U-Pb zircon ages of a tonalite and a granodiorite dyke from the southeastern part of the Bindal Batholith, central Norwegian Caledonides

AUGUST L. NISSEN, DAVID ROBERTS & L. PETER GROMET

Nissen, A.L., Roberts, D. & Gromet, L.P. 2006: U-Pb zircon ages of a tonalite and a granodiorite dyke from the southeastern part of the Bindal Batholith, central Norwegian Caledonides. *Norges geologiske undersøkelse Bulletin 446,* 5-9.

An elongate tonalite pluton and a c.10 m-thick granodiorite body in the southeastern part of the Bindal Batholith and Helgeland Nappe Complex, Nord-Trøndelag, have yielded U-Pb zircon ages of 429 ± 2 and 430 ± 2 Ma, respectively. These dates are interpreted to represent the crystallisation ages of these rocks and supersede previously published Cambrian Rb-Sr whole-rock isochron ages from these very same bodies. The zircon ages reported here are comparable to other published U-Pb emplacement ages for granitoid plutons in the eastern part of the Bindal Batholith. A foliation in parts of the tonalite and granodiorite, and folds affecting this foliation are considered to have formed during the Scandian orogenic event which, in this part of the Helgeland Nappe Complex, is believed to have initiated at the time of termination of calc-alkaline magmatism at around 428 Ma.

August L. Nissen[1] & David Roberts, Geological Survey of Norway, N-7491 Trondheim, Norway.
L.Peter Gromet, Department of Geological Sciences, Brown University, Providence, RI 02912, USA.
1 – Present address: Geocon, Ole Hogstads vei, 22b, 7046 Trondheim, Norway.

Introduction

In an earlier geochronological investigation aimed at determining the ages of a tonalite and a granodiorite from western Namdalen, Nord-Trøndelag, the Rb-Sr whole-rock method was employed (Nissen 1986). This study yielded whole-rock isochron ages of 503 ± 23 Ma for the tonalite and 526 ± 10 Ma for the granodiorite, each with significant scatter. These particular plutonic rocks form part of the extensive Bindal Batholith (Nordgulen 1993) that lies within the Helgeland Nappe Complex of the Uppermost Allochthon in the Caledonides of Norway. In general terms, granitoid plutons in the western part of the Bindal Batholith are peraluminous and fall in the age range 477-468 Ma whereas those in the east belong to a younger, metaluminous and calc-alkaline group with Late Ordovician to Early Silurian U-Pb zircon ages ranging from 448 to c. 430 Ma (Nordgulen 1993, Nordgulen et al. 1993, Bingen et al. 2002).

In view of the fact that the Cambrian Rb-Sr ages for the Namdalen area have not been supported by the subsequent U-Pb zircon age studies elsewhere in the Bindal Batholith, we decided in 1997 to separate and analyse zircons from samples taken from two of the original localities used in the Rb-Sr study. The aim was to determine if the Rb-Sr isochron dates, interpreted as indicating a Cambrian age of emplacement, were valid and, if not, what the likely crystallisation ages of these rocks were.

In this short contribution, we present the U-Pb data for zircon from these two samples, and an abbreviated data table with the isotope ratios and errors used to calculate the ages. Unfortunately, certain parameters, e.g., $^{206}Pb/^{204}Pb$, U content, Th/U ratio and information on fraction leaching are lacking, for reasons outside our control (see Acknowledgements). Nevertheless, there is general agreement, also the opinion of the reviewers, that it would be better to make these new ages known to the geoscience community as a short note so that the earlier Rb-Sr results and interpretations could be reconsidered in the light of the U-Pb ages.

Geological relationships

Here we present a short summary of the general geology, and of the field relationships and petrography of the samples. Further details can be found in Nissen (1986).

In this part of Norway the Helgeland Nappe Complex is dominated by the Bindal Batholith, which includes more than 50 separate plutons or intrusive complexes (Nordgulen 1993). The plutonic bodies intrude varied supracrustal successions of inferred Late Riphean to Ordovician age consisting of pelitic and psammitic schists and gneisses, calcareous mica schists, marbles, amphibolites, metaconglomerates and fragmented ophiolitic complexes (Stephens et al. 1985, Heldal 2001, Roberts et al. in press).

