First direct age determination for the Kelseaa Dolerite Dyke, Bornholm, Denmark

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The Danish island Bornholm on the southwestern margin of the Baltic Shield was subject to dyke injection during the Proterozoic. The dykes probably result from several magmatic events. We present U-Pb geochronological data for the largest of the dykes, the tholeiitic Kelseaa dyke. The resulting age, 1326 ±10 (2σ) Ma, places the dyke significantly earlier in the Proterozoic than previously assumed. No other dykes of this age have been reported from the western part of the Baltic Shield. The NE–SW strike of the Kelseaa dyke is evidence for extension oblique to the border of the Baltic Shield. The Kelseaa dyke is the first evidence for this event that was subsequent to the emplacement of the Bornholm and Karlshamn (SE Sweden) granites and prior to the intrusion of the Central Scandina-vian Dolerite Group, and possibly also the majority of mafic dykes on Bornholm.

Keywords: Baltic Shield, Proterozoic, mafic dyke, U-Pb baddeleyite.

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A large number of dolerite dykes are the only mafic intrusive rocks on the Danish island Bornholm, which is situated on the southwestern margin of the Baltic Shield. The dykes represent magmatic events that mainly took place during the Proterozoic. In order to be able to correlate these events to the evolution of Bornholm and the Baltic Shield, precise geochronological data are mandatory. Here we present a new, precise U-Pb baddeleyite age for the largest dyke on Bornholm, the Kelseaa dolerite dyke. The dyke age cannot be correlated to other known igneous or tectonic activity in the southern part of the Baltic Shield and is therefore important. We discuss the implications of this age for mafic magmatism and the Proterozoic development of the southern part of the Baltic Shield.

Geological setting

The northern part of Bornholm consists of Precambrian gneisses and granites (Fig.1). To the south the basement rocks are covered by Palaeozoic to Mesozoic sediments. The Precambrian granites can be regarded as belonging to two main suites; the older granites, which have gradational contact relations to the gneisses and are interpreted as representing partial melting of the gneisses; and the younger granites, which have clear intrusive contacts to the gneisses (e.g. Callisen 1934; Berthelsen 1989).

More than 250 mafic dykes have been intruded into the gneissic and granitic basement, and have been described by Callisen (1934) and Münther (1945).

The doleritic dykes are mainly exposed along the northern coast of Bornholm. They have been estimated to cause a minimum of 1.3% dilation along the *c.* 30 km long coastline (Münther 1973). They almost all strike between NNE–SSW and NNW–SSE and are all near vertical. Exceptions are the Kelseaa dyke, which strikes 40°, and a few NW–SE striking dykes (Forchhammer 1847; Münther 1945).

The width distribution of the dykes is strongly bimodal, in the sense that 4 dykes are 20 to 60 metres wide, whereas most of them do not exceed a few metres in width. The Kelseaa dyke is the largest on the island with a width of 60 metres; it can be traced along strike for *c.* 20 km. The Kelseaa dyke is an olivine tholeiite and is geochemically distinct from the other large dykes, which range in composition from trachybasalt to basaltic trachyandesite and the bulk

