

Sveconorwegian U-Pb zircon and monazite ages of granulite-facies rocks, Hisarøya, Gulen, Western Gneiss Region, Norway

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U-Pb zircon data from newly discovered granulite-facies rocks on Hisarøya, Gulen, Western Norway, yield a discordia line with upper and lower intercepts of 1646 ± 110 Ma and 987 ± 10 Ma, respectively. The upper intercept age overlaps with Gothian ages previously obtained from the Western Gneiss Complex and is interpreted to date a magmatic growth episode of the Baltic Shield, while the lower intercept age, anchored by a concordant rim analysis, is interpreted to date a Sveconorwegian granulite-facies event. A concordant U-Pb monazite age of 949 ± 3 Ma documents late stages in the prolonged Sveconorwegian metamorphism. We suggest that the granulite-facies rocks on Hisarøya, together with similar rocks on Bårdsholmen, Sunnfjord, form remnants of a once much larger granulite-facies terrane.

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Introduction

The Western Gneiss Complex (WGC) of Norway is an area of more than 25 000 km² of dominantly middle Proterozoic gneissic rocks outcropping between Bergen and Trondheim (Fig. 1). The WGC forms part of the Baltic shield, which according to Gorbatshev & Gáal (1987) grew during 4 orogenies between 3.5 and 1.5 Ga, followed by reworking during the Sveconorwegian and Caledonian events. Tucker et al. (1990) suggest that the Sveconorwegian influence was limited to the southern part of the WGC (Fig. 1). Skår & Pedersen (2003) found that the Sveconorwegian overprint also involved migmatitization and granite intrusion. During the Scandian phase of the Caledonian orogeny, the WGC was subjected to high- and ultra-high-pressure metamorphic conditions, while it constituted the root zone of the orogen (Andersen & Jamtveit 1990). In this paper we present new and precise geochronological evidence from Hisarøya. We use these data to discuss the age and metamorphic evolution of the southern part of the WGC.

Field description

The island of Hisarøya (Fig. 1) comprises ortho- and paragneisses that have been reworked at eclogite- and amphibolite-facies conditions during the Caledonian orogeny. Granitic gneiss, commonly characterized by augen texture, is the dominant rock type. In the nor-

thernmost part of the island, the gneisses are intensely deformed by top-to-the-west shearing along the Nordfjord Sogn Detachment Zone (e.g. Andersen & Jamtveit 1990). Further to the south, this shearing becomes less prominent, and in places the granite is coarse-grained and only slightly lineated.

The central part of Hisarøya, west of Hjartåsvågen (Fig. 1), is dominated by a complex of foliated amphibolites with local eclogites, coarse-grained rutile-bearing kyanite-garnet-micaschist and quartzite. Field observations suggest that these rocks were intruded by the granite mentioned above at an early stage. Later, during Caledonian deformation, they have been interfolded with the granite into a large-scale sheath-like fold structure, which today forms the low topography across the island.

The southern part of the island comprises a banded granulite complex where mafic and felsic rocks alternate on a scale of meters to 10's of meters. These rocks are variably eclogitized. Geothermobarometric estimates from an equilibrated mafic eclogite show temperatures of $562 \pm 35^\circ\text{C}$, and pressures of 15.3 ± 1 kbar (Røhr in prep.). In places, the granulite complex has been amphibolitized without significant deformation. More commonly, amphibolite-facies mineralogies are found within shear zones cross-cutting the granulites/eclogites.

The mafic granulites contain plagioclase, two pyroxenes, Ti-rich amphibole, biotite and opaques, and have a granoblastic texture. All stages of metamorphic

