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Late Neoproterozoic amphibolite-facies metamorphism of a pre-Caledonian basement block in southwest Wedel Jarlsberg Land, Spitsbergen: new evidence from U–Th–Pb dating of monazite

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Abstract – Southwest Spitsbergen, Wedel Jarlsberg Land, consists of two Proterozoic crustal blocks with differing metamorphic histories. Both blocks experienced Caledonian greenschist-facies metamorphism, but only the southern block records an earlier pervasive M1 amphibolite-facies metamorphism and strong deformational fabric. *In situ* EMPA total-Pb monazite geochronology from both matrix and porphyroblast inclusion results indicate that the older M1 metamorphism occurred at 643 ± 9 Ma, consistent with published cooling ages of *c.* 620 Ma (hornblende) and 580 Ma (mica) obtained from these same rocks. This region thus contains a lithostratigraphic profile and metamorphic history which are unique within the Svalbard Archipelago. Documentation of a pervasive late Neoproterozoic Barrovian metamorphism is difficult to reconcile with a quiescent non-tectonic regime typically inferred for this region, based on the occurrence of rift-drift sequences on the Baltic and Laurentian passive margins. Instead, our new metamorphic age implies an exotic origin of the pre-Devonian basement exposed in SW Spitsbergen and supports models of terrane assembly postulated for the Svalbard Archipelago.

Keywords: Svalbard, Caledonides, terranes, geochronology, tectonics.

1. Introduction

The western part of Spitsbergen Island exposes an elongate N–S-trending basement high (Fig. 1) uplifted in the axial zone of an Early Palaeogene fold-and-thrust belt (e.g. Lowell, 1972; Dallmann *et al.* 1993; Braathen, Bergh & Maher, 1995; Bergh, Braathen & Andresen, 1997). This elevated basement block consists of Precambrian to Early Palaeozoic metamorphic rocks collectively defined in the Svalbard Archipelago as the Hecla-Hoek Formation (Kulling, 1934). Deformation and metamorphism of this formation was originally ascribed solely to the Caledonian Orogeny that consolidated the pre-Devonian basement of Svalbard (e.g. Holtedahl, 1926; Harland, 1959, 1985; Ohta, 1982; Manby, 1990; Harland *et al.* 1992). However, several field studies recognize regional unconformities within the pre-Devonian basement of Svalbard that are often associated with metamorphic and lithological contrasts (Sandford, 1956; Krasilščikov, 1979; Birkenmajer, 1975, 1981, 1992; Björnerud, 1990). In addition, subsequent isotopic studies provide further evidence that the Caledonian basement of Svalbard includes older Proterozoic crustal domains overprinted by the Early Palaeozoic tectonic events (e.g. Peucat *et al.* 1989; Balashov *et al.* 1995; Gee, Björklund & Stølen, 1994; Gee *et al.* 1995; Johansson *et al.* 1995; Hellman *et al.* 1997; Johansson *et al.* 2004). Thus a growing body of evidence suggests that some of these Proterozoic terranes were likely subjected to both Grenvillian 950–1000 Ma and latest Neoproterozoic 660–620 Ma tectonothermal activity (Peucat *et al.* 1989) prior to Caledonian overprinting of variable extent.

In this study, we dated metamorphic monazite from basement rocks in the southern part of the Wedel Jarlsberg Land, immediately north of the Hornsund Fjord (Fig. 1), to better constrain the pre-Caledonian metamorphic history of the Hecla-Hoek Formation. The study area includes an amphibolite-grade polymetamorphic domain subjected to a complex structural and metamorphic evolution and preserving a long history of early tectonothermal events (Balashov *et al.* 1995, 1996; Manecki *et al.* 1998). The tectonometamorphic history of this area seems to be unique compared to that revealed by lower-grade greenschist-facies rocks representing the Hecla Hoek succession