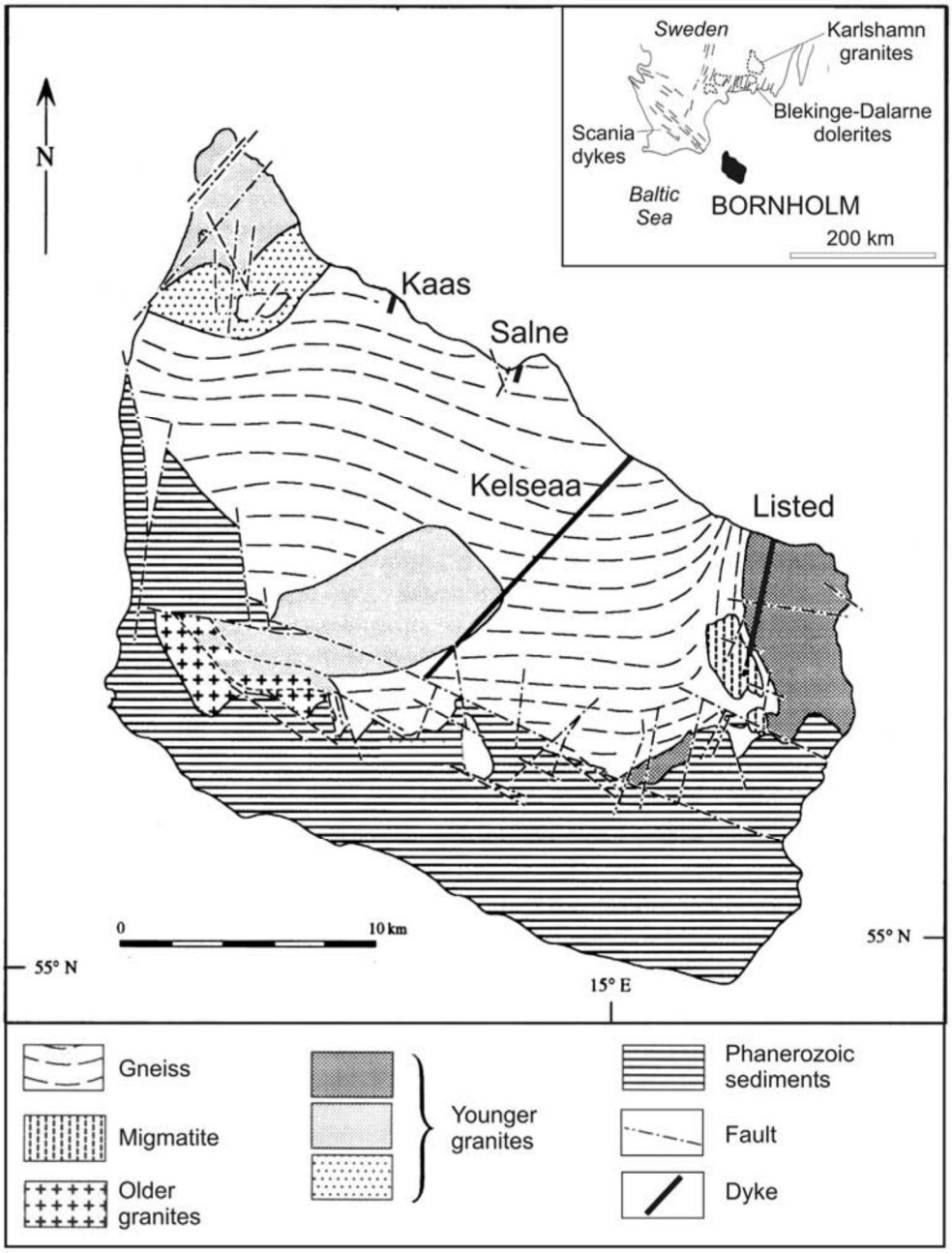

Fig. 1. Geological map of Bornholm. Some dyke occurrences are shown schematically. Modified from Abrahamsen & Lewandowski (1995). Inset shows the southern part of Sweden with the Blekinge-Dalsland dolerites and the Scania dykes. Modified after Klingspor (1976) and Obst (2004).

of the narrow dykes are compositionally different from the large ones and constitute a transitional to alkaline series. The NW–SE striking dykes are also geochemically distinct (Jensen 1989; Obst 2000).

Geochronology

The dykes have not been observed to cut the sedimentary deposits, except for one possible case reported by Larsen (1955), and their ages have so far largely been constrained by the age of the younger granites and of the oldest sedimentary unit, the Lower Cambrian Neksø Sandstone (Bruun-Petersen 1975).