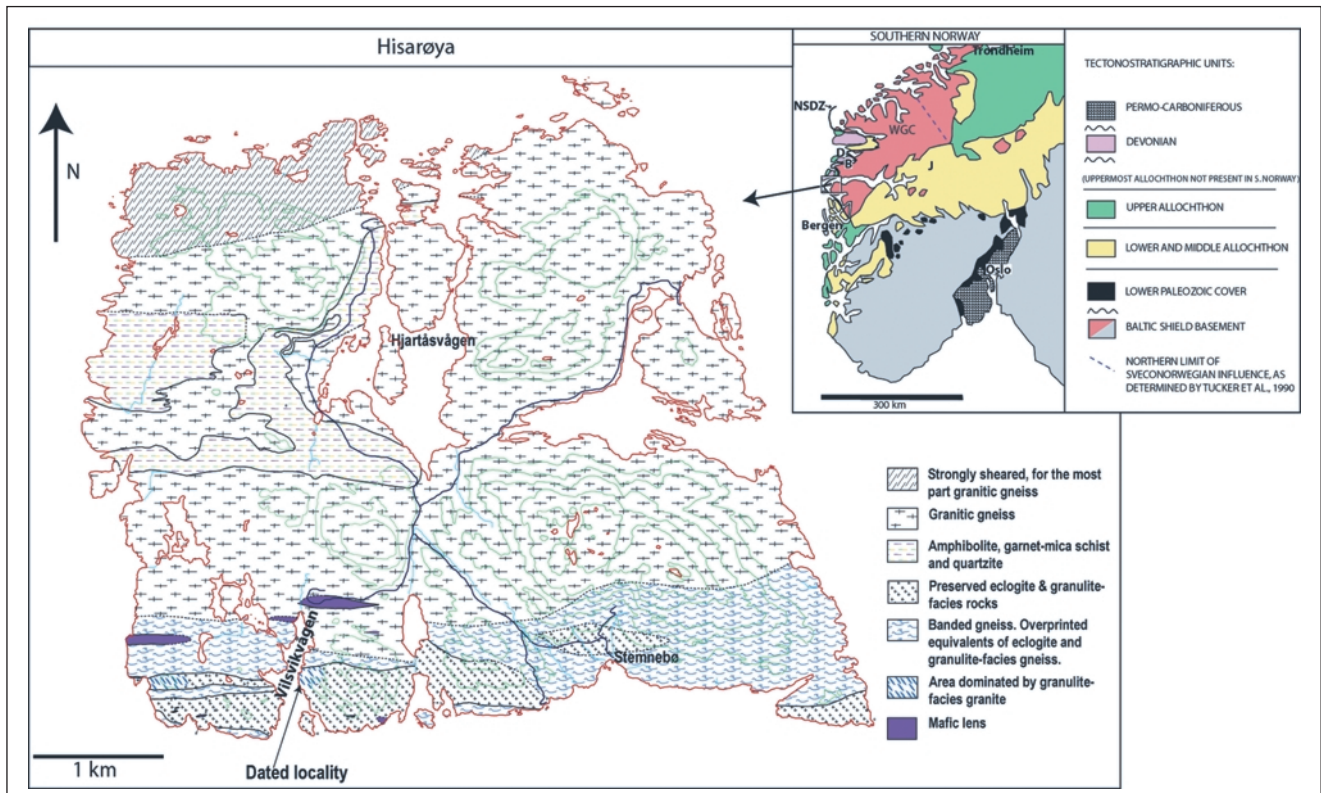


Fig. 1. Geological map of Hisarøya with inset showing its location in the WGC. Mapping on Hisarøya has been done by the main author, whereas the inset map is based on Fig 1 in Corfu & Andersen (2002). B: Bårdsholmen. D: Dalsfjord. J: Jotun Nappe. NSDZ: Nordfjord Sogn Detachment Zone.

transitions between granulite- and eclogite-facies mineral assemblages can be found. The least altered mafic granulites have clouded plagioclase while ferromagnesian minerals are slightly corroded and surrounded by thin coronas of garnet and omphacite. Fully equilibrated eclogites have a granoblastic texture and a strong fabric determined by alternating zones of garnet and omphacite. In addition the eclogites contain rutile and phengite.

The felsic rocks vary in composition from syenogranitic to monzonitic and granodioritic. These rocks have granulite-, eclogite- and amphibolite-facies mineral assemblages. Preserved granulites have plagioclase, perthitic K-feldspar, characteristic blue quartz, biotite, opaques, garnets that are up to one cm in size, and local pseudomorphs after orthopyroxene. The Caledonian high-pressure metamorphism has caused clouding of plagioclase, even in the best preserved granulites. Thin coronas of garnet around biotite and opaques are also common in these samples (Fig. 2b). More evolved eclogite-facies felsites contain quartz, zoisite, white mica (probably phengite), small garnets and bluish amphibole.

