Geochemistry and petrogenesis of trondhjemites and granodiorite from Gauldalen, Central Norwegian Caledonides

BART PANNEMANS & DAVID ROBERTS

Pannemans, B. & Roberts, D. 2000: Geochemistry and petrogenesis of trondhjemites and granodiorite from Gauldalen, Central Norwegian Caledonides. *Norges geologiske undersøkelse Bulletin 437*, 43-56.

In the Gauldalen district of Central Norway, three varieties of trondhjemite cutting rocks of the Gula Complex have been distinguished on the basis of nuances of colour and field relationships.The high Al_2O_3, Rb and Sr, and low Yb contents of all three types of trondhjemite signify their generation in a continental margin palaeotectonic setting. They are considered to have formed as melting products of a garnet-bearing amphibolite. Less common, spessartine-garnet granodiorites in this same area are calc-alkaline and peraluminous, and may have derived from an Al-rich sedimentary source. Field relations denote that greenish-white trondhjemite dykes and sheets are the oldest intrusions. One of these dykes has provided a Rb-Sr whole-rock isochron (minimum) age of 465+11 Ma. The garnetiferous granodiorites transect these early dykes and are themselves cut by dykes and larger bodies of white trondhjemite, including the type-locality Follstad trondhjemite U-Pb-dated (zircon and titanite) to 432+3 Ma.
All the trondhjemites and the granodiorite postdate an existing foliation in the host Gula rocks, but are themselves weakly foliated, folded and in places cut by a later cleavage. The overall, local and regional isotopic data and biostratigraphic constraints suggest that an early Caledonian tectonothermal event affected the Gula rocks before 465 Ma, and probably in Early to Mid Arenig time. The foliation, folds and cleavage in the trondhjemites and granodiorite, on the other hand, must postdate 432 Ma and are considered to have formed during the main Scandian tectonometamorphic event dated isotopically to around 425 Ma.

Bart Pannemans, Departement Fysico-Chemische Geologie, KU Leuven, Celestijnenlaan 200C, 2001 Leuven, Belgium.
David Roberts, Geological Survey of Norway, 7491 Trondheim, Norway.

Introduction

Trondhjemites constitute one of the more common varieties of plutonic or hypabyssal rocks in the Upper Allochthon of the Norwegian Caledonides, occurring principally in the *Köli* Nappes, i.e. in the outboard or suspect terranes lying tectonostratigraphically above the continent (Baltica)-ocean (Iapetus) transition zone amphibolites and schists that compose the generally higher grade *Skjøtingen Nappe (=Seve Nappes)*. The definition of the term trondhjemite stems from Goldschmidt's (1916) studies in central and southern Norway, in the Caledonides, and notably in the 'type locality' of this rock-type at Follstad, just south of Trondheim. Subsequent classification schemes categorise trondhjemites as leucocratic tonalites, with <10% of mafic mineral components (Barker 1979, Le Maitre 1989).

In Central Norway, trondhjemites are distinctive rock-types within the Köli Nappes of the Trondheim Nappe Complex (Loeschke 1976, Size 1979) (Fig. 1). In many places they stand out quite clearly, with their white to pale grey or greenish-grey colour, against the darker heterogeneous host rocks, either as dykes or as larger bodies. In some areas, they appear to coexist with subordinate diorites and gabbros (Nilsen & Wolff 1989). Based on relationships with the principal schistosities and cleavages, it has been suggested that there were perhaps three or four pulses of trondhjemitic intrusion in this region (Roberts 1978, Size 1979). In this contribution, we give brief descriptions of trondhjemites and associated leucogranitoid rocks from, and in the neighbourhood of, the valley Gauldalen – one of three major, transverse valleys cutting through the metamorphic allochthon of the Trondheim Region – and present geochemical data and a petrogenetic model for these same rocks.

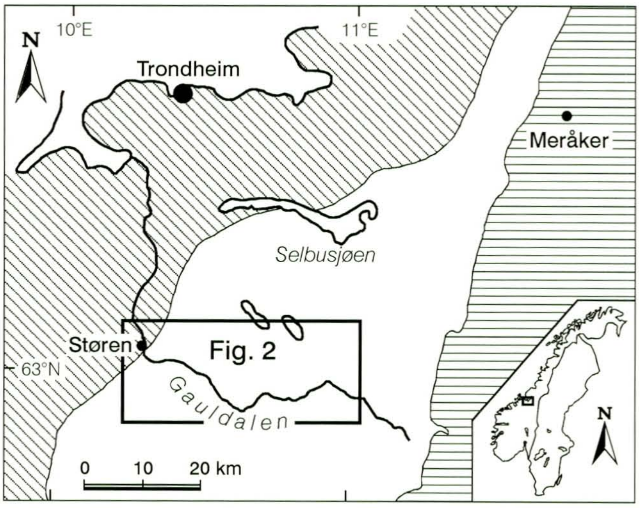

Fig. 1. Principal tectonostratigraphic units in the Caledonides of the central part of the Trondheim Region. Central blank area – Gula Nappe; diagonal lined area – Støren Nappe; horizontal lines – Meråker Nappe. Boxed area – Figure 2.

Regional setting

In the literature, the Trondheim Nappe Complex (TNC) has been subdivided into three principal tectonic units, each of Köli Nappe affinity -- the Meråker Nappe in the east, the central Gula Nappe and a western unit, the Støren Nappe (Fig. 1) (Wolff 1979). In general terms, the Meråker and Støren Nappes comprise mainly low-grade metasedimentary successions, but also include significant volumes of ophiolitic or immature volcanic arc rocks in the lower and middle parts of their lithostratigraphies. The Gula Nappe is a heterogeneous and in some ways enigmatic unit of rocks of generally, though not entirely, higher metamorphic grade. Detailed descriptions of lithologies of these units are contained in Nilson (1978), Wolff (1979) and Gee et al. (1985).

The *Støren Nappe* comprises a basal ophiolitic complex overlain unconformably by a Late Arenig to Ashgill volcano-sedimentary succession. The ophiolitic rocks are considered to have been deformed and metamorphosed, and obducted upon the Gula in earliest Ordovician time. The unconformably overlying Ordovician rocks of the Hovin Group were subsequently first metamorphosed and deformed during the Scandian orogeny, in Silurian to earliest Devonian time. In the *Meråker Nappe,* a bimodal magmatic complex (Fundsjø Group) was initially deformed and metamorphosed prior to uplift and erosion, and then overlain unconformably by mainly sedimentary rocks, with some volcanic members, of inferred Ordovician to Early Silurian age. This volcanosedimentary assemblage was then deformed during the Scandian orogeny. The tectonothermal histories of the Støren and Meråker Nappes are thus quite similar.

There is evidence to suggest that the rocks of the *Gula Nappe* (termed the Gula Group or, more recently, the Gula Complex) were involved in both the Early Ordovician and the Siluro-Devonian tectonometamorphic events (Guezou 1978, Lagerblad 1984, Sturt & Roberts 1991). In this part of the Gula, three formations have been distinguished -- from west to east, the Undal, Singsås and Åsli Formations (Nilsen 1983). In the west, the contact between the Undal Formation and the basal volcanites of the Støren Nappe is tectonic and mylonitic. The status of the eastern contact, against the Fundsjø Group, is controversial; either tectonic (Guezou 1978, Lagerblad 1984, McClellan 1994) or primary (Rui, 1972, Rui & Bakke 1975, Bjerkgård & Bjørlykke 1994). In this eastern area, a *Dictyonema (Rhabdinopora)*-bearing phyllite provides our only evidence of biostratigraphic age in the Gula, i.e., Tremadoc (Vogt 1941).

In a palaeotectonic context, the Støren ophiolite is considered to have been obducted upon Gula Group rocks in Early to Mid Arenig time (Grenne & Roberts 1981, Roberts et al. 1984, Sturt & Roberts 1991). The bimodal magmatic rocks of the Fundsjø Group may have experienced a similar fate. At any rate, these three units were then deformed, metamorphosed and uplifted, and unconformably overlain by the Ordovician, immature basinal sequences now occurring to the west and to the east. The western basin, at least, relates to back-arc spreading above a subduction zone (Roberts et al. 1984, Grenne & Roberts 1998). Subsequently, the basinal assemblages plus their ophiolitic and Gula substrates were involved in Scandian, southeastward thrust translation and imbrication, forming the Trondheim Nappe Complex.