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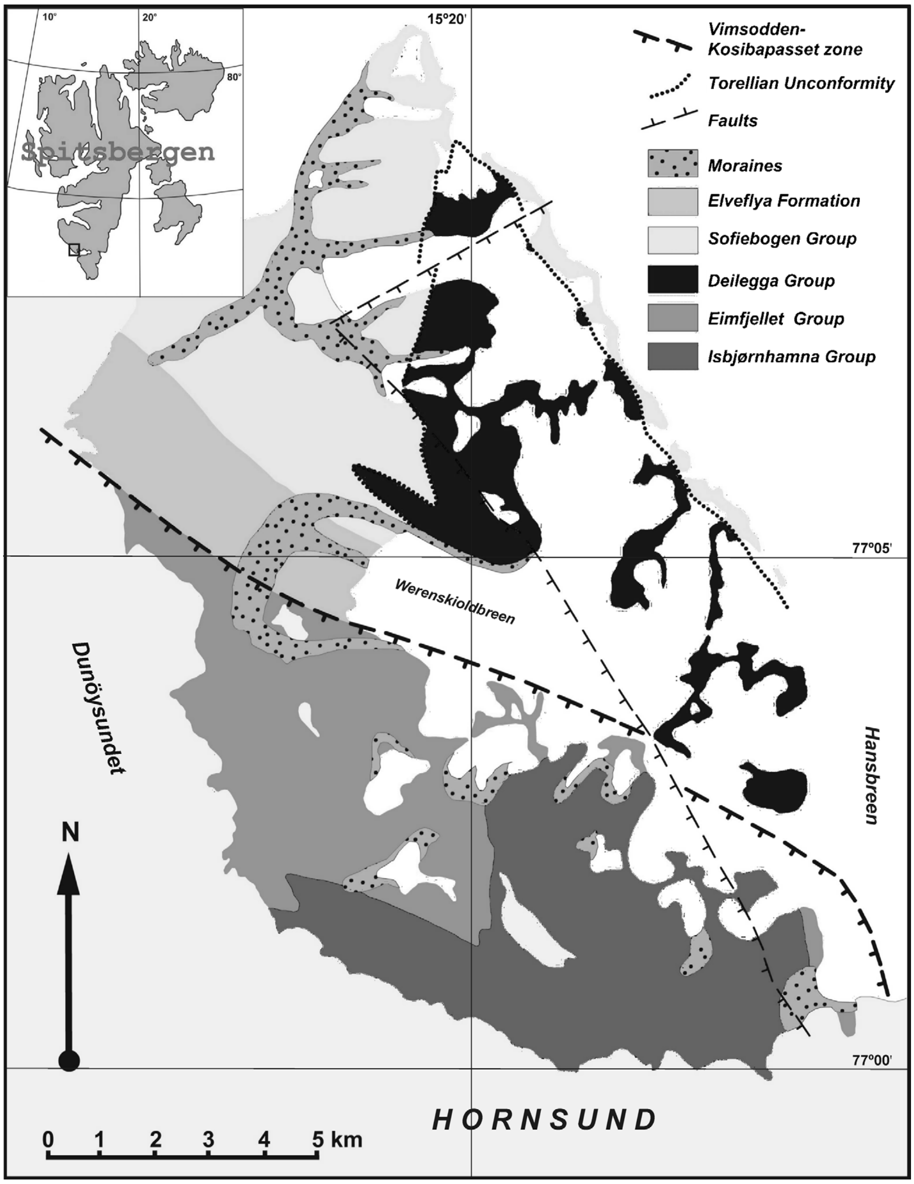

Figure 1. Geological sketch-map of SW part of Wedel Jarlsberg Land (after Czerny *et al.* 1993, modified). Inset shows location within the Svalbard Archipelago.

in the directly neighbouring basement domains. The study area thus offers a rare opportunity to unravel the enigmatic Proterozoic events which contributed to the pre-Caledonian development of the crystalline basement of Svalbard.

2. Geological setting

A stratified volcano-sedimentary polymetamorphic complex crops out in the SW part of Wedel Jarlsberg Land. This complex consists of a metasedimentary sequence known as the Isbjørnhamna Group and a metavolcanic succession of the Eimfjellet Group (Birkenmajer, 1958; Czerny *et al.* 1993). The Isbjørnhamna Group is composed of mica schists, paragneisses, calc-silicate rocks and marbles subjected to two metamorphic events. Amphibolite-grade Barrovian metamorphism of these rocks was followed by a retrogressive event under greenschist-facies conditions (Smulikowski, 1965; Majka *et al.* 2004). The younger metamorphism was responsible for partial to complete chloritization of garnet and biotite, disintegration of muscovite, sericitizaton of plagioclase and decomposition of kyanite.

The Isbjørnhamna Group includes three lithostratigraphic subdivisions: the Skoddefjellet, Ariekammen and Revdalen formations, considered to represent sections of a continuous sedimentary succession (Birkenmajer, 1975). The Skoddefjellet Formation consists of mutually layered (at the centimetre to decimetre scale) paragneisses and metapelites. A typical mineral assemblage related to progression of metamorphism in these rocks consists of Q + Pl + Bt + Ms ± Grt ± Chl with increasing amounts of plagioclase (oligoclase) and garnet in paragneisses and mica schists, respectively. Tourmaline, sphene, apatite, allanite, monazite, xenotime, zircon, ilmenite, hematite and magnetite are common accessory phases.

