

Emplacement ages and metamorphic overprinting of granitoids in the Sveconorwegian Province in Värmland, Sweden – an ion probe study

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North of Lake Vänern in the Sveconorwegian province of Sweden, veined and banded grey to red granitoids characterize the Western Segment in western Värmland. Two gneiss samples from Rackstad, north of Arvika, yielded concordant U-Pb emplacement ages of 1596 ± 11 Ma and 1590 ± 14 Ma, respectively from zircon cores, while metamorphic zircon rims in one of the samples gave a weighted mean Pb-Pb age of 971 ± 8 Ma. Patches of metamorphic zircon overgrowth pre-dating the metamorphic rims indicate that an even older metamorphic event influenced this rock. East of the Mylonite Zone, a N-S-trending Sveconorwegian shear zone, more massive reddish granitoids occupy the segment between this zone and another N-S-trending Sveconorwegian shear zone, the Protogine Zone. A sample from Hänsjön, north of Torsby, yielded concordant ages with a weighted mean of 1689 ± 12 Ma. One grain has a Pb-Pb age of 1770 ± 29 Ma, which is inherited from the source of the granite, and is similar to the age of early magmatism in the Transscandinavian Igneous Belt, east of the Torsby Segment. These results confirm that north of Lake Vänern, the Torsby Segment was formed ca. 100 Ma earlier than the adjoining segment to the west, in accordance with previous results from further south.

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Introduction

Southwestern Sweden is underlain mainly by metamorphosed mid-Proterozoic granitoids of the ca. 1.0 Ga Sveconorwegian Province, which is bounded to the east by granite plutons of the 1.66–1.85 Ga Transscandinavian Igneous Belt. The Sveconorwegian Province is further divided into three segments, from east to west: the Borås (previously southern part of Eastern Segment), Torsby (northern Eastern Segment) and Western (Median and Western Segment), as shown in Fig. 1. They each have some unifying lithostratigraphic and structural features, and are bounded by shear zones which reflect major Sveconorwegian displacements, but may have longer histories, as described by Berglund (1997) and references therein.

In this work we report new ion probe U-Pb dates on the granitoids of the Western and Torsby Segments in Värmland, on structural grounds considered to be the oldest rocks in these regions. In the Western Segment, structural studies indicate a pre-Sveconorwegian and Sveconorwegian tectonothermal history, while in the Torsby Segment only Sveconorwegian overprinting is verified (e.g. Larson et al. 1998). Thus, we expected to identify two types of metamorphic zircon in the Western Segment and one in the Torsby Segment.

The Sveconorwegian Province and the Mylonite Zone

The Torsby Segment (Fig. 1a) comprises several varieties of predominantly alkali-calcic and calc-alkaline granitoid with ages between 1.70 and 1.65 Ga (Persson et al. 1995 and references therein; Connolly et al. 1996; Heim et al. 1996). Mansfeld (1998) recently reported even older ages of 1.74 Ga from Norway. The Torsby Segment and Borås Segment have only subordinate supracrustal rocks, as described by Lundegårdh (1977, 1980, 1995) and Samuelsson et al. (1988).

Torsby Segment rocks pass into the less deformed part of the Transscandinavian Igneous Belt across the Protogine Zone (e.g. Larson et al. 1990), a Sveconorwegian shear zone which in its southern part coincides with both the pre-Sveconorwegian and Sveconorwegian deformation fronts (Berglund 1997). Gorbatshev (1980) drew its northern extension (Fig. 1a) along the Klarälven River valley in eastern Värmland. The Protogine Zone here separates the slightly deformed 1.78 Ga Transscandinavian Igneous Belt Filipstad Granite from the Munkfors gneissic granite (Jarl & Johansson 1988) with indistinguishable age (Welin & Kähr 1980). In this region the Torsby Segment clearly represents part of the Transscandinavian Igneous Belt reworked by ductile Sveconorwegian deformation (e.g. Stephens et al. 1994;

