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Karsten Obst · Jörg Hammer · Gerhard Katzung · Dietmar Korich

The Mesoproterozoic basement in the southern Baltic Sea: insights from the G 14–1 off-shore borehole

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Abstract The continuation of the Mesoproterozoic basement of the southern Fennoscandian Shield is documented in the G 14–1 off-shore borehole, northeast of the island of Rügen, where crystalline rocks of monzogranitic composition occur beneath flat-lying early Palaeozoic sediments at a depth of approximately 2,000 m. The greenish-grey, or partly reddish-grey, granites show a slightly porphyritic texture marked by plagioclase crystals or aggregates in a groundmass dominated by fresh microcline. Chloritized biotite occurs as a subordinate mafic phase. Ductile and brittle deformation is indicated by a weak foliation and the occurrence of several cataclastic zones, respectively. Major and trace element geochemistry suggest that these rocks are K-rich calc-alkaline granites and represent a restite-poor melting product of a granodioritic protolith. The low MgO, Cr, Ni and Co concentrations and relatively high content of accessory phases (apatite, zircon) point to formation of water undersaturated, high temperature (>900 °C) melts at low degrees of partial melting. Although the G 14 granite lacks hornblende, in contrast to most of the granites from Bornholm, it seems geochemically related to them. Analysed samples mostly fit an intermediate position between the Rønne and Vang granitoids, which both belong to a group of Mesoproterozoic intrusions showing partial ductile deformation. (Y+Nb) vs. Rb plots suggest that all these granitic rocks were generated in intracratonic conditions. A genetic relationship between them and contemporaneously intruded Karlshamn-group granites in Blekinge, eastern Scania and Småland is supported by intrusion age of 1,460±3 Ma obtained from Pb-Pb isotope ratios measured on single zircons of the G 14 granite.

Keywords Blekinge-Bornholm · Danopolonian Orogeny · Fennoscandian Shield · G 14 granite · Mesoproterozoic crust · NE Germany · Pb-Pb zircon ages

Introduction

The Baltic Sea off-shore borehole G 14–1 was drilled in 1986 at a position ~30 km northeast of the German island of Rügen. The drill cores give information about the lithostratigraphic succession at the southern margin of the East European Craton and allow conclusions about crustal evolution to be drawn. The early Palaeozoic cover sequence is similar to that known from the Danish island of Bornholm, and Scania in southernmost Sweden. The sediments represent flat lying deposits at the passive margin of Baltica and document the successive development of a foreland basin during the collision with Avalonia and accretion of the Danish-North German-Polish Caledonides (Beier and Katzung 1999; cf. Katzung 2001).

Crystalline rocks first occur at a total depth of 1,941.7 m including water depth (38.6 m) and height of platform above water surface (29.5 m). Piske and Neumann (1993) described them as microcline granite. Franke et al. (1994), however, referred to these rocks as foliated migmatite with partial porphyritic texture. Tschernoster (2000) could show that U-Pb age of the G 14 granite is similar to the granitic rocks of Bornholm, all ranging between 1.5 and 1.4 Ga.

Results of petrographical and geochemical investigations and age determinations on samples of the G 14

K. Obst (✉)
Geologischer Dienst,
Landesamt für Umwelt, Naturschutz und Geologie
Mecklenburg-Vorpommern,
Goldberger Straße 12, 18273 Güstrow, Germany
e-mail: karsten.obst@lung.mv.-regierung.de
Tel.: +49-3438-777711

J. Hammer
Bundesanstalt für Geowissenschaften und Rohstoffe,
Stilleweg 2, 30655 Hannover, Germany

G. Katzung
Ernst-Reinke-Str. 23,
10369 Berlin, Germany

D. Korich
Majakowskistr. 6,
18435 Stralsund, Germany

granite are presented in this paper, and the relation between the basement of the southern Baltic Sea and the Mesoproterozoic granitic rocks of Bornholm and Blekinge, southeastern Sweden, is discussed.

The crustal evolution of southern Scandinavia

The East European Craton is composed of three major crustal segments, Fennoscandia, Sarmatia and Volgo-Uralia, which formed a continent (Baltica) after amalgamation in the late Palaeoproterozoic (Gorbatschev and Bogdanova 1993). The crust of the southern part of Fennoscandia can be subdivided into the Svecofennian domain, mainly formed at about 1.90 to 1.86 Ga, in the east and the complex Sveconorwegian domain in the west, which suffered a high pressure metamorphic event between 1.0 and 0.9 Ga (e.g. Gaál and Gorbatschev 1987; Söderlund 1999). These units are separated from each other by the Transscandinavian Igneous Belt (TIB), mainly composed of 1.81 to 1.66 Ga old granites and related volcanic rocks (e.g. Åhäll and Larson 2000), and the Protogine Zone (PZ), which approximately coincides in the southern part with the Sveconorwegian Frontal Deformation Zone (Wahlgren et al. 1994). These tectonic zones do not separate different crustal segments because similar granitic rocks are exposed on both sides of the PZ, although with different degrees of deformation (Gorbatschev, personal communication 1999). Towards the SW, the granites are strongly affected by the Sveconorwegian orogeny and are now represented by gneissic granitoids (Connelly et al. 1996; Söderlund et al. 1999). On the basis of U-Pb age determinations several igneous belts can be distinguished between the TIB and the Oslo Rift which suggest a stepwise westward growing of the crust (Åhäll and Larson 2000).

A different evolution can be deduced for the crustal rocks of southeastern Sweden (Blekinge with adjacent areas in Scania), and the Danish island of Bornholm (Fig. 1). In Blekinge, the basement rocks seem to be separated from TIB granites in the north by a nearly E–W-oriented shear zone. South of this Småland-Blekinge Deformation Zone (SBDZ), the oldest crust apparently formed between 1.8 and 1.7 Ga (Johansson and Larsen 1989). Between 1.5 and 1.4 Ga older gneisses and granitoids were intruded by younger granites (e.g. Åberg et al. 1985a, 1985b; Kornfält and Vaasjoki 1999) showing different degrees of deformation. Nearly contemporaneously, the deformed supracrustal rocks of Bornholm were also intruded by a suite of granites (Larsen 1980; Tschernoster 2000). And, as in Blekinge, a penetrative foliation in the basement rocks, general WNW–ESE-oriented, is developed which coincides with several similarly oriented shear zones.

