U-Pb geochronology and geochemistry of trondhjemites and a norite pluton from the SW Trondheim Region, Central Norwegian Caledonides

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Zircon analyses from two trondhjemites and a biotite norite from a part of the southwestern Trondheim Region have yielded almost identical Early Silurian ages. The biotite norite and one of the trondhjemites, from a quarry in the Innset massif in the Støren Nappe, produced analytical data which define concordia ages of 435.8 ± 0.9 Ma and 434.8 ± 0.5 Ma, respectively. Zircons from a trondhjemite body at Nyvollen, Innerdalen, in the western Gula Complex, yielded an upper-intercept age of 433.8 ± 0.8 Ma. All three dates are interpreted to represent the ages of emplacement of these bodies.

Geochemical signatures from these, and other trondhjemites intruding the Köli Nappes of the Trondheim Region show them to be of high-alumina, continental-margin type. Field and microscopic studies indicate that the Innset massif, and other composite gabbro-trondhjemite bodies in this region, pre-date Scandian orogenic deformation and metamorphism. The ages reported here accord with a known pattern of gabbro-diorite-trondhjemite magmatism that is recorded in the Köli Nappes in several parts of the Scandinavian Caledonides in latest Ordovician/Early Silurian time. This sporadic magmatism is coeval with the early stages of oblique, Baltica-Laurentia plate collision, wherein short-lived, transtensional crustal segments developed in a broadly transpressive-convergent system, thus allowing localised penetration of these magmas. These rift-related, local transtensional settings were then quickly succeeded by prograde-metamorphic, sinistral-transpressive, Scandian orogenesis, which is dated to approximately 430-425 Ma in this particular part of central Norway.

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Introduction

Large areas of the Caledonides of Central Norway are dominated by metasedimentary and metavolcanic rocks of the Trondheim Nappe Complex, a tripartite element forming part of the Köli Nappes which constitute the upper half of the Upper Allochthon of Caledonide tectonostratigraphy. No less prominent on a geological map, even at 1:1 million scale (Sigmond et al. 1984), are the large bodies of trondhjemite, up to 200 km^2 in outcrop size, that occur scattered throughout this region, in some cases coexisting with diorite or gabbro. Trondhjemites also occur quite commonly as dykes in many areas.

Definition of the term trondhjemite derives from Goldschmidt's (1916) pioneering studies on the magmatic rocks of central and southern Norway. In current classification schemes it is formally defined as a leucocratic tonalite, with <10% of mafic mineral constituents (Barker 1979, Le Maitre 1989), but it has also been regarded as synonymous with plagiogranite and related sodic granitoid rocks. This is also the case in Norwegian geological literature, and on most geological maps, and it is therefore important for purposes of interpretation and tectonic modelling to try to distinguish between the two variants, either by geological affiliation or by geochemical signature.

Trondhjemites *sensu lato*, and granitic rocks in general, are favourite targets for geochronological investigation. This is largely because of the greater likelihood of finding sufficient quantities of euhedral zircon grains in these rocks, for U-Pb dating, than in mafic plutonic bodies. In recent years, several zircon dating studies in central Norway have concentrated more on the plagiogranitic variety of trondhjemite that occurs here and there in association with ophiolites and related rock assemblages (Dunning 1987, Dunning & Pedersen 1988, Bjerkgård & Bjørlykke 1994, Roberts & Tucker 1998, Roberts et al. 2002). By comparison, the ages or age range of non-ophiolitic trondhjemite bodies and dykes are less well defined (Dunning & Grenne 2000), even though these rocks are potentially important time markers in helping to provide better constraints on the geological evolution of any one particular area. In this contribution, we try to redress the balance, to some extent, in presenting U-Pb zircon dates from two trondhjemite bodies and an associated biotite norite pluton from the southwestern part of the Trondheim Region.

Regional setting

The geology of the Trondheim Region is dominated by rocks of Köli Nappe affinity, essentially three separate tectonic units, the Støren, Gula and Meråker Nappes, which together form the Trondheim Nappe Complex (Guezou 1978, Wolff 1979, Gee et al. 1985). Rocks of Seve Nappe affinity occur directly below the Köli Nappes in most places and, together, these two elements constitute the Upper Allochthon (Roberts & Gee 1985) (Fig. 1). An updated description of the geology and Caledonide tectonostratigraphy of central Norway and adjacent areas in Sweden has been presented by Roberts & Stephens (2000).

The geology of southwestern and southern parts of the Trondheim Region has been documented by, e.g., Rohr-Torp (1972, 1974), Nilsen (1974, 1978), Guezou (1978), Krill (1980, 1983, 1985) and Gee et al. (1985). The bedrock geology of the district is also covered by a comparatively modern map compilation at 1:250,000 scale (Nilsen & Wolff (1978). In order to understand the regional context of the plutonic bodies that we have dated (Fig. 2), it is necessary to consider

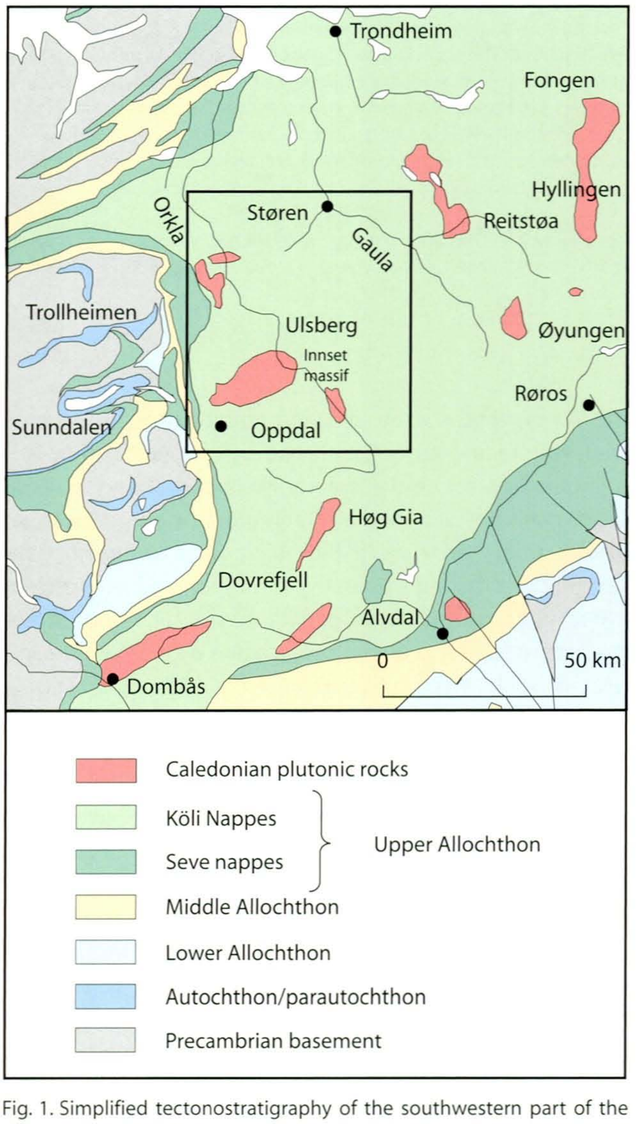

Fig. 1. Simplified tectonostratigraphy of the southwestern part of the Trondheim Region, showing the location of the area (box) depicted in Figure 2. Some of the principal trondhjemite or gabbro-diorite-trondhjemite massifs are also indicated.

