Petrology, Geochemistry and Genesis of the Type Area Trondhjemite in the Trondheim Region, Central Norwegian Caledonides

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Trondhjemite from the Follstad district of the Trondheim region is present within allochthonous Lower Paleozoic eugeosynclinal and partly miogeosynclinal rocks of the Caledonide orogen. Four periods of trondhjemite intrusive activity have been recognized, with the main Follstad trondhjemite a product of late tectonism and metamorphism in the upper greenschist facies. Field relations, mineralogy and major and trace element abundances all attest to the high degree of homogeneity of the trondhjemite, which is of the high-Al_2O_3 type (average 16.2%). Trondhjemites of the district average 71.5% SiO_2, 5.3% Na_2O_3, but only 1.3% K_2O. The REE abundances are depleted and highly fractionated. Barium greatly exceeds rubidium in abundance. Distinctive compositional characteristics of the Follstad trondhjemite support designation of the district as a type locality for trondhjemite. Petrogenetic models for the origin of the Follstad district trondhjemite that are based on anatexis of granitic crust or partial melting of greywacke are unlikely. Distinctive compositional gaps in the gabbro–trondhjemite suite, when compared with the other associated magmatic rocks in the Follstad district, cannot easily be explained by a fractional crystallization model. The petrogenetic model that best fits the data from the Follstad trondhjemite is based on equilibrium melting of a low-K_2O tholeiitic basalt during anatexis in an orogenic zone. Published experimental work on the partial melting of basalt shows that at 5 kb P_{H_2O} and between 825°–850°C, a melt of trondhjemite composition is produced. Residual hornblende would produce compositional trends similar to those of the Follstad district trondhjemite.

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Introduction

Trondhjemites have been called by other names in the literature including soda-granite, plagiogranite and leucogranodiorite. They are distinctive rock types and are abundant in continental Archean age rocks (Arth & Hanson 1975). The association of trondhjemites with younger mobile belts at continental margins and subduction zones indicates that the production and growth of continental crust may be associated with the genesis of trondhjemitic rocks.

The purpose of this paper is to quantify the mineralogic, chemical and petrologic characteristics of the type area of trondhjemite as first proposed by Goldschmidt (1916) and to provide the data necessary for this area to be used as a standard against which to compare other trondhjemite-bearing areas. Of equal importance in this study is an examination of the different petrogenetic models proposed for the origin of trondhjemite to determine which, if any, are consistent with the data from the type area trondhjemite.

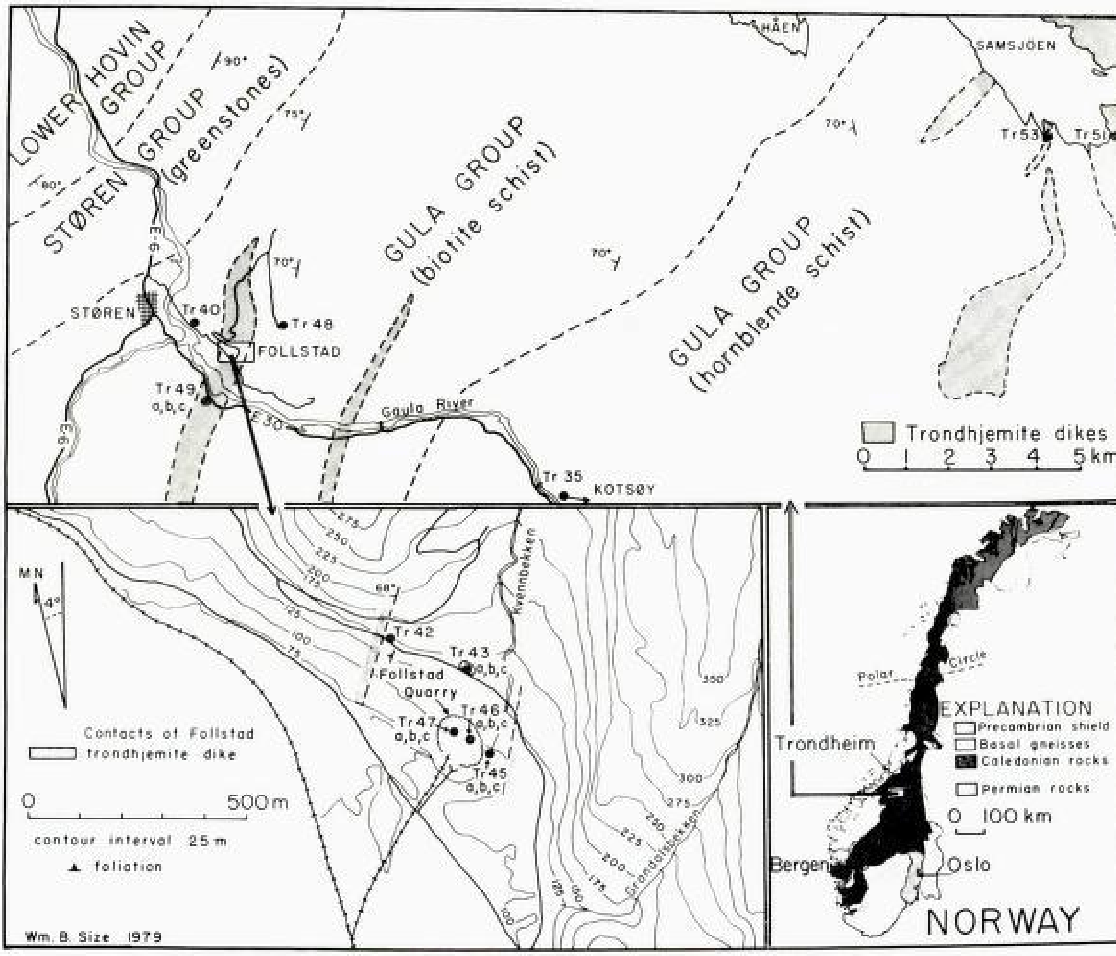

Fig. 1. General geologic maps and two sample location maps of the study area in the Central Norwegian Caledonides, south of the city of Trondheim. Geology after Wolff (1976). Sample number locations listed below Table 1.

The general study area is in the Trondheim region (Fig. 1), which is considered to represent the type area of the 'eugeosynclinal zone' of the Norwegian Caledonides (Strand & Kulling 1972). Petrochemistry of the eugeosynclinal magmatic rocks and interpretation of their relationships to the tectonic history of the Trondheim region have been discussed by Gale & Roberts (1972, 1974), Loeschke (1976) and Dypvik (1977).

The area reported in this study is located 45 km south of Trondheim (Fig.1) near the town of Støren (10°20′E. Long., 63°N. Lat.). The major area of interest is 2 km east of Støren at the Follstad quarry (Fig. 1). Replicate trondhjemite samples were collected from the quarry and from the same instrusive body north and south of the quarry. For comparison, other trondhjemite bodies were sampled from the surrounding area (Fig. 1); these and the quarried trondhjemites will hereafter collectively be called the 'Follstad district trondhjemite'.

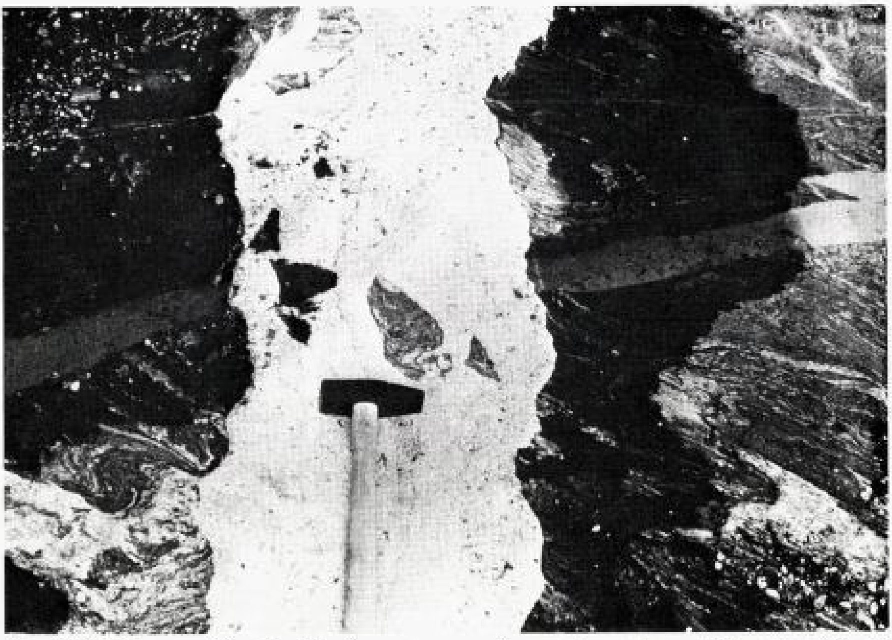

Fig. 2. Multiple trondhjemite dikes in outcrop on the southwest shore of Samsjøen (Tr 53, Fig. 1). Cross-cutting dikes contain xenoliths and are not chilled against the Gula schist country rock. The largest dike represents a composite intrusion.

Stratigraphic and tectonic setting of the Follstad district

Rocks of Late Precambrian to Silurian age in the Trondheim region Caledonides are allochthonous and rest with tectonic discontinuity on the Precambrian granitic and gneissic basement of the Baltic Shield to the east. These Caledonian nappe rocks are mainly eugeosynclinal-type basic volcanic rocks associated with a variety of sedimentary rocks which have undergone a polyphase tectonometamorphic history (Roberts 1967, Wolff 1967, 1976, Roberts et al. 1970, Rui 1972, Olesen et al. 1973). Rock assemblages in the principal nappe unit, the Trondheim Nappe (Wolff 1967), are collectively termed the Trondheim Supergroup (Gale & Roberts 1974) and comprise the basal Gula Schist Group followed by the Støren, Lower Hovin, Upper Hovin and Horg Groups.

