

# Geology of the Folldal area, southern Trondheim Region Caledonides, Norway

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The lowest stratigraphic unit in the Folldal area is the Gula Group, comprising turbidites and minor greenstones in the lower part (the Singsås Formation) and graphitic pelites with subordinate marble and conglomerate in the upper part (the Åsli Formation). The overlying Fundsjø Group is bimodal with basalts and rhyodacites, comagmatic gabbros and a large subvolcanic trondhjemitic intrusion. The bimodality, high content of volcanoclastics, intercalations of continental sediments, geochemistry and lead isotopes of massive sulphides reveal that the Fundsjø Group represents an island arc accumulation formed close to a continent. The contact between the Fundsjø and Gula Groups is interpreted to be primary, as shown by a gradual lithological transition and no break in metamorphism and structural elements across the contact. The Folldal Trondhjemite in the Fundsjø Group has yielded a U-Pb zircon age of  $488 \pm 2$  Ma. Relationships between published ages from the Gula Group and rocks in the Seve Nappes suggest a possible tectonic and metamorphic link between the Seve and the lower part of the Gula Group. Either a primary unconformity or a thrust marks the contact between the Åsli and Singsås Formations in the Gula Group.

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## Introduction

Rocks of the Gula Group, which consist mainly of metasediments, occupy the central part of the Caledonides in the Trondheim Region (Fig.1). The stratigraphic and tectono-stratigraphic position of this group,

in relation to the volcanic and sedimentary rocks of the Meråker and Støren Nappes, is important to any tectonic model of the Caledonides and has therefore been debated since at least the beginning of this century (see Gee et al. 1985 for a review).

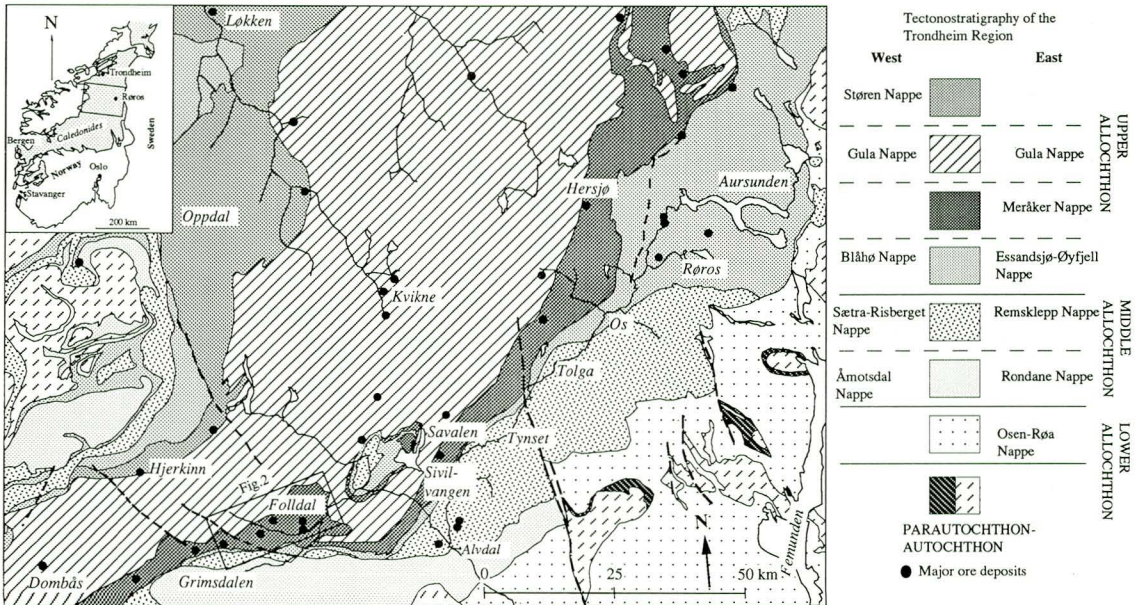


Fig.1. Tectonostratigraphic map of the southern part of the Trondheim Region (modified from Nilsen 1988). The Folldal Area (fig.2) is indicated.

There is now a common opinion that the rocks of the Støren Group in the Støren Nappe (west of the Gula Group) had a different origin to that of the rocks of the Fundsjø Group in the Meråker Nappe. They probably represent, respectively, an ocean floor and an island arc / marginal basin setting (Gale & Roberts 1974, Grenne & Lagerblad 1985, Grenne 1988). The intervening sediments of the Gula Group have a more uncertain origin. Based on lithology, sedimentology and geochemistry, Guezou (1978, p.14) considered that the Gula metasediments in the Dombås district are of epicontinental origin and "are devoid of either turbidites or rhythmic coarse clastic deposits". Nilsen (1978), however, reported that turbidites are found in the central part of the group further north, while graphitic phyllites with conglomerates and marbles occur both in the east and in the west. Both back-arc and fore-arc positions have been inferred, either for the whole group or part of the group (Gale & Roberts 1974, Grenne 1988, Stephens & Gee 1989).

Major differences in metamorphic grade and deformation (Wolff 1979) and age relationships (see below) indicate that an unconformity or thrust may exist internally within the Gula Group. Therefore, the natu-

re of the contact between the Fundsjø and Gula Groups and also the internal tectonic structure of the Gula Group are critical for the interpretation of the palaeotectonic setting of the Gula and Fundsjø Groups and for the existence of a separate Gula Nappe (Fig.1).

The Follidal area comprises both the Gula and the Fundsjø Groups, covering about 150 km<sup>2</sup> around the village of Follidal in the county of Hedmark (Figs.1 & 2). Because of extensive mining activity, mapping has been carried out by several workers and with different perspectives (e.g. Bjørlykke 1905, Marlow 1935, Page 1963, Heim 1968, 1972, Pedersen 1979 and by geologists at Follidal Verk A/S).

In this paper, data on petrography, structures and tectonics, petrology and geochemistry and one U-Pb zircon age determination will be presented from the Follidal area. The intention is to throw light on the nature of the contact between the Gula and Fundsjø Groups; and further, to compare petrography, geochemistry and the age of the volcanic rocks with work done elsewhere in the 'greenstone belt', especially in the Røros-Meråker district. These data also form a basis for a discussion of the origin of

Terrane (Stephens & Gee 1989)		Tectonic Complex (Gee et al. 1985)	Tectonostratigraphy and Lithological Units (Modified from Nilsen 1988)
Exotic terranes derived from outboard of Baltica	Metamorphic complexes	UPPER ALLOCHTHON	Gula Nappe; <i>Gula Group</i>
	Oceanic sequences		Meråker Nappe; <i>Fundsjø Group, Sulåmo Group</i>
Suspect terranes; probably outer tect. shortened margin of Baltica	Seve Nappes		Essandsjø-Øyfjell Nappe; <i>Aursund Group</i>
Tectonically shortened margin of Baltica	Platformal and miogeoclinal sediments and Precambrian crystalline rocks	MIDDLE ALLOCHTHON	Remsklepp Nappe; <i>Augen Gneiss Unit, Tynset Group</i>
		LOWER ALLOCHTHON	Rondane Nappe  Osen-Røa Nappe
Cratonic Baltica	Platformal sediments	PARAUTOCHTHON/AUTOCHTHON	
	Prec. cryst. basement	PRECAMBRIAN CRYST. BASEMENT	

Table 1. The divisions in tectonostratigraphy, terranes and lithological units in the Southern Trondheim Region.

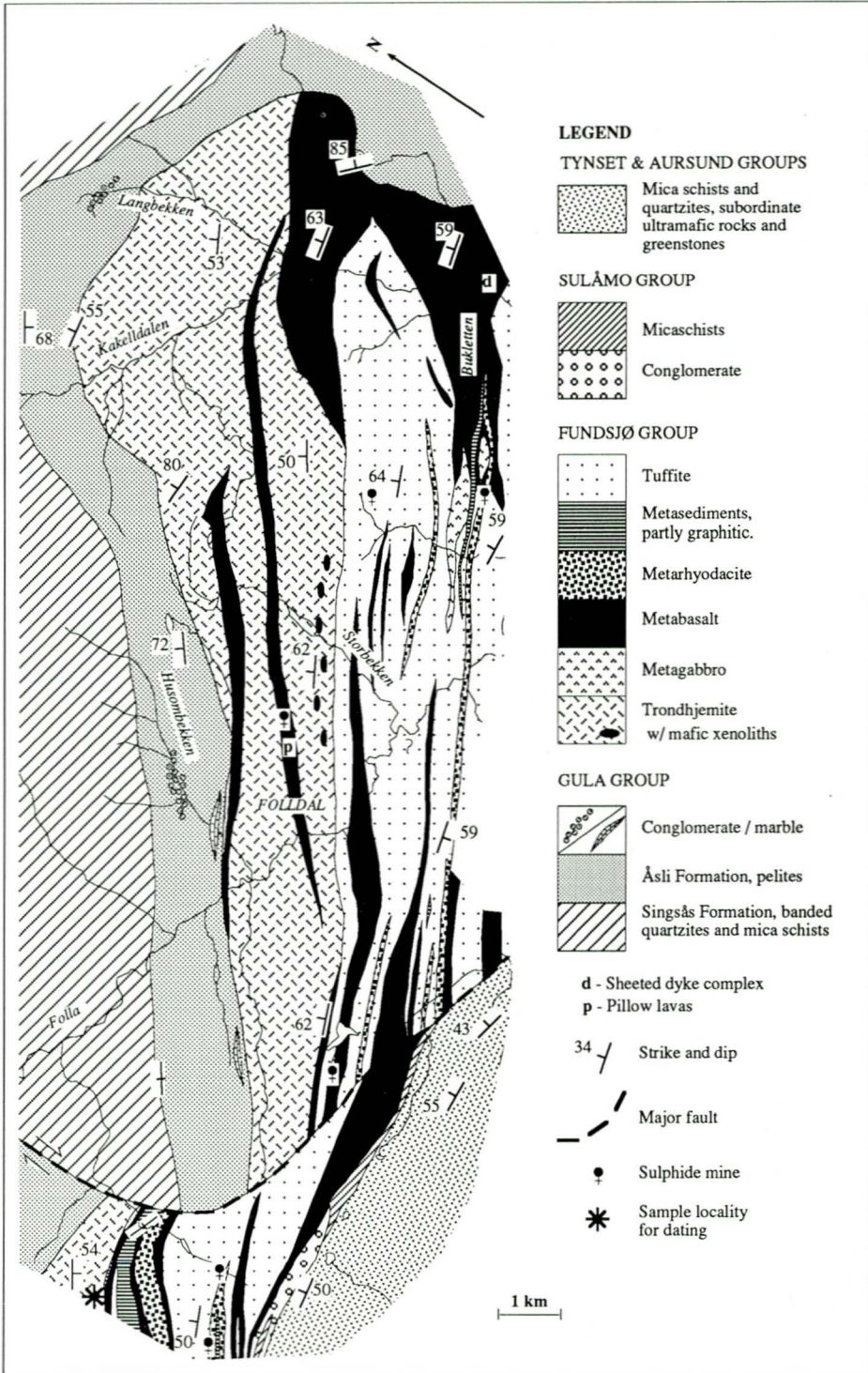


Fig.2. Simplified geological map of the Follidal Area.

and connection between the Gula Group and the Fundsjø Group and finally for the interpretations and understanding of the setting of the ore deposits in Folldal, work which is currently in progress.