briefly the situation a little farther north, in what is generally termed the western Trondheim Region. In the Støren district (Fig. 2), a fragmented ophiolite represented by mafic volcanites and dykes of the Støren Group lies with tectonic contact upon rocks of the Gula Complex (Gula Nappe). The 'Støren ophiolite' is considered to have been obducted upon the Gula rocks in Early Ordovician time; at which time these two rock units were initially deformed and metamorphosed (Lagerblad 1984, Pannemans & Roberts 2000). Following uplift and erosion, sedimentary and subordinate volcanic rocks of the Hovin and Horg Groups (Mid Arenig to possibly Llandovery age) (Fig. 2) accumulated in a marginal basin setting (Roberts et al. 1984); and were eventually deformed and metamorphosed at comparatively low grade during the Siluro-Devonian, Scandian orogeny. In the literature, the Støren ophiolitic rocks together with the unconformably overlying Hovin and Horg Groups have been termed the Støren Nappe (Gale & Roberts 1974). Although this is an unfortunate term in many ways, it is ingrained in the literature and is retained here, purely for convenience.

The Støren ophiolitic unit and the unconformably overlying Hovin Group metasedimentary rocks extend southwards into the area considered here, between Ulsberg and Oppdal. In this area, mapped and described by Rohr-Torp (1972, 1974), the Hovin Group metasedimentary rocks (also known as the 'Krokstad sediments'; Rohr-Torp, 1972) are intruded by the *Innset massif* (Naumann 1824, Goldschmidt 1916, Rohr-Torp 1974), a composite, elongate pluton covering an area of about 180 km^2 (Fig. 2) and ranging in composition from norite to trondhjemite. The contact-metamorphic effects seen around this massif were first noted by Keilhau (1850), and described in some detail by Rohr-Torp (1974) who concluded that the intrusion must have predated the main Scandian deformation and regional metamorphism of the Krokstad (Hovin) metasedimentary unit. Trondhjemites cutting different lithologies and tectonostratigraphic units are common in the Ulsberg-Oppdal-Kvikne area. In the Gula Nappe, they occur as separate, minor, weakly or negligibly foliated, massive bodies, some of which cover areas of up to 30 km^2 in the Kvikne-Innerdalen district (Rohr-Torp & Nilsen 1979) (Fig. 2).

The only previous, attempted dating of rocks from the Innset massif is recorded in an unpublished report (Peterman & Barker, 1976), which was later amended and revised by Barker & Millard (1979). In this Rb-Sr study, the authors analysed a biotite diorite and a leucogranodiorite from the Innset body, together with three trondhjemites from different areas 30-40 km north of Innset (well outside the Innset massif), and obtained an isochron age of 548 ± 35 Ma. Such an isochron age, derived from widely separate and geochemically different plutonic rocks, has little meaning; and its invalidity has since been proven by the U-Pb dating of zircon and titanite from one of these sampled trondhjemites, from the type locality at Follstad (Fig. 2). This gave a crystallisation age of 432 ± 3 Ma (Dunning & Grenne 2000).

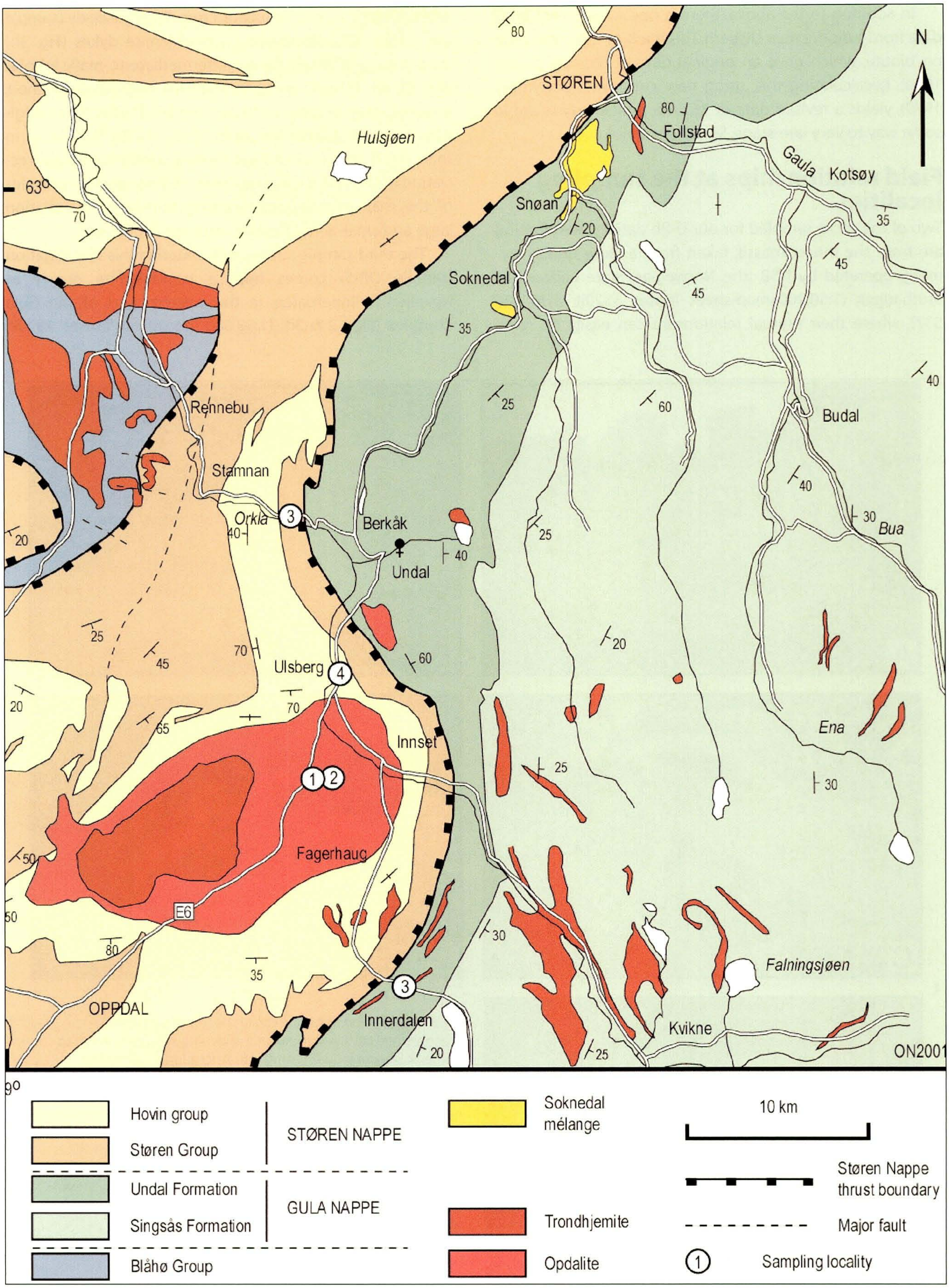

Fig. 2. Geological map of the Ulsberg-Kvikne- Soknedal district showing the locations of the samples (1-5) investigated in this geochronological/geochemical study.