The age of the younger granites has been constrained by Rb-Sr isotope analyses (Larsen 1980), where samples from three different intrusions yielded an Rb-Sr whole rock isochron of 1400 ± 60 (2σ) Ma. K-Ar analyses of granites and pegmatites yielded younger apparent ages of 1255–1340 Ma, probably reflecting cooling during later uplift (Larsen 1971). To the north of Bornholm the Karlshamn gran-

ites in Sweden have been dated by ion microprobe zircon U-Pb analyses to 1438–1465 Ma (Cecys *et al*. 2003; Kornfält 1996; Kornfält & Vaasjoki 1999). A monzogranite from an off-shore borehole south of Bornholm was dated by single zircons to have an age of 1460 ± 3 Ma and was suggested to be related geochemically to the granites on Bornholm and contemporaneous with these and the Karlshamn granites (Obst *et al*. 2004).

Palaeomagnetic studies indicate that several episodes of dyke injection took place during the Proterozoic (Abrahamsen 1977; Abrahamsen & Lewandowski 1995). For the Kelseaa dyke a palaeomagnetic age of *c*. 1360 Ma has been reported; other intrusive events are dated at *c*. 1220 and *c*. 950 Ma (Abrahamsen & Lewandowski 1995). A K-Ar analysis of plagioclase in the Kelseaa dyke yielded an age of 1100–1000 Ma (Larsen personal communication *in* Abrahamsen, 1977).

Palaeomagnetic results on a NW–SE to WNW–ESE trending dyke in the Hammer Granite were interpreted as reflecting a Permian age (Abrahamsen & Lewandowski 1992). This age is in agreement with suggestions based on geochemistry and orientation that this and a few other dykes with similar strike are related to a group of Scanian dykes (Jensen 1966; Obst 2000), which cut Permian sediments (Callisen 1934) and, based on K-Ar isotope analyses, were suggested to be of early Permian age (Klingspor 1976; Obst 2000).

Several authors (Callisen 1934; Münther 1945; Berthelsen 1989) have assumed that the Kelseaa dyke was related to the post Jotnian Central Scandinavian Dolerite Group, which in Sweden has been dated to *c*. 1270–1220 Ma (e.g. Solyom *et al*. 1992; Mattsson & Elming 2003). Here we present a new, precise age for the Kelseaa dyke from U-Pb analysis of baddeleyite.

Analytical technique

One sample was obtained from the medium-coarse grained gabbroic part of the Kelseaa dyke. Baddeleyite was concentrated from a 20 kg sample using standard separation techniques and was subsequently hand-picked to obtain the best quality grains for analysis. Baddeleyite (ZrO_2) occurs as brown wafers with a typical grain size of 10–20 µm Only grains without inclusions, fractures or overgrowths were selected after careful visual inspection using a binocular microscope. The U-Pb analytical work was carried out at the University of Alberta, Edmonton, Canada, and followed standard procedures described in detail by e.g. Heaman & Machado (1992).

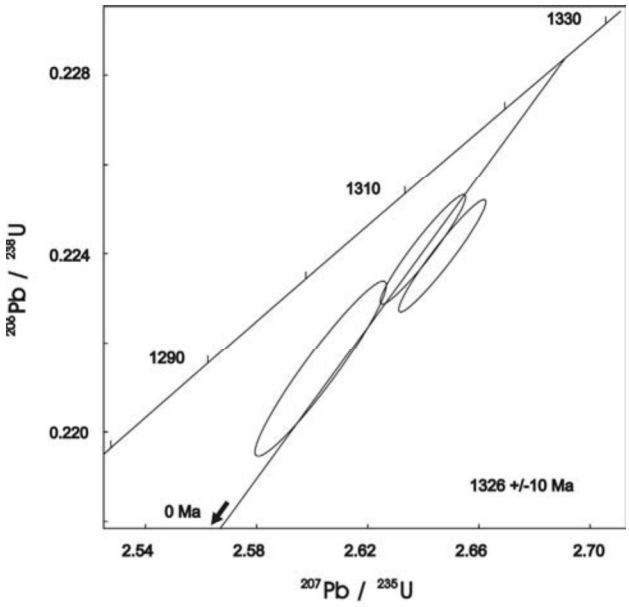

Fig. 2. U-Pb concordia diagram showing analyses of baddeleyite from the Kelseaa dyke.