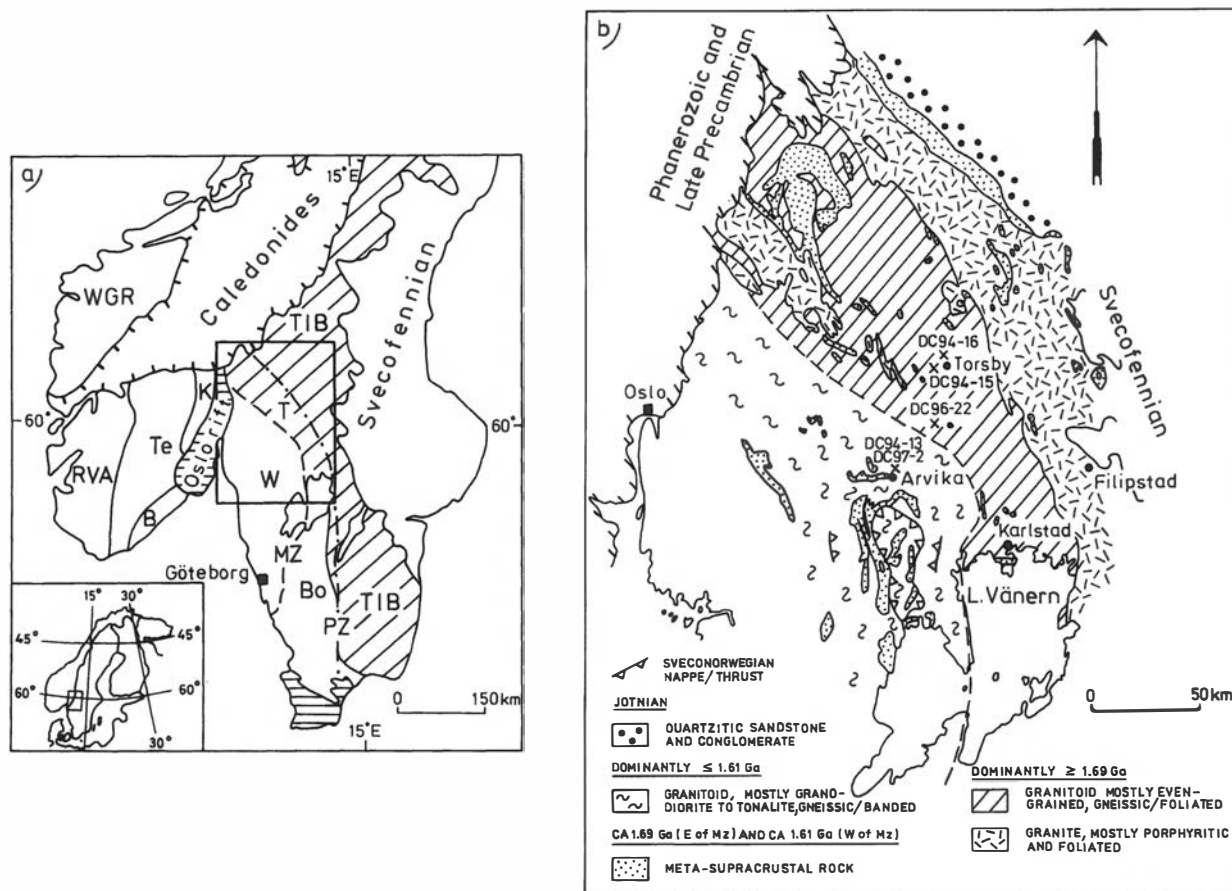


Fig. 1. (a) Geological provinces of the southern Baltic Shield. TIB – Transscandinavian Igneous Belt, WGR – Western Gneiss Region, RVA – Rogaland-Vest Agder, Te – Telemark, K – Kongsberg, B – Bamble, T – Torsby, W – Western Segment, Bo – Borås, MZ – Mylonite Zone, PZ – Protogine Zone, horizontal lines – Phanerozoic. (b) Northern part of the Sveconorwegian Province in Sweden and eastern Norway (see Fig. 1a). X – sampling sites for dated rocks.

Larson 1996). The position of the deformation front, shown in Fig. 1a (PZ), is well defined in areas where the aeromagnetic map of the Geological Survey of Sweden is available (cf. Henkel 1992). Wahlgren et al. (1994) termed it the 'Sveconorwegian Deformational Front' and placed it further to the east, claiming that this is 'the limit of crustal reworking during the Sveconorwegian' (cf. also Stephens et al. 1994). However, we prefer to regard the eastern limit of the Sveconorwegian penetrative, ductile deformation as the mappable and geophysically obvious structural boundary, and thus we denote the area between the Mylonite Zone and this boundary the Torsby Segment. The Torsby Segment may continue beneath the Caledonides into western Norway (Tucker et al. 1990), where it constitutes the northeastern part of the Western Gneiss Region.

In the Borås Segment, most rocks are suggested to have been deformed and metamorphosed during the Gothian (e.g. Connelly et al. 1996; 1.75–1.55 Ga ago according to Gaál & Gorbatshev 1987), but now generally have ca. 0.97 Ga Sveconorwegian amphibolite facies parageneses (Cornell et al. 1995), grading into granulite facies to the south, as described by Johansson et al. (1991). Borås Segment gneisses are generally veined and banded, while in the Torsby Segment to the north, the degree of

deformation and migmatization is usually lower (Larson et al. 1998).

The Western Segment differs in some major respects from the Torsby Segment. Most of the plutonic rocks are calc-alkaline and the major rock components are younger, having originated between 1.64 and 1.58 Ga (e.g. Åhäll et al. 1995; Persson et al. 1995 and references therein). The western parts also have major supracrustal components of graywacke and mafic lava, as described by Connelly & Åhäll (1996) and references therein.

The Mylonite Zone, which separates Torsby and Borås Segments from the Western Segment, varies from a shallow west-dipping branched Sveconorwegian shear zone in the south to a more steeply dipping mylonite zone to the north (MZ in Fig. 1). According to Stephens et al. (1993, 1996), the northern part of the Mylonite Zone was formed in a sinistral, transpressive tectonic regime. It was reactivated in a late Sveconorwegian extensional tectonic regime (e.g. Berglund 1997 and references therein). Thus, the Torsby and Borås Segments represent a deeper crustal level, having been uplifted relative to the Western Segment and parts of the Transscandinavian Igneous Belt late in the Sveconorwegian tectonic cycle (e.g. Welin & Blomqvist 1966; Andreasson & Rhode 1990; Jarl 1992; Johansson 1992). In northern and central Värmland, there is a marked contrast across the Mylonite

Zone between banded, veined and refolded rocks in the Western Segment and those in the Torsby Segment, which usually show less deformation.