Sample description

The dated sample was collected from the southern part of the island at Vilsvikvågen (Fig. 1). The sample has a quartz-monzonitic to quartz-monzodioritic composi-

tion. The granulite-facies mineral assemblage includes plagioclase, string-perthitic K-feldspar, quartz, biotite, orthopyroxene, garnet and opaques (mainly magnetite). Orthopyroxene is pseudomorphed by microcrystalline bastite aggregates. The garnet ($\text{Alm}_{62.5}\text{Pyr}_{13.5}\text{Grs}_{10.5}\text{Sps}_{9.0}$) is exceptionally enriched in Y (1.9 wt %) and HREE (ca. 2 wt %) (work in progress). Accessory minerals include zircon, monazite, xenotime and apatite. The granulite-facies minerals are medium-grained and display a granoblastic texture.

In addition to the dominant granulite-facies mineral assemblage, the rock contains a second generation of minerals, which is distinguished from the dominant assemblage by a finer grain size and by forming coronas on the early granulite-facies minerals. Second-generation garnets ($\text{Alm}_{59}\text{Pyr}_9\text{Grs}_{28}\text{Sps}_7$) typically form a rim around granulite-facies garnet (Fig. 2a), biotite (Fig. 2b), and opaques (Fig. 2b). Secondary garnet also forms dendrite-like textures in plagioclase, and it differs from the first generation by having significantly lower Y (0.3 wt %) and HREE (0.3 wt %). Plagioclase is clouded by needles of zoisite and amphibole, and this clouding is at its most intense near bastite (after opx), biotite and opaques. Monazites are slightly corroded (Fig. 3a), with a thin rim of apatite. In samples that show a stronger alteration, the apatite rim becomes coarser and a rim of allanite appears outside the apatite. By analogy with the mafic rocks, where the second gene-

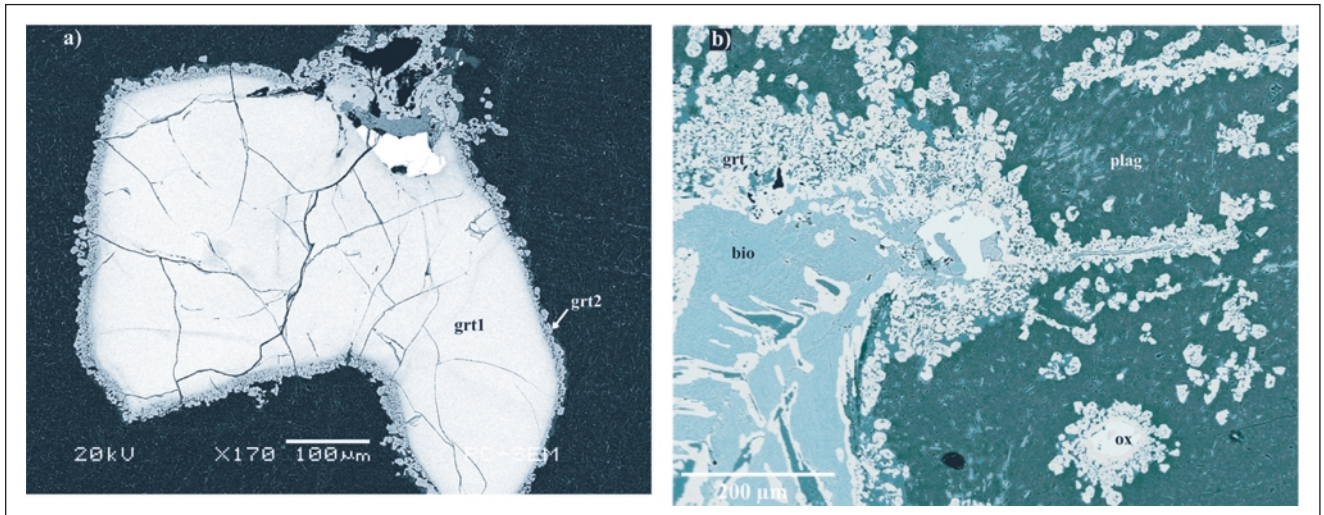


Fig. 2. Microtextures for the dated sample. a) Granulite-facies garnet, with poikiloblastic overgrowth of secondary garnet. b) Coronas of garnet around biotite (bio) and oxide (ox). Note dendrites of garnet penetrating plagioclase (plag) along fractures.

