Timing of late- to post-tectonic Sveconorwegian granitic magmatism in South Norway

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Dating of late- to post-tectonic Sveconorwegian granitic intrusions from South Norway by the SIMS U-Pb method on zircons and by internal Pb-Pb isochrons on rock-forming minerals indicates a major event of granitic magmatism all across southern Norway in the period 950 to 920 Ma. This magmatic event included emplacement of mantle-derived magma into the source region of granitic magmas in the lower crust east of the Mandal-Ustaoset shear zone, and formation of hybrid magmas containing crustal and mantle-derived components. West of the Mandal-Ustaoset shear zone, granitic magmatism started earlier, at c. 1030 Ma. A distinct group of granites, characterized by low Sr concentration and a high Rb/Sr ratio, is restricted to central Telemark, and shows evidence of involvement of a component related to the ca. 1500 Ma metarhyolite of the Telemark supracrustal sequence. Whereas one of these granites clearly belongs to the 920-950 Ma age group, two of the intrusions dated in this study (Otternes and Gunnarstul) are significantly older and may be genetically related to an earlier event of anorogenic magmatism in the region at c. 1120 to 1150 Ma.

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Introduction

Granitic intrusions in the continental crust are important indicators of tectonic regimes in the past, as well as potential sources of information on the composition and history of deep crustal protoliths. Recent studies on Sveconorwegian granites from South Norway have shed light on the timing of anorogenic and shortening stages of the evolution of this orogenic belt (Bingen & van Breemen 1998, Bingen et al. 1993), and on the nature and distribution of geochemical components in the deep crust at the end of the Sveconorwegian orogeny (Andersen et al. 1994, 2001a, Andersen 1997, Andersen & Knudsen 2000). Whereas most granitic rocks in southern Norway contain clear evidence of tectonic deformation (granitic gneiss, augen gneiss), a distinct group of granites is unfoliated or has only a weak and non-persistent foliation. These granites have anorogenic geochemical signatures, and are traditionally known as 'post-tectonic' or 'postkinematic' Sveconorwegian granites. Their Sr, Nd, Pb, and Hf isotope systematics suggest that they formed by mixing of a mantle-derived magma with regionally defined crustal components (Andersen 1997, Andersen et al. 2001a, 2002b).

In the present study, SIMS U-Pb zircon ages and internal Pb-Pb isochron ages are presented for a selection of inferred late- to post-tectonic Sveconorwegian granites from South Norway. The aim of the study has been to determine the timing of anorogenic granitic magmatism in the different parts of South Norway, and to search for evidence of inherited zircons in these granites for information about the source region of granitic magmas in the deep crust.

Geologic setting

The Precambrian areas of South Norway form part of the Southwest Scandinavian Domain of the Baltic Shield (Gaál & Gorbatschev 1987). The area of interest in this paper is restricted to the east by the Phanerozoic Oslo Rift, and to the west and northwest by the Caledonian nappes. Whereas the oldest dated rocks in South Norway west of the Oslo Rift are c. 1.60-1.66 Ga orthogneisses (Jacobsen & Heier 1975, Andersen et al. 2001b, Ragnhildstveit et al. 1994), indirect evidence from age distributions of detrital zircons in metasedimentary rocks (Knudsen et al. 1997b, Birkeland et al. 1997, Haas et al. 1999, Bingen et al. 2001) and radioisotope data from metasedimentary (Andersen et al. 1995, Knudsen et al. 1997a) and granitic rocks (Andersen et al. 1994, 2001a, Andersen 1997) point to the existence of protoliths of 1.7-1.9 Ga age, i.e. to rocks whose ages are similar to intrusions of the Transscandinavian Igneous Belt (TIB) and the Svecofennian domain of south and central Sweden (e.g. Åhäll & Larson 2000). In parts of South Norway (e.g. the Bamble and Telemark sectors, see below), the tectonometamorphic habit is largely a result of processes during the Sveconorwegian (i.e. Grenvillian) orogeny (1.2-0-9 Ga).

South Norway is a mosaic of crustal domains separated by Sveconorwegian shear zones (Fig. 1). These domains have traditionally been referred to as sectors, a non-genetic term which is retained here, in the absence of a generally accepted tectonic terrane model for the area (see discussion by Haas et al. 1999 and Andersen et al. 2001b). The medium- to high-grade metamorphic *Bamble sector* (Fig 1) consists of metasedimentary rocks and amphibolite intruded by

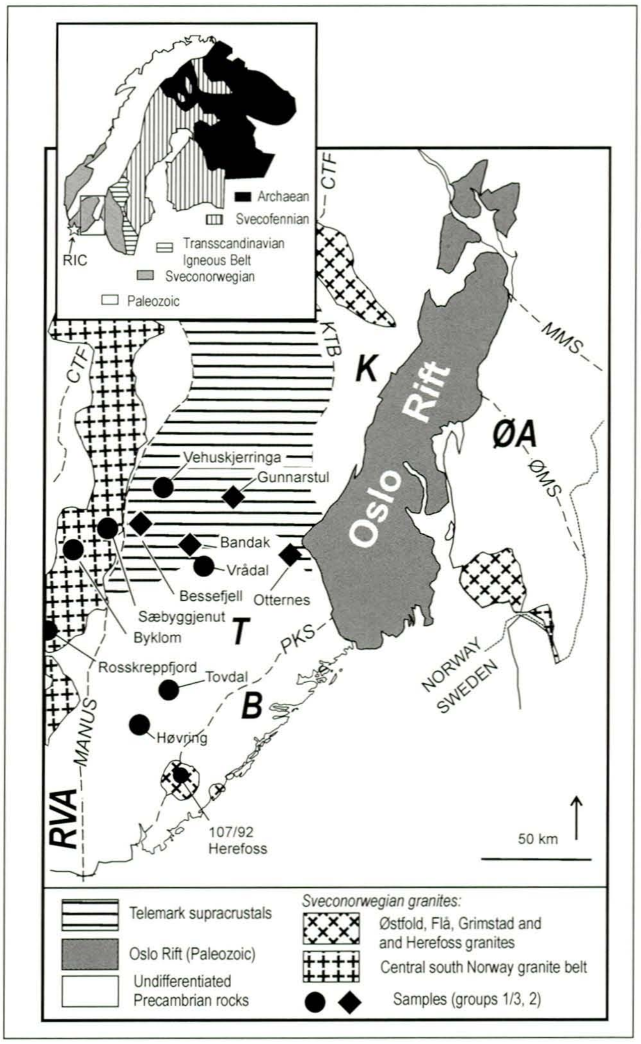

Fig. 1. Simplified geologic map of South Norway, showing main structural division of the Precambrian crust and position of intrusions sampled for dating. Sectors (large font): *B:* Bamble sector, *T:* Telemark sector, *K:* Kongsberg sector, *ØA:* Østfold-Akershus sector, *RVA:* Rogaland-Vest Agder sector. Shear zones (broken lines): PKS: Kristiandsand-Porsgrunn, MANUS: Mandal-Ustaoset, KTB: 'Kongsberg-Telemark boundary', MMS: Mjøsa-Magnor, ØMS: Ørje mylonite zone, CTF: Caledonian thrust front. Inset: Major crustal domains of the Baltic Shield. RIC: Rogaland Igneous Complex.

Sveconorwegian (1.2-0.9 Ga) gabbro, granite, and charnockite (Starmer 1985, Padget 1990, de Haas 1992, 1997). Granodioritic to tonalitic gneiss lenses having possible tectonic contacts with metasupracrustal rocks, constitute a minor but characteristic component of the Bamble sector (Andersen et al. 2001b). The *Kongsberg sector* (including the Begna sector of Bingen et al. 2001) is generally assumed to be related to the Bamble Sector (e.g. Starmer 1985 and references therein), but granodioritic to tonalitic gneiss is more abundant, especially in the southeastern part (Jacobsen & Heier 1978, Dons & Jorde 1978). The northeastern part of the Kongsberg sector is made up of poorly known gneisses, including rocks of supracrustal as well as intrusive origin, probably older than 1.6 Ga (Nordgulen 1999). The Bamble and Kongsberg sectors are separated from the *Telemark sector* by a system of Precambrian ductile shear zones (PKS-KTB in Fig. 1), whose southern part (the Porsgrunn-Kristiansand shear zone, PKS) shows evidence of Sveconorwegian thrusting, (Andresen & Bergundhaugen 2001, Bergundhaugen 2002). The Telemark sector is characterized by granitic gneiss of ambiguous origin in the south (Kleppe 1980, Falkum 1998) and a well-preserved, low-grade supracrustal sequence (Telemark supracrustal rocks) to the north (Dons 1960, Sigmond et al. 1997). The oldest part of the supracrustal sequence is the c. 1.5 Ga Rjukan Group rhyolite (Dahlgren et al. 1990) that was deposited in one or more extensional basins possibly related to a Mesoproterozoic continental rift (Sigmond et al. 1997). The Mandal-Ustaoset shear zone (*MANUS* line) separates the Telemark sector from the *Rogaland-Vest Agder sector*, which consists mainly of granodioritic to granitic gneiss and foliated to massive granite, with minor amounts of metasupracrustal rocks (Sigmond 1975, 1998, Bingen et al. 1993, de Haas et al. 1999), and which contains voluminous c. 930 Ma anorogenic anorthositic and mafic intrusions (the Rogaland Igneous Complex (RIC in inset to Fig. 1), Schärer et al. 1996).