Geochronology and deformation in Värmland

The N–S regional fabric in Värmland is deflected along the northern shore of Lake Vänern into the E–W trending Sveconorwegian Hammarö Shear Zone, as described by Berglund et al. (1997). In this area, Persson et al. (1995) dated the origin of the Forshaga monzonitic granitoid at 1674 ± 24 – 19 Ma (all uncertainties in this paper are 2σ) using U–Pb on zircon, and gave ages between 1688 and 1646 Ma for the Zakrisdal granitoid at Karlstad (Fig. 1b). They also obtained a 1612 ± 48 Ma Rb–Sr whole rock isochron for similar granitoids further north. In the central part of the Torsby Segment, Söderlund et al. (1996) reported a U–Pb zircon age of 1674 ± 7 Ma and two generations of titanite, one similar in age to the zircon and the other with a concordant age of ca. 960 Ma. Further north, in Norway, Heim et al. (1996) dated zircons from the massive Tricolor Granite at 1673 ± 8 Ma which post-dates foliated Trysil granitoids in this area. An even older date of 1737 ± 9 Ma was recently reported from the same area by Mansfeld (1998) for the Mo tonalite.

Ar–Ar dating by Page et al. (1996) clearly demonstrates a Sveconorwegian metamorphic overprint in eastern Värmland, with cooling ages of 960–1009 Ma for hornblende and 905–999 Ma for muscovite. These intervals overlap the 960 Ma age of metamorphic titanites recorded by Söderlund et al. (1996).

In the Western Segment in Värmland, 1.62–1.5 Ga U–Pb zircon ages were recorded by Persson (1986), which in most cases were considered to be intrusion ages. Close to Arvika (Fig. 1b), rehomogenization of the Rb–Sr systems at 1071 ± 33 Ma was succeeded by a slow cooling or thermal pulse at 970 ± 16 Ma (Persson 1986).

Analytical procedure

In this work the SHRIMP and NORDSIM ion probes were used to date both igneous and metamorphic episodes using zircon separated from gneisses. Cathodoluminescence (CL) images were used to interpret the zonation and growth history of the grains, and the high spatial resolution of the ion probes was used to date parts of the grains clearly seen to have an igneous or metamorphic origin.

Ion probe analyses were made as described by Williams & Claesson (1987) (SHRIMP) and Whitehouse et al. (1997) (NORDSIM). Regressions and weighted means were calculated using the program GEODATE, described by Harmer & Eglington (1994), and age uncertainties are given at the 95% (2σ) confidence level.

Petrography was done on polished thin sections. Microanalyses and point counting were done using a LINK Oxford energy dispersive spectrometer with a Ge

detector, mounted in a Zeiss DSM 940 scanning electron microscope at the Department of Earth Sciences, Göteborg University.

Samples

Western Segment

The Western Segment samples, DC94-13 and DC97-2, were collected in grey and red gneisses, respectively, close to the northern tip of Lake Racken, about 15 km southwest of the Mylonite Zone (Fig. 1b). DC94-13 is a foliated quartz monzodiorite. It is highly metamorphosed, showing isoclinal folding of hornblende-bearing leucocratic veins. DC97-2 is a foliated syeno-granite, dominated by K-feldspar and quartz-K-feldspar neosomes. On the bedrock map of Lundegårdh et al. (1992), these gneisses are seen to underlie large areas of the Western Segment.

Unpublished P–T data (DC) hint at temperatures of ca. $750 \pm 25^\circ\text{C}$ and pressures of ca. 6.6 ± 0.8 Kb for the gray gneiss DC94-13. In view of the high temperature at which these rocks were metamorphosed the formation of melts seems possible. We consider the metamorphic mineral parageneses to be Sveconorwegian, in accordance with Persson (1986), who dated metamorphic titanite and biotite as well as the rehomogenization of the Rb–Sr system between 1.1 and 0.97 Ga in a tonalitic rock close to the site of the Racken gneisses. In the Western Segment the Sveconorwegian event overprinted earlier metamorphism characterized by veins and isoclinal folds, as described by Larson et al. (1998).

Torsby Segment

Two Torsby Segment granite samples were taken in the Torsby Granite near Torsby (Fig. 1b). This granite usually shows a distinct E–W-trending lineation, but is not so strongly deformed and metamorphosed as the Racken samples, although the regional geological map (Lundegårdh et al. 1992) shows migmatization in parts of the Torsby Granite. DC94-15 is a pink to grey (brown) biotite granite with albitic plagioclase, K-feldspar and accessory igneous aegirine. The aegirine grains are veined by chlorite and an unidentified rare earth mineral. The modal composition shows that the rock is alkali feldspar granite.

The other Torsby Granite sample (DC94-16), collected in a road cut just north of Torsby, is petrographically similar. In this sample the aegirine has largely been replaced by hornblende, green biotite, epidote and chlorite, yielding composite grains. The green low-Ti biotite in particular seems unlikely to be igneous in origin. Igneous biotite (such as occurs in DC94-16) is usually brown because it concentrates Ti from the magma. However, this green biotite grew from Ti-poor aegirine during metamorphic recrystallization, while Ti was concentrated in titanite and rare ilmenite.