## Geological setting

The Caledonides of the southern Trondheim Region comprise tectonic and lithological units derived from several different environments, thrust upon a Precambrian basement with a thin, mostly Cambrian, sedimentary cover. According to Gee et al. (1985), the tectonostratigraphy of this region can be divided into three major allochthonous complexes; namely the Lower, Middle and Upper Allochthons (Table 1, Fig. 1). A new division of units has been proposed for the Scandinavian Caledonides in the last five years based on the terrane concept (e.g. Roberts 1988, Stephens 1988). Terranes are defined on the basis of their overall geological features and histories, which are distinctive from those of neighbouring terranes. In the Scandinavian Caledonides, outside of the tectonically shortened shelf and miogeoclinal sequences related to Baltica there are several suspect and exotic terranes of uncertain palaeogeographic origin (Table 1).

The Folldal area (Fig. 2) comprises units occurring above the arkosic rocks of the Rondane Nappe (Bockelie & Nystuen 1985) in the Middle Allochthon. The structurally lower units in the area are dominated by argillaceous sediments occurring both in the Remsklepp Nappe (Wolff 1979) of the Middle Allochthon and in the Essandsjø-Øyfjell Nappe (Nilsen 1988) of the Upper Allochthon. Most of the area is occupied by volcanic and volcanoclastic rocks of the Meråker Nappe and diverse sediments of the Gula Nappe, both units belonging to the Trondheim Nappe Complex. Most workers agree that these two units show internal stratigraphic inversion (Rui 1972, Nilsen 1988).

## The Gula Group

The Gula Group (Kjerulf 1876) comprises

two sedimentary units, the Åsli and Singsås Formations, (Nilsen 1978) in the eastern Trondheim Region. The Gula Greenstone, a metabasalt unit, is commonly found between the two and also within the Singsås Formation (Nilsen & Mukherjee 1972). All units are represented in the Folldal area and were described by Heim (1972) under the name Storhøi Formation. The Gula Group constitutes the Gula Nappe according to Roberts (1978) or Gula Nappe Complex (Gee et al. 1985). Because of possible confusion with the lithological term Gula Group, the terms Gula Nappe and Nappe Complex should really be avoided as names for this tectonic unit. They will, however, be used in this paper because of their common usage in the literature.

The Singsås Formation consists of psammitic to semipelitic quartz-plagioclase-mica schists. They show typically a rhythmical variation in quartz and mica content as well as grain size, on 0.5 - 2 m scale, from nearly pure quartzites to mica schists. Porphyroblasts of garnet and clino-amphibole are common. No primary sedimentary structures have been found in the Folldal area, but in other places, e.g. the Røros area, graded bedding, cross bedding and load casts are commonly observed in this unit and the rocks have been interpreted as turbidites (Rui 1972, Nilsen 1978).

The Åsli Formation is dominated by semipelitic garnet-chlorite-bearing mica schists. Based on a varying content of phyllosilicates and quartz the formation might be divided in a lower unit of quartz-rich schists and a higher unit of partly graphitic phyllosilicate-rich schists, a division also noticed by Heim (1972). Quartz, biotite and muscovite are main phases while chlorite, garnet and in some cases clino-amphibole are subordinate. Apatite, tourmaline and zircon are the most important accessory minerals in these schists. Benches of metasandstone, several metres thick, are intercalated in the upper unit. About 250-300 m below the Gula-Fundsjø contact, horizons of about 20 m-thick calcite marble are found at several localities at the same stratigraphic level. The marble is locally quite pure and coarse



Fig.3. L2 - lineation in calcareous conglomerate of the Gula Group. The clasts are mostly pure marble, while the matrix is calcite-rich metasilstone.

grained, though at some localities it has a high content of quartz and commonly fuchsitic muscovite, giving it a green colour.

About 500 m below one of the marbles in the stream Husombekken two lenses of conglomerate are found (the Husom Conglomerate, Heim 1972). They are at least 15 and 25 m thick and comprise mainly clasts of pure calcite marble and quartzite in a matrix consisting mainly of pale green clin amphibole and biotite (Fig.3). Clasts of quartz-albite rock, greenschist, gabbro and biotite schist are also present. Quartz, muscovite and calcite are subordinate matrix minerals. Although no pre-pebble foliation has been seen in the clasts, this might be due to subsequent deformation and metamorphism. The clasts are extremely elongated and ruler-shaped with maximum long-axes up to 1 m. A similar but less deformed conglomerate, also with calcite marble as clast material, is found in the stream Lang-

bekken in the northern part of the area (Fig.2).

A thin (15-20 m) horizon of fine-grained amphibolite separates the Åsli and Singsås Formations at one locality. It is at least 600 m in strike length and contains amphibole and epidote as main phases, while quartz, chlorite and ilmenite are subordinate. The mineralogy and position of this horizon between the sedimentary units fits with the Gula Greenstone.

## The Fundsjø Group

In the Folldal area, the Meråker Nappe (Wolff 1979) is represented by the dominantly volcanic Fundsjø Group together with the stratigraphically overlying sedimentary Sulåmo Group. The volcanic unit can be followed all the way from Meråker to Grimsdalen east of Dombås, and has a variety of local names (e.g. the Hersjø Formation is the name given to the group as a whole in the Røros area (Rui 1972, Grenne 1988)). To underline the continuity of the unit the term Fundsjø Group will be used here.

The Fundsjø Group widens in outcrop from about 1 km in thickness west of Alvdal to 5-8 km in the Folldal area (Fig.1). The reason for this is probably a combination of folding and primary differences in thickness, and especially due to the presence of a large felsic intrusive body near the stratigraphic base of the unit. The unit can be divided into essentially three lithologically different units: 1) Metabasalts and gabbros, 2) tuffitic and metasedimentary rocks and 3) felsic intrusive and extrusive rocks.

Greenstones, interpreted as metabasalts, are found mostly near the base of the unit, especially in the northeastern part of the area. They occur below, intercalated within, and above the large felsic intrusion (Fig.2). Thin horizons are also found intercalated in the overlying tuffites. The metabasalts are dark green, fine-grained and homogeneous with a weak foliation. White mm-thick streaks of albite and minor quartz in a green matrix of chlorite and amphibole define the main texture of the rocks.

Because of the high degree of deformation in the area primary textures in the basalts are rare. Structures resembling pillows have been found in the mine area just north of the village (p in Fig.2). West of Bukletten a possible sheeted dyke complex has been found in a road cut (d in Fig.2). Numerous fine-grained and metre-thick dykes intrude one another within the same strike trend. Because of deformation the dykes are now parallel to the regional foliation in the area. In some places it is possible to distinguish the individual dykes by the presence or absence of plagioclase phenocrysts, and some dykes have chilled margins.

Horizons of metabasalts heavily studded with mm to cm plagioclase phenocrysts are common both east of Bukletten and in horizons contained in the felsic intrusion. The best exposure is probably in the mine area just north of the village: Here one can see a sharp contact between a basalt without phenocrysts and a basalt with 30-40 % white phenocrysts of plagioclase (1-10 mm) in an amphibole-rich matrix. Eastwards from the contact the content and size of the phenocrysts gradually decrease to 1-5 mm, becoming more dispersed, until they finally disappear. The thickness of this phenocryst-bearing zone is about 2.5 m.

Clino-amphibole (actinolite and actinolitic hornblende), epidote, albite and chlorite are the main mineral constituents. Quartz and calcite are generally subordinate, while biotite, sphene and/or rutile and haematite are the most common accessories. Epidote/clinozoisite replace plagioclase to varying degrees.

The metagabbros have the same mineralogy as the metabasalts, consisting of unoriented 0.1-1 mm grains of actinolite/actinolitic hornblende, porphyroblastic epidote and fine-grained recrystallised albite in mm-large aggregates. These aggregates are probably a result of the breakdown of larger crystals of more Ca-rich plagioclase, Ca now taken up by epidote. Amphiboles might have formed from pyroxenes. Due to the extensive deformation and recrystallisation, no ophitic texture has been preserved and

only the 'spotted' texture distinguishes them from the metabasalts in the field.

At two localities small lenses of ultramafic rocks have been found associated with a metagabbro and metabasalt, respectively. These contain talc, chlorite and up to cm-sized euhedral crystals of magnesite. Growth of colourless clino-amphibole (tremolite ?) is observed at the contact with the country rocks. Both lenses have been mined for talc.

