Contrib Mineral Petrol (2003) 145: 502–513
DOI 10.1007/s00410-003-0466-x

ORIGINAL PAPER

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A Late Ordovician U–Pb age for the Tromsø Nappe eclogites, Uppermost Allochthon of the Scandinavian Caledonides

Received: 13 December 2002 / Accepted: 17 March 2003 / Published online: 14 May 2003

Abstract The Scandinavian Caledonides contain the record of several high-pressure events reflecting distinct episodes of collision and subduction in the course of the global Caledonian plate reorganization process. In this study, the timing and speed of one of these events in the Tromsø Nappe of the Uppermost Allochthon are detailed using multiple U–Pb geochronometers. This unit contains eclogites, the largest of which forms a whole mountain top, whereas many others occur as smaller lenses enclosed within a metamorphosed supracrustal sequence. A minimum age for the sedimentation is provided by a zircon age of 493 +5/−2 Ma for an eclogitized felsic intrusion. Formation of the eclogite, at pressures reaching 2.8 GPa, occurred at 452.1 ± 1.7 Ma as evidenced by U–Pb in eclogitic zircon. Similar ages of 451–450 Ma are also provided by high-Al titanite in eclogite and titanite in leucosome veins, the latter of which was formed by partial melting during the exhumation of the eclogite. An age of 449 Ma for a rutile porphyroblast in another vein further confirms the rapidity of this high-pressure process. Matrix rutiles in two other eclogites yielded ages of 436 Ma and younger, probably indicating partial resetting during a subsequent metamorphic overprint. Lead isotopic compositions with high $^{207}Pb/^{204}Pb$ ratios are indicative of old crustal sources, thus supporting the previously proposed notion that the Uppermost Allochthon was derived from the Neoproterozoic margin of Laurentia.

Introduction

The Scandinavian Caledonides are composed of a succession of thrust complexes that were juxtaposed onto autochthonous to parautochthonous Precambrian basement and its cover units during a series of events that culminated with the Early Devonian collision between Baltica and Laurentia (e.g. Roberts and Gee 1985). Geological and paleontological evidence suggests that the lowermost tectonic units were derived from the western margin of the Baltic Shield, whereas the highest allochthonous segments are of exotic, possibly Laurentian, origin (e.g. Pedersen et al. 1992). Several of these exotic elements underwent tectonism during episodes that predated, and were unrelated to, the terminal Scandian collision (ca. 400 Ma; Stephens and Gee 1989; Roberts et al. 2002). Knowledge of the provenance and previous tectonic history of the various allochthonous fragments provides important clues that constrain the pre-orogenic configuration of the various allochthonous segments.

Eclogites can play an important role in such reconstructions because they reflect metamorphic transformations at high pressures during episodes of subduction and collision. Although the best known eclogites of the Caledonides were formed in the lowermost Baltic units during the Scandian event (Western Gneiss Region; Fig. 1; e.g. Terry et al. 2000; Tucker et al. 2001; Root et al. 2001), older occurrences evidencing Cambrian to Early Ordovician ages have been found in the Upper Allochthon (Seve Nappe Complex; Mørk et al. 1988; Dallmeyer and Gee 1986). Middle Ordovician ages have been revealed by Sm–Nd garnet–clinopyroxene whole-rock systems in eclogite, and garnet pyroxenite as well as garnet peridotite from another part of the Seve Nappe Complex (Brueckner and van Roermund 2001). An intermediate age of eclogitization in the Middle to Late Ordovician has also been proposed for occurrences present in the Lindås Nappe of the Middle Allochthon (Bergen Arcs; Boundy et al. 1997; Bingen et al. 2001b), but this interpretation remains highly controversial and is not supported by

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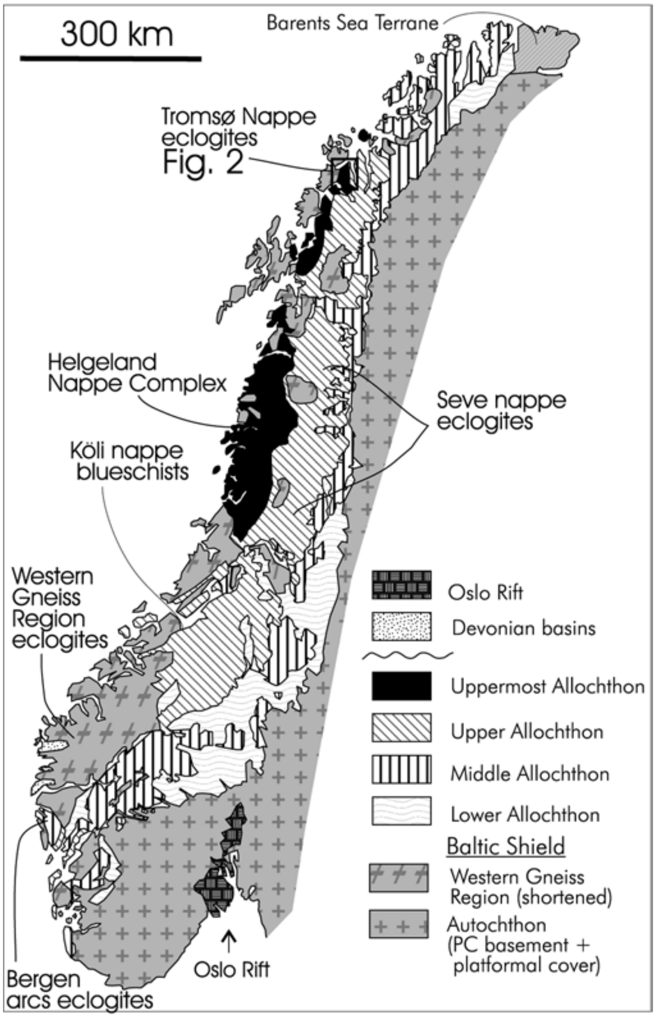

Fig. 1 Tectono-stratigraphic map of the Scandinavian Caledonides with location of the Tromsø Nappe eclogites (Fig. 2) and other units discussed in the text

more recent results which indicate a Silurian age (Austrheim and Bingen pers. comm. 2002; Glodny et al. 2002).

This paper reports on the age of eclogites in the Tromsø Nappe in the Uppermost Allochthon of northern Norway (Figs. 1, 2). As summarized in greater detail below, previous age determinations of these occurrences were clustered mainly in the Early Silurian. There were also some Ar-Ar data pointing to an older Ordovician age, and even a Sm/Nd data set indicating a Late Precambrian age of eclogitization. Our results now firmly show that these rocks underwent high- pressure metamorphism during a Late Ordovician event, which is distinct from both the older event in the Upper Allochthon, and the younger eclogitization of the lowermost units during Scandian collision.

Geological setting

The Tromsø Nappe is a member of the Uppermost Allochthon of the Scandinavian Caledonides (Figs. 1, 2; Roberts and Gee 1985; Krogh et al. 1990; Zwaan et al. 1998). In the Troms region, the Tromsø Nappe overlies a stack of tectonic units beginning with the autochthonous basement at the bottom, followed first by its Late Precambrian to Early Paleozoic cover, and then by elements of the Lower, the Middle, and the Upper Allochthons. The Upper Allochthon includes the Vaddas, Kåfjord and Nordmannvik Nappes, which are lateral equivalents of the Seve, Köli and Narvik Nappe Complexes and are overlain by the Lyngen Nappe Complex (Andresen and Steltenpohl 1994). The Lyngen Nappe Complex includes the Early Ordovician Lyngen ophiolite and the unconformable overlying Late Ordovician to Early Silurian carbonate shelf sequence of the Balsfjord Group (Bjørlykke and Olaussen 1981; Andresen and Steltenpohl 1994).