In order to distinguish between potentially Gothian and

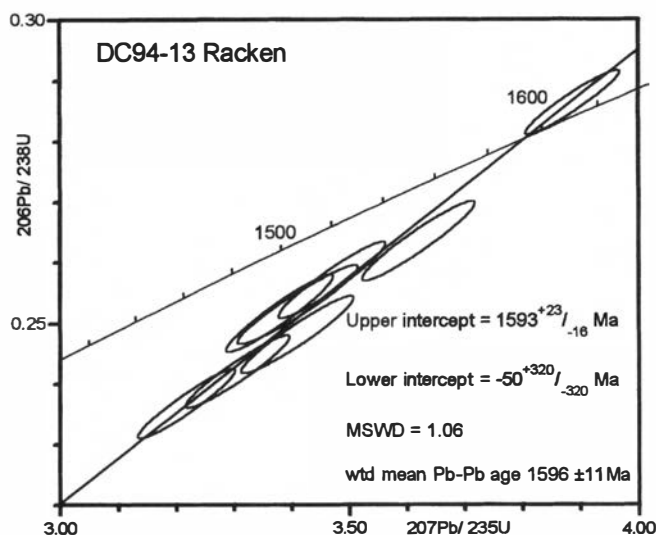


Fig. 2. SHRIMP data from DC94-13 (gray Racken).

Sveconorwegian metamorphic conditions, sample DC96-22 of metagabbro (so-called 'hyperite') was also investigated (Fig. 1b). Since zircons from this rock type have been dated by the U-Pb method at 1.47 Ga by Welin (1994) and a similar rock at 1.57 Ga by Wahlgren *et al.* (1996), the metamorphism could only be post-Gothian, while older rocks could have been affected by the Gothian. The metagabbro frequently shows metamorphic hornblende and garnet. This suggests high-grade conditions (which is strengthened by unpublished P-T data using garnet-biotite thermometry and garnet-plagioclase-hornblende thermobarometry yielding temperatures and pressures of ca. $680 \pm 20^\circ\text{C}$ and ca. 7.3 ± 0.5 Kb, respectively, and which are similar to estimated P-T conditions obtained in the Torsby granitoids). This shows that the upper amphibolite facies conditions, at least those recorded in the Torsby Segment, are related to the Sveconorwegian event.

Ion probe results

Western Segment – SHRIMP results

The Western Segment samples from Racken contain mainly simple, clear zircons with well-developed (001) prism faces and one or two pyramids, conforming to the R5 and D types of Pupin (1980). These are interpreted as high-temperature igneous zircons, which crystallized from a water-poor magma.

In the gray Racken sample DC94-13, only the cores of zircons showing igneous oscillatory zonation in CL images were dated (Table 1). Thin CL-bright rims, which might be metamorphic, were too thin to be properly targeted. As shown in Fig. 2, the spots analysed by the SHRIMP (DC94-13) are 7–14% discordant, with an imprecise lower intercept of -50 ± 320 Ma. Constraining the lower intercept through zero, the upper intercept is $1596 + 23/-16$ Ma (MSWD = 1.06). Since the data conforms to the 'recent' lead loss model, the more precise weighted mean

Pb-Pb age of 1596 ± 11 Ma can be used. The data set shows no sign of Sveconorwegian lead loss from the zircon cores. Constraining the lower discordia intercept through 1000 Ma increases MSWD to 2.5, so a Sveconorwegian lead loss model is not supported. This rock thus originated at 1596 ± 11 Ma.

Western Segment – NORDSIM results

In the red Racken sample DC97-2, 10–50 μm metamorphic rims, usually CL-bright, but sometimes dark, overgrow cores with typical igneous oscillatory zonation. In some grains, irregular patches of CL-bright zircon are seen to cut across the zonation, reflecting metamorphic reworking along fractures or in metamict zones within the zircons (Fig. 3). The NORDSIM analyses (DC97-2) on cores showing oscillatory igneous zonation (ig in Table 2) are too concordant to regress meaningfully (Fig. 4a). Their weighted mean Pb-Pb age is 1590 ± 14 Ma (MSWD = 1.3). Together with three CL-dark spots in metamict grains (dm in Table 2) they regress to 1585 ± 10 Ma and a lower intercept of 275 ± 11 Ma (MSWD = 1.5). The concordant igneous grains show a trend of constant Th/U around 0.6, which is typical for igneous zircon (Cornell *et al.* 1998), but which decreases in the discordant (7a, 16a and 21c) spots (Fig. 5). These results reflect the magmatic crystallization of the rock at 1590 ± 14 Ma and lead loss from metamict igneous zircon when the region was buried beneath Upper Palaeozoic molasse sediments that were subsequently exhumed (Tullborg *et al.* 1995).

CL-dark metamorphic zircon. – Six spots (in grains 15, 21 and 41) were sited in CL-dark, metamorphic rims (dr) and one (19a) in an overgrowth (do). Four spots in a single grain (21) have distinctly lower U and very low Th levels compared with the other three spots of this type (Fig. 5), although all have the low Th/U characteristics of metamorphic zircon (Cornell *et al.* 1998). The data from grain 21 show a small spread of Pb-Pb ages, with a weighted mean age of 1042 ± 36 Ma (MSWD = 3.2), regressing to a line with intercept $1043 + 25/-16$ Ma and -336 ± 293 Ma (MSWD = 2.7). However, if constrained through the origin or 275 Ma, the MSWD increases to 6.2 and 16.8, respectively, showing that this line does not strictly confirm to a simple lead loss model. The three other spots (15a, 19a and 41a) regress to a line of significantly lower age (Fig. 4b) with intercepts at 971 ± 8 (weighted mean Pb-Pb age 970 ± 19 Ma) and 29 ± 100 Ma (MSWD = 1.7), conforming to the recent lead loss model. Constraining through 275 Ma increases MSWD to 25.2, but hardly changes the upper intercept to $979 + 33/-26$, showing that these metamorphic spots did not experience the same lead loss history as the igneous and metamict grains. Their younger age seems to have rendered their crystal structure less susceptible to lead loss at 275 Ma. The 971 Ma age is thought to reflect the growth of new zircon in this sample during Sveconorwegian metamorphism.

