U-Pb age dating and paleotectonic significance of trondhjemite from the type locality in the Central Norwegian Caledonides

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

Zircon and titanite U-Pb data are reported from the trondhjemite type locality at Follstad, near Støren in Central Norway. A concordant fraction of acicular zircon and an overlapping fraction of titanite give an age of 432 ± 3 Ma for the intrusion of the pluton. Fractions of prismatic zircon display inheritance. The Follstad trondhjemite represents a suite of similar intrusions occurring in metasedimentary and metavolcanic rocks of the Upper Allochthon in the Scandinavian Caledonides. Trondhjemite emplacement, commonly with associated mafic magmatism, was broadly coeval with metamorphism and deformation during the climactic Caledonian (Scandian) orogenic event, immediately before rapid uplift and cooling in Late Silurian and Early Devonian times. A possible scenario for the formation of the Follstad and equivalent trondhjemites is that of partial melting of crustal rocks at garnet-amphibolite grade, facilitated by the emplacement of rift-related, mantle-derived mafic intrusions. The latter could have formed, in Early Silurian time, in a paleotectonic setting characterised by the development of extensional segments within a predominantly transpressional regime, due to highly oblique collision between the converging margins of Baltica and Laurentia.

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Introduction

The term 'trondhjemite' was introduced by Goldschmidt (1916) in his work on Caledonian intrusive rocks in central and southern Norway. It is now strictly defined as a leucocratic variety of tonalite (colour index = 10) consisting essentially of sodic plagioclase and quartz with minor biotite (Le Maitre et al. 1989), but the term has been widely used in the literature as a synonym for plagiogranites and other sodic granitoids irrespective of their modal composition.

Goldschmidt's type locality for trondhjemites was the intrusive body found in the Follstad quarry at Støren, some 50 km south of Trondheim (Fig. 1), which has been exploited for dimension stone under the commercial name 'Støren Granite' since 1956. This trondhjemite was the subject of a detailed petrographic and geochemical study by Size (1979), and further field and trace element investigations by Pannemans & Roberts (this volume). The purpose of the present account is to present new age data for the type trondhjemite as a basis for regional and paleotectonic considerations.

Regional setting

The Follstad trondhjemite belongs to a suite of similar intrusions which are particularly abundant in an extensive, essentially metasedimentary, rock unit traditionally referred to as the Gula Group or Complex (Wolff & Roberts 1980). This is tectonically bound to the east and west by metavolcanic and younger metasedimentary rocks of the Meråker and Støren Nappes, respectively (Fig. 2). Together with the Gula Complex, these units constitute the Trondheim Nappe Complex (TNC), which is equivalent in part to the Köli Nappe Complex and forms a major part of the Caledonian Upper Allochthon (Roberts & Gee 1985, Gee et al. 1985). The TNC is composed of a variety of metasedimentary and metavolcanic rocks that are generally considered as being derived from original depositional settings outboard of either the Baltican or the Laurentian continent. Amalgamation of these exotic terranes occurred during the polyphase Caledonian orogeny (Stephens & Gee 1989). The climactic stage of this orogeny included the collision of the two continents in Silurian time (Scandian phase of orogeny), accompanied by regional metamorphism and subsequent nappe transport to the east above the plate margin of Baltica.

The Støren and Meråker Nappes both contain thick metavolcanic units at their base. The Støren Group to the west is composed largely of MORB-type metabasalts of inferred Late Cambrian or earliest Ordovician age and is commonly referred to as the 'Støren Ophiolite' (Furnes et al. 1980), whereas the Fundsjø Group in the Meråker Nappe comprises a bimodal volcanic and sedimentary succession of oceanic arc and marginal basin affinity (Grenne et al. 1999), a trondhjemite from which has been dated at c.488 Ma (Bjerkgård & Bjørlykke 1994). The Fundsjø arc/marginal basin sequence is unconformably overlain by the metagreywacke-dominated sequences of the Sulåmo Group and younger metasedimentary rocks. Age constraints for the

