^{40}Ar–^{39}Ar biotite and hornblende geochronology from the Oskarshamn area, SE Sweden: discerning multiple Proterozoic tectonothermal events

PIA SÖDERLUND*, LAURENCE M. PAGE & ULF SÖDERLUND

Department of Geology, GeoBiosphere Science Centre, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden

Abstract – Twelve ^{40}Ar–^{39}Ar biotite and four hornblende age determinations have been carried out to constrain the cooling history of the Proterozoic bedrock near Oskarshamn, SE Sweden, an area identified as a possible site for long-term nuclear waste storage. The bedrock hosts *c.* 1.80 Ga granites and diorites of the Transscandinavian Igneous Belt and two 1.45–1.44 Ga granite intrusions, the Götemar and Uthammar plutons. Biotite was selected from three surface samples, representing both the older rocks and the younger granites, and from three cored boreholes at nine different depth levels. Hornblende was extracted from samples at the top and bottom of one borehole and at two sub-surface levels of another borehole. Three age groups were distinguished: ≥ 1.62 Ga, 1.51–1.47 Ga and 1.43–1.42 Ga. In the first group, two hornblende analyses yielded ages of 1799 ± 4 Ma and 1773 ± 13 Ma, which indicate initial fast cooling after emplacement of 1.80 Ga rocks of the Transscandinavian Igneous Belt. Two biotite ages of 1618 ± 7 Ma and 1621 ± 3 Ma are interpreted to date final cooling, through 300 °C, after the youngest suite (1.68–1.67 Ga) of the Transscandinavian Igneous Belt in south-central Sweden. Seven biotite ages, in the range 1.51–1.47 Ga, are enigmatic to interpret but largely coincide in age with the end of widespread rapakivi magmatism in Fennoscandia and the initiation of the Danopolonian event. The 1.43–1.42 Ga biotite and hornblende ages reflect cooling after thermal heating from the 1.45–1.44 Ga Götemar and Uthammar plutons. Later events thermally affected the bedrock in the Oskarshamn area as indicated by a poorly defined biotite age of 928 ± 6 Ma and other disturbed ^{40}Ar–^{39}Ar ages of samples bordering a complex deformation zone.

Keywords: ^{40}Ar–^{39}Ar geochronology, Mesoproterozoic, tectonothermal evolution, Fennoscandia.

1. Introduction

Sweden is part of the Fennoscandian Shield, which has an old and protracted history of crust-forming events associated with magmatism, tectonism, deformation and metamorphism. The oldest rocks of Archaean age occur in the northeast. Younger rocks have subsequently been accreted to the Archaean nucleus during different stages of orogenic and magmatic events throughout the Proterozoic era. Many of these events are reasonably well established by geographic and temporal definitions, such as the Svecofennian orogeny, the Transscandinavian Igneous Belt, the Gothian event and the Sveconorwegian orogeny. In intervening periods, different generations of mafic dyke swarms and felsic plutons were emplaced.

Scattered intracontinental rapakivi complexes intruded the Fennoscandian Shield (Fig. 1) between *c.* 1.65 and 1.47 Ga. In this study the term 'rapakivi' is used for the classic 1.65–1.47 Ga intrusive complexes such as the Wiborg and Åland complexes in Finland (Suominen, 1991; Alviola *et al.* 1999), the Salmi complex in Russia (Amelin, Larin & Tucker, 1997), the Riga massif in Estonia (Rämö, Huhma & Kirs, 1996), the Mazury complex in Poland (Dörr *et al.* 2002) and the smaller massifs in central Sweden, such

as the Nordingrå (Welin & Lundqvist, 1984), Ragunda (Persson, 1999), Mullnäset (Andersson, Neymark & Billström, 2002) and Noran (Claesson & Kresten, 1997) massifs. Our definition does not include younger AMCG-suits or A-type granites often mentioned in the same context with rapakivi magmatism (e.g. Bogdanova *et al.* 2001; Dörr *et al.* 2002; Skridlaite, Wiszniewska & Duchesne, 2003). Åhäll, Connelly & Brewer (2000) suggested that the emplacement of rapakivi intrusions was linked to Gothian (*c.* 1.69–1.55 Ga) orogenic activity in the west.

Younger Mesoproterozoic intrusions have been considered to represent plutonism associated with N–S compressive tectonism of the Danopolonian event (e.g. Čečys *et al.* 2002; Čečys & Benn, 2007; Bogdanova *et al.* 2008). Originally this event was proposed to include 1.54–1.45 Ga magmatism and compressional tectonism found in northern Poland, on Bornholm and in SW Sweden (Čečys *et al.* 2002; Bogdanova *et al.* 2008). Brander & Söderlund (2008) linked the 1.47–1.44 Ga mafic and felsic magmatism to an orogenic setting, and suggested that the age limits of the Danopolonian should be set by the 1.47–1.44 Ga intrusions, that is, not including the earlier, scattered events of rapakivi magmatism.

One of the strengths of ^{40}Ar–^{39}Ar geochronology lies in its potential to record low temperature effects

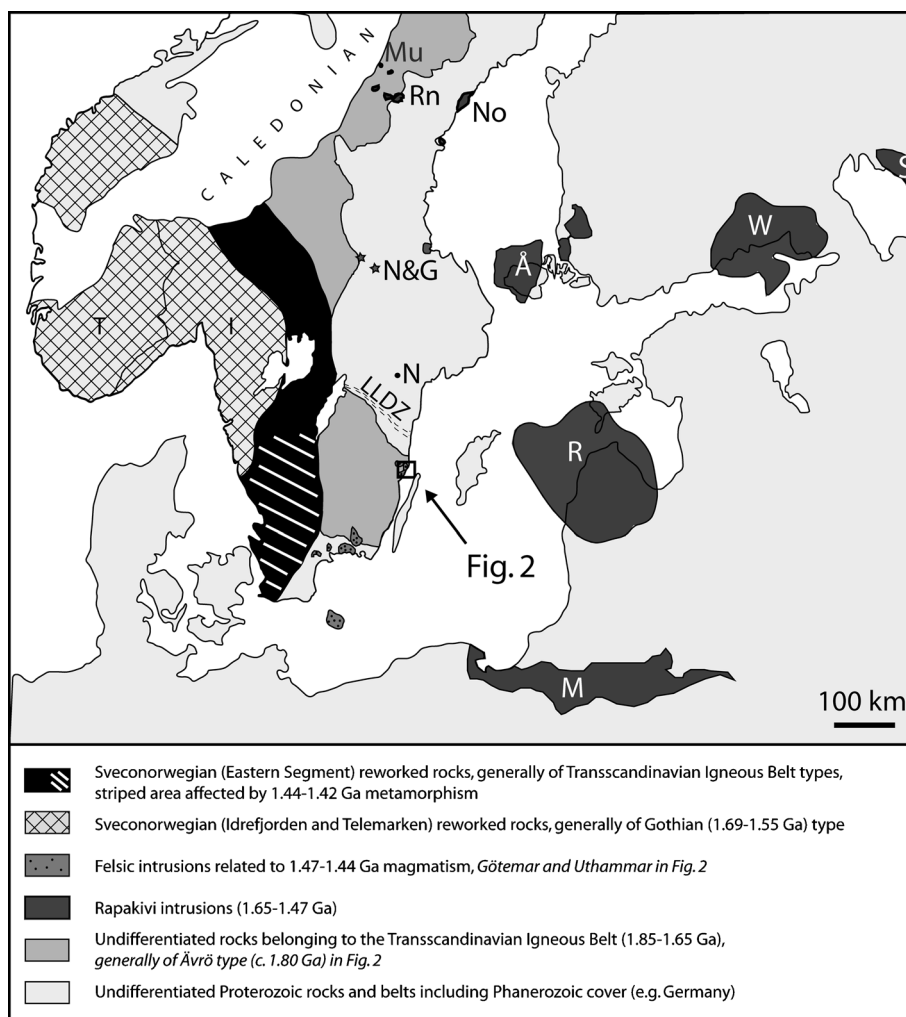*Author for correspondence: e-mail: pia.soderlund@geol.lu.se