The felsic igneous rocks of the Fundsjø Group, on grounds of texture, stratigraphic position and contact relationship to other lithologies, are divided into an intrusion and several extrusive equivalents. The intrusion occurs in the lower part of the Fundsjø Group. Small apophyses and aplitic dykes intrude the metabasalts (Fig.4). Xenoliths of mafic rocks are found in the upper part of the intrusion (Fig.5), occurring over a strike-length of at least 2 km (shown with black dots in Fig.2). The first deformation phase recognised in the area, which produced the regional foliation, has affected the intrusion,

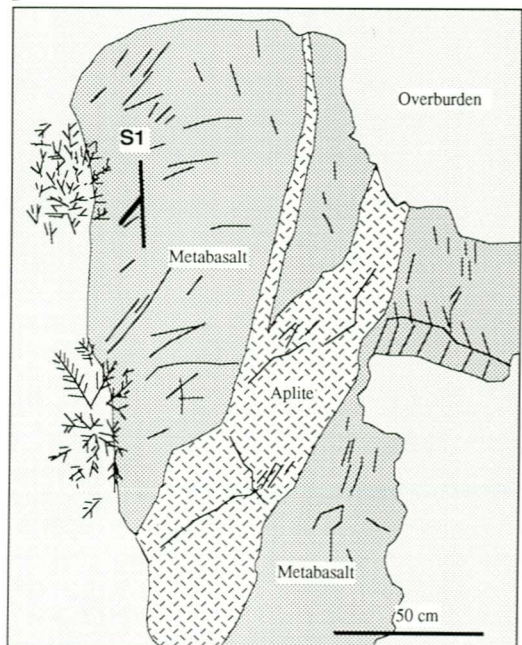


Fig.4. Drawing after a photograph of trondhjemitic aplite intruding metabasalt at an angle to the regional foliation S1 (shown by strike-dip symbol).

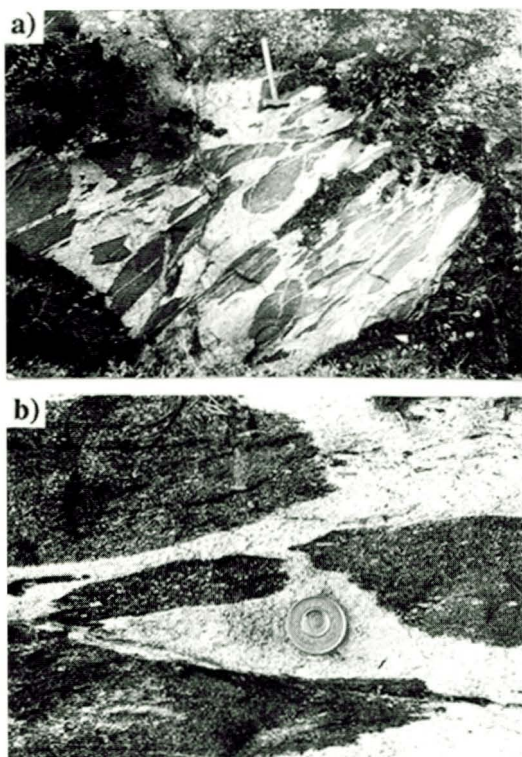


Fig.5. (a). Amphibolitic xenoliths in the trondhjemite intrusion below the contact to the stratigraphically overlying tuffites. The xenoliths are elongated parallel to the S1-foliation. (b) Close-up of the xenoliths, showing the foliation (S1) affecting the contact between the xenoliths and the felsic host.

the dykes, as well as the xenoliths (Fig.4, 5 b). This shows that the intrusion was emplaced before the thrusting and nappe formation.

The intrusion has a strike extension of more than 20 km. It appears to consist of three individual sills with maximum thickness of 800 m, divided by metabasaltic horizons. Because of its resistance to erosion the intrusion is reasonably well exposed. In outcrop it is quite homogeneous, though somewhat variable in grain-size. A faint foliation is present in the rock where it is more fine-grained (1-3 mm). It is dominated by albite and quartz and is grey-white in colour. Red garnet (1-3 mm) and up to cm long needles of green amphibole are the other major minerals. Muscovite and epidote are subordinate, while chlorite and apatite are common accessories.

The intrusion has earlier been called 'granulit' (Bjørlykke 1905). Goldschmidt (1916) kept this name but classified it as a trondhjemite. The mineralogy allows it to be classified as a trondhjemite and this is supported by geochemistry (see later). As it is very well exposed immediately east of the village the informal term *Folldal Trondhjemite* will be used for the intrusion.

It should be stated that trondhjemites in the Trondheim Region were intruded before, during and after the time of nappe formation and thrusting. According to Size (1979), four periods of trondhjemite intrusive activity are distinguished in the Støren area, ending with the post-tectonic trondhjemite s.s. Similarly, in the Tolga area, trondhjemites of two generations have been observed (Bjerkgård 1989). Trondhjemitic dykes of an early generation have been affected by the D2 deformation and are schistose, while the larger bodies in the area (the best example is the Tolga Trondhjemite) cross-cut all Caledonian structures.

The felsic extrusive rocks occur as conformable layers, mostly in the tuffites in the stratigraphically upper part of the group (Fig.2). These layers are 10-30 m thick while their lengths can be up to several kilometres. The contacts to the surrounding tuffites are always very sharp. A matrix of very fine-grained quartz and albite is dominating, giving the rock a grey-white colour and a weak foliation. In this matrix partly idiomorphic, sharply defined phenocrysts of albite (1-3 mm) and irregular aggregates of quartz occur and are evenly distributed. As in the trondhjemite, garnet porphyroblasts and needles of amphibole are common. Epidote and muscovite are subordinate, while chlorite and apatite are accessory minerals.

The upper part of the group is dominated by pale greyish-green chlorite schists with a pronounced schistosity. Alternating calcite-quartz laminae, fine-grained lenses of quartz-albite and thicker chlorite layers define a characteristic lamination on mm to cm-scale (Fig.6). Where deformation was less severe, lenses of quartz-albite and chlorite-amphibole rocks occur and are interpreted



Fig. 6. Laminated mafic tuffite, with alternating layers dominated by chlorite and calcite-quartz on cm scale. An F1-fold refolded by F2 can be seen near the pencil.

as clasts derived from the volcanic rocks. This observation, together with a high content of calcite and chlorite and a lamination which is possibly primary, strongly suggests that these rocks are volcanoclastic or tuffitic rocks.

Quartz, albite, chlorite, epidote/clinozoisite and calcite are the main constituents whilst muscovite and amphibole usually are subordinate. Amphibole is commonly found on

the planes of schistosity, sometimes oriented. Garnet, biotite, magnetite, sphene and apatite are the most common accessories, garnet occurring in porphyroblasts up to 1 cm in size.

The contents of the main and subordinate phases vary and the tuffites are classified as mafic or felsic on the basis of the ratio between mafic phases such as chlorite, epidote and amphibole and the felsic phases

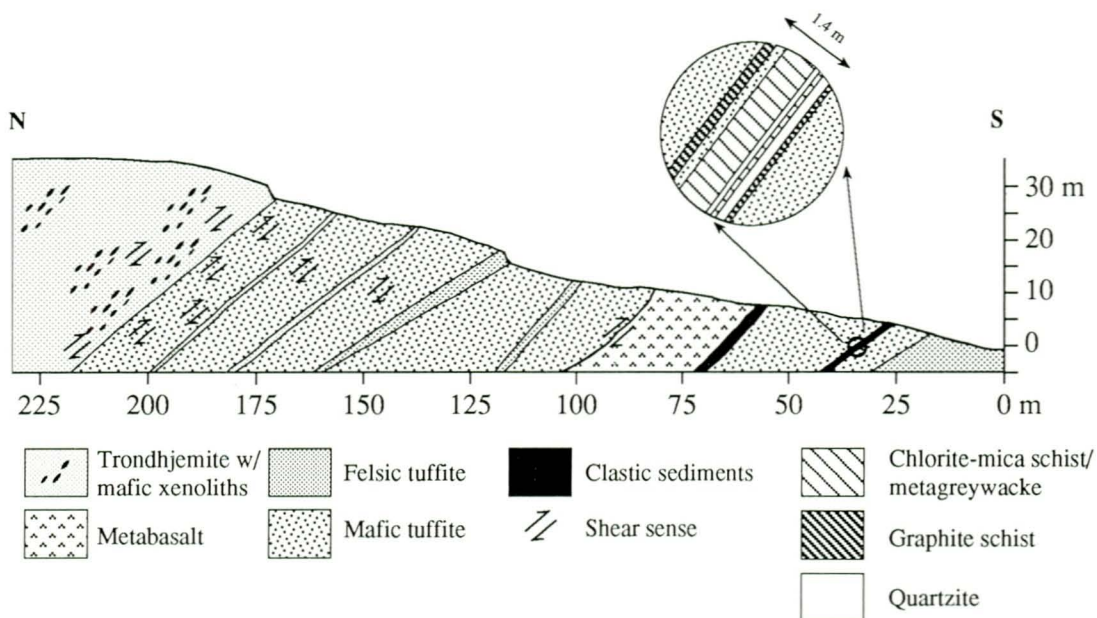


Fig. 7. A stream profile (Storbekken) showing the diversity of tuffites and the contact with the trondhjemitic intrusion. Notice the increased degree of shear deformation towards the contact.



quartz and albite. The tuffites are texturally dominated by a fine-grained quartz-albite matrix together with parallel-oriented phyllosilicates. More or less rounded mm-sized clasts of albite are found in this matrix, probably representing phenocrysts derived from the volcanic rocks which have been abraded during transport.

Intercalated in the tuffites are quartzites, graphitic pelites and more coarse-grained chlorite-mica schists (metagreywacke). These have thicknesses from less than 1 m to more than 25 m. Commonly the graphite schists grade into the mica schists with a corresponding decrease in the content of graphite. Quartz, muscovite and chlorite are the main mineral phases in the sedimentary rocks while biotite, garnet and, in more coarse-grained varieties also albite, are subordinate. Fig.7 shows the typical diversity from felsic to mafic tuffites and intercalations of clastic sediments in Storbekken east of Folldal.