So far, four geochemically and chronologically defined associations of Sveconorwegian granitic intrusions have been recognized in South Norway. Bingen & van Breemen (1998) identified three regionally important groups of deformed granitic intrusions, the *Gjerstad, Feda,* and *Fennefoss* augen gneiss suites. The Gjerstad suite has an anorogenic geochemical character and was emplaced in the time interval 1.19 to 1.12 Ga. Gjerstad suite intrusions are present in the Bamble, Telemark, and Rogaland – Vest Agder sectors (Hagelia 1989, Kullerud & Machado 1991, Andersen et al. 1994, Zhou et al. 1995, Simonsen 1997). The c. 1.05 Ga Feda suite is restricted to the Rogaland – Vest Agder sector and consists of high-K calc-alkaline granitoids, a composition which suggests that active subduction took place off SW Norway at this time. The c. 1035 Ma Fennefoss suite in the Telemark sector has a transitional geochemical signature between orogenic and anorogenic (Bingen & van Breemen 1998).

In addition to the deformed granitoids characterized by Bingen & van Breemen (1998), massive or weakly foliated Sveconorwegian granites exist in all crustal sectors of South Norway, comprising a fourth 'suite' of intrusions (Killeen & Heier 1973, Andersen 1997, Andersen et al. 2001a). They include two large batholiths, the Østfold (or Iddefjord) granite (which is a northern extension of the Båhus Batholith of SW Sweden) east of the Oslo Rift and the Flå granite in the Kongsberg sector. Granitic intrusions also make up a large N-S trending belt west of the Mandal–Ustaoset shear zone (the 'Central south Norway granite belt' in Fig. 1), as well as numerous smaller intrusive bodies in the Telemark and Bamble sectors. Some late- to post-kinematic granites have been dated by U-Pb or Pb-Pb systematics (Båhus: 922±5 Ma, Eliasson & Schöberg 1991; Flå: 928±3 Ma, Nordgulen et al.

1997; Herefoss: 926±8 Ma, Andersen 1997; Grimstad: 989±8 Ma, Kullerud & Machado 1991; Lyngdal: 946±5 Ma; Hidra charnockite: 933±3 Ma, Farsund: 946±7 Ma, Pasteels et al. 1979), or by whole-rock Rb-Sr isochrons (e.g. Pedersen & Falkum 1975, Killeen & Heier 1975, Kleppe 1980, Pedersen & Konnerup-Madsen 2000), but several remain undated.

Material studied

The samples dated in the present study were selected from the collection of Andersen et al. (2001a); field and petrographic data on the individual samples analysed are summarized in Appendix 1. Most samples appear unfoliated on outcrop and hand-specimen scale, notable exceptions being the samples from Herefoss and Ottternes. Parts of the Herefoss granite have a well-developed foliation parallel to the intrusive contacts, which has been shown to be related to flow during emplacement (Elders 1963). On the other hand, the foliation in the Otternes sample may have formed in response to tectonic deformation (see discussion below).

Based on the radioisotopic and trace element signatures of late Sveconorwegian granites from South Norway, Andersen et al. (2001a) defined three different petrogenetic groups of late- to post-tectonic granites.

Group 1: Granites belonging to this group crop out throughout South Norway, including north and central Telemark. These rocks are characterized by strontium contents above 150 ppm Sr, ^{87}Rb/^{86}Sr < 5, ^{87}Sr/^{86}Sr$_{0.93Ga}$ < 0.710 and ε_{Nd}<0. A crustal component involved in their petrogenesis has resided in a moderately LILE-enriched environment in the continental crust since 1.7-1.9 Ga. Group 1 includes the Østfold (Båhus), Flå and Herefoss granites, the intrusions of the central-south Norway Granite Belt, and several intrusions in the Telemark sector. Samples from three intrusions from the Rogaland-Vest Agder sector (Rosskreppfjord, Byklom, Sæbyggjenut) and a sample from the Herefoss granite (Andersen 1997) have been included in the present U-Pb SIMS study. In addition, two Group 1 granites from the Telemark sector (Vehuskjerringa, Vrådal) have been dated by internal Pb-Pb isochrons.

Group 2: Granites belonging to group 2 are restricted to the central Telemark sector. They are characterized by less than 150 ppm Sr, ^{87}Rb/^{86}Sr > 5, ^{87}Sr/^{86}Sr$_{0.93Ga}$ > 0.710 and ε_{Nd}<0. The Group 2 'Low Sr concentration' granites are, in general, spatially associated with low-Sr metarhyolite of the Telemark supracrustal sequence (e.g. Menuge & Brewer 1996); a c. 1.5 Ga crustal component with anomalously low Sr concentration has contributed to the petrogenesis of these granites (Andersen et al. 2001a). In the present study, four Group 2 intrusions (Bessefjell, Bandak, Gunnarstul, and Otternes granites) have been analysed.

Group 3: Among the intrusions studied by Andersen et al. (2001a), only one granite has a juvenile geochemical signature, suggesting insignificant contributions of old crustal material. This intrusion (the Tovdal granite) was accordingly placed in a group of its own. It is characterized by ^{87}Sr/^{86}Sr$_{0.93Ga}$ < 0.705 and ε_{Nd}>0.

Analytical methods

The present study is based on 5-8 kg samples of homogenous granite. The samples were crushed to a grain-size of less than 250 μm using a jaw crusher and a percussion mill. *Zircons* were separated from the <250 μm fraction by a combination of Wilfley-table washing, heavy liquid separation (1,1,2,2- tetrabromoethane and diiodomethane) and magnetic separation. The final, non-magnetic zircon fraction was then purified by hand picking under a binocular microscope, and selected grains were mounted on doubly adhesive tape, cast in epoxy and polished for the ion microprobe study. U-Pb dating of zircons was performed in the NORDSIM laboratory located at the Swedish Museum of Natural History in Stockholm during 1998-2000, using a CAMECA IMS1270 ion microprobe; analytical conditions and data reduction procedures are described by Whitehouse et al. (1997, 1999). Corrections for common lead were made using measured ^{206}Pb/^{204}Pb ratios and present-day average crustal lead of Stacey & Kramers (1975). This correction works well for moderate common-lead levels, but becomes problematic when common-^{206}Pb exceeds ca. 2 percent of total ^{206}Pb. U-Pb data are given in Table 1.

Additional separates of rock-forming minerals for the Pb-Pb isochron study were prepared by a combination of heavy liquid and magnetic separation, followed by hand picking. Lead was separated and analysed by methods described by Andersen (1997). Whole-rock and K-feldspar lead isotope data are taken from Andersen et al. (2001a), data are given in Table 2. All geochronological calculations have been made using Isoplot/Ex version 2.32 (Ludwig 2000). The preferred age estimate for multi-grain populations of concordant and equivalent zircons is the 'concordia age' of the population, which is a weighted average incorporating information from the ^{206}Pb/^{238}U and ^{207}Pb/^{235}U ratios in all grains (Ludwig 2000). Most of the samples have more complex zircon populations that lost lead late in the history of the sample. Such lead loss may have occurred during the Caledonian orogeny, or during the Late Paleozoic rifting event which affected the southwestern parts of the Baltic Shield or in recent time. Regression lines for zircon populations which did not give meaningful, unconstrained lower intercepts, were accordingly calculated with a forced intercept of 250 ± 250 Ma.

Results

Zircons

Zircons in the study samples have moderately elongated, prismatic habits. BSE images reveal more or less strongly developed oscillatory 'magmatic' zoning (Fig. 2b,d,e), as well as more complex internal structures, suggesting the presence of different types of xenocrystic cores (Fig. 2a,c,e). Some grains also have thin, BSE-bright overgrowths (Fig. 2c)

Table 1. SIMS U-Pb data on zircons.