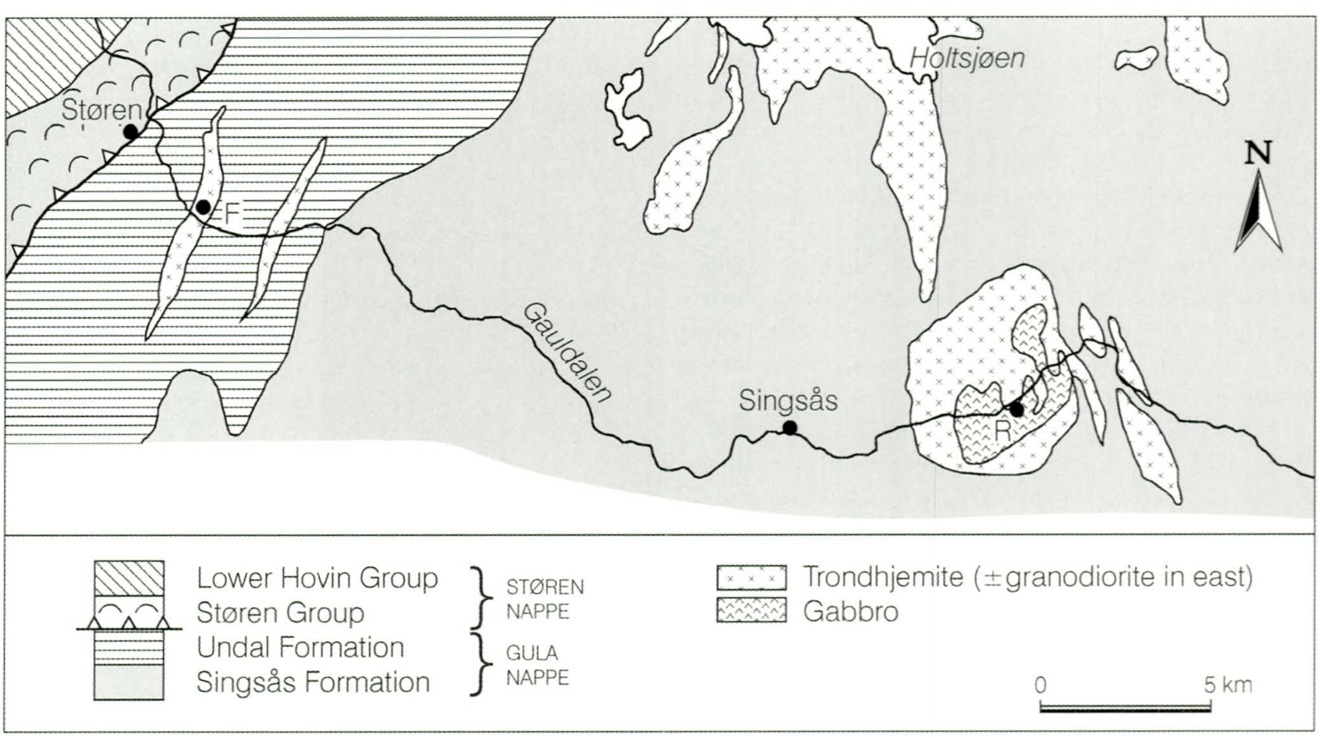

Fig. 2. Simplified geological map of the Gauldalen district. F – Follstad, R – Reitstøa.

Fig. 3. (a) The quarry at Follstad, showing the massive nature of the white trondhjemite. Photo taken looking c. NNW, in August 1999. (b) Close-up of the trondhjemite at the Follstad quarry. Although this is the most massive variant of the trondhjemite, the rock shows a hypidiomorphic-granular texture and a very faint foliation. Thickness of pencil, 7 mm.

In this general, overall scenario, two principal types of trondhjemite are recognised in this district; (1) sills and dykes associated with the early ophiolites or with MORB-type mafic volcanite units. These have oceanic geochemical traits, akin to plagiogranites, and have yielded U-Pb zircon ages in the range 495-480 Ma (Dunning 1987, Dunning & Grenne, in prep.). (2) Bodies ranging from dyke swarms to major plutons. These are particularly common in the Gula and carry continental-margin geochemical signatures. The only reliable isotopic date so far is that from the type-locality Follstad trondhjemite, with a U-Pb zircon and titanite age of 432 ± 3 Ma (Dunning & Grenne 2000 -- this volume). However, it has been suggested that these particular trondhjemites may have intruded over a wide interval of time, throughout the Ordovician and Silurian periods (Size 1979, Roberts & Sundvoll 1996). The trondhjemites described in this account all belong to the continental margin category.

Plutonic and dyke rocks in Gauldalen

Several trondhjemite bodies and associated plutonic rocks and dykes intrude the Gula Complex along Gauldalen (Nilsen & Wolff 1988). Here, we consider selected bodies in two areas; (1) in western Gauldal, at and in the neighbourhood of Follstad, near Støren; and (2) in the vicinity of Reitstøa, between Singsås and Haltdalen, some 40 km southeast of Støren in the central part of the Gula Complex (Fig. 2). We also touch upon the geochemistry of trondhjemite dykes from an area 6 km south of Støren; these dykes are the subject of another paper in this volume, cited later.

Western Gauldalen

The Follstad trondhjemite and associated dykes

The trondhjemite at Follstad, north of the Gaula river c. 2 km southeast of Støren, served as a type locality for Goldschmidt (1916) and was the subject of a petrological and major-element geochemical study by Size (1979). The trondhjemite is excellently exposed in a large quarry, where it is worked under the commercial name 'Støren granite'.

Field relationships and petrography

The *Follstad trondhjemite* is a c. 7 km-long and up to 400 m-wide, NNE-SSW-trending body intruding phyllites and schists of the Undal Formation. In the vicinity of the main quarry (Fig. 3a) this white to very pale grey trondhjemite has a thickness of c. 375 metres, and dips at c. 70° to the WNW (Size 1979). Although the body is fairly regular in shape, there is a prominent dyke apophysis in a smaller quarry in the southern part of the western contact showing partly assimilated and hornfelsed xenoliths of schistose Gula rocks up to 4 m across. In general, the contact zone of the trondhjemite does not display any particularly clear, chilled margins, even though hornfelsic texture is evident in the adjacent country-rock schists and phyllites (Size 1979). Thinner dykes of similar 'white' trondhjemite occur within the Gula phyllites outside of the main body, and some are boudinaged and affected by later folds.

The petrography and textures of the Follstad trondhjemite have been described in some considerable detail by Size (1979). Here, we present only a brief account, combining the main aspects of Size's description and our own field and thin-section observations. The trondhjemite is a massive and homogeneous rock, carrying a weak foliation defined by biotite and muscovite. No visible differences in character could be detected over the entire, 7 km length of the body. The presence of biotite gives the medium-grained rock a speckled appearance (Fig. 3b). Plagioclase (An_{25} – calcic oligoclase) forms almost 60% of the mode, and quartz 26%. Together, these minerals show a hypidiomorphic-granular

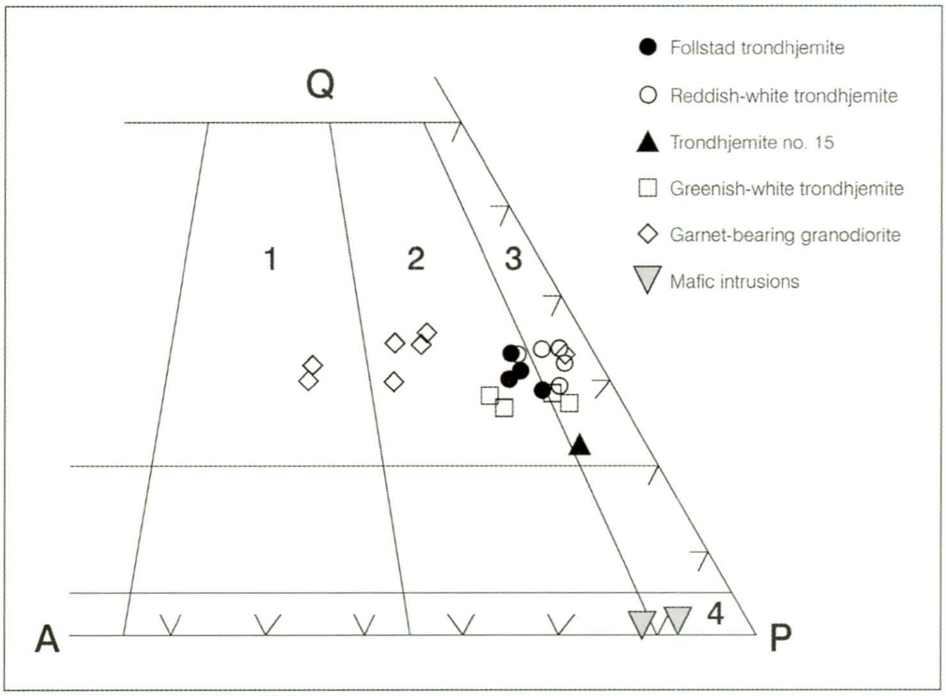

Fig. 4. Normative compositions of the trondhjemites, garnet-bearing granodiorites and mafic rocks plotted on a QAP diagram (Streckeisen 1976). Fields: 1 – granite; 2 – granodiorite; 3 – tonalite; 4 – gabbro and diorite.

texture, although in the more foliate parts the texture is close to granoblastic. Most plagioclase laths display rims of untwinned and unzoned albite. The other main minerals present are muscovite (6%), K-feldspar (c. 3%), epidote (>4%) and biotite (2%). Accessory minerals include magnetite, titanite, zircon, apatite, chlorite and calcite.

Despite its massive character, the trondhjemite has clearly been affected by regional metamorphism. The change-over to more granoblastic and allotriomorphic-granular textures and a more conspicuous, though weak, foliation corresponds with increased contents of biotite and epidote; and the general mineral assemblage muscovite-biotite-quartz-oligoclase-epidote is indicative of upper greenschist facies (Goldschmidt 1916, Size 1979). This grade of metamorphism is slightly lower than the almandine-amphibolite facies assemblages generally encountered in the metasedimentary rocks of the Gula Group.

Other trondhjemite dykes

Along part of the eastern contact of the Follstad body, there is a 40 cm-thick, pale reddish-white to grey trondhjemite dyke trending parallel to the main body, with a sharp contact against the latter. The dyke contains xenoliths of the Undal schists. Similar dykes, also trending c. NNE-SSW, are present a few metres away from the main contact. For descriptive purposes, these are referred to hereafter as the *reddish-white trondhjemites (dykes)*.