In the study area, almandine–amphibolite facies pelitic and quartz schists and subordinate amounts of quartzites of the Gula Schist Group lie tectonically beneath Støren Group greenstones (Fig. 1). Traditionally, the Gula Group has been considered Cambrian (Wolff 1967, Guezou 1975), but a Precambrian age has also been suggested (Roberts 1978). The Follstad trondhjemite bodies intrude these rocks (Fig. 2) and are late-tectonic with respect to the principal Silurian deformation. The overlying Støren Group, in tectonic contact with the Gula, consists of a 2.5 km pile of basic volcanic rocks, locally with pillow structure, which are generally thought to be of Tremadocian to early Arenig age (Roberts et al. 1970). These volcanic rocks represent metamorphosed tholeiite-type basalts indicative of both ocean floor and, in part, island-arc tectonic set-

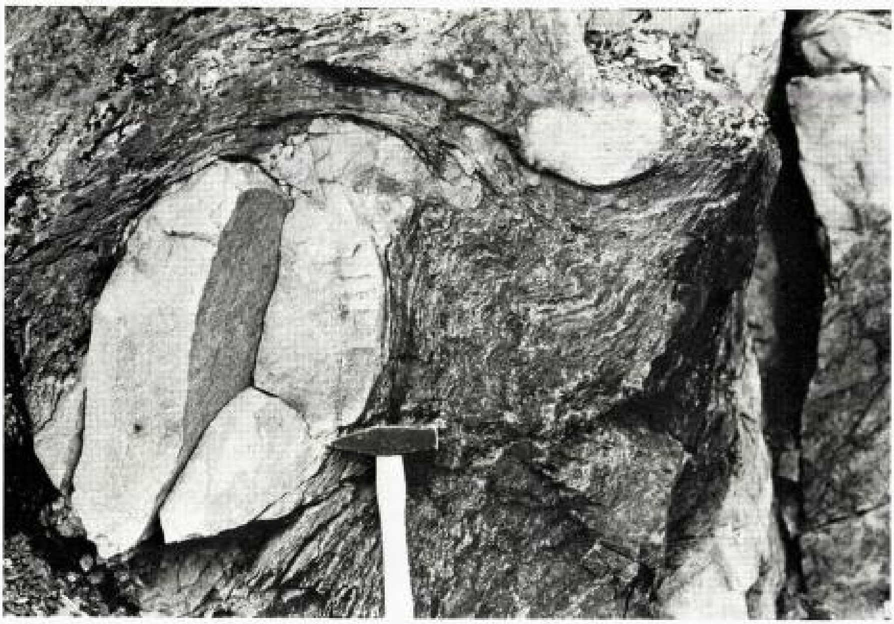

Fig. 3. Deformed trondhjemite dike northeast of the Follstad quarry (Tr 48, Fig. 1). The dike is boudined and sheared with the plane of shear conformable to the adjacent Gula schist country rock foliation. Later small-scale folding is also evident.

tings (Gale & Roberts 1974, Loeschke 1976). The overlying Lower Hovin Group is of Lower to Middle Ordovician age and the Upper Hovin of Upper Ordovician age. These groups are mainly flysch-type sedimentary rocks metamorphosed in lower to upper greenschist facies.

The climactic Caledonian deformation and metamorphism in the region occurred in Middle Silurian (Roberts et al. 1970). Four major phases of deformation have been documented (e.g., F_1–F_4), with the pervasive metamorphic fabric associated with the F_1 isoclinal fold episode. Major thrusting is thought to have occurred towards the end of the F_2 deformation, forming the Trondheim Nappe, but important pre-metamorphic thrusting is also recognized in the obduction of the Støren Nappe (Gale & Roberts 1974). A minimum age for the last metamorphic phase is given as 438 ± 12 m.y. B.P. (Wilson et al. 1973, p. 58). This date is also assigned as a minimum age for the F_3 period of folding.

Folds of F_1 age, together with the associated regional schistosity and local shearing, are present in the Gula Schist Group in the study area, but this F_1 fabric is not present in the trondhjemite bodies. Some of the smaller trondhjemite dikes in the Follstad district were boudinaged and sheared prior to later folding (Fig. 3). However, the main intrusion at the Follstad quarry shows only weak metamorphism and very little mechanical deformation. Therefore, it appears that the trondhjemite dikes in the Follstad district were emplaced at different times with the older, more deformed ones being post-F_1 deformation and the Follstad quarry trondhjemite being possibly post-F_3 deformation. The radiometric ages for these rocks lend support to this conclusion.

Age relationships of trondhjemitic rocks in the Follstad district to country rocks have been outlined by Wilson et al. (1973). The last thermal peak of metamorphism of the Gula Schist, which is the country rock for the Follstad trondhjemite, gives K/Ar dates of 418 and 415 m.y. B.P., whereas the trondhjemite itself yields ages of 407 and 403 m.y. B.P. This trondhjemite could therefore post-date the F_3 folding period.

Field relations of the Follstad district trondhjemite

There were three or four periods of trondhjemite intrusive activity in the Follstad district during the Lower Paleozoic (Roberts 1978). The oldest trondhjemite bodies tend to lie within the regional foliation (Fig. 3). Younger trondhjemite intrusions cut across the foliation and tend to be contorted into later, open folds. An even younger phase is represented by the Follstad body, which has little mechanical deformation, but contains a metamorphic mineral assemblage. The youngest phase of trondhjemite emplacement is represented by the trondhjemite pegmatites. No examples of this last type are found in the study area, but such rocks occur in the Verdal and Stjørdalen valleys as described by Wolff (1960, 1967) and Roberts (1967), and some have been dated by Wilson et al. (1973).

Most of the trondhjemite bodies in the study area are discordant and contain xenoliths of country rock, as can be seen at Samsjøen (Fig. 2) and in the Kvennbekken stream just west of the main Follstad quarry. At contacts with the country rock, trondhjemite is not chilled and shows a fluxion foliation. Many of the dikes show evidence of being multiple intrusions, judging from the sharp discontinuities in grain size and mineral proportions across the dike (Fig. 2). Most of the dikes in the area are not as wide as the Follstad body, and even the smaller ones do not show any chilling, a good indication that the wall rock was at a reasonably high temperature at the time of intrusion.

The Follstad trondhjemite body (Fig. 1) is approximately 375 m wide in the vicinity of the main quarry. It has a general strike of N20°–25°E and dips approximately 68° to the northwest. Its western contact with the Gula phyllite is very sharp with slight silicification and hornfelsic texture as the only contact metamorphic effects. Iron-staining and a weakly developed cataclastic zone were observed at the contact.

Sampling and analytical methods

Thirty samples of trondhjemite were taken from dikes in the Follstad district (Fig. 1; Table 1). Other trondhjemite intrusives from the surrounding region were also sampled for comparison (numbers Tr 35, 40, 42, 48, 51, 53). However, Sample Tr 40 was ultimately determined to be a quartz keratophyre and Sample Tr 51 is a leuco-monzogabbro.

Rock samples for statistical analysis of variance were taken from fresh exposures of trondhjemite in the Follstad district. At each outcrop location (Fig. 1) three rock samples, each weighing 2 kg, were taken 5 m from one another in a triangular arrangement. Two thin-sections were cut perpendicular to one another from each rock sample. The remainder of the sample was then trimmed to remove any surface alteration and then powdered in an

Fig. 4. Block of trondhjemite from the main quarry at Follstad showing biotite streaking and faint foliation. The trondhjemite is usually very homogeneous and massive.

agate mill for chemical analysis. The powders were split for major and minor element analysis.

A detailed petrographic analysis, including the modal analysis method of Chayes (1956), was performed on each thin-section. At least 1000 counts were made on each thin-section and usually the slide was turned around and an additional 1000 counts were made. Results of these modal analyses are presented in Table 1 as means and standard deviations of replicate samples.

Chemical analyses of SiO_2, TiO_2, Al_2O_3 and CaO were done by X-ray fluorescence spectrometry using the method of Padfield & Gray (1971) (J. Sandvik, analyst); total iron, MnO, Na_2O and K_2O were determined by atomic absorption spectrophotometry; FeO by titrimetry; H_2O (total), CO_2, and H_2O^- by gravimetry; and P_2O_5 by spectrophotometry. Results of the chemical analyses are given in Table 2. All analyses listed are believed accurate to $\pm$ 2% or better of the amount present. CIPW norms based on these chemical analyses are given in Table 3.

Trace element analyses were done by neutron activation at the Nuclear Research Laboratory at Virginia Polytechnic Institute and State University (T. F. Parkinson, analyst). Samples were irradiated in a thermal flux of 1.3×10^{12}n/cm^2-sec, using high resolution Ge-(Li) detectors. U.S. Geological Survey standard rocks, BCR-1, AGV-1, G-2 and GSP-1 were used as standards. Results of trace element analyses are given in Table 4.

Petrography

TEXTURE AND STRUCTURE

Follstad trondhjemite is whitish in color, speckled with dark brown biotite. In hand-specimen it is homogeneous and massive, having only a weak foliation which is defined by biotite and muscovite (Fig. 4) and which strikes N40°E and dips to the northwest. Prominent jointing strikes N5°–12°E and dips 45°–47° to the northwest.