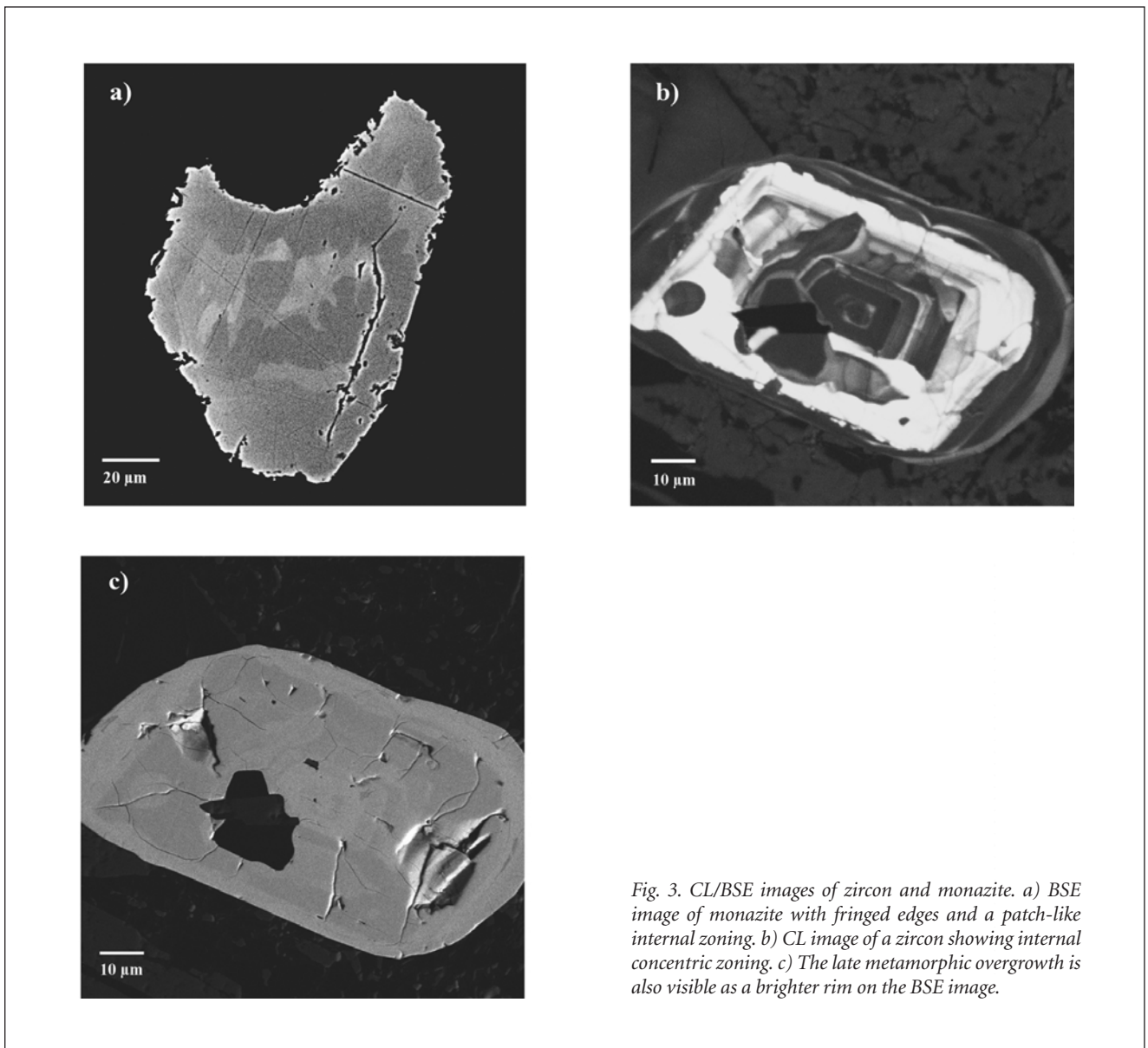


Fig. 3. CL/BSE images of zircon and monazite. a) BSE image of monazite with fringed edges and a patch-like internal zoning. b) CL image of a zircon showing internal concentric zoning. c) The late metamorphic overgrowth is also visible as a brighter rim on the BSE image.