Figure 1. Simplified geological map of southern Fennoscandia (modified from Brander & Söderlund, 2008). I – Idefjorden terrain; LLDZ – Loftahammar-Linköping Deformation Zone; M – Mazury complex; Mu – Mullnäset complex; N – Norrköping; No – Nordingrå complex; N&G – Noran and Gustaf massif; R – Riga complex; Rn – Ragunda complex; S – Salmi complex; T – Telemarken terrain; W – Wiborg complex; Å– Åland complex.

of low-grade or distal tectonic processes, which may not be registered by traditional higher-temperature geochronometers. The bedrock in the Oskarshamn area, in particular the Simpevarp–Laxemar area (Fig. 2, left), has been studied in detail by the Swedish Nuclear Fuel and Waste Management Company (SKB), as it has been chosen as a possible site for underground long-term storage of nuclear waste. For the site-evaluation process it is important to understand the thermal history of rocks in the area. This study aims to investigate the thermal evolution in the 300–500 °C interval of the upper crust in the Simpevarp–Laxemar area, Oskarshamn (Fig. 2, left), where the bedrock consists predominantly of 1.80 Ga igneous rocks and neighbouring 1.45–1.44 Ga granite plutons. ^{40}Ar–^{39}Ar analyses of hornblende and biotite from surface samples, together with samples from cored boreholes, allow us to constrain a detailed tectonothermal history of the region. We have also dated a N–S-striking, 15–20 m wide, fine-grained dolerite dyke with the ^{40}Ar–^{39}Ar technique on a whole-rock sample.

2. Geological framework

The crystalline basement in the Oskarshamn area, SE Sweden, comprises 1.80 Ga intrusions of granite–syenite–diorite–gabbro composition and related volcanic equivalents belonging to the Transscandinavian Igneous Belt (Fig. 1). The Transscandinavian Igneous Belt is more than 1500 km long in a NS direction and up to a few hundred kilometres wide and extends from SE Sweden into Norway, where it disappears beneath the Caledonides (Högdahl, Andersson & Eklund, 2004 and references therein). Rocks of the belt typically show magma-mingling and -mixing processes, which in mesoscopic scale often result in heterogeneous textures and mineralogical and chemical compositions. Dykes of fine- to medium-grained granite and pegmatite are associated with the magmatic suite. In Sweden the Transscandinavian Igneous Belt is usually subdivided into four main provinces: the Småland-Värmland Belt; the Dala Province; the Rätan Batholith and the Revsund granitoid suite, going from south to north. The ages of these rocks span a total period of *c.*
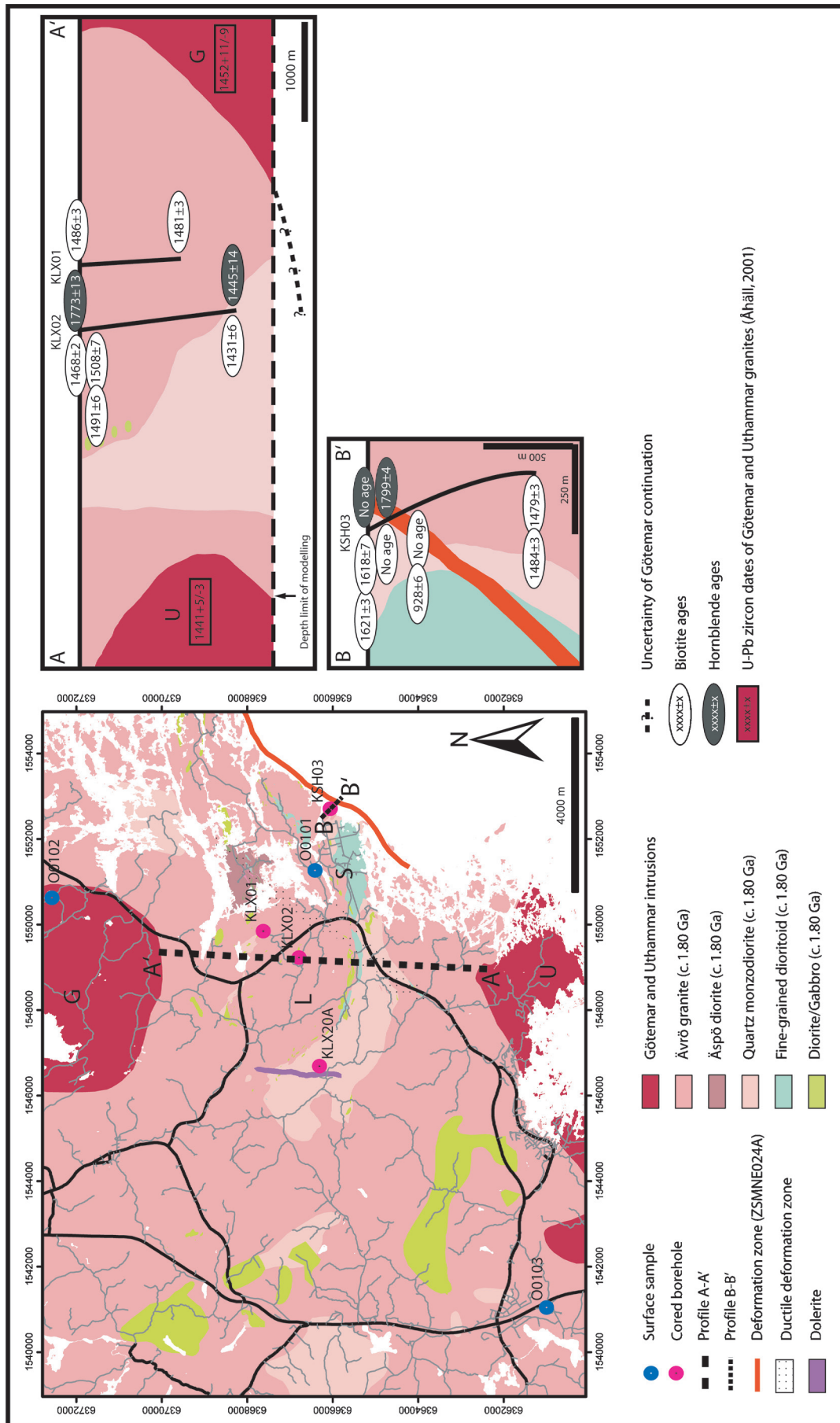
Figure 2. Left panel map: local geology of the Oskarshamn area. G – Götemar granite; L – Laxemar investigation area; S – Simpevarp investigation area; U – Uthammar granite. Right panel: profiles of the bedrock at depth with inserted cored boreholes. Upper right: profile A–A' shows the cored boreholes KLX01 and KLX02; depth scale equals length scale. Lower right: profile B–B' shows the cored borehole KSH03 and the penetrated deformation zone. The left panel map is made after Permission M2001/5268, 2007-05-14, 09:43, from GSD-Fastighetskartan © Lantmäteriet, Gävle 2001. Coordinates in RT 90, 2.5 gon V.