The Uppermost Allochthon consists of two main parts. The lower part, referred to as Nakkedal Nappe Complex by Zwaan et al. (1998), is dominated by quartzo-feldspathic gneiss with minor amphibolite and migmatite, followed upwards by banded amphibolitic rocks forming the Skattøra Migmatitic Complex (Selbekk et al. 2000), which locally also contains layers and pods of anorthosite, pyroxenite and serpentinite. The Skattøra Migmatitic Complex is intersected by numerous mafic to anorthositic dykes, and has a strongly mylonitized upper boundary separating it from the Tromsø Nappe.

The Tromsø Nappe comprises a mixed assemblage of marble, amphibolite, garnet–mica schist, various gneiss types, ultramafic rocks and eclogite (Krogh et al. 1990). These authors describe three main occurrences of eclogite including Lanesodden, Bøntuva and Tromsdalstind. In Lanesodden, eclogite lenses are dispersed in highly folded calc–silicate rocks and marbles (see also Fig. 2 in Bryhni et al. 1977). The Bøntuva locality includes small eclogite lenses in marble in addition to a larger body of mixed calc-silicate rocks and eclogite, which is generally retrogressed. The Tromsdalstind occurrence is formed by a structurally and compositionally heterogeneous 0.4 km^3 eclogite body, which occupies a whole mountain top near the city of Tromsø. Besides a variety of mafic rock types, this body also contains sparse layers of eclogitized tonalitic/trondhjemitic gneiss, which are locally transitional into mafic rocks. One of the eclogite samples analyzed in this study was taken at a fourth locality at Tønsvika from decimeter- to meter-sized eclogite lenses enclosed in calc-silicate gneisses (Fig. 2).

Four main fabric elements have been distinguished in the Tromsø Nappe. The dominant foliation is an S2 structure with associated isoclinal folds. Relicts of an earlier S1 fabric are preserved inside early garnets, whereas a younger D3 deformation locally refolds S2. The last structural overprint D4 developed open folds and a local crenulation cleavage.

Thermobarometric information extracted from mineral assemblages of the Tromsdalstind sequence indicates a two-stage evolution: an early high-pressure event

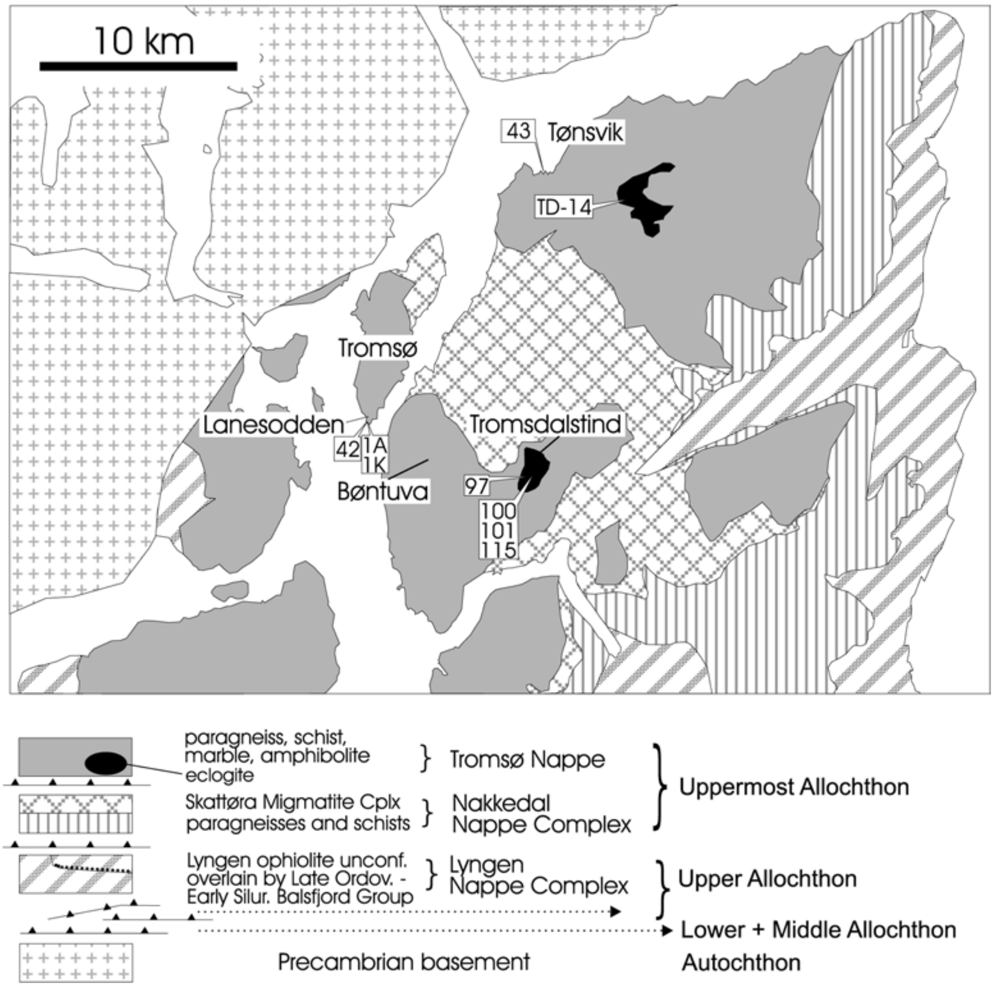

Fig. 2 Geological map of the region around Tromsø, northern Norway, showing the main geological and tectonostratigraphic relationships (from Zwaan et al. 1998)

which, by use of the garnet–clinopyroxene–phengite–kyanite–quartz geothermobarometer (Ravna and Terry 2001, 2003) and mineral compositions from Krogh et al. (1990), was found to have reached peak conditions of ca. 2.8 GPa at temperatures of 725 °C (Ravna and Roux 2002). These values are upgraded from the 1.7–1.8 GPa and 675 °C originally indicated by Krogh et al. (1990). This HP event was followed by further heating during decompression accompanied by partial melting and the formation of amphibole-bearing pegmatitic veins. A second episode of metamorphism associated with the development of D2 fabrics involved a renewed pressure increase from 0.8 up to 1.0–1.1 GPa at maximum temperatures of about 665 °C followed by cooling and decompression (Krogh et al. 1990). The first of these two events has been interpreted as indicating an early episode of subduction down to depths of 80 km, followed by uplift and imbrication that led to juxtaposition of the Tromsø Nappe onto the Skattøra Migmatitic Complex. The second event has been understood to indicate an episode of underthrusting followed by uplift, which put the Nakkedal Nappe Complex on top of the Lyngen Nappe Complex, causing the D3 deformation present in both nappe segments.