Spot 1	^{207}Pb/^{206}Pb	±σ %	^{207}Pb/^{235}U	±σ %	^{206}Pb/^{238}U	±σ %	ρ Error correlation	^{208}Pb/^{232}Th	±σ %	Disc. %	U ppm	Th ppm	Pb ppm	Th/U	^{206}Pb/^{204}Pb meas.	f_{206}%	^{207}Pb/^{206}Pb Ma	±σ Ma	^{207}Pb/^{235}U Ma	±σ Ma	^{206}Pb/^{238}U Ma	±σ Ma	^{208}Pb/^{232}Th Ma	±σ Ma
Tovdal																								
n442-01a	0.07034	0.8	1.5175	1.6	0.15646	1.4	0.87	n.d.		0	182	23	32	0.13	35160	0.1	938	17	937	10	937	12		
n442-02a	0.07226	1.5	1.5304	2.0	0.15361	1.2	0.66	n.d.		-6	249	34	43	0.13	10500	0.2	993	31	943	12	921	10		
n442-03a	0.07099	0.9	1.4726	1.7	0.15045	1.4	0.87	n.d.		-3	127	49	23	0.38	33370	0.1	957	18	919	10	903	12		
n442-04a	0.07082	0.7	1.5686	1.6	0.16065	1.4	0.90	n.d.		0	139	39	26	0.28	106910	0.0	952	14	958	10	960	13		
n442-05a	0.07070	1.0	1.4936	1.8	0.15322	1.5	0.84	n.d.		0	79	18	14	0.23	>106	0.0	949	20	928	11	919	13		
n442-06a	0.06957	1.9	1.4987	2.8	0.15624	2.0	0.76	n.d.		0	43	33	9	0.78	15700	0.1	916	40	930	17	936	17		
n442-07a	0.06998	1.3	1.5066	2.9	0.15615	2.6	0.92	n.d.		0	54	68	12	1.28	15320	0.1	928	26	933	18	935	22		
n442-08a	0.06956	1.0	1.5293	1.8	0.15945	1.5	0.82	n.d.		1	84	20	15	0.24	>106	0.0	915	21	942	11	954	13		
Herefoss																								
n440-02a	0.07004	0.8	1.6631	1.4	0.17222	1.1	0.87	n.d.		9	124	82	27	0.67	9160	0.2	929	16	995	9	1024	10		
n440-03a	0.06858	1.1	1.5054	2.5	0.15921	2.2	0.93	n.d.		3	53	67	12	1.26	9120	0.2	886	23	933	15	952	20		
n440-04a	0.07026	0.5	1.5980	1.1	0.16496	1.0	0.91	n.d.		3	258	25	47	0.10	79550	0.0	936	10	969	7	984	9		
n440-04b	0.07046	0.5	1.5694	1.1	0.16155	0.9	0.87	n.d.		1	211	126	43	0.60	52300	0.0	942	11	958	7	965	8		
n440-05a	0.06922	1.1	1.5560	2.3	0.16304	2.0	0.90	n.d.		4	76	62	16	0.81	22330	0.1	905	23	953	14	974	18		
n440-06a	0.06953	1.0	1.5340	1.6	0.16002	1.3	0.87	n.d.		2	83	59	17	0.71	20710	0.1	914	20	944	10	957	11		
n440-09a	0.07079	1.0	1.4766	1.9	0.15127	1.7	0.89	n.d.		-2	57	21	10	0.37	19150	0.1	951	21	921	12	908	14		
n440-10a	0.07072	1.6	1.5969	2.7	0.16377	2.2	0.87	n.d.		0	26	36	6	1.36	9590	0.2	949	33	969	17	978	20		
n440-11a	0.07072	1.8	1.5518	3.0	0.15914	2.4	0.80	n.d.		0	28	35	6	1.27	>1e6	0.0	949	37	951	19	952	21		
n440-12a	0.07062	1.3	1.5350	2.3	0.15765	1.9	0.83	n.d.		0	72	82	16	1.14	68120	0.0	946	27	945	14	944	17		
Høvring																								
n716-01a	0.06835	1.8	1.3374	2.6	0.14192	1.9	0.73	0.04346	4.1	-3	135	139	27	1.03	1970	1.0	879	37	862	15	855	15	860	35
n716-02a	0.09160	0.5	2.5700	2.0	0.20350	1.9	0.96	0.06453	4.0	-20	319	105	78	0.33	3028	0.6	1459	10	1292	15	1194	21	1264	48
n716-04a	0.07011	2.3	1.3287	3.0	0.13744	1.9	0.63	0.04329	4.0	-12	116	117	22	1.01	923	2.0	932	47	858	17	830	15	857	34
n716-05a	0.07085	1.2	1.3622	2.3	0.13946	1.9	0.85	0.04787	3.9	-12	461	422	89	0.91	921	2.0	953	25	873	13	842	15	945	36
n716-06a	0.07099	0.6	1.4575	2.0	0.14892	1.9	0.95	0.04561	4.0	-7	259	84	45	0.33	13965	0.1	957	13	913	12	895	16	901	35
Sæbyggjenut																								
n447-01a	0.07029	1.3	1.4867	2.1	0.15340	1.7	0.93	n.d.		0	231	217	49	0.94	3460	0.5	937	27	925	13	920	14		
n447-03a	0.07208	2.6	1.5363	4.4	0.15458	3.5	0.82	n.d.		0	30	31	6	1.05	>106	0.0	988	52	945	27	927	30		
n-705-01a	0.07293	1.5	1.5240	3.4	0.15156	3.0	0.89	0.04672	7.1	-11	39	36	8	0.94	4205	—	1012	31	940	21	910	25	923	64
n705-02a	0.06715	2.3	1.3094	3.8	0.14141	3.0	0.79	0.04262	7.0	1	57	50	11	0.88	2948	0.6	843	48	850	22	853	24	844	58
n705-03a	0.06950	1.5	1.3488	3.4	0.14076	3.1	0.90	0.04501	7.0	-8	117	110	23	0.94	7042	0.3	913	30	867	20	849	24	890	61
n705-05a	0.07204	2.3	1.3657	3.8	0.13749	3.0	0.79	0.04183	7.1	-17	134	108	24	0.81	1386	1.4	987	46	874	22	830	23	828	58
n705-06a	0.06838	2.0	1.2305	3.6	0.13051	3.0	0.83	0.04121	7.0	-11	80	89	15	1.10	3663	0.5	880	42	815	21	791	22	816	56
n705-07a	0.07108	1.5	1.3814	3.4	0.14095	3.0	0.89	0.04425	6.9	-12	176	180	34	1.02	9107	0.2	960	31	881	20	850	24	875	59
Rosskreppfjord																								
n443-01a	0.07321	1.1	1.7126	2.3	0.16965	2.0	0.97	n.d.		0	265	24	50	0.09	1880	1.0	1020	22	1013	14	1010	19		
n443-02a	0.06514	0.9	0.8951	1.2	0.09966	0.8	0.81	n.d.		-21	2191	935	263	0.43	3460	0.5	779	19	649	6	612	5		
n443-03a	0.07394	0.7	1.7394	1.4	0.17062	1.2	0.87	n.d.		0	151	89	32	0.59	>106	0.0	1040	14	1023	9	1016	11		
n443-03b	0.07349	0.8	1.7102	1.5	0.16877	1.3	0.88	n.d.		0	154	109	33	0.71	29260	0.1	1028	16	1012	10	1005	12		
Byklom																								
n441-01a	0.07259	1.4	1.6806	3.6	0.16791	3.3	0.92	n.d.		0	40	79	11	1.98	>1e6	0.0	1003	28	1001	23	1001	31		
n441-02a	0.07330	1.4	1.6070	2.1	0.15900	1.5	0.76	n.d.		-5	96	177	25	1.83	33320	0.1	1022	28	973	13	951	14		
n441-04a	0.07168	0.7	1.7103	1.3	0.17306	1.2	0.88	n.d.		3	119	75	26	0.63	88420	0.0	977	13	1012	9	1029	11		
n441-06a	0.07106	0.8	1.6332	1.0	0.16669	0.7	0.94	n.d.		2	444	925	127	2.08	5420	0.3	959	16	983	6	994	6		
n441-08a	0.07257	2.4	1.5920	3.2	0.15911	2.0	0.86	n.d.		-2	61	108	16	1.78	2200	0.8	1002	49	967	20	952	18		
n441-09a	0.07119	1.1	1.6146	1.9	0.16450	1.6	0.91	n.d.		0	152	269	40	1.77	11230	0.2	963	22	976	12	982	15		
n441-10a	0.07199	1.5	1.5254	1.9	0.15369	1.2	0.92	n.d.		-5	318	541	80	1.70	1150	1.6	986	30	941	12	922	10		
n441-11a	0.07211	1.9	1.6298	3.0	0.16392	2.2	0.85	n.d.		0	41	51	10	1.26	7400	0.3	989	40	982	19	979	20		
n441-12a	0.07274	1.2	1.5970	1.7	0.15922	1.3	0.73	n.d.		-3	141	150	31	1.07	55680	0.0	1007	25	969	11	952	11		
n441-13a	0.07310	3.8	1.6260	4.2	0.16132	1.7	0.73	n.d.		-2	409	860	113	2.10	3960	0.5	1017	77	980	26	964	15		
Bessefjell																								
n448-01a	0.06937	0.9	1.5944	1.6	0.16669	1.4	0.88	n.d.		7	94	137	23	1.47	34900	0.1	910	18	968	10	994	13		
n448-02a	0.07127	1.3	1.6477	2.6	0.16767	2.3	0.90	n.d.		0	72	72	17	1.01	17230	0.1	965	26	989	17	999	21		
n448-02b	0.07096	0.7	1.5454	1.7	0.15795	1.5	0.93	n.d.		0	247	191	50	0.77	42300	0.0	956	14	949	10	945	13		
n448-04a	0.07048	2.3	1.4520	3.4	0.14942	2.5	0.92	n.d.		0	47	49	10	1.04	3210	0.6	942	48	911	20	898	21		
n448-08a	0.06771	2.2	0.9970	3.1	0.10679	2.2	0.90	n.d.		-22	270	115	36	0.43	5970	0.3	860	45	702	16	654	14		
n448-10a	0.07060	1.2	1.4787	1.9	0.15191	1.5	0.78	n.d.		-1	183	156	37	0.85	>106	0.0	946	24	922	12	912	13		
n448-12a	0.06398	1.0	0.6295	1.5	0.07136	1.1	0.90	n.d.		-40	2101	811	181	0.39	4100	0.5	741	21	496	6	444	5		
Bandak																								
n708-01a	0.08800	1.0	2.3404	3.2	0.19290	3.0	0.95	0.05160	7.2	-19	1359	625	317	0.460	689	2.72	1382	20	1225	23	1137	31	1017	71
n708-02a	0.08593	0.4	2.0681	3.0	0.17455	3.0	0.99	0.05156	6.8	-24	2029	679	420	0.335	4490	0.42	1337	8	1138	21	1037	29	1016	68
n708-03a	0.08470	0.5	1.7917	3.1	0.15343	3.0	0.99	0.04923	6.8	-32	1835	349	323	0.190	5350	0.35	1309	9	1042	20	920	26	971	65
n708-04a	0.06346	0.7	0.7600	3.1	0.08686	3.1	0.97	0.01086	7.6	-27	5312	1122	503	0.211	1140	1.64	724	16	574	14	537	16	218	16
n708-05a	0.06356	0.9	0.7684	3.2	0.08768	3.0	0.96	0.01661	8.9	-27	5723	790	547	0.138	673	2.78	727	19	579	14	542	16	333	30
n708-06a	0.06103	0.5	0.6840	3.1	0.08129	3.0	0.99	0.02325	7.4	-22	11600	875	1021	0.075	1623	1.15	640	10	529	13	504	15	464	34
n708-07a	0.09060	1.1	2.1305	3.3	0.17054	3.1	0.94	0.02742	7.4	-32	1720	1161	352	0.675	935	2	1438	20	1159	23	1015	29	547	40
n708-08a	0.09331	0.9	3.1292	3.2	0.24321	3.0	0.95	0.06905	7.1	-7	724	363	218	0.501	1545	1.21	1494	18	1440	25	1403	38	1350	92
n708-09a	0.07404	0.6	0.9796	3.1	0.09596	3.0	0.98	0.02715	6.8	-45	2666	1385	312	0.520	1819	1.03	1043	12	693	15	591	17	541	37
n708-10a	0.08105	1.1	1.0710	3.4	0.09584	3.2	0.95	0.01861	7.6	-54	1981	1649	236	0.833	808	2.31	1223	21	739	18	590	18	373	28
Gunnarstul																								
n449-01a	0.07735	0.3	2.0557	0.8	0.19276	0.8	0.97	n.d.		0	1318	850	325	0.64	2330	0.8	1130	7	1134	6	1136	8		
n449-02a	0.07703	0.4	2.0725	1.1	0.19514	1.0	0.96	n.d.		1	754	766	199	1.02	11420	0.2	1122	7	1140	7	1149	10		
n449-03a	0.07828	1.0	2.0054	1.2	0.18581	0.7	0.82	n.d.		-4	970	675	235	0.70	1090	1.7	1154	20	1117	8	1099	7		
n449-04a	0.07928	0.7	2.0605	1.3	0.18850	1.1	0.90	n.d.		-4	812	501	192	0.62	2090	0.9	1179	14	1136	9	1113	11		
n449-05a	0.07765	1.4	1.9603	1.9	0.18310	1.3	0.96	n.d.		-3	272	94	59	0.35	1670	1.1	1138	28	1102	13	1084	13		
n449-07a	0.07857	1.2	2.0132	2.0	0.18584	1.7	0.84	n.d.		-3	156	63	34	0.40	30600	0.1	1161	23	1120	14	1099	17		
n449-08a	0.07730	2.2	1.9913	3.1	0.18683	2.2	0.98	n.d.		0	152	55	34	0.36	3840	0.5	1129	43	1113	21	1104	22		
Otternes																								
n450-02a	0.07245	0.5	1.2879	0.8	0.12892	0.7	0.98	n.d.		-22	2738	1200	427	0.44	2080	0.9	999	10	840	5	782	5		
n450-03a	0.07565	1.4	1.4580	1.8	0.13979	1.1	0.97	n.d.		-22	1437	904	246	0.63	1170	1.6	1086	28	913	11	843	9		
n450-04a	0.07758	0.4	1.7422	1.0	0.16288	0.9	0.95	n.d.		-14	2653	1112	520	0.42	4400	0.4	1136	8	1024	6	973	8		
n450-06a	0.08005	0.9	2.1098	2.3	0.19115	2.2	0.95	n.d.		-2	377	151	87	0.40	8180	0.2	1198	18	1152	16	1128	22		