A simplified geology of the southeastern part of the Bindal Batholith based on a variety of map-compilation sources is shown in Fig. 1. In this area, diverse plutonic rocks that are well exposed in the high mountain terrain extend into the higher western slopes and hills of the valley Namdalen. The samples used in this study derive from a large body of tonalite, and a smaller body of granodiorite cutting mica gneisses (Fig. 1) (Nissen 1986).

Tonalite

This is a dark grey, medium-grained rock, massive in western areas but foliated towards the east. The sample taken for analysis (L184) comes from near the central part of a 5-6 km-wide elongate pluton (Fig.1). Adjacent to host rocks of mica schists and mica gneiss, the tonalite is more strongly foliated and also folded, and acquires a gneissic character. Contacts with medium-grained granodiorite are generally diffuse, and such granodiorite or a finer grained variety occurs as dykes parallel to or discordant to the foliation in the tonalite. These dykes are usually foliated only along their marginal zones. Modal compositions of the tonalite show the following main minerals (in vol.%, averages of 8 samples): quartz 25%, plagioclase 42%, K-feldspar <7%, biotite 17%. The principal accessory minerals are pyroxene, hornblende, titanite and epidote (Nissen 1986).

Fine-grained granodiorite

Several elongate bodies and dykes of granodiorite up to 1 km in length are present broadly parallel with the foliation in the mica gneisses and schists 1-3 km southwest of the tail-end of the main tonalite intrusion (Fig. 1). The granodiorite dykes are pale grey, fine grained and weakly foliated. Thicker dykes and bodies are fine- to medium-grained. The sample taken for study (L1284) comes from a road-cut in a granodiorite body estimated to be approximately 10 m thick. The road-cut is aligned parallel to the strike of the body and judged to be within 1-3 metres of one of the contacts. Modal determinations of the granodiorite show the following (vol.%, averages of 5 samples): quartz 30%, plagioclase 40%, K-feldspar 14%, biotite 8%, muscovite 5%. Accessory minerals are present in only negligible amounts.

Where mutual field relationships can be seen within and adjacent to the tonalite massif, it is clear that the tonalite is intruded by both the medium-grained and the fine-grained granodiorite (Nissen 1986).