200 Ma, from *c.* 1.85 to *c.* 1.65 Ga, which is often subdivided into four magmatic periods at 1.85–1.65, 1.81–1.76, 1.71–1.69 and 1.67–1.65 Ga (Andersson *et al.* 2007 and references therein). Rocks of all periods occur in the Småland–Värmland Belt in SE Sweden, which is separated into a northern and southern block by the WNW–ESE-trending Oskarshamn–Jönköping Belt. This belt is made up of 1.84–1.82 Ga Svecofennian rocks of mainly juvenile supracrustal origin (Mansfeld, 1996; Åhäll, Connelly & Brewer, 2000; Mansfeld, Beunk & Barling, 2005). The northern part of the Småland–Värmland Belt, to which the Oskarshamn area belongs, is dominated by coarse-grained granitoids with associated rhyolitic volcanites (Andersson *et al.* 2007 and references therein). At about 100 km west of the study area, 1.78 and 1.80 Ga plutons have intruded coeval supracrustal rocks (Wikman, 1993; Wikström, 1993; Mansfeld, 1996; Persson & Wikman, 1997), of which some have conglomerate clasts dated at 1.81–1.80 Ga (Söderlund & Rodhe, 1998). Although this area must have been tectonically active at this period of time, these observations imply shallow emplacement of intrusions belonging to the Transscandinavian Igneous Belt.

The two dominant lithologies in the studied area (Simpevarp–Laxemar area, Fig. 2, left) are 1800 ± 4 Ma Ävrö granite, which is heterogeneous in composition, ranging from quartz monzodiorite to granite, and an equigranular quartz-monzodiorite dated at 1802 ± 4 Ma (U–Pb zircon: Wahlgren *et al.* 2004). Fine-grained diorite makes up a major part of the Simpevarp peninsula. The diorite is locally intruded by small composite intrusions of diorite to gabbro, granite, as well as dykes and patches of fine-grained granite and pegmatite. The results of magma-mingling and -mixing are commonly seen in the study area and indicate temporal and genetic relationships between the different rock types. Younger intrusions, the 1452+11/-9 Ma Götemar and the 1441+5/-3 Ma Uthammar granites (Åhäll, 2001) (Fig. 2, left), occur in the area, as well as well-preserved N–S-striking dolerite dykes (Wahlgren *et al.* 2006a), possibly belonging to the 978–946 Ma Blekinge-Dalarna Dolerites (Söderlund *et al.* 2005).

Ductile deformation zones of mesoscopic to regional character penetrate all lithologies, and the majority of these zones display polyphase brittle reactivation. For a more extensive description of the geology of the Simpevarp–Laxemar area, see Wahlgren *et al.* (2006b).

3. Geochronology

3.a. Analytical procedures

About 0.5 kg of each rock sample was processed for mineral separation. The sample was reduced in size by using a sledge-hammer, followed by grinding in a swing mill. The clay size fraction was removed using a Wilfley table and the remaining fraction was sieved through a 500 μm mesh. Biotite was hand-picked under a microscope from the coarser fraction, whereas hornblende was collected from the finer fraction. The dolerite whole-rock sample was collected from small rock pieces after this first crushing step. The selected biotite, hornblende and whole-rock separates were irradiated for 35 hours at the NRG-Petten HFR RODEO facility in the Netherlands, together with the 28.34 Ma TCR sanidine standard (Renne *et al.* 1998) or the 25.26 Ma DRA–1 sanidine standard (Wijbrans *et al.* 1995, recalculated following Renne *et al.* 1998). J-Values were calculated with a precision of better than 0.25 %.

Argon isotope analyses were performed on a Micromass 5400 mass spectrometer with a Faraday cup and an electron multiplier at Lund University, using a metal extraction line with two SAES C50-ST101 Zr–Al getters and a cold finger cooled to about $-155\,^{\circ}$C by a Polycold P100 cryogenic refrigeration unit. Single grains of biotite or hornblende were loaded into a copper sample holder, and samples were step-heated using a defocused 50 W CO_2 laser. Sample clean-up time, using the hot Zr–Al SAES getters and the cold finger, was five minutes. The sample holder was carefully moved during the heating to provide even heating of the grain. The entire analytical process was automated, using software originally developed at the Berkeley Geochronology Centre (Al Deino) and modified specifically for the laboratory at Lund University. Regressions were fitted to data collected from ten scans over the mass range of 40 to 36. Peak heights and backgrounds were corrected for mass discrimination, isotopic decay and interfering nucleogenic Ca-, K- and Cl-derived isotopes. Isotopic production values for the cadmium-lined position in the Petten reactor are ^{36}Ar/^{37}Ar(Ca) $= 0.000270$, ^{39}Ar/^{37}Ar(Ca) $= 0.000699$, and ^{40}Ar/^{39}Ar(K) $= 0.00183$. ^{40}Ar blanks were measured before every new sample and after every three sample-steps. Blank values were subtracted for all incremental steps from the sample signal. Age plateaus were determined using the criteria of Dalrymple & Lanphere (1971), which specify the presence of at least three contiguous incremental heating steps with statistically indistinguishable ages and constituting greater than 50 % of the total ^{39}Ar released during the experiment. In some cases, where the plateau criteria were not fulfilled, a forced-fit age was calculated from integrating age steps in a specific interval.

