Preliminary U-Pb geochronology in the West Troms Basement Complex, North Norway: Archaean and Palaeoproterozoic events and younger overprints

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This paper reports new U-Pb ages for zircon and titanite in four magmatic units of the West Troms Basement Complex. A granite, present as a megalens within the NNW-trending Senja Shear Belt at the southwestern tip of Kvaløya, yields a zircon age of 2689 ± 6 Ma showing that the unit is an integral part of the Archaean basement in the region rather than a Palaeoproterozoic intrusion. By contrast, a Palaeoproterozoic origin of the Ersfjord granite is well confirmed by a zircon age of 1792 ± 5 Ma. This age shows that the granite is coeval with the main generation of mangerites in Lofoten and formed during one of the dominant plutonic episodes across the Baltic Shield. Zircon in a smaller, late-synkinematic granitic dyke at Otervika yields 1774 ± 5 Ma, indicating that deformation along major NW-SE-striking, block-bounding shear zones of the Senja Shear Belt was in the waning stages at this time. Titanite ages of about 1770 Ma were found in three different samples. Two of them also contain a secondary titanite generation formed at about 1755 Ma, indicating prolonged episodes of metamorphic resetting and low-temperature new growth and/or recrystallization most likely during the waning stages of Svecokarelian shearing. One titanite population was strongly affected by an enigmatic Neoproterozoic disturbance. One of the samples also contains U-rich accessory minerals which yield Carboniferous ages, probably reflecting fluid activity during post-Caledonian extensional faulting in the West Troms Basement Complex

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Introduction

Precambrian basement is exposed along the coast of northern Norway on a chain of islands stretching from southern Lofoten to Vanna in West Troms (Figs. 1 & 2). This basement comprises crustal blocks made up of migmatites, granitoid rocks and greenstone belts, at least in part of Archaean age, all metamorphosed and deformed to variable degrees and intruded by widespread granitoid plutons between 1900 and 1700 Ma. The various blocks are separated by major shear zones. In contrast to basement units exposed along the coast of central and southern Norway, this crustal segment received only a weak metamorphic overprint during the Caledonian orogeny. Its role during the Caledonian orogeny remains, therefore, something of a puzzle. Although there are several lines of evidence suggesting that it is simply the autochthonous extension of the Fennoscandian Shield emerging from beneath the Caledonian nappe stack (Griffin et al. 1978, Olesen et al. 1997), there have also been suggestions that it may be in a parautochthonous to allochthonous position (e.g., Brueckner 1971, Dallmeyer 1992, Motuza 1998). The present configuration was also substantially influenced by post-Caledonian extension and Late

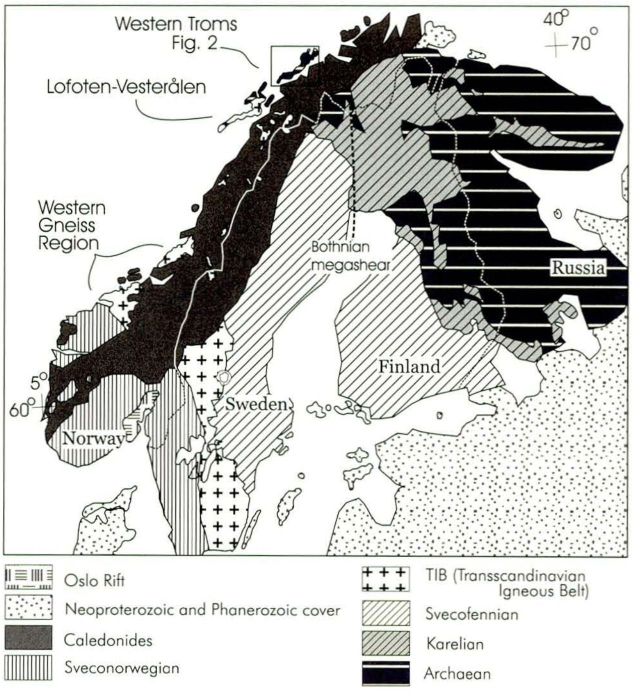

Fig. 1. Simplified geological map of the Baltic Shield.

Palaeozoic to Mesozoic displacements between fault-bounded blocks related to the opening of the North Atlantic Ocean (Olesen et al. 1997).

Mapping and preliminary geochronology (see summary in Zwaan et al. 1998) have delineated the major geological components of the region, highlighting at the same time a range of critical problems that remain to be solved. These questions concern (i) the development and extent of the Archaean crust, (ii) the Palaeoproterozoic modifications of the basement blocks by shearing, terrane accretion, metamorphism and extensive magmatism, (iii) the possible correlation of these blocks with Palaeoproterozoic units and shear zones in the Baltic Shield farther east, and finally (iv) the Caledonian and post-Caledonian evolution of the region. In this paper we make a contribution towards the resolution of some of these questions by presenting new U-Pb analyses for zircon and titanite in various units of the Precambrian basement on Kvaløya (Figs. 3 & 4).

Geological setting

The West Troms Basement Complex (WTBC; Fig. 2) comprises (i) a northeastern zone composed dominantly of intermediate to mafic (tonalitic to anorthositic) intrusive rocks underlying Ringvassøya and parts of Kvaløya, (ii) a dominantly granitic southwestern zone constituting most of Senja and the remainder of Kvaløya (Zwaan 1995), and (iii) a network of NNW-SSE-striking ductile shear zones (e.g., the Senja Shear Belt) and narrow, medium- to high-grade metamorphic, partly anatectic and mylonitic, metasupracrustal rocks that divide the WTBC into crustal blocks (Zwaan & Bergh 1994).

The northeastern part of the WTBC consists mainly of gneisses subdivided into weakly banded to nebulitic tonalitic to anorthositic gneisses with abundant cross-cutting dolerite dykes in the north and an assemblage of intermediate to mafic banded gneisses, including anorthosite, to the southwest. On Ringvassøya, the tonalitic gneisses are tectonically overlain by a c. 28 km-long and 10 km-wide