The deformation of the supracrustal rocks and emplacement of the younger granites in Blekinge and Bornholm is assumed to represent an orogenic event south of the exposed shield area termed the Danopolonian orogeny by Bogdanova (2001). These processes might also be related to a thermal event at 1.46 to 1.42 Ga in SW Sweden (so-called Hallandian orogeny; Hubbard 1975), which is suggested by formation of secondary zircon in orthogneisses and associated with extensive veining and intrusion of felsic dykes (Christoffel et al. 1999; Söderlund 1999).

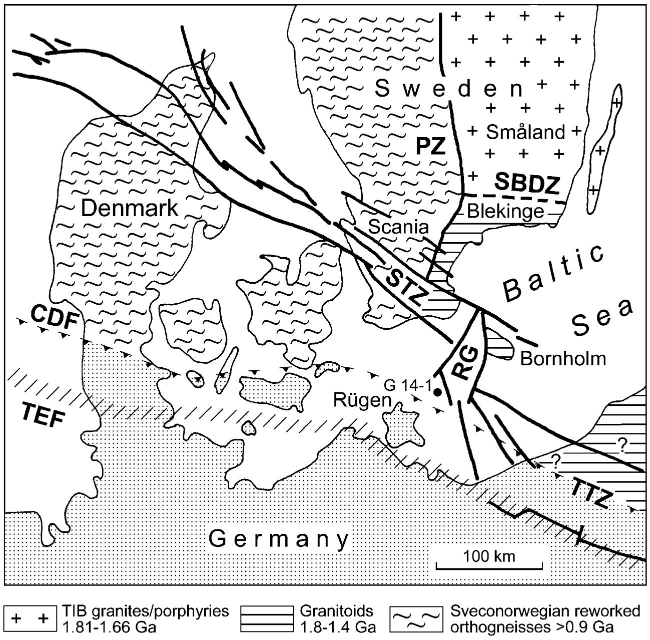


Fig. 1 Simplified sketch showing different domains of Proterozoic rocks in southern Fennoscandia (without Phanerozoic cover) and major tectonic fault zones (Berthelsen 1988, 1992, modified). The *dotted area* represents the accreted crust of Avalonia. *CDF* Caledonian Deformation Front, *PZ* Protogine Zone, *RG* Rønne Graben, *SBDZ* Småland-Blekinge Deformation Zone, *STZ* Sorgenfrei-Tornquist Zone, *TEF* Trans-European Fault, *TTZ* Tornquist-Teisseyre Zone

Basement rocks of Blekinge and adjacent areas

The oldest dated rocks of southeastern Sweden are the Tving granitoids, which crop out in the N and E of the province Blekinge (Fig. 2a), and have an age of 1.77 Ga obtained by U-Pb measurements on zircons (Johansson and Larsen 1989; Kornfält 1993). This age is typical for the Småland TIB granites to the north of the SBDZ (Jarl and Johansson 1988; Kornfält 1993; Åhäll and Larsen 2000), but the Tving granitoids are more mafic and mostly have higher K/(K+Na+Ca) ratios (Lindh et al. 2001).

Rocks of the Västanå formation, which occur in a narrow NNW trending zone along the border between Blekinge and Scania, parallel to the PZ (Kornfält and Bergström 1983), show a slightly younger age. The suite comprises acid metavolcanites, metabasites, quartzites and mica schists. Towards the east, it gradually passes into the "Coastal Gneiss" of Blekinge, which probably represents a pile of metamorphosed acid volcanics. U-Pb

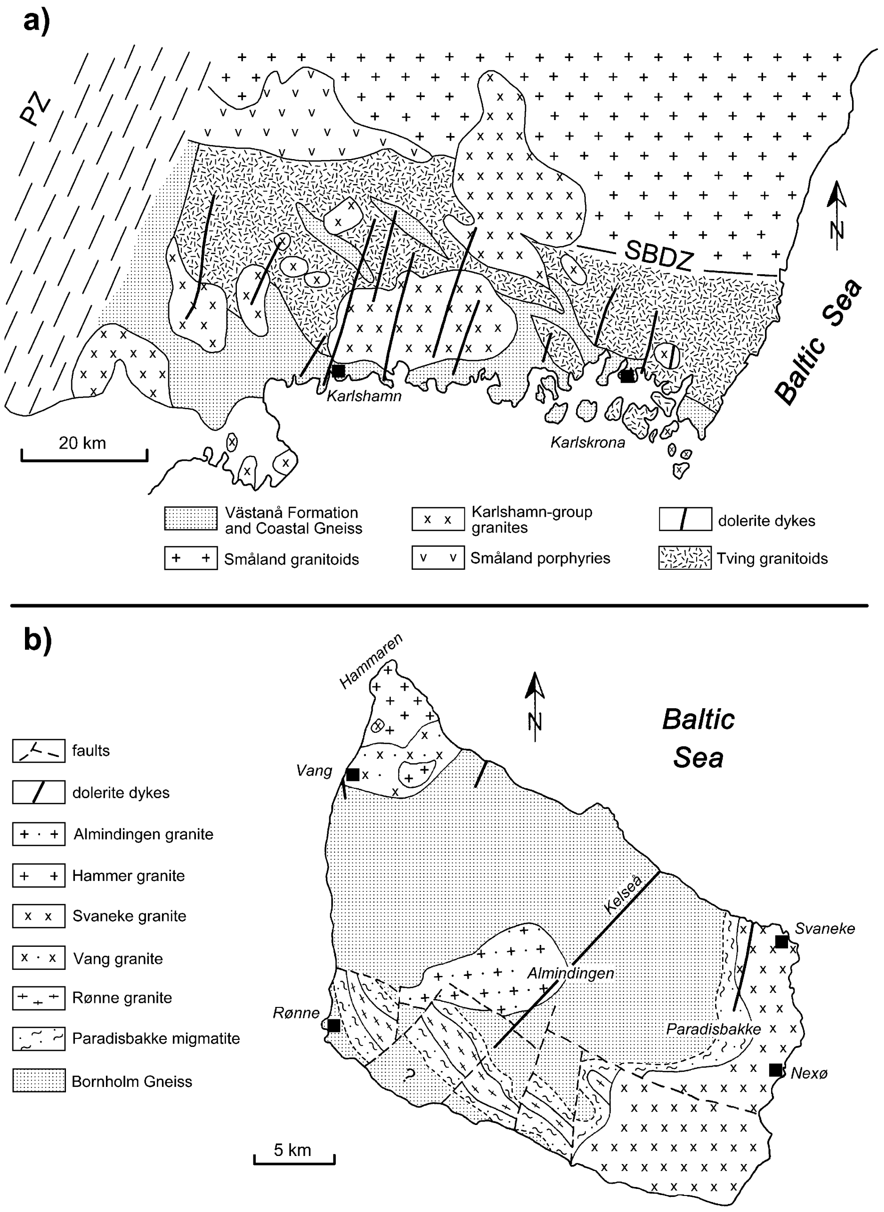


Fig. 2 Distribution of Precambrian rocks in Blekinge (**a**; Johansson and Larsen 1989, modified), and on the Danish island of Bornholm (**b**; Katzung 1994, modified)

zircon ages are about 1.70 Ga for the Västanå rocks and the "Coastal Gneiss" (Johansson and Larsen 1989).