3.b. Samples and results

Samples for ^{40}Ar–^{39}Ar biotite and hornblende dating were collected from three cored boreholes, at nine depth levels in total, and from three surface locations. All chosen grains were fresh and showed no signs of alteration under the optical microscope. The dolerite sample for ^{40}Ar–^{39}Ar whole-rock dating was collected from a fourth borehole. The locations of the sampling sites are shown in Figure 2, and the release age spectra are shown in Figures 3 and 4, respectively. Table 1 summarizes the ages; tabulated age data
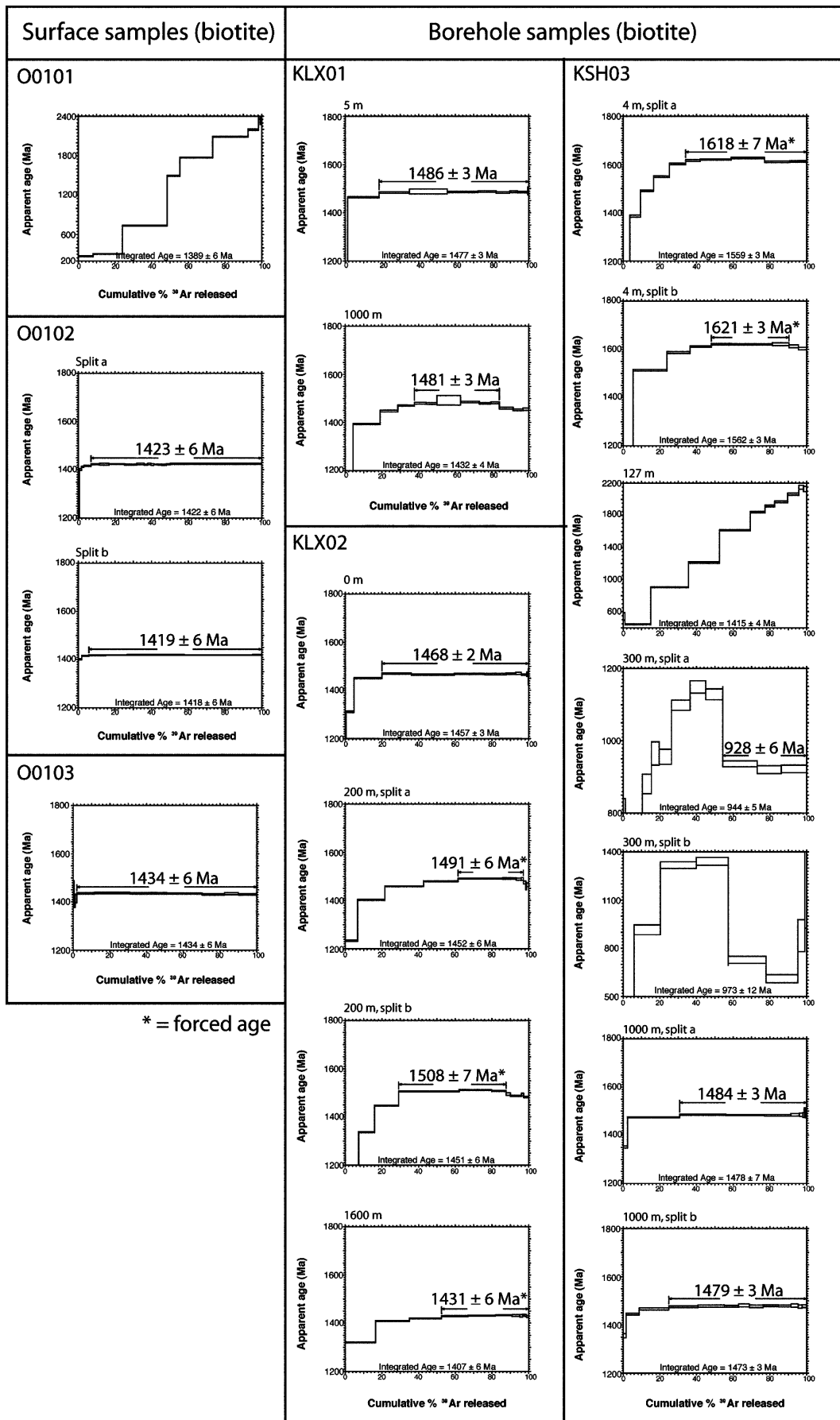
Figure 3. ^{40}Ar–^{39}Ar step heating spectra for biotite samples.

Table 1. ^{40}Ar–^{39}Ar ages and sample information

	Sample	Age (Ma)	Coordinates (surface and top of boreholes)	Inclination (boreholes)	Rock type	Approximate distance from Götemar/ Uthammar granites (km)
Surface samples (biotite)	O0101	No age	N6366376.2/E1551326.7		Medium-grained granite-syenite (*c.* 1.80 Ga)	4
	O0102a	1423 ± 6	N6372555.8/E1550665.8		Coarse-grained Götemar granite (*c.* 1.45 Ga)	0
	O0102b	1419 ± 6	N6372555.8/E1550665.8		Coarse-grained Götemar granite (*c.* 1.45 Ga)	0
	O0103	1434 ± 6	N6361002.0/E1541165.2		Quartz-rich Ävrö granite (*c.* 1.80 Ga)	1
Borehole samples (biotite)	KLX01-5	1486 ± 3	N6367485.5/E1549923.1	85°	Ävrö granite (*c.* 1.80 Ga)	3
	KLX01-1000	1481 ± 3		85°	Ävrö granite (*c.* 1.80 Ga)	1.2
	KLX02-0	1468 ± 2	N6366768.2/E1549224.1	85°	Ävrö granite (*c.* 1.80 Ga)	3.5
	KLX02-200a	1491 ± 6*		85°	Ävrö granite (*c.* 1.80 Ga)	3.5
	KLX02-200b	1508 ± 7*		85°	Ävrö granite (*c.* 1.80 Ga)	3.5
	KLX02-1600	1431 ± 6*		85°	Ävrö granite (*c.* 1.80 Ga)	0.5
	KSH03-4a	1618 ± 7*	N6366017.8/E1552711.2	59°	Ävrö granite (*c.* 1.80 Ga)	5
	KSH03-4b	1621 ± 3*	N6366017.8/E1552711.2	59°	Ävrö granite (*c.* 1.80 Ga)	5
	KSH03-127	No age		59°	Quartz monzodiorite (*c.* 1.80 Ga)	5
	KSH03-300a	928 ± 6		59°	Ävrö granite (*c.* 1.80 Ga)	5
	KSH03-300b	No age		59°	Ävrö granite (*c.* 1.80 Ga)	5
	KSH03-1000a	1484 ± 3		59°	Ävrö granite (*c.* 1.80 Ga)	5
	KSH03-1000b	1479 ± 3		59°	Ävrö granite (*c.* 1.80 Ga)	5
Borehole samples (hornblende)	KLX02-0	1773 ± 13*	N6366768.2/E1549224.1	85°	Ävrö granite (*c.* 1.80 Ga)	3.5
	KLX02-1600	1445 ± 14*		85°	Ävrö granite (*c.* 1.80 Ga)	0.5
	KSH03-4	No age	N6366017.8/E1552711.2	59°	Ävrö granite (*c.* 1.80 Ga)	5
	KSH03-127	1799 ± 5		59°	Quartz monzodiorite (*c.* 1.80 Ga)	5
Borehole dolerite sample (whole rock)	KLX20A-189a	904±3	N6366335/E1546605	50°	Fine-grained dolerite	Irrelevant
	KLX20A-189b	898±3	N6366335/E1546605	50°	Fine-grained dolerite	Irrelevant