Information on the timing of these events has remained unclear even though a substantial amount of geochronological work has been done. The oldest date of 598 ± 107 Ma was reported by Griffin and Brueckner (1985) based on a two-point Sm/Nd isochron for garnet and pyroxene from a thoroughly retrogressed sample of the Tromsdalstind eclogite. Amphibole was also analyzed but plotted slightly below the line disrupting the fit. Because of the limited spread in Sm/Nd between these mineral phases, Griffin and Brueckner (1985) suggested that the minerals had not yet reached equilibrium and that the age was probably not meaningful. Krogh et al. (1990) stressed the state of partial disequilibrium in this particular sample, which made the meaning of the date uncertain, but nevertheless they considered the 598 Ma date to be a plausible age for the high-pressure event. The latter authors also reported a Rb/Sr whole-rock age of 433 ± 11 Ma for a suite of biotite–K–feldspar gneisses from the Tromsø Nappe. They also reported K-Ar ages of 437 ± 16 Ma for amphibole in a retrogressed eclogite, and 448 ± 20 Ma and 436 ± 20 Ma for amphibole in an oligoclasite dyke and in gneiss of the Skattøra Migmatitic Complex, respectively. Selbekk et al. (2000) obtained ages of

456 ± 4 for titanites in a migmatitic gabbro and an anorthositic dyke of the Skattøra Migmatitic Complex. Also, Skjerlie (2002) mentions a titanite age of 454 Ma for a felsic vein in the Tromsdalstind eclogite. An unpublished Rb-Sr age of 460–490 Ma for metasupracrustals of the Tromsø Nappe, obtained by Taylor and Binns, was also mentioned by Bryhni et al. (1977). Dallmeyer and Andresen (1992) applied the Ar-Ar method to hornblende in amphibolitic mylonites in the Tromsø Nappe yielding, in three cases, isotope correlation ages of 429 to 419 Ma, which is similar to two plateau ages of 427–418 Ma for muscovite in garnetiferous schists. A fourth amphibole concentrate, however, indicated an older date of 481 Ma. Samples from the tectonic unit at the base of the Nakkedal Nappe Complex provided hornblende ages of 452, 444 and 432 Ma in addition to a muscovite age of 410 Ma (Dallmeyer and Andresen 1992). Coker-Dewey et al. (2000) reported an Ar-Ar muscovite age of 441 ± 2 Ma for a granite inferred to belong to the base of the Tromsø Nappe, whereas muscovite from a schist in the immediately underlying part of the Lyngen Nappe Complex yielded a plateau age of 432 ± 2 Ma, which they interpreted as closely approximating the time of metamorphism associated with overthrusting by the hot Tromsø Nappe.

In synthesis, while these results leave a somewhat blurry picture of the exact timing of development of the Uppermost Allochthon in the Tromsø region, they do contain elements supporting a pre-Scandian age of metamorphism and deformation that preceded its Scandian translation onto the Late-Ordovician–Early Silurian strata of the Balsfjord Group in the Lyngen Nappe Complex.

U-Pb results

Analytical procedures

The U-Pb analyses were carried out by use of the ID-TIMS method following the standard procedures of Krogh (1973). Zircon and rutile were dissolved with HF (+ HNO_3) in Teflon bombs at 184 °C, and titanite in HF (+ HNO_3) in Savillex vials on a hot plate. Zircon fractions smaller than 5 µg were measured without additional chemical separation, the others were processed with a simple HCl chemical separation. Titanite was prepared either using the standard HBr–HCl–HNO_3 procedure, or various versions of a simplified technique (Corfu and Andersen 2002). The analyses were measured with a MAT 262 mass spectrometer in static with a Faraday assembly, and/or by peak-jumping with an ion counting SEM. Blank corrections were 2 pg or less Pb and 0.1 pg U for zircon and 10 pg (or less) for Pb and 0.3 pg U for titanite and rutile. The decay constants used were those of Jaffey et al. (1971). The data were plotted and regressed using the Isoplot program developed by Ludwig (1999). Errors represent the 2 sigma level.

(Trondhjemitic) orthogneiss in Tromsdalstind eclogite

The unit is part of the 'internal gneisses' of Krogh et al. (1990), generally trondhjemitic to dioritic in composition, which occur as layers within the large Tromsdalstind eclogite. At the sampled location the felsic gneiss enclave surrounds itself a 1-m-wide boudinaged eclogite layer, and smaller eclogite boudins. All these units are transected by hornblende leucosome, which forms thin discordant to subconcordant veins as well as irregular masses filling the extensional gaps in the neck of boudins. As the eclogite is approached, the gneissosity bends around the eclogite boudins, and the gneiss reveals a marked enrichment in garnet.

The zircon population extracted from this felsic gneiss (sample 97) exhibits a variety of forms including reasonably well-preserved euhedral to subhedral crystals together with subrounded equant grains. The results define two distinct groupings according to their different morphologies (Table 1, Fig. 3). The two uppermost concordant analyses were obtained from pieces of one well-preserved euhedral zircon tip, which was broken during abrasion. The other two data points in this upper group, one of them very imprecise, were obtained from fractions of subhedral to anhedral tips and short prisms, respectively. Because of their morphology and coherent behavior this type of zircon is regarded as a primary magmatic phase formed during the crystallization of the trondhjemitic protolith. The second group of analyses, which provided more discordant data points but with similar $^{207}Pb/^{206}Pb$ ages as the upper group, was obtained from two fractions of the equant anhedral grains. All zircon analyses fit on a common regression line defining an upper intercept age of 488 ± 10 Ma. This correlation suggests that all the different zircon types belong to the same, but variably resorbed, primary population. Resorption could be related to the eclogitization event but the main Pb loss event must have occurred in more recent times. The fact that the $^{206}Pb/^{238}U$ ages of the two discordant fractions coincide exactly with the age of the eclogite (see below) is a bit puzzling but because of the consistently higher $^{207}Pb/^{206}Pb$ ages this is probably just a coincidence. The question does not greatly affect the evaluation of the age of the trondhjemitic protolith. The upper intercept age of the common line discussed above is essentially the average $^{207}Pb/^{206}Pb$ age of all the analyses, which also overlaps the Concordia age of 492.6 ± 1.3 Ma calculated from the two most concordant analyses. To account for any potential downward bias due to Pb loss, the uncertainty on the latter age was increased to include the upper range covered by the upper intercept age, resulting in an age of $493 + 5/-2$ Ma (Fig. 3).

One analysis of a rutile fraction from this sample yields a concordant age of about 436 Ma. Its significance will be discussed below.

Eclogite, Tønsvika

The sample (43) represents one of several eclogite lenses occurring within calc-silicate gneisses at this locality (Roux 2002). The several-meter-wide body is quite heterogeneous and has garnet, omphacite, quartz, calcite, biotite and rutile as its main mineral phases. The sample collected for dating was taken from a particularly biotite- and garnet-rich portion of the lens.

The zircons extracted from this sample are anhedral and subequant with somewhat irregular but smooth external surfaces. CL images reveal in most cases an irregular faint alternation of darker and lighter domains reminiscent of 'auroral lights' patterns (Fig. 4b, c). Euhedral, oscillatory growth zoning was only seen locally in one grain (Fig. 4a). A few grains also reveal features suggestive of intermediate resorption (Fig. 4a) and/or superimposed recrystallization (Fig. 4d).