Anastomosing fractures roughly perpendicular to the dykes coincide with a pattern of leaching and alteration, where the reddish hue has been replaced by a greenish-white colour. This clearly indicates that fluids have been percolating from the main Follstad body through the reddish-white dykes and into the country rocks. Field relationships thus suggest that the reddish dykes may represent a slightly earlier stage of intrusion than the main trondhjemite body. The reddish-white dykes are fine grained, consisting mainly of quartz, plagioclase and some biotite, and contain conspicuous phenocrysts of zoned plagioclase. In the leached parts of the rock, biotite has been replaced by epidote, in some cases in one and the same crystal, and a fibrous clinozoisite has been precipitated in the associated microfractures.

In many parts of the district, both Gula and Støren rocks (but not the overlying Hovin Group) are cut by fine-grained, grey-white to greenish-white trondhjemite dykes trending

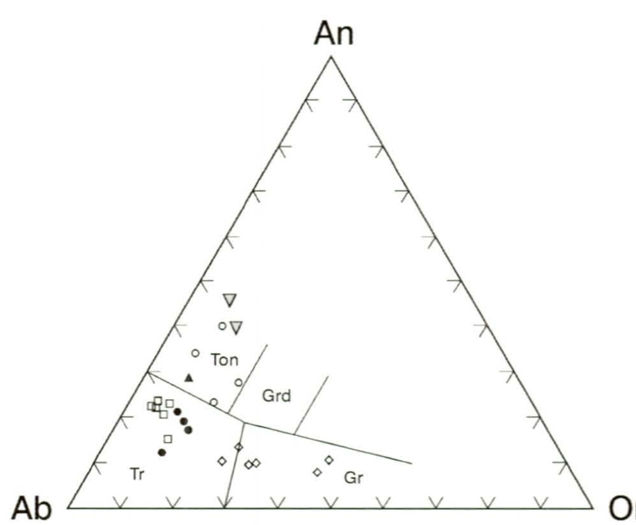

Fig. 5. The same samples as in Fig. 4 plotted on the An-Ab-Or diagram of O'Connors (1965). Fields: Gr – granite; grd – granodiorite; ton – tonalite; tr – trondhjemite.

Fig. 6. Contact relationships between diverse trondhjemites or granodiorites and country-rock schists, etc., of the Gula Complex, Gauldalen; all localities on map-sheet Haltdalen 1620 I (4-NOR edition coordinates). (a) Trondhjemite dyke cutting variably deformed metasedimentary rocks; looking ENE. Road-cut exposure on the R30 road, c.600m SSE of Gillset; 0370 8150. (b) Apophyses from a trondhjemite dyke cutting mica schists (+ garnet) and felsic gneisses; looking north. Road outcrop on R30, c. 9940 8335. (c) Granodiorite dyke, partly pegmatitic and weakly foliate, cutting the penetrative schistosity in the Gula host-rocks at a low angle; looking NNW. R30 outcrop, c. 0010 8300. (d) Granodiorite, partly pegmatitic (muscovite flakes up to 2 cm), cutting and enclosing schistose, Gula country rock; looking SE. R30 road-cut, 0015 8295.

Table 1. Major and trace element data for the Follstad (white), reddish-white and greenish-white trondhjemites, Gauldalen. Major elements in wt.%, trace elements in ppm.

	Follstad trondhjemite				Reddish-white trondhjemite					Greenish-white trondhjemite				
	B1	B11	B16	B22	B2	B7	B10	B12	B13	B15	B4	B5	B6	B20
SiO_2	70.90	72.21	72.93	73.46	72.71	71.20	72.92	72.68	72.83	66.62	66.80	67.63	66.39	66.80
Al_2O_3	16.57	16.16	15.47	15.33	16.16	16.70	15.85	15.86	16.10	17.80	17.18	16.29	16.33	18.19
Fe_2O_3	1.32	1.15	1.34	0.49	1.24	1.53	1.04	1.39	1.03	1.74	1.95	1.60	1.79	2.00
TiO_2	0.22	0.16	0.21	0.07	0.20	0.24	0.17	0.21	0.20	0.32	0.28	0.24	0.24	0.30
MgO	0.47	0.35	0.45	0.15	0.44	0.60	0.30	0.54	0.51	0.96	1.24	1.05	1.07	1.29
CaO	2.92	2.36	2.50	1.62	2.95	2.86	1.96	2.94	3.03	4.09	4.55	3.12	3.64	5.36
Na_2O	5.52	5.42	5.21	5.94	5.18	5.70	5.49	5.62	5.36	5.36	4.61	4.78	4.13	3.97
K_2O	1.19	1.62	1.38	1.32	0.84	0.90	1.25	0.64	0.59	1.07	0.80	1.84	2.07	1.03
MnO	0.02	0.02	0.02	0.01	0.02	0.02	0.02	<0.01	0.01	0.02	0.02	0.02	0.02	0.03
P_2O_5	0.07	0.07	0.06	0.03	0.06	0.08	0.05	0.07	0.07	0.10	0.08	0.08	0.07	0.09
LOI	0.84	1.08	0.84	0.37	0.51	0.50	0.69	0.55	0.53	0.89	2.29	3.40	4.04	0.72
Total	100.03	100.61	100.43	98.79	100.31	100.33	99.74	100.51	100.24	98.97	99.80	100.05	99.79	99.78
Nb	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Zr	94	72	91	68	95	86	108	85	96	81	78	89	78	51
Y	<5	<5	5	5	7	5	<5	<5	8	5	<5	<5	6	<5
Sr	633	505	532	757	688	750	610	694	650	621	581	485	416	626
Rb	22	34	25	34	15	18	22	10	10	22	31	64	73	29
Ba	346	382	383	519	332	284	424	283	256	295	263	362	320	144
U	0.6	0.6	0.8	1.0	1.1	<10	1.1	1.1	<10	0.9	<10	1.4	1.2	1.4
Th	1.8	1.5	2.6	0.6	1.8	<10	1.9	1.4	<10	1.3	<10	1.9	2.1	0.7
V	16	12	16	<5	17	23	12	19	18	23	33	27	29	36
Cr	3.1	2.5	4.1	2.4	4.4	<5	2.4	8.0	<5	5.0	12.0	12.3	11.7	6.4
Sc	1.80	1.76	<10	1.24	1.86	<10	1.20	<10	<10	<10	<10	3.44	4.16	3.80
Hf	2.10	1.80	2.25	1.93	1.93	-	2.17	1.84	-	1.91	-	1.99	1.67	1.04
Ta	0.09	0.60	0.13	0.24	0.11	-	0.11	0.10	-	0.12	-	0.12	0.14	0.08
Co	2.0	1.5	1.9	0.5	1.9	-	1.0	2.5	-	4.4	-	4.7	4.0	6.4
Ga	14	15	16	16	14	16	14	16	15	12	16	14	14	15
Zn	26	24	27	12	16	35	33	8	<5	23	37	25	26	35

between 060° and 070°. For convenience of description these dykes, which are up to 2 m in thickness, are here referred to as the *greenish-white trondhjemites*. The mineralogy is roughly the same as for the other trondhjemites, except that contents of epidote (clinozoisite), chlorite and calcite are higher, thus explaining the slightly greenish hue of most of these dykes. Four modal analyses show that these samples straddle the line separating the fields of trondhjemite and granodiorite (Fig. 4), while the normative compositions signify that they are trondhjemites (Fig. 5). These particular dykes are the subject of a separate contribution in this same volume (Roberts & Sundvoll 2000).

In the present study, greenish-white trondhjemite dykes were sampled along a forestry road c. 3 km northeast of Follstad. There, the dykes are folded and schistose, but they also cut the earliest foliation present in the polydeformed rocks of the Gula Complex. Although the mutual relationship between the white and the greenish-white trondhjemites has not been observed, there is isotopic dating evidence to suggest that the greenish-white trondhjemite dykes are older than the white, Follstad-type trondhjemites (other papers in this volume).

Reitstøa district, central Gauldalen

In this central part of Gauldalen, several plutonic bodies and dykes varying from mafic to felsic intrude the high-grade rocks of the Singsås Formation (Nilsen 1978, Nilsen & Wolff 1989). On his first map compilation, Nilsen (1978) indicated just one composite pluton in the Reitstøa area – an opdalite, or hypersphene-bearing diorite – but on the 1:250,000 scale bedrock map this was separated into two units, trondhjemite-granite-monzonite and gabbro-diorite, without giving the specific rock names for this particular area. Our study has indicated, however, that plutonic rocks ranging from granite and trondhjemite to gabbro are present in this small area. We refer to this magmatic assemblage, quite informally, as the Reitstøa magmatic complex. Our geochemical data, however, appear to show that the different plutonic rocks originated in slightly different geological settings. In our investigations, attention was focused on a stretch of road outcrop 10 km west of Reitstøa where the mutual relationships of the different members of the complex are more easily seen.

Trondhjemites

Dykes of both the white and the greenish-white trondhjemites also occur in this district, as well as larger bodies of a white, medium-grained, Follstad-type trondhjemite. The mineral parageneses of these trondhjemite varieties are the same as in those described from western Gauldalen; mostly quartz, plagioclase and biotite, with minor concentrations of epidote. These dykes cut across the regional schistosity (Fig. 6a,b). Greenish-white dykes are also found in this particular area, but the field relationships are too diffuse to permit any definite conclusions to be made.

Garnet-bearing granodiorite

In the Reitstøa area, white leucogranitoid rocks containing garnets form a significant element of the local geology (Fig. 6c,d). The bodies are very irregular both in form and in texture. Although most are medium grained and weakly to moderately foliated, others are of finer grain size. Pegmatitic varieties are also present locally, with megacrysts of microcline up to 30 cm across. In some exposures, the different varieties of granitoid can be seen together, with their slightly different grain size, texture and colour and a varying content of garnet. In many cases, there is a marked concentration and alignment of the wine-red garnets parallel to the contact zone between apparently different granitoid intrusions, a feature which is considered to relate to flow differentiation in the intruding magma.