The rocks mentioned above are regionally metamorphosed under greenschist to amphibolite facies conditions and subsequently sheared, possibly during the Danopolonian Orogeny. Folding and deformation took place between 1.7 and 1.45 Ga ago. The lower limit is suggested by the age of the partly deformed and partly undeformed Karlshamn-group granites that intruded these units. The coarse-grained, porphyritic Karlshamn and Eringsboda granites, which form large massifs, the medium- to fine grained Spinkamåla granite and the foliated Vånga granite are considered to belong to this group of granites. The Karlshamn type contains 1 to 5 cm K-feldspar phenocrysts in a groundmass of plagioclase, K-feldspar, quartz and biotite. The Spinkamåla type is less porphyritic, and the K-feldspar, which often occurs as Karlsbad twins, only reaches lengths up to 1 cm. Both types are mostly greyish, contrary to the similar composed, coarse-grained Vånga granite, which is more reddish. Detailed petrographic descriptions of these rock types are given by Kornfält and Bergström (1983, 1990) and Lundegårdh (1978).

Based on U-Pb zircon data Åberg (1988) suggest a 1.40 Ga intrusion age for the Karlshamn granite. Slightly older U-Pb ages of 1.45 Ga were presented by Kornfält (1996) and Kornfält and Vaasjoki (1999). A similar chemical U-Th-Pb zircon age was obtained for the Vånga granite (Geisler and Schleicher 2000).

Nearly at the same time, the small Götemar and Jungfrun granites intruded north of the SBDZ at the eastern coast of Småland (Åberg et al. 1983, 1984). Furthermore, it should be noted that also the Beden granodiorite from the Romeleåsen horst in SE Scania has an U-Pb zircon age of 1.45 Ga (Johansson et al. 1993). Similar ages were reported for the granitic intrusions of Stenshuvud and Tåghusa in Linderödsåsen in eastern Scania (Čečys et al. 2002), which also belong to the Karlshamn-group granites.

The Mesoproterozoic rocks of Blekinge are cut by several dolerite dykes, which trend approximately NNE. They belong to a dyke swarm that can be followed northwards as far as Dalarna. They intruded at about 0.95 Ga (Johansson and Johansson 1990; Söderlund 1999).

Basement rocks of Bornholm

Bornholm is a slightly southwards-inclined horst structure bordered by NW and NNE trending faults. Precambrian rocks are exposed in the northern and central parts of the island, whereas they are buried beneath remains of Lower Palaeozoic and Mesozoic cover sediments towards the south. The crystalline basement consists of Mesoproterozoic gneisses and various granites (Fig. 2b). The so-called Bornholm Gneiss is the dominant rock type: it has either a light grey or reddish colour. The fine-grained gneisses are mainly composed of K-feldspar, quartz and plagioclase and contain different amounts of mafic minerals (biotite and hornblende) which are aligned in layers. Relics of hypersthene and diopsidic pyroxene occur only locally within the hornblende crystals, e.g. near Maegård (Micheelsen 1961), but are difficult to explain (Jørgart and Nielsen 1995). A few inclusions of folded quartzites, phyllites, leptitic gneisses (Noe-Nygaard 1957), skarns (Callisen 1956), feldspathic sandstones and volcanic rocks (Jørgart 1977) have been reported, suggesting the existence of an older supracrustal complex, now eroded away.

Towards the south and east the gneisses are surrounded by relatively dark rock types which either have a partly foliated (Rønne granodiorite) or migmatitic texture (Paradisbakke migmatite). They were thought to represent the bottom of a crustal pile initially folded and metamorphosed in granulite facies and later granitized under amphibolite-facies conditions (Micheelsen 1961), but more likely is that granodioritic melts intruded at relatively deep levels in the crust under transpressional conditions (Bogdanova 2001, personal communication). Anatexis of the gneisses and granitoids, however, is indicated by the occurrence of leucocratic veins, schlieren and melanocratic restites (Jørgart and Nielsen 1995). These restites contain a higher amount of mafic minerals, mainly hornblende. Partial melting is further indicated by a gradual change of texture between the gneiss and a small occurrence of “Hallegård granite” in the eastern part of the island (Jørgart 1982). In NW Bornholm, the grey, partially penetratively deformed Vang granite is separated from the Bornholm Gneiss, but it has a similar composition and no sharp border could been found during mapping along the western coast of the island. Typically, hornblende and biotite occur in small clusters.

The gneisses, migmatites and granitoids display a marked foliation which mostly is oriented approximately WNW–ESE (e.g. Micheelsen 1961). Only in the eastern part of the island it turns into N–S direction, probably induced by the younger intrusion of the Svaneke granite. Similar $^{207}Pb/^{206}Pb$ model ages obtained from discordant U-Pb measurements on zircon fractions were calculated for the Bornholm Gneiss, the Rønne granodiorite and the Vang granite pointing to an intrusive event at 1.45 Ga (Tschernoster 2000). The zircons of the gneiss contain relict cores. Geisler-Wierwille (1999) postulated a protolith age of more than 1.7 Ga. Preliminary U-Pb zircon dating has yielded an age of about 1.47 Ga for the Rønne granodiorite (Johansson et al. 2004). Measurements on zircons from the Paradisbakke migmatite were less successful and the data display disturbances of the U-Pb system, probably due to Pb-loss (Tschernoster 2000).

Medium-grained, leucocratic granites intruded into the older rock types in the northwestern and central part of Bornholm forming the distinct bodies of the Hammer and Almindingen granites, respectively (e.g. Callisen 1934). These reddish, K-feldspar and quartz-rich rocks contain only small amounts of mafic minerals, mostly biotite. In the east the simultaneous intrusion of a large pluton, represented by the Svaneke granite complex may have caused the intense folding in the neighbouring metamorphic rocks (cf. Platou 1970). Different grain size and flow patterns within the complex might reflect several intrusion stages. The dominant coarse-grained variety probably intruded the fine-grained roof of the batholith. Rb-Sr analyses of Larsen (1980) suggest that these “younger” granites were formed at about 1.4 Ga. The U-Pb zircon age for the Svaneke granite is about 1.45 Ga (Johansson et al. 2004). Geisler-Wierwille (1999) obtained an U-Th-Pb zircon age of 1.42 Ga for the Hammer granite.