In addition to the above, there is one recorded mineral date from a diorite near Ulsberg. This is a K-Ar determination on biotite, which gave an original date of 355 Ma (Broch 1964). Recalculating this, using new constants (Dalrymple 1979), yields a revised date of 362 Ma; which may relate in some way to very late-stage, Scandian cooling.

Field relationships at the sampling localities

Two of the rocks sampled for our U-Pb dating investigation are from the Innset massif, taken from a large quarry formerly operated by NSB (the Norwegian State Railway) at Stuthaugen (1:50,000 map-sheet 'Innset' 1520II; UTM 496 537), where their mutual relationship can easily be seen. There, a massive, weakly foliated trondhjemite body (sample DR-1) (Fig. 3a) and sporadic trondhjemite dykes (Fig. 3b) transect one of the dominant, intermediate-to-mafic lithologies of the Innset massif, in this case a medium-grained, greenish-grey, biotite norite (sample DR-2) which was originally termed 'opdalite' by Goldschmidt (1916). The biotite, in this case, is primary. In places, there is a pervasive autobrecciation of the wall rocks, and there are spectacular examples of the main trondhjemite cutting through and isolating large and small xenoliths of biotite norite (Fig. 3c).

The third sample successfully dated in this investigation (sample DR-5) comes from a trondhjemite quarry at Nyvollen in Innerdalen, in the western part of the Gula Complex (Figs. 2 & 3d) (1:50,000 map-sheet 'Innset' 1520II;

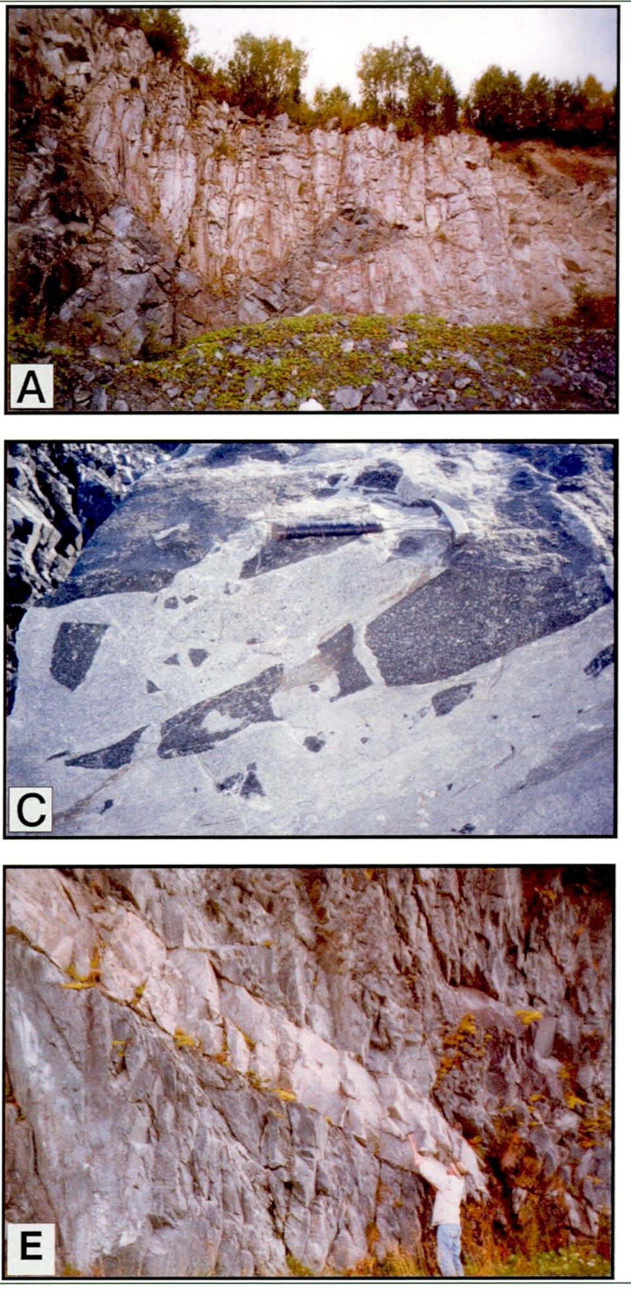

Fig. 3. Field photographs of some of the trondhjemites. (a) Trondhjemite cutting through and enclosing xenoliths of biotite norite, Stuthaugen quarry, south of Ulsberg; looking north. (b) Trondhjemite dyke transecting biotite norite, Stuthaugen quarry. (c) Trondhjemite cutting through and isolating xenoliths of biotite norite; surface of a large block, Stuthaugen quarry. (d) The south-eastern contact zone of the trondhjemite at Nyvollen quarry, Innerdalen; looking northeast. The host rocks are schists/phyllites and metasiltstones of the Undal Formation (Fig. 2). (e) Gently dipping trondhjemite dyke cutting metagreywackes and phyllites of the 'Krokstad unit'. Road-cut along the E6 just north of Ulsberg, looking south-southeast.

UTM 536 421). In the Innerdalen-Kvikne district, many such trondhjemites carry distinct flakes of biotite, making the rock suitable as an ornamental stone. In Innerdalen, the trondhjemite is quarried under the commercial name 'Crystal White'. At Nyvollen, the trondhjemite occurs as a composite dyke more than 100 metres across trending at c. 035° and dipping at just over 30° to the southeast (Fig. 3d). This is more or less concordant with the schistosity in the host-rock Undal Formation (Nilsen 1978, Nilsen & Wolff 1989), here represented by dark grey to black, graphitic metapelites with intercalations of grey metasiltstone.

As well as the three samples mentioned above, two finer-grained trondhjemite dykes were also sampled, from north of Ulsberg and west of Berkåk (Fig. 2). The c. 1.3m-thick dyke west of Berkåk (1:50,000 map-sheet 'Rennebu' ; UTM 481 678) (sample DR-3) lies subparallel to the ESE-dipping foliation in schistose metabasalts with mafic dykes, part of the Støren ophiolitic unit. Just two fractions of zircon from this trondhjemite dyke were analysed; both are discordant and the apparent ages obtained point to inheritance and wall-rock contamination. The second trondhjemite dyke, in outcrops along the E6 road just north of Ulsberg (1:50,000 map-sheet 'Rennebu', UTM 505 602) (sample DR-4; Fig. 3e), was found to contain too few and poorer-quality zircons, and was not analysed. This particular ENE-WSW-trending dyke is c. 1.5 m thick and cuts steeply dipping, greenish-grey greywackes and pelites of the 'Krokstad unit'. Its location is within the outer part of the contact aureole of the Innset massif (Rohr-Torp 1974).