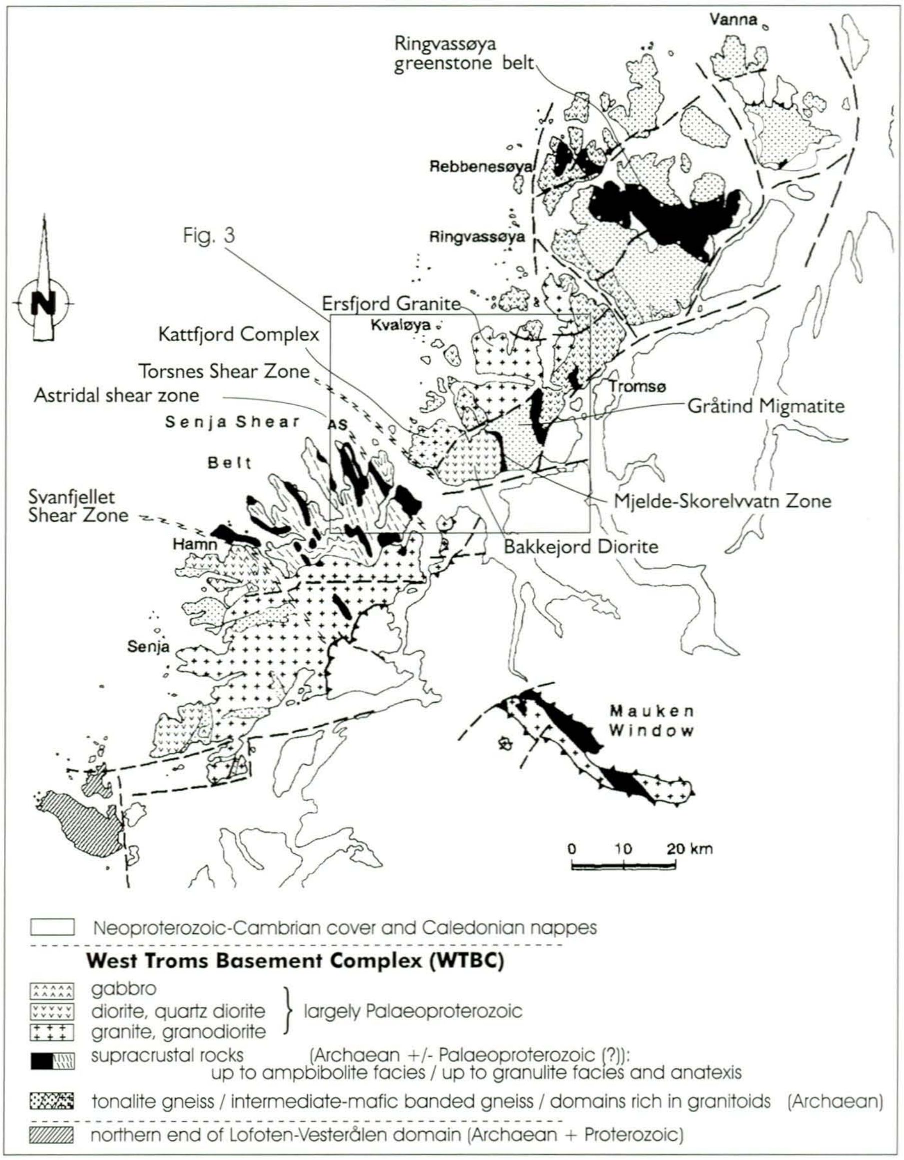

Fig. 2. Geological map of the West Troms Basement Complex (WTBC). Modified from Zwaan (1995).

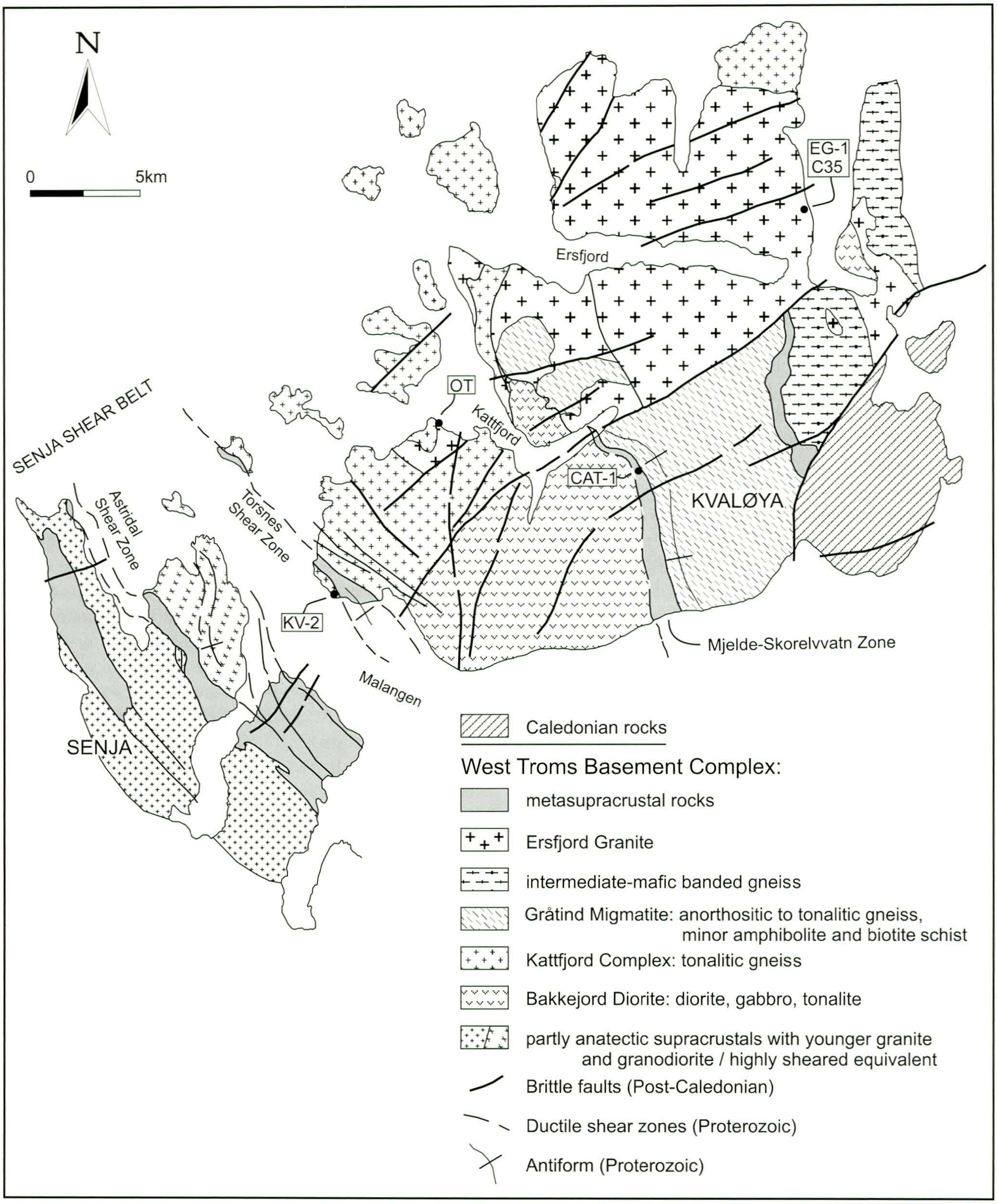

Fig. 3. Geological map of Kvaløya and northernmost Senja showing the locations of the analysed samples. Modified from Zwaan et al. (1998).

greenstone belt composed of mafic to felsic metavolcanic rocks of tholeiitic and calc-alkalic affinity (Motuza et al. 2001a,b). The greenstone belt had previously been considered to be of Palaeoproterozoic age (Zwaan 1989, 1995) but recent U-Pb age determinations on metavolcanic rocks have yielded Archaean ages of 2849 ± 4 and 2835 ± 14 Ma (Motuza et al. 2001a), which are similar to an age of 2842 ± 3 Ma reported by Zwaan & Tucker (1996) for a tonalitic sample in the underlying gneiss complex. On Kvaløya, metasupracrustal rocks occur as steep, narrow belts, the most prominent of which is the Mjelde-Skorelvvatn Zone (Binns 1983, Armitage 1999). The metasupracrustal rocks are of mixed sedimentary and volcanic origin, the volcanic rocks generally occurring as amphibolitic units, also including ultramafic bodies of komatiitic affinity (Motuza 1998,Armitage, unpublished data). These inliers, and the main gneissic foliation, both have a NNW-SSE strike. The supracrustal rocks were metamorphosed at greenschist- to amphibolite-facies conditions (Zwaan 1995, Motuza 1998).