Trondhjemite samples from dikes in the Follstad district are holocrystalline, medium-grained (0.5–1.5 mm) and hypidiomorphic–granular in texture (Fig. 5). As the degree of alteration increases, the rock texture grades into allotriomorphic–granular. Slightly metamorphosed varieties of trondhjemite have a weakly developed granoblastic texture. Further details of metamorphic recon-

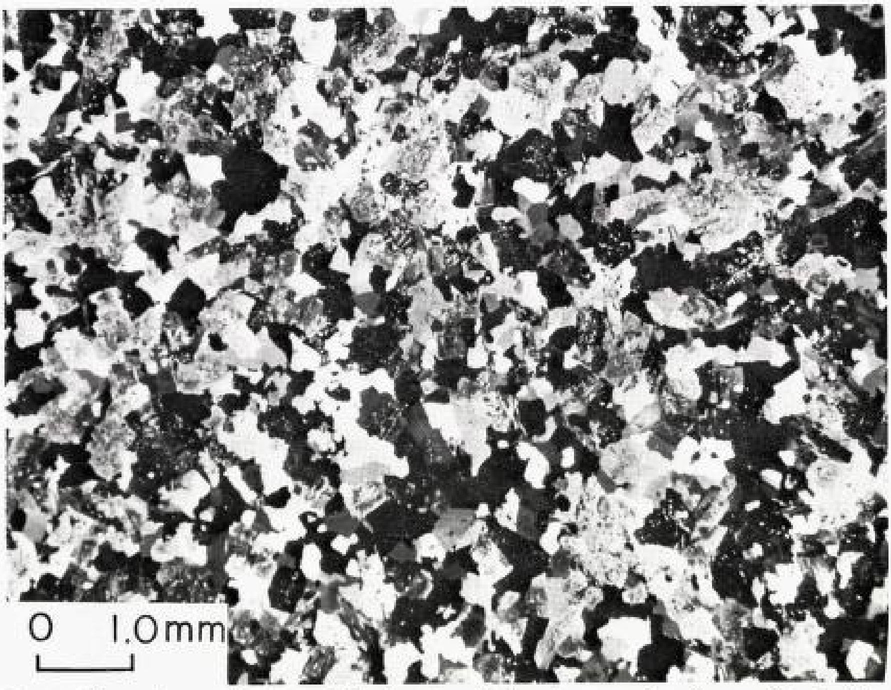

Fig. 5. Photomicrograph of trondhjemite from Follstad quarry showing typical hypidiomorphic–granular texture with slight overprinting of a granoblastic, recrystallized texture. Crossed-polars.

stitution of the rocks are given in the section on evidence of metamorphism. Alteration of trondhjemite ranges from slight to moderate and is best seen in thin-section. Cores of plagioclase are commonly partially replaced by sericite, epidote and calcite.

Three different types of mineral clusters are present in the rock: (1) mafic clusters, consisting of epidote, biotite, muscovite, sphene and zircon; (2) quartz clusters; and (3) clusters of plagioclase laths with small angular–interstitial spaces filled with albite. These clusters appear more indicative of magmatic synneusis than metamorphic segregation.

In thin-section, biotite and muscovite are commonly bent and crudely aligned to define a faint foliation (Fig. 4). Locally quartz and plagioclase have been microsheared into a mortar structure. Grain boundaries rarely interlock; rather, most are straight to slightly curved, indicating recrystallization. Overgrowths of albite on plagiclase are conspicuous, even in hand-specimen.

MODAL MINERAL DESCRIPTION

Trondhjemites from the Follstad district show a very small degree of modal variation. The composite average for 30 samples (Table 1) can therefore be viewed as representative of the entire intrusion. A triangular plot of the relative modal percentages of quartz, alkali feldspar and plagioclase (Fig. 6) shows that most samples plot in the tonalite field and none of them in the trondhjemite

Table 1. Means and standard deviations (in parentheses) of replicate modal analyses (1000 counts) of trondhjemitic rocks from the Follstad district, central Norway. Sample locations listed below and shown on Fig. 1

	Follstad Quarry				
Series Number of Samples	Tr 43 6	Tr 45 6	Tr 46 6	Tr 47 6	Tr 49 6
Quartz	25.5 (3.9)	27.2 (1.3)	26.0 (0.8)	25.3 (1.3)	26.3 (1.2)
K. Feldspar	1.0 (0.2)	1.8 (1.2)	2.4 (0.8)	2.7 (0.2)	8.6 (1.7)
Plagioclase	59.4 (4.1)	58.4 (2.2)	57.2 (2.3)	60.5 (2.4)	53.4 (6.4)
Muscovite	6.2 (1.2)	5.8 (0.8)	6.2 (1.2)	4.5 (0.9)	7.1 (3.6)
Biotite	2.4 (1.1)	1.8 (1.1)	2.6 (0.8)	2.0 (0.5)	0.4 (0.3)
Magnetite	tr.	tr.	tr.	tr.	tr.
Apatite	tr.	tr.	tr.	0.1	tr.
Sphene	0.2	0.3	0.4	0.3	tr.
Zircon	tr.	tr.	tr.	tr.	tr.
Epidote	4.8 (0.8)	4.6 (0.8)	5.1 (0.8)	4.5 (0.9)	3.1 (1.2)
Chlorite	tr.	tr.	tr.	—	0.6
Calcite	tr.	tr.	tr.	—	tr.
TOTAL	99.5	99.9	99.9	99.9	99.5
Density g/cm³	2.69 (0.01)	2.68 (0.01)	2.69 (0.01)	2.68 (0.01)	2.67 (0.01)

Location of trondhjemite samples (grid references refer to 1:50,000 map sheet M711 1621 III 'Støren'):

Tr 43 (a, b, c) — Follstad, small quarry located 125 m to the north of main quarry (670 901).

Tr 45 (a, b, c) — Follstad, 25 m east of main quarry in Kvenbekken Stream (670 899).

Tr 46 (a, b, c) — Follstad, main quarry, center section of quarry wall face (669 899).

Tr 47 (a, b, c) — Follstad, main quarry, western margin of quarry wall face (669 899).

Tr 49 (a, b, c) — Follstad area, road outcrop approximately 3 km southeast of Støren, on Highway 30 (665 887).

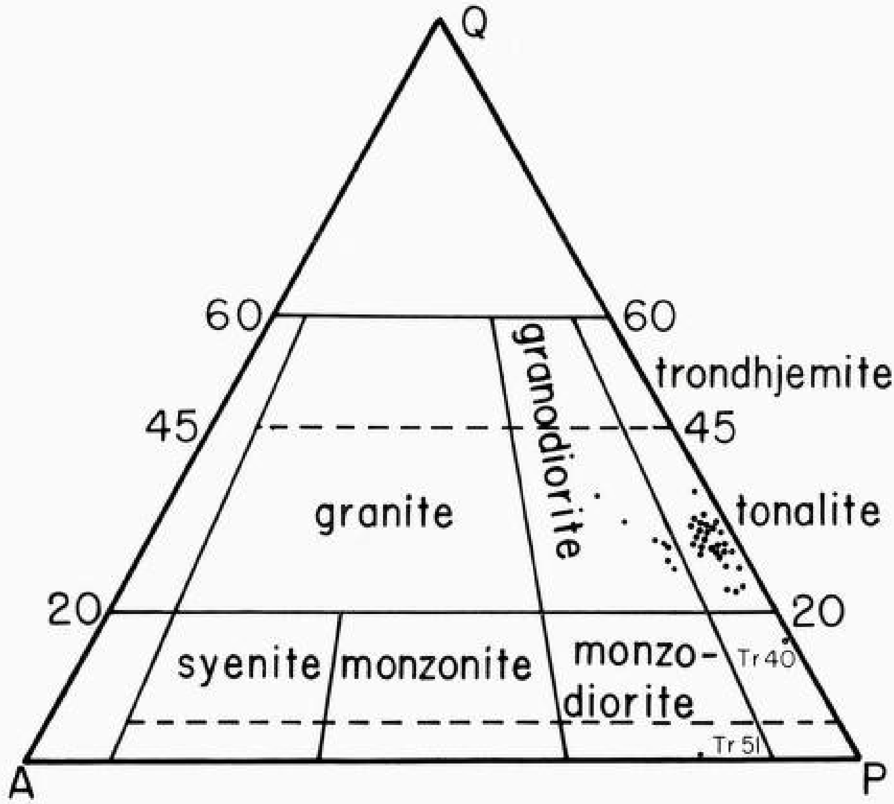

Table 1 (Continued)

Pooled Tr 43–49 30	Surrounding Region					
	Tr 35	Tr 40	Tr 42	Tr 48	Tr 51	Tr 53
26.1 (2.2)	25.1	12.3	26.0	15.8	tr.	21.9
3.3 (2.9)	4.2	—	2.9	2.1	17.5	3.9
57.8 (4.3)	60.3	63.8	60.2	50.9	81.0	69.2
5.9 (2.0)	6.5	10.3	4.2	20.8	1.1	0.3
1.9 (1.0)	3.2	—	1.8	—	—	tr.
tr.	tr.	0.4	tr.	tr.	—	tr.
tr.	tr.	—	tr.	—	—	tr.
0.2	—	0.9	tr.	0.1	0.1	—
tr.	—	—	tr.	—	—	—
4.4 (1.1)	—	4.8	4.9	—	—	—
tr.	—	3.4	—	4.8	0.2	4.7
tr.	0.7	4.0	—	5.6	0.1	—
99.6	100.0	99.9	100.0	100.1	100.0	100.0
2.68 (0.01)	2.66	2.70	2.66	2.66	2.61	2.62

Tr 35 — Kotsøy, approximately 0.5 km south of the village in a road outcrop.