Petrographic features

Samples DR-1, DR-2 and DR-4 are comparatively fine-grained, leucocratic rocks with a heterogranular, sub-porphyritic texture. A faint foliation is defined by sheet-silicate minerals, principally muscovite, which constitute up to c.15 vol.% of the mode (Table 1). Quartz and plagioclase (An_{0-15}) constitute 70-90 vol.% of the rocks and occur as an anhedral groundmass with a grain size of 0.05- 0.1 mm. In a few cases, there are anhedral plagioclase phenocrysts with a grain size of 1-2 mm. The feldspars are strongly saussuritised, sericitised and partly chloritised. The principal accessory minerals are clinozoisite, titanite, zircon, apatite and secondary calcite, all with grain sizes of c. 0.1 mm.

Goldschmidt (1916) considered the presence of muscovite and chlorite in this particular type of trondhjemite to be a replacement feature arising from late-magmatic, hydrothermal-pneumatolytic activity. However, the muscovite, chlorite and clinozoisite are clearly metamorphic replacements after K-feldspar and biotite, and in all probability related to the low-grade Scandian overprint of the contact aureole around the Innset massif. The field and petrographic character of dykes DR-3 and DR-4 are reminiscent of the 'greenish-white trondhjemites' described by Pannemans & Roberts (2000) from the Støren-Gauldalen district farther to the north.

Table 1. Modal compositions of trondhjemite samples DR4 and DR5 and biotite norite DR2.

Mineral/Sample	DR4	DR5	DR2
plagioclase	41.8	60.4	65.4
quartz	34.0	29.4	1.8
microcline	0.0	2.4	1.2
orthopyroxene	0.0	0.0	13.2
clinopyroxene	0.0	0.0	10.6
biotite	0.0	4.3	6.9
chlorite	2.2	0.0	0.0
muscovite	15.6	2.3	0.0
clinozoisite	1.4	1.0	0.0
sphene/zircon	1.0	0.1	0.0
apatite	0.0	0.1	0.1
carbonate	4.1	0.0	0.0
ore minerals	0.0	0.0	0.9
Sum	100.1	100.0	100.1

The Innerdalen trondhjemite (sample DR-5) is a medium-grained, heterogranular rock with a grain size of 1-3 mm, and is composed principally of more or less unaltered plagioclase and quartz (c. 90 vol.% of the mode; Table 1). Although intergranular microcline and biotite are minor mineral constituents, it is the biotite that makes the rock particularly attractive as an ornamental stone. Accessory minerals are muscovite, zircon, clinozoisite and apatite.

The biotite norite from the Innset massif (sample DR-2; Table 1) is a massive, heterogranular, medium-grained rock with a grain size of 1-3 mm. Plagioclase (An_{40}) and orthopyroxene are the chief mineral constituents (approximately 80 vol.%), and clinopyroxene, biotite and opaque ore minerals are subordinate. Microcline-perthite, quartz, apatite, zircon and chlorite are accessory constituents. The orthopyroxene (hypersthene) occurs as weakly chloritised subhedral prisms, usually as evenly distributed aggregates, together with non-pleochroic, colourless clinopyroxene and brown biotite.

Geochemical traits

Major and trace element analyses of the five samples collected for this geochronological study were carried out at the Geological Survey of Norway, Trondheim, principally for comparison with analytical data derived from trondhjemites investigated in other parts of the Trondheim Region. The rock samples were analysed using an automatic Philips PW1480 XRF spectrometer. Major elements were determined on glass discs, prepared by fusing one part of pre-ignited (1000°C) rock powder with 7 parts of $Li_2B_4O_7$. Trace elements were determined on pressed powder pellets, using wax as a binder. The analytical data and CIPW normative compositions are presented in Table 2. The REE analyses were determined by ICP-MS at the Afd. Fysico-chemische geologie, University of Leuven, Belgium.

Normative and modal data from the five samples are depicted in Figs. 4a & b. These plots clearly show the trondhjemitic nature of the leucocratic rocks. The chemical and mineralogical composition of the biotite norite taken from

Table 2. Chemical and normative compositions of trondhjemites and biotite norite from the Berkåk-Innset-Innerdalen area.

	DR1	DR3	DR4	DR5	DR2
SiO_2	69.49	67.83	68.04	69.32	54.83
TiO_2	0.21	0.28	0.26	0.18	1.12
Al_2O_3	15.50	16.80	15.89	16.26	16.46
FeO	1.41	1.50	1.58	1.19	7.46
MnO	0.02	0.03	0.02	0.02	0.11
MgO	0.66	0.76	0.82	0.54	6.90
CaO	2.70	3.63	2.51	2.37	7.22
Na_2O	5.51	6.00	5.49	6.08	3.51
K_2O	1.32	1.32	2.06	1.60	1.22
P_2O_5	0.07	0.10	0.08	0.06	0.26
CO_2	0.00	0.00	0.00	0.00	0.00
H_2O	0.86	1.74	2.72	0.46	0.27
Sum	97.75	99.99	99.47	98.08	99.36
$Fe^{3+}/(Fe^{2+}+Fe^{3+})$ 0.25					
Zr	82	90	96	84	90
Y	3.6	3.9	3.2	3.4	18.2
Sr	580	681	302	868	443
Rb	27	18	62	32	26
Zn	29	33	36	23	62
Ni	6	9	9	6	125
Cr	7	10	11	8	264
Ba	440	271	354	304	300
Nb	<5	6	<5	<5	6
V	22	17	33	19	120
Qz	26.02	9.49 2	1.90	22.13	3.44
Cor	0.27	0.00	0.27	0.37	0.00
Or	8.05	7.94	12.58	9.68	7.26
Ab	48.10	51.65	47.99	52.68	29.91
An	13.35	15.27	12.33	11.64	25.74
Ne	0.00	0.00	0.00	0.00	0.00
Lc	0.00	0.00	0.00	0.00	0.00
Ac	0.00	0.00	0.00	0.00	0.00
Na-met	0.00	0.00	0.00	0.00	0.00
Cpx	0.00	1.95	0.00	0.00	6.94
Wo	0.00	0.00	0.00	0.00	0.00
Opx	3.05	2.31	3.58	2.51	20.93
Ol	0.00	0.00	0.00	0.00	0.00
Il	0.41	0.54	0.51	0.35	2.14
Mt	0.59	0.61	0.66	0.49	3.03
Hm	0.00	0.00	0.00	0.00	0.00
Ap	0.17	0.24	0.19	0.14	0.61
	100	100	100	100	100

the Innset massif (DR-2) corresponds well with the analyses presented by Goldschmidt (1916).

The four trondhjemites of the present study are very similar in almost all respects to the diverse trondhjemites from the Gauldalen district described by Pannemans & Roberts (2000) and Roberts & Sundvoll (2000), and also to the type-locality Follstad trondhjemite (Size 1979, Dunning & Grenne 2000). All these rocks, including our own samples, are characteristic of high-Al_2O_3 trondhjemites reported from continental margin environments. This can be seen quite clearly from the Rb/Sr variation diagram (Fig. 5a), and the same features are evident from a plot of ytterbium against Al_2O_3 (Fig. 5b).