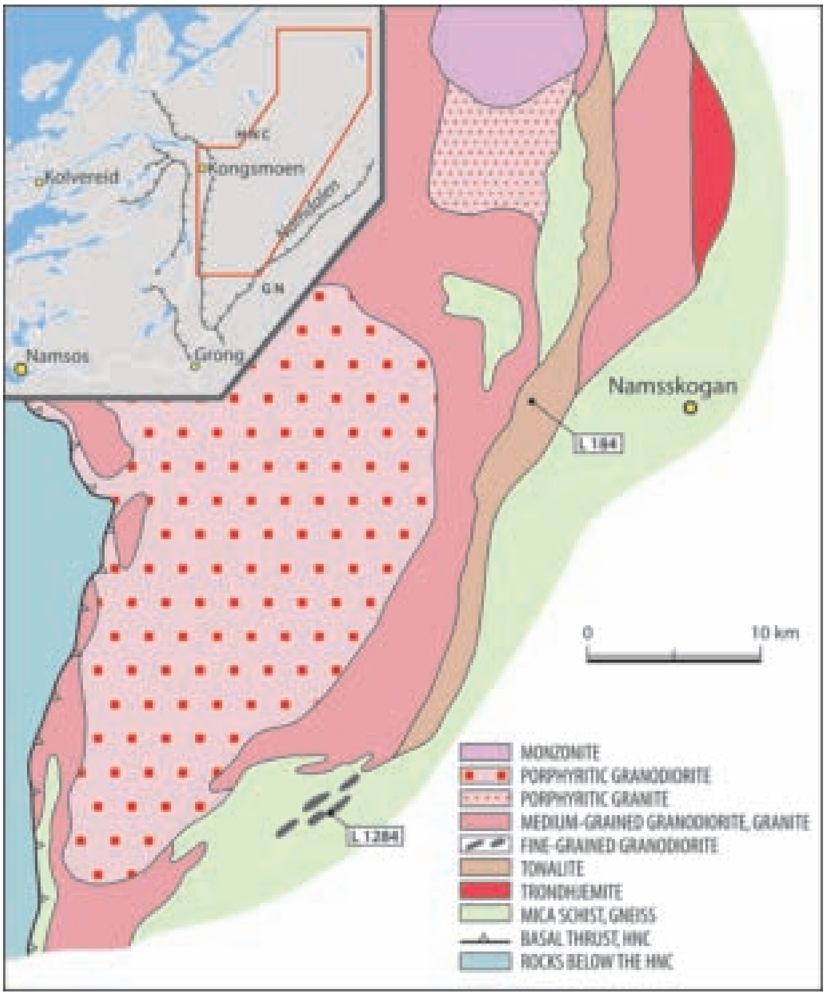

Fig. 1. Simplified geological map of the southeastern part of the Bindal Batholith and Helgeland Nappe Complex, Namdalen, Nord-Trøndelag, central Norwegian Caledonides, showing the locations of samples L184 and L1284. The map is based on diverse sources, but mainly Gustavson (1981), Nordgulen et al. (1990) and Roberts (1997).

U-Pb zircon dating

Analytical methods

Initial preparation of the samples, crushing and separation into zircon concentrates, was performed at the Geological Survey of Norway, Trondheim. The chemical separations and zircon analyses by ID-TIMS were carried out by Dr. Nicholas Walker at the Department of Geological Sciences, Brown University, Rhode Island, USA. Zircon concentrates were cleaned in successive solutions of 2N HNO_3, 2N HCl and distilled H_2O, and then split by magnetic character using a Frantz Isodynamic Barrier separator, followed by sieving and/or hand sorting to provide populations of desired size range. Four representative sub-populations were hand-picked to purity from each sample and either air abraded for 6 hours in a device similar to that described by Krogh (1982) or chemically leached in 48% HF in a Teflon screw-top capsule held at 70°C for 24 hours. Zircon dissolution and ion-exchange procedures were comparable to those described by Krogh (1973) and Parrish et

Table 1. U-Pb analytical data for L1284 and L184.

Sample/fraction	$^{207}Pb/^{235}U$	err%	$^{206}Pb/^{238}U$	err%	err corrl	Ages $^{207}Pb/^{235}U$	Ages $^{206}Pb/^{238}U$	Ages $^{207}Pb/^{206}Pb$
L184 - Tonalite								
75µ prisms, colorless	0.519519	0.351	0.0680425	0.330	0.945	424.8 ± 1.5	424.4 ± 1.4	427.4 ± 2.5
150µ prisms, colorless	0.525468	0.258	0.0687763	0.250	0.971	428.8 ± 1.1	428.8 ± 1.1	428.9 ± 1.4
125µ prisms, colorless	0.522633	0.259	0.0684558	0.248	0.957	426.9 ± 1.1	426.8 ± 1.1	427.2 ± 1.7
100µ prisms, colorless	0.523668	0.247	0.0684696	0.238	0.964	427.6 ± 1.1	426.9 ± 1.0	431.2 ± 1.4
L1284 - Granodiorite								
120µ 2:1	0.544743	0.347	0.0699674	0.342	0.985	441.5 ± 1.5	436.0 ± 1.5	470.8 ± 1.3
75-80µ 3,4:1	0.529728	0.258	0.0691696	0.248	0.964	431.6 ± 1.1	431.2 ± 1.1	434.2 ± 1.5
150µ equant, brown	0.573242	0.286	0.0726252	0.277	0.969	460.1 ± 1.3	452.0 ± 1.3	501.0 ± 1.6
150µ 2:1 colorless	0.548712	0.237	0.0706700	0.230	0.971	444.2 ± 1.1	440.2 ± 1.0	464.7 ± 1.4

Notes: Pb/U isotopic ratios are corrected for blank, fractionation, common Pb, and spike.
Errors in isotope ratios and ages are reported to the 95% confidence limit.

al. (1987). A mixed ^{205}Pb-^{233}U-^{235}U tracer was employed. Lead was loaded to W filaments and U to Re filaments and analysed on the Finnigan MAT 261 multicollector mass spectrometer at Brown University. Pb was analysed in static multicollector mode employing faraday cup collection of masses 208, 207, 206 and 205 while simultaneously collecting mass 204 in a secondary electron multiplier. Uranium was analysed in peak hopping mode utilising a secondary electron multiplier.