Three U-Pb analyses yielded overlapping results on or near Concordia (Fig. 3) and indicate relatively low U contents around 50–60 ppm and intermediate Th/U of 0.3–0.4. The age of 452.1 ± 1.7 Ma represents the upper intercept of a line constrained at 50 ± 50 Ma. It corresponds crudely to the mean $^{207}Pb/^{206}Pb$ age of the analyses and is indistinguishable from the U-Pb age of the concordant pair.

One analysis carried out on a large fraction of unabraded rutile plots nearly concordantly at an age of about 428 Ma. To evaluate whether the position of this analysis was due, at least in part, to Pb loss, a second fraction was very strongly abraded and analyzed. The analysis is very imprecise because of the small amount of Pb

Table 1 U–Pb data

Mineral, characteristics[a]	Weight (mg)[a]	U (ppm)[b]	Th/U[c]	Pbc		^{206}Pb/^{204}Pb[e]	^{207}Pb/^{235}U[f]	2σ (abs)[f]	^{206}Pb/^{238}U[f]	2σ (abs)[f]	rho	^{207}Pb/^{206}Pb[f]	2σ (abs)[f]	^{206}Pb/^{238}U Ma[f]	± 2σ (abs)	^{207}Pb/^{206}Pb	± 2σ (abs)
				(ppm)[d]	(pg)[d]												
C-01-97 eclogitized trondhjemite, Tromsdalstind																	
Z tip eu [1/3]	2	251	0.73		6.0	435	0.6239	0.0054	0.07957	0.00032	0.54	0.05687	0.00041	493.6	1.9	486	16
[1/3]	1	200	0.61		1.0	966	0.6221	0.0051	0.07926	0.00031	0.58	0.05693	0.00038	491.7	1.8	489	15
Z tips sb-an [8]	2	30	0.70		7.0	59.9	0.6302	0.0417	0.07881	0.00064	0.26	0.05800	0.00374	489.0	3.8	530	135
Z sp sb-an [16]	3	109	0.64		1.9	888	0.6179	0.0056	0.07868	0.00036	0.56	0.05695	0.00042	488.2	2.2	490	16
Z eq an [17]	5	60	0.06		1.7	807	0.5689	0.0070	0.07244	0.00047	0.48	0.05696	0.00061	450.8	2.8	490	23
Z eq an [16]	5	57	0.04		0.9	1395	0.5590	0.0071	0.07156	0.00080	0.84	0.05665	0.00038	445.6	4.8	478	15
R eq-sp sb-an N	305	4.8	0.11	0.1	36	194	0.5310	0.0106	0.06997	0.00039	0.35	0.05503	0.00103	436.0	2.3	414	41
C-99-43 eclogite, Tønsvika																	
Z fr an [32]	267	56	0.33	0.0	4.6	14819	0.5603	0.0014	0.07259	0.00017	0.92	0.05599	0.00005	451.7	1.0	451.9	2.1
Z eq an [27]	210	60	0.42	0.0	9.8	5840	0.5589	0.0012	0.07242	0.00015	0.87	0.05598	0.00006	450.7	0.9	451.5	2.4
Z eq an N [10]	83	54	0.31	0.1	10	2008	0.5582	0.0020	0.07219	0.00018	0.75	0.05608	0.00013	449.4	1.1	455.6	5.1
R eu-an fr r N	922	5.5	0.00	0.0	39	574	0.5278	0.0029	0.06871	0.00013	0.40	0.05571	0.00028	428.4	0.8	441	11
R an fr r	4	6.8	0.00		4.0	47.2	0.5109	0.0658	0.06821	0.00072	0.50	0.05433	0.00673	425.4	4.4	385	255
C-01-115 large rutile porphyroblast, Tromsdalstind																	
R fr* r op [4]	2,723	2.2	0.00	0.0	20	1403	0.5552	0.0039	0.07221	0.00037	0.69	0.05577	0.00029	449.4	2.2	443	11
R fr* r op [3]	466	2.3	0.05	0.0	5.3	939	0.5535	0.0047	0.07207	0.00029	0.45	0.05570	0.00043	448.6	1.7	440	17
C-01-100 hbl-leucosome, Tromsdalstind																	
T an b-y	338	197	0.23	6.6		155	0.5564	0.0122	0.07243	0.00026	0.13	0.0557	0.0012	450.8	1.5	441	48
T an b-y N 25%-al	1,529	165	0.25	5.9		147	0.5551	0.0130	0.07231	0.00027	0.20	0.055	0.0012	450.1	1.6	439	50
25%-al		165	0.26	5.9		146	0.5478	0.0132	0.07208	0.00032	0.16	0.0551	0.0013	448.7	1.9	417	52
50%-al		165	0.25	5.8		148	0.5659	0.0135	0.07259	0.00033	0.18	0.0565	0.0013	451.8	2.0	474	51
1A eclogite lens in marble, Lanesodden																	
T fr ly N	190	87	0.07	0.2		1702	0.5570	0.0024	0.07226	0.00023	0.73	0.05591	0.00017	449.7	1.4	449	7
1 K lens of amphibolitized eclogite, Lanesodden																	
T an-fr br N	150	193	1.90	3.6		257	0.5548	0.0073	0.07248	0.00024	0.26	0.0555	0.0007	451.1	1.4	433	28

[a] *Z* Zircon; *R* rutile;*T* titanite; *eu* euhedral; *sb* subhedral; *an* anhedral; *eq* equant; *sp* short prismatic (l/w = 2–4); *fr* fragments; *fr** fragment of large centimeter-sized crystal; *b* brown; *y* yellow; *ly* pale-yellow; *r* red; *op* opaque; *N* non abraded (all the others abraded; Krogh 1982); *[3]* number of grains in fraction; *25%-al* aliquot

[b, d] Weight and concentrations are known at better than 10% for weights over 20 μg and at about 50% for those below 3 μg

[c] Th/U model ratio inferred from 208/206 ratio and age of sample

[d] *Pbc* Total common Pb in sample (initial + blank)

[e] Raw data corrected for fractionation and blank

[f] Corrected for fractionation, spike, blank and initial common Pb (calculated with the Stacey and Kramers (1975) model, except for titanite corrected with initial Pb composition inferred from low-U titanite (6/4 = 18.55, 7/4 = 15.74; Table 2); error calculated by propagating the main sources of uncertainty; errors represent the last significant digits of the values