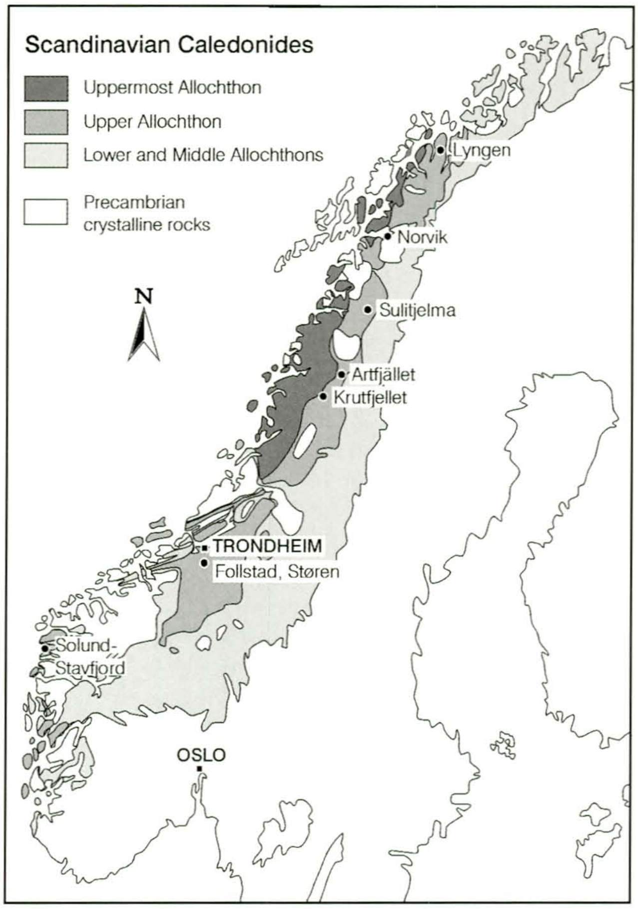

Fig. 1. Simplified tectonostratigraphic map of the Scandinavian Caledonides showing the location of the Follstad trondhjemite in the Upper Allochthon (after Grenne et al. 1999). Precambrian crystalline rocks are autochthonous to the east and south, and allochthonous (mainly Lower Allochthon) or of uncertain tectonostratigraphic status in windows in the Caledonides and in northwestern parts of Norway.

sedimentary units are limited to Early Silurian (Llandovery) graptolites in a graphitic phyllite near the top of the sedimentary succession (Siedlecka 1967).

The Støren Ophiolite to the west is unconformably overlain by the Lower Hovin Group, a predominantly greywacke-shale sequence which contains Late Ordovician (Caradoc) graptolites in black shales in its upper parts and which is overlain by metasedimentary rocks and rhyolitic tuffs of latest Ordovician and inferred Early Silurian age (Chaloupsky 1970). Northwest of these sequences, Early Ordovician (c.485 Ma; Grenne & Dunning, in prep.) ophiolites in the Vassfjell-Løkken area (Fig. 2) are considered as equivalents of the ophiolitic sequences of SW Norway (Grenne et al. 1999, Pedersen & Dunning 1997). They are unconformably overlain by a sequence of sedimentary and volcanic (shoshonitic) rocks in the classical Hølonda district, which contain a rich fossil fauna of clear Laurentian affinity (Bruton & Bockelie 1980) yielding ages that range from Early to Middle Ordovician (Middle Arenig to Early Llanvirn). These sequences have traditionally been correlated with the Støren and Hovin Groups *sensu stricto* to the southeast (e.g., Vogt 1945, Chaloupsky 1970), but such a relationship is highly uncertain in view of the presence of an intervening tectonic boundary (Fig. 2) and the significant differences in lithostratigraphy and known ages (Grenne & Roberts 1998).

Whereas the Hovin, Sulåmo and younger sediment-dominated successions were apparently affected only by deformation and metamorphism related to the Scandian continent-continent collisional orogeny, the underlying Støren and Fundsjø groups both witnessed an earlier tectonic event. This early deformation also affected rocks of the Gula Complex and has been tentatively related to obduction of the oceanic units upon Gula sequences in earliest Ordovician time (Furnes et al. 1980, Lagerblad 1983).

The Gula Complex is a heterogeneous unit comprising predominantly metasedimentary and subordinate metavolcanic rocks (Nilsen 1978, Wolff 1976, Nilsen & Wolff 1989). The age is unknown, but it has traditionally been considered as largely Cambrian with possible elements of Precambrian rocks. It is divided into three formations (Fig. 2): the central Singsås Formation of psammitic and semipelitic clastic metasedimentary rocks and thin mafic metavolcanic units with associated ribbon-cherts and graphitic schists, bordered to the east by the Åsli Formation and to the west by the Undal Formation of mainly metapelites. The Singsås and Åsli formations have been affected by medium- to high-grade metamorphism, whereas the Undal Formation is generally of low metamorphic grade, ranging from chlorite-sericite phyllites in northern and central areas to garnet-biotite schists farther south.

Trondhjemites and associated intrusive rocks in the TNC

The Gula Complex is intruded by numerous trondhjemite bodies, as well as subordinate granodiorite, diorite and gabbro. On the regional scale (Fig. 2), there is an obvious spatial relationship between the occurrence of larger mafic intrusions and trondhjemite bodies as seen, e.g., from the 1:250,000 map-sheet 'Røros' (Nilsen & Wolff 1989). The Reitstøa area shows one example of this, which has been described in some detail by Pannemans & Roberts (this volume). Further south, trondhjemite-gabbro complexes up to 30 km in length are found at Høggia and Vålåsjøen. Similar relationships have been noted at a smaller scale near Skjækerdalen in the northern part of the Trondheim District (Hildreth 1997).