## The Sulåmo Group

A highly deformed conglomerate with clasts of quartzite, greenschist, quartz-albite rock, chlorite-mica schist and marble in a chlorite-amphibole matrix is situated at the contact to the Fundsjø Group. The greenschist and quartz-albite clasts may have been derived from the Fundsjø Group. Graphitic phyllites and mica schists are folded into the conglomerate and a thin horizon of calcite marble occurs at the lower contact. These lithologies constitute the upper part of the Randan Group of Heim (1972). The stratigraphic position and lithologies represented in the clasts makes a correlation with the Sætersjø Conglomerate in the Røros area (Rui 1972) and the Lille Fundsjø Conglomerate in the Meråker area (Wolff 1967) probable. These conglomerates are interpreted to mark a major unconformity between the Fundsjø Group volcanites and the overlying sediments (Hardenby et al. 1981, Grenne & Lagerblad 1985).

## Structures and tectonics

Structures ascribed to two phases of folding

are recognised in the Folldal area in addition to later fractures and fault zones. The most pronounced structure is a penetrative westerly dipping foliation or schistosity affecting all units. The data from the Fundsjø Group are shown in Fig.8 a. There is a general trend of increasing dip of the foliation planes westwards, while the strike is nearly constant. On a micro-scale this structure, here called S1, is due to a parallel alignment of mica and chlorite. Recrystallisation of quartz to elongate grains and an increasing grain size are also important in the development of the foliation.

An earlier foliation or possibly the primary S0-layering is seen to be isoclinally folded, especially on the micro-scale. At the meso-scale, hinge-zones of these folds, which are F1 structures, are isolated and disrupted, showing the S1-foliation to be partly a transposition structure as well as the axial plane foliation. On the mega-scale, structures of this phase are developed as isoclinal and recumbent folds with flat-lying axes trending ENE-WSW. The folds are responsible for a repetition of the different lithologies across strike (Fig.2).

The D2 deformation phase is represented by meso-scale folds (about 0.1-30 m in wavelength) of a more open style, small-scale crenulations and by mineral lineations. F1-folds are also seen refolded by F2 (Fig.6). Crenulations are generally well developed in the incompetent schists and tuffites. D2 fold axis orientations for the Fundsjø and Gula Groups are shown in Fig.8 b. The axes in the Fundsjø Group are quite well concentrated and have a mean plunge of 41° towards 269°. Measurements of axial planes to some of these folds show strikes between 020° and 110° and dips varying between 40° and 75° to the north and northwest. The fold axes and lineations in the Gula Group show a larger spread, but are within the same range as the Fundsjø data.

Other lineations in the Fundsjø Group have the same trend and plunge as the fold axes (Fig.8 b). The lineations are due to recrystallisation of quartz, growth of mica and

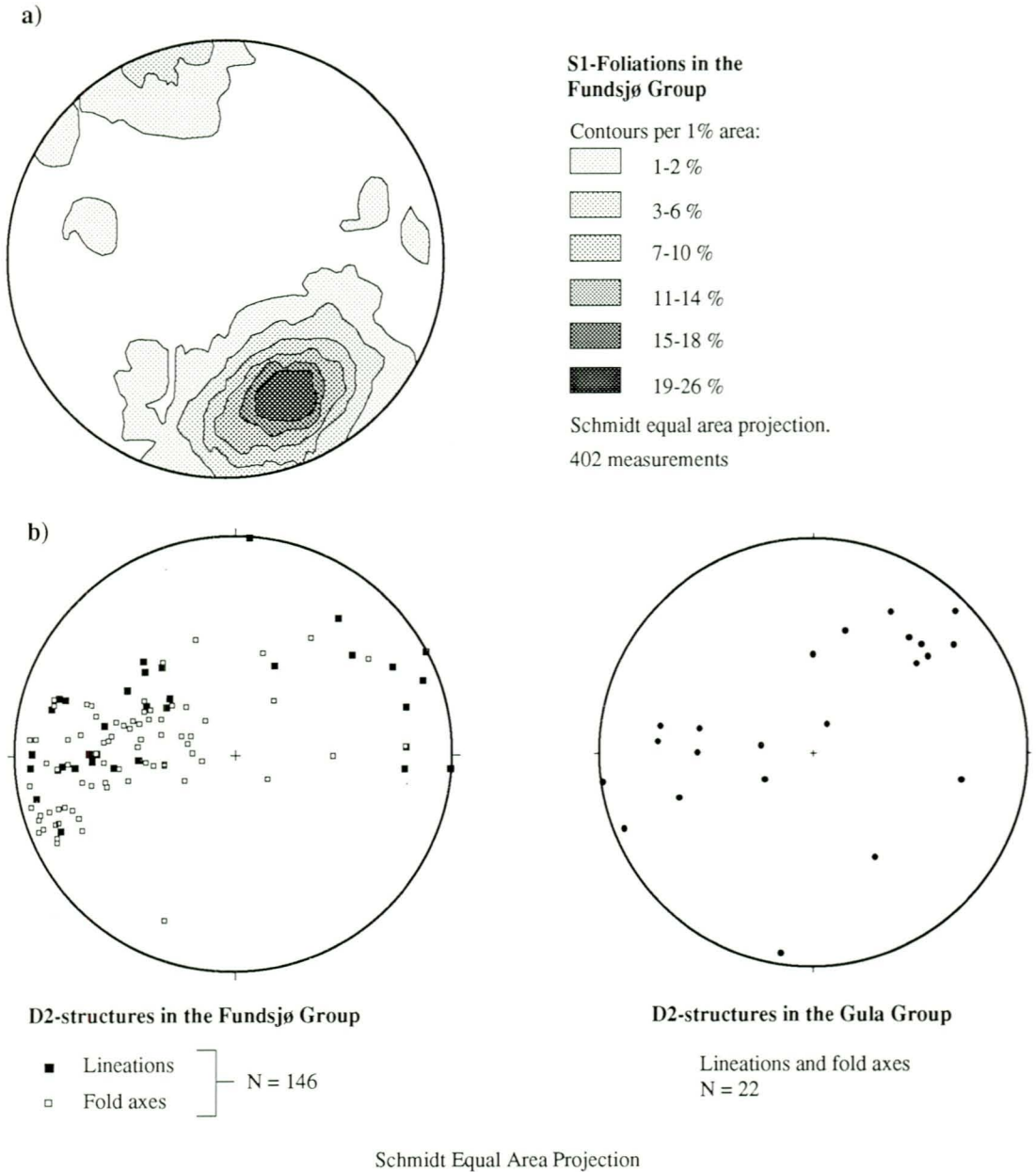


Fig.8. (a) S1-foliations (contoured) of the Fudnsjø Group. (b) F2-folds and lineations of the Fudnsjø and Gula Groups.

especially amphibole parallel to the b-axis of the D2-phase. Growth of garnet was also important and accompanied biotite. These minerals (garnet, biotite and amphibole) represent the highest grade of metamorphism, namely the transition from greenschist to amphibolite facies (see later), and were formed during D2.

The conglomerates of the Åsli Formation in the Husombekken stream section were also affected by this deformation phase as the marble clasts are extremely elongated and ruler-shaped (Fig.3) parallel to the a-axis. The clasts have lengths (X-axes) up to 1 metre and the ratio between the X and Z axes is up to 60 : 1.

Development of mylonitic rocks is mostly restricted to nappe boundaries, but has also occurred internally within units, especially where there is a strong contrast in competence between lithologies. An example is the contact between the Folldal Trondhjemite and the structurally underlying tuffites (Fig.7): within a 50 m zone below the contact, the mafic tuffites are transformed into fine-grained, mylonitic, banded schists. A 12 m-thick layer of felsic tuffite or fine-grained trondhjemite aplite has been transformed into a rock with a texture resembling augengneiss with rounded quartz-feldspar clasts in a chlorite-amphibole-epidote matrix. Lenses or 'fishes' of less deformed material show a top-to-the-SE movement. The deformation can be traced to about 90 m below the contact, where mafic tuffites have been displaced along a reverse fault at the contact to underlying metabasalts, the movement sense shown by lenses / 'fishes' of quartz. The trondhjemite has also been affected by this deformation. Usually it is coarse grained with a very poorly developed foliation, but near this contact it is very schistose and mafic xenoliths are strongly flattened and elongated. This deformation can be traced for at least 40 m into the intrusion.

### *Contact between the Fundsjø and Gula Groups*

The contact between the Gula and Fundsjø Groups is exposed at several localities in the Grimsdalen, Folldal and Savalen areas. In Grimsdalen there is a gradual change over about 50 m from tuffitic chlorite schists belonging to the Fundsjø Group to pelitic graphite-chlorite-mica schists of the Gula Group. This is in contrast to the view of Pedersen (1979) who claimed there to be a tectonic contact on the basis of observations of mylonitic rocks in both groups. In the stream Husombekken in Folldal, the contact is between tuffite and slightly graphitic pelite. The contact is quite sharp, but marked by an increasing content of muscovite and decreasing content of chlorite in the tuffite within a sequence of about 40 cm. Some differential movement in the tuffite is recorded by the presence of rotated clasts of

epidote, 'fishes' of quartz-albite and by a strongly preferred orientation of amphibole.

At Sivilvangen east of Savalen (Fig.1), several intercalations up to 5 m-thick of both chloritic mica schists and dm-banded mafic-felsic tuffites are found up to 150 m into the graphitic pelites of the Gula Group. The contact itself is gradual and thin intercalations of pelites are found at least 15 m into the tuffites of the Fundsjø Group. Both the tuffites and the pelites at the contact consist of extremely fine-grained mylonitic quartz and phyllosilicates. This deformation is traced up to 5 and 25 m away from the contact, respectively. The deformation is also shown by dm-long and cm-thick lenses of psammitic quartz-rich schist in the pelites. The intercalations might possibly be due to small-scale folding or thrusting but may also be relict primary features overprinted by a local development of mylonitic rocks.

About 3 km north of Sivilvangen, a lens of metagabbro occurring about 100 m inside the Fundsjø Group is strongly deformed and more or less transformed to a mylonitic epidote-chlorite schist. This metagabbro is surrounded by tuffites, and the deformation is thought to be a result of a high competency contrast. The contact between the Gula and the Fundsjø Group is found 100 m west of and structurally above this locality, where it seems to record a gradual transition from a felsic, tuffitic, quartz-albite rock of the Fundsjø Group to graphitic pelite of the Gula Group.