Table 1. U-Pb data

Fraction analyzed ^a	Weight ^b (μg)	U ^b (ppm)	Th/U ^c	Pbc ^d (pg)	²⁰⁶ Pb/ ²⁰⁴ Pb ^e	²⁰⁷ Pb/ ²³⁵ Uf	2σ (abs)	²⁰⁶ Pb/ ²³⁸ Uf	2σ (abs)	ρ	²⁰⁷ Pb/ ²⁰⁶ Pb ^e	2σ (abs)	²⁰⁶ Pb/ ²³⁸ Uf	(Ma)	²⁰⁷ Pb/ ²³⁵ Uf	(Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb ^e	(Ma)	2σ ^g (abs)	Disc. ^h (%)
(1) Z subrnd [4]	<1	682	0,23	2,1	3804	1,9961	0,0276	0,18328	0,00249	0,97	0,07899	0,00028	1084	1114	1171,9	7,1	8,1			
(2) Z euhdr [1]	<1	1041	0,11	1,2	9930	1,8438	0,0088	0,17601	0,00081	0,89	0,07598	0,00017	1045	1061	1094,5	4,4	4,9			
(3) Z rim [1]	<1	972	0,05	11,0	934	1,6601	0,0093	0,16626	0,00079	0,86	0,07242	0,00021	991	993	997,8	5,8	0,7			
(4) M subrnd NA [1]	5	561	31,94	20,6	1367	1,5475	0,0084	0,15852	0,00075	0,76	0,07080	0,00025	949	949	951,6	7,2	0,3			
(5) M subrnd NA [1]	4	61	74,54	2,4	1038	1,5783	0,0102	0,16205	0,00084	0,68	0,07064	0,00034	968	962	947,0	9,8	-2,4			
(6) M subrnd NA [1]	5	132	66,57	2,3	2878	1,5720	0,0062	0,16139	0,00051	0,80	0,07064	0,00017	965	959	947,1	4,8	-2,0			

Table 1. U-Pb data.

^a(N) = fraction number, see Fig 4; Z = zircon; M = monazite; subrnd = sub-rounded; euhedr = euhedral; NA = not abraded; [N] = number of grains in fraction. ^{b,d} Weight and concentrations are known to better than 10%, except for those near and below the ca. 1 μg limit of resolution of the balance. ^c Th/U model ratio inferred from 208/206 ratio and age of sample. ^d Pbc = total common Pb in sample (initial + blank). ^e Raw data corrected for fractionation and blank. ^f Corrected for fractionation, spike, blank and initial common Pb; error calculated by propagating the main sources of uncertainty. ^g Uncertainty of 208Pb/206Pb age. ^h Disc. = degree of discordance

ration of minerals includes omphacite, we interpret this second generation of minerals to represent the Caledonian eclogite-amphibolite facies influence in the area.

Zircons appear to have preserved some of their magmatic characteristics. When viewed with cathodoluminescence (CL) imaging, a concentric zoning of the grain interiors is clearly visible (Fig. 3b). We believe that these parts of the zircons record the earliest part of the rock's history. The internal euhedral concentric zoning is cut and / or surrounded by zones of bright luminescence, possibly representing zones of secondary recrystallization. The zircon outer rims display a faint, diffuse and irregular zoning, which appears as a more uniform and brighter zone when viewed with Back-Scattered Electron (BSE) imaging (Fig. 3c). This part of the grain is interpreted to represent later metamorphic overgrowth, and the interpretation is supported by U-Pb analysis (see below). The internal compositional variations found within the monazites form a patch-like pattern of uncertain petrogenetic significance (Fig. 3a). However, as mentioned above, their corroded rims and the overgrowths of apatite plus allanite may be interpreted as resulting from Caledonian metamorphic reactions.

Nine clear grains (6 zircons and 3 monazites) were chosen for mass spectrometry. The monazites were all clear, sub-rounded tabular grains. The zircons were divided into three groups: z-subr - four sub-rounded grains; z-euh - an euhedral grain; z-rim - and a concentric shrapnel, probably part of a metamorphic rim (Figs. 3b,c).

Analytical procedure

The sample was crushed in a jaw crusher and pulverized in a hammer mill before mineral separation, which was performed using a Wilfley table, Frantz magnetic separators and heavy liquids. The grains were later submerged in ethanol and individually picked under a binocular microscope. The zircons were abraded with pyrite (Krogh 1982) before cleaning in concentrated nitric acid. A mixed spike solution of ²³⁵U and ²⁰⁵Pb was later added to all samples. The zircons were dissolved in a mix of hydrofluoric and nitric acids at 185°C, while the monazites were dissolved with hydrochloric acid on a hot-plate. The monazites, weighing 4 and 5 μg (one and two grains, respectively), were subsequently treated with ion exchange resin to remove the REE. All zircons, including the group of four sub-rounded grains, weighed less than 1 μg , so no treatment was necessary.