The principal minerals are plagioclase, quartz, microcline, biotite and garnet. Based on their mode (QAP diagram: Fig. 4), four samples fall in the field for granodiorites and the other two in the granite field. The An-Ab-Or normative diagram, on the other hand, indicates that the rocks sampled are mostly granites, going over into the trondhjemite field (Fig. 5). As the primary classification and naming of plutonic rocks should be based on mineral content (Le Maitre 1989), we will hereafter refer to these rocks as *granodiorites*. It should be understood, however, that two of the rocks sampled may indeed be representative of granites *sensu stricto*. The heterogeneity in texture and grain size does allow for such a possibility. On the other hand, K-metasomatism may possibly account for this higher potassium content, even though, as yet, no direct evidence for this process has been detected.

Field relationships show that these varitextured, garnetiferous granodiorites are cut by dykes and larger sheets of the white, Follstad-type trondhjemite. Although cross-cutting relationships with the greenish-white trondhjemites have not been observed, in one locality a fine-grained, grey trondhjemite dyke which is chemically very similar to the greenish variety is cut by a garnet-bearing granitoid body. These mutual relationships would suggest that the garnet-bearing granodiorites intruded at some stage in time between the early, greenish-white trondhjemite dykes and the somewhat later, white, Follstad-type trondhjemites.

Mafic bodies

Although mafic plutonic rocks form a substantial part of the Reitstøa magmatic complex (Nilsen & Wolff 1989), they were not a target of this particular investigation. Just two samples of gabbro were collected for chemical analysis (Fig. 4).

Geochemistry and petrogenesis

All rock samples investigated in this study were analysed on fused glass beads (major elements) or pressed powder pellets using an automatic Philips PW 1480 XRF spectrometer, at the Geological Survey of Norway, Trondheim. Samples were first heated to 1000°C and (for the major elements) melted with 7 parts of $Li_2B_4O_7$ on a glass plate; for the trace elements, 9/2 parts of Hoechst C-wax was added. REE, U, Th, Ta and Hf were determined by INAA at the Chemico-Physical Laboratory, University of Leuven, Belgium. Samples were measured after 1 and 3 weeks with a 75 cm³ Ge(Li)-detector and a 16 mm² x 7 mm LEPS.

Trondhjemites

The results of the chemical analyses are presented in Tables 1-3. From Table 1 it can be seen that one of the prime differences between the white and the greenish-white trondhjemites is that the latter have lower SiO_2 contents, compensated by slightly higher Al_2O_3 values. Plots of the normative compositions in a Streckeisen diagram and a An-Ab-Or diagram according to O'Connors (Barker 1979) clearly show the samples to be trondhjemites (Fig. 5), and by definition they are high-Al_2O_3 trondhjemites. Harker diagrams (Fig. 7) show no significant variations over the small range of SiO_2 contents. The reddish-white trondhjemites have geochemical signatures that strongly resemble those of the white trondhjemites. Although their K_2O contents are, if anything, just marginally lower (due to minor alteration of biotite, in

Table 2. Major and trace element data for the garnet-bearing granodiorites and two gabbros, Gauldalen. Major elements in wt%, trace element in ppm.

	Garnet-bearing granodiorite							Gabbro	
	B17	B18	B19	B21	B23	B38c	B41b	B44	B41a
SiO_2	74.73	72.27	73.06	77.37	72.46	72.88	74.99	48.55	50.84
Al_2O_3	15.24	15.00	15.05	14.94	16.39	14.89	14.85	19.57	16.22
Fe_2O_3	0.30	1.11	0.50	0.21	0.96	0.58	0.33	10.91	8.53
TiO_2	0.02	0.10	0.02	0.01	0.13	0.06	0.03	1.72	1.16
MgO	0.08	0.27	0.08	0.01	0.57	0.25	0.06	3.65	7.18
CaO	1.08	1.39	1.24	1.34	2.90	1.48	1.75	7.49	10.34
Na_2O	3.82	4.65	4.47	4.96	5.50	3.61	4.65	4.34	3.30
K_2O	4.90	3.52	3.16	2.63	0.57	5.09	2.82	1.49	0.75
MnO	0.01	0.11	0.02	0.03	0.04	0.05	0.01	0.18	0.16
P_2O_5	0.03	0.05	0.03	0.03	0.04	0.08	0.03	0.80	0.18
LOI	0.38	0.37	0.53	0.35	0.46	0.22	0.31	0.55	0.81
Total	100.59	98.84	98.16	101.89	100.03	99.19	99.83	99.25	99.47
Nb	21	39	46	20	<5	13	<5	20	9
Zr	22	52	37	35	73	31	48	317	111
Y	6	20	16	15	11	20	10	45	29
Sr	177	166	160	159	441	155	297	983	611
Rb	100	85	78	66	17	131	72	44	19
Ba	624	438	431	200	462	649	740	603	168
U	13.0	16.6	16.4	<10	1.8	4.0	1.8	<10	<10
Th	<10	5.9	6.2	<10	2.6	2.0	1.4	<10	<10
V	<5	7	<5	<5	12	6	<5	87	161
Cr	<5	3.3	2.4	<5	10.2	3.2	3.0	<5	197
Sc	<10	2.31	<10	<10	<10	<10	1.21	22	34
Hf	-	2.09	1.65	-	2.13	1.15	1.66	-	-
Ta	-	4.61	4.68	-	0.18	1.63	0.48	-	-
Co	-	0.9	0.1	-	2.4	0.6	0.4	15	32
Ga	12	18	17	13	14	11	12	22	16
Zn	<5	24	7	<5	10	13	<5	90	59

Table 3. Rare-earth element contents (ppm) of diverse trondhjemites and garnet-bearing granodiorites, Gauldalen.

	Follstad trondhjemite				Reddish-white trondhjemite			
	B1	B11	B16	B22	B2	B10	B12	B15
La	8.3	6.5	11.5	1.9	7.7	9.3	7.1	7.2
Ce	15.7	12.2	22.0	3.5	14.5	16.2	12.8	14.2
Nd	6.1	4.7	9.1	1.7	5.9	6.2	5.4	7.2
Sm	1.21	1.04	1.67	0.58	1.19	1.21	1.06	1.46
Eu	0.44	0.36	0.44	0.20	0.39	0.36	0.38	0.55
Tb	0.103	0.103	0.143	0.101	0.102	0.103	0.096	0.131
Yb	0.25	0.25	0.29	0.31	0.25	0.25	0.22	0.19
Lu	0.04	0.038	0.044	0.044	0.04	0.037	0.033	0.027

	Greenish-white trondhjemite				Garnet-bearing granodiorite				
	B5	B6	D2	B20	B18	B19	B23	B38c	B41b
La	8.6	7.4	6.7	4.0	10.4	10.4	8.9	6.3	3.9
Ce	16.0	13.2	13.6	8.6	15.7	14.8	16.7	12.1	8.0
Nd	6.6	5.1	6.1	3.9	3.9	4.5	7.1	4.3	2.6
Sm	1.31	1.11	1.25	0.99	1.53	1.52	1.73	1.67	0.91
Eu	0.41	0.41	0.42	0.42	0.31	0.31	0.60	0.64	0.35
Tb	0.111	0.124	0.120	0.101	0.415	0.351	0.256	0.469	0.189
Yb	0.27	0.25	0.24	0.21	1.90	1.22	0.98	1.40	0.64
Lu	0.039	0.043	0.040	0.033	0.264	0.197	0.132	0.182	0.091

certain samples), they are likely to be broadly coeval with the white trondhjemites.

Rb and Sr abundances and the Rb:Sr ratio are known to be particularly sensitive indicators in discriminating between continental trondhjemites that formed by partial melting of K-poor rocks (Helz 1976, Rapp et al. 1991), and plagiogranites generated by differentiation of K-poor tholeiitic melts (Dixon & Rutherford 1979, Pedersen & Malpas 1984). Discrimination based on these particular elements and ratios (Fig. 8) clearly shows that our Gauldalen trondhjemites have mean Rb and Sr values, and Rb:Sr ratios, far exceeding those typifying the oceanic plagiogranite type of trondhjemite. A Yb/Al_2O_3 plot (Fig. 9) also helps to highlight the continental margin affiliation of these rocks.

The chondrite-normalised REE patterns of all three types of trondhjemite are strongly fractionated, with moderately high enrichments for the LREE and relatively low contents for the HREE (Fig. 10a,b,c and Table 3); and in the HREE sector there is just a hint of upward concavity. With one exception, La_N/Tb_N ratios fall in the range 6 to 14. La and Ce contents are 10-20 times chondrites, and Yb and Lu are only 1-2 times. In most of the samples there is a very small positive Eu anomaly. The REE data are similar to those presented by Barker & Millard (1979) from the Follstad trondhjemite. Size (1979) also reported data for 5 rare-earth elements, but his samarium values are 4-5 times greater than those reported here (or by Barker & Millard 1979); these high values probably relate to analytical error.