The central and southwestern parts of the WTBC are dominated by granitic and migmatitic rocks of various composition. One of the most prominent bodies is the Ersfjord Granite on Kvaløya that intrudes basement gneisses such as the highly deformed, tonalitic to dioritic Gråtind Migmatite and the massive Bakkejord Diorite (Figs. 2 & 3). Undeformed, metamorphosed mafic dykes are prevalent in the Bakkejord Diorite, but they are scarce in the Gråtind Migmatite to the east of the Mjelde-Skorelvvatn Zone, where they occur as highly deformed amphibolitic lenses parallel to the main foliation. This zone has a prominent NNW-SSE-striking foliation with steep westerly dips and consists of metasupracrustal rocks which have formerly been correlated with the Ringvassøya Greenstone Belt (Binns 1983). The kinematics of the zone indicate that it developed during a Palaeoproterozoic progressive crustal contraction and transpressional event (Armitage 1999, Armitage & Bergh in prep.).

The Bakkejord Diorite is flanked farther to the west by the Kattfjord Complex, which comprises 'biotite gneiss of tonalitic composition' (Zwaan et al. 1998) and is in contact with metasupracrustal rocks of the Torsnes Shear Zone (Fig. 2). Part of the complex is exposed at Oterneset/Sandneshamn, where a late-kinematic, foliation-cutting granite is itself cut by later, virtually undeformed, granitoid pegmatite dykes.

The 30 km-wide Senja Shear Belt is confined between the Svanfjellet Shear Zone (Cumbest 1986) in the southwest and the Torsnes Shear Zone (Nyheim et al. 1994) in the northeast (Fig. 2). It is defined by narrower (<3 km-wide), approximately NW-SE-striking, anastomosing, ductile shear zones that enclose mega-lenses and blocks of gneiss and granitoid rocks and narrow belts of highly deformed metasupracrustal rocks, interpreted as intermediate to mafic metavolcanic rocks and mainly quartzitic terrigenous sedimentary rocks (Zwaan & Bergh 1994) commonly associated with ultramafites. The rocks have undergone amphibolite-facies metamorphism, locally reaching granulite facies with partial anatexis (Zwaan 1995). The deformation history included two main phases: early E-W oblique crustal contraction possibly associated with accretionary tectonics (D1) followed by NW-directed sinistral strike-slip translation (D2). In the Mjelde-Skorelvvatn Zone, Armitage (1999) mapped a subhorizontal folding phase (his D2) post-dating D1, but interpreted to be part of the same progressive deformation event as D1. His D3 is thus equivalent to the regional D2 event for sinistral shearing; this paper follows the regional nomenclature. Some of the granitoid rocks are deformed where they extend into the Senja Shear Belt. The fact that pegmatites and aplites are far less deformed than the main granitic bodies suggests that intrusion of the latter was most likely contemporaneous with the shearing event.

Previous age determinations in the WTBC include the Archaean U-Pb ages of 2835-2850 Ma for tonalitic and metavolcanic rocks on Ringvassøya (Zwaan & Tucker 1996, Motuza et al. 2001a) and a U-Pb age of c. 2400 Ma for mafic dykes cross-cutting the above units (Kullerud et al. in prep). Farther south, the Ersfjord Granite had been investigated with the Rb-Sr whole-rock system yielding somewhat different dates of 1706 ± 30 Ma (Andresen 1979) and 1779 ±17 Ma (Romer et al. 1992). Andresen (1979) also reported a highly disturbed Rb-Sr array for the Rødberghamn Granite cropping out on the mainland east of Senja. Two granitic to quartz-dioritic bodies from Senja have provided Rb-Sr isochron ages of 1746 ± 93 Ma and 1768 ± 49 Ma (Krill & Fareth 1984), and 1822 ± 5 Ma (Lindstrøm 1988). Zwaan et al. (1998) also list several unpublished Palaeoproterozoic U-Pb dates for granitic to noritic units on Senja. Dallmeyer (1992) reported Ar-Ar data for hornblende samples from Kvaløya and Senja that provide a complex range of dates between 1950 and 900 Ma, the best behaved of which define late Sveconorwegian (i.e., c. 900 Ma) ages.

U-Pb data

Sample characteristics and field relations

The paper reports results for five samples of magmatic rocks from Kvaløya (Fig. 3). Sample **KV-2** represents coarse-grained foliated granite from the southwestern tip of the island. The unit occurs as a tectonized mega-lens forming an integral part of the Torsnes Shear Zone along the northwestern edge of the Senja Shear Belt (Fig. 2). Two samples, **EG-1** and **C35**, represent the Ersfjord Granite, which at the sampling locality is slightly heterogeneous in terms of grain size and abundance of biotite, and weakly strained. As discussed above, this unit played a major role in the intrusive history of the WTBC and it was therefore important to refine the previous age constraints, especially in view of the conflict between the two existing Rb-Sr whole-rock determinations (Andresen 1979, Romer et al. 1992). Sample **OT** represents a foliation-cutting granite in the Kattfjord Complex at Oterneset. The dyke was interpreted by Pedersen (1997) as a syn- to late-kinematic (shear-induced) remnant of the