The analysed fractions were all washed in warm 2N HNO_3 prior to digestion. The samples were spiked with a mixed ^{205}Pb-^{235}U tracer solution and dissolved in a mixture of HF and HNO_3 in teflon bombs at 220°C. Pb and U were separated and analysed together on a VG 354 solid source mass spectrometer. Estimated total blanks are 8 pg for Pb and 2 pg for U. The isotopic composition of the common Pb in excess of blank was calculated using the model 1320 Ma Pb composition of Stacey & Kramers (1975). The decay constants used for ^{235}U and ^{238}U and the $^{238}U/^{235}U$ ratio are those recommended by Steiger & Jäger (1977): 9.8485×10^{-10} α^{-1}, 1.55125×10^{-10} α^{-1} and 137.88.

Three fractions of baddeleyite were analysed. Table 1 summarizes the results which are shown graphically in Figure 2. All errors are reported at the 2σ level. Blank, common and radiogenic Pb constitute 0.2–0.5, 0.4–3 and 97–99 %, respectively, of the total Pb in the sample fractions.

Results and implications

The mineral baddeleyite commonly occurs in mafic rocks and is ideal for U-Pb analysis because it usually has high U contents and negligible amounts of initially incorporated common Pb. Furthermore, baddeleyite is not prone to inheritance as is commonly the case for zircon.

Table 1. U-Pb results for the Kelseaa dyke.

Fraction	Weight	Pb	U	Th	Common Pb	Atomic ratios*				$^{207}Pb/^{206}Pb$ age		Discordance
	µg	ppm	ppm	ppm	pg	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Ma	2σ error	%
59656-1B	8	179	842	29	36	2491	0.22142 ±161	2.6030 ±193	0.08526 ±19	1322	4.4	3
59656-2B	12	266	1261	13	13	15908	0.22395 ±102	2.6468 ±128	0.08572 ±12	1332	2.6	2
59656-3B	11	203	963	12	12	12793	0.22409 ±100	2.6398 ±126	0.08544 ±12	1325	2.7	2

*) Atomic ratios corrected for mass fractionation, blank and initial common Pb.
All errors are quoted on the 2σ level.

U-Pb isotopic data are listed in Table 1 and plotted in Figure 2. The data points are 2 to 3% discordant along a discordia line assuming a zero age for a very minor post-formational disturbance of the baddeleyite. Because the three analyses show little spread in $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$, the intercepts for discordia based on regression are not well defined, and the resulting calculated age of 900 ± 1800 Ma (2σ) for the lower intercept and 1371 ± 300 Ma (2σ) for the upper cannot be assigned any age significance. We therefore assume a zero age for the lower intercept, and prefer the highly precise $^{207}Pb/^{206}Pb$ age information.

The mean $^{207}Pb/^{206}Pb$ age is 1326 ±10 Ma (2σ). This is interpreted to be the intrusion age for the Kelseaa dyke. This is older than most previous estimates.

Regarding the substantial uncertainty related to the apparent polar wander curve for the Baltic Shield (Personen *et al*. 1991; Elming *et al*. 1993), the U-Pb age is in overall agreement with the palaeomagnetic data of Abrahamsen & Lewandowski (1995), who reported an age of *c*. 1360 Ma for the Kelseaa dyke.

The U-Pb age is slightly, but significantly, younger than the Rb-Sr whole rock age for the younger granites of *c*. 1400 Ma (Larsen 1980) and indicates that the Kelseaa magmatism took place relatively soon after formation of the younger granites.

In order to understand the causes and extent of the events responsible for mafic magmatism on Bornholm it is important to be able to correlate the dykes both geochemically and geochronologically with other dyke swarms within the Baltic Shield.