Results and age interpretation

Abbreviated analytical data from the two samples, L184 (tonalite) and L1284 (granodiorite), are provided in Table 1 and are reproduced here as Figs. 2 and 3. Four fractions were analysed from each of the samples. Information on the size, form, colour and aspect ratio of the zircons in each fraction are given in the table and the figures.

Some description, explanation and interpretation of the age data were communicated to D.R. by Dr. Walker in February 1998. The discussion below is based on this information, partly modified and with some amplification.

Sample L184: This is a tightly grouped dataset with 2 concordant and 2 very slightly discordant fractions (Fig. 2). All fractions consist of colourless prisms, and the simple systematics suggest these are composed entirely of magmatic zircons that grew during crystallisation of the tonalite magma. Of note is that even though the range in U-Pb ages is quite small (429 to 425 Ma), there is a good correlation between grain size and U-Pb age with smaller-sized grains giving younger U-Pb ages. This correlation is the earmark of a cogenitic suite of magmatic zircons where a small but increasing degree of post-crystallisation diffusive Pb loss occurs in progressively smaller grains (e.g., Silver & Deutsch 1963). Based on the systematics of these analytical data, the crystallisation age of the tonalite is interpreted to be given by the coarsest and oldest grains in the array, at 429 ± 2 Ma (Fig. 2).

Sample L1284: Four zircon fractions from this granodiorite dyke are non-colinear (Fig. 3). If regressed, these would yield a discordia array with c. Silurian and Proterozoic intercepts with large errors (429 ± 44 Ma and 1190 ± 770 Ma with MSWD = 29). The considerable scatter in the array and an upper intercept extending to an impossibly old intrusive age are indicative of a Palaeozoic magma containing variable amounts of inherited zircon of mixed Proterozoic ages. The presence of variable amounts of inherited components is also suggested by morphological differences among the analysed fractions. One fraction consists of small elongate zircon prisms (3:1 to 4:1 aspect ratios) and gives concordant

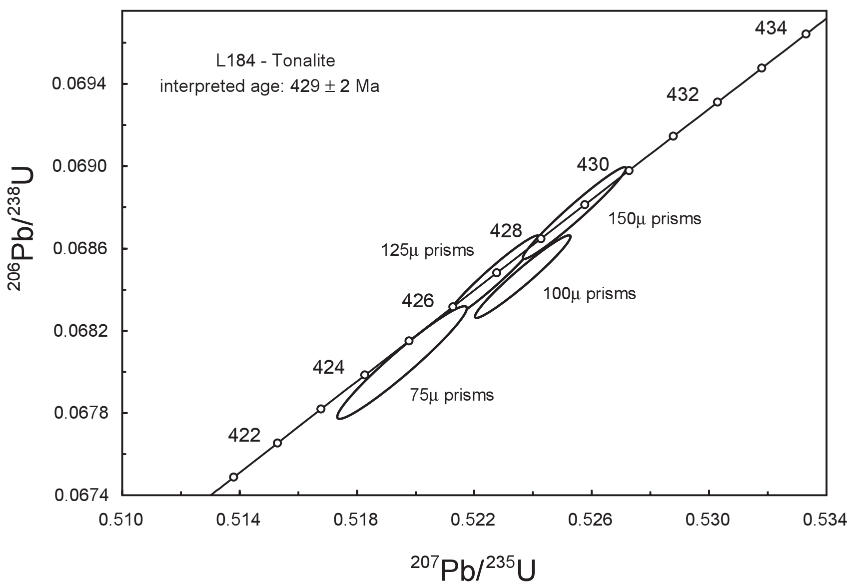

Fig. 2. U-Pb concordia diagram for tonalite sample L184. Error ellipses are 2 sigma. The age interpretations is based on the age of the coarsest fraction. See text for discussion.