Table 1. U-Pb data, Kvaløya, West Troms Basement Complex

no.	Mineral characteristics[1]	Weight [µg][2]	U [ppm][2]	Th/U[3]	Pbcom [ppm]	Pbcom [pg][4]	^{206}Pb/^{204}Pb[5]	^{207}Pb/^{235}U[6]	2 σ [abs][6]	^{206}Pb/^{238}U[6]	2 σ [abs][6]	rho	^{207}Pb/^{206}Pb[6]	2 σ [abs]6	^{206}Pb/^{238}U[6] [Ma][6]	^{207}Pb/^{235}U[6]	^{207}Pb/^{206}Pb	2 σ [abs]	Disc. [%][7]
	KV-2: coarse grained foliated granite in Torsnes Shear Zone																		
1	z eu sp+tips [34]	12	241	0.47		1.9	47379	12.771	0.027	0.50542	0.00098	0.97	0.18327	0.00010	2637.0	2662.9	2682.6	0.9	2.1
2	z eu sp [15]	8	229	0.48		1.5	38148	12.693	0.039	0.50323	0.00150	0.98	0.18294	0.00012	2627.6	2657.1	2679.7	1.1	2.4
3	z tips [50]	10	209	0.42		11.0	5963	12.541	0.034	0.49703	0.00127	0.97	0.18300	0.00011	2601.0	2645.8	2680.2	1.0	3.6
4	z tips [25]	12	328	0.41		2.1	59371	12.417	0.035	0.49414	0.00135	0.98	0.18226	0.00010	2588.6	2636.5	2673.5	0.9	3.9
	EG-1: Ersfjord granite																		
5	Z an-sb eq-sp	15	140	0.77		3.0	13761	4.966	0.010	0.31786	0.00059	0.95	0.11331	0.00007	1779.3	1813.5	1853.2	1.1	4.6
6	Z eu-sb sp [18]	15	302	0.72		9.5	9220	4.618	0.010	0.30691	0.00059	0.96	0.10913	0.00006	1725.5	1752.5	1784.9	1.1	3.8
7	Z eu-sb lp	26	209	0.85		10.4	10036	4.608	0.011	0.30619	0.00066	0.97	0.10914	0.00006	1721.9	1750.6	1785.1	1.1	4.0
8	Z eu-sb tips [24]	19	273	0.70		8.6	11505	4.582	0.013	0.30489	0.00080	0.97	0.10900	0.00007	1715.5	1746.1	1782.8	1.2	4.3
9	Z eu tips [15]	10	226	0.74		4.4	9740	4.601	0.026	0.30486	0.00185	0.85	0.10945	0.00036	1715.3	1749.4	1790.3	5.9	4.8
10	Z eu lp fr [5]	2	505	0.66		3.9	4775	4.338	0.093	0.29031	0.00622	1.00	0.10838	0.00010	1643.1	1700.6	1772.3	1.7	8.3
11	T fr br	139	132	3.78	2.7		889	4.702	0.013	0.31531	0.00063	0.76	0.10816	0.00019	1766.8	1767.6	1768.6	3.3	0.1
12	T fr br	98	131	3.77	2.2		1062	4.698	0.013	0.31494	0.00068	0.82	0.10819	0.00017	1765.0	1766.9	1769.2	2.9	0.3
13	T lenses lbr NA	124	120	3.45	1.8		1160	4.653	0.013	0.31413	0.00071	0.86	0.10744	0.00015	1761.0	1758.9	1756.4	2.6	-0.3
	C35: Ersfjord granite (C-99-35)																		
14	Z lp fr [1]	--	--	0.83		3.0	3291	8.855	0.044	0.42262	0.00204	0.89	0.15197	0.00035	2272.4	2323.2	2368.2	4.0	4.8
15	Z eu tip [1]	--	--	0.52		12.6	2404	4.779	0.015	0.31684	0.00089	0.90	0.10940	0.00014	1774.3	1781.2	1789.4	2.3	1.0
16	Z eu tip [1]	--	--	0.22		2.5	8830	4.679	0.012	0.31098	0.00072	0.92	0.10912	0.00011	1745.5	1763.5	1784.8	1.8	2.5
	OT: Oternesset granite, Kattfjord Complex																		
17	Z eu-sb tips [1]	1	623	0.25		369	52.4	6.364	0.197	0.34725	0.00298	0.10	0.13292	0.00431	1921.4	2027.3	2137	56	11.6
18	Z eu-sb tips [12]	20	271	0.55		169	655	5.330	0.020	0.31916	0.00096	0.81	0.12111	0.00026	1785.6	1873.6	1972.7	3.9	10.9
19	Z rim-fr [1]	2	426	0.75		1.2	14039	4.648	0.045	0.31152	0.00303	0.99	0.10822	0.00011	1748.2	1758.0	1769.6	1.9	1.4
20	Z eu lp [1]	1	248	0.34		0.6	7362	4.488	0.015	0.30076	0.00088	0.93	0.10822	0.00014	1695.1	1728.7	1769.7	2.3	4.8
21	Z concave tip [1]	9	72	0.25		15.0	785	4.177	0.018	0.28392	0.00095	0.79	0.10669	0.00029	1611.1	1669.4	1743.6	4.9	8.6
22	T fr br	269	111	3.43	1.5		1304	4.637	0.013	0.31190	0.00074	0.88	0.10783	0.00015	1750.0	1756.0	1763.1	2.5	0.8
23	T lbr-cl rims [20]	110	19	1.51	1.8		149	3.223	0.037	0.23441	0.00072	0.10	0.09972	0.00115	1357.6	1462.7	1619	21	17.9
24	T fr lbr chl-in NA [6]	27	12	1.26	1.4		106	2.954	0.051	0.22413	0.00113	0.21	0.09559	0.00162	1303.6	1395.9	1540	32	16.9
25	T fr lbr-cl	196	13	1.25	1.6		108	2.624	0.048	0.20160	0.00083	0.12	0.09441	0.00172	1183.9	1307.5	1516	34	24.0
26	T fr cl-lbr	115	11	1.13	1.6		76.2	1.949	0.060	0.16525	0.00102	0.08	0.08554	0.00262	985.9	1098.1	1328	58	27.8
27	T fr cl NA [1]	15	11	1.06	1.2		84.3	1.969	0.051	0.16123	0.00105	0.26	0.08855	0.00221	963.6	1104.8	1395	47	33.2
	CAT-1: syntectonic granitoid dyke, Mjelde-Skorelvvatn Zone																		
28	z lp [1]	1	100	0.17		1.1	2638	12.000	0.045	0.47538	0.00174	0.94	0.18308	0.00024	2507.1	2604.4	2681.0	2.1	7.8
29	T fr br [50]	95	143	0.98	5.3		498	4.616	0.019	0.31078	0.00076	0.61	0.10772	0.00034	1744.5	1752.2	1761.3	5.8	1.1
30	T lenses lbr [29]	37	113	1.07	3.5		563	4.621	0.016	0.31265	0.00063	0.59	0.10719	0.00030	1753.7	1753.0	1752.2	5.0	-0.1
31	T fr br [35]	55	169	0.91	6.0		509	4.525	0.016	0.30799	0.00058	0.52	0.10655	0.00033	1730.8	1735.5	1741.2	5.6	0.7
32	T lenses lbr NA	164	127	1.04	5.3		437	4.451	0.018	0.30408	0.00054	0.42	0.10615	0.00038	1711.5	1721.8	1734.3	6.6	1.5
33	U or NA [4]	1	315655	0.00		350	3150	0.408	0.001	0.05540	0.00014	0.91	0.05337	0.00006	347.6	347.2	344.7	2.7	-0.9
34	U br-rd [7]	5	241135	0.00		1113	3447	0.368	0.006	0.05053	0.00080	0.99	0.05288	0.00013	317.8	318.5	323.7	5.7	1.9

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[1] Z = zircon; T = titanite; U = uranium-rich mineral; eu = euhedral; sb = subhedral; an = anhedral; lp = long-prismatic; sp = short-prismatic; eq = equant; in = inclusions of other minerals; fr = fragment; br = brown; lbr = pale brown; cl = colourless; or = orange; rd = red; chl-in = inclusions of chlorite; NA = not abraded (all the others abraded. Krogh (1982); square brackets indicate the number of grains for fractions of less than 50 grains.

