåg, 120 km west of Surnadal. By contrast with eastern Trollheimen, the nappes are strongly attenuated either by the original process of nappe emplacement, by processes of early extensional collapse, or by the later shearing parallel to fold axes that appears to cover a large part of this region and indicates a major phase of late Scandinavian sinistral shear parallel to the length of the orogen. The metamorphic discontinuity between the Søren Nappe and the underlying Blåhø-Surna Nappe recognized near Surnadal persists throughout this region. Other discontinuities between the Blåhø-Surna and the underlying Sætra and Risberget, and between the Sætra and Risberget and underlying Baltica basement are probable, based on the preservation of evidence for relatively low grade eclogite-facies metamorphism of diabase dikes in the Sætra and Risberget Nappes. When ages of peak metamorphism in different nappes are known, the differences can be integrated into a coherent model for Scandinavian subduction and uplift in the region. Meanwhile, the dramatic metamorphic contrast between Baltica basement and the Søren Nappe 600 m higher, requires major extensional faulting after original nappe stacking and peak eclogite-facies metamorphism of basement, and before tight folding and sinistral shearing.

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