It follows from the above that the Gauldalen trondhjemites are likely to have formed as melting products of a K-poor rock with a mineralogy that caused the rare-earth elements to strongly fractionate. A mathematical model was used to calculate the theoretical change in the REE, starting from different rock types, with different degrees of partial melting and involvement of minerals. Because of the many parameters involved, a preliminary process of elimination was necessary in order to track down the most likely candidate. The low K_2O contents are interpreted to indicate that the trondhjemites have a primary origin, which is also supported by the rather low $^{86}Sr/^{87}Sr$ ratio of 0.70794±9 for the greenish trondhjemite dykes (Roberts & Sundvoll 2000). This excludes a generation by recycling of old crustal material, and the origin of the magmas has to be sought in the mantle, either directly or indirectly. Production of trondhjemitic melt directly from the mantle is doubtful. Martin (1987) calculated, for Archaean trondhjemites, that the melting of olivine and pyroxene cannot explain the marked REE fractionation. It would also involve very low degrees of melting which could not account for the vast volumes of trondhjemites that occur in the Archaean. The mineralogy of the Gauldalen

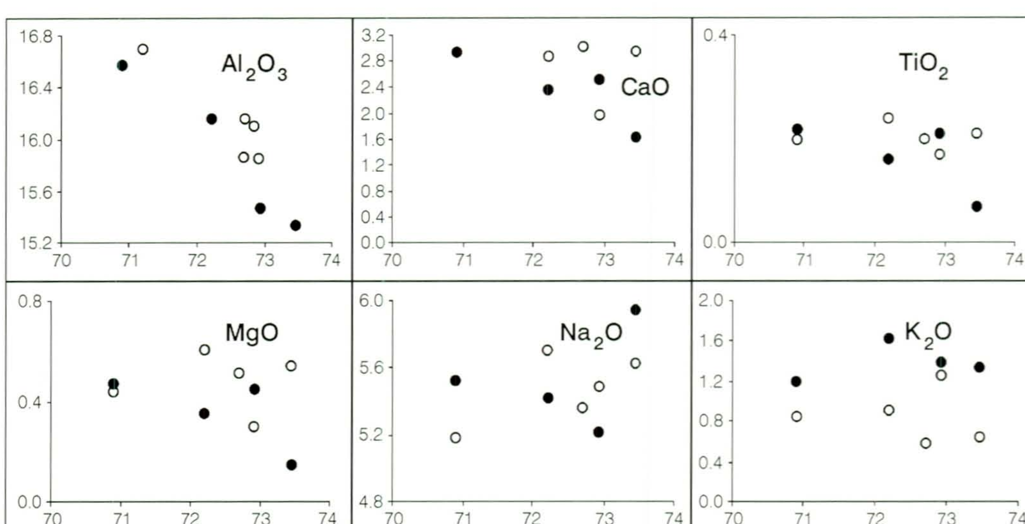

Fig. 7. Samples of the white and greenish-white trondhjemites plotted on Harker diagrams, in the SiO_2 range 70-74%.

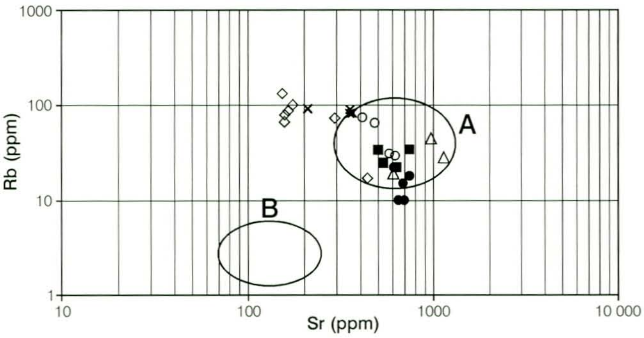

Fig. 8. Rb-Sr diagram showing the distribution of the samples from Gauldalen. Symbols as in Fig. 4. A – field of continental trondhjemites; B – field of plagiogranites/oceanic trondhjemites.

Table 4. Values used in the REE calculations.

	La	Ce	Nd	Eu	Sm	Tb	Yb	Lu
Enriched MORB	3.7	11.5	10	3.3	1.3	0.87	5.1	0.56
Depleted MORB	1.7	5.34	4.88	1.88	0.77	0.57	2.93	0.46
Ocean-island basalt	37	80	38.5	10	3	1.05	2.16	0.30
Archaean tholeiite	9.86	24	15	3.76	1.37	0.73	2.32	0.34

	Eclogite		*Amphibolite*		*Garnet*	
	Xi	Pi	Xi	Pi	Xi	Pi
Clinopyroxene	0.35	0.35	0.35	0.35	–	–
Hornblende	–	–	0.35	0.55	0.35	0.35
Garnet	0.35	0.55	–	–	0.35	0.55
Plagioclase	0.3	0.1	0.3	0.1	0.3	0.1

trondhjemites also precludes a mantle origin; both the white and the greenish-white trondhjemites contain biotite, pointing to a water-rich source region somewhere in the crust.

The alternative to a primary origin is the melting of a tholeiitic basalt. This was the interpretation favoured by Size (1979) for the Follstad intrusion. Because of the widespread presence of metabasalts in the Caledonian allochthon of Central Norway, their occurrence deeper in the source region is very likely. The original basaltic rocks will have been metamorphosed, grading from basalt through greenschist-facies equivalents to amphibolite and eclogite. These diverse rocks were used as starting points for the different REE calculations. For the modelling, the formulae used were those described by Shaw (1970); and the Kd-values for the different minerals were taken from Martin (1987). The use of Shaw's formulae assumes an equilibrium situation, to allow diffusion to redistribute the elements through the system; the diffusion time, however, was calculated to 8,000 years and this is far below the expected duration of the Early Ordovician orogeny. Fractional crystallisation will also influence the patterns, but the Kd-values of quartz, plagioclase and biotite are too small to erase the influence of the melting event. However, a small portion of fractional crystallisation was evidently involved to explain the minor, positive, europium anomaly; and this is in accord with the presence of plagioclase phenocrysts in the rocks and thin-sections.

The different REE patterns that were obtained by 20% fractional crystallisation after the partial melting of a tholeiite that was metamorphosed to amphibolite or eclogite are shown in Fig. 11 (see also Table 4). Both an enriched and a depleted tholeiite were used in the calculations. For a depleted tholeiite, in all cases it was difficult to obtain a good fit. Similarly, an ocean island basalt, being rich in La and Ce, is an improbable candidate; so it is most likely that the source rock was enriched. Using an enriched tholeiite as source, different grades of metamorphism were employed in the calculations. An eclogite provides a good explanation for the HREE, but shows deficiencies at the LREE side of the pattern because of the low Kd-values of omphacite and garnet. A garnet-free amphibolite, on the other hand, does not fit at the HREE side of the pattern. The best fit, it would seem, is obtained by a combination of garnet and hornblende, or a garnet-bearing amphibolite. This accords well with the mineralogy and geochemistry of the trondhjemites. There are low contents of Y (generally <5 ppm), an element with a high affinity for garnet, and low abundances of the HREE. The presence of biotite and the lack of perthitic textures in the plagioclase do provide evidence of a high water pressure, so water-rich minerals would have to have been present in the source rock. Biotite is a possibility, but hornblende is more likely in view of the low Kd-values of biotite. Hydrothermal activity, low-grade metamorphism and fractional crystallisation will hardly have influenced the REE contents and ratios. Thus, as the greenish-white trondhjemites have similar REE patterns to those of the white, Follstad-type trondhjemites, a similar source rock could be assumed for their origin.

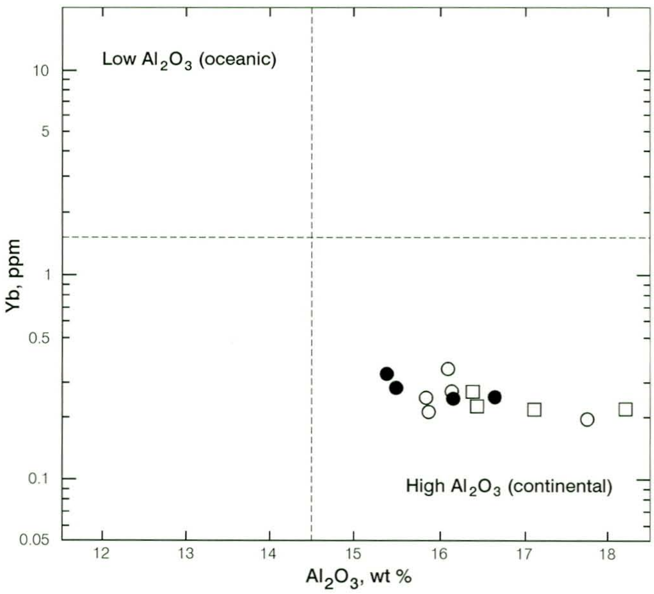

Fig. 9. The white, greenish-white and reddish-white trondhjemites plotted on a Yb vs. Al_2O_3 diagram (Arth 1979). The vertical dashed line separates low-Al and high-Al types, and the horizontal line separates rocks depleted in HREE from those undepleted. Symbols as in Fig. 4.