[2] weight and concentrations of grains known to about +/- 10%. except for samples below 3µg where the uncertainty is about 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 (using Stacey and Kramers (1975) model); error calculated by propagating the main sources of uncertainty

[7] degree of discordance (in percent).

Ersfjord Granite. Sample **CAT-1** was collected from a fine-grained granitic dyke that intruded syn-kinematically with the lateral shearing event D2 (= D3 of Armitage 1999) along the Mjelde-Skorelvvatn Zone (Armitage 1999).

Analytical procedure

Zircon and titanite were analysed by ID-TIMS using a mixed ^{205}Pb/^{235}U spike at the Geological Museum in Oslo. Zircon was dissolved in teflon bombs in an oven at 184°C and titanite in Savillex vials on a hot-plate. Pb and U were extracted from zircon with anion exchange resin in HCl medium (Krogh 1973), and titanite also with anion exchange resin, but experimenting with different techniques and various combinations of HCl, HBr, and HNO_3 acids (Corfu & Andersen 2002). Zircon fractions smaller than 4 μg were measured without any chemical purification. Grains of a U-rich mineral in sample CAT-1 were dissolved in Savillex vials and separated with the same HCl procedure used for zircon. The measurements were carried out on a MAT262 mass spectrometer using multiple Faraday cups in static mode and/or by peak jumping using an ion-counting electron multiplier system. Further details of the procedure are summarized in Corfu & Evins (2002). Analytical uncertainties were calculated by propagating the main sources of error including terms of 1% on the ^{207}Pb/^{204}Pb and 2% on ^{206}Pb/^{204}Pb ratios of initial common Pb. Plotting and regression calculations were performed using the program of Ludwig (1999). Decay constants are those of Jaffey et al. (1971). Age uncertainties are reported at 2σ.

Zircon data for the coarse-grained, foliated granite (sample KV-2)

The four analyses carried out on zircon from this sample represent fractions of euhedral short prisms or of crystal tips. They provide data that are between 2 and 4% discordant and somewhat scattered (nos. 1-4, Fig. 4a; Table1). Because there is no good evidence for the presence of xenocrystic cores, the scatter is attributed to multiple Pb loss in the course of a complex geological history. Three of the analyses can be fitted to a line with an upper intercept of 2692 ± 3 Ma, whereas another set of two fits on a steeper line with an intercept at 2686 ± 3 Ma. By combining these two bounding ages and their uncertainties we obtain an age of 2689 ± 6 Ma for the crystallization of this body.

Zircon data for the Ersfjord Granite (samples EG-1 and C35)

Sample **EG-1** contained an abundant population of zircon but those recovered were dominantly of small grain size, a factor which had a negative influence on our attempts to extract concordant data. In addition, the population also contains traces of an inherited zircon component as reflected by analysis no. 5, which has a ^{207}Pb/^{206}Pb age of 1853 Ma (Fig. 4c), significantly older than the age of the rest of the population (Fig. 4b). Three fractions chosen to represent the dominant, core-free zircon types in this sample yield a tightly spaced group of analyses, approximately 4% discordant (6-8). Two less precise analyses, representing zircon domains (fragments of long and thin euhedral prisms and tips of such crystals) with a very low probability of having cores, overlap (9), or plot more discordantly (10) than this group. Because of the lack of internal spread, these five data points by themselves do not define a proper discordia line, but they all fit (MSWD = 1.5) on a line constrained to pass through a lower intercept of 400 ± 100 Ma, the time of Caledonian activity known to have affected this region, yielding an upper intercept age at about 1796 Ma.

To verify the validity of this projection, zircons were extracted from a second sample from the same outcrop **(C35)**. Two analyses of single, pink euhedral tips (15-16) are more concordant than those in **EG-1** and define a line projecting to 1792 ± 3 Ma. Inclusion of data points 6-10 into the regression yields a similar upper intercept age of 1792 ± 5 Ma. The lower precision reflects some scatter in the data (MSDW = 3.0) possibly due to complex Pb loss or residual amounts of inheritance in some of the fractions. A third analysis (14) on a square fragment of a zircon prism from sample **C35** shows that this was an inherited grain with a primary age of about 2550 Ma, as defined by the projection from 1792 Ma.

The zircon upper intercept age of 1792 ± 5 Ma is considered to date the magmatic crystallization of the Ersfjord granite. The age is older than the Rb-Sr whole-rock age of 1706 ± 30 Ma reported for the same body by Andresen (1979), and also somewhat older but within error of the age of 1779 ±17 Ma given by Romer et al. (1992). This relationship between U-Pb in zircon and Rb-Sr whole-rock data is not uncommon, and probably reflects disturbances of the Rb-Sr system by metamorphic overprints during the late stages of the Palaeoproterozoic events (see below) as well as during the Caledonian orogeny.

Zircon data for the Oterneset granite (sample OT)

The zircon population of this sample is very complex as it contains a major proportion of inherited material. This relationship is indicated by the presence of composite grains with cores and overgrowths, and was confirmed by two analyses (nos. 17 and 18), which yielded discordant data with pre-Svecofennian ^{207}Pb/^{206}Pb ages of 2140 and 1973 Ma (Fig. 4c). Three further analyses were carried out subsequently on specific zircon domains deemed to be free of inheritance. One single piece of a crystal rim (no. 19) yields a less than 2% - discordant analysis with a ^{207}Pb/^{206}Pb age of 1770 Ma whereas a single crystal tip, with a concave surface interpreted to represent the interface of the tip to a core, yields a discordant analysis (no. 21; Fig. 4b). These two data points define a discordia line with a Caledonian lower intercept age and an upper intercept age of 1774 ± 5 Ma, which is taken to indicate the time of magmatic crystallization of the