Samples are denoted in the format KLX01–5, where 'KLX01' refers to the sample name and '5' refers to the borehole length where the sample was taken. Coordinates in RT 90, 2.5 gon V. ∗ – Forced age; a-b refers to individual splits of the same sample.
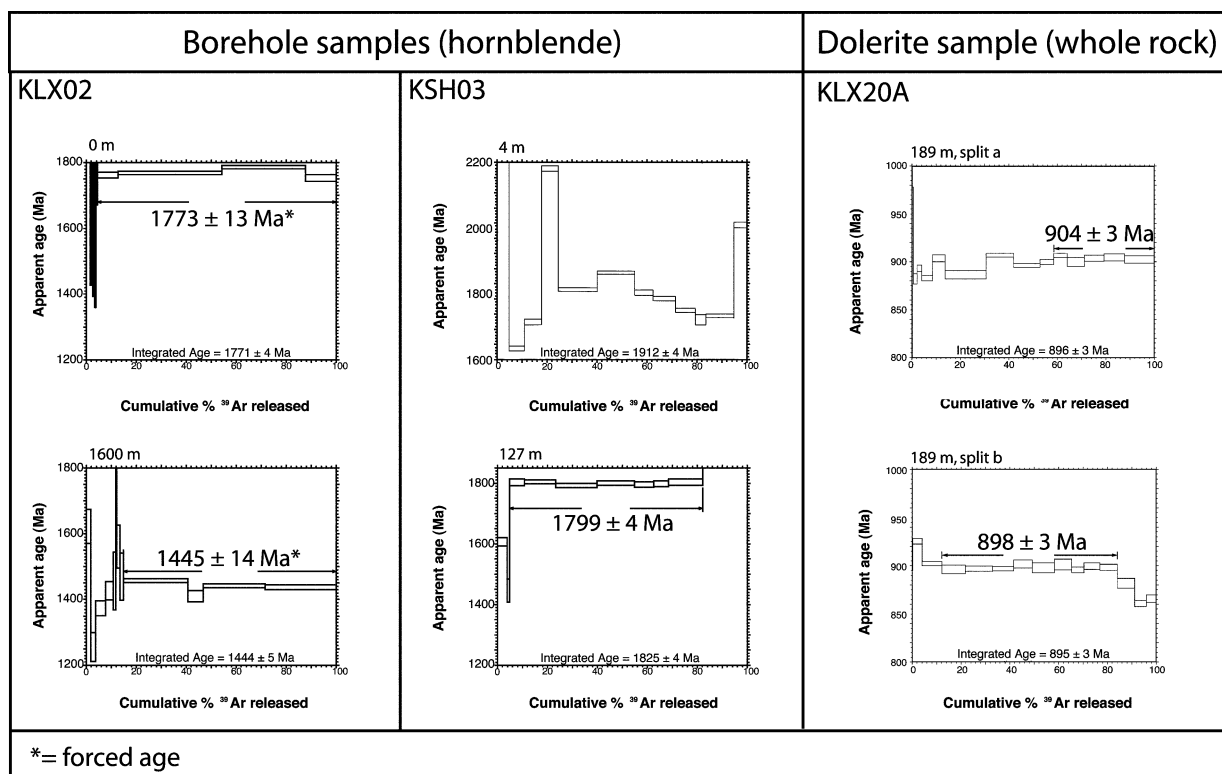

Figure 4. ^{40}Ar–^{39}Ar step heating spectra for hornblende and whole-rock samples.

is available from authors on request, or online at http://www.earthchem.org/earthchemWeb/index.jsp. Reverse isochron diagrams were inconclusive, as most steps were too radiogenic to yield isochrons.

Surface sample O0101 is located just outside the Oskarshamn power plant. It is a homogeneous, medium-grained rock with sparse K-feldspar phenochrysts. The sample yielded an uninterpretable staircase-like spectrum that is not considered further. Surface sample O0102 is a coarse-grained variety of the Götemar intrusion. From this sample, duplicate analyses of biotite (O0102a and O0102b) yielded, within error, identical ages of 1423 ± 6 Ma and 1419 ± 6 Ma, defined by *c.* 95 % of total ^{39}Ar release. Surface sample O0103 is a red, homogeneous, quartz-rich granite situated about 1 km west of the Uthammar intrusion. The analysis yielded a plateau age of 1434 ± 6 Ma defined by almost 100 % of the total ^{39}Ar release.

KLX01 is a 1000 m long, subvertical borehole located a few kilometres south of the Götemar granite. It is dominated by Ävrö granite with subordinate mixing-mingling lithologies of fine-grained diorite to gabbro, fine-grained granite, diorite to gabbro, medium- to coarse-grained granite and certain sections of pegmatite. Samples were taken at subsurface level (at 5 m borehole length) and at 1000 m borehole length; both samples were made up of Ävrö granite. The near-surface sample, KLX01–5, yielded an age of 1486 ± 3 Ma, representing about 80 % of the total ^{39}Ar release. At 1000 m borehole length, the sample KLX01–1000 yielded an age of 1481 ± 3 Ma (defined by 50 % of the total ^{39}Ar release).

KLX02 is a 1700 m long, subvertical borehole located a few hundred metres southwest of KLX01. The dominant rock type is Ävrö granite in the 0–1450 m interval, except for the 540–960 m interval where the granite shows mingling with fine-grained diorite. Quartz monzodiorite dominates in the 1450–1700 m interval. Subordinate associated rock types comprise fine-grained diorite to gabbro and fine-grained granite. The borehole penetrates a brittle deformation zone between 770 and 960 m borehole length (Hultgren *et al.* 2004). Samples were taken from three levels, all represented by Ävrö granite. At the surface, sample KLX02–0 yielded an age of 1468 ± 2 Ma, defined by 80 % of the ^{39}Ar release. At the 200 m borehole length, two splits of sample KLX02–200 (KLX02–200a and KLX02–200b) were analysed, yielding similar ages of 1491 ± 6 Ma and 1508 ± 7 Ma. However, both results represent forced plateau ages; KLX02–200a comprises three overlapping steps but only 35 % of ^{39}Ar release, whereas KLX02–200b is based on three non-overlapping steps represented by 55 % of the ^{39}Ar release. At 1600 m borehole length, sample KLX02–1600 yielded an age of 1431 ± 6 Ma defined by 45 % of the ^{39}Ar release. In addition to biotite, hornblende from samples KLX02–0 and KLX02–1600 were also dated with ^{40}Ar–^{39}Ar geochronology. These samples yielded forced plateau ages of 1773 ± 13 Ma and 1445 ± 14 Ma, respectively. The ages were defined by

about 80 % of the released ^{39}Ar gas, but with slightly inconsistent age steps.