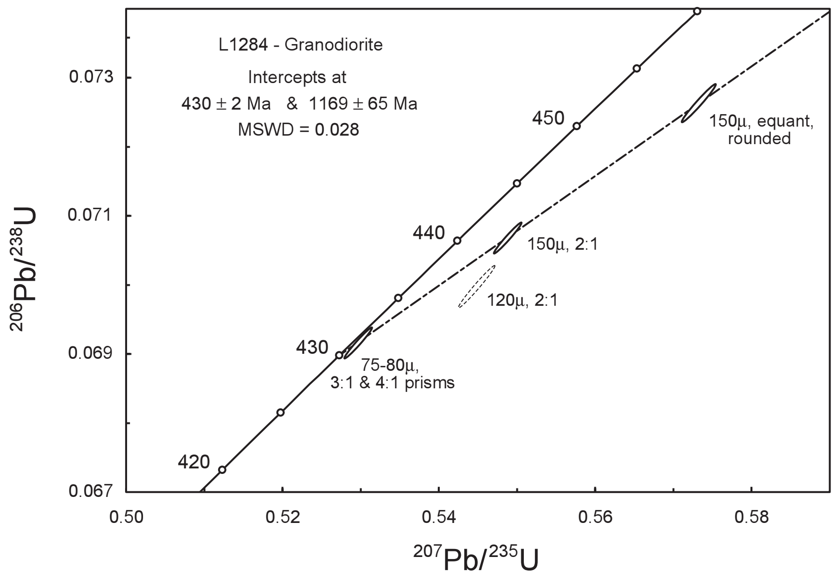

Fig. 3. U-Pb concordia diagram for granodiorite sample L1284. Error ellipses are 2 sigma. Intercept ages are calculated for a regression of three of the four data points (the excluded analysis is marked with a line). See text for discussion.

or very nearly concordant U-Pb ages of 431-432 Ma. The elongate crystal forms and the nearly concordant ages at the low end of the discordia array both suggest that the age of this fraction represents a nearly pure magmatic component generated during the crystallisation of the granodiorite, and hence provides a good estimate of its magmatic age. In contrast, zircons in the other fractions vary from stubby (2:1 aspect ratio) to equant grains. This morphology, coupled with the older U-Pb ages, suggests that the grains in these fractions consist of cores of inherited zircon overgrown by younger magmatic rims.

Three of the four fractions analysed are colinear, whereas the remaining one falls below the array due to either Pb loss or the presence of older inherited zircon. The three colinear fractions yield intercept ages of 429.9 ± 1.5 Ma and 1169 ± 65 Ma with a MSWD of 0.028 (Fig. 2). The lower intercept age is identical, within error, to the individual U-Pb ages for the fraction of elongate zircon prisms (see Table 1).

Based on these systematics, we interpret the granodiorite to have crystallised at 430 ± 2 Ma from a magma containing inherited zircon components with an average Mesoproterozoic age. The inherited zircon components are considered strong evidence that the granodiorite magma had become contaminated with older crustal material. Given that the granodiorite is a relatively thin body intrusive into metasedimentary rocks (mica schists and gneisses), the presence of inherited zircon is not surprising. Moreover, inherited zircons derived from metasedimentary wall rocks are expected to include detrital grains of variable age, leading to non-linear discordia arrays such as is observed. The presence of such older crustal material is potentially significant to the interpretation of the Rb-Sr whole-rock isochron ages published for these rocks (see discussion below).

From these data, it seems clear that the crystallisation ages of the tonalite and granodiorite at 429 ± 2 Ma and 430 ± 2 Ma, respectively, are analytically indistinguishable. Nonetheless, the field relationships indicate that where present in the same outcrop, the granodiorite intrudes and therefore is younger than the tonalite (Nissen 1986).

Discussion

The ages generated by ID-TIMS U-Pb analysis of zircons from these two magmatic bodies clearly establish their crystallisation ages at around 430 Ma, or Early Silurian. These ages are in excellent agreement with U-Pb zircon ages reported from geochemically comparable felsic plutons in the Bindal Batholith, especially from the eastern areas of this extensive composite massif (Nordgulen et al. 1993). The variable incorporation of older crustal materials into these magmatic rocks during their emplacement is clearly indicated by the zircon inheritance in the granodiorite. We suggest that this contamination is the likely cause for the older and rather imprecise Rb-Sr whole-rock isochron ages reported previously. Thus, there is no justification for continuing to consider the two reported Cambrian Rb-Sr whole-rock isochron ages as the time of intrusion of these bodies. Other Rb-Sr whole-rock isochrons reported from this general region (Nissen 1988) in the age range 568-493 Ma should also be viewed with suspicion.