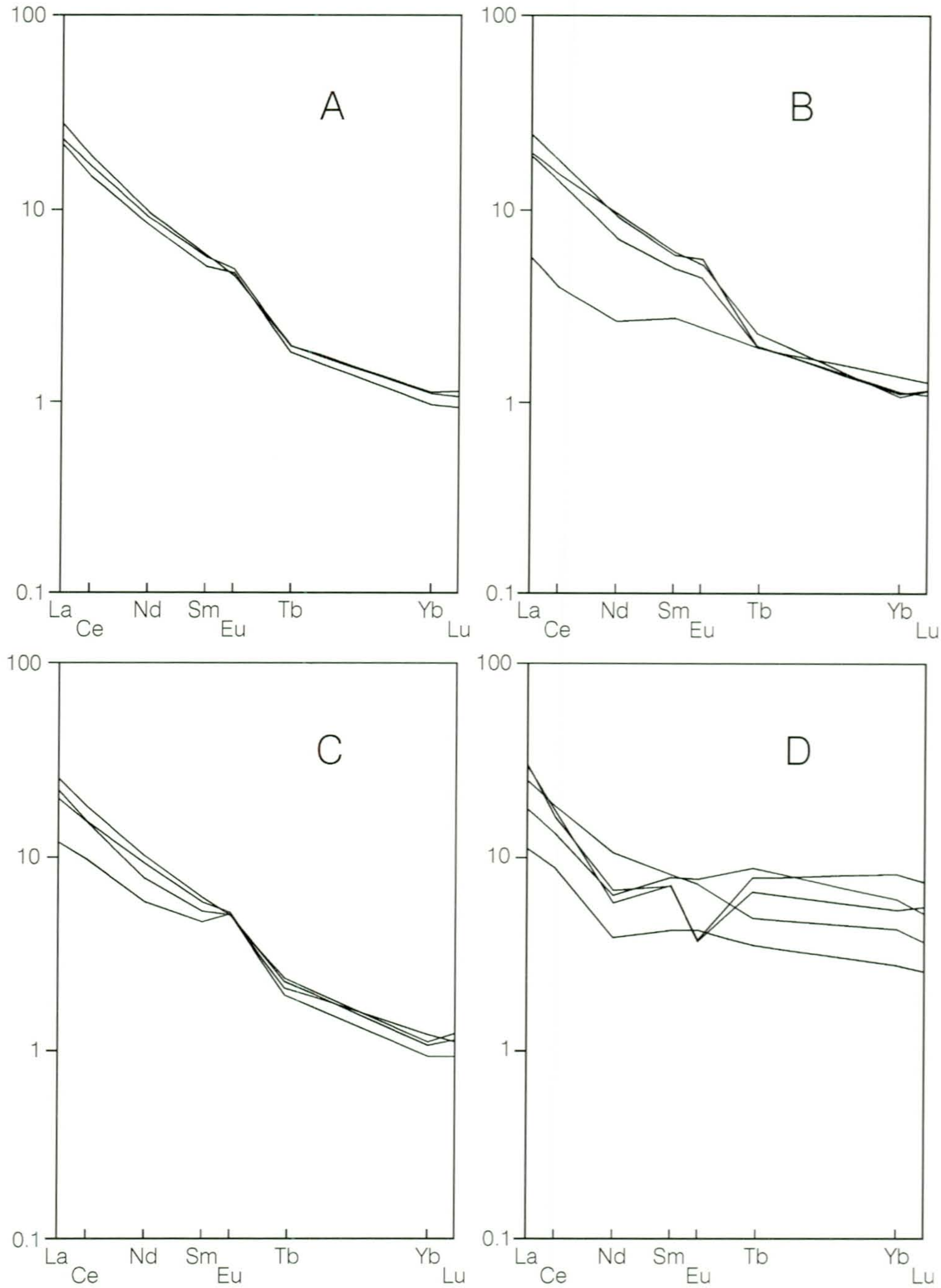

Fig. 10. Chondrite-normalised REE patterns of the (A) reddish-white, (B) white, (C) greenish-white trondhjemites and (D) the garnet-bearing granodiorites.

After the formation of the melt, other processes will have influenced its composition. In the magma, plagioclase started to crystallise and became concentrated near the top of the magma chamber. This would explain why the reddish-white dykes, which predated the Follstad body, are relatively rich in plagioclase phenocrysts, an enrichment which can also be deduced from the more prominent Eu anomalies in the REE patterns. Because the phenocrysts show no resorption structures, this fractionation could be assumed to have occurred at shallow depths. After the crystallisation and cooling of the reddish dykes, their geochemistry was changed to some degree by percolation of fluids across the dykes which gave rise to an anastomosing pattern of 4 cm-wide zones where the reddish hue is replaced by a green coloration, the biotite being replaced by epidote-clinozoisite. At the centre of these zones, microfractures (lined by fibrous zoisite) facilitated the channelling of fluids through the rock. These fractures probably formed when fluids were expelled from the cooling Follstad body, taking up calcium from plagioclase and recycling it into the lattices of epidote and calcite.

A phenomenon that is probably related to this autometasomatic process is the occurrence of a sulphide dissemination, mainly pyrite, which is found in all rocks except for the Follstad intrusion. In some thin-sections the pyrite is seen as an infill in voids in the Gula schists; in others, it has an intergranular location. Although it is generally claimed that all

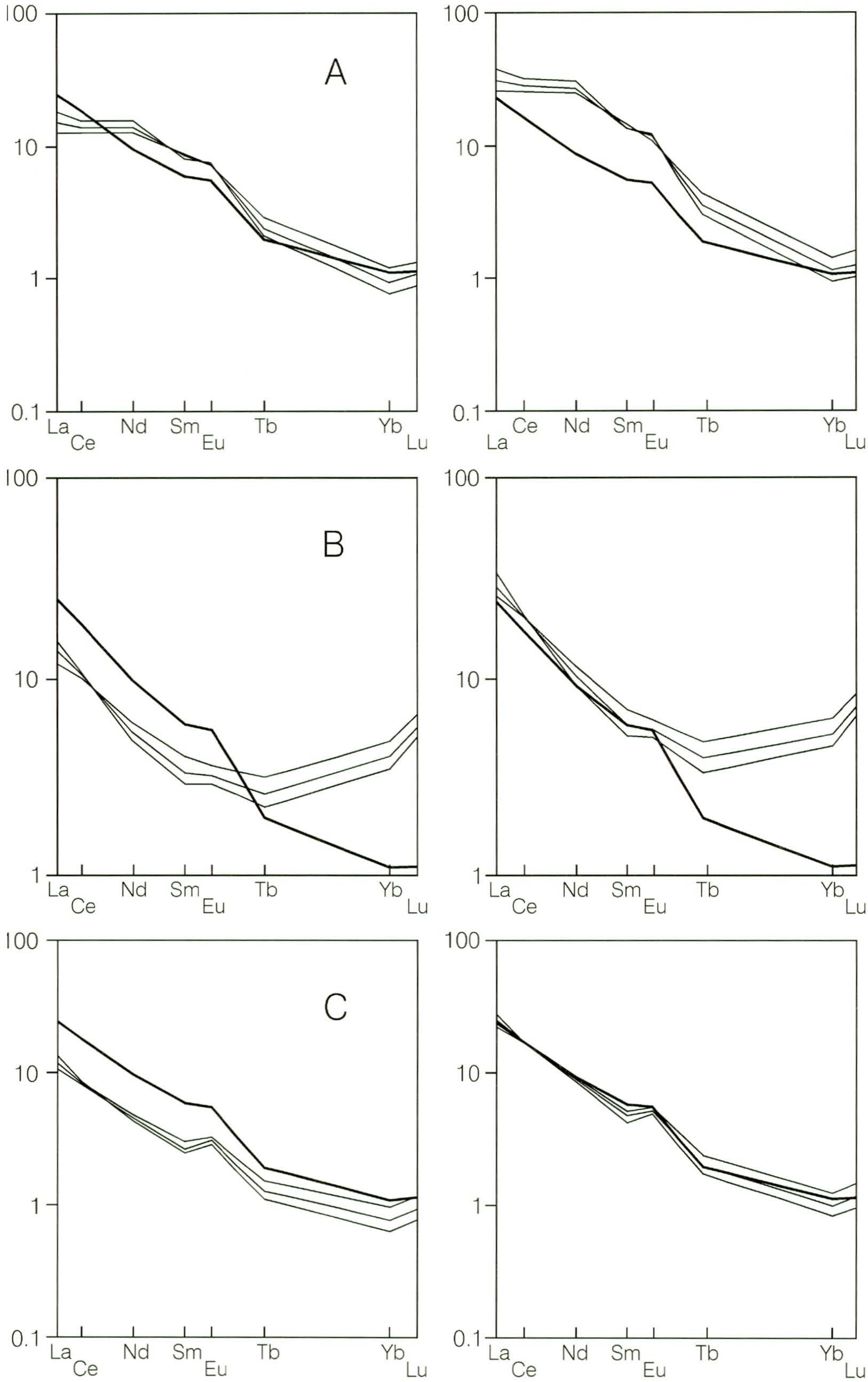

Fig. 11. Calculated chondrite-normalised REE patterns for (a) eclogite, (b) garnet-free amphibolite and (c) garnet-bearing amphibolite. The columns to the left start from a depleted tholeiite, and those to the right from an enriched tholeiite. The bold line represents the pattern of sample BP1, and the others a partial melt of 10%, 20% and 30%.

these sulphide mineralisations are likely to be of regional metamorphic origin, the forceful emplacement of the large Follstad body is believed to have triggered some relocation of metal ions. The Ca-rich fluids that were expelled from the Follstad body upon cooling probably played a role here, and had the potential to carry metal ions in solution. The fluid pressures caused fracturing in the host rocks and along grain boundaries where the sulphides could be precipitated.

Garnet-bearing granodiorite

Chemical data for these garnetiferous granitoids, presented in Tables 2 and 3, show that the rocks are calc-alkalic and peraluminous and, following the terminology of Chappell & White (1974), can be classified as S-type granites. In the An-Ab-Or diagram (Fig. 5), the granitoids plot far outside the TTG fields, and thus their genesis requires a different explanation from that of the trondhjemites. U and Th contents are higher in the granodiorites, though with highly variable U/Th ratios. Nb and Y contents are also higher than in the trondhjemites; in the case of Y, this indicates that garnet was less involved in the formation of the melt.