Besides the major rock types, veins and lenses of pegmatites, aplites and leucogranites are found. Furthermore, the gneissic and granitic rocks are cut by several younger, undeformed dolerite dykes of which the Kelseå dyke is the oldest (about 1.3 Ga, cf. Obst 2000).

Granites of the G 14–1 off-shore borehole

The G 14–1 off-shore borehole is situated west of the Adler Ground in the southern Baltic Sea, about 30 km northeast of Rügen and approximately 50 km southwest of Bornholm (Fig. 1). It has penetrated a fine- to medium-grained, partly porphyritic biotite granite, which occur between 1941.7 to 1997.0 m (final depth). The greenish-grey, but partly (primarily?) reddish-grey rocks show foliation dipping 45°.

Several cataclastic and mylonitic shear zones occur within the granite itself and at the border to the overlying Lower Cambrian sandstones. These zones are more than 10 cm thick with diffuse borders and dip with angles between 40 and 60° in opposite direction to the foliation planes.

Table 1 Typical modal analyses (vol%) of Mesoproterozoic granitic rocks from the G 14–1 borehole (this paper), Bornholm (Micheelsen 1961) and Blekinge (Kornfält and Bergström 1983, 1990). *bt* biotite, *hbl* hornblende, *kfsp* K-feldspar, *pl* plagioclase, *q* quartz

Rock type	kfsp	pl	q	hbl	bt	Others
G 14–1						
granite (*n*=10)	37	30	21	±	8	4
Bornholm						
Dark gneiss	35	24	25	5	7	5
Light gneiss	38	22	30	2	6	3
Paradisbakke migmatite	35	25	23	8	7	2
Rønne granodiorite	29	30	21	10	5	5
Vang granite	33	22	27	5	6	5
Svaneke granite	36	26	25	2	7	3
Hammer granite	41	18	33	1	4	3
Blekinge						
Vånga granite (Ivö klack)	51	17	25	0	5	2
-”- (Knutstorp)	44	7	43	0	4	2
-”- (Knutstorp)	41	12	46	0	±	1
Karlshamn granite (Ekestad)	34	37	12	2	7	8
-”- (Stärnö)	28	33	23	2	7	7
-”- (Hanö)	37	32	15	0	4	12
Spinkamåla granite (Joggesö)	48	26	23	±	1	2
-”- (Hundsjön)	34	35	20	0	9	2
-”- (Ugglesjön)	44	26	22	0	3	5

Petrography

The granite samples taken from different depths of the G 14–1 borehole consist of subhedral K-feldspar (37%, mostly fresh microcline), turbid plagioclase (30%, partially altered into a mixture of sericite, clay minerals, calcite and epidote), quartz (21%) with slightly undulatory extinction, greenish pale and often totally chloritized biotite (8%). Accessory minerals are titanite, epidote, apatite and, in lesser amounts, opaques and zircon.

Rare phenocrysts of mostly xenomorphic or corroded plagioclase crystals or aggregates, which range in size between a few mm and 2 cm, occur in a fine-grained (0.2–0.5 mm) groundmass with granular texture. They are often altered and sometimes replaced by K-feldspar. They show poikilitic intergrowths with biotite, quartz, titanite and rare muscovite. The shaggy chloritized biotite flakes are partly aligned in parallel defining a weak foliation. The G 14 granite contains no hornblende, in contrast to most of the granitic rocks from Bornholm.

Modal analyses of 13 samples show no difference in mineralogy between the greenish and reddish varieties. They mostly have a typical monzogranitic composition (Table 1). The reddish variety contains more accessory titanite and two samples (G 14–11 and G 14–4) exhibit rounded grains of a strongly altered mafic phase (amphibole?), which is rimmed by titanite crystals.

Leucocratic, pegmatitic schlieren occur locally. They are composed of quartz, microcline and minor amounts of sericitized plagioclase. The mineral grain size varies between 0.5 mm and more than 1 cm. Graphophyric intergrowths are rare. These rocks are intensely fractured and thin fissures are filled with alteration products that consist of a mixture of sericite, clay minerals and calcite.

Recrystallization features are common in most granite samples but one sample taken from a cataclastic zone shows a “sandstone-like” texture. Rounded clasts or mineral relics of the granite are surrounded by a greenish, cryptocrystalline matrix, which consists of clay minerals, sericite and calcite. The size of the fragments varies between a few mm and 2 cm. The groundmass grains range from less than 0.1 to 0.3 mm. The clasts are fractured and the fissures are annealed with calcite and sericite.

Geochemistry

Major and trace element compositions of 12 granite samples, two pegmatitic samples and one sample taken from a cataclastic zone were determined by XRF spectrometry on glass beads. Sample preparation was done using a WC jaw-crusher and an agate mill in Greifswald. The analyses were performed at the Geochemical Laboratory of the University of Göttingen. Furthermore, six samples were selected for determination of REE and other trace elements as shown in Table 2 using an ICP-MS at the BGR in Hanover.

The general monzogranitic composition of the G 14 granite samples determined on the basis of mineralogy is well supported by the geochemical data. In a mesonormative plot nearly all samples are within the QAPF field 3b of the IUGS classification diagram (Fig. 3). The reddish variety can be distinguished from the greenish-grey variety by higher CaO and Sr contents and slightly lower K_2O and Rb concentrations. Trace element patterns normalized to continental crust also suggest only slight differences in composition between the granite samples, but the reddish variety (sample G 14–9) deviates and shows higher REE concentrations, probably due to the relatively high amount of accessory titanite (Fig. 4a).

SiO_2, K_2O und Rb are enriched in the sample from the cataclastic zone, while the concentrations of TiO_2, Fe_2O_3, MgO, Na_2O, P_2O_5, Ba, Co, Sr, V, Zn and Zr are depleted. The leucocratic pegmatites also show higher concentrations of SiO_2, K_2O and Rb, but lower values for all the other analysed elements (Fig. 4b).

When comparing the geochemistry of the G 14 granites with granitic rocks of the basement from Bornholm similarities are evident (Fig. 5). The gneisses and granites from Bornholm outline a differentiation trend in several plots of major elements vs. SiO_2 content. The leucocratic Hammer and Almindingen granites, which show a very similar geochemistry, are the most differentiated rocks of this suite. The gneisses could be considered as their protoliths, while the more mafic granites and migmatites, however, are probably restites formed during partial melting of the gneisses or similar crustal rocks.