REE analytical data (Table 3) for three of the trondhjemites (samples 1, 3 and 4) are comparable in almost all respects with those reported from the Gauldalen district, with moderately high LREE enrichments and low HREE contents, and a very small, positive Eu anomaly (Fig. 6). The sample from Innerdalen (DR-5) shows a slight upward convexity and somewhat lower contents of LREE in its chondrite-normalised pattern. From the modal, normative and other geochemical data, this disparity in just the LREE is difficult to explain, but a likely cause is that of variation in the composition of the mafic source rock material.

U-Pb isotopic data

Analytical technique

The U-Pb analyses were carried out by isotope dilution (Krogh 1973). The zircon crystals were picked under a binocular microscope, abraded (Krogh 1982), and dissolved at 185°C in teflon bombs after addition of a $^{205}Pb/^{235}U$ spike. After dissolution, the U and Pb were purified on anion exchange resin with HCl and then loaded (together) on outgassed Re-filaments with Si-gel and phosphoric acid. Measurements were carried out with a MAT262 mass spectrometer in static mode, or, for small amounts of Pb and all $^{207}Pb/^{204}Pb$ ratios, in dynamic mode using an ion-counting ETP-multiplier. Pb data were corrected for 0.1%/amu fractionation and the U for 0.12%/amu, with an additional adjustment to correct for an exponential SEM bias determined from regular runs of the NBS 982 Pb standard. Blank correction was 2 pg Pb and 0.1 pg U. The initial Pb was corrected using Pb compositions calculated with the Stacey & Kramers (1975) model. The results were plotted and regressed using the software of Ludwig (1999). The decay constants are those of Jaffey et al. (1971). Uncertainties in the isotopic ratios and the ages are given and plotted at 2 sigma.

Table 3. Rare earth element abundances (ppm) of four trondhjemites and a biotite norite from the Berkåk-Innset-Innerdalen area.

	DR1	DR3	DR4	DR5	DR2
Y	3.6	3.9	3.2	3.4	18.2
La	8	8.6	8.8	2.43	18.4
Ce	6.6	18.6	19.4	7.5	40.2
Pr	1.85	2.24	2.3	0.97	4.8
Nd	6,87	8,89	8,86	4,03	19.4
Sm	1.35	1.77	1.68	1.06	4.18
Eu	0.43	0.61	0.54	0.42	1.47
Gd	0.99	1.26	1.1	0.86	3.61
Tb	0.13	0.16	0.14	0.13	0.56
Dy	.7	0.82	0.67	0.65	3.39
Ho	0.13	0.14	0.12	0.12	0.68
Er	0,.33	0.35	0.29	0.31	1.82
Tm	0.046	0.046	0.04	0.045	0.25
Yb	0.31	0.29	0.25	0.29	1.69
Lu	0.048	0.044	0.04	0.046	0.26

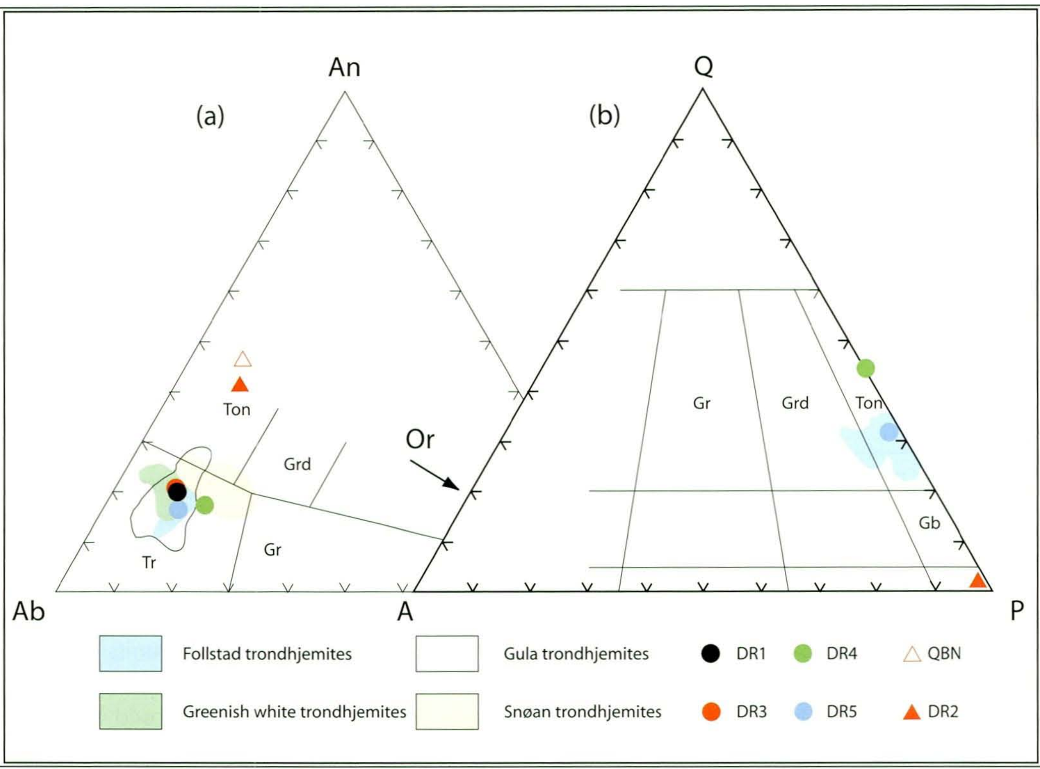

Fig 4. (a) Normative (An-An-Or) and (b) modal (Q-A-P) diagrams of tronhjemites and associated rocks from the west-central Trondheim Region. The An-Ab-Or diagram is from O'Connors (1965). Gr - granite; Grd - granodiorite; Ton - tonalite; Qgb - quartz gabbro; Gb - gabbro/diorite. The fields of 'Follstad trondhjemites' and 'Greenish-white trondhjemites' are from Pannemans & Roberts (2000) (nornative) and Size (1979) (modal); and the 'Snøan trondhjemites' from Roberts & Sundvoll (2000). The field for 'Gula trondhjemites' (12 samples) encompasses analyses by Goldschmidt (1916) and O. Nilsen (unpublished data). QBN - One quartz-biotite norite sample from the Innset massif, taken from Goldschmidt (1916) (modal analysis not available).