Table 1. SHRIMP analyses of zircons from samples DC94-13 and DC94-16.

Sample/spot #	U ppm	Th ppm	Th/U meas.	Pb ppm	204Pb 206Pb	206Pb 238U	±	207Pb 235U	±	207Pb 206Pb	Ages Ma			Concordance (%)	
											206/238	207/235	207/206		±
DC94-13															
D2B	207	234	1.13	61	0.000133	0.2421	0.0061	3.305	0.092	0.0990	1398	1482	1605	16	87
E4.1	374	159	0.43	101	0.000199	0.2572	0.0064	3.469	0.095	0.0978	1476	1520	1583	16	93
F4.1	145	92	0.64	40	0.000242	0.2517	0.0065	3.378	0.095	0.0973	1447	1499	1573	16	92
F3.A	261	166	0.64	68	0.000260	0.2368	0.0059	3.217	0.086	0.0986	1370	1461	1597	13	86
H1C	259	318	1.23	82	0.000649	0.2531	0.0066	3.409	0.107	0.0977	1454	1506	1580	27	92
H3A	192	150	0.78	54	0.000151	0.2482	0.0065	3.409	0.100	0.0996	1429	1506	1617	19	88
H4B	182	161	0.89	56	0.000199	0.2636	0.0067	3.619	0.100	0.0996	1508	1554	1616	15	93
DC94-16															
C2A.1	76	64	0.84	26	0.000305	0.2920	0.0098	4.171	0.167	0.1036	1651	1668	1690	34	98
C2B.1	235	194	0.83	80	0.000186	0.2967	0.0096	4.192	0.142	0.1025	1675	1672	1669	14	100
C2C.1	111	86	0.78	38	0.000161	0.2998	0.0069	4.348	0.118	0.1052	1691	1703	1717	22	98
B1A.1	97	73	0.75	33	0.000090	0.2987	0.0071	4.369	0.122	0.1061	1685	1707	1733	22	97
B1B.1	299	287	0.96	106	0.000224	0.2949	0.0086	4.239	0.135	0.1042	1666	1682	1701	18	98
B2A.1	77	57	0.74	26	0.000169	0.2980	0.0107	4.448	0.182	0.1083	1681	1721	1770	29	95
A1A.1	83	64	0.77	29	0.000345	0.3025	0.0093	4.264	0.156	0.1022	1704	1686	1665	31	102
A1B.1	204	145	0.71	57	0.0003445	0.2462	0.0064	3.221	0.144	0.0949	1419	1462	1526	65	93
F1A.1	124	85	0.69	42	0.000046	0.3041	0.0088	4.357	0.140	0.1039	1712	1704	1695	20	101
F1B.1	108	90	0.83	38	0.000253	0.3006	0.0080	4.239	0.130	0.1023	1694	1682	1666	23	102
A4A.1	208	157	0.75	69	0.000195	0.2924	0.0092	4.146	0.138	0.1028	1654	1664	1676	15	99
H3A.1	400	275	0.69	136	0.000056	0.3032	0.0064	4.330	0.097	0.1036	1707	1699	1689	10	101
I3A.1	251	126	0.50	74	0.000589	0.2748	0.0108	3.745	0.169	0.0989	1565	1581	1603	34	98
A3A.1	66	51	0.77	23	0.000207	0.3042	0.0101	4.422	0.188	0.1054	1712	1717	1722	43	99

Table 2. NORDSIM analyses of zircons from sample DC97-2.