Table 2 Major and trace element geochemistry of crystalline rocks from the G 14–1 off-shore well. XRF data – normal, ICP-MS data – italic. *Fe is analysed as total Fe_2O_3

Sample	G14–15	G14–14	G14–13	G14–12	G14–6	G14–5	G14–11	G14–4	G14–3	G14–10	G14–2	G14–9	G14–8	G14–7	G14–1
Depth	1,934–1,943	1,934–1,943	1,943–1,949.7	1,943–1,949.7	1,943–1,949.7	1,943–1,949.7	1,943–1,949.7	1,943–1,949.7	1,943–1,949.7	1,943–1,949.7	1,943–1,949.7	1,986–1,988	1,986–1,988	1,986–1,988	1,986–1,988
Below top	7.75–7.97	8.53–8.65	0.40–0.50	1.06–1.28	1.40–1.50	2.00–2.05	4.25–4.42	4.60–4.70	5.60–5.70	6.35–6.52	6.70–6.90	0.11–0.26	1.03–1.18	1.57–1.70	1.80–1.90
Type	Greenish	Pegmatitic	Cataclastic	Greenish	Pegmatitic	Greenish	Greenish	Greenish	Reddish	Reddish	Reddish	Reddish	Greenish	Greenish	Greenish
wt%															
SiO_2	64.9	74.2	68.0	66.1	73.8	65.7	65.0	65.1	65.1	64.8	64.9	63.8	63.6	65.9	64.3
TiO_2	0.887	0.046	0.600	0.906	0.116	0.898	0.859	0.906	0.909	0.906	0.896	0.941	0.883	0.844	0.922
Al_2O_3	14.8	12.9	14.3	14.5	12.5	15.2	14.8	14.6	14.5	14.4	14.6	14.7	14.4	13.9	14.6
Fe_2O_3*	3.94	1.29	2.82	4.06	2.94	4.75	4.95	5.22	5.02	5.04	4.94	5.02	4.93	4.35	5.07
MnO	0.096	0.024	0.084	0.080	0.041	0.059	0.070	0.074	0.086	0.076	0.088	0.101	0.101	0.088	0.097
MgO	0.68	0.18	0.58	0.74	0.52	0.81	0.86	0.82	0.94	0.90	0.95	0.97	1.00	0.90	1.15
CaO	1.86	0.41	1.66	1.77	0.51	1.02	1.36	1.73	2.75	2.28	2.78	2.92	1.06	1.74	1.68
Na_2O	2.36	1.91	1.51	3.12	1.63	3.35	3.66	3.38	3.69	3.79	3.49	3.78	3.43	3.30	3.19
K_2O	6.00	7.36	6.54	5.12	5.98	5.36	4.79	5.08	4.76	5.16	5.02	4.09	5.98	5.81	6.02
P_2O_5	0.195	0.012	0.046	0.353	0.02	0.335	0.325	0.348	0.334	0.335	0.332	0.34	0.322	0.306	0.338
ppm															
Ba	*1,140*	*440*	*880*	*1,120*	764	1,054	1,014	1,025	1,266	1,346	1,275	*1,220*	*1,420*	1,280	1,367
Ce	*89.9*	*9.98*	*115*	*163*	70	135	127	130	135	142	142	*158*	*160*	118	143
Co	*8.0*	*3.8*	*6.4*	*8.7*	6	9	11	11	11	11	9	*8.7*	*10.2*	9	6
Cs	*3.50*	*3.73*	*4.18*	*1.58*								*1.34*	*1.27*		
Ga	*17.7*	*12.2*	*18.3*	*17.3*	16	17	18	18	17	18	21	*20.9*	*18.1*	18	19
Hf	*9.64*	*1.25*	*7.04*	*9.07*								*7.67*	*8.66*		
La	*35.9*	*5.0*	*60.6*	*68.2*								*68.8*	*74.6*		
Nb	*20.1*	*2.79*	*13.4*	*19.6*	7	22	20	21	22	22	23	*19.2*	*19.7*	22	21
Pb	*9.8*	*10.6*	*10.4*	*8.6*	12	11	22	12	16	11	20	*19.7*	*11.8*	15	20
Rb	*194*	*362*	*223*	*143*	267	151	132	140	133	145	137	*134*	*196*	178	211
Sc	*9.1*	*1.0*	*10.5*	*10.0*	6	7	8	14	9	10	13	*11.6*	*10.4*	11	9
Sr	57	50	46	88	60	76	98	95	202	181	190	163	58	84	81
Ta	*1.46*	*0.57*	*0.98*	*1.45*								*1.29*	*1.46*		
Th	*13.4*	*7.99*	*15.8*	*13.5*	33	12	9	12	10	10	12	*12.5*	*12.9*	11	12
U	*3.87*	*0.43*	*3.25*	*2.61*								*3.11*	*2.67*		
V	*45*	*6*	*34*	*45*	11	37	43	44	39	42	44	*48*	*42*	35	40
W	*25*	*28*	*27*	*28*								*22*	*25*		
Y	*38.9*	*5.27*	*35.9*	*40.6*	24	57	45	40	60	59	60	*68.6*	*44.1*	52	56
Zn	*109*	*13*	*54*	*83*	71	61	102	140	101	89	90	*96*	*93*	92	100
Zr	482	36	342	478	120	497	480	489	478	486	480	498	485	449	488
Pr	*11.1*	*1.03*	*12.4*	*17.5*								*17.8*	*17.4*		
Nd	*43.4*	*3.82*	*45.1*	*64.7*								*67.7*	*64.9*		
Sm	*9.11*	*0.86*	*8.55*	*12.0*								*12.9*	*11.6*		
Eu	*1.98*	*0.24*	*1.62*	*2.55*								*3.01*	*2.57*		
Gd	*8.05*	*0.96*	*7.13*	*10.1*								*11.9*	*9.85*		
Tb	*1.17*	*0.17*	*1.03*	*1.38*								*1.81*	*1.39*		
Dy	*7.08*	*1.12*	*6.25*	*7.76*								*11.3*	*8.21*		
Ho	*1.42*	*0.24*	*1.25*	*1.46*								*2.26*	*1.55*		
Er	*4.24*	*0.74*	*4.01*	*4.39*								*6.71*	*4.56*		
Tm	*0.65*	*0.13*	*0.63*	*0.66*								*0.99*	*0.67*		
Yb	*4.70*	*0.96*	*4.57*	*4.51*								*6.51*	*4.56*		
Lu	*0.78*	*0.17*	*0.76*	*0.74*								*1.01*	*0.75*		