McClellan (1993) has described the contact east of Savalen as a ductile shear zone with widespread mylonitisation textures in the rocks of both groups.

### **Metamorphism**

The metabasalts of the Fundsjø Group have a typical prograde mineral assemblage of hornblende + albite + epidote + chlorite + quartz ± calcite ± biotite, while the tuffites have chlorite + albite + quartz + epidote + calcite ± hornblende ± garnet ± muscovite ± biotite. Amphibole and biotite are observed to have formed at the expense of chlorite.

The assemblage of the felsic rocks is albite + quartz + garnet + hornblende ± muscovite ± epidote. These assemblages and especially the coexistence of albite and hornblende, place the metamorphism at the transiti-

on between greenschist and amphibolite facies according to Winkler (1979) and Turner (1981).

Garnets have commonly overgrown the S1-

#### Main elements (wt.%)

##### Mafic rocks

	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO(t)	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	L.O.I	Sum
G7-mg	47.9	0.50	14.6	9.0	0.20	11.8	9.7	1.5	0.59	0.08	3.0	99.0
G8-mg	48.1	0.81	15.7	10.7	0.27	9.1	7.9	3.3	0.19	0.10	3.5	99.6
G1-mb	54.0	0.62	16.0	8.9	0.19	5.3	9.7	2.5	0.56	0.07	1.5	99.3
G2-mb	44.8	0.47	14.4	9.7	0.24	7.0	14.7	2.0	0.13	0.05	6.9	100.3
G3-mb	46.4	0.64	15.2	11.0	0.26	8.0	15.1	0.9	0.22	0.09	1.2	99.1
G4-mb	49.5	0.28	14.2	9.5	0.21	8.9	9.9	2.9	0.08	0.06	4.1	99.6
G5-mb	53.7	0.25	10.9	8.9	0.22	10.5	9.4	1.1	0.00	0.05	4.2	99.2
G6-mb	52.6	0.26	12.6	9.4	0.20	10.1	7.8	3.7	0.41	0.04	2.6	99.8
G9-mb	52.9	0.88	15.7	11.0	0.27	4.8	10.8	1.3	0.01	0.09	1.7	99.5
G10-mb	46.2	1.02	15.6	10.4	0.27	8.9	11.7	2.6	0.20	0.08	2.3	99.3
G11-mb	49.2	1.50	13.8	12.9	0.25	6.9	11.5	2.0	0.15	0.12	1.0	99.3
G12-mb	53.1	0.79	15.9	12.3	0.24	5.6	5.5	5.3	0.15	0.08	0.9	99.7
G14-mb	49.0	0.74	14.8	9.2	0.23	6.4	13.8	1.9	0.05	0.11	2.9	99.2

##### Felsic rocks

D1-trh	77.3	0.17	12.0	3.1	0.14	0.3	1.9	4.0	0.66	0.05	0.3	99.8
D5-trh	75.5	0.21	12.0	3.5	0.11	0.6	2.2	3.7	0.62	0.07	0.4	98.9
D6-trh	74.5	0.20	12.5	2.7	0.09	0.5	2.0	4.9	0.22	0.05	0.4	98.2
D7-trh	74.8	0.16	12.7	2.5	0.10	0.5	1.1	4.5	0.78	0.05	0.6	97.8
46-92-trh	74.7	0.27	12.5	2.9	0.04	0.6	2.7	4.9	0.31	0.06	0.4	99.2
D3-rh	80.7	0.22	10.5	1.6	0.09	0.3	2.3	3.6	0.13	0.06	0.3	99.8
D4-rh	76.5	0.19	12.6	2.5	0.10	0.4	1.7	3.5	1.28	0.06	0.7	99.4
2462-rh	78.4	0.21	12.1	2.1	0.09	0.3	0.9	5.0	0.28	0.07	0.4	99.9

#### Trace elements (ppm)

##### Mafic rocks

	Mo	Nb	Zr	Y	Sr	Rb	Pb	Cu	Zn	Cr	Co	Ni
G7-mg	13	4	40	11	177	11	0	0	61	690	57	194
G8-mg	12	4	58	23	133	5	6	0	56	372	51	152
G1-mb	14	3	41	19	128	12	0	6	60	300	38	58
G2-mb	14	3	43	16	109	5	2	54	78	463	42	117
G3-mb	16	3	53	18	69	6	1	9	78	609	64	170
G4-mb	14	4	44	11	47	3	1	31	74	634	80	109
G5-mb	15	3	40	7	83	2	1	30	67	1419	60	295
G6-mb	12	5	46	5	41	8	1	12	81	1315	88	277
G9-mb	14	4	54	25	111	3	2	197	70	73	50	18
G10-mb	14	3	45	30	324	4	18	0	54	358	58	125
G11-mb	13	4	70	45	246	4	0	0	49	131	62	63
G12-mb	15	3	52	23	70	2	1	11	92	44	32	15
G14-mb	14	3	31	20	318	3	9	0	58	298	44	105

##### Felsic rocks

D1-trh	11	6	93	35	70	17	4	0	62	99	3	2
D5-trh	11	6	102	45	96	7	1	0	18	80	3	4
D6-trh	7	5	168	74	135	6	4	0	22	100	12	3
D7-trh	10	6	113	27	79	18	6	0	25	93	1	3
46-92-trh	1	3	69	29	125	9	8	2	14	126	5	6
D3-rh	13	5	64	24	155	4	3	0	29	86	2	1
D4-rh	7	7	186	53	69	14	9	0	56	82	2	4
2462-rh	8	7	133	63	73	9	11	0	34	97	9	2

Table 2. XRF analyses of mafic and felsic rocks in the Follidal area. mg - metagabbro; mb - metabasalt; trh - trondhjemite; rh - rhyodacite. Sample G9 - mb represents the dyke complex, samples G11, G12 and G14 - mb are from the basalts intercalated in the trondhjemite. Analyses have been done at University of Oslo.

foliation as defined by inclusions of epidote, chlorite and quartz. The parallel alignment of amphiboles and simultaneous growth of biotite and garnet in F2-folds suggest that the peak of metamorphism was reached during this phase. Some later retrogression is shown by local chloritisation of the amphibole.

In the Åsli Formation of the Gula Group, the typical prograde paragenesis is quartz + muscovite + biotite + chlorite ± albite ± garnet. This is a typical assemblage of the upper part of the greenschist facies, according to Winkler (1979) and shows that there was no apparent difference in metamorphic grade between the upper part of the Gula and the Fundsjø Groups. The metamorphic grade increases westwards and stratigraphically lower in the Gula Group, as shown by the appearance of kyanite and staurolite, as well as andesine in the Singås Formation (Heim 1972, Pedersen 1979).

## Geochemistry of igneous rocks

The geochemical compositions of both felsic and mafic igneous rocks in the Fundsjø Group (Table 2) show a clear chemical bimodality. The highest value of SiO<sub>2</sub> in the metabasalts is 54 wt.% (average 50.2 %), while the lowest in the felsic rocks is 74.5 % (average is 76.8 %).

### Mafic rocks

Most samples of greenstones analysed, including two metagabbros, are from the thick unit in the Bukletten area (Fig.2), one sample is from the dyke complex and three from the horizons intercalated in the trondhjemite. Based on CIPW-norm calculations (not shown) the rocks are classified as olivine-tholeiites to quartz-tholeiites. Half of the samples from Follidal have a loss-of-ignition (L.O.I.) of more than 2.5 % and should be considered as altered (Le Bas et al. 1986). By comparison with MORB and low-K tho-

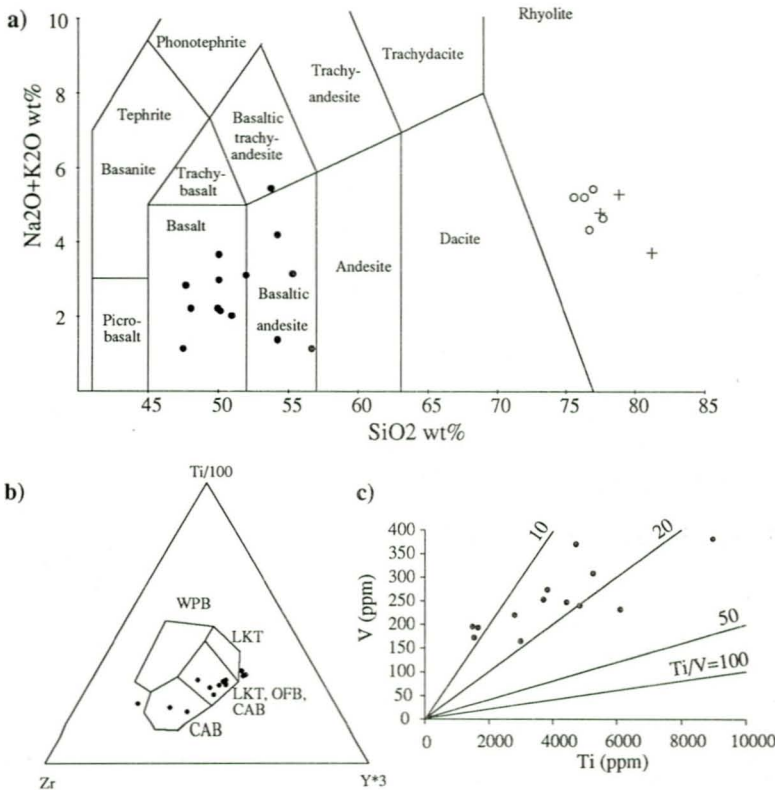


Fig.9 (a) Classification of the volcanic rocks in Follidal from the Fundsjø Group by the total alkalis vs. SiO<sub>2</sub> diagram (after Le Bas et al.1986). Filled circles - metabasalt; open circles - trondhjemite; crosses - rhyodacite. (b) The metabasalts plotted in the Ti-Zr-Y discriminant diagram of Pearce & Cann (1973). (c) The metabasalts plotted in the Ti-V discriminant diagram of Shervais (1982).