Results

One of the three zircon analyses (Table 1) is concordant and the others variously discordant. When plotted in a Concordia diagram (with the program Isoplot 3.0,

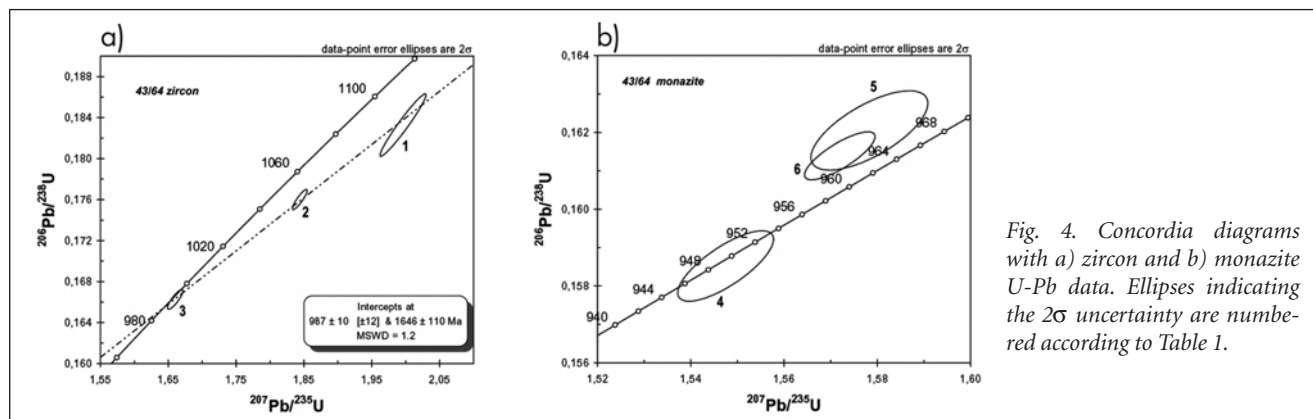


Fig. 4. Concordia diagrams with a) zircon and b) monazite U-Pb data. Ellipses indicating the 2σ uncertainty are numbered according to Table 1.

Ludwig 2003) they define a discordia line with intercept ages at 1646 ± 110 Ma and 987 ± 10 Ma (Fig. 4a). The latter corresponds to the age of the concordant analysis of the single zircon rim, thus confirming that this concentric shrapnel is part of the late metamorphic overgrowth (Fig. 3b, c). The low Th/U ratio in this grain compared to the other grains can also be seen as an indicator for a secondary origin (Rubatto 2002). In fact, low Th/U ratios are a common, but not exclusive, feature of secondary new growth, likely reflecting growth in the presence of aqueous fluids, either fluid-assisted solid-solid reactions or growth in water-rich melts (e.g. Söderlund et al. 2002; Andersson et al. 2002). On the other hand, metamorphic zircon found in high-grade rocks can exhibit the contrary behaviour with high Th/U (e.g. Corfu et al. 1994; Bingen et al. 2001). We suggest that the lower intercept age represents fluid-assisted zircon crystallization during the granulite-facies event, whereas the upper intercept represents the intrusive age of the rock.

Of the three monazite analyses one plots on Concordia defining a Concordia age of 949 ± 3 Ma, whereas the other two are reversely discordant (Fig. 4b). There are two possible explanations for this relationship: (1) the two reversely discordant analyses reflect initial isotopic disequilibrium caused by excess ^{230}Th (Schärer 1984), and thus the $^{207}\text{Pb}/^{235}\text{U}$ age of 960 ± 3 Ma best approximates the age of the grains. The alternative is that the grains are reversely discordant because of U loss or Pb gain caused by recent alteration or an analytical problem. The latter possibility is supported by the fact that all three analyses have $^{207}\text{Pb}/^{206}\text{Pb}$ ages that overlap at 948 ± 4 Ma, whereas the former would be consistent with the fact that the two analyses with reversely discordant data also have the highest apparent Th/U ratios. By contrast, the data do not show any simple indication in favour of a link between the negative discordance and the Caledonian overprint.