Comparable trondhjemites, sometimes associated with gabbro, are found also in adjoining units east and west of the Gula Complex (Wolff 1976, Nilsen & Wolff 1989). The most prominent example is seen in the Fongen-Hyllingen area to the east (Fig. 2). The Fongen gabbro complex, dated at 426 $^{+8}/_{-2}$ (U-Pb zircon age on a late differentiate; Wilson et al. 1983), intruded metavolcanites and metapelites of the Fundsjø Group that had already been involved in an early phase of deformation and low-grade metamorphism, predating the metamorphic peak. Trondhjemites are very abundant particularly above the roof-zone of the large gabbroic intrusion (Kisch 1962) and also postdate an early tectonic fabric. West of the Gula Complex, trondhjemite dykes are rather scarce in the Støren Group in the Gauldal region (but see Roberts & Sundvoll, this volume), but are quite common farther south towards Berkåk and Innset. In that area, they are also found above the Støren metavolcanites, where metasedimentary rocks of inferred equivalents of the Hovin Group have been intruded by a large trondhjemitic-gabbroic complex (the 'Innset Massif'; Goldschmidt 1916, Rohr-Torp 1974).

The majority of the intrusions in the Gula Complex form cross-cutting dykes or larger bodies of varying size and shape. Most dykes cut the penetrative, Scandian or earlier, tectonic fabric in the surrounding schists (Fig. 3a), but there are also abundant similar dykes that are parallel to the foliation. Examples of clearly syn-kinematic multiple intrusions are seen locally (Fig. 3b). In the central parts of the Gula Complex, trondhjemites are generally almost undeformed or only weakly sheared and metamorphosed at low grade (Pannemans & Roberts, this volume). The relationships are more varied in the Undal Formation, at least where investigated by us in the Gauldal district. Here, some trondhjemites form swarms of dykes that lie, in general, parallel to the strong foliation in the Undal phyllites but locally cut the foliation at a low angle. Along the several hundred metres-

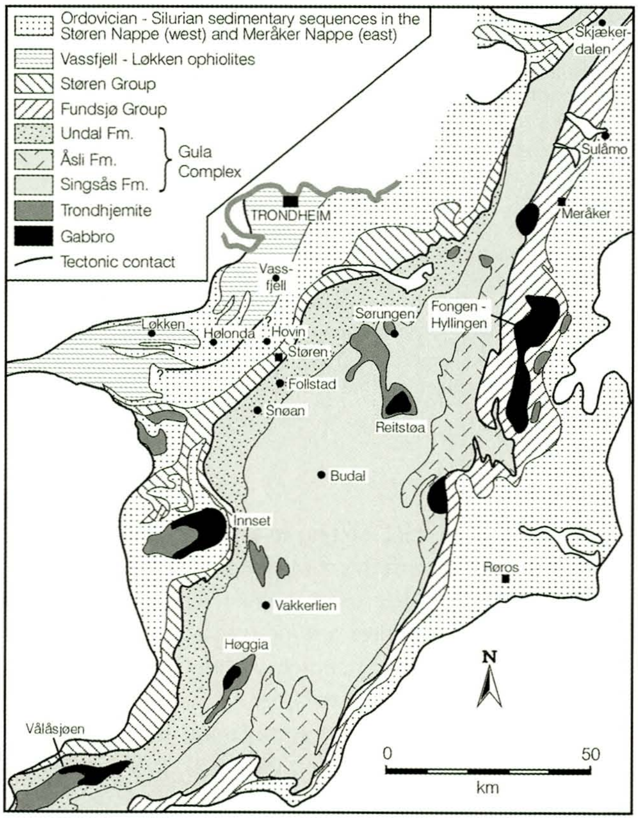

Fig. 2. Simplified geological map showing major units and intrusions in the Trondheim Nappe Complex (after Wolff 1976 and Nilsen & Wolff 1989).

wide mylonitic contact to the Støren Group, all trondhjemites have been aligned parallel to the foliation and are themselves highly sheared, in some cases to protomylonites (Fig. 3c). As noted above, trondhjemites are comparatively scarce in the Støren Group west of the tectonic contact to the Undal Formation.

The Follstad trondhjemite

The Follstad trondhjemite is located in the Undal Formation of the Gula Complex, where it constitutes an elongate, strike-parallel, 7 km-long and nearly 400 m-wide body with a general orientation of N20°-25°E and a steep northwesterly dip (Size 1979). The dimension-stone quarry at Follstad is located in the central part of the intrusion. This part, as well as most of the body elsewhere, comprises a rather homogeneous and massive, medium-grained, white rock with speckles of dark brown biotite. Fluxion banding related to magma flow can be seen locally, with darker biotite-rich zones commonly being aligned subparallel to each other (Fig. 3d). Further details can be found in a companion paper in this volume (Pannemans & Roberts 2000).