The third borehole, KSH03, was drilled with an inclination of about 60° and comprises two cores; KSH03B represents the first 100 m of borehole length of the bedrock and KSH03A the following 900 m. For simplicity, the two boreholes are treated as one and referred to as KSH03. The borehole penetrates a major NE-trending deformation zone (ZSMNE024A: Wahlgren *et al.* 2006b), which is modelled with a northwesterly dip (Fig. 2, left and lower right). The bottom of the borehole reaches a depth of about 870 m. The dominant rock type is Ävrö granite, but some sections are made up of quartz monzodiorite and fine-grained granite. Subordinate rock types include diorite to gabbro and medium-grained granite. Biotite samples were taken from four different levels (4, 127, 300 and 1000 m), where the distances refer to the length of the borehole, thus uncorrected for the inclination. All samples consist of Ävrö granite except KSH03–127, which is from a quartz monzodiorite. Duplicate analyses from sample KSH03–4 (KSH03–4a and KSH03–4b) yielded identical ages, within error, of 1621 ± 3 Ma (45 % of total ^{39}Ar release) and 1618 ± 7 Ma (forced plateau of five non-overlapping steps comprising 70 % of total ^{39}Ar release), respectively. At 127 m, sample KSH03–127 yielded a staircase-like spectrum with no interpretable result. The two splits of sample KSH03–300 at 300 m (KSH03–300a and KSH03–300b) yielded ages that are difficult to interpret. KSH03–300a yielded an age of 928 ± 6 Ma. The plateau is defined by 45 % of total ^{39}Ar release with previous steps giving older ages (around 1150 Ma). KSH03–300b did not yield an interpretable age. At 1000 m, sample KSH03–1000 was analysed twice (KSH03–1000a and KSH03–1000b) and yielded two identical plateau ages, within error, of 1484 ± 3 Ma and 1479 ± 3 Ma. Both plateaus were defined by ≥ 70 % of total ^{39}Ar release.

Two hornblende samples, one from KSH03–4 and one from KSH03–127, were also analysed. Sample KSH03–4 did not yield an interpretable age, whereas sample KSH03–127 yielded a well-defined plateau age of 1799 ± 4 Ma, representing 75 % of the released ^{39}Ar gas.

Borehole KLX20A was drilled with an inclination of 50° to the west. The sample of fine-grained dolerite was collected from near the 189 m level, borehole length. Two splits were analysed, yielding ages of 904 ± 3 Ma and 898 ± 3 Ma, representing 40 % and 70 %, respectively, of the ^{39}Ar gas released.

3.c. Interpretation of the dolerite whole-rock age and ages bordering a fracture zone through KSH03

Published U–Pb baddeleyite dates from the Blekinge-Dalarna Dolerites in SE Sweden fall in the range 970–946 Ma (Söderlund *et al.* 2005). A slightly younger result (*c.* 935 Ma) from a dolerite near Gothenburg in the Idefjorden terrain was reported by Hellström,

Johansson & Larson (2004). The age for the dolerite in borehole KLX20A is thus several tens of millions of years younger than earlier reported for the Blekinge-Dalarna Dolerites in southern Sweden.

KSH03 intersects a ductile deformation zone/fault zone between borehole length 162 and 275 m (ZSMNE024A; Fig. 2, lower right). The zone has been subjected to polyphase brittle reactivation (Hultgren *et al.* 2004), which possibly explains scatter in the ^{40}Ar–^{39}Ar biotite spectra of samples at the border of the zone (127 m and 300 m; Fig. 3). The poorly defined biotite age of 928 ± 6 Ma at the 300 m level (Fig. 3) indicates late Sveconorwegian disturbance that may relate to the emplacement of dolerite intrusions. The second analysis of the same sample (KSH03–300b) did not yield an interpretable age. Drake, Page & Tullborg (2007) have dated adularia from two fracture zones in KSH03A, yielding ages of 989 ± 2 Ma and 401 ± 1 Ma. We realize that our age spectra from the 127 and 300 m borehole length in KSH03 are inconclusive and they will not be discussed further.

4. Discussion

The ^{40}Ar–^{39}Ar biotite and hornblende ages from Oskarshamn fall into three groups: ≥ 1.62 Ga, 1.51–1.47 Ga and 1.43–1.42 Ga (Table 1). The ages obtained from the boreholes KLX01, KLX02 and KSH03 are shown in vertical cross-sections in Figure 2, upper and lower right panels.

4.a. Cooling following crystallization of *c.* 1800 Ma, and younger, Transscandinavian Igneous Belt rocks

The hornblende ages of 1799 ± 5 Ma and 1773 ± 13 Ma (Fig. 2, upper and lower right; Fig. 4) are suggested to date cooling through 500 °C after emplacement of 1.80 Ga plutons. The 1799 ± 5 Ma age indicates fast cooling in a magmatically highly active area. The age spectrum does not show any indications of excess Ar. The 1773 ± 13 Ma ages derived from a forced plateau where the spectrum indicates minor Ar loss, and therefore the age is interpreted as a minimum age for cooling through the 500 °C isotherm. The rapid cooling, as indicated by these results, favours shallow emplacement of the intrusion, in agreement with preservation of coeval supracrustal rocks in scattered areas in the Småland–Värmland Belt (Wikman & Kornfält, 1995; Söderlund & Rodhe, 1998; Wahlgren *et al.* 2004).

The *c.* 1620 Ma biotite ages of borehole KSH03 are based on duplicates yielding indistinguishable results. The spectra show signs typical for loss of Ar and the ages are thus interpreted as minimum ages. The biotite grains in the sample are fresh with no signs of alteration (e.g. chloritization). If our interpretation of the hornblende ages are correct, that is, that they indicate shallow emplacement and initial fast cooling to 500 °C, the subsequent cooling to 300 °C must

have been extremely slow (on average 1.1 °C Ma^{-1}) on the assumption that the *c.* 1620 Ma biotite ages represent continuous cooling from the event of magma crystallization. An alternative interpretation, and the one preferred here, is that the *c.* 1620 Ma biotite ages reflect regional heating followed by cooling associated with the youngest period (1.68–1.67 Ga) of Transscandinavian Igneous Belt magmatism in south-central Sweden.

4.b. Interpretation of younger ages

The younger ages fall into two separate age groups: *c.* 1.51–1.47 Ga and *c.* 1.43–1.42 Ga, which provide evidence for two distinct thermal events. The age groups coincide with regionally tectonothermal events: the 1.65–1.47 Ga rapakivi intrusions (cf. Alviola *et al.* 1999; Dörr *et al.* 2002 and references therein) and magmatism of the 1.47–1.44 Ga Danopolonian event (Bogdanova *et al.* 2008; Brander & Söderlund, 2008).

The older group ^{40}Ar–^{39}Ar ages range between 1508 ± 7 and 1468 ± 2 Ma. The perhaps most straightforward interpretation is that these ages represent incomplete resetting during thermal heating from the 1.45–1.44 Ga Götemar and Uthammar intrusions. The relatively narrow age interval of this group is, however, defined by as many as seven analyses, and incomplete resetting would be expected to result in a more scattered age range. Further, similar ^{40}Ar–^{39}Ar hornblende ages (*c.* 1.57–1.47 Ga: Page *et al.* 1999; Beunk & Page, 2001) occur in the area close to the Loftahammar–Linköping Deformation Zone (Fig. 1), which indicates a similar thermal history further to the north. One statistically significant ^{40}Ar–^{39}Ar biotite age from a surface sample close to Norrköping (Fig. 1) gave 1494 ± 3 Ma (Page *et al.* 2007). The latter results cannot be explained by partial resetting of younger *c.* 1.45 Ga intrusions, as there are no intrusions of such age present in these areas.