1: Analysed spots are identified by Nordsim laboratory log numbers

n.d.: Not determined

Table 2. Lead isotope data for minerals and whole-rocks.

	$^{206}Pb/^{204}Pb$	2σ	$^{207}Pb/^{204}Pb$	2σ	$^{208}Pb/^{204}Pb$	2σ
Byklom 083096-3						
Biotite	17.819	0.020	15.546	0.021	50.803	0.081
Magnetite	17.515	0.014	15.475	0.018	40.348	0.064
Apatite	24.830	0.020	16.046	0.019	46.044	0.073
Titanite	46.959	0.037	17.614	0.021	54.026	0.086
K-feldspar	16.772	0.013	15.429	0.018	36.415	0.058
Whole-rock[1]	17.308	0.014	15.502	0.019	39.874	0.062
Rosskreppfjord 080296-4						
Titanite	493.1	0.4	50.17	0.07	210.36	0.37
Hornblende	21.629	0.020	15.808	0.022	37.636	0.067
Magnetite	21.251	0.019	15.845	0.022	41.255	0.073
Whole-rock[1]	19.880	0.016	15.694	0.019	38.966	0.061
Vrådal 081696-1						
Biotite	19.635	0.018	15.619	0.021	40.450	0.071
Magnetite	20.994	0.019	15.719	0.021	40.223	0.071
Apatite	19.527	0.018	15.619	0.021	40.313	0.071
K-feldspar	16.717	0.015	15.383	0.015	36.173	0.015
Monazite	127.2	0.5	23.194	0.086	1312	5
Whole-rock[1]	17.478	0.014	15.506	0.019	37.674	0.059
Vehuskjerringa 072406-1						
Biotite	20.620	0.016	15.682	0.019	40.429	0.063
Pyrite	19.209	0.015	15.609	0.019	39.210	0.061
Apatite	29.814	0.023	16.331	0.020	51.827	0.081
Titanite	211.8	0.2	29.002	0.035	236.2	0.4
K-feldspar	17.047	0.014	15.409	0.020	36.451	0.061
Whole-rock[1]	18.734	0.015	15.565	0.019	38.169	0.060

[1]: Data from Andersen et al. (2001a)

and embayments (Fig. 2b). The zircons from the Tovdal granite (Fig. 2d) have more elongated, slender prismatic habits, with less complex zoning patterns than zircons from any of the other granites, and they lack cores. The most frequent type of core has near-euhedral shapes, well-developed internal oscillatory zoning (Fig. 2a, c), and is discordantly overgrown by the enclosing grains. These cores lack abraded surfaces and lack evidence of strong metamictization. Cores of this type are typical in most of the Group 1 granites; the examples shown in Fig. 2 come from Herefoss (Fig. 2a) and Rosskreppfjord (Fig. 2c). Other cores are heterogeneous, fractured, and more or less metamict (Fig. 2e). The example in Fig. 2e comes from the Sæbyggjenut granite (Group 1 intrusion from the Rogaland-Vest Agder sector), but similar cores are abundant in the Group 2 granites as well.

U-Pb data

Group 1 and 3 intrusions. Five concordant zircons and one weakly inversely discordant zircon from the Tovdal granite give a concordia age of 940 ± 10 Ma (Fig. 3a). Two normally discordant (3 and 6 %) grains give higher ages, but still within uncertainty of the concordia age. A regression line calculated for all zircons together gives an upper intercept age of 947 +21/-17 Ma, assuming a forced lower intercept at 250 ± 250 Ma. We believe the concordia age (940 ± 10 Ma) is the best estimate of the emplacement age of the Tovdal granite.

Of 14 grains analysed from the Herefoss granite, four were discarded because of high contents of common lead. The remaining 11 grains define a regression line with an upper intercept of 920 +16/-27 Ma (forced lower intercept, Fig. 3b). This age is indistinguishable from the internal Pb-Pb lead isochron age of 926 ± 8 Ma reported by Andersen (1997), which is regarded as the best estimate of the emplacement age. Apparently xenocrystic cores (Fig. 2a) cannot be distinguished from the bulk of the zircon fraction in terms of U-Pb systematics.

Four discordant zircons from the Høvring granite yield an age of 971 +63/-34 Ma, assuming lead loss at 250 ± 250 Ma (Fig. 2c). This age is indistinguishable from a Rb-Sr whole-rock isochron age of 945 ± 53 Ma reported by Pedersen (1981) and Pedersen & Konnerup-Madsen (2000). A single, strongly discordant but distinctly older grain lies on a discordia line to an upper intercept at 2082 +340/-200 Ma (assuming lower intercept at 971 Ma) and must have been inherited from an Early Proterozoic source.

Among the intrusions from the Rogaland-Vest Agder sector, the Sæbyggjenut granite gives an upper intercept age of 959 +50/-32 Ma, based on seven concordant to normally discordant zircons and a forced intercept at 250 ± 250 Ma (Fig. 3d). Two additional analyses were discarded due to high common lead contents. Three of the four zircons analysed from the Rosskreppfjord intrusion are concordant at 1020 Ma, but with a high MSWD. The fourth zircon is strongly discordant, a regression line gives an upper intercept of 1036+23/-22 Ma with a Paleozoic unconstrained lower intercept (Fig. 3e); this is regarded as the best estimate of the emplacement age. The Byklom intrusion gives an upper intercept age indistinguishable from Sæbyggjenut, which may be given as 979 +9/-12 Ma, with a negative intercept, or 970 +14/-18 Ma with a forced intercept (Fig. 3f). The former is accepted as the best estimate of its emplacement age.

Group 2 granites. The Bessefjell granite was dated by a Rb-Sr whole-rock isochron to 904 ± 16 Ma (Killeen & Heier 1975, recalculated using $\lambda^{87}Rb=1.42 \times 10^{-11}\ a^{-1}$). Seven zircons, ranging from concordant to 40 % discordant define a regression line with intercepts at 209 Ma and 940 ± 19 Ma (Fig. 4a), which is regarded as the emplacement age.