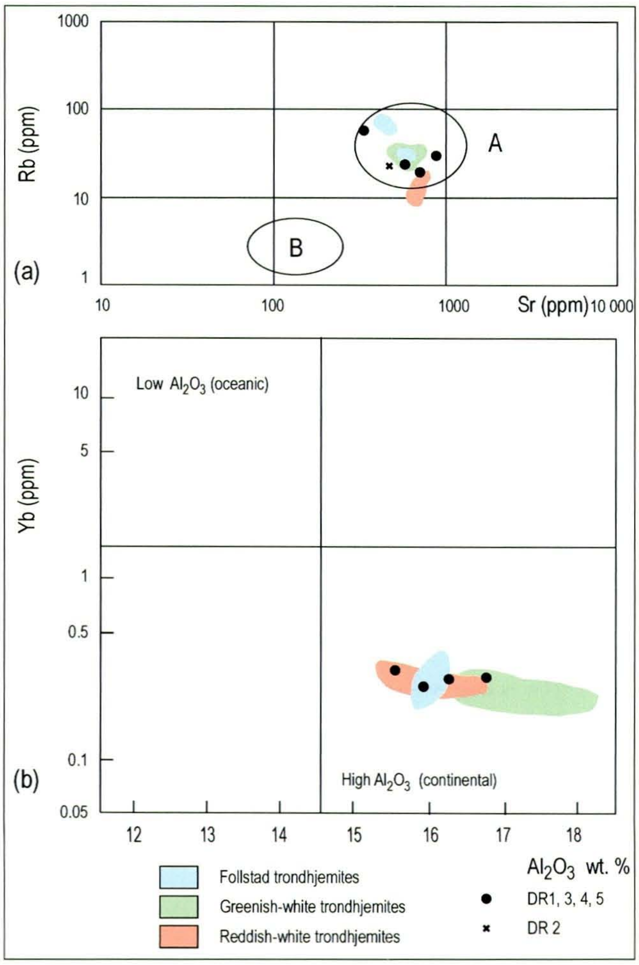

Fig. 5. The trondhjemite and norite analyses (DR1-5) plotted on (a) Rb-Sr and (b) Yb vs. Al_2O_3 diagrams. In (a), A represents the field of continental trondhjemites, and B the field of plagiogranites/-oceanic trondhjemites. Fields for other trondhjemites (cf. Pannemans & Roberts 2000) are also shown.

Results

Five analyses have been carried out on zircons from sample DR-1 using selections of various types of grains, including broken prisms and tips, in an attempt to avoid grains with xenocrystic components (Table 4, Fig. 7). All five analyses are concordant within error but one of them plots at a somewhat younger age suggesting that these zircons have lost some Pb. The two uppermost data points overlap and define a concordia age of 434.8 ± 0.5 Ma.

Sample DR-2 contains a larger population of good-quality zircon with no optical evidence for xenocrystic components. Four analyses of broken euhedral crystals plot on or nearly on the concordia curve, yielding overlapping $^{207}Pb/^{206}Pb$ ages. Calculation of a regression line anchored at a lower intercept of 50 ± 50 Ma yields an upper intercept age of 435.8 ± 0.9 Ma (Fig. 7).

Sample DR-5 had a rather sparse and heterogeneous population of zircons, which showed clear evidence for the probable presence of inherited grains. Indeed, one of the analyses provides a Mesoproterozoic apparent age. Four

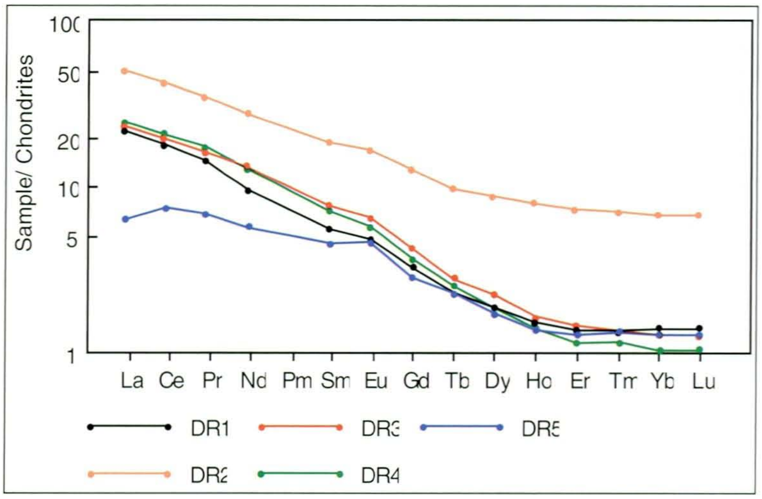

Fig. 6. Chondrite-normalised REE plots of the trondhjemites and biotite norite from the Berkåk-Innset-Innerdal area. Element normalisation values from Taylor & McClellan (1985).

other analyses, carried out on parts of zircon crystals deemed to be free of cores, are concordant, but they exhibit a distinct dispersion in age. The oldest age was obtained from the tip of a single zircon. A somewhat younger analysis obtained from 3 flat crystals is imprecise and also overlaps the two younger data points (Fig. 7). Because the latter were obtained from well abraded, good-quality material, they are not suspected of being discordant, i.e., having lost Pb. Calculation of a concordia age using the three youngest analyses provides an age of 433 ± 0.8 Ma, which is considered to be the best estimate for the age of intrusion of this trondhjemite. This interpretation implies that the above-mentioned zircon tip contained a xenocrystic component.

Discussion

The zircon ages reported here, and their interpretation as ages of emplacement of the respective bodies, denote that the magmatism represented at these three localities was broadly coeval at around 435 Ma. On recent absolute time-scales for the Early Palaeozoic (Tucker & McKerrow 1995, McKerrow & van Staal 2000), this would correspond to a roughly Mid Llandovery age for this plutonic and hypabyssal event. The dated trondhjemites and biotite norite occur in two separate, adjacent, tectonostratigraphic units of Köli affinity – the Støren and Gula Nappes – parts of which are considered to have been tectonically juxtaposed in approximately Mid Arenig time (Grenne & Roberts 1981, Sturt & Roberts 1991, Roberts et al. 2002).

Geochemical signatures for the dated trondhjemites, one from the Innset massif and the other from Nyvollen, Innerdalen, are similar. The similar, high-alumina, continental

Table 4. U-Pb data on zircons from the three investigated samples.

zircon characteristics	Weight	U	Th/U	Pbc	^{206}Pb/^{204}Pb	^{207}Pb/^{235}U	2σ	^{206}Pb/^{238}U	2σ	rho	^{207}Pb/^{206}Pb	2σ	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb
	[µg]	[ppm]		[pg]			[abs]		[abs]			[abs]		[Ma]	
(01)	(1)	(2)	(3)	(4)	(5)	(6)	(6)	(6)	(6)		(6)	(6)	(6)	(6)	(6)
DR-1															
B6	17	282	0.29	31.5	681	0.5321	0.0031	0.06964	0.00018	0.55	0.05541	0.00027	434.0	433.2	428.9
B20	10	289	0.53	33.4	397	0.5338	0.0055	0.06984	0.00029	0.44	0.05542	0.00051	435.2	434.3	429.7
fr	61	342	0.56	2.5	36411	0.5356	0.0013	0.06989	0.00015	0.96	0.05558	0.00004	435.5	435.5	435.5
eu sp 1gr	28	50	0.29	2.5	2464	0.5320	0.0022	0.06966	0.00019	0.76	0.05539	0.00015	434.1	433.2	428.0
B5	15	223	0.33	3.2	4545	0.5280	0.0021	0.06913	0.00025	0.88	0.05540	0.00011	430.9	430.5	428.4
DR-2															
fr	220	265	0.54	37.5	6803	0.5336	0.0016	0.06961	0.00019	0.96	0.05560	0.00004	433.8	434.2	436.5
fr	336	170	0.56	52.6	4774	0.5346	0.0013	0.06979	0.00014	0.92	0.05555	0.00005	343.9	434.8	434.5
fr	354	218	0.56	6.3	53907	0.5348	0.0015	0.06976	0.00018	0.97	0.05560	0.00003	434.7	435.0	436.2
eu broken	279	233	0.57	17.0	16701	0.5322	0.0013	0.06947	0.00015	0.96	0.05556	0.00004	433.0	433.3	434.8
DR-5															
tip 1 gr	1	558	0.60	0.8	3286	0.5392	0.0022	0.07034	0.00022	0.78	0.05560	0.00014	438.2	437.9	436.4
flat crystals 3 gr	1	725	0.49	5.1	643	0.5354	0.0039	0.06987	0.00027	0.63	0.05558	0.00031	435.4	435.4	435.6
fr (lp crystals)	11	199	0.47	2.1	4652	0.5317	0.0021	0.06956	0.00022	0.88	0.05544	0.00010	433.5	433.0	430.1
fr 2gr	37	191	0.45	3.8	8070	0.5319	0.0017	0.06956	0.00019	0.89	0.05546	0.00008	433.5	433.1	430.9
B23	18	56	0.33	12.3	821	1.8558	0.0195	0.15705	0.00156	0.95	0.08570	0,.00028	940.4	1065.5	1331.5