Sample/spot #	U ppm	Th ppm	Th/U meas.	Pb ppm	204Pb 206Pb	206Pb 238U	Ages Ma		Concordance (%)							
							207Pb 235U	±								
DC97-2	240	140	0.58	84	0.000036	0.2791	0.0085	3.763	0.122	0.0978	0.0011	1587	1585	1582	20	100
	98	60	0.62	35	0.000065	0.2808	0.0109	3.746	0.153	0.0968	0.0013	1595	1581	1563	26	102
	908	80	0.09	260	0.000019	0.2556	0.0037	3.410	0.051	0.0967	0.0004	1467	1507	1562	8	94
	343	819	2.39	70	0.002941	0.1460	0.0036	1.680	0.044	0.0834	0.0024	879	1001	1279	56	69
	156	168	1.08	40	0.001852	0.1813	0.0062	2.310	0.085	0.0924	0.0027	1074	1215	1475	56	73
	146	30	0.20	22	0.001282	0.1324	0.0084	1.185	0.085	0.0649	0.0049	802	794	772	159	104
	266	136	0.51	75	0.000240	0.2279	0.0045	3.009	0.063	0.0958	0.0009	1323	1410	1543	17	86
	599	185	0.31	56	0.005000	0.0673	0.0019	0.688	0.019	0.0741	0.0017	420	532	1045	45	40
	2043	229	0.11	311	0.001087	0.1294	0.0054	1.404	0.058	0.0787	0.0012	785	891	1163	31	67
	998	16	0.02	149	0.000324	0.1365	0.0021	1.337	0.021	0.0710	0.0005	825	862	958	13	86
	3437	561	0.16	336	0.001471	0.0818	0.0010	0.871	0.012	0.0773	0.0011	507	636	1128	28	45
	2169	928	0.43	292	0.000820	0.1105	0.0033	1.318	0.040	0.0865	0.0006	676	853	1349	12	50
	95	4	0.04	16	0.003571	0.1367	0.0047	1.335	0.049	0.0708	0.0044	826	861	952	126	87
	82	3	0.04	15	0.000719	0.1607	0.0037	1.703	0.046	0.0768	0.0018	961	1010	1117	46	86
	253	158	0.63	90	0.000054	0.2810	0.0054	3.812	0.077	0.0984	0.0006	1597	1595	1594	11	100
	259	159	0.61	94	0.000107	0.2819	0.0052	3.853	0.073	0.0991	0.0005	1601	1604	1608	9	100
	100	2	0.02	20	0.000637	0.1775	0.0033	1.976	0.040	0.0808	0.0011	1053	1107	1215	28	87
	1725	7	0.00	322	0.000148	0.1731	0.0013	1.707	0.014	0.0715	0.0002	1029	1011	971	6	106
	95	62	0.65	33	0.000094	0.2702	0.0089	3.585	0.123	0.0962	0.0010	1542	1546	1552	20	99
	552	2	0.00	87	0.000060	0.1466	0.0024	1.487	0.026	0.0736	0.0005	882	925	1029	14	86
262	1	0.00	47	0.000057	0.1655	0.0025	1.679	0.027	0.0736	0.0005	987	1001	1030	13	96	
467	26	0.06	122	0.000038	0.2345	0.0042	3.096	0.058	0.0958	0.0005	1358	1432	1543	10	88	
727	1	0.00	124	0.000040	0.1592	0.0063	1.591	0.064	0.0725	0.0004	952	967	1000	13	95	
290	1	0.00	44	0.000053	0.1417	0.0017	1.463	0.019	0.0749	0.0004	854	915	1064	12	80	
58	32	0.54	21	0.000267	0.2871	0.0106	3.860	0.150	0.0975	0.0014	1627	1605	1577	28	103	
125	82	0.66	45	0.000053	0.2837	0.0072	3.322	0.102	0.0977	0.0008	1610	1597	1581	16	102	
78	39	0.50	25	0.000086	0.2585	0.0087	3.561	0.123	0.0999	0.0009	1482	1541	1623	16	91	
206	155	0.75	80	0.002564	0.2708	0.0059	3.659	0.084	0.0980	0.0018	1545	1563	1587	33	97	
243	2	0.01	42	0.000380	0.1561	0.0044	1.594	0.047	0.0741	0.0010	935	968	1043	27	90	
1283	12	0.01	198	0.000143	0.1432	0.0017	1.414	0.018	0.0716	0.0004	863	895	976	12	88	

Spot description codes: ig – oscillatory zoned igneous, br – CL-bright rims, bo – CL-bright overgrowths, dr – CL-dark rim, do – CL-dark overgrowth, dm – dark metamict, mixed spots indicated by two codes.

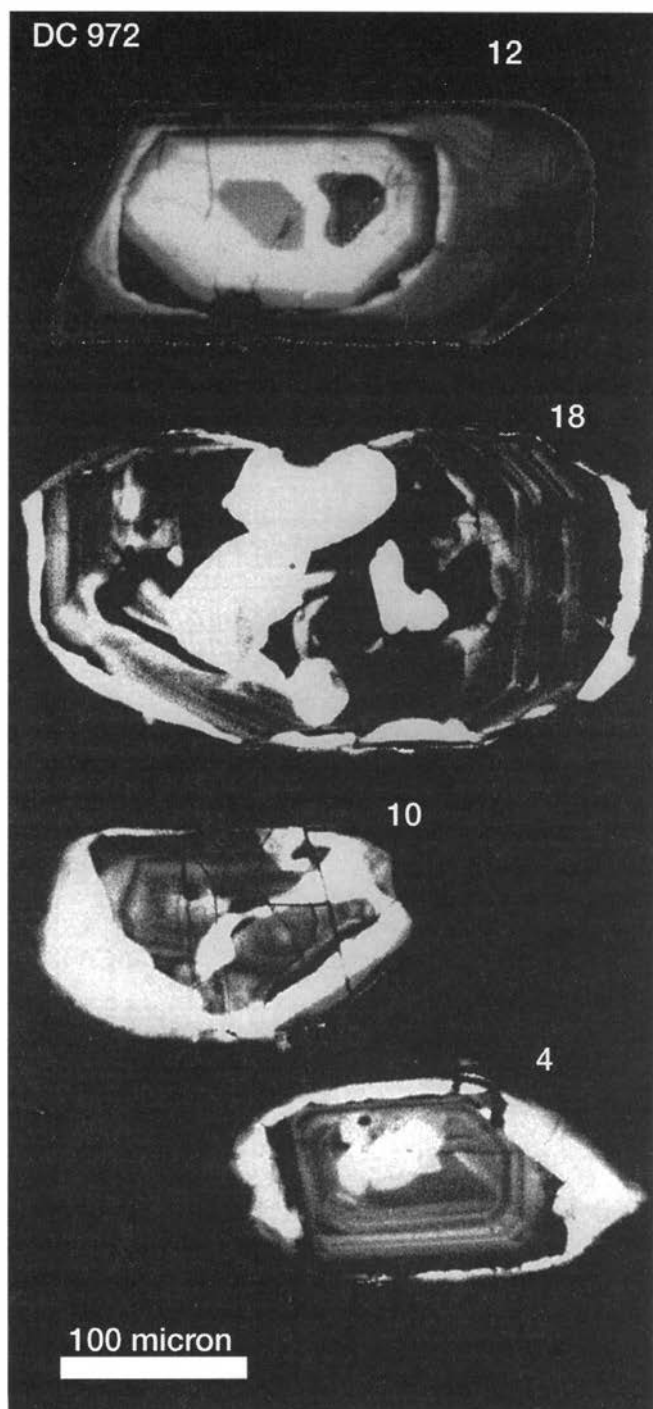


Fig. 3. Cathodoluminescence images of zircons from DC97-2 showing CL-dark rim on igneous core (12), igneous zoned core with CL-bright rim and patches (18), resorption of igneous zoned core by CL-bright rim and patches (10) and CL-bright rim on igneous core. (Note that the edge of crystal 12 image was enhanced.)