The episodic and prolonged activity of rapakivi magmatism has been suggested to originate from extensive thermal activity in the lower crust (e.g. Puura & Flodén, 1999), possibly as the result of distal active margin processes in the west (Åhäll, Connelly & Brewer, 2000). Although no rapakivi intrusions have been observed in the Oskarshamn area, we cannot dismiss regional heating associated with rapakivi magmatism that caused resetting of the ^{40}Ar–^{39}Ar system in biotite at 1.51–1.47 Ga. Another possibility is early thermal activity related to the onset of the Danopolonian event. Presently, data are too sparse to make any final interpretation of this group of ^{40}Ar–^{39}Ar ages.

The youngest age group (1.43–1.42 Ga biotite ages) reflects local thermal effects associated with emplacement of the Götemar and Uthammar intrusions at 1.45–1.44 Ga. Geophysical modelling indicates that the southern contact of the Götemar granite dips to the south. The positions of the boreholes with

respect to the intrusions are illustrated in Figure 2, upper right. Sample O0102 is from the 1452+11/-9 Ma Götemar granite (Åhäll, 2001) (Fig. 2, left) and dates cooling through 300 °C of the granite at *c.* 1.42 Ga. Sample O0103 is from the 1.80 Ga Ävrö granite less than one kilometre from the Uthammar granite (Fig. 2, left). The intrusion at 1441+5/-3 Ma of the Uthammar granite (Åhäll, 2001) thermally affected the surrounding bedrock, which was subsequently cooled below 300 °C at 1434 ± 6 Ma. At the bottom of KLX02, the hornblende and biotite ages demonstrate that this locality, consisting of 1.80 Ga Ävrö granite, was thermally affected by the Götemar intrusion and cooled below 500 °C at 1445 ± 14 Ma, and subsequently cooled below 300 °C at 1431 ± 6 Ma (Fig. 2, upper right). The age difference between the biotites taken in the surrounding bedrock (*c.* 1.43 Ga) and that within the pluton (*c.* 1.42 Ga) reflects the more rapid cooling of the thermal aureole at a distance from the intrusion.

5. Conclusions

The 1799 ± 5 Ma and 1773 ± 13 Ma hornblende ages suggest that the 1.80 Ga granites belonging to the Transscandinavian Igneous Belt in the Oskarshamn area crystallized at a shallow level and initially cooled rapidly. The *c.* 1620 Ma biotite ages are suggested to reflect regional cooling after the youngest (1.68–1.67 Ga) magmatism in the Transscandinavian Igneous Belt in south-central Sweden.

The 1.51–1.47 Ga biotite ages are enigmatic to interpret. They may represent partial resetting by the *c.* 1.45–1.44 Ga Götemar and Uthammar plutons, or reflect regional heating by rapakivi magmatism. A third possibility is that the ages are associated with thermal activity at the onset of the Danopolonian event. Further investigations are needed for better understanding of this group of ages. The 1.43–1.42 Ga biotite ages date cooling of the Götemar and Uthammar granite intrusions and the thermally affected bedrock in the immediately adjacent area.

Whole rock samples from a 15–20 m wide dolerite dyke yielded ages of *c.* 900 Ma, possibly indicating that the 978–946 Ma Blekinge-Dalarna Dolerites extend toward younger ages. These dolerite intrusions are believed to have affected the bedrock locally in the Oskarshamn area as indicated by a poorly defined biotite age of 928 ± 6 Ma and other disturbed ages of samples bordering a complex deformation zone.

References

ÅHÄLL, K.-I. 2001. Åldersbestämning av svårdaterade bergarter i sydöstra Sverige. *Svensk kärnbränslehantering AB*, R-01–60.

ÅHÄLL, K.-I., CONNELLY, J. N. & BREWER, T. S. 2000. Episodic rapakivi magmatism due to distal orogenesis?: Correlation of 1.69–1.50 Ga orogenic and inboard, 'anorogenic' events in the Baltic Shield. *Geology* **28**, 823–6.

ALVIOLA, R., JOHANSON, B. S., RÄMÖ, O. T. & VAASJOKI, M. 1999. The Proterozoic Ahvenisto rapakivi granite-massive-type anorthosite complex, south-eastern Finland; petrography and U–Pb chronology. *Precambrian Research* **95**, 89–107.

AMELIN, Y. V., LARIN, A. M. & TUCKER, R. D. 1997. Chronology of multiphase emplacement of the Salmi rapakivi granite–anorthosite complex, Baltic Shield: implications for magmatic evolution. *Contributions to Mineralogy and Petrology* **127**, 343–68.

ANDERSSON, U. B., NEYMARK, L. A. & BILLSTRÖM, K. 2002. Petrogenesis of Mesoproterozoic (Subjotnian) rapakivi complexes of central Sweden: Implications from U–Pb zircon ages, Nd, Sr and Pb isotopes. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **92**, 201–28.

ANDERSSON, U. B., RUTANEN, H., JOHANSSON, Å., MANSFELD, J. & RIMŠA, A. 2007. Characterization of the Paleoproterozoic Mantle beneath the Fennoscandian Shield: Geochemistry and Isotope Geology (Nd, Sr) of ~1.8 Ga Mafic Plutonic Rocks from the Transscandinavian Igneous Belt in Southeast Sweden. *International Geology Review* **49**, 587–625.

BEUNK, F. F. & PAGE, L. M. 2001. Structural evolution of the accretional continental margin of the Paleoproterozoic Svecofennian orogen in southern Sweden. *Tectonophysics* **339**, 67–92.

BOGDANOVA, S., BINGEN, B., GORBATSCHEV, R., KHERASKOVA, T. N., KOZLOV, V. I., PUCHKOV, V. N. & VOLOZH, YU. A. 2008. The East European Craton (Baltica) before and during the assembly of Rodinia. *Precambrian Research* **160**, 23–45.

BOGDANOVA, S. V., PAGE, L. M., SKRIDLAITE, G. & TARAN, L. N. 2001. Proterozoic tectonothermal history in the western part of the East European Craton: ^{40}Ar/^{39}Ar geochronological constraints. *Tectonophysics* **339**, 39–66.

BRANDER, L. & SÖDERLUND, U. 2008. Mesoproterozoic (1.47–1.44 Ga) orogenic magmatism in Fennoscandia; Baddeleyite U–Pb dating of a suite of massif-type anorthosite in S Sweden. *International Journal of Earth Sciences*, doi 10.1007/s00531-007-0281-0, 18pp.

ČEČYS, A. & BENN, K. 2007. Emplacement and deformation of the ca. 1.45 Ga Karlshamn granitoid pluton, southeastern Sweden, during ENE-WSW Danopolonian shortening. *International Journal of Earth Sciences* **96**, 397–414.

ČEČYS, A., BOGDANOVA, S., JANSON, C., BIBIKOVA, E. & KORNFÄLT, K.-A. 2002. The Stenshuvud and Tåghusa granitoids: new representatives of Mesoproterozoic magmatism in southern Sweden. *GFF* **124**, 149–62.

CLAESSON, S. & KRESTEN, P. 1997. The anorogenic Noran intrusion – a Mesoproterozoic rapakivi massif in south-central Sweden. *GFF* **119**, 115–22.