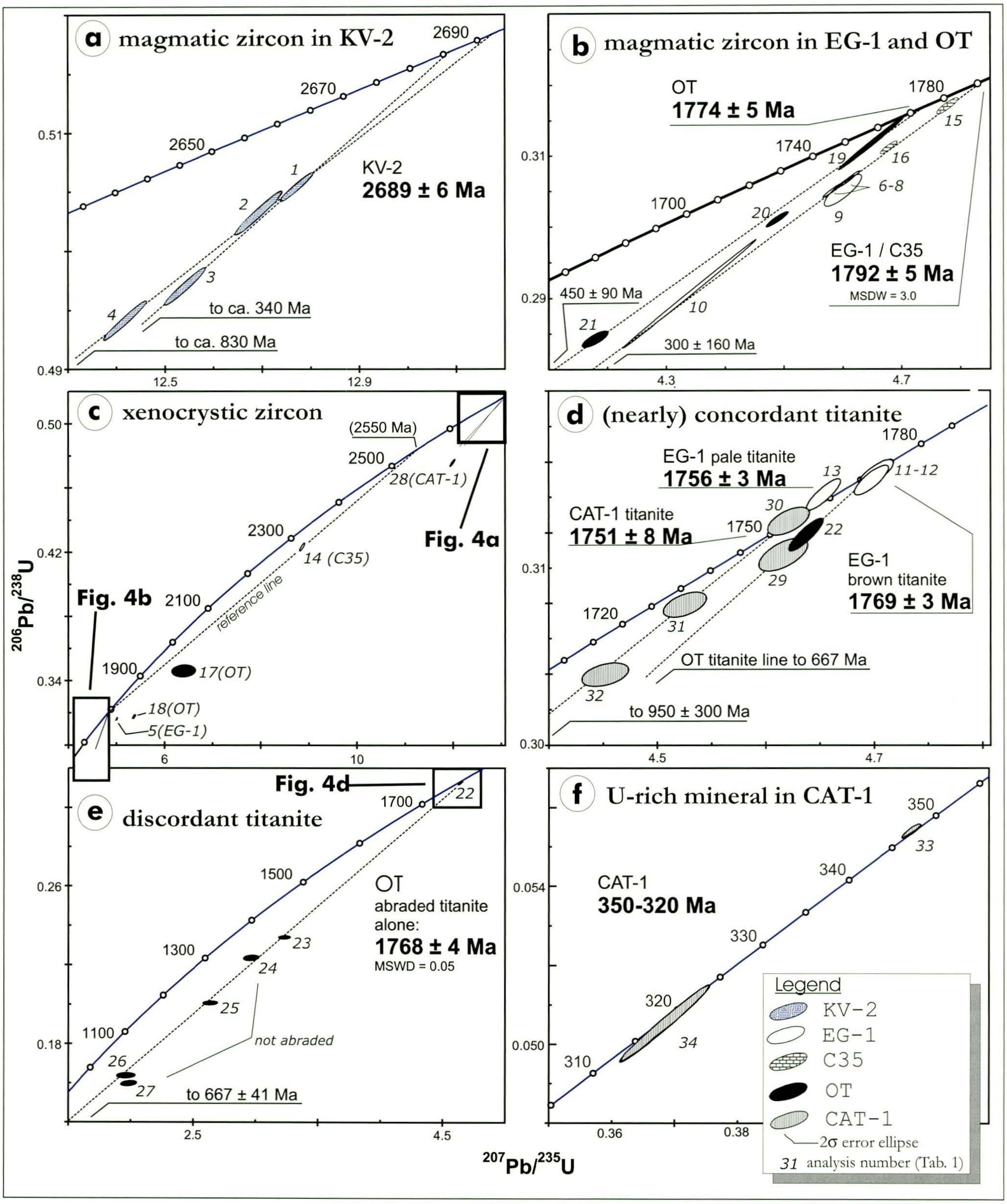

Fig. 4. Concordia diagrams showing the results for zircon, titanite and a U-rich mineral in the four samples investigated. The analytical data for figures (a) to (e) are discussed in the text.

granite. The third analysis of a single euhedral prism (no. 20) yields the same ^{207}Pb/^{206}Pb age as no. 19 but is more discordant and plots to the right of the discordia line through nos. 19 and 21. The position of this data point probably indicates that the grain contained a small inherited zircon core inside the prism.

Zircon data for the syn-tectonic D3 granitic dyke in the Mjelde-Skorelvvatn Zone (sample CAT-1)

Although very abundant, the zircon population of this sample consists almost entirely of highly metamict and altered, yellowish-grey, opaque prisms. Because these crystals would likely yield very discordant U-Pb data, no attempt was made to analyse them. In addition to this dominant zircon type there are also very subordinate amounts of clear transparent zircons, occurring as subrounded grains or as more or less euhedral prisms. The analyses of one of these prisms yields a discordant Archaean age (no. 28; Fig. 4c) strongly suggesting that all the clear zircons are probable xenocrysts inherited from the country rock. No meaningful magmatic crystallization age could therefore be extracted from this zircon population.

Titanite data

The U-Pb data for titanite from the Ersfjord (**EG-1**) and Oternesset granites (**OT**) and the Mjelde-Skorelvvatn Zone granitic dyke (**CAT-1**) reveal a complex multistage history (Fig. 4d,e).

The Ersfjord granite (**EG-1**) contains dark brown titanite that provides two overlapping concordant analyses with an age of 1769 ± 3 Ma (nos. 11-12; Fig. 4d), and a distinct type of light-brown titanite fragments and lenses, one analysis of which (no. 13) is concordant at an age of 1756 ± 3 Ma.

Titanite from sample **CAT-1** has a somewhat similar appearance as that in the Ersfjord granite, consisting of a mixture of brown and pale fragments and ovoid lenses. One of the analyses of brown titanite (no. 29) is 1% discordant and in the Concordia diagram it displays an affinity with the brown titanite in **EG-1**. By contrast, another selection of brown titanite fragments from this sample (31) has a younger ^{207}Pb/^{206}Pb age and fits on a line through two data points for cohabiting pale-brown titanite lenses, one concordant (no. 30, the abraded grains) and the other discordant (no. 32, the unabraded ones). A regression through the three analyses yields an upper intercept age of 1751 ± 8 Ma and a lower intercept age of c. 950 ± 300 Ma. The upper intercept is identical within error with the age of the palebrown titanite lenses in sample **EG-1**, suggesting that they both represent a coeval generation grown during a secondary event. The distinction in age between the two brown titanite generations in sample **CAT-1** is somewhat puzzling because the two selections were made using roughly the same criteria, though at different times.

The Oterneset (**OT**) titanite population provides a different type of data pattern. In terms of morphology and colour, the population resembles very much that in the other two samples as it comprises deeply coloured brown grains together with a very pale-brown to colourless titanite variety. One analysis of brown titanite (no. 22, Fig. 4d) is less than 1% discordant, indicating an age similar to that of the older brown generation in samples **EG-1** and **CAT-1**. By contrast, the pale-brown varieties exhibit a much higher degree of discordance between 17 and 33% (Fig. 4e). The abraded fractions (nos. 23, 25, 26) are colinear with the nearly concordant analysis yielding an upper intercept age of 1768 ± 4 Ma and a lower intercept age of 667 ± 41 Ma. The two unabraded titanite fractions (nos. 24 and 27) deviate, respectively, to the left and to the right from this line.

The high degree of discordance of the pale titanite in the Oterneset (**OT**) sample is due either to mixing between two distinct growth phases or to some secondary process that reworked the original titanite causing Pb loss. Some of the analyses were carried out specifically to evaluate this question. Fraction no. 23, which represents pale-brown rims separated from brown titanite interiors, provides the least discordant data point of the group (Fig. 4e), thus indicating that the rims do not represent a newly grown phase. A second attempt (no. 24) was made using colourless titanite fragments that had inclusions of chlorite, assuming that the chlorite may represent new growth during a low-grade overprint. The result of this test, however, leads to the same conclusion as for the clear rims. The third test was carried out on a single colourless fragment (no. 27), to evaluate whether the multigrain fractions may represent mixtures of old and young pale titanite. Although this single grain yields the most discordant analysis, its position is not much different from that of the multigrain fraction of similar fragments (no. 26). Hence, one must conclude that the discordance is most likely the result of some recrystallization process that affected the titanite rather than of new growth. This recrystallization process was accompanied by considerable Pb loss and probably also by loss of U and especially of Th, because the U concentration was reduced to the 10-20 ppm level from over 100 ppm in brown titanite, and Th/U decreased from 3.4 to values of 1.5-1.0.