Tr 40 — Follstad area, road outcrop at intersection of new bridge over Gaula River and road tunnel from Støren to Follstad (660 904). Quartz keratophyre.

Tr 42 — Follstad district, approximately 8 m from western contact of trondhjemite with Gula phyllite (668 901).

Tr 48 — Follstad district, approximately 1.2 km northeast of main quarry. Small sheared dike (679 905).

Tr 51 — Samsjøen Lake, southeast shore, near water outlet tunnel (867 953). Leuco-monzogabbro.

Tr 53 — Samsjøen Lake, southwestern shore, near water outlet tunnel (848 955).

field. Chemically and mineralogically, however, the rocks from the Follstad district are true trondhjemites; in fact, the quarry at Follstad is viewed as the type-locality of trondhjemite, as first proposed by Goldschmidt (1916). The boundary between tonalite and trondhjemite (45% quartz), as shown in the diagram, is not truly representative of the natural system. Most trondhjemitic rocks from other areas would also plot in the tonalite field of Streckeisen (1967). The mafic index of tonalite is higher than that of trondhjemite and the SiO_2 content is lower, so there is actually a real difference between the two rock types.

Plagioclase: Plagioclase is present as subhedral laths ranging from 0.1–2.0 mm and averages 58% by volume of the rock. Crystals show no apparent orientation apart from their tendency to form clusters or glomeroclasts. Composition of plagioclase ranges from An_{21} to An_{30} with an average composition of An_{25} (calcic oligoclase). Compositional zoning is present, but is oscillatory and not strongly developed. Twinning is also present, but is not abundant.

Fig. 6. Triangular plot of the relative percentages of modal quartz (Q), alkali feldspar (A) and plagioclase (P) for the trondhjemitic rocks in the Follstad district listed in Table 1. Rock name field boundaries after Streckeisen (1967, p. 160).

Two stages of plagioclase genesis have been distinguished in the trondhjemites. Most plagioclase laths have a mantle of albite that is usually unzoned and untwinned. Albite may be a reaction mineral developed during metamorphism, as discussed below. In the plagioclase rimmed by albite, only the core of the lath is altered. Alteration is moderate with sericite, calcite, and epidote being the most common replacement minerals. There is a strong negative correlation between plagioclase and microcline ($r = -.88$); as the anorthite content of the plagioclase decreases, the microcline content increases. This variation indicates that some differentiation has taken place in these rocks.

Alkali feldspar: Alkali feldspar is present as small, angular, interstitial grains ranging from 0.1 to 0.7 mm. Average modal content is only 3.3%. Grains are mainly microcline, although some have a patchy or braid–perthitic intergrowth with albite. Microcline composition is $Or_{62} : Ab_{38}$ determined by X-ray diffraction. Alteration of alkali feldspar is not extensive and sericite is the most common secondary mineral. The strong negative correlation between alkali feldspar and both epidote and biotite ($r = -.92$) indicates a reaction between them.

Quartz: Quartz is present as anhedral interstitial grains ranging from 0.1 to 1.5 mm. Quartz is abundant, with an average modal content of 26%, and tends to form in clusters commonly showing a faint granoblastic texture with straight to slightly curved grain boundaries meeting at 120°. Some grains have undulatory extinction but most grains are unstrained, demonstrating that the quartz may be partially recrystallized.

Biotite: Biotite is the major mafic mineral in trondhjemite. It is present as subhedral plates ranging from 0.2 to 1.6 mm. The modal content averages only 1.9% of the rock. Grains are commonly bent and often found associated with muscovite in subhedral arrangement. Biotite is also found in mafic clusters dispersed unevenly throughout the rock. Alteration is variable with chlorite as the most common secondary mineral. There are a few chlorite pseudomorphs of biotite. Epidote and biotite are closely associated in the trondhjemite and sometimes show a mutual reaction texture. The correlation coefficient is positive between epidote and biotite ($r = .99$).

Muscovite: Muscovite is also present as small subhedral plates in the rock. Its modal average is 5.9%. Some of the secondary sericite in the plagioclase has a recrystallized texture and a sagenitic structure. Where muscovite shows a mutual reaction texture with other minerals it has a spongy texture.

Epidote: Epidote, which is a metamorphic mineral in these rocks, is present as well-crystallized, subhedral to euhedral prisms locally with compositional zoning. Optical properties show it to be an iron-poor epidote having about 10 wt.% Fe_2O_3. As already noted there is a mutual reaction texture between epidote and biotite. Epidote is also associated with small grains of magnetite and has been observed as an alteration product after plagioclase. Epidote modal variability is related to the degree of recrystallization in the trondhjemite. The trondhjemite that is more highly recrystallized typically contains greater amounts of epidote.

Accessory minerals: Where present, magnetite is present in trace amounts and commonly forms small subhedral grains associated with epidote. Sphene is present as subhedral to euhedral prisms, up to 1 mm across: it has also been observed included in biotite. Zircon is present as small, slightly rounded grains commonly included in biotite and showing pleochroic haloes. Apatite is ubiquitous as small, euhedral grains evenly dispersed throughout the rock. In rare instances apatite has a very pale green pleochroism.

ANALYSIS OF MINERAL VARIANCE

The Follstad district trondhjemite samples were taken from a variety of locations to permit a statistical analysis-of-variance test. Modal variation for the most abundant minerals was determined first within each of the sample outcrops. This comparison of local versus regional variation permits the degree of homogeneity of the trondhjemite to be determined. An F-test, which is a test for equivalence of means, was used to determine if variation at each level of comparison is significant or is due to random variation in the samples. The calculated F-value for each mineral was compared with the tabular F-value at the 5% level of significance. Although details of the analysis-of-variance tests are not included here, they are available from the author on request.

Within each outcrop (local fluctuation) major mineral variation was determined to be insignificant in the trondhjemitic rocks from the Follstad district. On the regional scale of comparison (among outcrops) the mineral also have an insignificant amount of variation. This shows that the trondhjemite is homogeneous throughout its extent. Means and standard deviations for the modal percentages given in Table 1 also show only a small amount of mineral fluctuation in the trondhjemites. This homogeneity demonstrates that no older or younger fractionates or differentiates are present in the sampled population. A high degree of compositional homogeneity also seems to be characteristic of trondhjemites worldwide. The possible genetic importance of this homogeneity will be discussed in the section on petrogenesis.

Evidence of metamorphism

Textural and mineralogical features of the Follstad trondhjemite collectively indicate that the rock has undergone metamorphism. Quartz occurs in granoblastic clusters with slightly curved to straight grain boundaries meeting at 120°. Biotite, muscovite, epidote and microcline show mutual reaction textures between grains. Small, euhedral, incipient epidote shows good crystal form, with the amount of epidote greater in the trondhjemites that show evidence of advanced recrystallization. Albite rims on plagioclase are untwinned and unzoned. The amount and perfection of twinning in the plagioclase is less in trondhjemites showing advanced recrystallization.

Table 2. Means and standard deviations (in parentheses) of replicate major element chemical analyses in weight per cent from trondhjemite samples listed in Table 1. (J. Sandvik, analyst)

	Follstad Quarry									
Series	Tr 43		Tr 45		Tr 46		Tr 47		Tr 49	
No. of Samples	3		3		3		3		3	
SiO_2	71.58	(0.14)	71.54	(0.25)	71.24	(0.26)	70.84	(0.09)	72.14	(0.33)
TiO_2	0.25	(0.01)	0.23	(0.02)	0.24	(0.01)	0.23	(0.01)	0.20	(0.0)
Al_2O_3	16.38	(0.12)	16.15	(0.27)	16.34	(0.20)	16.46	(0.22)	15.70	(0.25)
Fe_2O_3	0.64	(0.03)	0.52	(0.03)	0.60	(0.04)	0.66	(0.03)	0.48	(0.08)
FeO	0.79	(0.02)	0.76	(0.05)	0.82	(0.02)	0.81	(0.03)	0.76	(0.04)
MnO	0.020	(0.002)	0.022	(0.002)	0.019	(0.002)	0.020	(0.002)	0.024	(0.002)
MgO	0.51	(0.02)	0.46	(0.02)	0.50	(0.01)	0.52	(0.02)	0.40	(0.02)
CaO	2.83	(0.26)	2.71	(0.04)	2.87	(0.02)	3.04	(0.13)	2.16	(0.07)
Na_2O	5.35	(0.07)	5.37	(0.15)	5.38	(0.18)	5.37	(0.16)	5.19	(0.12)
K_2O	1.27	(0.04)	1.42	(0.07)	1.33	(0.04)	1.30	(0.01)	1.62	(0.17)
P_2O_5	0.09	(0.01)	0.08	(0.01)	0.08	(0.01)	0.09	(0.0)	0.08	(0.0)
H_2O^+	0.52	(0.02)	0.50	(0.10)	0.45	(0.0)	0.70	(0.11)	0.73	(0.26)
H_2O^-	0.02	(0.01)	0.03	(0.01)	0.03	(0.01)	0.07	(0.02)	0.04	(0.01)
CO_2	—		—		—		—		—	
TOTAL	100.25		99.79		99.90		100.11		99.52	

Table 3. CIPW normative mineral percentages calculated from chemical analyses listed in Table 2. Non-normative CO_2 and H_20 subtracted from totals. The differentation index is that of Thornton & Tuttle (1960)