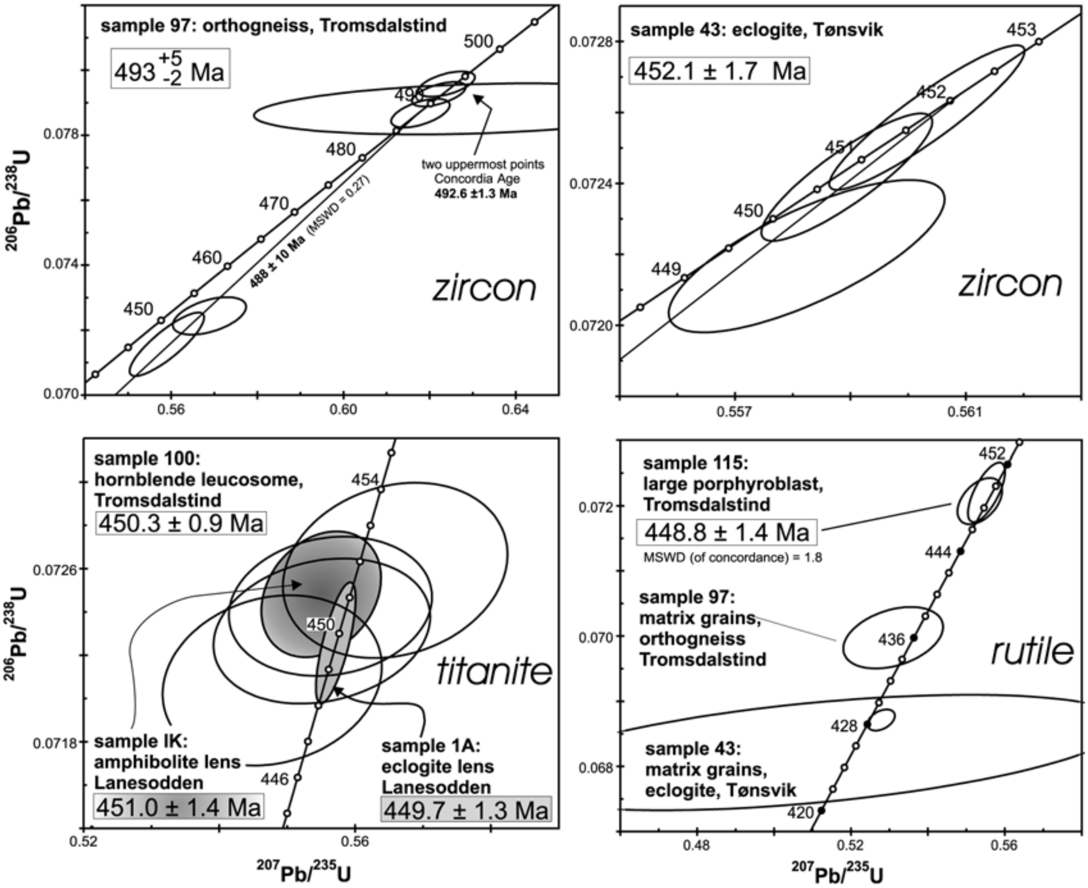

Fig. 3 Concordia diagrams showing the U-Pb data for zircon, titanite and rutile from the Tromsø Nappe. *Ellipses* indicate the uncertainty at the 2σ level

available, but it shows, nevertheless, that the younger age of the rutile, with respect to the coexisting zircon, is probably not the result of recent surface related Pb loss (Fig. 3).

Large rutile porphyroblasts in Tromsdalstind eclogite

In contrast to the finer-grained rutile dispersed in the matrix, very large (several centimeters) rutile porpyroblasts are a common sight in the Tromsdalstind eclogite. The large porphyroblasts appear to have developed during retrogressive phases post-dating the eclogitization.

Some fragments of rutile from one large, ruby-red and translucent crystal (sample 115) were abraded and analyzed. Although they only contain about 2.2 ppm U, they are virtually free of initial common Pb and hence they can be used to recover good quality ages. The two analyses overlapped defining a Concordia age of 448.8 ± 1.4 Ma (Fig. 3).

Titanites in leucosomes, eclogite, amphibolitized eclogite and calc-silicate

Late leucosome veins and patches are a widespread feature throughout the Tromsdalstind eclogite and its satellite bodies. The most common type is characterized by the presence of blocky, 1–5-cm-sized euhedral amphiboles together with plagioclase and quartz (Krogh et al. 1990); this type was succeeded by biotite ± white mica-bearing leucocratic veins. Titanite from two samples of the main early generation was investigated in this study: one of them (sample 100) is from near the top of the Tromsdalstind eclogite and the second from an occurrence of largely retrogressed eclogite at Telegrafbukta (sample 42).

Titanite is also present in veins composed largely of feldspar, chlorite and epidote, which appears to postdate all the other elements and may represent hydrothermal fracture filling. One sample (101), also from Tromsdalstind, is representative of this type of vein.

In addition to the above selections, three titanite fractions were recovered from lenses of eclogite and amphibolitized eclogite from the Lanesodden occurrence as well as from a calc-silicate rock from Mt. Fløya on the mainland. Sample 1A represents a small lens, a 4–5 cm thick folded and boudinaged layer of eclogitic rock in marble. Analyses of garnet, clinopyroxene and titanite are given by Krogh et al. (1990). This sample contains the highest Al content (13.2% Al_2O_3) recorded in titanite in any of the Tromsø Nappe eclogites. Unpublished analyses for F by Ulrike Troitzsch (personal communication) confirm F-saturation. High-Al (and F) contents tend to be restricted to titanite in high-pressure rocks and, thus, the system has been discussed as a possible thermobarometric indicator (e.g. Troitzsch and Ellis 2002 and references therein), although low-Al titanite also occurs in eclogites (Ye et al. 2002). Sample 1 K is from a ca. 2×4- m large lens in marble from the same locality. This is a totally recrystallized amphibolite facies rock containing plagioclase + diopside + biotite + titanite + quartz, with some hornblende. Although the chemistry of this particular titanite has not been analyzed, titanites from other similar samples show fairly high Al contents (probably 3–5 wt% Al_2O_3). Domains of finer-grained diopside + plagioclase ± biotite are interpreted as recrystallized symplectites after omphacite. This assemblage apparently equilibrated at 1.0 GPa/650 °C (Krogh et al. 1990). Sample TD-14 from Fløya is a garnet + clinopyroxene-rich calc-silicate rock, and analyses of these minerals and of titanite are given in Krogh et al. (1990). The titanite is fairly Al-rich (5.6% Al_2O_3) and is suspected to be part of the HP assemblage.

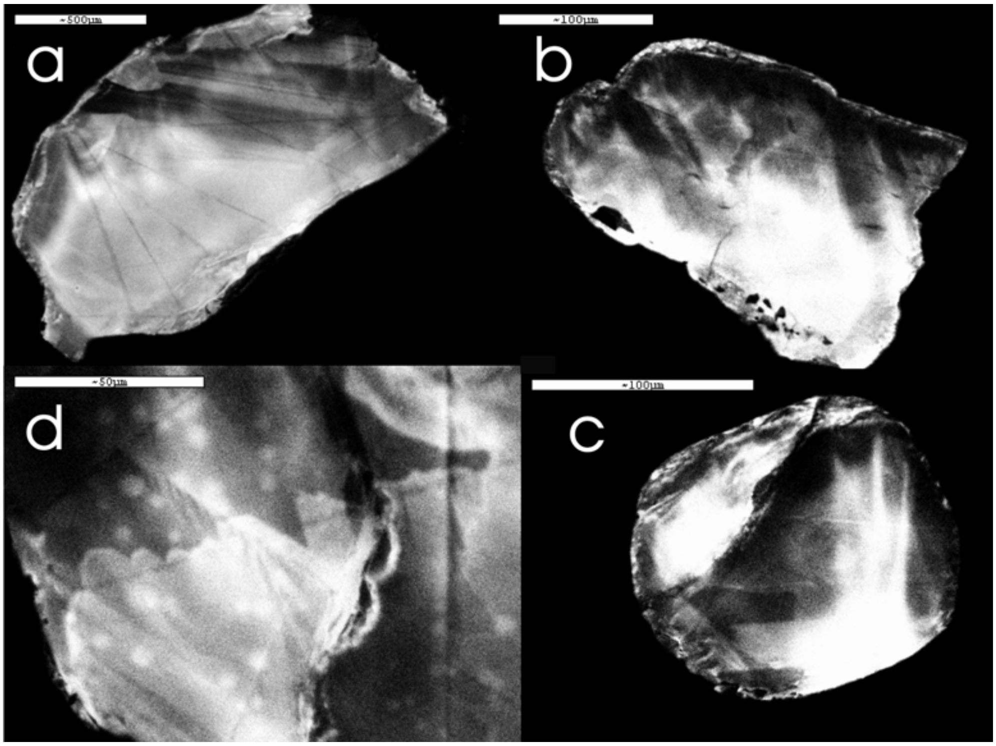

Fig. 4 Cathodoluminescence images for zircon in eclogite sample 43: **a** local domain of oscillatory growth zoning surrounding a zone of more homogeneous luminescence (*top left corner* shows some necking suggestive of resorption); **b** and **c** wavy and irregular, 'auroral lights'-type cathodolumiscence pattern typical for zircon in this sample; **d** a botryoidal recrystallization front in a grain with the normal wavy texture