The Bandak granite (Fig. 4b) has a zircon population dominated by zircons whose data plot along a poorly defined lead-loss line from an upper intercept at c. 1500 Ma to a Paleozoic lower intercept. Some grains fall to the left of this line, indicating additional lead loss, or growth of new zircon in Sveconorwegian time. Two of these plot near a possible lead-loss line from a late Sveconorwegian upper intercept, suggesting that crystallization of new zircon in Sveconorwegian time did actually take place. The Bandak granite was dated by a Rb-Sr whole-rock isochron age of 1002 ± 76 Ma (MSWD=0.57, $^{87}Sr/^{86}Sr_i$ = 0.765 ± 0.021) by

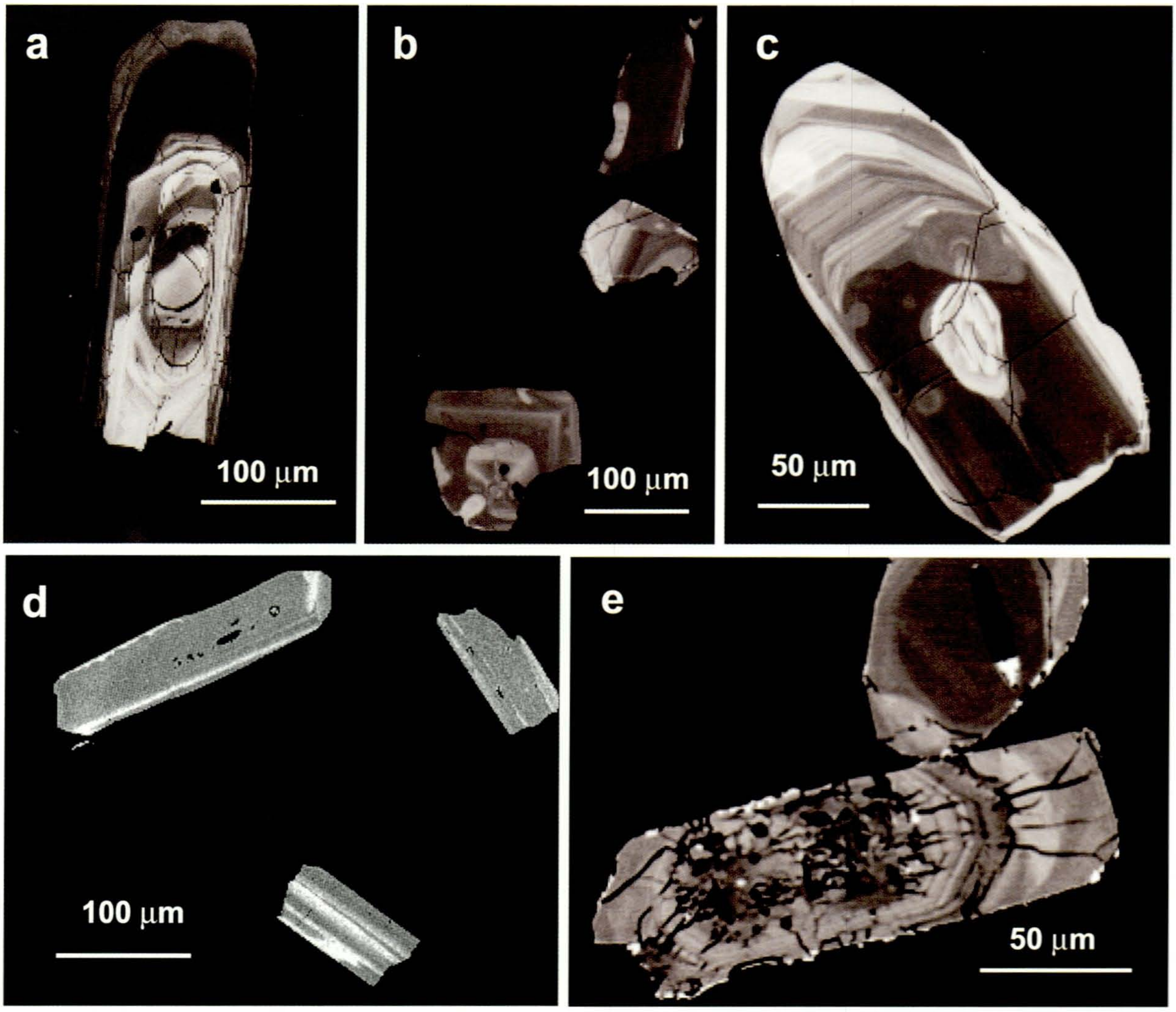

Fig. 2. Electron backscatter photomicrographs of zircons from late- and post-tectonic Sveconorwegian granites in South Norway. *(a)* Zircon from the Herefoss granite, containing an apparent xenocrystic core. Both core and enclosing grain have oscillatory magmatic zoning. Ages of zircon cores in the Herefoss granite are indistinguishable from enclosing zircon. *(b)* Fragments of zircons from Byklom granite, characterized by zircons with simple magmatic zoning and absence of cored grains. Lowermost grain has a small, BSE-bright embayment (bottom left), probably due to late- or post-magmatic hydrothermal alteration. *(c)* Zircon from Rosskreppfjord granite, with magmatic zoning and a thin BSE-bright overgrowth. BSE-bright central area is part of the magmatic zoning and not a xenocrystic core. BSE-bright rim is too thin for dating and probably formed by late- or post-magmatic hydrothermal alteration. *(d)* One terminated zircon and two fragments from Tovdal granite. Zircons from this sample differ from all others studied by a more slender habit, simple magmatic zoning with few zones, and absence of xenocrystic cores. *(e)* Two zircons from Sæbyggjenut granite, illustrating two morphological types in this granite: One type (upper grain) is internally homogeneous or lacks magmatic zoning. This particular grain contains a low-atomic number inclusion (BSE dark). The other type (lower grain) contains a heterogeneous, fractured and partly metamict core. White spots at grain surfaces and along fractures are parts of the gold coating which could not be removed by polishing after the SIMS session.

Kleppe (1980). Its Sveconorwegian Sr, Nd and Pb isotope composition resembles the other Sveconorwegian Group 2 granites and is distinct from that of the Mid Proterozoic Tinn granite (Andersen et al. 2001a). A population of undated single zircons give hafnium isotope model ages similar to those observed in other Group 2 granites (Andersen et al. 2002b). The Bandak granite is thus interpreted as a Sveconorwegian granite which has suffered heavy contamination by Mid Proterozoic crustal material, at least locally. The zircons analysed in the present study do not give new information on its emplacement age.

Seven zircons from the Gunnarstul granite, ranging from concordant to 4 % discordant, give upper intercept ages of 1133 +6/-6 Ma with no defined lower intercept, or 1134 ± 21 Ma with a forced intercept at 250 ± 250 Ma (Fig. 4c). An early Sveconorwegian age is also obtained from the Otternes granite, where six variably discordant zircons define a poorly defined regression line with a model 2 (Ludwig 2000) age of 1233 ± 90 Ma (Fig. 4d).

$^{208}Pb/^{232}Th$ ratios were only reported in analyses done in 2000. Data for the Høvring, Sæbyggjenut, and Bandak granites are presented in Table 1. $^{208}Pb/^{232}Th$ ages are, in general,

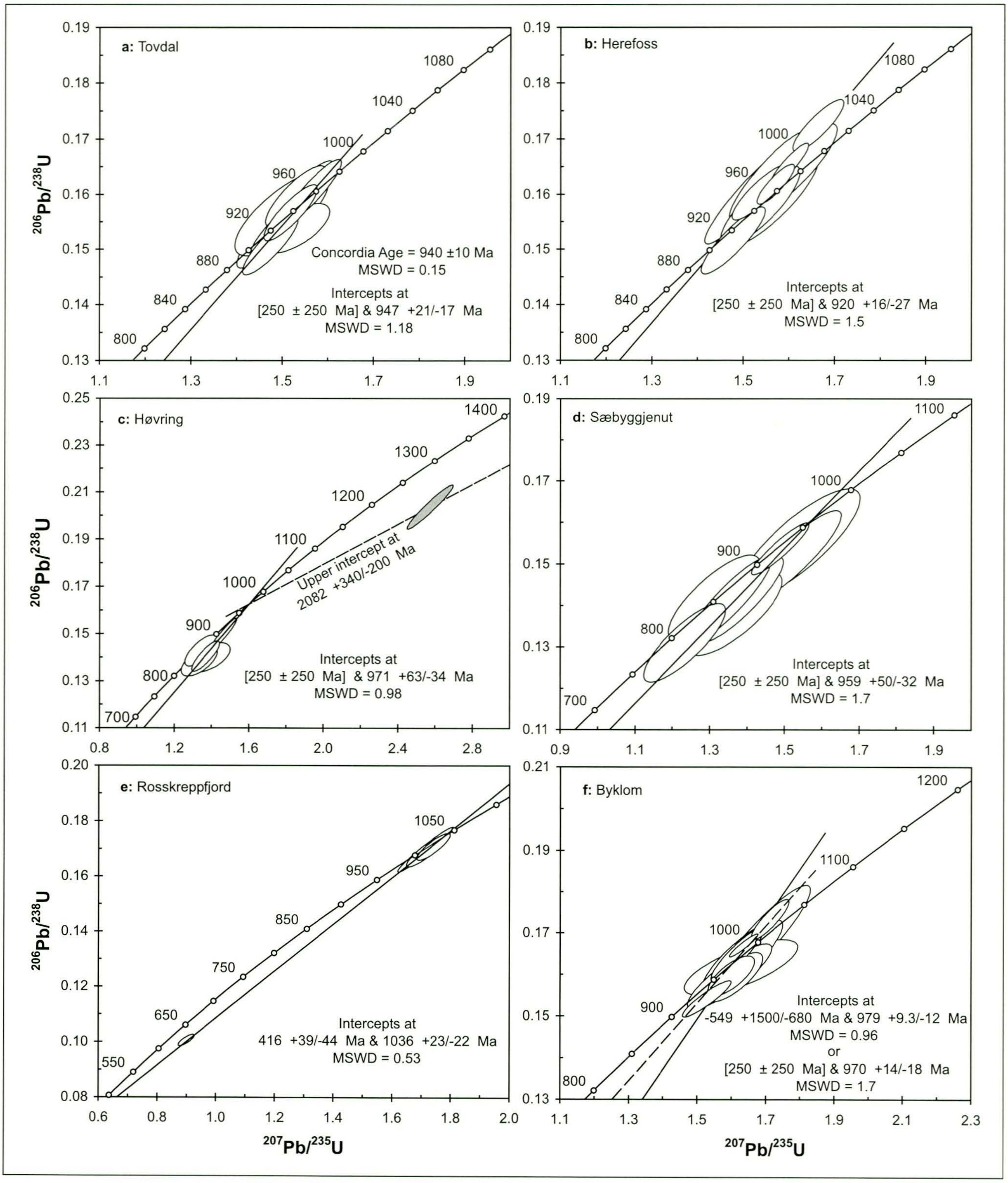

Fig. 3. Concordia diagrams for Group 1 and Group 3 granites. Single SIMS spot analyses are plotted with 2 σ error ellipses.

indistinguishable from the corresponding ^{206}Pb/^{238}U ages. Some of the grains from the Bandak granite have significantly lower ^{208}Pb/^{232}Th ages, however, which is a characteristic feature in zircons that have lost a significant amount of their lead in a late event (e.g. Andersen 2002).