	Metabasalt	Metagabbro	Trondhjemite	Extrusive	N-MORB	LKT	IAG
	Folldal <sup>1</sup>	Folldal	Folldal	rocks Folldal		SW Pacific	Shichito R.
SiO <sub>2</sub>	50.2 (3.2)	47.9-48.1	74.5-77.3	76.6-80.7	50.45	50.73	70.0-74.6
TiO <sub>2</sub>	0.7 (0.4)	0.5-0.8	0.15-0.21	0.19-0.22	1.62	0.83	0.25-0.58
Al <sub>2</sub> O <sub>3</sub>	14.5 (1.5)	14.6-15.7	12.0-12.7	10.5-12.6	15.26	17.38	12.9-13.7
FeO(t)	10.3 (1.3)	9.0-10.7	2.5-3.5	1.6-2.5	10.43	9.38	1.8-3.7
MnO	0.23 (0.0.3)	0.2-0.3	0.09-0.14	0.09-0.10	-	0.19	0.10-0.18
MgO	7.5 (1.9)	9.1-11.8	0.3-0.6	0.3-0.4	7.58	6.97	0.4-1.0
CaO	10.9 (2.8)	7.9-9.7	1.1-2.2	0.9-2.3	11.30	11.51	1.3-3.0
Na <sub>2</sub> O	2.4 (1.2)	1.5-3.3	3.7-4.9	3.5-5.0	2.68	2.06	4.6-5.5
K <sub>2</sub> O	0.2 (0.2)	0.2-0.6	0.2-0.8	0.1-1.3	0.11	0.26	0.9-1.3
P <sub>2</sub> O <sub>5</sub>	0.08 (0.02)	0.1	0.05-0.07	0.06-0.07	-	0.09	0.04-0.13
L.O.I	2.7 (1.7)	3.0-3.5	0.3-0.6	0.3-0.7	-	-	-
Mo	14 (1)	12-13	7-11	7-13	-	-	-
Nb	4 (0.5)	4	5-6	5-7	3.5	1.7	-
Zr	47 (10)	40-58	93-168	64-186	104	30.8	171-253
Y	20 (11)	11-23	27-74	24-63	36	15.8	47-63
Sr	140 (100)	133-177	70-135	69-155	113	224	45-176
Rb	4 (3)	5-11	6-18	4-14	1.26	4.1	10.6-20
Pb	3 (5)	0-5.6	1-6	3-11	0.49	4.0	3-4
Zn	69 (12)	56-61	18-62	29-56	-	78.2	57-88
Cr	513 (444)	372-690	80-100	82-97	251	82.4	0
Co	56 (17)	51-57	1-12	2-9	47	35.7	3-38
Ni	122 (88)	152-194	2-4	1-4	150	35.5	0-7
V	258 (66)	165-239	6-13	6-9	-	286	0-14
K/Rb	293	296 - 441	314 - 714	250 - 755	700	526	498-666
Ti/V	15.0	18.2-20.3	-	-	28-35 <sup>2</sup>	17.4	-
Sr/Zr	3.2	2.3-4.4	-	-	1.09	7.3	-
Rb/Sr	0.053	0.040-0.063	0.043-0.248	0.027-0.203	0.011	0.018	0.065-0.400
K <sub>2</sub> O/Na <sub>2</sub> O	-	-	0.045 - 0.171	0.036-0.371	-	-	0.169-0.281
Rb/Zr	-	-	0.034-0.186	0.066-0.076	-	-	0.059-0.103
Number of Analyses	11	2	4	3	26	43	4

Table 3. Geochemistry of the intrusive and volcanic rocks in Folldal. Values of MORB (Hofmann 1988), Low-K Tholeiite (LKT) (Ewart 1982) and Island Arc Granite (IAG) (Ikeda & Yuasa 1989) are shown for comparison. <sup>1</sup>Standard deviations in brackets. <sup>2</sup>Ti/V from Hawkins et al. 1990.

leites (Table 3), the Folldal greenstones have normal Na<sub>2</sub>O and Sr contents while CaO is lower than both MORB and LKT, suggesting some alteration, probably by interaction with sea water (spilitisation). This is probably also one reason why in the total alkali - silica diagram (Fig.9 a) the mafic rocks spread out in the fields of basalt and basaltic andesite. The close association and similarity in geochemistry between the metagabbros and the basalts (Tables 2 and 3) suggest that they belong to the same magmatic system, with the gabbros as the intrusive equivalents of the basalts.

The Folldal metabasalts are enriched in K and Rb and depleted in P, Zr, Y and Ti compared to MORB (Fig.10 a). A similar pattern was also found in Grimsdalen from drillcore

samples by Skyseth & Reitan (1992). This pattern is typical of low-K tholeiites from island arcs (IAT) and shows similarities to average SW Pacific IAT (Ewart 1982) with respect to Zr, Ti and Y. The lower values of Sr, K and Rb might be due to alteration, as discussed above. One important exception is the extremely high values of Ni and Cr (respectively, 1.5 and 3 times as high as IAT). These values suggest an influence from a primitive source (discussed below). Compared to the Folldal data, basalts from destructive margins near continents, such as the western part of America, are highly enriched in Nb, P, Zr, Y and Ti compared to MORB (Ewart 1982).

In the Ti-Zr-Y diagram (Pearce & Cann 1973, Fig.9 b), the rocks plot as CAB, LKT

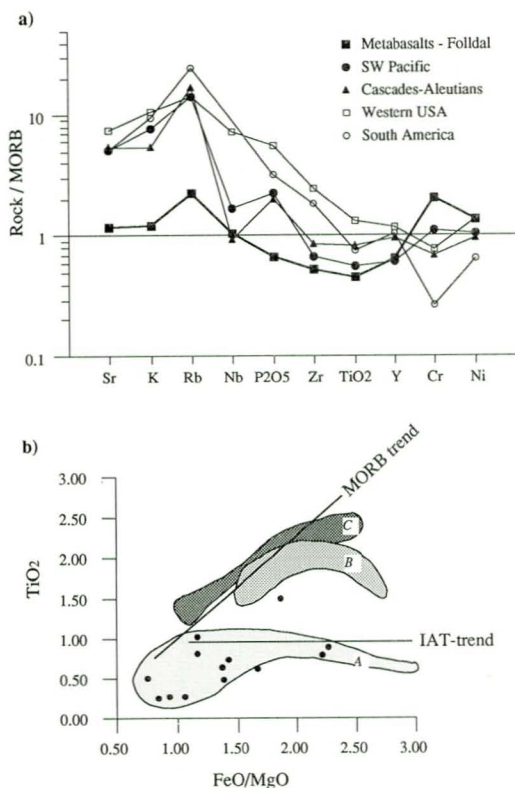


Fig.10 (a) Average of the Folldal greenstones (13 analyses) normalised to MORB (MORB-data from Pearce 1983). Data from active continental margins and island arcs are shown for comparison (data from Ewart 1982). (b)  $TiO_2$  vs.  $FeO/MgO$  trend diagram for the 13 Folldal samples. Domains of basalt types (A, B, C) distinguished by Grenne (1988) from the Røros Area are shown for comparison.

and OFB, while in the Ti-V diagram (Shervais 1982, Fig.9 c) most samples plot above the line  $Ti/V = 20$ , which is typical of IAT or small scale back-arc basins (op.cit.). Regarding the ratio  $K/Rb$  the Folldal basalts are quite similar to IAT (Table 3), while the  $Sr/Zr$  ratios is lower than that of IAT. The latter may be the result of Sr loss during alteration. Similarly, in the  $TiO_2$  vs.  $FeO(t)/MgO$  differentiation diagram, the Folldal samples follow an IAT trend (Fig.10 b).

**Felsic rocks**

As shown in Table 2, there is a striking similarity in chemistry between the Folldal trondhjemite and the extrusive rocks. This is further supported in the total alkali - silica diagram, both plotting as rhyodacites (Fig.9 a). In an or-ab-an diagram (Fig.11) all the Folldal samples plot as trondhjemites. Based

on the geochemistry and field relationships as described above it seems reasonable to interpret the trondhjemite as a subvolcanic intrusion related to the extrusive rocks.

The high content of  $Na_2O$  ( $> 4\%$ ) in the felsic rocks suggests alteration by spilitic or hydrothermal processes, though the alteration has probably not been pervasive. Compared to both trondhjemites from modern island arcs (Table 3) and the presumably unaltered post-tectonic trondhjemite from near Støren (see Size 1979), the sodium content is similar.

The bimodal volcanism in the Fundsjø Group is a typical feature of both arc and back-arc environments. Compared to felsic rocks of an arc back-arc setting (Gill & Stork 1979, Ikeda & Yuasa 1989, Fryer et al. 1990, see Table 3 for a comparison with island arc granite from Izu-Bonin arc), the Folldal Trondhjemite and extrusive equivalents are similar with respect to most main and trace elements. Most characteristic is a low content of  $Al_2O_3$  and  $TiO_2$ , as well as a high  $K/Rb$ -ratio; but as in the metabasalts, the content of Cr is anomalously high compared to felsic rocks in an arc setting (80-100 ppm compared to  $< 10$  ppm, op.cit.).

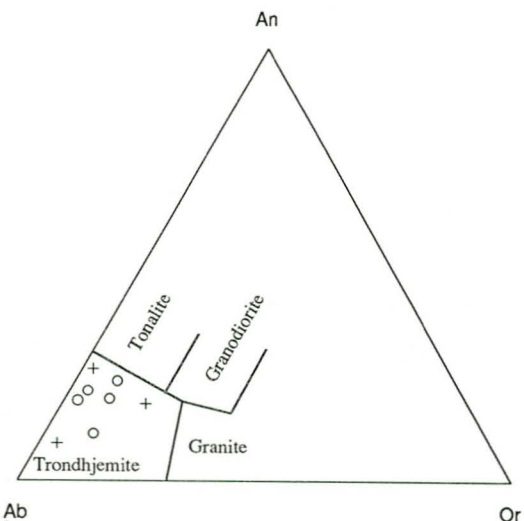


Fig.11. Classification of the felsic rocks in Folldal according to the Or-Ab-An diagram of Barker (1979). Open circles - trondhjemite; crosses - rhyodacite.