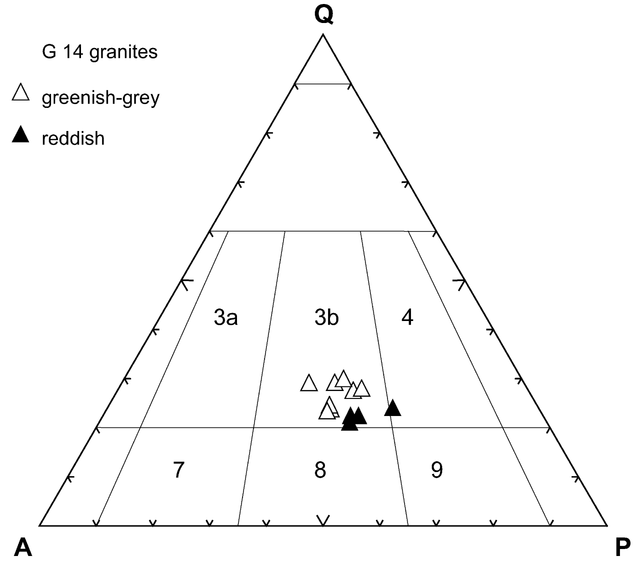


Fig. 3 Mesonormative QAPF classification (upper part) of plutonic rocks (Le Maitre 2002). Nearly all G 14 granite samples plot in the

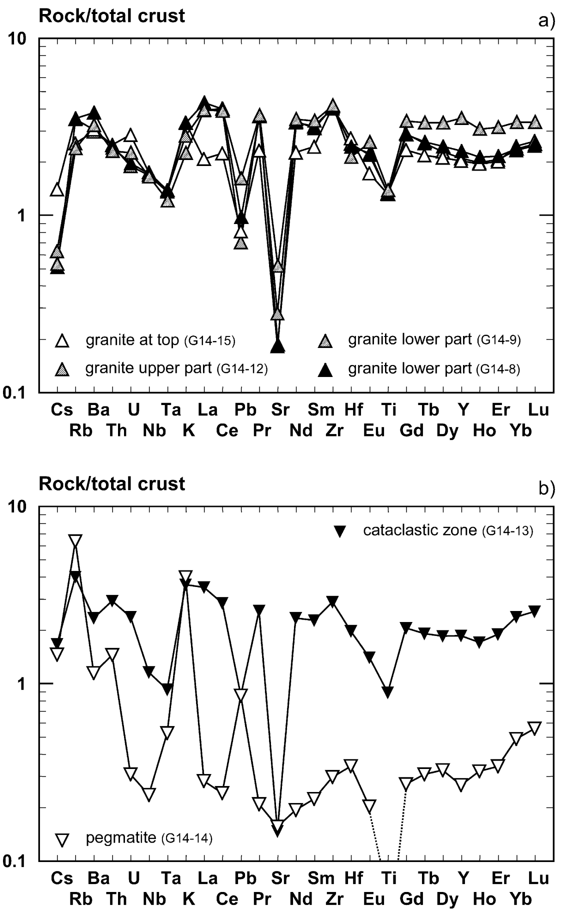


Fig. 4 Crust-normalized trace element patterns of the G 14 granites (**a**) and samples of pegmatitic and cataclastic zones (**b**). The different pattern of the reddish granite sample G14–9 is probably due to the relatively high amount of accessoric titanite, which is most likely responsible for a slight enrichment of REE. The normalization factors are from Rudnick and Fountain (1995)

The gap between the Rønne granodiorite and the Vang granite is filled by the samples of the G 14 granites, which often follow the same trend; only the samples of the greenish-grey variety partly deviate, probably due to alteration. The trends of the trace elements are not so obvious. The contemporaneously formed granites from Blekinge (Vånga, Spinkamåla, Eringsboda and Karlshamn types) also correlate with the Bornholm and G 14 suites, whereas the older granitoids of Tving type and the "Coastal Gneiss" behave differently (not shown).

Genetic implications

The G 14 granites probably represent a restite-poor melting product of a granodioritic protolith. The low MgO, Cr, Ni and Co concentrations and the relatively high content of accessory phases (apatite, zircon) point to formation of water undersaturated, high temperature (>900 °C) melts and low partial melting degrees. The occurrence of titanite and a complementary lack of primary muscovite is typical for I-type granites. The A/CNK-ratios of all G 14 granite samples as well as of the granitoids from Bornholm and Blekinge, which are all below 1.1, support this. They may, however, have been changed by a relatively intense metasomatic alteration, which has especially affected plagioclase.

Based on the petrogenetic classification for granitic rocks suggested by Barbarin (1999) the G 14 granites and the leucocratic Bornholm granites can be considered as K-rich calc-alkaline granites (KCG), while at least the more mafic granites of Bornholm are of the amphibole-rich calc-alkaline type (ACG). Both reflect a mixed source, but a dominant crustal component can be assumed as indicated by relatively high K_2O and low CaO contents.