Lead isochrons

Lead isotope data for rock-forming minerals and their corresponding whole-rocks are given in Table 2, and isochron diagrams are shown in Fig. 5. None of the study samples has a perfect fit to mineral isochrons; ages have therefore been cal-

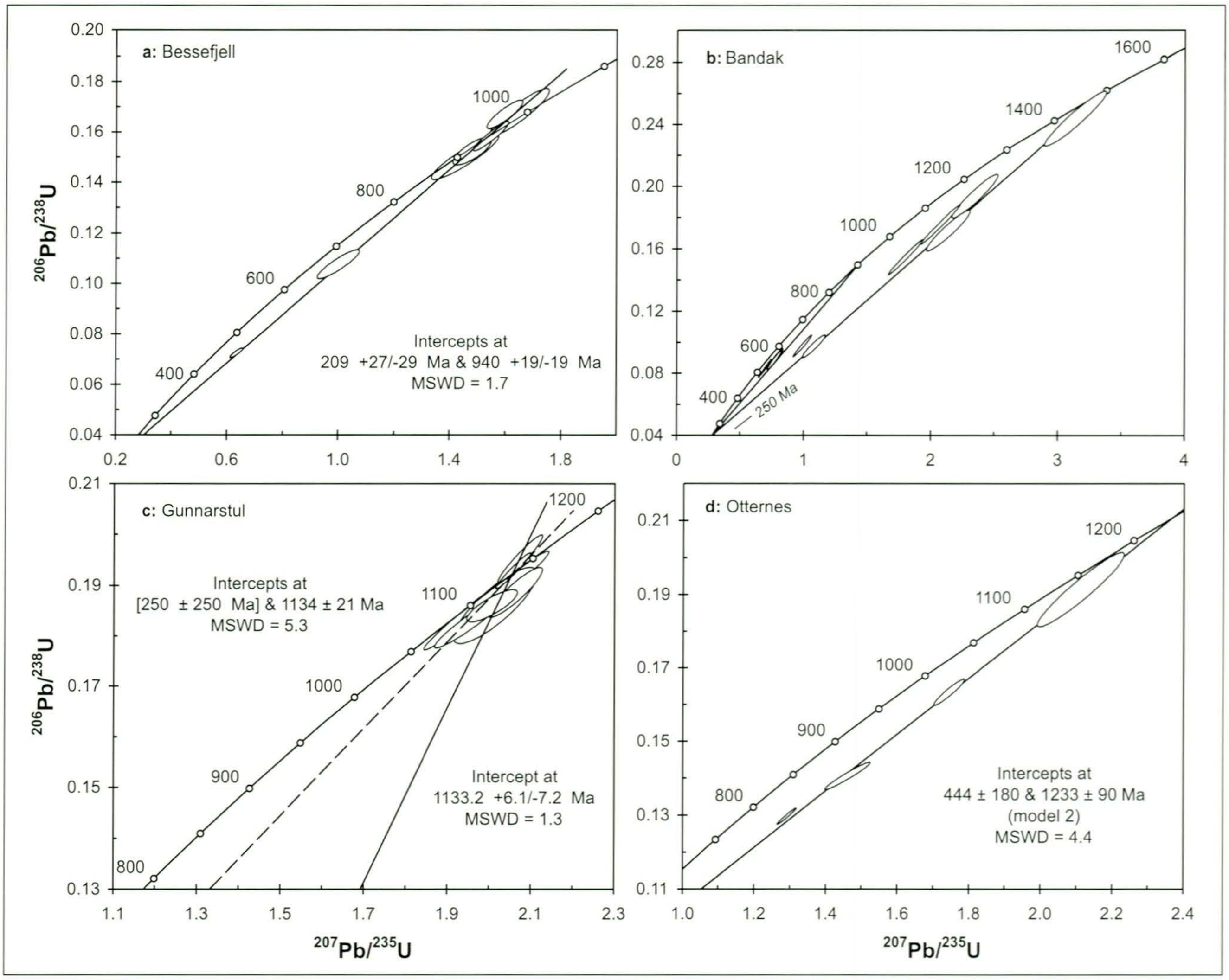

Fig. 4. Concordia diagrams for Group 2 granites. Single SIMS spot analyses are plotted with 2 σ error ellipses.

culated using Model 2 of Isoplot (Ludwig 2000), which assigns equal weight and uncorrelated errors to all points. Three of the four isochrons in Fig. 5 (i.e. Fig. 5b,c,d) are strongly controlled by a single, highly radiogenic mineral, which is titanite in the case of the Byklom, Rosskreppfjord, and Vehuskjerringa granites, and monazite in the Vrådal granite. The *Byklom* granite (Fig. 5a) has less total spread in lead isotope composition than the other three samples, and both apatite and titanite have moderately high radiogenic compositions. The age calculated from the line (983±68 Ma) has a large uncertainty, reflecting the moderate spread, but it agrees with the 980±18 Ma SIMS zircon U-Pb age (Fig. 3f). The *Rosskreppfjord* granite has a larger internal spread in radiogenic isotope composition; the age of 1009 ± 10 Ma is heavily controlled by titanite at $^{206}Pb/^{204}Pb$=493 (Fig. 5b), and agrees within uncertainty with the SIMS U-Pb age (Fig. 3e). The magnetite falls slightly off the isochron line. It should be noted that a K-feldspar separate was not analysed from this granite.

The agreement between U-Pb zircon and Pb-Pb mineral isochron ages for the Byklom and Rosskreppfjord granites is good, suggesting that an internal Pb-Pb isochron based on rock-forming minerals may in fact give a good representation of the emplacement age of a granite, in cases where no metamorphic recrystallization has taken place. Where a granite has been metamorphosed, a Pb-Pb mineral isochron probably reflects the metamorphic recrystallization age, however, rather than the emplacement age (e.g. Andersen et al. 2002a).

Zircon U-Pb ages are not available from the Vrådal and Vehuskjerringa granites, which are Group 1 intrusions from central Telemark. The *Vrådal* intrusion (Sylvester 1964, 1998) gives a Pb-Pb isochron age of 939 ± 20 Ma (Fig. 5c), based on seven points, but which is largely controlled by radiogenic monazite. Kleppe (1980) reported a Rb-Sr whole-rock isochron age of 895±38 for the Vrådal intrusion, whereas Sylvester (1964) published mineral Rb-Sr ages at 877±27 and 908±20 Ma (recalculated to $\lambda^{87}Rb = 1.42 \times 10^{-11}\ a^{-1}$). The present Pb-Pb isochron age of 939 ± 20 Ma is assumed to be the best estimate of the intrusion's age. The *Vehuskjerringa*