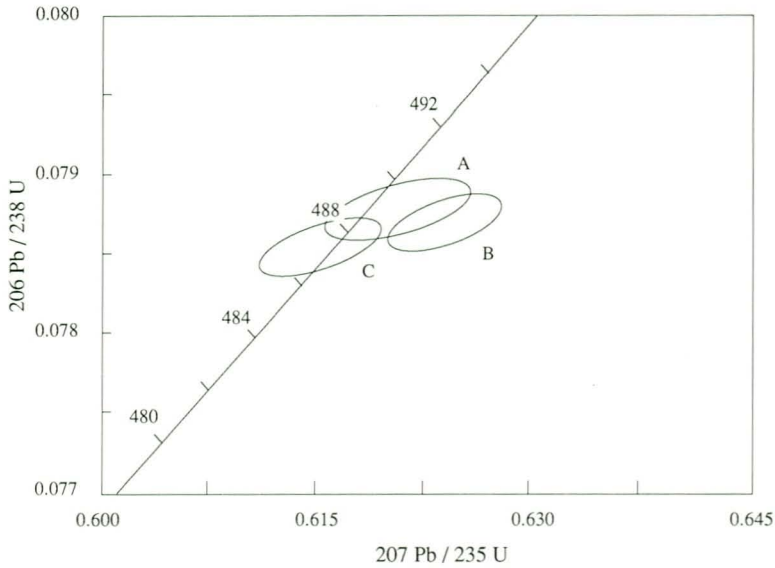


Fig.12. Concordia diagram for the analysed zircons from the Folldal Trondhjemite: Three fractions of fair quality zircon were analysed from one sample. The best estimate for the age of the trondhjemite can be estimated to be  $488 \pm 2$  Ma based on zircon fractions A and C which intersect concordia and each other. Fraction B is slightly discordant, which is probably a result of analytical problems. The amount of zircon in this sample was very small and therefore the amount of Pb analysed was quite small.

## Age of the Folldal Trondhjemite

Four samples of trondhjemite and two samples of metarhyodacite, each around 30 kg in weight, were collected. The samples were crushed to 125-250 mesh in a sling mill and the heavy minerals collected with a 'Goldhound' (used for gold prospecting and easy to clean). A Frantz magnetic separator was used to remove magnetic minerals. The remaining concentrates (a few grams) were sent to the Geochronology Division at the Geological Survey of Canada. Clear zircons were picked out and analysed following the method outlined in Parrish et al. (1987). U and Pb blanks were approximately 1 and 15 picograms, respectively.

Only one of the samples of trondhjemite contained enough zircons of fair quality to provide an age (sample locality marked by the asterisk in Fig.2). The result is shown in Fig.12. As can be seen, two of the three fractions intersect the concordia and the age is calculated to  $488 \pm 2$  Ma.

## Discussion

### *Origin of the volcanites*

The volcanic rocks in Folldal have most likely been formed in an island arc setting, as discussed above. This is in agreement with

work in the Røros-Meråker part of the Fundsjø Group: Grenne & Lagerblad (1985) and Grenne (1988) distinguished between two types of basalt, one type with a typical IAT-signature (low  $TiO_2$ , Zr and high Rb) and the other with similarities to MORB. As seen in Fig.10 b the Folldal samples are similar to type A of Grenne (1988), which display an IAT trend. In the Røros and Meråker areas, some samples intermediate between the two have also been found, as well as transitional calc-alkaline to within-plate type metabasalts (Grenne 1988). Based on this, Grenne & Lagerblad (1985) concluded that the metabasalts represented immature arc to arc rifting volcanism, while Grenne (1988) claimed a possible opening of a marginal basin above a mature subduction zone.

The Folldal basalts have anomalously high content of Ni and Cr. The contents of these elements are also high in the Fundsjø Group metabasalts in the Røros-Meråker area (Grenne & Lagerblad 1985, Grenne 1988), showing it to be a regional feature. High values of these elements are also known from some of the Stekenjokk volcanites in the Stikke and Gelvenåkkø Nappes in northern Jämtland in Sweden (Stephens 1982) and the Gjersvik Group volcanites in the Gjersvik Nappe north of the Grong-Olden Culmination (Lutro 1979). Both these units have been correlated with the Fundsjø



Group (Stephens & Gee 1985). These anomalies suggest an influence from a primitive source. In fact, two of the samples from Folldal might be classified as boninites, with  $Mg/Mg+Fe^{2+} \geq 0.6$  and  $SiO_2 \geq 53$  wt.% (Crawford et al. 1989). In this regard it is interesting that boninites have recently been reported from the nearby Einunnfjell-Savalen area (McClellan 1993). Boninites are either among the first melt products in a primitive island arc (Hawkins et al. 1984), or formed at a later stage because of subduction of an active spreading ridge (Crawford et al. 1989), in both cases by partial melting of the mantle wedge above the subducted slab. Boninitic melts are known to be very rich in elements such as Cr and Ni (Ni = 70-450 ppm, Cr = 200-1800 ppm, Hawkins et al. 1984) and the two samples from Folldal have 277 and 295 ppm Ni and 1315 and 1419 ppm Cr, respectively.

In the Røros-Meråker area volcanites with both IAT and MORB characteristics are found, while only IAT volcanic rocks have been found in the Folldal area. Two possible explanations for this are: 1) MORB volcanites might be present also in Folldal, but not detected because of too few samples; or 2) there is a development from arc to rifted arc/back-arc northwards, the samples with IAT signature in the Røros-Meråker area representing disruption of the arc, as envisaged by Grenne (1988). A higher content of  $Na_2O$  in the northern part of the group might support the latter interpretation because a higher degree of spilitisation might be suspected in a rifting environment because of increased water depth and increased heat flow.

Two possibilities exist for the origin of the trondhjemite and associated volcanic rocks (see Barker 1979 for review): 1) partial melting of the downgoing slab; or 2) fractional crystallisation from the basaltic magma. Based on field observations and experimental studies, trondhjemitic melts have been shown to be generated by partial melting of amphibolites (Drummond & Defant 1990). Furthermore, the volume of felsic rocks in Folldal is around 30 % and in Meråker about 50 % (Grenne & Lagerblad 1985), if in both

cases the felsic intrusive rocks are included. This is far too much to be generated by fractional crystallisation from a mafic magma. As seen in Table 2, the felsic volcanites generally have a slightly higher content of incompatible elements, and especially LIL elements like Rb, K and Zr, compared to the basalts, but also values as low as the average for the basalts. The increase is generally too little to conclude that the felsic rocks have differentiated from the mafic magma. One would also expect to find intermediate compositions. On this basis, the mafic and felsic rocks seem to have different origins. A possibility is that the felsics have formed by partial melting from the downgoing slab and the mafics from the mantle above the slab.

### *Relationship between the Gula and Fundsjø Groups*

The contact between the Gula and Fundsjø Groups has been variously described as of either primary or tectonic origin. A tectonic contact has been reported from the Dombås-Grimsdalen area (Guezou 1978, Pedersen 1979), the area east of Savalen (McClellan 1993) and in Tydal north of the Røros area (Horne 1979). In contrast, Rui (1972) and Rui & Bakke (1975) found no evidence for a tectonic contact between the units in the Røros area and claimed a conformable contact (see below), a conclusion also reached by Fox from work near the Hersjø deposit (Fox et al. 1988).

In the Meråker area, a unit is distinguished, the Gudå Formation (Wolff 1973) or Gudå Group (Lagerblad (1983), containing both greenstones and graphitic schists with conglomerates and marble. The conglomerates usually contain quartzitic and calcareous pebbles in a mafic matrix and are thus similar to the Husom Conglomerate in Folldal (Heim 1972 and this work). Based on tectonostratigraphic position and lithologies the unit is correlated with the similar 'heterogeneous banded sequence' of Rui (1972) in the Røros area (Lagerblad 1983). According to Nilsen (1978) this sequence belongs to the Åsli Formation. Rui (1972) considered this unit as transitional between the Gula and the Fundsjø Groups. In the Meråker

area the contact between the Gudå Formation and the Fundsjø Group is similarly described as transitional, with decreasing amounts and thicknesses of sedimentary layers eastwards into the Fundsjø Group (Wolff 1973). This corresponds to what we have observed in the Savalen and Grimsdalen areas (this work).

Further north, in northern Jämtland, the Remdalen Group in the Stikke Nappe structurally overlies the Stekenjokk volcanites with a conformable contact (Stephens 1982). The structural base of this group consists of quartzitic conglomerate and limestone in quartz-graphite phyllite followed by a succession of quartz-graphite phyllites and greenschists (Remdalen Greenschist) together with quartz porphyry and limestone and uppermost, calcareous quartz-graphite phyllites. The whole stratigraphic succession is probably inverted as in the Trondheim Region (op.cit.). The association of conglomerate and limestone is then in the same stratigraphic position and is very similar to the upper part of the Gula Group. The occurrence of transitional units with intercalations of greenstones or tuffites between the Gula and Fundsjø Groups in the Savalen, Røros and Meråker areas suggests a close relationship between the units. The development of mylonitic rocks seen at some localities might be due to mechanisms other than large-scale thrusting (cf. the contact between the trondhjemite and tuffites in the Folldal area, described above).

The clasts in the conglomerates in the Åsli Formation are from several sources. Clasts of marble and quartzite are always dominating and are derived from nearby lithologies in the Gula Group. Igneous clasts have been recognised in Folldal (Heim 1972, see above) and also in the Tynset-Røros areas (Færden 1949, Ellevold 1976). These conglomerates are overlain by sediments, mostly graphitic pelites of considerable thickness (up to 500 m), making perhaps the volcanites in the Gula Group (the Gula Greenstone) the most probable source for these clasts. In contrast, the conglomerates and associated tuffites and greenstones of the

Gudå Formation (see above) in the Tynset-Meråker area are found close to the Gula-Fundsjø contact. In this case the clastic material might have been partly derived from the growing arc and partly from the Gula rocks.