Size (1979) demonstrated that the Follstad rocks are true trondhjemites in terms of chemical and mineralogical composition (Le Maitre et al. 1989). The primary texture is hypidiomorphic-granular. Calcic oligoclase (An_{21-30}) and interstitial quartz are the major primary phases with average modal contents of 58 and 26 %, respectively. The plagioclase forms subhedral, weakly zoned laths which are generally clustered in larger glomerocrystic aggregates. Microcline is present as interstitial grains and makes up c.3 % of the rock on average. Biotite and muscovite form subhedral plates with modal contents of about 2 % and 6 %, respectively. Apatite, titanite and zircon are accessory phases, the latter two occurring partly as inclusions in biotite.

The primary texture and mineralogy is variably overprinted by metamorphic recrystallisation and shearing, with the gradual development of an allotriomorphic-granular texture which locally grades into a mortar structure. The mineral paragenesis indicates that metamorphism took place under upper greenschist facies conditions (Size 1979). This is broadly equivalent to the metamorphic grade of the host phyllites of the Undal Formation (Nilsen 1978).

The contact of the Follstad trondhjemite to the surrounding phyllites is sharp, with no evidence of chilling against the wall rocks which have undergone minor silicification and development of a hornfels texture. Thinner, but otherwise identical, dykes near the intrusion are clearly discordant to the strong foliation in the host phyllites. The lack of chilling evidence even in thin dykes was taken by Size (1979) to indicate that the wall rocks were at high temperatures at the time of intrusion. In a minor quarry south of Follstad, the western contact of the intrusive body shows some variety in trondhjemite types, from early brownish-grey, comparatively fine-grained dykes, to later, 'normal' medium-grained types. The latter may grade into coarser, almost pegmatitic varie-

Fig. 3. Photographs of typical trondhjemite intrusions in the Gula Complex. **A)** trondhjemite dyke cutting regional tectonic fabric in the Singsås Formation, Gula Complex (locality: Sørungen, Selbu); **B)** Syn-tectonic trondhjemite dykes in the Singsås Formation, Gula Complex. A folded dyke is cut by a similar, but straight dyke which is parallel to the foliation in the host schist. The dykes show no evidence of internal deformation. Dyke margins are marked by stippled line (locality: Reitstøa); **C)** protomylonitic trondhjemite bands in the mylonite zone separating the Gula Complex (Undal Formation) from the Støren Group (locality: Hundberga, Støren); **D)** fluxion banding in typical medium-grained trondhjemite from the Follstad body. Width of field c.1.3 m (locality: abandoned quarry near Egga, 2 km south of the Follstad quarry); **E)** fine-grained trondhjemite dyke cutting normal, medium-grained trondhjemite, Follstad trondhjemite body. The irregular contact indicates dyke intrusion into a trondhjemite that was only partly crystallised (locality: same as D).

ties, and are in places succeeded by a new generation of brownish-grey, fine-grained trondhjemite dykes (Fig. 3e). Abundant evidence of similar multiple intrusion is noted also for other trondhjemite bodies and dykes in the Gula Complex.

The geochemistry of the Follstad trondhjemite and related intrusions in the Gula Complex has been studied by Size (1979) and Pannemans & Roberts (this volume). All these trondhjemites are of the high-Al_2O_3 type with relatively low K_2O (c.1.3 %), and are further characterised by highly fractionated REE patterns and very low contents of Y and the heavy REE. According to these authors, a possible petrogenetic model is that of partial melting of a garnet-bearing amphibolite source rock with the composition of potassium-poor tholeiitic basalt, during crustal anatexis in an orogenic zone. Subordinate granodiorites are interpreted to have formed from a metasedimentary source under similar conditions (Pannemans & Roberts, this volume).

The composition of the trondhjemites is fairly uniform throughout the Gula Complex (Table 1). It is argued by Roberts & Sundvoll (this volume) that there is a slight difference between the Follstad intrusion and a supposedly older generation of more foliated and metamorphosed trondhjemites which occur a few kilometres to the southwest, near Snøan (Fig. 2). Data from several varieties of multiple trondhjemite intrusions within the Follstad body and in the Singsås Formation, however, show a compositional overlap with the Snøan dykes with the exception of Rb and Sr. With respect to these elements, the Snøan dykes are similar to the highly sheared and partly mylonitic trondhjemites that occur within the tectonic contact zone between the Gula and Støren units.