Discussion

We suggest that the 1646 ± 110 Ma zircon intercept

approximately dates the intrusion of the granite, and that this event is represented by the magmatic cores of the zircons. This age corresponds to the main crust-forming event in the Southwest Scandinavian Domain, referred to as the Gothian event (Gorbatshev & Gál 1987). Gothian intrusion ages presented from other parts of the WGC range between 1686 and 1631 Ma (Tucker et al. 1990; Skår et al. 1994; Austrheim et al. 2002; Skår & Pedersen 2003). Our upper intercept age, although with a high degree of uncertainty, falls within this range.

The 987 ± 10 Ma intercept probably dates the granulite-facies metamorphic event. This event, represented by the metamorphic overgrowth seen in the Scanning Electron Microscopy (SEM) pictures (Fig. 3b,c), must have had a large impact on the zircon chemistry, and corresponds to the Sveconorwegian-/Grenvillian Orogeny (Gorbatshev & Gál 1987). The time span between the zircon lower intercept age of 987 ± 10 Ma and the concordant monazite age of 949 ± 3 Ma indicates that the Sveconorwegian event was either long-lasting or alternatively consisted of two or more events.

A Sveconorwegian high-T event has already been reported from this area by Skår & Pedersen (2003), who obtained an age of 969 ± 8 Ma for migmatitization of various gneissic units, a zircon age of 966 ± 2 Ma for intrusion of a granite, and titanite ages ranging from 973 to 951 Ma dating intrusion of dykes and concurrent metamorphism. Our concordant monazite age of 949 ± 3 Ma corresponds to the youngest pegmatitic event recorded in that study. Engvik et al. (2000) described granulite-facies rocks from Bårdsholmen in Sunnfjord (Fig. 1). The rocks at Bårdsholmen have many similarities to the layered granulite on Hisarøya, both with respect to rock types and metamorphic evolution. A Sveconorwegian age of 'close to 1000 Ma' has been obtained for zircon in these rocks by Gromet & Andersen (1994), an age which Engvik et al. (2000) interpreted to represent the granulite-facies metamorphism. Their dating by the zircon evaporation method also indicated the presence of ages up to at least 1400 Ma, probably the same relationships observed in this study and in the migmatites of Skår & Pedersen (2003).

Thus, the existing data indicate that the rocks on Hisarøya and Bårdsholmen may be remnants of a regional granulite-facies terrain of Sveconorwegian origin.

The U-Pb data and Precambrian evolution outlined for Hisarøya bear many resemblances with the ages and metamorphic evolution recorded for the Middle Allochthon of Western Norway. Corfu & Andersen (2002) reported intrusive ages of 1634 ± 3 Ma from a Dalsfjord Suite monzonite, which also recorded a Sveconorwegian event represented by concordant U-Pb titanite ages ranging between 960 and 920 Ma. From the Lindås Nappe, Bingen et al. (2001) obtained a late Sveconorwegian U-Pb zircon age of 929 ± 1 Ma for the granulite-facies metamorphism. And in the Jotun nappe, Schärer (1980) documented a pervasive, metamorphic-deformational event that strongly reset zircon and formed titanite at ca. 900 Ma in amphibolite-facies rocks, whereas Lundmark (work in progress) obtained ages between ca. 950 and 900 Ma for rocks in the higher grade part of the nappe. These data support previous interpretations suggesting that the basement rocks within the nappes of the Middle Allochthon were derived from a common region in southwestern Baltica.

One interesting aspect of our data is the fact that none of the analyzed systems seems to have been affected at all by the Caledonian orogeny. Only the reversely discordant monazite analyses could be interpreted as reflecting such an event, but, as discussed above, the evidence points more convincingly towards either a recent disturbance of the U-Pb system of these grains or initial disequilibrium in 960 Ma monazite. Thus the U-Pb data do not provide direct confirmation that the corrosion of monazite and the development of thin rims of apatite (Fig. 3a) are related to Caledonian eclogitization processes (Fig. 2). The fact that Pb did not diffuse out of monazite when heated to temperatures of 560°C (Røhr in prep.) is in accord with the high closure temperatures proposed for this mineral (e.g. Heaman & Parrish 1991).

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