In a study of the strontium isotope composition of various plutons within the Bindal Batholith, Nordgulen & Sundvoll (1992) demonstrated a clear geographical distribution based on the initial $^{87}Sr/^{86}Sr$ ratios. Low initial ratios (0.704-0.705) characterise the younger granitoids in south-eastern parts of the batholith. Farther west, initial ratios rise (0.705-0.710) and reach a peak (>0.715) in westernmost areas where U-Pb ages in the range 477-468 Ma are prevalent. The tonalite and the granodiorite considered here have initial $^{87}Sr/^{86}Sr$ ratios at 430 Ma ranging from 0.7043 to 0.7057 and 0.7044 to 0.7074, respectively (recalculated from the data of Nissen 1986). Such variation in the isotopic compositions of each of these intrusions at the time of their crystallisation is strong evidence that they originated either by contamination of more primitive magmas with crustal materials, or possibly were generated mostly or entirely from mixed crustal sources.

Nordgulen et al. (1993) reported a U-Pb zircon age of 437 ± 4 Ma from a tonalite west of Gåsvassfjellet, in Nordland county, approximately 25 km north-northeast of our tonalite sample L184 locality. Judging from the geological map (Fig. 1), the Gåsvassfjellet body may be part of the same intrusive complex as the 429 ± 2 Ma tonalite pluton studied here. Thus, there is little doubt that this tonalite is of Early Silurian age.

The foliation observed in the tonalite and granodiorite from Namdalen and the folds that deform this foliation along the margins of the tonalite are now constrained to be no older than 430 Ma, and are considered to relate to the Mid Silurian-Early Devonian Scandian orogeny. The precise age of this deformation and metamorphism in the western Namdalen area is not known, but preliminary U-Pb monazite data have indicated that this probably started directly after the cessation of magmatic activity at around 428 Ma (Bingen et al. 2002). Within the Helgeland Nappe Complex as a whole there is documented evidence of an earlier and significant Ordovician tectonothermal event (Nordgulen & Schouenborg 1990, Nordgulen et al. 1993). This is now believed to correspond to the Mid Ordovician Taconian orogenic event that affected the continental margin of Laurentia (Yoshinobu et al. 2002). Ultimately, the Helgeland Nappe Complex and other 'Laurentian' thrust sheets of the Uppermost Allochthon were emplaced onto the Baltoscandian margin during the Scandian orogeny (Roberts et al. 2001, in press, Yoshinobu et al. 2002).

Conclusions

An elongate tonalite massif and a granodiorite dyke in the southeastern part of the Helgeland Nappe Complex, Nord-Trøndelag, have yielded similar U-Pb zircon ages of 429 ± 2 and 430 ± 2 Ma, respectively. These dates supersede previously published, Cambrian, Rb-Sr whole-rock isochron ages from these very same bodies. The zircon ages are interpreted to represent the crystallisation ages of these rocks and, as such, they are comparable to other published U-Pb zircon crystallisation ages for granitoid plutons in the eastern part of the Bindal Batholith. A foliation in parts of the tonalite and granodiorite, and folds affecting this foliation are considered to have formed during the Scandian orogenic event. In this part of the Helgeland Nappe Complex, in the Namdalen area, the onset of Scandian deformation is believed to have been broadly coeval with the termination of calc-alkaline magmatism at around 428 Ma.

Acknowledgements

The analyses presented here are the careful work of Dr. Nicholas Walker, formerly a senior research scientist at the Department of Geological Sciences, Brown University, USA. Under circumstances unknown to us, in 2002 Dr. Walker abruptly left the field of geochronology without providing us with the original complete tables of analytical data. Numerous attempts to contact Dr. Walker from the time of completion of the work through the final preparation of this manuscript have gone unanswered. We therefore regret that we are unable to include Dr. Walker as a co-author as we had planned, but we are nevertheless indebted to him for his analytical input. We are grateful, too, for the constructive comments and suggestions of the reviewers, Drs. Fernando Corfu and Øystein Nordgulen. Irene Lundquist assisted with production of the final version of Figure 1.

References

Bingen, B., Nordgulen, Ø. & Solli, A. 2002: U-Pb geochronology of Paleozoic events in the Mid Scandinavian Caledonides. *In* Eide, E.A. (coord.) BATLAS – Mid Norway plate reconstruction atlas with global and Atlantic perspectives. *Geological Survey of Norway, Trondheim,* 66-67.