	Follstad Quarry					Pooled
Series	Tr 43	Tr 45	Tr 46	Tr 47	Tr 49	Tr 43–49
Number of Samples	3	3	3	3	3	15
Q	28.75	28.37	27.86	27.32	30.81	28.62
C	1.26	1.06	1.01	0.91	2.02	1.25
or	7.49	8.37	7.88	7.66	9.57	8.19
ab	45.30	45.41	45.55	45.47	43.97	45.14
an	13.49	12.88	13.71	14.48	9.22	12.76
hy	1.82	1.77	1.90	1.88	1.70	1.81
mt	0.93	0.76	0.87	0.96	0.70	0.84
il	0.47	0.44	0.46	0.45	0.38	0.44
ap	0.20	0.19	0.19	0.21	0.19	0.20
Differentiation Index	81.54	82.15	81.29	80.45	84.35	81.95

As biotite and epidote contents increase, the other minerals — microcline, chlorite, muscovite and quartz — show a corresponding decrease These characteristics suggest that the trondhjemite has been subjected to regional metamorphism and converted into the assemblage muscovite–biotite–quartz–albite–epidote, an assemblage representative of the upper greenschist facies (Winkler 1965). The degree of metamorphism was first reported by Goldschmidt (1916). At the top of the biotite zone of regional metamorphism, albite can coexist with plagioclase of composition An_{23}. This feldspar coexistence is displayed in the Follstad district trondhjemite as albite rims on plagioclase laths of An_{25}. The upper greenchist facies assemblage present in these rocks is of lower grade than the almandine–amphibolite facies assemblage present in the Gula Group, but of higher grade than the lower greenschist facies assemblage present in the Hovin Groups.

able 2 (Continued)

pooled Tr 43–49 15	Surrounding Region					
	Tr 35	Tr 40	Tr 42	Tr 48	Tr 51	Tr 53
71.47 (0.48)	73.89	64.98	72.33	67.29	65.83	71.19
0.23 (0.02)	0.07	0.30	0.17	0.26	0.05	0.25
16.20 (0.34)	15.72	17.37	16.17	16.08	19.94	16.36
0.58 (0.08)	0.37	0.52	0.52	0.14	0.03	0.21
0.78 (0.04)	0.73	1.08	0.62	1.43	0.08	1.23
0.021 (0.002)	0.029	0.025	0.022	0.021	0.002	0.026
0.48 (0.05)	0.23	1.09	0.36	1.14	0.02	0.82
2.72 (0.33)	2.11	3.94	1.91	3.57	2.15	2.57
5.33 (0.14)	4.62	5.92	5.66	4.42	7.34	5.68
1.39 (0.15)	1.89	1.82	1.81	2.00	4.25	0.91
0.08 (0.01)	0.06	0.10	0.08	0.09	0.05	0.11
0.58 (0.16)	0.31	1.28	0.52	0.94	0.04	0.69
0.04 (0.02)	0.01	0.06	0.03	0.06	0.03	0.11
—	—	1.46	—	1.92	—	—
99.90	100.04	99.94	100.20	99.36	99.81	100.16

Surrounding Region					
Tr 35	Tr 40	Tr 42	Tr 48	Tr 51	Tr 53
34.64	17.28	27.86	29.11	2.66	27.46
2.38	2.12	1.62	4.82	—	1.62
11.17	10.76	10.70	11.82	25.12	5.38
39.09	50.09	47.89	37.40	62.11	48.06
10.08	9.66	8.95	4.99	8.91	12.03
1.55	3.82	1.37	4.96	0.19di / 0.50 wo	3.76
0.54	0.75	0.75	0.20	0.04	0.30
0.13	0.32	0.32	0.49	0.09	0.47
0.14	0.19	0.19	0.21	0.12	0.25
84.90	78.13	86.45	78.33	89.89	80.90

Major element geochemistry

Major element analyses and CIPW norms for the Follstad district trondhjemite showed relatively high contents of silica and sodium compared with the low content of potassium (Tables 2 & 3). The Na_2O/K_2O ratio averages 3.8. The high Na_2O content relative to K_2O is in part due to alteration and metasomatism (sericitization, albitization). The trondhjemite averages 16.2% Al_2O_3, which classifies it as the high alumina type (greater than 15% Al_2O_3) as defined by Barker & Arth (1976). In contrast to trondhjemites worldwide, the Follstad district trondhjemite has relatively low amounts of total iron (average 1.36%) and the FeO/Fe_2O_3 ratio is relatively high at 1.34. The total iron-to-magnesium ratio is also low (average 2.83) in comparison to that in trondhjemites from

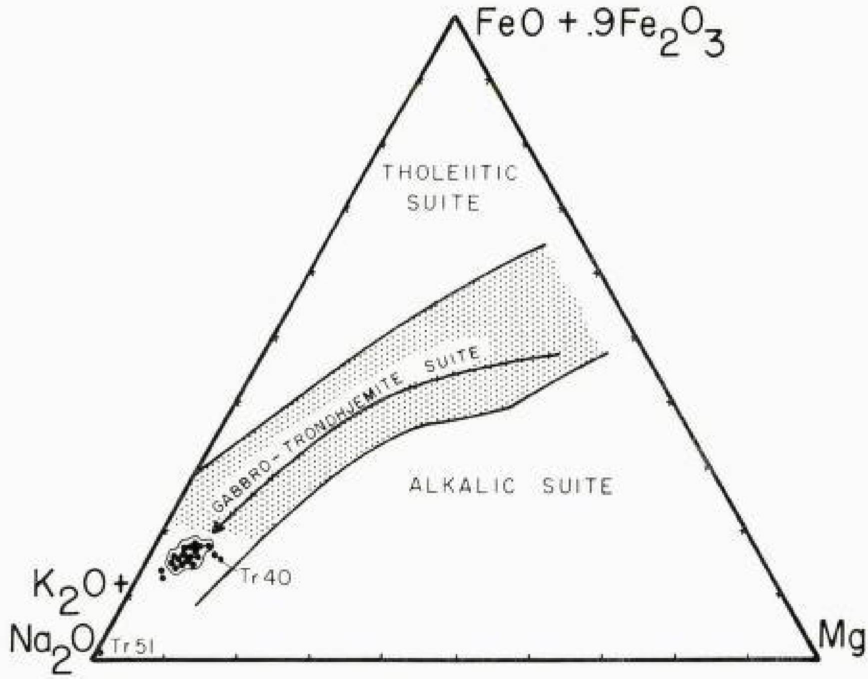

Fig. 7. AFM plot for the Follstad trondhjemites. Gabbro–trondhjemite trend after Barker & Arth (1976, p. 598). Shaded area represents locations for the eugeosynclinal magmatic rocks in the Trondheim region (Loeschke 1976, p. 45). The shaded area is also representative of the calc-alkaline rock suite. Group of points outlined represents trondhjemite samples from the Follstad quarry.

other regions (Arth & Hanson 1975). The low iron-to-magnesium ratio, together with the low potassium content, indicates that these rocks represent a primitive magma type that has not further differentiated to leucogranodiorite or leucomonzonite by the removal of plagioclase.

A comparison of the K_2O content versus SiO_2 shows that the Follstad trondhjemites plot in the continental trondhjemite field of Coleman & Peterman (1975, p. 1105), with more K_2O than the oceanic plagiogranites. There is not enough range in the compositions of these rocks to show any trend in crystallization. However, the correlation coefficients for major oxides show that as silica and potassium increase, there is a corresponding decrease in calcium, iron, magnesium, sodium and aluminum.

Trondhjemites plotted on an AFM diagram (Fig. 7) are at the low temperature end of the gabbro–trondhjemite trend (Barker & Arth 1976), which is a sub-trend of the more general calc–alkaline suite of Green & Ringwood (1968). Other eugeosynclinal magmatic rocks from the Trondheim region are represented by the shaded area of Fig. 7 (Loeschke 1976, p. 45). This field also shows a calc–alkaline trend, with Follstad trondhjemite at the most differentiated end. This demonstrates that Follstad district trondhjemite may represent the lowest temperature melt of a basaltic magma.

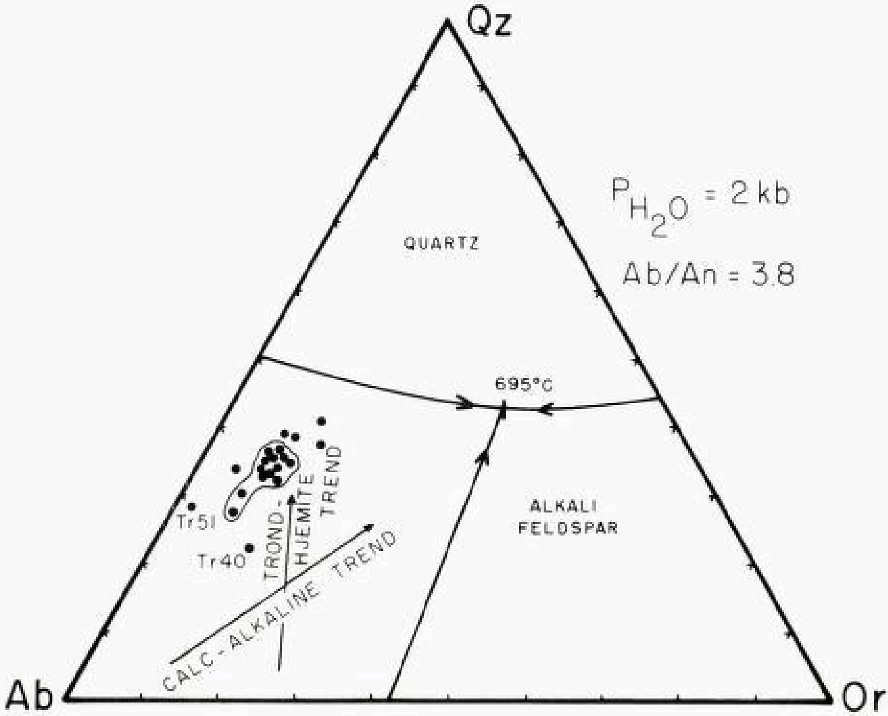

Fig. 8. Triangular plot of the relative percentages of normative quartz (Q), orthoclase (Or) and albite (Ab) for the Follstad trondhjemites. Eutectic position for Ab/An = 3.8, P_{H_2O} = 2 kb, projected from the Q–Ab–Or–An–H_2O system (Winkler 1965, p. 188). Calc–alkaline trend and gabbro–trondhjemite trend after Barker & Arth (1976). Group of points outlined represents trondhjemite samples from the Follstad quarry.