DALRYMPLE, G. B. & LANPHERE, M. A. 1971. ^{40}Ar/^{39}Ar technique of K–Ar dating: a comparison with the conventional technique. *Earth and Planetary Science Letters* **12**, 300–8.

DÖRR, W., ZDZISLAW, B., MARHEINE, D., SCHASTOK, J., VALVERDE-VAQUERO, P. & WISZNIEWSKA, J. 2002. U–Pb and Ar–Ar geochronology of anorogenic granite magmatism of the Mazury complex, NE Poland. *Precambrian Research* **119**, 101–20.

DRAKE, H., PAGE, L. & TULLBORG, E.-L. 2007. Oskarshamn site investigation. ^{40}Ar/^{39}Ar dating of fracture minerals. *Svensk kärnbränslehantering AB*, P-07-27.

HELLSTRÖM, F. A., JOHANSSON, Å. & LARSON, S.-Å. 2004. Age and emplacement of late Sveconorwegian monzogabbroic dykes, SW Sweden. *Precambrian Research* **128**, 39–55.

HÖGDAHL, K., ANDERSSON, U. B. & EKLUND, O. 2004. The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evolution. *Geological Survey of Finland, Special Paper* **37**, 125 pp.

HULTGREN, P., STANFORS, R., WAHLGREN, C.-H., CARLSTEN, S. & MATTSSON, H. 2004. Oskarshamn site investigation. Geological single-hole interpretation of KSH03A, KSH03B, KLX02, HAV09 and HAV10. Revised June 2006. *Svensk kärnbränslehantering AB*, P-04-231.

MANSFELD, J. 1996. Geological, geochemical and geochronological evidence for a new Palaeoproterozoic terrane in southwestern Sweden. *Precambrian Research* **77**, 91–103.

MANSFELD, J., BEUNK, F. F. & BARLING, J. 2005. 1.83–1.82 Ga formation of a juvenile volcanic arc – implications from U–Pb and Sm–Nd analyses of the Oskarshamn–Jönköping Belt, southeastern Sweden. *GFF* **127**, 149–57.

PAGE, L. M., BEUNK, F., BOGDANOVA, S. & WIJBRANS, J. 1999. ^{40}Ar/^{39}Ar geochronological constraints on the tectonothermal history of the western part of the East European Craton in the southern Peri-Baltic region. *Journal of Conference Abstracts* **4**(1), 131.

PAGE, L., HERMANSSON, T., SÖDERLUND, P. & STEPHENS, M. B. 2007. Forsmark site investigation. ^{40}Ar/^{39}Ar and (U–Th)/He geochronology Phase II. *Svensk Kärnbränslehantering AB*, P-06–211.

PERSSON, A. I. 1999. Absolute (U–Pb) and relative age determinations of intrusive rocks in the Ragunda rapakivi complex, central Sweden. *Precambrian Research* **95**, 109–27.

PERSSON, P.-O. & WIKMAN, H. 1997. U–Pb zircon ages of two volcanic rocks from the Växjö region, Småland, south central Sweden. *Geological Survey of Sweden* **C830**, 50–6.

PUURA, V. & FLODÉN, T. 1999. Rapakivi-granite-anorthosite magmatism – a way of thinning and stabilisation of the Svecofennian crust, Baltic Sea Basin. *Tectonophysics* **305**, 75–92.

RÄMÖ, O. T., HUHMA, H. & KIRS, J. 1996. Radiogenic isotopes of the Estonian and Latvian rapakivi granite suites: new data from the concealed Precambrian of the East European Craton. *Precambrian Research* **79**, 209–26.

RENNE, P. R., SWISHER, C. C., DEINO, A. L., KARNER, D. B., OWENA, T. L. & DEPAOLO, D. J. 1998. Intercalibration of standards, absolute ages and uncertainties in ^{40}Ar/^{39}Ar dating. *Chemical Geology* **145**, 117–52.

SKRIDLAITE, G., WISZNIEWSKA, J. & DUCHESNE, J.-C. 2003. Ferro-potassic A-type granites and related rocks in NE Poland and S Lithuania: west of the East European Craton. *Precambrian Research* **124**, 305–26.

SÖDERLUND, U., ISACHSEN, C., BYLUND, G., HEAMAN, L., PATCHETT, P. J., VERVOORT, J. D. & ANDERSSON, U. B. 2005. U–Pb baddeleyite ages and Hf, Nd isotope chemistry constraining repeated mafic magmatism in the Fennoscandian Shield from 1.6 to 0.9 Ga. *Contributions to Mineralogy and Petrology* **150**, 174–94.

SÖDERLUND, U. & RODHE, A. 1998. Constraints on syn-intrusive ca. 1.8 Ga conglomerate deposits associated with the Småland-Värmland Belt, SE Sweden; Pb–Pb zircon evaporation dating of the Malmbäck conglomerate. *GFF* **120**, 69–74.

SUOMINEN, V. 1991. The chronostratigraphy of southwestern Finland with special reference to Postjotnian and Subjotnian diabases. *Geological Survey of Finland Bulletin* **356**, 106 pp.

WAHLGREN, C.-H., AHL, M., SANDAHL, K.-A., BERGLUND, J., PETERSSON, J., EKSTRÖM, M. & PERSSON, P.-O. 2004. Oskarshamn site investigation. Bedrock mapping 2003 – Simpevarp subarea. *Svensk Kärnbränslehantering AB*, P-04-102.

WAHLGREN, C.-H., BERGMAN, T., AHL, M. & EKSTRÖM, M. 2006a. Oskarshamn site investigation. Modal and geochemical analyses of drill core samples 2006 and updated bedrock map of the Laxemar subarea. Classification of rock types in KLX08, KLX10, KLX11A, KLX12A, KLX18A and KLX20A. *Svensk Kärnbränslehantering AB*, StB P-06-279.

WAHLGREN, C.-H., HERMANSON, J., FORSSBERG, O., CURTIS, P., TRIUMF, C.-A., DRAKE, H. & TULLBORG, E.-L. 2006b. Oskarshamn site investigation. Geological description of rock domains and deformation zones in the Simpevarp and Laxemar subareas. Preliminary site description Laxemar subarea – version 1.2. *Svensk Kärnbränslehantering AB*, R-05-69.

WELIN, E. & LUNDQVIST, T. 1984. Isotopic investigations of the Nordingrå rapakivi massif, north-central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* **106**, 41–9.

WIJBRANS, J. R., PRINGLE, M. S., KOPPERS, A. A. P. & SCHEEVERS, R. 1995. Argon geochronology of small samples using the Vulkaan argon laserprobe. *Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen* **98**, 185–218.

WIKMAN, H. 1993. U–Pb ages of Småland granites and a Småland volcanite from the Växjö region, southern Sweden. *Geological Survey of Sweden* **C823**, 65–72.

WIKMAN, H. & KORNFÄLT, K.-A. 1995. Updating of a lithological model of the bedrock of the Äspö area. *Svensk Kärnbränslehantering AB*, PR 25-95-04.

WIKSTRÖM, A. 1993. U–Pb dating of the Stormandebo rhyolite in the Västervik area, southeastern Sweden. *Geological Survey of Sweden* **C823**, 73–6.