The REE patterns of these rocks are somewhat complex (Fig. 10d) with moderate LREE enrichment, fairly flat HREE, and negative Eu and Nd anomalies in some, but not all, of the samples. La_N/Tb_N ratios fall in the range 2 to 5.

The source rock for these granitoids could have been an Al-rich sediment that had undergone a comparatively low- to medium-grade metamorphism, as is indicated by the hydrous nature of the melt. The garnets were investigated by semi-quantitative SEM analysis, which showed them to be Mn-rich (>15% spessartine). This contrasts with the more Ca-rich, almandine garnets from the schists of the Gula Complex country rocks. A high spessartine content is typical for garnets of magmatic origin (du Bray 1988); and also the fact that most magmatic garnets are found in Al-rich aplitic to pegmatitic rocks points to a magmatic origin. Similar speassartine-garnet granitoids have been reported from Nevada, USA (Kistler et al. 1981), and Saudi Arabia (du Bray 1988). These calc-alkalic rocks were interpreted to have formed from the melting of sediments, yielding a melt rich in aluminium which facilitated the crystallisation of garnet. The REE patterns reported by Kistler et al. (1981) also show a negative Nd anomaly, which these authors ascribed either to the role played by apatite, zircon or titanite in the residue, or to melting of REE-poor Archaean sediments.

Mafic bodies

As noted earlier, the mafic bodies were not examined in any detail in this investigation. However, the analytical data from just two samples were added to the diagrams solely for comparative purposes.

Discussion

Field relationships of three types or colour varieties of trondhjemite described here from different parts of the Gauldalen district show that, in relative terms, the greenish-white trondhjemite dykes are the oldest, and the white, Follstad-type trondhjemites the youngest intrusions. The reddish-white dykes are believed to have been emplaced at about the same time as, or just slightly earlier than the white, Follstad-type trondhjemites. The leucocratic, garnet-bearing granodiorites occupy an intermediate temporal position, since they transect the early trondhjemite dykes in one area and are themselves cut by dykes and larger sheets of white trondhjemite.

Although only two of these four varieties of felsic plutonic or hypabyssal rock have so far been dated by isotopic methods, the results do appear to support the overall field relationships – a U-Pb age of 432±3 Ma for the Follstad trondhjemite (Grenne & Dunning, this volume), and an interpreted, minimum, Rb-Sr isochron age of 465±11 Ma for greenish-white trondhjemite dykes from Snøan (Roberts & Sundvoll, this volume). Thus, continental margin type, trondhjemite intrusive activity in the Gula Complex spans a time interval of more than 30 million years.

A feature common to all these trondhjemites and the granodiorite is that they cut an early foliation in the Gula metasedimentary complex (Fig. 6); yet, they are themselves variably foliate and in places deformed by folds and a later crenulation cleavage. As noted earlier, the older Snøan-type dykes are known to cut both Gula and Støren rocks, but *not* the unconformably overlying, Late Arenig and younger, Hovin Group succession. Their true age may therefore be close to Mid Arenig (Roberts & Sundvoll 2000), i.e., intruding shortly after the Early Ordovician deformation, metamorphism and ophiolite obduction.

The weak foliation, fold structures and cleavages observed at different places in the trondhjemites and granodiorite are likely to have formed during the later, Siluro-Devonian, Scandian orogenic event. The U-Pb date of 432±3 Ma for the Follstad trondhjemite thus provides a maximum age for the upper greenschist-facies metamorphism of this body, and for the Scandian regional metamorphism in the rocks of the Gula Nappe. There have been two attempts to date the regional metamorphic fabrics in the Gula, initially employing the K-Ar method (Wilson et al. 1973) and later using conventional ^{40}Ar-^{39}Ar techniques (Dallmeyer 1990). After first converting the dates reported in Wilson et al. (1973) using the 'new' decay constants documented by Dalrymple (1979), in both studies all muscovites and biotites, and most hornblendes, record dates in the range c. 432 to 416 Ma, which were interpreted to represent post-metamorphic cooling ages. K-Ar analytical data on phyllitic schists gave ages of around 425-426 Ma, while two samples of biotite from the Follstad trondhjemite yielded recalculated, K-Ar cooling ages of 411 and 415 Ma. Thus, Scandian peak metamorphism in the Gula Nappe rocks occurred in Late Llandovery to Wenlock time, and was immediately followed by rapid uplift and cooling through into the Early Devonian.

Although there is no *direct* evidence of a pre-Scandian thermal event in the Gula, Dallmeyer (1990) noted that the ^{40}Ar-^{39}Ar hornblende data carried widespread evidence of the presence of intracrystalline extraneous argon components that "clearly point toward a pre-Silurian tectonothermal history" for these polymetamorphic rocks. Likewise, some of the K-Ar hornblende data reported by Wilson et al. (1973) suggested to these authors the possibility that a pre-Silurian, early Caledonian, orogenic event may have been responsible for some of the amphibolite-facies metamorphism. The subjacent Skjøtingen (Seve) Nappe, by contrast, has yielded more widespread and fairly consistent, ^{40}Ar-^{39}Ar hornblende data favouring the view that "significant orogenic activity occurred during and/or shortly prior to Arenig" (Dallmeyer 1990). These hornblendes were later variably rejuvenated during the Scandian (c. 425-400 Ma) thermotectonic event.

From the geochemical data and petrogenetic considerations, it has been suggested that the trondhjemites originated from a garnet-bearing amphibolite. Based on the regional geology, further constraints can be placed on this model. Size (1979) considered there to have been a common magma source from which trondhjemitic magmas escaped and penetrated the polydeformed Gula metasedimentary succession at different times. However, it seems improbable that such a magma could have continued to exist, unchanged, throughout evolving tectonic settings. More likely, the trondhjemitic magmas formed intermittently by similar processes of equilibrium melting of comparable source rocks, i.e. low-K metamorphosed basalts, which are particularly common rock-types in the region, and show transitions from low-grade metabasalts through garnetiferous amphibolites to eclogites. Garnet-bearing amphibolites occur at temperatures between 550 and 750°C and at pressures equivalent to depths of 20-30 km (Bucher & Frey 1994), in both subduction zone and orogenic situations. In both cases, however, there is a lack of heat to induce melting, since the subducting slab in a subduction zone or the overriding nappes in orogens are cold and thus depress the geotherms. Increasing the temperature by deeper burial will also raise pressures and amphibolite will be gradually transformed to eclogite; and the dehydration will raise the solidus even more.

In the case of the Gula trondhjemites, their paleogeological situation, high Al_2O_3 contents and other geochemical traits, and their local association with gabbros and diorites, are all pointing consistently to a continental margin setting rather than a subduction zone. In a polyorogenic scenario, the lack of sufficient heat is more apparent than real when one considers the geothermal evolution during the sequential development of the orogen. During the active period of initial convergent movement, the thrust emplacement of relatively cold crustal sheets and ophiolite slabs would have depressed the geotherms, but as these processes slowed down and ceased this would have given way to an extension of the thickened crust, locally with rifting involved, and a gradual rebounding of the geotherm. This general increase in temperature would have facilitated a partial melting of the amphibolites, resulting in the intermittent emplacement of trondhjemitic melts. The Late Ordovician-Early Silurian time interval is known to record an important period of crustal extension and bimodal magmatism in the Upper Allochthon of the Norwegian Caledonides (Stephens et al. 1985, Sturt & Roberts 1991, Pedersen et al. 1991), during which time the requisite heat to induce partial melting at intermediate to shallow crustal depths would have been readily available (see also Dunning & Grenne 2000).

Conclusions

Three types or colour varieties of trondhjemite cutting rocks of the Gula Complex in the Gauldalen district of Central Norway have been distinguished on the basis of field relationships. The trondhjemites show comparable geochemical features, with high Al_2O_3, Rb and Sr contents and low Yb values that signify their generation in a continental margin palaeotectonic setting. They are considered to have formed as melting products of a garnet-bearing amphibolite. Less common, spessartine garnet-bearing granodiorites along Gauldalen are calc-alkaline and peraluminous, and may have derived from an Al-rich metasedimentary source.

Field relationships denote that the greenish-white trondhjemite dykes and sheets are the oldest intrusions. In one area, these rocks have provided a Rb-Sr whole-rock isochron (minimum) age of 465±11 Ma. The garnetiferous granodiorites cut these early dykes, and are themselves transected by dykes and larger bodies of white trondhjemite. This latter variety includes the Follstad trondhjemite which has given a U-Pb age (zircon and titanite) of 432±3 Ma.

All the trondhjemites and the granodiorite postdate an early foliation in the Gula rocks, but they are themselves weakly and variably foliated, and locally folded and cut by a later crenulation cleavage. The above isotopic evidence, together with regional isotopic data and biostratigraphic constraints, thus suggests that an early tectonothermal event affected the Gula rocks before 465 Ma, and probably in Early-Mid Arenig time. The foliation, folding and cleavages in the trondhjemites and granodiorite, on the other hand, must postdate the 432 Ma age of the Follstad trondhjemite, and are considered to have formed during the main Scandian tectonothermal event dated isotopically to around 425 Ma.

Acknowledgements

We are grateful to the reviewers, William Size and Odd Nilsen, for their careful, constructive and helpful comments on the manuscript; and to Tor Grenne for comments on an early version of the text, and for diverse discussions on the geology of the Trondheim region. Jan Hertogen is thanked for carrying out the REE analyses, and for his invaluable help and advice in supervising the first author during his 'Diplom' thesis studies in Leuven. The digital line drawings were prepared by Irene Lundquist.