(1) all zircon fractions consisted of clear, transparent grains; all were abraded; fr = fragments; eu = euhedral; sp = short-prismatic; lp = long-prismatic; 2 gr = indicates number of grains analyzes (no indication means more than 10 grains)

(2,4) weight and concentrations are known to better than 10%, except those below 2 µg which are known to +/– 50%

(3) Th/U model ratio inferred from 208/206 ratio and age of sample

(4) Pbc = total common Pb in sample (initial + blank)

(5) raw data corrected for fractionation and blank

(6) corrected for fractionation, spike, blank and initial common Pb; error calculated by propagating the main sources of uncertainty

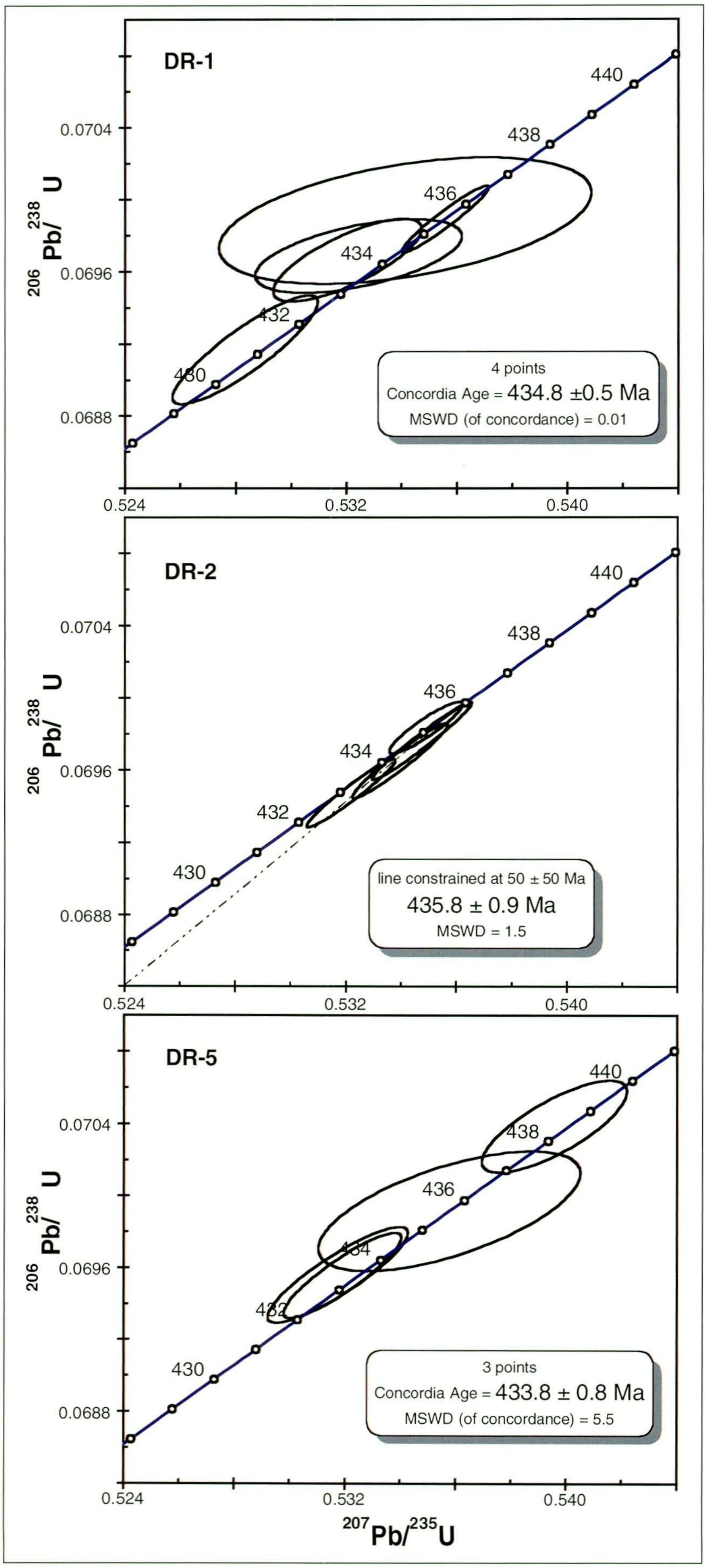

Fig. 7. Concordia diagrams for the zircons analysed from samples DR1, DR2 and DR5. See main text for explanation.

margin-type chemistry is also evident in the other two trondhjemite dyke samples from which we were unable to obtain reliable zircon ages. The same geochemical traits are also reflected in diverse trondhjemite bodies from the Gauldalen district (Pannemans & Roberts 2000), including the Follstad trondhjemite which has yielded a U-Pb zircon/titanite age of 432 ± 3 Ma (Dunning & Grenne 2000) – again, indistinguishable temporally from the Innset and Nyvollen trondhjemites. Thus, there is a strong case for believing that emplacement of high-alumina, continental-margin trondhjemite and related bodies occurred widely in the Köli rocks of the Trondheim Region in earliest Silurian time.

Contact-metamorphic features around the Innset massif have been described in some detail by Rohr-Torp (1974). An inner zone of hornfels, 1-2 km in width, is followed (to the southeast) by a 3-4 km-wide zone of spotted rocks. The spots consist of c. 60% sericite and, in places, prismatic outlines show that they are pseudomorphs after cordierite porphyoblasts (Rohr-Torp, *op. cit.*). An important aspect of these field and microscopic studies is that the earliest schistosity recorded in the Krokstad metasediments is deflected around the Innset massif, and also around the pseudomorphic spots. This led Rohr-Torp to conclude that the Innset massif intruded the Mid/Late Ordovician Krokstad sedimentary succession at some time before the main, Scandian deformation. The ages of the norite and trondhjemite reported here thus support Rohr-Torp's (1974) observations and predictions.