Gustavson, M. 1981: Geologisk kart over Norge, berggrunnskart MOSJØEN – M 1:250 000. *Norges geologiske undersøkelse.*

Heldal, T. 2001: Ordovician stratigraphy in the western Helgeland Nappe Complex in the Brønnøysund area, North-central Norway. *Norges geologiske undersøkelse Bulletin 438,* 47-61.

Krogh, T. E. 1973: A low contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determination. *Geochimica et Cosmochimica Acta 37,* 485-494.

Krogh, T. E. 1982: Improved accuracy of U-Pb ages by the creation of more concordant systems using an air abrasion technique. *Geochimica et Cosmochimica Acta 46,* 560-567.

Nissen, A.L. 1986: Rb-Sr age determination of intrusive rocks in the southeastern part of the Bindal Massif, Nord-Trøndelag, Norway. *Norges geologiske undersøkelse Bulletin 406,* 83-92.

Nissen, A.L. 1988: Aldersbestemmelse av dypbergarter etter Rb/Sr-metoden i den sørlige del av Bindalmassivet, Nord-Trøndelag og Nordland. *Norges geologiske undersøkelse Rapport 88-005,* 29 pp.

Nordgulen, Ø. 1993: *The Caledonian Bindal Batholith: regional setting based on geological, geochemical and isotopic data.* Dr. scient. Thesis, University of Bergen.

Nordgulen, Ø. & Schouenborg, B. 1990: The Caledonian Heilhornet Pluton, north-central Norway: geological setting, radiometric age and implications for the Scandinavian Caledonides. *Journal of the Geological Society, London 147,* 439-450.

Nordgulen, Ø. & Sundvoll, B. 1992: Strontium isotope composition of the Bindal Batholith, Central Norwegian Caledonides. *Norges geologiske undersøkelse Bulletin 423,* 19-39.

Nordgulen, Ø., Solli, A. & Thorsnes, T. 1990: MAJAFJELLET, berggrunnskart 1825 2, 1:50 000, foreløpig utgave. *Norges geologiske undersøkelse.*

Nordgulen, Ø., Bickford, M., Nissen, A.L. & Wortman, G. 1993: U-Pb zircon ages from the Bindal Batholith, and the tectonic history of the Helgeland Nappe Complex, Scandinavian Caledonides. *Journal of the Geological Society, London 150,* 771-783.

Parrish, R.R., Roddick, J.C., Loveridge, W.D. & Sullivan, R.W. 1987: Uranium Lead analytical techniques at the geochronology laboratory. *Geological Survey of Canada Paper 87-2,* 3-7.

Roberts, D. 1987: Geologisk kart over Norge. Berggrunnsgeologisk kart GRONG, M 1:250 000. *Norges geologiske undersøkelse.*

Roberts, D., Heldal, T. & Melezhik, V.A. 2001: Tectonic structural features of the Fauske conglomerates in the Løvgavlen quarry, Nordland, Norwegian Caledonides, and regional implications. *Norsk Geologisk Tidsskrift 81,* 245-256.

Roberts, D., Nordgulen, Ø. & Melezhik, V.A. 2006: The Uppermost Allochthon in the Scandinavian Caledonides: from a Laurentian ancestry through Taconian orogeny to Scandian crustal growth on Baltica. *Geological Society of America Special Publication* (in press).

Silver, L.T. & Deutsch, S. 1963: Uranium-lead isotopic variations in zircons: a case study. *Journal of Geology 71,* 721-758.

Stephens, M.B., Gustavson, M., Ramberg, I.B. & Zachrisson, E. 1985: The Caledonides of central-north Scandinavia – a tectonostratigraphic overview. *In* Gee, D.G. & Sturt, B.A. (eds.) *The Caledonide orogen – Scandinavia and related areas.* John Wiley & Sons, Chichester, 135-162.

Yoshinobu, A., Barnes, C.G., Nordgulen, Ø., Prestvik, T., Fanning, M. & Pedersen, R.B. 2002: Ordovician magmatism, deformation and exhumation in the Caledonides of central Norway. *Geology 30,* 883-886.