The triangular plot of normative Qtz–Or–Ab (Fig. 8) shows that all of the trondhjemites plot away from the eutectic melting composition in the Or–Ab–An–Qtz–H_2O system. The trondhjemites, as plotted, show a slight decrease in An content that corresponds with distance away from the minimum melt composition, as would be expected in a fractional crystallization process or a partial melting process. However, rocks so poor in K_2O, yet rich in SiO_2, cannot be easily accounted for unless a low K_2O-bearing parent material is invoked. Also shown in Fig. 8 are the eutectic point and cotectic lines for P_{H_2O} = 2 kb at an Ab/An ratio of 3.8, which is near the Follstad district trondhjemite ratio of 3.5. If the trondhjemite represented a melt composition, it would have crystallized at approximately 750°–800°C. The calc–alkaline crystallization trend shows potassium enrichment towards the lower temperatures (Fig. 8), whereas the gabbro–trondhjemite trend does not (Barker & Arth 1976). Arth & Barker (1978) would identify this as the calc–alkaline trondhjemitic trend. This deviation is explained by differences in parental material (tholeiitic versus alkalic basaltic magma).

On a triangular plot of normative Or–Ab–An (Fig. 9) all the samples from the Follstad district are in the trondhjemite field as defined by O'Connor (1965). Sodium enrichment and potassium depletion in these rocks is obvious.

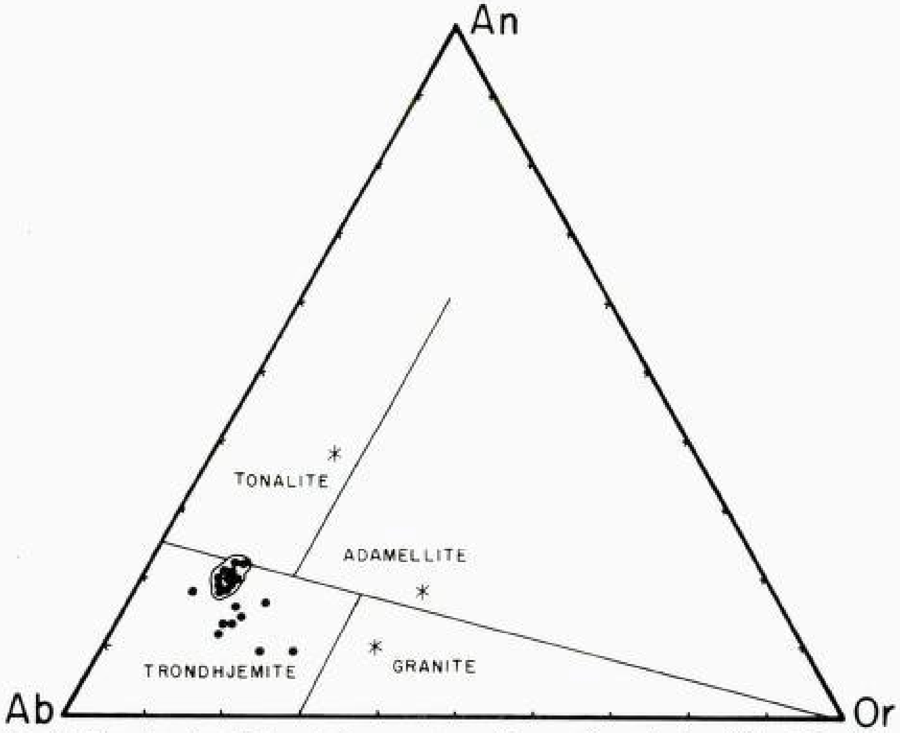

Fig. 9. Triangular plot of the relative percentages of normative orthoclase (Or), albite (Ab) and anorthite (An) for the Follstad trondhjemites. Rock name field boundaries after O'Connor (1965). Asterisks represent average composition for each major rock from LeMaitre (1976). Group of points outlined represents trondhjemite samples from the Follstad quarry.

Average tonalite (LeMaitre 1976) has a much higher An content than the trondhjemitic rocks (Fig. 9).

Almost all of the trondhjemites are peraluminous, having corundum in their norms (Table 3). This indicates that trondhjemites have modal mica or that the rocks have undergone chemical alteration, or both. The trondhjemites with the highest proportion of normative corundum (Tr 48, Tr 49a, b, c,) show the highest degree of alteration in thin-section. However, partial fusion of a tholeiitic basalt yields a melt of trondhjemitic composition that is also corundum-normative. This alternative will be examined more closely in the section on petrogenesis.

Trace element geochemistry

Selected trondhjemite samples from the Follstad district were analyzed for trace elements and rare earth elements (Table 4). Barium content ranges from 240 to 350 ppm, whereas the rubidium content is much lower, ranging from 20 to 43 ppm. This enriched proportion of barium to rubidium indicates a more primitive trondhjemite, as reported by Bouseily & El Sakkary (1975). As the Or/Ab ratio increases in Follstad trondhjemite, the Ba content increases. This

Table 4. Trace element and rare earth element analyses, in ppm, from trondhjemitic samples listed in Table 1. Analytical methods given in text

	Follstad Quarry				Surrounding Region	
Sample	Tr 43	Tr 46	Tr 47	Tr 49	Tr 51	Tr 53
La	8.4	5.5	6.4	6.5	1.2	9.9
Ce	27	19	19	21	4.5	24
Sm	5.0	4.3	4.4	5.3	1.1	7.3
Yb	0.30	0.20	0.15	0.13	0.27	0.63
Lu	0.038	0.05	0.05	0.03	0.03	0.03
Rb	20	39	43	28	60	49
Ba	240	290	280	350	600	92
U	0.43	0.41	0.69	0.58	0.56	0.69
Th	4.4	2.7	3.2	4.2	0.87	3.2
Cr	1.7	ND	3.0	ND	0.78	5.8
Ni	62	91	ND	ND	30	340
Ba/Rb	12.0	7.4	6.5	12.5	10.0	1.9
K/Rb	470	246	279	428	600	186
La/Lu	221	110	128	216	40	330

correlation has also been reported by McCarthy & Hasty (1976). The Ba/Rb ratio in the trondhjemite from the Follstad district ranges from 6.5 to 12.5, which is similar to that in other trondhjemites located in similar tectonic settings. For example, in Nova Scotia, trondhjemite from the Shelbourne pluton has a Ba/Rb ratio from 4.1 to 4.9 (Albuquerque 1977, p. 6). In the Uusikaupunki complex of southwest Finland the Ba/Rb ratio is from 3.1 to 11.6 for trondhjemites (Arth & Barker 1978). The K/Rb ratios are also similar in these three areas: Follstad, K/Rb = 246–470; Nova Scotia, K/Rb = 207–222; Finland, K/Rb = 261–320.

A plot of rare earth element (REE) abundances normalized to the average chondrite abundances (Haskin et al. 1968), shows that the Follstad trondhjemite is fractionated with HREE depleted relative to the LREE (Fig. 10). The highly fractionated nature of REE in Follstad district trondhjemite is shown in the La/Lu ratio, which ranges from 110 to 221. The LREE are from 20 to 30 times chondrites, whereas the HREE abundances in the trondhjemites are almost chondritic. This pattern of highly fractionated REE is characteristic of the high Al_2O_3-type trondhjemite defined by Barker & Arth (1976). One analysis of REE in a trondhjemite from the Follstad quarry has no Eu anomaly (Barker, pers. comm., 1978). This indicates that plagioclase was not an important cumulate phase if trondhjemite was derived by fractional crystallization; or it indicates that plagioclase was remelted if trondhjemite had its origin due to partial anatexis. The REE element pattern for Follstad district trondhjemite is similar to the pattern in trondhjemites from Nova Scotia (Albuquerque 1977) and Colorado (Barker et al. 1976), except that these trondhjemites from Nova Scotia and Colorado have a negative Eu anomaly.