The precise age of the Scandian deformation and metamorphism within the Trondheim Nappe Complex has not been accurately determined. From a biostratigraphic standpoint, sedimentation in, e.g., the Meråker Nappe continued into Early/Mid Llandovery time, based on finds of monograptids (Getz 1890). K-Ar data on phyllitic schists in the Gula Complex have given (recalculated) ages of 425-426 Ma, with hornblende dates up to 432 Ma (Wilson et al. 1973). $^{40}Ar/^{39}Ar$ analytical data from the Meråker Nappe yielded hornblende plateau ages of 427-420 Ma; and from the Gula, hornblende gave plateaux of 432-424 Ma (Dallmeyer 1990). Plateau ages for biotite and muscovite from Gula rocks were in the ranges 433-427 and 424-418 Ma, respectively (Dallmeyer, op. cit.). Although all these dates pertain to post-metamorphic cooling, the higher-T hornblendes would be registering plateaux closest to peak metamorphism, and suggest that this occurred during the period 430-425 Ma. This corresponds to a latest Llandovery to Wenlock age. Intrusion of the widespread trondhjemite and related mafic bodies in the Gula and Støren Nappes would thus appear to have taken place just shortly before the attainment of peak Scandian metamorphism.

The relationship between the continental-margin trondhjemites and Scandian metamorphism/deformation, with magmatism pre-dating the latter, has also been described and illustrated by Size (1979), Dunning & Grenne (2000), Pannemans & Roberts (2000) and Roberts & Sundvoll (2000). Trondhjemites in the Gula Complex cut an earlier foliation of inferred Early Ordovician age, but many of these bodies and dykes are folded, and also affected by a variably developed schistosity or cleavage. These folds and schistosity are undoubtedly Scandian. In a few cases, especially in the central parts of larger trondhjemite bodies, only the faintest hint of a foliate structure can be discerned. The trondhjemites dated in the present study show mineral parageneses typical of regional-metamorphic replacement, as well as synchronous or later sericitisation and chloritisation, features which provide evidence of Scandian overprint.

In the southern Trondheim Region, the only radiometric dating study on trondhjemites of high-alumina type is that of Berthomier et al. (1972a, b), from the Høg-Gia massif (Fig. 2), approximately 30 km south of Innerdalen. Three trondhjemite samples from this composite gabbro-diorite-trondhjemite massif in the Gula Complex gave a Rb-Sr mineral/whole-rock isochron age of c. 443 ± 8 Ma (recalculated using a decay constant of 1.42, this would be 468 Ma). Even though this particular age is less precise than our own U-Pb zircon dates, Berthomier et al. (1972a) considered that the Høg-Gia massif intruded in Ordovician time, well before the main phase of Caledonian (Scandian) metamorphism. Clearly, a U-Pb age would be desirable from this massif, before valid comparisons can be made with other trondhjemites dated by zircon chronology.

The zircon ages for the trondhjemites and norite reported here fit into a known pattern of magmatism in the Köli Nappes documented from other parts of the Upper Allochthon. Over an interval of 10-15 million years in Late Ordovician/Early Silurian time, many composite gabbro-diorite-trondhjemite plutons penetrated these Köli volcanosedimentary assemblages. Most U-Pb and Sm-Nd ages for these major plutonic complexes range between 440 and 430 Ma; e.g., those at Sulitjelma, Råna, Artfjället and Krutfjellet (Senior & Andriessen 1990, Pedersen et al. 1991, Mørk et al. 1997). In the eastern Trondheim Region, a late, felsic differentiate of the Fongen-Hyllingen complex has yielded a U-Pb zircon age of 426 $^{+8}/_{-2}$ Ma (Wilson et al. 1983). This major body, cutting the Fundsjø Group, is known to have intruded shortly before peak Scandian metamorphism, but it also penetrated an already foliated, volcanosedimentary succession. Descriptions of the andalusite-bearing contact aureoles of the Hyllingen gabbro and nearby Øyungen gabbro (Fig. 1) (Birkeland & Nilsen 1972) clearly show that these mafic plutons pre-dated the Scandian regional metamorphism.

The palaeotectonic scenario for the composite plutonic bodies has been discussed by Dunning & Grenne (2000) and Pannemans & Roberts (2000). In short, the mafic magmas were probably derived from a mantle source, and the trondhjemites by partial melting under garnet-amphibolite conditions at depths in the range 20-30 km. The continental margin character of the felsic and mafic intrusions and their emplacement immediately prior to the earliest stages of oblique plate collision between Baltica and Laurentia were considered to stem from a short-lived, rift-related, extensional or transtensional regime (Grenne et al. 1999). In such an oblique, continent-collisional setting, in a broadly transpressive-convergent system (Dunning & Grenne 2000) of sinistral character (Roberts 1983, Braathen et al. 2002), locally developed areas of relative crustal transtension, akin to surficial pull-apart basins, could be envisaged as having facilitated the emplacement of these mafic to felsic intrusions. This stage of collision-related, tectonomagmatic development was then quickly succeeded by the polyphase, Scandian, transpressive regime in prograde P-T metamorphic conditions, and ultimately by late-Scandian, sinistral transtension coeval with orogenic collapse and Devonian basinal sedimentation.

Conclusions

Precise U-Pb zircon ages are presented from two trondhjemites and a biotite norite from the Gula and Støren Nappes in a part of the southwestern Trondheim Region, central Norway. A trondhjemite and a biotite norite (traditionally termed 'opdalite') from a quarry in the Innset massif, northeast of Oppdal, gave almost identical ages, though field relationships show the trondhjemite to be the younger of the two intrusions. Zircons from the biotite norite define an average $^{207}Pb/^{206}Pb$ age of 435.5 ± 1.5 Ma, whereas a concordant analysis alone has a concordia age of 435.8 ± 0.9 Ma. Three analyses of zircons from the trondhjemite are concordant within error and define a concordia age of 434.8 ± 0.5 Ma.

Zircons from a second trondhjemite, sampled from a working quarry at Nyvollen, in Innerdalen, in the western part of the Gula Complex, yielded an upper intercept age of 433 ± 0.8 Ma. All three dates, from the Nyvollen and Innset massif occurrences, are interpreted to represent the ages of emplacement of these bodies, at around 435 Ma; which is Early Silurian (approximately Mid Llandovery) on currently accepted time-scales.

Geochemical signatures from the dated trondhjemites, and from two other, unsuccessfully dated trondhjemite dykes, show them to be of high-alumina, continental-marginal type and, thus, similar to many other trondhjemite bodies that intrude the Köli Nappes of the Trondheim Region. Field and microscopic studies indicate that the Innset massif, and composite trondhjemite-gabbro bodies within the Gula Complex, predate Scandian orogenic deformation which, it has been suggested, occurred at around 430-425 Ma in this part of the Caledonides.

The ages reported here fit into a known pattern of composite, gabbro-diorite-trondhjemite magmatism that occurred widely in the Köli Nappes of the Upper Allochthon in different parts of the Scandinavian Caledonides in latest Ordovician/Early Silurian time. In a palaeotectonic context, this continental margin magmatism dates to the early stages of oblique, Baltica-Laurentia plate collision, wherein short-lived, rift-related, transtensional crustal segments developed in a broadly transpressive-convergent system and thus allowed ingress of these magmas. These local transtensional settings were then quickly succeeded by the prograde-metamorphic, sinistral-transpressive regime which characterised the Scandian orogeny.

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