High-precision U-Pb geochronological data exist only for a small part of the numerous Proterozoic mafic dyke swarms in Sweden and Finland (e.g. Suominen 1991; Wahlgren *et al*. 1996). It has recently become apparent that the U-Pb system should usually be chosen for dating relatively old mafic igneous rocks. Most geochronological data on the Swedish dyke swarms are based on the Sm-Nd, Rb-Sr and K-Ar systems. The two latter systems are less reliable than U-Pb because of their susceptibility to post-magmatic isotopic disturbance, and the Sm-Nd method is often plagued by large uncertainties. Furthermore, the south Swedish dyke swarms may have been susceptible to remagnetization during the Sveconorwegian orogeny (Bylund 1992), which may also have affected the radiogenic isotope systematics, whereas Bornholm is essentially unaffected by this orogeny.

The age of 1326 ±10 Ma for the Kelseaa dyke is significantly older than published ages for the Central Scandinavian Dolerite Group (Solyom *et al*. 1992; Mattsson & Elming 2003) and unpublished U-Pb baddeleyite ages of *c*. 0.95 Ga for the Blekinge-Dalarne dolerite swarm (Söderlund *et al*. 2002). To our knowledge, no dykes of approximately 1326 Ma age have been reported from the western part of the Baltic Shield. The strike of the Kelseaa dyke is at a high angle to the present margin of the Baltic Shield. Abrahamsen & Lewandowski (1995) concluded that Bornholm has not rotated relative to the Baltic Shield after dyke injection. This suggests that the Kelseaa dyke is related to continental rifting oblique to the present margin of the Baltic Shield.

The numerous dykes on Bornholm may represent significant events of mafic magmatism in the Proterozoic. The differences in the geochemical characteristics of the dykes that have from tholeiitic to alkaline affinities make it unlikely that they are cogenetic and, consequently, coeval (own unpublished data). The Kelseaa dyke has a composition that is distinctly different from other dykes which could well be related to the palaeomagnetic ages of 1200 and 950 Ma obtained by Abrahamsen & Lewandowski (1995). The WNW–ESE trending dykes may be of Permian age (Jensen 1989; Abrahamsen & Lewandowski 1992; Obst 2000). The Kelseaa dolerite is the only evidence for the oldest of these, perhaps four, episodes of mafic dyke intrusion on Bornholm. Around 1 km^3 magma is represented for each 1 km of vertical extent of the dyke. Magma emplacement of this magnitude suggests a significant melting event in the mantle, and further evidence for this should

be detectable in the surrounding region of Sweden and the Baltic Sea.

The Kelseaa dolerite postdates the 1.5–1.4 Ga crustal deformation and granite intrusion in Blekinge, which has been termed the Danopolian orogeny (Bogdanova 2001), and the contemporaneous Hallandian event in SW Sweden (Hubbard 1975; Christoffel *et al*. 1999). We suggest that the Kelseaa dolerite is an expression of a subsequent extensional event, which has hitherto remained undetected.

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Resumé på dansk

Bornholm, som ligger på den sydvestlige grænse af det Baltiske Skjold blev intruderet af gange i Proterozoikum. Gangbjergarterne er formentlig resultatet af flere magmatiske hændelser. Vi præsenterer U-Pb geokronologiske data for den største af gangene, Kelseaagangen. Den resulterende alder, 1326 ±10 (2σ) Ma, placerer gangen signifikant tidligere i Proterozoikum end tidligere antaget. Ingen andre gange af denne alder er rapporteret fra den vestlige del af det Baltiske Skjold. Palæomagnetiske resultater (Abrahamsen 1977; Abrahamsen & Lewandowski 1992 & 1995) indikerer at andre episoder med gangintrusioner på Bornholm er senere end Kelseaagangen. Dens retning viser at ekstension forekom i en skæv vinkel i forhold til den nutidige rand af Det Baltiske Skjold, og er det første bevis for en sådan begivenhed. Der er ikke tidligere blevet rapporteret om ekstension efterfølgende intrusionen af Bornholms og Karlshamns graniter og før intrusionen af De Centralsvenske Doleritgange, og formentlig før intrusionen af hovedparten af Bornholms mafiske gange.

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