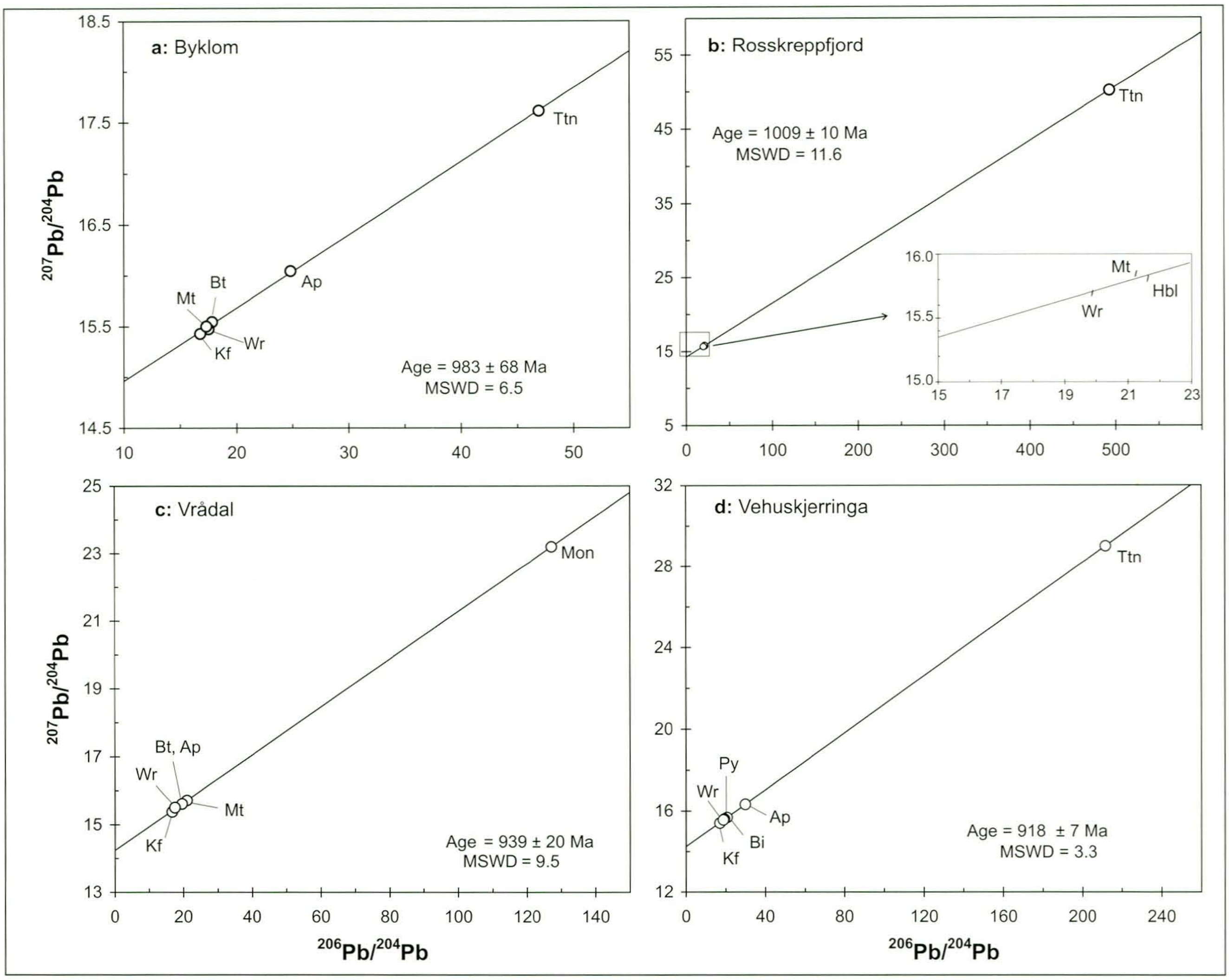

Fig. 5. Internal Pb-Pb isochrons. The circles exaggerate the actual size of the error ellipses. Isochrons are calculated using regression model 2 of Isoplot (Ludwig 2000).

granite yields a better-fitted reference line (MSWD=3.3, Fig. 5d) and an age of 918 ± 7 Ma, which is assumed to represent its emplacement age.

Discussion

Timing of Sveconorwegian granitic magmatism

The present age data (Table 3) are summarized in Fig. 6, which also includes published U-Pb and Pb-Pb ages or ranges of ages for Sveconorwegian magmatic rocks from adjacent parts of South Norway. The compilation of published data in Fig. 6 indicates that 'post-tectonic' granites from across South Norway concentrate in the period 920-950 Ma, which also includes the emplacement of anorthosite, charnockite, and granite in Rogaland (Pasteels et al. 1979) and granites in Caledonian basement windows and the Western Gneiss Region (Corfu 1980). Of the 11 granites dated in the present study, five were emplaced within this age interval (Tovdal, Herefoss, Vrådal, Vehuskjerringa, Bessefjell), and two other intrusions (Høvring and Sæbyggjenut) have age uncertainty ranges extending into this period, although their nominal ages are older. The emplacement of the juvenile Tovdal granite at 940 Ma indicates that mafic magmas were ponded in the lower crust at this time. Although the Tovdal granite is the only known example in the region of a late Sveconorwegian granite with a juvenile geochemical signature, the presence of Group 1 granites containing a well-defined mantle-derived component in all sectors of South Norway suggests that the mafic 'underplating' event was of regional importance.

By contrast, the granites from the Rogaland-Vest Agder sector dated in this study, and possibly the Høvring granite from the southwestern part of the Telemark sector, yield emplacement ages between the main group of post-tectonic granites and the age of the synorogenic granites of the Feda suite. A granitic intrusion from Jølster in the Western Gneiss Region dated by Skår (1998) also falls within this interval. The Grimstad granite in the Bamble sector has been dated at 989 ± 9 Ma by U-Pb on zircons (Kullerud & Machado 1991), but insufficient data have been published for the significance of this date to be evaluated. Onset of Group 1

Table 3. Summary of geochronological results.

		Ages (Ma)							Mineral			
		Concordia		Intercept ages					isochron age		MSWD	Comment
Sample	**Sector**		**2σ**	**Upper**	**+2σ**	**-2σ**	**Lower[1]**	**2σ**		**2σ**		
Group 1 and 3 granites												
Tovdal	T	940	10	947							0.15	
					21	17	[250]	[250]			1.18	
Herefoss	B			920	16	27	[250]	[250]			1.5	
Høvring	T			971	63	34	[250]	[250]			0.98	
				2082	340	200	[971]	[60]				Single, inherited grain
Vrådal	T								939	20	9.5	Model 2 age
Vehuskjerringa	T								918	7	3.3	Model 2 age
Sæbyggjenut	RVA			959	50	32	[250]	[250]			1.7	
Rosskreppfjord	RVA			1036	23	22	416	+39/-44			0.53	
		1020	13								10.2	
									1009	10		Model 2 age
Byklom	RVA			979	9	12					0.96	Negative lower intercept
				970	14	18	[250]	[250]			1.7	
									983	68	6.5	Model 2 age
Group 2 granites												
Bessefjell	T			940	19	19					1.7	
Gunnarstul	T			1133	6	7					1.3	Lower intercept undefined
				1134	21	21	[250]	[250]			5.3	
Otternes	T			1233	90	90	444	180			4.4	Model 2 age

[1]: Lower intercepts ages given in [square brackets] are forced lower intercepts.

granitic magmatism west of the Mandal - Ustaoset shear zone as early as c. 1036 Ma indicates that this region has seen a transition from a shortening to an anorogenic (extensional ?) tectonic regime within c. 15 Ma after the Feda magmatism at c. 1050 Ma.

Sources of inherited zircons

Except for one Early Proterozoic zircon in the Høvring granite and the dominantly inherited population in the Bandak granite, apparently xenocrystic cores do not give ages significantly different from zircons without visible cores (Herefoss, Sæbyggjenut Figs. 2,3). This observation indicates that most of the cores observed formed during early crystallization of the magma itself, or that they lost all radiogenic lead while residing in the granitic magma. The source of the single, old zircon in the Høvring granite cannot be positively identified, but it should be noted that the age of the TIB granitoids would fall within its very wide uncertainty range. The source of inherited zircons in the Bandak granite must have been rocks of c. 1500 Ma age, i.e. of the same age as the rhyolite of the Rjukan Group of the Telemark supracrustal sequence (Dahlgren et al. 1990; Sigmond 1998). The Bandak granite intruded metarhyolite which has not yet been dated, and it is locally rich in xenoliths of metarhyolite (Appendix 1). The presence of abundant, c.1500 Ma zircons in the granite suggests that the country rocks are equivalents of the c. 1500 Ma Rjukan Group metarhyolite, rather than the c.1150 Ma rhyolite of the Bandak Group (Dahlgren et al. 1990, Laajoki et al. 2000).

Age and significance of the Group 2 granites

The Group 2 granites can be divided into an older and a younger group. The 940 Ma Bessefjell granite is coeval with the main group of post-tectonic Group 1 granites. The Gunnarstul and Otternes granites are much older; Gunnarstul is coeval with the anorogenic Gjerstad suite augen gneisses (Bingen & van Breemen 1998) and the imprecise age of the Otternes granite overlaps both these rocks and the younger, c. 1150 Ma volcanism in Telemark (Dahlgren et al. 1990, Laajoki et al. 2000). The Otternes granite has a distinct foliation, which may have been formed in the same tectonic event that formed the gneissic foliation in the c.1150 Ma Gjerstad suite augen gneiss intrusions in the Bamble and Telemark sectors. The Gunnarstul granite lacks this foliation, which may suggest that it was emplaced after the cessation of this tectonic event, or that Sveconorwegian deformation was not pervasive in the eastern part of the Telemark sector.

The wide range of ages for the Group 2 granites indicates that the granitic magmas with a distinct Group 2 geochemical signature did not form in a separate event. Sr, Nd and Pb isotope data suggest collectively that Group 2 granites plot on a mixing line between a juvenile, Sveconorwegian component and a Mid Proterozoic crustal component with highly elevated Rb-Sr ratio (Andersen et al. 2001a). The trace element and isotopic properties of this component resemble both the c. 1500 Ma Rjukan group rhyolite (Menuge & Breweer 1996, Brewer & Menuge 1998) and the 1476 Ma Tinn granite (Andersen et al. 2001a, 2002a), and the presence of Group 2 granites in parts of the Telemark