Sample preparation and dating

Approximately 20 kg of fresh sample material were collected for age dating from one single outcrop in the Follstad trondhjemite quarry at Støren (UTM-WGS84 32VNQ 566850 6989700, 1:50,000 map-sheet 'Støren' 1621 III). The sample was separated into mineral constituents using standard techniques of crushing and mineral separation with a Wilfley table, Frantz isodynamic separator and heavy liquids under clean conditions.

Mineral fractions were dissolved in concentrated HF and 8N HNO_3 in Teflon bombs over 5 days and U and Pb extracted using standard procedures of ion exchange chemistry. The isotopic ratios were measured using a Finnigan-MAT 262 multi-collector thermal ionization mass spectrometer in static mode. The Faraday cups were calibrated against NBS 981 and ^{204}Pb was measured in the secondary electron multiplier in ion counting mode.

Uncertainties in the isotopic ratios and ages are reported at two sigma in Table 2, and these total uncertainties consider propagation of uncertainties from mass spectrometry measurements, isotopic fractionation, Pb and U blanks, and the uncertainty on the isotopic composition of initial common Pb. Full details of the analytical procedure are reported in Dube et al. (1996).

The sample yielded a large amount of clear to pale brown titanite and zircon (Table 2). The zircon occurs as 50 to 100 micron prisms and very thin elongate needles. One large fraction of titanite analysed is concordant with $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages of 429 and 435 Ma, respectively (Fig. 4). Four fractions of zircon were analysed, and three of these were composed of larger equant euhedral prisms, and all are discordant. The discordance is interpreted to result from the presence of older inherited zircon present as cores in some of the igneous grains.

The fourth fraction, of much smaller sample weight, was composed entirely of fine-grained needles and yields a concordant data point with $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages of 432 and 437 Ma, respectively (Fig. 4). The data from this point and the titanite, interpreted to be igneous, together indicate an age of 432 ±3 Ma, based on the $^{206}Pb/^{238}U$ age of the concordant zircon, with the uncertainty large enough to include the titanite ages.

Table 1. Major and trace element compositions of representative trondhjemites from the Undal Formation of the Gula Complex (Follstad quarry, Støren), Singsås Formation of the Gula Complex (Bjørnkletten quarry, Budal) and the mylonite zone separating the Undal Formation from the Støren Group (Hundberga, Støren).

Sample No.	TGST97 65	TGST97 69	TGST97 67	TGST97 122	TGST97 124	TGST97 126	TGST97 53	TGST97 45	TGST97 49
Rock type	trondhjemite, early dyke	trondhjemite, normal type	trondhjemite, late dyke	sheared trondhjemite	mylonitic trondhjemite	mylonitic trondhjemite	early trondhjemite	normal trondhjemite	trondhjemite, late dyke
Locality	*Follstad (Undal Formation)*			*Hundberga (Støren-Undal contact)*			*Bjørnkletten (Singsås Formation)*		
SiO_2	71.19	70.68	68.06	67.89	67.05	65.30	69.20	67.36	73.83
Al_2O_3	15.80	15.83	17.97	16.37	16.15	16.32	17.06	18.30	15.52
TiO_2	0.20	0.38	0.33	0.17	0.16	0.26	0.18	0.17	0.14
Fe_2O_3	1.19	1.45	1.79	1.21	1.15	1.94	1.32	1.25	0.87
MnO	0.01	0.02	0.03	0.03	0.06	0.04	0.02	0.02	0.02
MgO	0.45	0.48	0.95	0.67	0.67	1.05	0.79	0.86	0.25
CaO	4.07	2.85	4.11	2.65	2.95	3.71	3.65	4.20	1.89
Na_2O	5.69	5.89	5.73	5.70	4.92	5.20	5.54	5.93	5.70
K_2O	0.65	1.38	1.11	1.63	2.54	1.96	0.78	1.05	1.78
P_2O_5	0.07	0.07	0.10	0.07	0.07	0.08	0.07	0.07	0.04
LOI	0.50	0.73	0.96	2.90	2.79	3.84	0.22	0.32	0.29
Total	99.81	99.76	101.14	99.30	98.51	99.69	98.83	99.52	100.33
Nb	<5	<5	<5	<5	<5	5	<5	<5	<5
Zr	93	95	78	79	83	65	83	68	89
Ce	33	31	32	21	23	28	27	23	26
Y	<5	7	<5	7	6	8	7	<5	<5
Sr	641	601	687	438	280	447	573	702	635
Rb	15	20	22	63	82	68	28	28	37
Ba	285	329	284	326	350	258	330	305	337
Cr	<5	22	<5	5	6	11	9	8	9
V	17	22	20	16	12	32	14	13	9

XRF analyses carried out at the Geological Survey of Norway. Major elements measured on fused glass beads prepared by 1:7 dilution with lithiumtetraborate, and traces on pressed powder pellets. The samples were analysed on a Philips PW 1480 sequential X-ray spectrometer equipped with a Sc/W-anode X-ray tube, using common international standards for calibration.