Crystal fractionation of amphibole would deplete a magma in all REE except

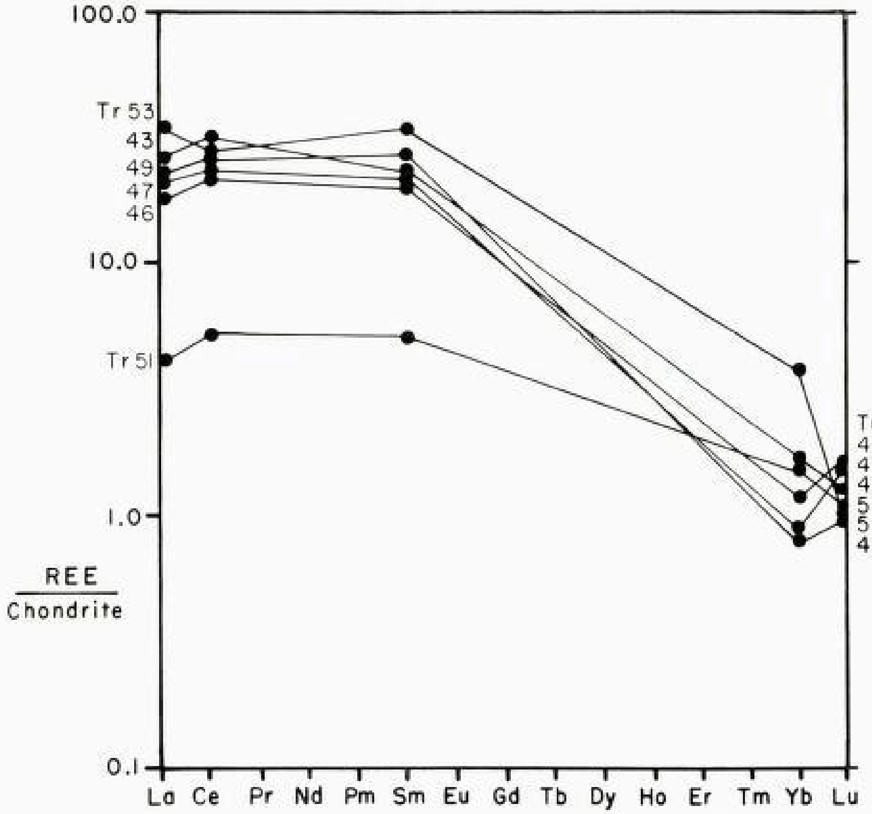

Fig. 10. Rare earth element plot for the Follstad trondhjemites. REE values are normalized to average chondrite values of Haskin et al. (1968). Numbers Tr 43, 46, 47, 49 from the Follstad quarry area; Tr 51, 53 from Samsjøen.

cerium (Arth & Barker 1976, p. 535). This pattern is present in the Follstad district trondhjemite, although no associated amphibole-bearing cumulate rocks are present in the area. In Finnish trondhjemites, where amphibole is present, a cerium enrichment is again present in the REE pattern (Arth & Barker 1978).

Relationship of trondhjemite composition to tectonic setting

Interpretation of the Caledonian tectonic history of the Trondheim region in a plate tectonic context has been given by Gale & Roberts (1974), whereas Gee (1978) has presented a broader scheme for development of the entire nappe system in the region. Only the more salient points pertaining to the origin of trondhjemitic rocks need be mentioned here.

Of major importance is recognition of the allochthonous character of Lower Paleozoic rocks in the Trondheim region. Development of the eastward-moving nappe pile can be dated stratigraphically to post-Llandoverian but prior to the Old Red Sandstone molasse sedimentation (Strand 1960, Roberts et al. 1970, Gee & Wilson 1974, Gee 1978). These allochthonous rocks now rest upon continental gneiss and granite of the Baltic Shield. Estimated amounts of east-southeastward displacement of the nappes range from 200 to 250 km for the Støren Nappe, to 400–500 km of cumulative nappe movement (Gale & Roberts 1974), to over 1000 km for the entire nappe sequence in the region (Gee 1978). Gee suggests that a considerable amount of this apparent displacement may be due to stretching.

Trondhjemites are found entirely within the allochthon, and structural studies and radiometric ages show that they both pre-date and post-date the time of nappe formation and thrusting. This apparent contradiction indicates there were several periods of trondhjemite intrusive activity in the region. Field relations support this by the presence of trondhjemitic intrusives showing differing degrees of deformation.

Gale & Roberts (1974) have shown that the Støren Nappe was obducted upon the Gula rocks pre- to syn-F_1. Therefore, Follstad district trondhjemites, which are virtually undeformed and intrude the Gula Schist Group, post-date the juxtaposition of the Støren Nappe upon the Gula rocks. However, the Gula rocks may also represent an allochthonous unit, provisionally termed the Gula Nappe by Roberts (1978). Later the Støren Nappe and Gula moved as one unit, the Trondheim Nappe.

Translation of the nappes above their respective basal overthrusts has produced a telescoping of possible time-correlative rock sequences consisting of, from east to west: continental-margin facies, back-arc facies, island arc-trench facies and ocean floor volcanic rocks. As noted earlier, the thick sequence (2.5 km) of the Støren Group consists mainly of basaltic greenstone with subordinate clastic rocks, representative of ocean floor and partly island-arc tholeiite (Gale & Roberts 1974, Loeschke 1976). Quartz keratophyre, which is intercalated in the greenstone, may be a differentiate of these basalts or a product of partial fusion of the basalts. The quartz keratophyres are interpreted as being dikes, flows, tuffs and reworked volcano-clastic rocks. They are similar in bulk chemistry to the trondhjemites and may represent their nearer surface equivalents.

Interpretation of tectonic development of the region (Gale & Roberts 1974) shows that from Late Precambrian to latest Cambrian time, the Iapetus Ocean was opening, producing ocean ridge basalts at the spreading center. After this early opening, initial stages of closure in Early to Middle Ordovician time led to development of an eastward-dipping subduction zone with the production of an island-arc and back-arc sequence of volcanic rocks and sediments close to the continental margin. Flysch-type sediments were deposited in the back-arc. Continent to continent collision occurred in Mid-Silurian time, resulting in large-scale obduction of the primitive ocean floor based island-arc and back-arc pile onto the continental margin and the Gula Group rocks. Before that, the subduction of oceanic basalt and possibly some sediments beneath the back-arc and continental margin set the stage for partial remelting and fusion of basalt, producing trondhjemitic magma. There was possibly an appreciable time interval (from earliest Ordovician to Mid-Silurian) between the commencement of subduction and the ultimate intrusion of trondhjemite into the nappe pile.

Petrogenetic interpretation

Magmas are mainly derived from fusion of pre-existing rocks. However, the important petrogenetic questions remaining are how far the remobilized magma migrated from its source and what has modified it along the way (fractionation, contamination). This history is difficult to interpret if the source rock, the residual phases or the cumulus phases are not known. Such is the case for the origin of Follstad district trondhjemite.

Several tectonic and genetic settings could have produced trondhjemitic rocks as described from the Follstad district. Three general models, each with refinements, are the basis for the origin of all magmatic rocks: (1) perfect equilibrium melting and/or crystallization, (2) perfect fractional crystallization, and (3) perfect fractional melting. In a natural system none of these models is acceptable, but rather some modification or non-equilibrium process. The distinction between a trondhjemite magma produced by partial melting and one produced by fractional crystallization can be determined from the relative abundance of the derivative rock types. However, Follstad trondhjemites show little evidence of differentiation.

A downgoing slab of oceanic crust in a subduction zone is favorable to equilibrium melting. This setting provides for continual movement of new material into the region of magma generation and the removal of residium by sinking or lateral convection. Characteristics of equilibrium melting include: (1) no separation of melt from crystals once the magma is generated, and (2) little difference among compositions of successive magma generated. These features are common to trondhjemitic rocks in general and to Follstad district trondhjemite in particular. Plagioclase in the rock shows evidence of being an early phase that did not separate from the magma. In addition, the bulk composition of Follstad district trondhjemite has been shown to be extremely homogeneous.

Early ideas on the origin of trondhjemitic rocks included fractional crystallization of basaltic magma, as first proposed by Goldschmidt (1916) for this region of the Caledonides. This model was also proposed for the origin of the gabbro–trondhjemite suite in the Uusikaupunki–Kalanti area, southwest Finland (Hietanen 1943). However, a fractional crystallization model is difficult to apply in the case of Follstad district trondhjemite, because there are significant compositional gaps in the magmatic rock series from the Trondheim region. Loeschke (1976, p. 48), for example, has shown a compositional gap between 55–65% SiO_2 for the magmatic rocks of the region. Also, there are no examples of more highly differentiated rocks than the trondhjemite in the region, even though exposure is relatively good. Compositional gaps in this rock series can better be explained by equilibrium melting of a more primitive source rock.

The trondhjemite trend, as shown in Fig. 8, can be produced by partial melting of rocks in which residual hornblende was the predominant K_2O-bearing phase (Helz 1976, p. 179). Fractional crystallization of basaltic magma would produce a trend towards higher K_2O which is not seen in the gabbro–

trondhjemite trend. Increasing the P_{H_2O} or f_{O_2} wold not change the trend, only the volume of the melt and the composition.

Several models have been proposed for the origin of trondhjemite rocks. However, some of these models as applied to the Follstad trondhjemite are not well supported by the evidence and will be dispensed with first. These include the model that the trondhjemite is an integral part of an ophiolite complex (similar to the oceanic plagiogranite of the Troodos Complex, Cyprus; Coleman & Peterman 1975, p. 1105). This model is unlikely for the simple reason that the trondhjemites are not pre-tectonic. However, the Støren volcanic rocks may still represent a fragment of a dismembered ophiolite (Roberts, pers. comm. 1976). In addition, the K_2O content in an ophiolite oceanic plagiogranite is significantly lower than even the low K_2O content of Follstad trondhjemite. Also, the HREE show an enriched pattern in the Troodos plagiogranite whereas the Follstad trondhjemite shows a depleted HREE pattern.