Table 2 Pb–Pb data for least radiogenic titanite

Mineral, characteristics[a]	Weight (mg)[b]	U (ppm)[b]	Th/U[c]	Pbt (ppm)[d]	Pbc (ppm)[d]	^{206}Pb/^{204}Pb[e]	2σ (%)[e]	^{207}Pb/^{204}Pb[e]	2σ (%)[e]
C-00-100 hornblende–leucosome, Tromsdalstind									
T an b-y	338	197	0.23	20.4	6.6	155.3	0.34	23.36	0.32
T an b-y N 25%-al	1529	165	0.25	17.5	5.9	147.1	0.28	22.90	0.31
25%-al		165	0.26	17.5	5.9	146.6	0.33	22.80	0.35
50%-al		165	0.25	17.6	5.8	148.3	0.43	23.08	0.44
C-00-101 very late feldspar–chlorite–epidote vein, Tromsdalstind									
T eu fr ly	630	2.2	0.28	1.3	1.1	26.47	0.60	16.19	0.59
C-99-42 hornblende–zoisite–titanite leucosome, Telegrafbukta, Tromsø Island									
T eu fr ly	849	1.7	0.25	2.3	2.1	22.02	0.33	15.91	0.35
T eu fr ly	1098	2.0	0.26	2.7	2.5	22.34	0.33	15.97	0.35
TD-14 calc-silicate rock, Fløya									
T an ly N	227	19	0.37	3.8	2.4	54.22	0.74	17.66	0.42

[a] *T* Titanite; *eu* euhedral; *an* anhedral; *fr* fragments of large crystal; *b* brown; *y* yellow; *ly* light yellow, nearly colorless; *N* non abraded (all the others abraded; Krogh 1982); *25%-al* aliquot

[b,d] Weight and concentrations are known at better than 10%

[c] Th/U model ratio inferred from 208/206 ratio and age of sample

[d] *Pbt* Total amount of Pb; *Pbc* total common Pb (initial + blank)

[e] Corrected for fractionation, spike and blank; error calculated by propagating the main sources of uncertainty

Titanite of leucosome sample 100 consists of brown-yellow lenticular grains of up to several millimeters in size, which can be rather irregular in shape and have local inclusions of other minerals, most commonly of rutile. Two fractions were analyzed, one abraded and the other unabraded. The latter was split (after dissolution but before chemical separation) into three aliquots, which were processed separately to test some aspects of the analytical procedure. The results indicate higher-than-usual amounts of U (165–197 ppm) as well as initial Pb (6.6–5.9 ppm), which maintains the ^{206}Pb/^{204}Pb ratio at a low 146–155 (Table 1). The relations between U and initial Pb are just marginally better in the brownish, anhedral grains of sample 1 K, whereas the pale titanite in eclogite 1A contains only 0.2 ppm initial Pb together with 87 ppm U, yielding the best ^{206}Pb/^{204}Pb ratio (1702) of all these titanite samples. At the other end of the spectrum, the titanites in samples 42, 101 and T-14 contain little U (down to 2 ppm for the almost colorless titanite crystals in samples 42 and 101 that are locally over 1 cm in size) and 2.1 to 1.5 ppm initial Pb (Table 2). Because of the resulting low ^{206}Pb/^{204}Pb ratios, it is not possible to use the latter analyses for a precise and accurate age determination. They are, however, nevertheless useful because they allow us to obtain an estimate of the initial Pb composition in these units. When plotted in a ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb diagram (Fig. 5) the non-radiogenic analyses define a line that can also be extended to pass through the four more radiogenic analyses of sample 100. The poor MSWD of 3.7 of the line defined by all eight data points, is caused partly by the slight deviation of analysis TD-14 and partly by the internal disagreement in the three duplicate analyses of sample 100,

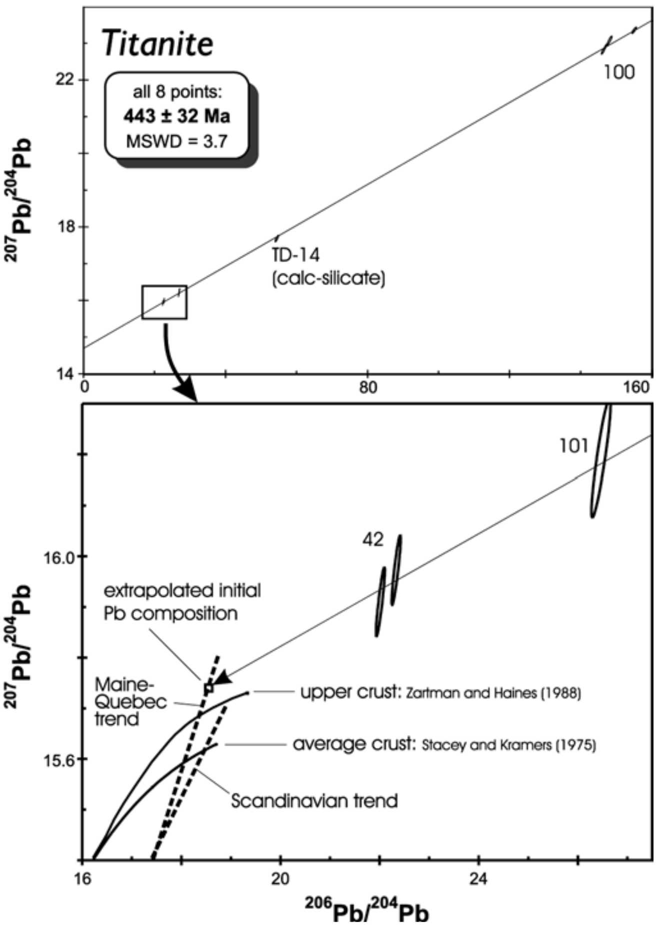

Fig. 5 Pb–Pb plot of the titanite data (Table 2). The indicated initial Pb composition has been calculated by subtracting the radiogenic Pb portion from the two fractions of sample 42. The ‘Main-Quebec’ and ’Scandinavian’ trends are from Bjørlykke et al. (1993)

which is perhaps a result of imperfect aliquoting, or of some bias resulting from their being used to test different chemical separation procedures. Nevertheless, the general agreement suggests that titanite in the various samples had comparable initial Pb compositions at the time of crystallization. It is notable that the regression line passes well above average (upper) crustal evolution curves (e.g. Stacey and Kramers 1975; Zartman and Haines 1988), indicating the presence of an important component of Pb derived from ancient upper crustal sources. An initial Pb composition was calculated by subtracting the radiogenic Pb component present in the two titanite analyses of sample 42. Use of this composition (Table 1) to correct for the initial Pb in the four concordant analyses of sample 100 yields a U-Pb Concordia age of 450.3 ±0.9 Ma (Fig. 3). As a comparison, a Stacey and Kramers (1975) composition would increase this age by some 2 Ma. The single analysis of the high-Al (and low-initial Pb) titanite in eclogite sample 1A yields a Concordia age of 449.7 ± 1.3 Ma, whereas titanite in the amphibolitized eclogite 1 K provides an age of 451.0 ± 1.4 Ma.