Table 2. U-Pb isotopic age data for the Follstad trondhjemite.

Fraction and description	Weight (mg)	Conc. U (ppm)	Conc. Pb rad (ppm)	Measured T.C. Pb (pg)	Measured $^{206}Pb/^{204}Pb$	Corrected Atomic Ratios * $^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±	Age (Ma) $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
Z1 small clear euh prisms	0.095	616	42.7	11	15545	0.1020	0.06946	21	0.5431	25	0.05671	10	433	440	480
Z2 clear euh needles abr	0.008	378	26.4	8	1640	0.1133	0.06931	28	0.5316	26	0.05562	20	432	433	437
Z3 clear euh prisms abr	0.025	511	36.1	21	2685	0.1157	0.07008	24	0.5520	20	0.05712	10	437	446	496
Z4 clear euh prisms abr	0.029	469	33.8	17	3524	0.1135	0.07150	44	0.5658	34	0.05739	8	445	455	507
T1 clear pale brown abr	1.035	57	3.8	2434	118	0.0757	0.06879	30	0.5270	57	0.05556	52	429	430	435

Notes: * Isotopic ratios corrected for fractionation, spike, laboratory blank of 2-10 picograms of common lead and initial common lead at the age of the sample calculated from the model of Stacey & Kramers (1975), and 1 picogram U blank. 2 sigma uncertainties reported after the ratios refer to the final digits and are calculated as outlined in Dube et al. (1996). T.C.Pb = total common lead, Z = zircon, T = titanite, euh = euhedral, abr = abraded (cf. Krogh 1982).

Discussion

Precise zircon dating of Caledonian rocks over the last two decades has demonstrated the existence of fairly well-defined magmatic provinces and epochs of different paleotectonic significance. The one that is best documented is that representing various oceanic and continental-margin arc sequences, which were developed in the early stages of plate convergence prior to closure of the Iapetus Ocean. Ages from these sequences range mostly from 495 to 470 Ma (Early Ordovician), but also extend into the Mid to Late Ordovician with ages of around 460 Ma for arc-related plutons (see Grenne et al. 1999 for a review).

The 432 ±3 Ma crystallisation age of the Follstad trondhjemite places the intrusion in a time interval where it is generally accepted that collision tectonics was active during the climactic, Scandian phase of the Caledonian orogeny (see, e.g., Stephens et al. 1993, Grenne et al. 1999, and references therein). A minimum age of the penetrative Scandian deformation and metamorphism in the Gula Nappe is provided by $^{40}Ar/^{39}Ar$ cooling ages for hornblende of about 425-430 Ma (Dallmeyer 1990), but the age of peak metamorphism is poorly known in the TNC part of the Upper Allochthon. The Narvik Nappe Complex in northern Norway, which may possibly be correlatable with the Gula Complex, has yielded U-Pb ages of metamorphic monazite and zircon which show that peak metamorphism occurred at c.432 Ma (Northrup 1997). East of the TNC, rocks of the Seve Nappes in the central Swedish Caledonides have yielded metamorphic U-Pb ages from sphene, monazite and zircon that range from 425 to 440 Ma (Gromet et al. 1996). Thus, metamorphism seems to have been broadly coeval with trondhjemite emplacement, immediately before the rapid uplift and cooling that occurred in Late Silurian and Early Devonian times. This is in accordance with the general absence of chilled margins in the Follstad trondhjemite indicating that it was emplaced into hot country rocks.

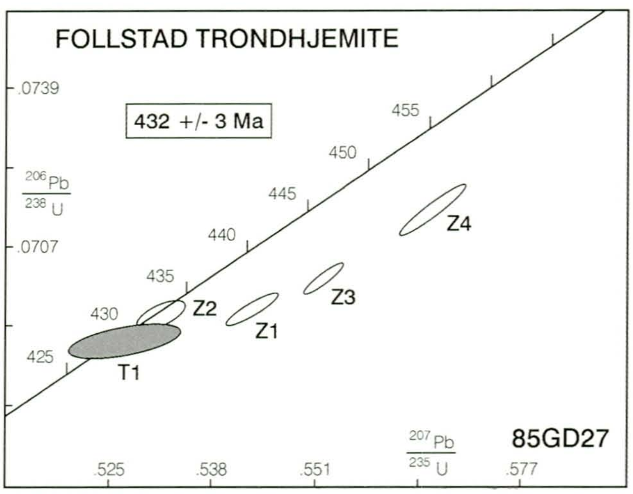

Fig. 4. U-Pb concordia diagram showing zircon and titanite data from the Follstad trondhjemite, Støren. The letters Z1-4 and T1 refer to zircon and titanite fractions, respectively, as described in Table 2.