CL-bright metamorphic zircon. – CL-bright rims (br in Table 2) and patches cutting across grain cores (bo) have low U content in contrast with the dr and do spots discussed above (Fig. 5). Texturally, the CL-bright zircon is younger than the igneous and older than the dark metamorphic zircon, which forms the outermost rims. Grain 10 has a CL-bright rim and a patch cross-cutting the igneous zonation (Fig. 3), but it was difficult to analyse

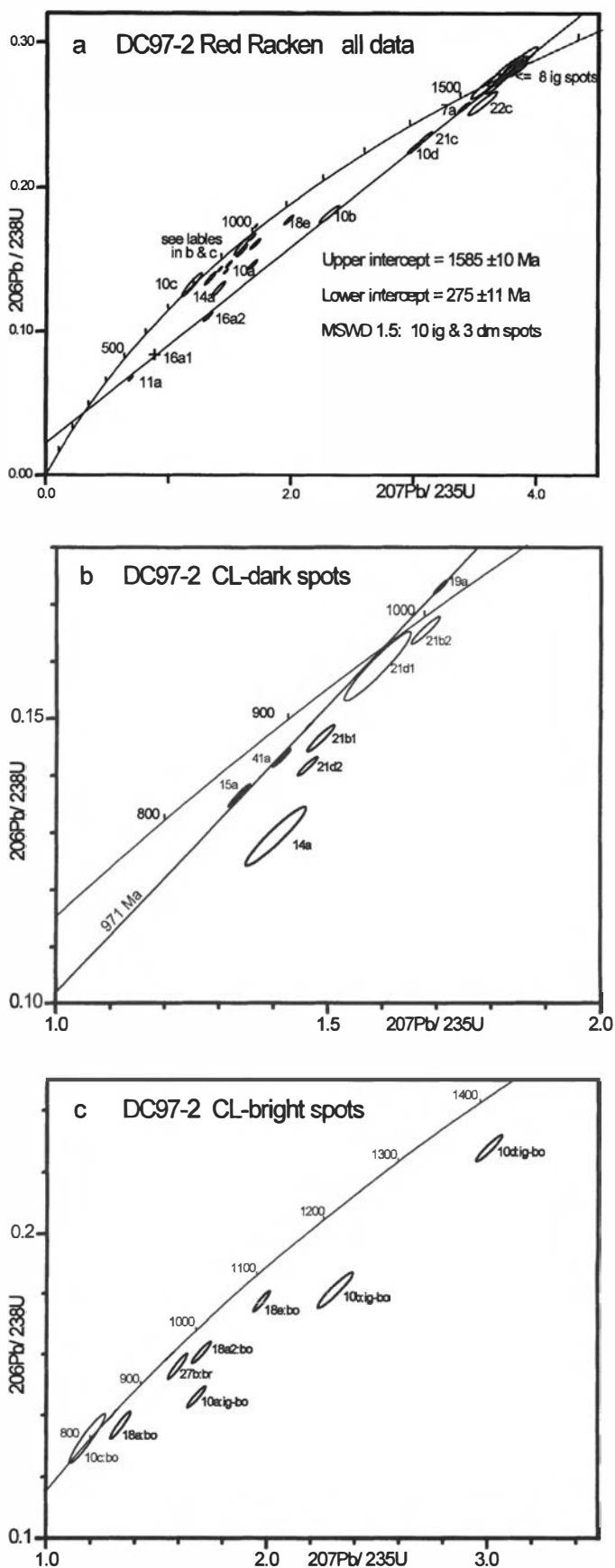


Fig. 4. NORDSIM data from DC97-2 (red Racken). (a) All spots. (b) CL-dark spots representing Sveconorwegian metamorphic zircon growth. (c) CL-bright spots indicating variable lead loss from pre-Sveconorwegian metamorphic zircons.

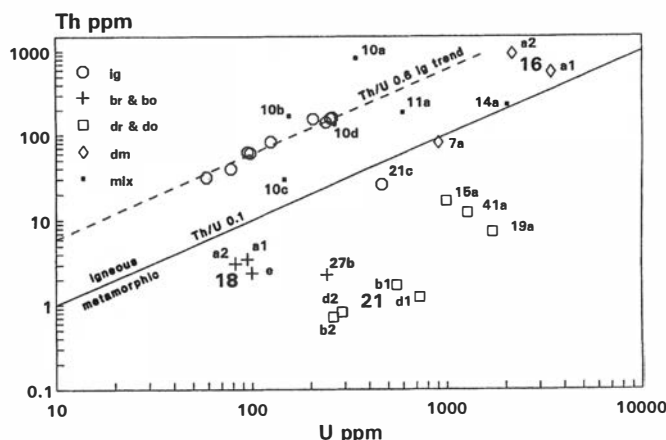


Fig. 5. U/Th diagram of analysed zircons showing the igneous Th/U trend of ca. 0.6 and typical Th/U values for metamorphic zircons of less than 0.1. Description codes: ig – oscillatory zoned igneous, br & bo – CL-bright rim or overgrowth, dr & do – CL-dark rim or overgrowth, dm – dark metamict, mix – mixed analysis.