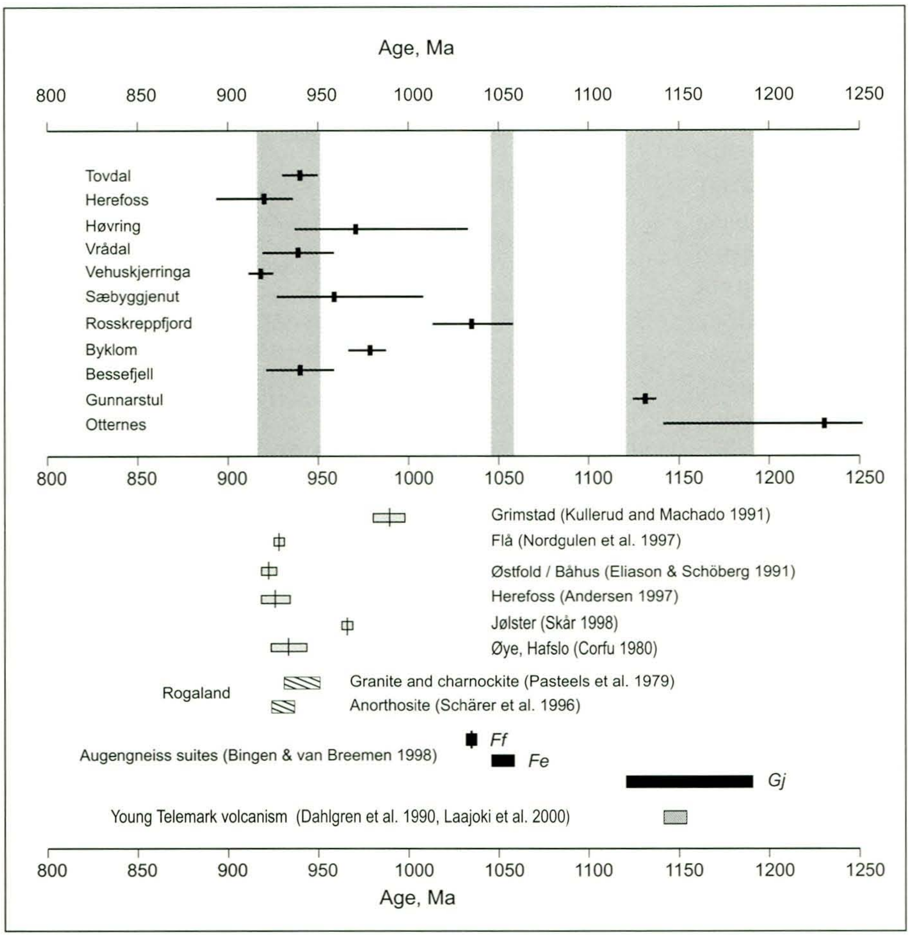

Fig. 6. Summary of geochronologic data from present study, compared to published data. Upper part of figure contains data from present study, given as recommended age ± 2σ (Table 3). Shaded fields represent the time of emplacement of main suite of post-tectonic granites (see text), and of orogenic Feda and anorogenic Gjerstad suite augen gneisses (Bingen & van Breemen 1998). Lower part of the figure summarizes published age data of mid- to late Sveconorwegian igneous rocks from South Norway (including relevant data from basement windows in the Caledonides and from the Western Gneiss Region). The data are given as either 'boxplots' with mean age and ± 2σ confidence interval, where such are available, or as bars indicating total duration of magmatic event. Abbreviations: *Ff:* Fennefoss augen gneiss (Telemark sector), *Fe:* Feda suite augen gneiss, and *Gj:* Gjerstad suite augen gneiss.

sector suggests the existence of deep crustal protoliths of similar chemistry at the time of granitic magmatism.

Tectonic setting

The main event of granite emplacement in the Telemark sector is contemporaneous both with emplacement of large granitic batholiths in the Kongsberg sector (Flå granite) and the area east of the Oslo rift (Østfold / Båhus granite) and with emplacement of granite/charnockite, mafic rocks and anorthosite in Rogaland. Deep crustal melting and emplacement of granitic intrusions throughout south Norway in this period appears to be associated with mafic underplating. On the other hand, the parent magma of the Rogaland anorthosite is assumed to have formed by partial melting of mafic protoliths in the deep crust, without the participation of juvenile, mantle-derived magma (Schärer et al. 1996, Schiellerup et al. 2000).

A common interpretation in orogenic belts is to link post-orogenic plutons to orogenic collapse and decompressional melting (England & Houseman 1988). Such a hypothesis has also been suggested for the generation of post-Sveconorwegian granites in South Norway (Eliasson 1992), but independent evidence for orogenic collapse was not presented. Such data now appear to exist. One line of evidence is provided by the shear zone separating the Bamble and Telemark sectors (Fig. 1). Structural observations across this shear zone demonstrate that it initiated as a top-toward-NW shortening shear around 1090 Ma (Andresen & Bergundhaugen 2001), followed by top-toward-SE extensional shearing and crustal thinning. Another line of evidence in support of collapse of the Sveconorwegian orogen exists in southern Sweden. There, exhumation of eclogite, dated at c. 970 - 956 Ma, has been linked to late-/post-orogenic collapse by Möller (1998, 1999). Thus, temporal and spatial links between extension and post-orogenic granites exist. The juvenile component in some of the granites also suggests that crustal thinning, rather than crustal thickening, is a likely mechanism for magma-generation in the deep crust.

Conclusions

New SIMS U-Pb data on zircons from Sveconorwegian granites from South Norway confirm the existence of an event of granitic magmatism across the region at 920 to 950 Ma. The emplacement of juvenile, mantle-derived material into the crust in this period is demonstrated by the 940 Ma Tovdal granite and by the presence of distinct, mantle-derived components in the other granites. In the western part of South Norway (west of the Mandal-Ustaoset shear zone), this magmatism started earlier, possibly as early as c. 1030 Ma, and was of longer duration. Granites formed in this event include both intrusions with normal trace element distributions (Group 1 of Andersen et al. 2001a) and intrusions with distinct, negative Sr concentration anomalies and high initial ^{87}Sr/^{86}Sr ratios (Group 2 granites of Andersen et al. 2001a). The 'low Sr' granites thus reflect the presence in the deep crust of a protolith of suitable composition (e.g. rocks related to the c. 1500 Ma metarhyolite of the Rjukan Group) and not the existence of a separate event of granitic magmatism. Group 2 granites also formed much earlier (before 1120 Ma), however, simultaneous with emplacement of anorogenic granite of the Gjerstad augen gneiss suite. This conclusion suggests that granites with a Group 2 geochemical signature could form in the region whenever mafic, mantle-derived magmas came into contact with suitable protoliths in the lower crust. The emplacement of mafic magmas into the crust and the resulting anorogenic granitic magmatism is most likely related to extensional tectonic events, one of which may have been of regional extent in South Norway (the 'Gjerstad augen gneiss event'), the other an orogen-wide event of late-/post-orogenic collapse.

The present study gives a somewhat two-sided impression of the importance of inherited zircons in these granites. Whereas one of the granites studied is totally dominated by inherited zircons, to the extent that its emplacement age cannot be determined from the SIMS data obtained, apparent xenocrystic cores in other granites have ages indistinguishable from the bulk of the zircon populations. This may suggest that the cores formed at an early stage of the crystallization history of the magma itself, or that their U-Pb system was totally reset in the magma. Spatially resolved Hf isotope data by laser ablation ICPMS are needed to distinguish between these two mechanisms.

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Appendix 1

Petrography and field relationships of samples analysed

Sample numbers are taken from Andersen (1997) and Andersen et al. (2001a). Localities are given by UTM coordinates (map datum: WGS84).

Bandak 072196-3 (32VML658849): Fine-grained and weakly foliated, two-feldspar biotite leucogranite, with traces of secondary chlorite and epidote. Zircon and monazite are accessory minerals. The pluton intruded metavolcanic supracrustal rocks, which also occur as xenolithic screens within the intrusion.

Bessefjell 072496-2 (32VML412952): Massive, medium-grained, two-feldspar biotite granite, intruding quartzite and metabasalt of the Telemark Supracrustal sequence. Dated to 904±16 Ma by Rb-Sr (Killeen & Heier 1975, recalculated with λ^{87}Rb=1.42 $\times 10^{-11}$ a^{-1}).

Byklom 083096-3 (32VML083833): Medium-grained, massive, gray, two-feldspar granite. Titanite and magnetite are minor minerals; pyrite, zircon and allanite are accessory phases.

Gunnarstul 083193-1 (32VMM879073): Fine-grained, massive, two-feldspar biotite granite, with secondary muscovite. The plagioclase is extensively sericitized, and biotite is chloritized. The Gunnarstul granite intruded mafic metavolcanic rocks of the Telemark supracrustal sequence.

Herefoss 107/92 (32VVMK594804): Coarse-grained, foliated, biotite-hornblende granite (Andersen 1997).

Høvring 082996-2 (32VMK396014) Two-feldspar biotite granite with minor hornblende and accessory titanite, allanite, apatite, pyrite, and zircon. The Høvring (or Høvringsvatn) complex is a composite intrusion, consisting of granite, and younger, monzonitic intrusive facies. Granites in the complex have been dated at 945 ± 53 by a whole-rock Rb-Sr isochron (Pedersen 1981).

Otternes 072696-2 (32VNL149794): Foliated, two-feldspar leucogranite with minor titanite, biotite, magnetite, and allanite. Intrudes granitic gneiss and quartzite.

Rosskreppfjord 080296-4 (32VLL939463): Coarse-grained, two-feldspar, biotite-hornblende granite with minor titanite and magnetite, and accessory zircon.

Sæbyggjenut 072496-3 (32VML254926): Coarse-grained 'tricolor' biotite - hornblende granite with pink perthite, pale green plagioclase, and clear quartz. Apatite, titanite, magnetite, and pyrite are accessory minerals.

Tovdal 072396-3 (32VML544170): Weakly foliated, biotite-hornblende granite with minor titanite, apatite, magnetite, and fluorite, and accessory allanite and zircon. The Tovdal granite intruded banded gneiss, probably of supracrustal origin.

Vehuskjerringa 072496-1 (32VMM546120): Medium grained biotite granite with magnetite, titanite, and apatite, intruding quartzite, quartz schists, and metabasalt of the Bandak Group.

Vrådal 081696 (32VML740747): Two-feldspar biotite granite intruding granitic gneiss (Sylvester 1964, 1998).