Similar arguments are valid for the Fongen-Hyllingen complex and adjacent trondhjemites. A late, syenite differentiate of this magmatic complex was emplaced at 426 $^{+8}/_{-2}$ Ma, just prior to the D_2 deformation and accompanying medium- to high-grade metamorphism at a crustal depth of 15-20 km. Adjacent trondhjemites are temporally overlapping with this tectonomagmatic event (Olesen et al. 1973, Wilson et al. 1983).

Elsewhere in the Caledonides, zircon ages from this Early Silurian period represent essentially three different magmatic settings. The most prominent one is that of the batholithic intrusions which are found mainly in the Uppermost Allochthon of central Norway (Fig. 2), with a span of crystallisation ages of c.450-430 Ma. Batholithic magmatism includes a wide range of magma types of gabbroic to granitic compositions, but trondhjemites are absent or scarce (see, e.g., Nordgulen et al. 1993 and references therein). The paleotectonic setting has been interpreted in terms of an active continental margin above a west-dipping subduction zone in Ordovician time, possibly along the margin of Laurentia (e.g., Stephens & Gee 1989), with continued magmatism in a continent-continent collision zone during the Silurian, Scandian orogenic phase (e.g., Grenne et al. 1999).

In the Köli Nappes of the Upper Allochthon there are several gabbro complexes that have been dated at around 440-430 Ma. The Sulitjelma and Råna layered intrusions in

Nordland have similar ages of 437 ± 2 and 437 $^{+1}/_{-2}$ Ma, respectively (Pedersen et al. 1991, Tucker et al. 1990). The Artfjället gabbro in northern Sweden is 434 ± 5 Ma (Senior & Andriessen 1990). Comparable, but less precise, ages of around 435 Ma have been obtained by Sm-Nd dating from the Krutfjellet gabbro (Mørk et al. 1997). Some of these intrusions share the syn-tectonic and syn-metamorphic characteristics of the Fongen intrusion in the TNC. Moreover, they have, in general, been interpreted to reflect a paleotectonic regime characterised at least partly by crustal extension (Sturt & Roberts 1991, Stephens et al. 1993), and some are closely associated with mafic dyke swarms and associated pillow lavas, such as at Sulitjelma. It is possible that also the Solund-Stavfjord ophiolite belongs to this tectonomagmatic stage although it has yielded a slightly older zircon age of 443 ± 3 Ma (Dunning & Pedersen 1988).

Trondhjemites are concentrated in the Köli Nappes of the Upper Allochthon and, as noted above, some of these are spatially associated with gabbros of the type just mentioned. Reliable zircon dates, however, exist only for a few of the trondhjemites. Within the TNC, two trondhjemitic pegmatites in high-grade schists west of Trondheim, have been dated at about 431 ± 2 and 423 ± 2 Ma by U-Pb on zircon (R.D. Tucker, in Solli et al. 1997). Earlier, Rb-Sr and U-Pb zircon dating of trondhjemites within the Gula Complex have been reported in a preliminary form by Klingspor & Gee (1981). According to these authors, zircons from the Vakkerlien trondhjemite near Kvikne defined a U-Pb discordia line with an upper intercept of 477 $^{+8}/_{-5}$ Ma, but the intrusion was later reinterpreted to have an age of 509 $^{+8}/_{-4}$ Ma (I. Klingspor & D.G. Gee, pers. comm. in Stephens et al. 1985). Rb-Sr wholerock age determinations indicated ages in the order of c.478 to 447 Ma, with large uncertainties, for this and three other trondhjemites in the Gula Complex. Rb-Sr data from trondhjemite dykes in the Snøan area, just southwest of Follstad, have given an isochron age of 465 ± 11 Ma, interpreted by Roberts & Sundvoll (this volume) as a minimum age of intrusion and reflecting a phase of post-emplacement thermal resetting. In our opinion, all these ages should be considered with caution until they are confirmed by precise zircon dating.

Stephens & Gee (1985) argued for a correlation between the Gula Complex and the Upper Köli Nappes in Västerbotten, Sweden, where there is evidence that granitic and gabbroic magmatism occurred in the Early Silurian (Stephens et al. 1993 and references therein), broadly contemporaneous with the Follstad trondhjemite. In northern Norway, Upper Allochthon metasedimentary sequences that can possibly be correlated with the Gula Complex (the Narvik Nappe Complex) contain granitic dykes that have yielded U-Pb zircon ages of 437 ± 1 Ma (Northrup 1997). This age is identical to that of the Råna gabbro which is located in the same unit. Farther north, a syn-tectonic granite in the Lyngen Nappe Complex of central Troms has been dated at 432 ± 7 Ma by the Rb-Sr method (Lindstrøm & Andresen 1995).