Another unlikely model for the origin of Follstad district trondhjemite is partial fusion of gneiss and granite of the continental crust margin. The trondhjemite is situated within the Trondheim nappe, which partly rests on such basement, and magma may therefore have been generated or contaminated by fusion of basement rocks. However, the composition of the low temperature melt of such source rocks is enriched in K_2O and even with progressive melting of these rocks at higher temperatures the K_2O content in the melt would not be diluted to resemble the composition of a trondhjemitic magma. Also, data from Peterman & Barker (1976) show a $^{87}Sr/^{86}Sr = .7039$ from Follstad trondhjemite, which is indicative of a less radiogenic source than continental crustal rocks.

A model of partial melting of greywacke as the source for trondhjemitic magma is not so easily discounted. Flysch-type greywacke and associated volcanoclastic rocks are abundant in Lower Paleozoic rocks of the Trondheim region, and they show differing effects of metamorphism and recrystallization. Experimental studies by Kilinic (1972) on partial melting of greywacke show that a trondhjemitic magma can be produced by this process. Albuquerque (1977) used this model to explain the origin of trondhjemites in the Shelbourne pluton of Nova Scotia. He estimated that trondhjemite melts formed from partial fusion of greywacke above the minimum melt temperature in the Qtz–Ab–Or system at about 715°–730°C, and at a pressure of 5.5–6.5 kb. However, in both of these examples the composition of the trondhjemites is significantly higher in both SiO_2 and K_2O than the Follstad district trondhjemite. Average greywacke, which has about 67% SiO_2 and 2% K_2O, would produce abundant quantities of 'granitic melt' before changing towards a melt of trondhjemitic composition. These granitic rocks are not evident in the Trondheim region. In addition, partial melting of greywacke would produce a melt showing HREE enrichment. Follstad region trondhjemite has a depleted HREE pattern. Wyllie (1977), in his crustal anatexis experiments, concluded that source rocks such as shale and greywacke cannot produce melts of tonalitic or dioritic composition under conditions of normal regional metamorphism.

The high Al_2O_3 content and low K_2O content of Follstad region trondhjemite require a more primitive source such as island-arc basalts or ocean floor, low-K_2O tholeiites. Approximately 10–35% partial melting of low-K_2O basalt would produce a high-Al_2O_3 trondhjemitic magma. This model of partial melting of basaltic rock is of special interest, because greenstones are very abundant in the Follstad district. These greenstones are metamorphosed and recrystallized to differing degrees and thus may have undergone partial remelting at deeper levels.

Green & Ringwood (1968) proposed a two-stage development for the calc-alkaline rock series, of which trondhjemites constitute a sub-trend. First, partial melting of mantle source rock below a spreading center would produce a high-Al_2O_3 tholeiitic magma, leaving garnet and clinopyroxene as residiuum. In the second stage this basalt crust is subducted under an island-arc type continental margin. At greater depths along the Benioff zone, the basalt partially melts, and if at shallow depths where hornblende would be residual it would produce a magma of trondhjemitic composition. Such a model produce not only the major element characteristics of trondhjemites, but also the trace element and rare earth element characteristics of the Follstad district trondhjemite (low abundance of REE, highly fractionated REE pattern, HREE abundances near chondritic, no Eu anomaly, slight Ce enrichment).

Critical to the origin of trondhjemitic magma is the influence of the mafic phases. In the trondhjemite system (Hb–Bi–Pl–Q), early removal of hornblende (or its being a residual phase) almost seems necessary to produce not only the K_2O and Al_2O_3 abundances in trondhjemites, but also the REE pattern characteristic of these rocks. The depletion of HREE is distinctive in these trondhjemitic rocks. Arth & Barker (1976, p. 535) have shown that removal of hornblende from a magma produces such a pattern in the REE. Removal of plagioclase enriches the melt in all REE except europium.

Fractionation of hornblende, plagioclase and some biotite from a basaltic melt yields about 24% by volume of trondhjemitic magma ($SiO_2 = 71\%$). However, a 20–30% partial melting of a low-K_2O tholeiitic basalt yields the same trondhjemitic magma with the added possibility of being able to produce greater proportions of trondhjemitic rocks over the more basic types (as observed in the Uusikaupunki–Kalanti complex of southwest Finland; Hietanen 1943). The temperature increase necessary to melt hornblende and plagioclase produces a gap between the melting points of tonalitic and granodioritic rocks (Wyllie 1977, Piwinskii 1967). This increase partially explains why trondhjemites are so deficient in mafic minerals. With excess water in the system most rocks begin melting just below 700°C (upper almandine–amphibolite facies range), and most minerals will melt within a narrow temperature range (about 100°C). However, a much wider temperature interval is necessary to melt mafic minerals to produce a resultant magma of tonalitic composition (Piwinskii 1968). Such magmas do not reach their liquidus until about 950°–1000°C (Wyllie 1977). This temperature is too high to be developed during normal regional metamorphism. This fact may explain why trondhjemites are more common in such tectonic settings than tonalites.

The composition of the initial melt during anatexis depends on many factors of which the source material is one of the more important. In the granite system an increase in water pressure can move the composition of the eutectic melt towards the Ab component, whereas an increase in the An content of the parent material can shift the minimum melt composition towards a greater Or component, counteracting the effect of change in pressure (Winkler 1965, p. 188). In Fig. 8 the eutectic melt composition is plotted at P_{H_2O} = 2 kb, with an Ab/An ratio of 3.8. The minimum melt temperature is 695°C. A temperature increase of approximately 70° could produce a magma of the composition shown in the Follstad district trondhjemite plotted in Fig. 8.

Models for the origin of trondhjemitic magmas are clearly polygenic, but the model that most closely fits the data for the Follstad district trondhjemite is one of equilibrium melting of a low-K_2O tholeiitic basalt during anatexis in an orogenic zone. Helz (1976) performed melting experiments on tholeiites in the low temperature melting range (680°–1000°C, P_{H_2O} = 5 kb) and determined that within the hornblende stability field, partial melts of all the starting basalts are strongly quartzo–feldspathic and corundum-normative (the Follstad trondhjemites are also corundum normative). The composition of the low temperature melts are quite consistent and insensitive to differences in starting materials, P_{H_2O} or f_{O_2}. One exception is that the relative abundances of calcium, sodium and potassium vary directly from the source rock to the magma.

The results of Helz' experiments can be directly related to the Follstad district trondhjemite. Støren Group greenstones are similar in composition to the basalts used by Helz (1976) as starting material, except that the K_2O is lower in the greenstones (K_2O = 0.16–0.22%) than in the basalts (K_2O = 0.49–0.97%). The solidus for the basalts is at about 690°C and the melt compositions are all similar up to the upper stability field of hornblende. The Or is relatively constant as long as hornblende is the only alkali-bearing phase. The melts move out towards the center of the Q–Or–Ab ternary only when plagioclase begins to separate from the melt (Stern 1974). The closest natural analog to the melts derived in the partial melting experiments of the tholeiitic basalts is the trondhjemite suite. At 825°–850°C and P_{H_2O} = 5 kb, the composition of the partial melts from the 1921 Kilauea tholeiite and the Picture Gorge tholeiite (Helz 1976) had almost the same bulk composition as Follstad district trondhjemite. The slight difference is that K_2O content is lower in these trondhjemites than in the basaltic melt. This difference could be accounted for by the lower K_2O content of Støren greenstones, if they were comparable to the parent material for the trondhjemite.

Summary

Trondhjemite of the Follstad district intrudes a sequence of associated Lower Paleozoic metasedimentary and metavolcanic rocks of the Caledonide orogen in central Norway. There were four periods of trondhjemite intrusion in this district, with the oldest intrusives the most deformed. Trondhjemite at the Follstad quarry near Støren is late-tectonic, and has an upper greenschist facies mineral assemblage. Follstad district trondhjemite is homogeneous in mineral and chemical composition, and shows little evidence of any earlier or later differentiation. Its composition is at the low temperature minimum of the gabbro–trondhjemite trend, which is a sub-trend of the calc-alkaline series. However, distinctive compositional gaps in the trondhjemite compared to other associated magmatic rocks in the Trondheim area are difficult to explain by a simple fractional crystallization model.

Composition of the Follstad trondhjemite is characteristic of trondhjemites of other regions associated with mobile belts and greenstones (Shelbourne pluton, Nova Scotia, Albuquerque 1977; Twillingate pluton, eastern Newfoundland, Strong et al. 1974). Trondhjemites associated with basic volcanic rocks are peraluminous; high in SiO_2, Al_2O_3 and Na_2O, but low in K_2O; usually late-tectonic; extremely homogeneous in composition; depleted and show a highly fractionated REE pattern; and have low abundances of Rb compared with Ba.

The petrogenetic interpretation for the origin of the Follstad trondhjemite is based on the model of equilibrium melting of a K_2O-poor tholeiitic basalt during anatexis in an orogenic zone. The regional tectonic setting of the Follstad district and the character of the associated rocks support this model. Other models, such as anatexis of continental crust or partial melting of greywacke, would not produce the composition of Follstad trondhjemite.

The composition of the Follstad trondhjemite plots away from minimum melting temperatures in the Or–Ab–An–Qtz–H_2O system. Melting experiments of Piwinskii (1968) and Wyllie (1977) show that below 2 kb pressure, temperatures necessary to produce an anatectic melt of trondhjemitic composition are too high to be produced during normal regional metamorphism. However, in the range of 5–10 kb P_{H_2O} a trondhjemitic melt can be produced between 760°–840°C. This work agrees with the work of Helz (1976) on the partial melting of tholeiitic basalts, which produce a trondhjemitic melt at 825°–850°C at $P_{H_2O} = 5$ kb. Composition of the trondhjemite produced would show major element, trace element and REE abundances as seen in the Follstad trondhjemite if hornblende is a residual phase.

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