The fossil locality at Nordaunevoll with the graptolite *Dictyonema flabelliforme sociale* first described by Vogt (1889) is situated very close to the Fundsjø Group (Rui 1972) in the Åsli Formation. The host rock is a very conspicuous V, U and Mo-rich graphite phyllite (Gee 1981). The age of the graptolite is Tremadocian, that is to say 488-505 Ma (Harland et al. 1989). The trondhjemite in Folldal, intruding slightly older basalts, is dated to  $488 \pm 2$  Ma (p.68), which indicates a continuous stratigraphic sequence from at least the Åsli Formation and upwards through the Fundsjø Group. A corresponding relationship appears to exist in the Stekenjokk area in Jämtland, where similar U- and Mo-rich graphite phyllites (but not containing fossils) are intercalated in the greenstones (Stephens 1982) and an age of  $492 \pm 1$  Ma has been obtained from a trondhjemite (Claesson et al. 1987).

Stephens et al. (1993) were able to date (U-Pb zircon) a trondhjemite clast in a conglomerate from Storfjället to  $489 +10/-5$  Ma and a trondhjemite from Gjersvik to  $483 +5/-3$  Ma, both in the Köli Nappes of the Upper Allochthon and probably correlatives of the Fundsjø Group (see above). These rocks are within error margins identical in age to the Folldal trondhjemite. The authors (op.cit.) use these ages to indicate that the terrane containing these trondhjemites was considerably separated from Baltica at that time. This is probably not true (see discussion below).

A high content of Cr is typical of the Fundsjø metabasalts, both in Folldal and partly at both Røros and Meråker (see above). According to data by Ellevold (1976) the phyllites in the Åsli Formation also have high contents of Cr and which seem to decrease away from the contact. This might be interpreted as a decreasing influence from the volcanic rocks which may have

been the source. A similar feature also seems to be displayed by Sc and Co (op.cit.). The regional extent of the conglomerates in the Åsli Formation indicates a major uplift event of the Gula rocks. This might have happened during a phase of compression in connection with the development of a subduction zone leading at last to formation of the arc-related Fundsjø Group. The marble horizons indicate shallow-marine conditions. Such conditions are also indicated by the black schists in the upper part of the Åsli Formation, which contain the platformal graptolite *Dictyonema* at one locality.

### *Correlations with Gudbrandsdalen*

Recently, the greenstones in the Otta-Dombås area have been identified to represent an ophiolite complex, the Vågåmo Ophiolite (Sturt et al. 1991). These greenstones have an N-MORB signature and have been interpreted to represent either the ancient crust of Iapetus or oceanic crust from a marginal basin (op.cit.). The ophiolite has a thrust boundary to the underlying sediments of the Heidal Series (Sturt et al. 1991). The Heidal Series comprises mostly quartzitic schists and garnet-mica schists and may be correlated with the Aursund Group (Table 1, Fig.1). Both the ophiolite and the Heidal Series are overlain unconformably by the Sel Series, which generally commences with conglomerates (op.cit.). These conglomerates vary laterally but generally contain clasts derived from the ophiolite as well as from the Heidal Series. Fossils in this conglomerate give an Early Llanvirn age ( $\approx 470$  Ma). The relationship between the Heidal Series, Vågåmo Ophiolite and Sel Series demonstrates a probable Early Ordovician obduction of the ophiolite onto the Fennoscandian Shield (op.cit., Sturt & Roberts 1991).

Recent mapping by Sturt & Ramsay in Grimsdalen shows that the major unconformity which oversteps the Vågåmo Ophiolite onto the subjacent Heidal Group (Sturt et al. 1991), passes stratigraphically beneath the Fundsjø Group volcanites. This precludes a correlation of these volcanites with the

Vågåmo Ophiolite (B. Sturt, pers. comm.1993). Even so, the Otta conglomerates can be compared with conglomerates in the Sulåmo Group (see above), since both are polymict and contain clasts derived from the underlying volcanites. These relationships and correlations point to a similar obduction and post-obduction history of the Vågåmo ophiolite and the 'Fundsjø arc'.

### *Ensimatic vs. ensialic arc*

Closely tied to the question of the connection between the Gula and Fundsjø Groups is whether the arc/back-arc system developed in an ensimatic or an ensialic setting. An ensimatic setting has been proposed by Grenne & Lagerblad (1985) and Grenne (1988). This is also in accordance with what has been suggested for the Middle Köli and Gjersvik volcanic rocks (e.g. Stephens & Gee 1989). Indeed, the widespread occurrence of low-K tholeiites in the Follidal, Grimsdalen and Røros-Meråker areas (see above) is in favour of an ensimatic setting for the volcanites. In ensialic environments such rocks are rare (see for instance the compilation by Thorpe 1982) and confined to the oceanic side of the arc (Baker 1982). The Tonga-Kermadec-New Zealand arc system shows that with increasing influence of continental crust, the magmas change from low-K tholeiites to calc-alkaline basalts (Ewart 1982). Further, the low content of incompatible elements in the felsic rocks also supports an ensimatic setting. The compilation by Ewart (1979) indicates that low-K rhyolites are restricted to ensimatic arcs.

On the other hand, as Grenne (1988) proposed, the presence of quartzites and quartzofeldspathic wackes intimately related to the volcanites supports a near-continent origin of the arc. This is also supported by lead isotopes, which indicate a continental component in the massive sulphides in the Fundsjø Group (Bjørlykke et al. 1993 and unpublished data from Follidal).

The contact between the upper part of the Gula Group and the Fundsjø Group in the Follidal area seems to be primary and in places gradual (see above), implying that the

arc must have formed above the Gula Group. One possible (and probable?) answer to the ensimatic signature of the arc is that it may overlie only the outer and platform Åsli Formation of the Gula Group. The thickness of this unit is only a few hundred metres at the most, which might be too thin to influence the trace-element composition of the volcanic rocks. Because of the generally much higher content of Pb in sediments than in volcanites, lead isotopes are very sensitive to any influence from sediments (Hawkesworth 1982). This might explain why the lead isotopes of the sulphides give an ensimatic signature, in opposition to the trace elements.

Of fundamental importance in this context is the status of the central part of the Gula Group and the nature of the Åsli-Singsås contact. The Singsås Formation consists mostly of outer marginal sediments such as turbidites, but of importance are also greenstones and associated chert (Gula Greenstone, Nilsen 1978). The greenstones have formed in an oceanic environment (Nilsen 1974), and pillow lavas have been identified near Savalen (Rui 1977). The massive sulphide deposits at Fløttum and Bukkhammer are very low in radiogenic lead (206/204 Pb of 17.909 and 17.806, respectively, Bjørlykke et al. 1993), supporting the ensimatic character of the volcanic rocks.

The Singsås Formation has been metamorphosed partly to upper amphibolite facies and contains migmatitic gneisses in the Meråker area (Wolff 1979). A possible syn-tectonic trondhjemitic intrusion in this formation at Vakkerlien has been dated by the U-Pb method on zircons to 509  $\pm$  5/-4 Ma (Klingspor & Gee, referred to in Stephens et al. 1985). The trondhjemite is cross-cutting a nickeliferous metagabbro (Boyd & Nixon 1985) possibly comagmatic with the Gula Greenstones (Nilsen 1974), thus providing a minimum age for the unit. The age fits very well with the metamorphic Sm/Nd age of 505  $\pm$  18 Ma of the Seve eclogites (Mørk et al. 1988). Thus, it is possible that the Seve and Gula units have been involved in the same tectonic event around 505 Ma.

Because of the marked difference in metamorphic grade between the Singsås and Åsli Formations, the age difference between these formations and the close relationship between the Åsli Formation and the Fundsjø Group, the Singsås-Åsli contact must be either a primary unconformity or a thrust contact.

As discussed above, the Gjersvik and Fundsjø volcanites are likely correlatives. Stephens et al. (1993) used ages from Gjersvik to indicate a considerable distance between Baltica and the Gjersvik Terrane (see above). This is negated by the Gula-Fundsjø stratigraphy and particularly by the continental Pb-isotope signatures of the massive sulphide deposits in the Fundsjø Group.

Fieldwork, geochemistry and dating in the Folldal area have shown that there is probably a continuous stratigraphy from at least the upper part of the Gula Group and upwards through the Fundsjø Group. This means that the nappe contact between the Meråker and Gula Nappes in this area either does not exist or that the contact is further to the west, i.e. between the Åsli and Singsås Formations. More work, such as more dating of obvious pre-tectonic igneous rocks in the Singsås Formation and detailed fieldwork along the Åsli-Singsås contact is needed to answer these questions.

## Summary and concluding remarks

1. The bimodal character, large volume of volcanoclastic rocks and geochemistry of the Fundsjø Group volcanites favour their formation in an island arc setting. Intercalations of continental sediments in the volcanites and the lead isotopes of the massive sulphides show that the arc must have formed close to a continent.
2. Based on field relationships, mineralogy and geochemistry, the Folldal Trondhjemite and felsic extrusive rocks are interpreted to be comagmatic.
3. The large volume of felsic volcanites and

trondhjemites in the Fundsjø Group and their trace element chemistry show that they cannot have been derived from the same magma as the mafic rocks. A possibility is that the felsic rocks have been formed by partial melting from the downgoing slab and the mafic rocks from the mantle wedge above the slab.

4. There are no differences between the Fundsjø Group and the upper part of the Gula Group regarding degree of metamorphism or structures. The contact between the Fundsjø Group and the Åsli Formation of the Gula Group has been observed to be partially gradational and is interpreted to be primary.

5. Age determination and palaeontological data are in accordance with a primary upper Gula-Fundsjø contact: the Dictyonema schist in the upper part of the Gula Group is Tremadocian in age (488-505 Ma), while the age of the Folldal Trondhjemite intruding slightly older basalts is  $488 \pm 2$  Ma (U-Pb on zircons).

6. The lower or central part of the Gula Group, the Singsås Formation, consists of outer shelf-marginal sediments and minor greenstones with MORB character. A cross-cutting, probably syntectonic trondhjemite has been dated to  $509 \pm 5/-4$  Ma, comparable to the metamorphic age of  $505 \pm 18$  Ma for the Seve eclogites in northern Sweden, and is considered to provide at least a tectonic and metamorphic link between the Seve Nappes and the lower part of the Gula Group.

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