spots of a single type, and there were mixed spots, with Th/U ratios higher than 0.1. The spots scatter (MSWD = 8.8; Fig. 4c) about a mixing line on concordia with intercepts around 1680 and 590 Ma. Three spots in grain 18, which has larger CL-bright patches, together with 27b, have Th/U ratios lower than 0.1, confirming their metamorphic origin (Fig. 5). These four spots give an isochron line with low MSWD of 0.84, but imprecise intercepts of 1464 ± 191 – 140 and 747 ± 82 – 116 Ma. These results suggest that most of the CL-bright spots have undergone variable lead loss. It is possible that the imprecise 1464 Ma age could reflect pre-Sveconorwegian metamorphism; however, the low U content and multi-stage evolution make this difficult to prove. It can, however, be observed that Hansen et al. (1989) suggested a high-grade metamorphic event to have formed new zircon growth at ca. 1.4 Ga in western Värmland.

Torsby Segment – SHRIMP results

The zircons from the Torsby Segment, Hänsjön sample DC94-16 have shapes which, according to the classification of Pupin (1980), formed under high temperature in rocks such as alkaline or sub-alkaline granites. In CL images they commonly show the cyclic growth zonation characteristic of igneous zircon. Most grains show thin ($< \mu\text{m}$) CL-bright rims that could represent metamorphic overgrowth, but are too thin to analyse properly.

SHRIMP data (Table 1) are illustrated in a concordia diagram (Fig. 6). Ten of the data points form a tight cluster around 1690 Ma on concordia. A few grains, such as A3A, have cores that might be inherited from older rock, but still plot within error of this cluster. However, one spot (B2A1) has a distinctly older Pb-Pb age of 1770 ± 29 Ma. It seems likely that this is an inherited grain, although this is not perceptible on the CL image. Two spots plot to the left of the cluster: rim spot A1B.1 and core 13A.1. If these are included in a regression (omitting only B2A1 and A3A.1), they control a line which supports the ancient lead loss

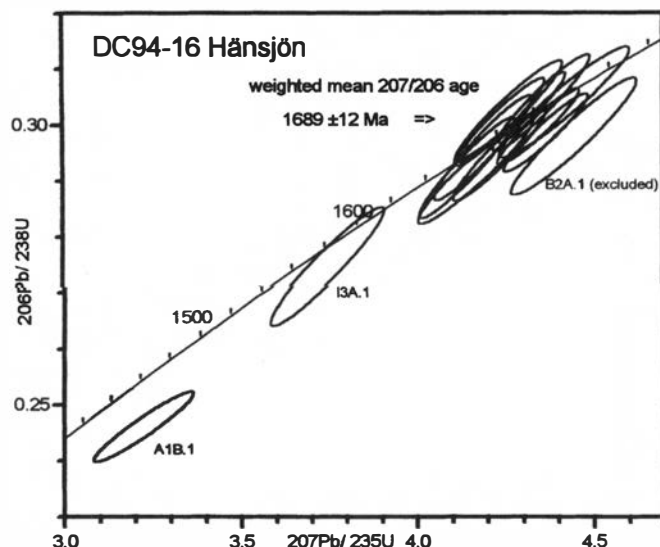


Fig. 6. SHRIMP data from DC94-16.

model, with intercepts 1709 ± 39 – 23 Ma and 1117 ± 200 Ma. Since the analysed spots likely include thin rims of metamorphic overgrowths, they are interpreted to represent mixed ages, though they are without low Th/U ratios. The ten nearly concordant grains do not show any significant trend, which suggests that they are free of ancient lead loss. If this is correct, their weighted mean Pb-Pb age of 1689 ± 12 Ma represents the age of origin of the rock. Even if this is not true, the less precise 1709 Ma discordia intercept U-Pb age is not significantly different from the Pb-Pb age.

Conclusion

The ion probe technique combined with CL images of zircons is an excellent way to analyse pristine parts and overgrowths in single crystals. The sometimes irregular overgrowths of metamorphic zircon on igneous zircon shown in CL images demonstrate the difficulties of avoiding mixed age populations using conventional techniques even if the zircons are severely abraded. This means that discordant zircon populations yielded by conventional U-Pb analyses in poly-metamorphic terrains, such as the Southwest Scandinavian Domain, may represent mixed ages.

We conclude that the Torsby Granite, to the east of the Mylonite Zone, is 1689 ± 12 Ma old, and was metamorphosed during the Sveconorwegian orogeny. Furthermore, the source from which the granite was derived included material as old as 1770 ± 29 Ma.

The Racken gneiss, to the west of the Mylonite Zone, crystallized 1590 ± 14 Ma to 1596 ± 11 Ma ago and was metamorphosed during the Pre-Sveconorwegian (CL-bright zircon overgrowth) as well as during the Sveconorwegian (CL-dark zircon rims), in accordance with structural studies by Larson et al. (1998) in the Western Segment.

The ion probe dating results confirm earlier studies, showing that polymetamorphic gneisses to the west of the Mylonite Zone generally are ca. 100 Ma younger than foliated granitoids to the east of the Mylonite Zone in Värmland.

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