On a regional scale, the age and field relationships of the intrusions may provide some information on the history of tectonic juxtaposition of the different nappe units within the TNC. Their occurrence in the Gula as well as in the Meråker and Støren Nappes seems to imply that these units were at least close to each other, if not stacked together, at the time of intrusion. It is possible that this proximity was due to obduction of the Støren and Fundsjø Groups on to Gula sequences, as suggested by previous authors, but there is no unequivocal evidence of such an Early Ordovician amalgamation of the terranes. At any rate, the mylonitic contact zone between the units as seen now in the Gauldal region must be a result, at least in part, of subsequent nappe movements. This is because (1) trondhjemites which, in our view, are similar to the Follstad intrusion are themselves mylonitised along this zone, and (2) the trondhjemites are much more abundant on one side of the contact in the vicinity of Støren.

In a paleotectonic context, available data indicate that the Follstad trondhjemite belongs to an Early Silurian tectonomagmatic epoch lasting perhaps over a time interval of 15 Ma or more and represented mainly in the Upper Allochthon of the Caledonide orogen. The period was characterised by orogenic, continent collision-related, deformation and metamorphism penecontemporaneous with emplacement of felsic and mafic (rift-related) intrusions. Moreover, existing zircon ages show that this magmatism was coeval with the late stages of batholith development farther west, now represented mainly in the uppermost parts of the nappe pile. This implies considerable variations in magmatic activity across the collision zone.

It has been demonstrated elsewhere (Size 1979, Pannemans & Roberts, this volume) that the Follstad and similar trondhjemites in the region were probably formed by partial melting of mafic rocks under garnet-amphibolite conditions. Similar conclusions have been drawn for comparable trondhjemites worldwide (e.g. Drummond et al. 1996, Rollinson 1996, Martin 1999). Such rocks have often been interpreted as the products of dehydration melting of a downgoing slab of young and hot oceanic crust in a subduction zone. Such an origin, however, seems highly unlikely for the Caledonian trondhjemites under consideration, since there is overwhelming evidence that they formed during the interaction of two continental plates and that young oceanic crust subduction was not involved at this stage.

Unless the intimate spatial and temporal relationships between mafic and felsic intrusions in the Upper Allochthon are pure coincidence, which we consider unlikely, this may be a key to our understanding of the origin of trondhjemites in this part of the orogen. There is little doubt that the mafic magmas, ranging in composition from tholeiitic to alkaline or calc-alkaline (see Grenne et al. 1999 and references therein), were derived from a mantle source. It is very likely that these hot mafic melts would provide sufficient heat for partial melting of deep crustal rocks which were at garnet-amphibolite grade. It seems less obvious why garnet amphibolites of basaltic origin should play such a dominating role in the source region; there is evidence of more K-rich metasedimentary sources that gave rise to contemporaneous granodioritic to granitic magmas but these appear to have been subordinate.

The paleotectonic setting of this magmatism is not unequivocal, but there is general consensus that the Scandian phase was characterised by highly oblique collision between the continents. This may have been due in part to a rapid anticlockwise rotation of Baltica and a lateral relative movement of the converging margins of Baltica and Laurentia at the Ordovician-Silurian boundary (e.g., Torsvik et al. 1996). Such a scenario would be broadly equivalent to the situation for Late Cenozoic magmatism across the Arabia-Eurasia collision zone in Turkey (Pearce et al. 1990) and might allow the development of extensional segments that facilitated episodic rift magmatism and associated trondhjemite formation, within a predominantly transpressional regime.

Conclusions

The age of intrusion of the trondhjemite body at the type locality at Follstad is estimated at 432 ± 3 Ma from overlapping concordant zircon and titanite U-Pb analyses. The trondhjemite is a representative of an extensive suite of intrusions that are concentrated in the Köli Nappes of the Upper Allochthon of the Scandinavian Caledonides. Trondhjemite emplacement was commonly associated with mafic magmatism, and the magmatism was broadly coeval with metamorphism and deformation during the early stages of the Scandian, climactic Caledonian, orogenic event. The geochemical composition of the trondhjemites indicates that they were formed as products of partial melting of garnet-amphibolite grade, deep crustal rocks. We suggest that this partial melting was facilitated by the emplacement of the contemporaneous rift-related, mantle-derived mafic intrusions.

A possible scenario is a paleotectonic setting characterised by the development of extensional segments within a predominantly transpressional regime, due to highly oblique continental collision. This was probably a consequence of the rapid anticlockwise rotation of Baltica and a lateral relative movement of the converging margins of Baltica and Laurentia at the Ordovician-Silurian boundary.

Acknowledgements

The authors are grateful to Mike Stephens and Bernard Bingen for their helpful reviews of the manuscript.

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