An interesting aspect of these **OT** data concerns the 667 ± 41 Ma lower intercept age defined by the titanite line (Fig. 4e). Is this Neoproterozoic age geologically significant or just an artefact of complex Pb loss? A related question is whether we might be biasing the age by using only the data points for abraded fractions to calculate the line shown in Fig. 4e. Because analysis no. 27 deviates significantly to the right of the line, a different regression using all the pale titanite data (but not no. 22) decreases the value of the lower intercept age to 580 ± 230 Ma, but this line has a low probability of fit (MSWD = 4.6) leading to a highly inflated error on the age. On the other hand, a regression of analyses 23-26 alone, leaving out the analysis of the single unabraded fragment no. 27, has an MSWD = 2.7 and yields intercepts that are less precise but indistinguishable from those shown in

Fig. 4e. Hence, the majority of the titanite results for this sample seem to be pulling consistently towards the 667 ± 41 Ma lower-intercept age. The exception is analysis 27, but this may simply reflect the presence of titanite domains affected by younger disturbances. Thus, the possibility appears to exist that this region was affected by a Neoproterozoic tectonometamorphic event.

U-rich mineral in syn-tectonic granitic dyke (CAT-1)

In addition to zircon and titanite, sample **CAT-1** also contains brown to orange and red, paramagnetic fragments of an unidentified heavy mineral. Two fractions (nos. 33 and 34; Fig. 4f) have U contents of 20 to 30% and provide nearly concordant Carboniferous ages; the unabraded grains yield a slightly reversely discordant age of about 347 Ma, whereas the abraded grains are younger at about 318 Ma (Fig. 4e). The difference in age between the two analyses means that there are systematic complications that need to be resolved by more detailed work before these ages can be properly interpreted. Keeping this in mind, however, the data can be taken as an indication that the Mjelde-Skorelvvatn Zone was probably faulted during one or a sequence of Carboniferous events leading to the deposition of such high-U minerals. Hydrothermal activity may have been related to the development of brittle faults that cut across the Precambrian grain of the Mjelde-Skorelvvatn Zone and are common near the **CAT-1** sample site (Armitage 1999).

Geological implications

The new results, in general, support the present geological understanding of the region and constrain the timing of major tectonomagmatic events. The data (i) confirm the presence of Archaean basement, (ii) document the occurrence of 1800-1790 Ma intrusive units correlative with extensive late-orogenic (late-Svecofennian) suites present throughout the region, and (iii) pick up a well defined late-tectonic overprint at 1770-1750 Ma, reflecting the late Svecokarelian tectonothermal activity that has affected a vast region of the Baltic Shield from the Atlantic coast in the west to the Belomorian belt in the east (e.g., Gaal & Gorbatchev 1987). There are also some indications concerning the timing of Neoproterozoic and Palaeozoic events, but in this respect the data are not yet clearly defined and remain rather speculative. Below, we discuss our results and their possible relationship to these events in chronological order.

Archaean

The presence of Archaean crust in the WTBC has been previously documented by Zwaan & Tucker (1996) and Motuza et al. (2001a) on Ringvassøya, an observation confirmed by the 2.4 Ga age of a mafic dyke swarm in the same area (Kullerud et al. in prep). The present work documents a further Archaean age for a coarse-grained granite at the southwestern tip of Kvaløy. This granite is now part of a mega-lens surrounded by highly deformed metasupracrustal and mylonitic rocks within the Palaeoproterozoic Senja Shear Belt (Zwaan 1995, Pedersen 1997). We interpret the granite as a remnant of a formerly more extensive Archaean basement suite in the region.

Indirect indications for the presence of old crust are also given by the abundance of Archaean zircons as inherited xenocrystic grains in other units.

Outside the WTBC, the presence of Archaean crust is well known in the Vesterålen area to the south (Heier & Compston 1969, Taylor 1974, Jacobsen & Wasserburg 1978, Corfu, unpublished data) where it appears to taper out (Skår 2002). These Archaean crustal remnants correlate with the southern parts of the Archaean craton exposed in the Baltic Shield east of the Caledonides (Romer et al. 1992, Gaal & Gorbatchev 1987).

Palaeoproterozoic: 1800-1790 Ma magmatism

The age of 1792 ± 5 Ma for the Ersfjord granite places this intrusion in the context of an intensive and very widespread magmatic episode that is recorded across the Baltic Shield. One example is the anorthosite-mangerite-charnockite-granite (AMCG) suite in the Lofoten - Vesterålen region (Griffin et al. 1978). These rocks were probably derived by melting of underthrusted mafic and felsic lower crust, and the melts were subsequently processed through complex fractionation and contamination processes prior to their emplacement in the middle crust (Markl 2001, Corfu in press). In many other parts of the Baltic Shield the 1800-1790 Ma magmatic suite includes abundant granitic rocks of predominantly crustal derivation (e.g., Öhlander & Skjöld 1994, Åhäll & Larson 2000, Skår 2002, Weihed et al. 2002) but there is also a suite with shoshonitic affinity interpreted to have been produced by melting of subcontinental lithospheric mantle (Eklund et al. 1998). These events also correlate with late-Svecokarelian deformation along major NW-SE to N-S-trending crustal-scale shear systems (Högdahl et al. 2001, Weihed et al. 2002). Elsewhere in the Shield the intense flare-up of magmatic activity and deformation has been discussed in terms of a shift from N-NE to E-SE in the direction of plate convergence (Romer et al. 1992, Åhäll & Larson 2000, Weihed et al. 2002, Corfu in press). The Senja Shear Belt records a polyphase tectonothermal evolution including a main early phase of E-W oblique crustal contraction and possibly accretionary tectonics (D1) followed by a superimposed phase of strike-slip translation (D2; Zwaan & Bergh 1994, Nyheim et al. 1994, Pedersen 1997). Pedersen (1997) related the development of some of these structures along the Astridal Shear Zone on Senja (Figs. 2 & 3) to oblique convergence and contraction. By analogy with the large-scale regional relationships, especially the evidence for E-W contraction (e.g., Weihed et al. 2002), it could be speculated that the D1 deformation was related to the 1800-1790 Ma event and to the emplacement of the main mass of the Ersfjord

Granite. No D1 structures have been observed in the granite, however, and thus the latter would have been, at best, very late-kinematic with respect to D1.