Discussion

Implications concerning the origin and provenance of the Tromsdalstind sequence

The Tromsdalstind sequence has been regarded as a platformal sedimentary succession based on the presence of thick carbonates and metapelites (Krogh et al. 1990). The common occurrence of mafic rocks, interpreted to be metabasalts and gabbros together with local trondhjemitic to tonalite bodies, indicates a magmatically active setting. The present study provides some additional evidence concerning the origin of the sequence. One piece of information extracted from it is the latest Cambrian age of 493 + 5/−2 Ma obtained for the protolith of the felsic gneiss inside the Tromsdalstind eclogite, indicating that this intrusive activity took place at about the same time as the formation of the early generation of ophiolites and arc-related magmatic suites now preserved on both the Laurentian and Baltican sides of the Caledonian orogen (Dunning and Pedersen 1988). The original tectonic setting of the units in the Uppermost Allochthon has been considered to correspond to that of a rifted margin based on the sedimentary rock association and the inferred alkaline composition of gabbroic protoliths in the Skattøra Migmatite Complex (Selbekk et al. 2000). This notion of an extensional continental margin is also supported by the available isotopic data. As discussed above, the Pb compositions of the titanites, though imprecise, point towards initial Pb compositions with the high ^{207}Pb/^{204}Pb characteristics of ancient upper continental crust (Fig. 5). This indication of a Precambrian source is also supported by the Sm–Nd data reported by Griffin and Brueckner (1985) regarding a sample of the Tromsdalstind eclogite, because recalculation of their data (obtained from garnet, clinopyroxene and amphibole) at an age of 450 Ma yields ε_{Nd} values of −8.0 to −8.7. Unless they are the result of extensive metasomatism during eclogitization, these unradiogenic Nd isotopic signatures must indicate a provenance of the mafic units from melting of an ancient enriched subcontinental lithosphere. An additional indication for Proterozoic sources is also provided by the high initial ratio of 0.7122 defined by the Rb-Sr data reported by Krogh et al. (1990) for the feldspathic gneisses at the base of the Tromsø Nappe.

Thus, the available isotopic evidence points towards a genesis of the sequence during late Cambrian extension and rifting of a Precambrian continental margin.

Timing of eclogitization

An eclogitization process is commonly related to a series of mineralogical reactions reflecting the progressive increase and subsequent decrease in pressure and temperature, and it is therefore not a priori clear at which stage of the process zircon crystallization occurred. Indeed, it has been shown that zircon growth can accompany the entire cycle of subduction and exhumation of eclogitized crust (e.g. Hermann et al. 2001). The zircon population extracted from the eclogite at Tønsvik is very uniform in appearance and age. Under CL the grains display an auroral lights pattern similar to that observed in eclogitic zircon from Dabie Shan (Rowley et al. 1997).

There are local domains characterized by oscillatory growth zoning and resorption that could be taken to indicate that this was an original igneous population formed in a gabbroic protolith and then reworked and isotopically reset during the eclogitization event, an interpretation similar to that proposed by Liati and Gebauer (1999) concerning zircon in eclogite from the Rhodope Zone. However, such an interpretation seems highly debatable since it requires a process that can entirely reset the isotopic system of some zircons, while leaving behind traces of the original internal textures without affecting zircon populations in comparable units. Oscillatory zoning is in itself not an uncommon feature of eclogitic zircon and has been interpreted as indicating growth in the presence of a melt or supercritical fluid (e.g. Gebauer et al. 1997). The Th/U ratio of about 0.3–0.4 for the Tønsvika zircons is considerably higher than values of less than 0.1 most commonly observed in eclogitic zircon (e.g. Gebauer et al. 1997; Bingen et al. 2001a). However, by itself, such Th/U ratios do not prove very much as there are well-documented exceptions such as that reported about the Nevado-Filabride Complex in southern Spain by Lopez Sanchez-Vizcaino et al. (2001).

The occurrence of the Tønsvika eclogite in a series of lenses within marbles has been interpreted to indicate that these were originally basaltic flows intercalated in limestones and dismembered during the subsequent orogenic events. By contrast, the larger Tromsdalstind eclogite, with its internal felsic gneisses, is thought to represent a gabbroic massif (Krogh et al. 1990). A derivation from a basaltic protolith devoid of primary magmatic (i.e. Cambrian) or xenocrystic zircon, is consistent with the presence of only one generation of zircon in the dated eclogite. It thus appears reasonable to conclude that the Tønsvika eclogite zircons formed at 452.1 ± 1.7 Ma in the course of the high-pressure metamorphic event, an age corroborated by those of titanite and rutile. Zircon growth would have been fed by the freely available Zr in the basaltic matrix and promoted by the fluid phase present throughout the peak reactions (Krogh et al. 1990).

Formation of a metamorphic zircon generation may also have occurred in the felsic (trondhjemitic) gneiss but, as discussed above, the presently available data are somewhat ambiguous and, taken at face value, they suggest that the 'metamorphic-looking' grains are resorbed magmatic crystals whose apparent U-Pb age just coincidentally matches the age of eclogite metamorphism (Fig. 3).

The three titanite samples that had sufficiently radiogenic Pb isotopic ratios define overlapping ages of 450.3 ± 0.9, 451.0 ± 1.4 and 449.7 ± 1.3 Ma, which are also within error of the zircon age. Since these minerals formed either during the eclogitization process (1A) or during the uplift phase that caused partial melting of the eclogite (the leucosomes) the nearly identical ages show that these processes were very rapid, spanning not more than a few million years. This is also supported by the age of 448.8 ± 1.4 Ma of the large rutile porphyroblasts, whose growth postdated the eclogite event.

Krogh et al. (1990) suggest that the Tromsø Nappe was juxtaposed on the Skattøra Migmatitic Complex during exhumation from the ca. 80 km depth reached during the subduction and collisional event (Ravna and Roux 2002). Krogh et al. (1990) also conclude that the formation of anorthositic melts by partial melting of the Skattøra gabbro occurred as a result of this juxtaposition. The available age relations are consistent with a general coincidence of the two events, but in detail there is some disagreement because the titanite ages of 456 ± 4 and 456 ± 3 Ma obtained by Selbekk et al. (2000) are slightly older than the age determined for titanite in the present study. In one case, the difference could reflect the correction for initial Pb, i.e., the use of a Stacey and Kramers (1975) composition, by Selbekk et al. (2000), which could have biased the age upward. However, their analyses of titanite from a gabbro have $^{206}Pb/^{204}Pb$ ratios of around 1,000, which are not very susceptible to the kind of initial Pb correction used. It would thus appear that the Skattøra anorthosite dykes were generated during a common subduction–collisional process, but presumably already during its early phases. This semi-separate genesis is supported by the fact that anorthositic dykes are never seen as having penetrated the generally highly mylonitic contact to the overlying Tromsø Nappe (Selbekk et al. 2000).