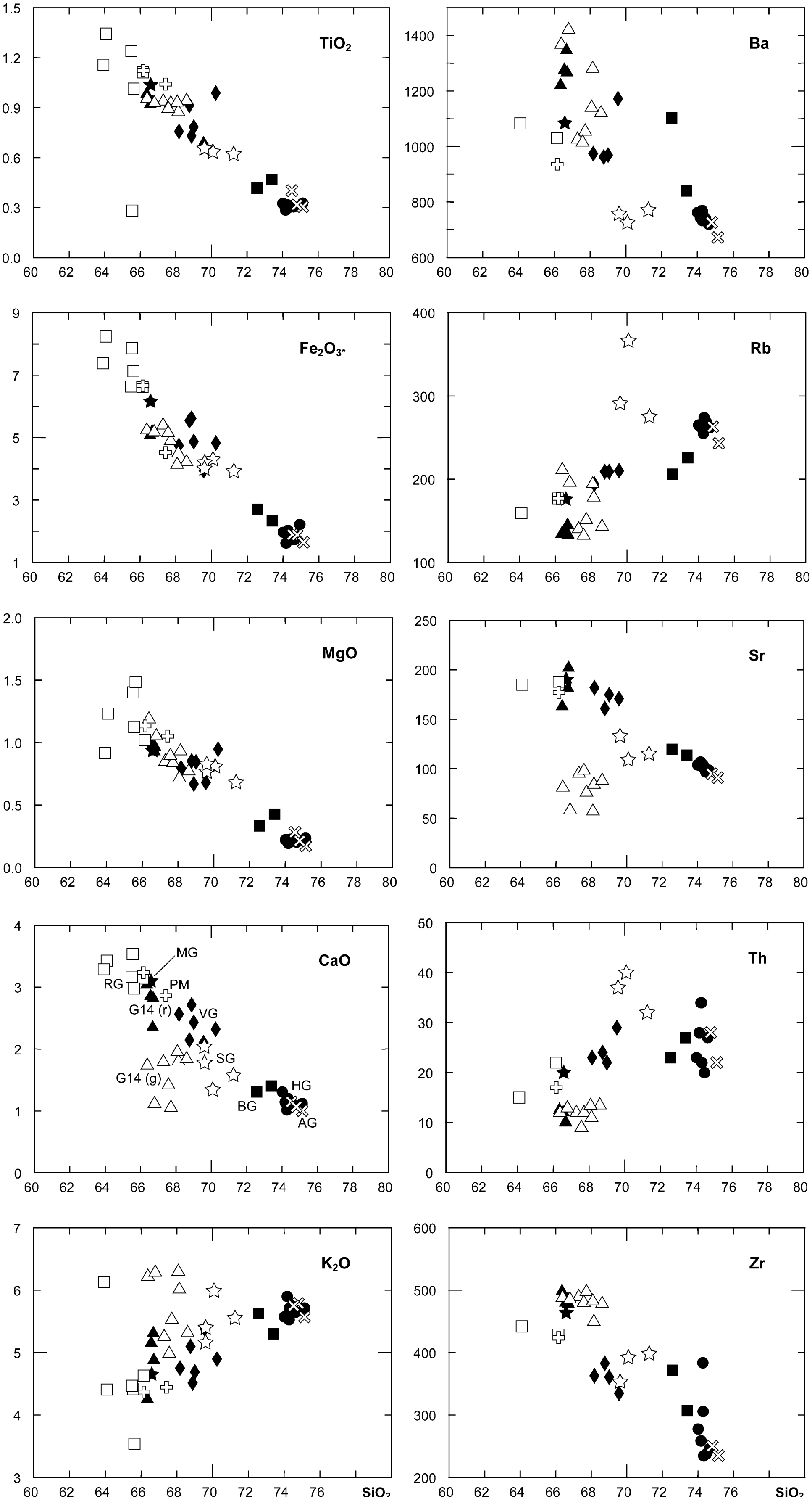
According to the geochemical classification of Frost et al. (2001), the G 14 granites and the Bornholm granites represent ferroan type magmas. A further subdivision is difficult as it is based mainly on rather mobile alkali elements. Using the modified alkali-lime index (MALI), most samples plot in the fields for the alkali-calcic and calc-alkaline rock series; only a few of the presumably altered greenish-grey G 14 granite variety are in the alkaline field. Based on the aluminium saturation index (ASI) the rocks can be additionally characterized as meta- to weakly peraluminous granites.

In the (Y+Nb) vs. Rb diagram of Pearce et al. (1984) designed for the determination of the tectonic setting of intermediate to acid rocks, all granitic samples from the G 14–1 borehole and from Bornholm plot in the within-plate field (Fig. 6).

Age determinations of G 14 granites

U-Pb isotope measurements of zircons suggest a genetic relationship between the G 14 granites and the crystalline rocks of Bornholm. A common discordia age of about 1.45 Ga was determined by Tschernoster (2000).

Fig. 5 Major (wt%) and trace element (ppm) concentrations plotted versus SiO_2 content of the G 14 granites (data in Table 2) compared with analyses of Mesoproterozoic granitic rocks from Bornholm (data from Vinx, unpublished, and Noe-Nygård 1963). *AG* Almindingen granite, *BG* Bornholm Gneiss, *G14 (g/r)* – G 14 granite (greenish or reddish variety), *HG* Hammer granite, *MG* Maegård granite, *PM* Paradisbakke migmatite, *RG* Rønne granodiorite, *SG* Svaneke granite, *VG* Vang granite



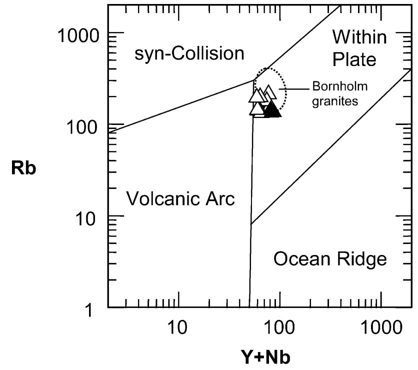


Fig. 6 The granites of the G 14–1 borehole (symbols as in Fig. 3) and the granitic rocks from Bornholm (data from Vinx, unpublished) are characterized by similar Rb and (Y+Nb) values and plot both in the within-plate field suggested by Pearce et al. (1984)

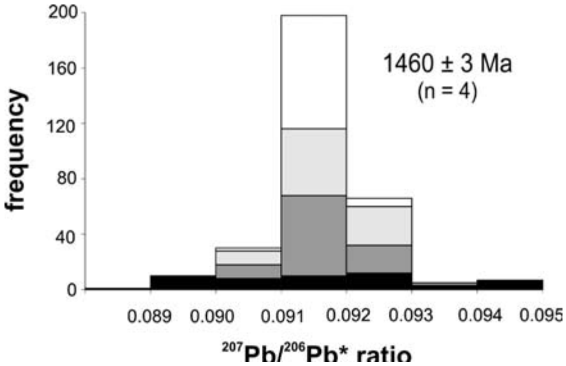


Fig. 7 Histogram of corrected ^{207}Pb/^{206}Pb isotope ratios of four euhedral zircon crystals from the sample G 14–1

Pb-Pb isotope ratios of the G 14 granites obtained by evaporation of single zircons support this. Four optically clear crystals without inclusions were separated from sample G 14–1 to determine the ^{207}Pb/^{206}Pb isotope ratios on a MAT 262 mass-spectrometer equipped with an ion counting system (Philips 6665) using the Pb evaporation technique (Kober 1987). These ratios measured at the Geochemical laboratory at the University of Freiberg were ^{204}Pb-corrected by means of a program based on the two-stage model from Stacey and Kramers (1975). The obtained isotope ages of the zircons (quoted with 2σ-mean errors) are very similar: 1,462±9.0, 1,460±1.9, 1,460±2.7 and 1,458±1.2 Ma (Fig. 7; Table 3). Thus, the mean intrusion age of the G 14 granite is 1,460±3 Ma.