Palaeoproterozoic: 1775 -1750 Ma magmatism, metamorphism and deformation

Our study provides evidence for at least two episodes that caused new growth and/or resetting of titanite in the Ersfjord Granite some 30 to 50 m.y. after its intrusion. The first of these episodes corresponds to the intrusion (dated by zircon and titanite) of the granitic dyke (**OT**) in the Kattfjord Complex at 1774 ± 5 Ma. This event is also indicated by the 1769 ± 3 Ma age of brown titanite in sample **EG-1** and by titanite in the syn-tectonic granite dyke of the Mjelde-Skorelvvatn Zone (**CAT-1**). Thus, this 1770 Ma episode is marked by magmatism that formed the Oterneset Granite and also by metamorphism that reset or formed titanite in the Ersfjord Granite. Because it was not possible to date magmatic zircon in sample **CAT-1**, it remains uncertain whether the 1768 Ma age of the oldest titanite generation in this sample represents the actual time of emplacement (as for **OT**) or just a superimposed event as observed in **EG-1**. The titanite age provides, in any case, a lower limit for the time of intrusion of the dyke.

A younger generation of titanite is present in both the Ersfjord Granite and the syn-tectonic dyke in the Mjelde-Skorelvvatn Zone where they yield overlapping ages of 1756 ± 3 Ma and 1751 ± 8 Ma, respectively. This generation consists predominantly of pale-brown to colourless titanite that can be differentiated relatively easily from the older brown varieties. This is a very common situation (e.g., Corfu & Stone 1998), whereby the secondary titanite generation grows locally during retrogressive events from Ti liberated during breakdown of Ti-bearing phases such as biotite or ilmenomagnetite. Normally, one also observes a distinct decrease in U and Th/U between the first and the second generation, but this is not the case for the **EG-1** and **CAT-1** titanites (Table 1). It is, nevertheless, assumed that the second generation of titanite records growth during some late-metamorphic and possibly deformational overprint.

The magmatic and metamorphic events in the period between 1775 and 1750 Ma probably represented the natural continuation and gradual declining in intensity of the principal 1800-1790 Ma magmatic episode, remaining active nonetheless across the Shield (e.g., Romer & Smeds 1997, Åhäll & Larson 2000, Bibikova et al. 2001, Högdahl et al. 2001, Rehnström 2003). The NNW-SSE-striking Senja Shear Belt and related high-strain zones of the WTBC (Fig. 2) represent structures of shield-wide proportions linking up with the Svecokarelian deformation zones (e.g., Baltic-Bothnian megashear) on the Baltic Shield to the east (Fig. 1; Berthelsen & Marker 1986, Gaal & Gorbatchev 1987, Henkel 1991, Olesen et al. 1997). It is, thus, likely that the timing of the late movements recorded in the WTBC also applies to the structure as a whole. The D2 event is well verified structurally in sheared rocks of the Torsnes, Astridal and Mjelde-Skorelvvatn Shear Zones. The age of the late-kinematic granitic dyke represented by sample **OT** indicates that regional deformation was still active by 1774 ± 5 Ma. The **CAT-1** granitic dyke in the Mjelde-Skorelvvatn Zone is clearly syn-tectonic with respect to the D3 deformation event of Armitage (1999), equivalent to the D2 event of Pedersen (1997), thus constraining its timing at or before 1768 Ma, the age of titanite. Because we have been unable to date zircon, the age of intrusion could be older than that of the titanite.

Neoproterozoic to Palaeozoic resetting of titanite

The titanite results in sample **OT**, and more weakly those in sample **CAT-1**, are suggestive of a Neoproterozoic disturbance. As argued above, the available evidence favours partial resetting by some mechanism of recrystallization or perhaps leaching rather than new growth. Because we did not succeed in finding titanite that would be entirely reset, the significance of the 667 ± 41 Ma lower intercept age remains somewhat enigmatic, and therefore it is not yet possible to affix a definite interpretation to that age. There could be some causal link with the apparent Sveconorwegian, Ar-Ar hornblende ages reported by Dallmeyer (1992) from Kvaløya and Senja, but because of the unsystematic nature of the Neoproterozoic dates in this region, it is difficult to reach a conclusive interpretation concerning their significance. A much better constrained late-Neoproterozoic titanite age (637 Ma) has been found in a granitic gneiss of the Skárjá nappe in the Seve Nappe Complex farther east (Rehnström et al. 2002), but there the titanite actually records a phase of crystallization during deformation of the host rock. The pre-tectonic provenance of the unit remains speculative.

The present data set allows us to concur with the conclusion of Dallmeyer (1992) concerning the weakness of the thermal overprint that affected the WTBC during the Caledonian orogeny. This is evidenced mainly by the absence or only limited amount of U-Pb discordance observed for most of the titanites. On average, the degree of titanite discordance is considerably lower than that seen, for example, in Lofoten-Vesterålen farther to the south (Corfu, in press, and unpublished data), and clearly much less than that reported by Skår (2002) in the basement windows in Nordland.

The apparent Carboniferous ages provided by the unidentified U-rich minerals in sample **CAT-1** may reflect brittle faulting in the Mjelde-Skorelvvatn Zone causing fluid circulation and deposition of U-rich minerals. This can likely be linked to the numerous brittle faults that overprinted the shear zone in the vicinity of the CAT-1 intrusion (Armitage 1999). Palaeomagnetic studies of other brittle fault systems in the WTBC and Lofoten-Vesterålen have indicated at least two components of faulting in the Permian and Tertiary that are related to specific stages of the opening of the North Atlantic (Olesen et al. 1997). The present data may be recording an earlier phase in this evolution.

Conclusions

The new U-Pb results from the WTBC lead to the following conclusions:

(1) Archaean granite (2689 ± 6 Ma) is present in the southwestern part of Kvaløya forming megablocks floating within sheared rocks of the Senja Shear Belt.

(2) The Ersfjord Granite yields a zircon age of 1792 ± 5 Ma, showing that it was correlative with the extensive and compositionally diverse plutonic suites that were emplaced across the Baltic Shield in a major event at 1800-1790 Ma. Although not directly constrained by our data and lacking evidence of D1 deformation, it is possible that this event coincided broadly with the first E-W contractional phase (D1) recorded in the regional shear systems, by analogy with the relationships seen elsewhere in the Baltic Shield (e.g., Weihed et al. 2002).

(3) A younger, late-synkinematic granitic dyke cutting the Kattfjord Complex was emplaced at 1774 ± 5 Ma. A second, late-kinematic syn-D2 dyke in the Mjelde-Skorelvvatn Zone could not be dated by zircon, but the titanite indicates an age of 1768 ± 4 Ma, which is thus a minimum age for D2 deformation, caused by SE-directed strike-slip translation in the large regional shear zones.

(4) The Ersfjord Granite and the granitic dyke from the Mjelde-Skorelvvatn Zone both contain two titanite generations, an early one formed at around 1769 Ma and a younger one formed at around 1755 Ma. Titanite in the Kattfjord Complex dyke yields an age of 1768 ± 4 Ma, but also evidence for a very strong Neoproterozoic disturbance, possibly indicative of a regional event at that time.

(5) The granitic dyke cutting the Mjelde-Skorelvvatn Zone contains traces of a very U-rich mineral, which yields Carboniferous ages, probably indicating crystallization from hydrothermal fluids during brittle faulting of the shear zones. By contrast, none of the mineral systems were substantially affected by the Caledonian event, confirming the results of previous studies in the region.

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