Scandian events

The next evolutionary stage occurred during the Scandian collisional phase which brought the Nakkedal and Tromsø Nappes on top of the Late Ordovician to Early Silurian Balsfjord Group of the Lyngen Nappe Complex. This event is linked to development of M2 metamorphism, which represents a second clockwise P–T-loop reaching 1.0–1.1 GPa and ca. 665 °C and was associated with the development of the dominant D2 fabrics in the Tromsø Nappe (Krogh et al. 1990). These elements have been interpreted to represent underthrusting of the Uppermost Allochthon along a deep crustal shear zone prior to uplift and juxtaposition on the Lyngen Nappe Complex (Krogh et al. 1990). Coker-Dewey et al. (2000) also suggest that the overthrusting of the hot Nakkedal Nappe Complex on the Balsfjord Group was responsible for the development of the inverted metamorphic gradient observed at the top of the latter unit. They report an Ar-Ar muscovite age of 432 ± 2 Ma, which they interpret as dating this metamorphic event. In general most of the Rb-Sr, K-Ar and Ar-Ar ages known in the Nakkedal and Tromsø Nappes are consistent with this indication, but some are somewhat younger suggesting the effects of a later resetting or protracted diffusion (Krogh et al. 1990; Dallmeyer and Andresen 1992). The three data points for matrix rutile reported in this paper present us with the same type of uncertainty. The two more precise analyses yield apparent ages of around 436 and 428 Ma, and the less precise one merely tells us that these rutile ages probably were not due to recent Pb loss. Because the matrix rutiles were formed as a part of the eclogite paragenesis, their ages have to reflect some sort of resetting. A slow cooling hypothesis could be supported by the fact that the large (centimeter) porphyroblast more or less preserves the primary age, whereas the smaller crystals (100 μm) are too young. Such an interpretation, however, is complicated by the fact that the suite was cooled (rapidly?) and uplifted, prior to the new underthrusting and heating event in the Silurian. Thus, resetting during M2 (and M3) seems more likely. In any case, these young rutile ages are unable to yield a more precise definition of the timing of Scandian events.

Paleogeographic considerations

One of the interesting issues of the Scandinavian Caledonides concerns the provenance of the various fragments of the Uppermost Allochthonous. Recent paleogeographic reconstructions (Torsvik and Rehnström 2001; Cocks and Torsvik 2002) show that in the Late Cambrian (western) Baltica was situated at intermediate to high latitudes facing the Aegir Sea and Siberia. As pointed out by Roberts et al. (2002), the high latitude prevented widespread carbonate deposition in Baltic sedimentary successions of this age in contrast to the development of thick carbonate formations on the more temperate Laurentian and Siberian margins. Thus, the geological and temporal relationships observed for the Tromsø Nappe are consistent with a derivation from a Laurentian or Siberian margin. This interpretation is also supported by the Pb isotope evidence from titanite that was discussed above. As shown in Fig. 5, this composition lies above the mature upper crust curve of Zartman and Haines (1988), indicating a source with a substantial component of old crust rich in ^{207}Pb. The composition fits directly on the Pb isotopic trend defined by the Maine-Quebec segment of the Appalachians on Laurentia, but it deviates from the flatter trend defined by the Scandinavian Pb compositions (Bjørlykke et al. 1993).

Yoshinobu et al. (2002) discuss geological constraints and Middle to Late-Ordovician ages of granitic magmatism obtained in the Helgeland Nappe Complex, a component of the Uppermost Allochthon in north-central Norway (Fig. 1). In their interpretation, which is consistent with that of Roberts et al. (2002), they view the Helgeland Nappe Complex as a Taconic collisional stack of continental and oceanic fragments overthrust on the Laurentian margin. The youngest of the magmatic events related to this collision occurred in the latest Ordovician (Nordgulen et al. 1993) less than 5 million years after the Tromsdalstind high-pressure event, thus supporting a general affinity for all these processes. There is nevertheless a profound qualitative difference between the events in these different segments of the Uppermost Allochthon, namely very high-pressure metamorphism with only small amounts of partial melting during exhumation in the Tromsø Nappe, in contrast to the lower pressures (0.7 to 0.4 GPa) and relatively high temperatures existing at this point in time in the Helgeland Nappe Complex. This suggests that if they were spatially related, these nappes must have represented differentially subducted segments of the complex, or, even that the Tromsø Nappe represented a portion of the subducted lower plate.

By contrast, Brueckner and van Roermund (2001) speculate that the Mid-Ordovician high-pressure event, indicated by Sm–Nd isotopic data from the N-Jämtland part of the Seve Nappe Complex, may reflect an intra-oceanic collision involving a continental fragment. High-pressure metamorphism dissociated from main continental collision has also been suggested by Eide and Lardeaux (2002) concerning the blueschists of the Köli Nappe Complex (Fig. 1). Hence, the exact plate-tectonic setting of these various high-pressure occurrences might not be completely understandable until a much wider body of data has accumulated.

Main conclusions

Zircon in an eclogite of the Tromsø Nappe yields an age of 452.1 ± 1.7 Ma, which dates the high pressure event. This date is corroborated by ages of 451–450 Ma for titanite in eclogite (with a high-Al composition) and in neosome veins, and for a large rutile porphyroblast in the same type of veins. The tight grouping of these ages demonstrates that the high pressure (2.8GPa) processes spanned a very short period of time. A second high-pressure loop reaching 1.1GPa was related to the Scandian thrusting events and probably caused the partial resetting of the U-Pb ages in matrix rutiles.

The data also provide some information concerning the pre-collisional history of these rocks. The elevated ^{207}Pb/^{204}Pb ratio of the initial Pb composition obtained from the eclogite implies a derivation from old and mature upper crustal sources, which is consistent with the previously made proposals that the Uppermost Allochthon in the Scandinavian Caledonides is an exotic terrane with respect to Baltica and was probably derived from the Laurentian margin. The eclogites occur in a metasedimentary sequence, which was formed in a passive margin setting and was intruded at $493+5/-2$ Ma by gabbroic/tonalitic/trondhjemitic plutons, reflecting the magmatic activity widespread at this time along and outboard of the Laurentian margins.

The minerals used for dating the Tromsø Nappe eclogites—zircon, titanite and one rutile porphyroblast—yield relatively simple, internally consistent, and well-constrained data sets that can be used with great confidence in determining the tectonic history. This does not apply, however, to some of the titanites having very low U-Pb ratios because they are critically dependent on how well one can determine their initial Pb composition.

It is also apparent that, while the large rutile porphyroblast yielded a robust U-Pb age, the smaller matrix rutiles provide partially reset dates, which by themselves are of little value for a tectonic interpretation.

Acknowledgments We would like to thank Gunborg Bye Fjeld and Morten Schjoldager for help in preparing the mineral separates, as well as Turid Winje for assistance at the scanning electron microscope, and Dieter Gebauer, Tony Carswell and an anonymous reviewer for their helpful reviews.

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