References

Arth, J.G. 1979: Some trace elements in trondhjemites – their implications to magma genesis and paleotectonic setting. *In* Barker, F. (ed.) *Trondhjemites, dacites and related rocks.* Elsevier, Amsterdam, 123-132.

Barker, F. 1979: Trondhjemite: definition, environment and hypotheses of origin. *In* Barker, F. (ed.) *Trondhjemites, dacites, and related rocks. Elsevier, Amsterdam,* 1-12.

Barker, F. & Millard, Jr., H.T. 1979: Geochemistry of the type trondhjemite and three Associated rocks, Norway. *In* Barker, F. (ed.) *Trondhjemites, dacites and related rocks.* Elsevier, Amsterdam, 517-529.

Bjerkgård, T. & Bjørlykke, A. 1994: Geology of the Folldal area, southern Trondheim Region Caledonides, Norway. *Norges geologiske undersøkelse Bulletin 426,* 53-75.

Bucher, K. & Frey, M. 1994: *Petrogenesis of metamorphic rocks.* Springer-Verlag,

Chappell, B.W. & White, A.J.R. 1974: Two contrasting granite types. *Pacific Geology 8,* 173-174.

Dallmeyer, R.D. 1990: $^{40}Ar/^{39}Ar$ mineral age record of a polyorogenic evolution within the Seve and Köli Nappes, Trøndelag, Norway. *Tectonophysics 179,* 199-226.

Dalrymple, G.B. 1979: Critical tables for conversion of K-Ar ages from old to new constants. *Geology 7,* 558-560.

Dixon, S. & Rutherford, M.J. 1979: Plagiogranites and late-stage immiscible liquids in ophiolites and mid-ocean ridge suites: an experimental study. *Earth and Planetary Science Letters 45,* 45-60.

du Bray, A. 1988: Garnet compositions and their use as indicators of peraluminous granitoid petrogenesis, southeastern Arabian Shield. *Contributions to Mineralogy and Petrology 100,* 205-212.

Dunning, G.R. 1987: U-Pb zircon ages of Caledian ophiolites and arc sequences: implications for tectonic setting. (Abstract) *Terra Cognita 7,* 179.

Dunning, G.R. & Grenne, T. 2000: U-Pb age dating and palaeotectonic significance of trondhjemites from the type locality in the Central Norwegian Caledonides. *Norges geologiske undersøkelse Bulletin 437,* 57-65.

Gee, D.G., Guezou, J.C., Roberts, D. & Wolff, F.C. 1985: The central-southern part of the Scandinavian Caledonides. *In* Gee, D.G. & Sturt, B.A. (eds.) *The Caledonide orogen – Scandinavia and related areas.* John Wiley & Sons, Chichester, 109-133.

Goldschmidt, V.M. 1916: Geologisch-Petrographische studien im Hochgebirge des südliche Norwegens, IV. Übersicht die Eruptivegesteine im kaledonischen Gebirge zwischen Stavanger und Trondheim. *Vidensk. Selsk. Skr. 1, Mat. Naturv. Kl. 2,* 1-140.

Grenne, T. & Roberts, D. 1981: Fragmented ophiolite sequences in Trøndelag, central Norway. *Guide to Excursion B12, Uppsala Symposium,* 40 pp.

Grenne, T. & Roberts, D. 1998: The Hølonda Porphyrites, Norwegian Caledonides: geochemistry and tectonic setting of Early – Mid-Ordovician shoshonitic volcanism. *Journal of the Geological Society, London 155,* 131-142.

Guezou, J.C. 1978: Geology and structure of the Dombås-Lesje area, southern Trondheim Region, South-central Norway. *Norges geologiske undersøkelse 340,* 1-34.

Helz, R.T. 1976: Phase relations of basalt in their melting ranges at PH_2O= 5 kb, Part II. Melt compositions. *Journal of Petrology 17,* 139-193.

Kistler, R.W., Ghent, E. & O'Neill, J. 1981: Petrogenesis of garnet two-mica granites in the Ruby Mountains, Nevada. *Journal of Geophysical Research 68 B11,* 10591.

Lagerblad, B. 1984: Tectono-metamorphic relationships of the Gula-Fundsjø Group contact zone in the Inndalen-Færen area, Trøndelag, central Norwegian Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar 105,* 131-153.

Le Maitre, R.W. 1989: *A classification of igneous rocks and glossary of terms. Recommendations of the IUGS Subcommission on the systematics of igneous rocks.* Blackwell Scientific Publications, Oxford, 193 pp.

Loeschke; J. 1976: Petrochemistry of eugeosynclinal magmatic rocks of the area around Trondheim (central Norwegian Caledonides). *Neues Jahrbuch für Mineralogie, Abhandlungen 128,* 1-44.

Martin, H. 1987: Petrogenesis of Archaean trondhjemites, tonalites and granodiorites from Eastern Finland: major and trace element geochemistry. *Journal of Petrology 28,* 921-953.

McClellan, E.A. 1994: Contact relationships in the southeastern Trondheim Nappe Complex, central-southern Norway: implications for early Paleozoic tectonism in the Scaandinavian Caledonides. *Tectonophysics 231,* 85-111.

Nilsen, O. 1978: Caledonian sulphide deposits and minor iron-formations from the southern Trondheim Region, Norway. *Norges geologiske undersøkelse 340,* 35-85.

Nilsen, O. 1983: The nature and tectonic setting of m'elange deposits in Soknedal, near Støren, Central Norwegian Caledonides. *Norges geologiske undersøkelse 378,* 65-81.

Nilsen, O. & Wolff, F.C. 1988: Geologisk kart over Norge, berggrunnskart RØROS og SVEG – 1:250 000. *Norges geologiske undersøkelse.*

O'Connor, J.T. 1965: A classification for quartz-rich igneous rocks based on feldspar ratios. *United States Geological Survey Professional Paper 525-B,* 79-84.

Pedersen, R.B. & Malpas, J. 1984: The origin of oceanic plagiogranites from the Karmøy ophiolite, western Norway. *Contributions to Mineralogy and Petrology 88,* 26-52.

Pedersen, R.B., Furnes, H. & Dunning, G. 1991: A U/Pb age for the Sulitjelma Gabbro, north Norway: further evidence for the development of a Caledonian marginal basin in Ashgill-Llandovery time. *Geological Magazine 128,* 141-153.

Rapp, R.P., Watson, E.B. & Miller, C.F. 1991: Partial melting of amphibolite/eglogite and the origin of Archean trondhjemites and tonalites. *Precambrian Research 51,* 1-25.

Roberts, D. 1978: The Caledonides of South-central Norway. In Schenk, P. (ed.) The Caledonides of the North Atlantic Region. *Geological Survey of Canada Special Paper 78-13,* 17-24.

Roberts, D. & Sundvoll, B. 1996: Geochemistry and Rb-Sr dating of trondhjemite dykes from the Gula Group, near Snøan, Sør-Trøndelag. *Norges geologiske undersøkelse Report 96.163,* 11 pp.

Roberts, D. & Sundvoll, B. 2000: Geochemistry and Rb-Sr isochron age of trondhjemite dykes from the Gula Complex, near Støren, Central Norway. *Norges geologiske undersøkelse Bulletin 437,* 67-74.

Roberts, D., Grenne, T. & Ryan, P.D. 1984: Ordovician margional basin development in the central Norwegian Caledonides. *In* Kokelaar, B.P. & Howells, M.F. (eds.) Marginal Basin Geology. *Geological Society of London, Special Publication 13,* 233-244.

Rui, I.J. 1972: Geology of the Røros district, southeastern Trondheim region, with a special study of the Kjøliskarvene-Holtsjøen area. *Norsk Geologisk Tidsskrift 52,* 1-21.

Rui, I.J. & Bakke, I. 1975: Stratabound sulphide mineralization in the Kjøli area, Røros district, Norwegian Caledonides. *Norsk Geologisk Tidsskrift 55,* 51-75.

Shaw, D. 1970: Trace element fractionation during anatexis. *Geochimica et Cosmochimica Acta 34,* 237-243.

Size, W.B. 1979: Petrology, geochemistry and genesis of the type area trondhjemite in the Trondheim Region, Central Norwegian Caledonides. *Norges geologiske undersøkelse 351,* 51-76.

Stephens, M.B., Furnes, H., Robins, B. & Sturt, B.A. 1985: Igneous activity within the Scandinavian Caledonides. *In:* Gee, D.G. & Sturt, B.A. (eds.): *The Caledonide Orogen – Scandinavia and related areas.* John Wiley & Sons. Chichester, 623-656.

Streckeisen, A. 1976: To each plutonic rock its proper name. *Earth Science Reviews 12,* 1-33.

Sturt, B.A. & Roberts, D. 1991: Tectonostratigraphic relationships and obduction histories of Scandinavian ophiolitic terranes. *In* Peters, T. (ed.) *Ophiolite genesis and evolution of oceanic lithosphere.* Kluwer Academic Publishers, Amsterdam, 745-769.

Vogt, Th. 1941: Geological notes on the Dictyonema locality and the upper Guldal district in the Trondheim area. *Norsk Geologisk Tidsskrift 20,* 171-192.

Wilson, M.R., Roberts, D. & Wolff, F.C. 1973: Age determinations from the Trondheim Region Caledonides, Norway: a preliminary report. *Norges geologiske undersøkelse 288,* 53-63.

Wolff, F.C. 1979: Beskrivelse til de berggrunnsgeologiske kart Trondheim og Østersund 1:250 000. *Norges geologiske undersøkelse 353 (Skrifter 31),* 76 pp.