Comparing this with age data of Mesoproterozoic rocks from southeastern Sweden and Bornholm (Table 4), it is evident that the basement of the southern Fennoscandian Shield was effected by a magmatic event between 1.5 and 1.4 Ga.

Conclusions

Based on petrography, geochemistry and age determinations, the drilled granites from the G 14–1 off-shore borehole in the southern Baltic Sea correlate with Mesoproterozoic intrusions from Bornholm and southeastern Sweden. Similar age data point to melting and emplacement of granites between 1.5 and 1.4 Ga. Contemporaneous deformation is indicated by roughly WNW–ESE-oriented foliation and shear zones in the basement rocks and partly in these granites themselves. The SBDZ is most prominent, and regarded as the approximate northern limit of this structural pattern (Kornfält 1996). Deformation and magmatism might have been genetically related to an orogenic event named the Danopolonian orogeny by Bogdanova (2001), but also corresponds to a thermal event known as the Hallandian orogeny in SW Sweden dated between 1.46 to 1.42 Ga (e.g. Söderlund 1999).

Possibly, collisional movements south of the limits of today's Fennoscandia have caused the penetrative deformation in the supracrustal rocks of Bornholm and Blekinge at about 1.45 Ga. The slightly older, less differentiated intrusions or more mafic restites were partly affected by the deformation and exhibit a weak foliation or even migmatitic textures. They can be considered as synorogenic granites (e.g. Rønne granodiorite, Vånga granite). Only the undeformed Hammer and Almindingen granites of Bornholm, intruded as leucocratic differentiates, seem to slightly post-date the orogenic movements. This model, however, needs confirmation by further structural investigations and more precise timing of the deformation history.

The G 14 granites directly indicate the continuation of the crystalline basement exposed in the southeastern Fennoscandian Shield. Besides these, a few fossil-free sediments drilled on northern Rügen and east of Greifswald are comparable with south Scandinavian Neoproterozoic rocks. The Mesoproterozoic crust of the Fennoscandian Shield, however, can be traced even further south by means of geophysical measurements. Hoffmann et al. (1998) suggest on the basis of magne-

Table 3 Uncorrected ^{207}Pb/^{206}Pb and ^{206}Pb/^{204}Pb ratios, corrected ^{207}Pb/^{206}Pb ratios and resulting age for each measured zircon crystal of the granite sample G14–1

#	Scans	Uncorrected 207/206	Uncorrected 204/206	Corrected 207/206	Age
z 1	50	0.0924189±0.000498195	8.662E-05±7.21136E-06	0.0917396±0.000437519	1,462±9.0
z 2	86	0.0922993±0.000109715	6.715E-05±1.52189E-06	0.0916441±0.000091927	1,460±1.9
z 3	90	0.091703±0.000128	2.79E-05±1.58E-06	0.091648±0.000129	1,460±2.7
z 4	90	0.092212±0.000056	7.34E-05±1.01E-06	0.09153±0.0000558	1,458±1.2

Table 4 Compilation of age data of Mesoproterozoic granitic rocks in southern Fennoscandia that are probably related to the Danopolonian orogenic event at about 1.45 Ga. *WR* whole rock, *Min* mineral;*)** monazite

Rock type	U-Pb zircon	Pb-Pb zircon	U-Pb-Th zircon	Rb-Sr WR	Rb-Sr WR-Min	K-Ar model	Reference
G 14–1							
Granite		1,460±3					This paper
	1,455+12/-10				1,271±102		Tschernoster (2000)
Bornholm							
Bornholm gneiss	1,472+66/-36				1,336±74		Tschernoster (2000)
Paradisbakke migmatite					1,296±6		Tschernoster (2000)
Rønne granodiorite	1,469±26						Johansson et al. (2004)
	1,441+24/-18				1,385±26		Tschernoster (2000)
						1,330±50	Larsen (1971)
						1,285±15	Larsen (1971)
				1,400±60			Larsen (1980)
Vang granite					?1,467±175		Tschernoster (2000)
				1,400±60			Larsen (1980)
Svaneke granite	1,453±19						Johansson et al. (2004)
						1,325±15	Larsen (1971)
						1,255±15	Larsen (1971)
Hammer granite			1,424±25				Geisler-Wierwille (1999)
	?1,562+33/-30						Tschernoster (2000)
						1,340±30	Larsen (1971)
Blekinge							
Vånga granite			1,448±25				Geisler and Schleicher (2000)
	?1,584+54/-45			1,452±24	1,240±7	1,221±18	Åberg et al. (1985a)
Karlshamn granite	1,452±8						Kornfält (1996)
	1,445±10						Kornfält and Vaasjoki (1999)
	1,403+121/-86						Åberg et al. (1985b)
				1,422±31			Springer (1980)
Eringsboda granite				1,358±114			Åberg and Kornfält (1986)
Spinkamåla granite				1,358±24			Springer (1980)
SE Scania							
Beden granodiorite	1,449+23/-11						Johansson et al. (1993)
Stenshuvud granite	1,458±8						Čečys et al. (2002)
Tåghusa granite	1,442±9						Čečys et al. (2002)
SE Småland							
Götemar west granite	1,468+53/-47			1,377±27	1,352±21	1,383±20	Åberg et al. (1984)
	1383±14)*						Åberg et al. (1984)
Götemar east granite	1382+75/-61			1,377±27	1,380±21	1,418±20	Åberg et al. (1984)
	1,397±14)*					1,438±20	Åberg et al. (1984)
Jungfrun granite	1,480+40/-31			1,386±21	1,380±10	1,412±20	Åberg et al. (1983)

totelluric measurements that the border between the palaeocontinents Baltica (of which Fennoscandia forms the western part) and the accreted terrane Avalonia is marked by the Stralsund-Anklam fault system, south of the island of Rügen. This is in agreement with results of seismic investigations in N Poland presented by Dadlez (1997). Gossler et al. (1999) interpreted various seismic profiles traversing N Germany towards S Sweden. They pointed out that the crust of Fennoscandia is bound by the so-called Tornquist Conversion Zone, which is positioned slightly south of the CDF (Fig. 1). Towards the south, a 200-km-wide transition zone is supposed to exist with pieces of Fennoscandian crust. This is also indicated by the occurrence of zircon crystals in drilled Lower Permian rhyolitic lavas or ignimbrites in NE Mecklenburg-Vorpommern (boreholes Friedland 1 and Penkun 1), with $^{207}Pb/^{206}Pb$ ages of 1.46 and 1.48 Ga in relict cores using SHRIMP techniques (Breitkreuz and Kennedy 1999).

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