The Ariekammen Formation is distinguished by the presence of carbonate rocks. The formation mostly consists of carbonate–mica schists with irregular layers of mica schists and paragneisses of the Skoddefjellet type. A mineral assemblage characteristic of these rocks comprises $C + Q + Bt + Grt + Pl + Ms \pm Ep$ with Ca-enriched plagioclase and the same accessory minerals as those in the Skoddefjellet Formation. In addition, some varieties of schists contain rare mejonite. Notably, a discontinuous horizon of yellow and white calcite marbles occurs in the middle of the formation. Porphyroblasts of garnet up to 6 cm across are abundant at the base of this horizon.

The Revdalen Formation in the uppermost part of the Isbjørnhamna Group represents a uniform sequence of rusty weathered mica schists. These rocks consist of $Q + Pl + Bt \pm Ms \pm Grt \pm Chl$ and accessory phases similar to those found in the Skoddefjellet Formation. Metamorphic zonation is indicated by the local presence of chloritoid, staurolite or kyanite.

In the Isbjørnhamna Group metapelites, the dominant planar structure is a pervasive S1 foliation containing a strong visible L1 lineation. These structures are interpreted to have formed during the older M1 amphibolite-facies metamorphism, as younger, greenschist-facies Caledonian metamorphic overprinting was not associated with a strong deformational overprint of the metapelites. S1 foliation is predominantly expressed by flat, parallel arrangement of muscovite and biotite phyllosilicates and by flattened pophyroblasts of garnet and staurolite. However, in samples where chloritoid is present in the paragenesis, dominant phyllosilicates are muscovite and chlorite. In such samples, prismatic porphyroblasts of chloritoid also lay within the foliation planes.

The contact of the Isbjørnhamna Group with the adjacent greenschist-facies Deilegga and Sofiebogen groups to north is clearly tectonic. A 0.5 km thick high-strain zone making up the strike-slip to oblique-slip sinistral Vimsodden–Kosibapasset shear zone developed under greenschist-facies conditions. The Vimsodden–Kosibapasset shear zone is located directly at the contact of two crustal domains which differ in both metamorphic grade and structural evolution. The northern domain, comprising the Deilegga and Sofiebogen groups, resembles the Vimsodden–Kosibapasset zone in terms of metamorphic grade and structural pattern despite the much lower strain intensity. On the other hand, the margin of the southern domain, corresponding to the Isbjørnhamna Group, shows features of intense mylonitization and retrogression providing evidence for its post-peak metamorphism juxtaposition against the lower-grade crustal blocks to the north.

Initial thermochronological data from the study area were reported by Gayer *et al.* (1966), who obtained K–Ar mica ages of 565 and 595 Ma. Subsequent Rb–Sr whole-rock dating of samples from the Isbjørnhamna Group yielded a late Grenvillian age of 936 Ma (Gavrilenko *et al.* 1993). Detrital zircons from the mica schists belonging to the same group dated by the Pb-evaporation method on small populations of grains gave a poorly constrained age of *c.* 1500 Ma (Balashov *et al.* 1996). The meta-igneous suite of mafic and felsic rocks of the overlying Eimfjellet Group yielded a consistent group of single-zircon Pb-evaporation ages of *c.* 1160 ± 40 Ma (Balashov *et al.* 1996). Rhyolitic metaconglomerates belonging to the same suite yielded *c.* 1200 Ma U–Pb detrital zircon ages and a lower intercept age of *c.* 930 Ma, thought to be the time of regional metamorphism (Balashov *et al.* 1995). $^{40}Ar/^{39}Ar$ step heating of mineral separates yielded a 616 Ma age for hornblende from the Eimfjellt Group and 585–575 Ma ages for biotite and muscovite from the Isbjørnhamna Group (Manecki *et al.* 1998).

3. Analytical methods and sampling selection

In order to constrain the timing of amphibolite-facies metamorphism, *in situ* electron microprobe total-Pb monazite geochronometry was applied to selected metamorphic samples. Monazite was principally chosen because it contains large amounts of Th and U, has minor ^{204}Pb, and exhibits little elemental diffusion under high temperatures (Catlos, Gilley & Harrison, 2002). Furthermore, monazite is an ideal mineral for dating polyphase tectonometamorphic histories because of its high closure temperature ($> 850\,^{\circ}C$) and its ability to record multiple metamorphic events (Cherniak *et al.* 2004). Five samples of fine- to medium-grained mica schists from the Skoddefjellet and Revdalen formations were selected for monazite dating (Fig. 2). These rocks underwent amphibolite-facies M1 metamorphism followed by a minor M2 retrogressive event that brought about relatively weak retrogressive changes (e.g. partial chloritization of garnet and biotite).

Only samples from staurolite and kyanite zones were selected for monazite dating. These samples are metamorphosed at *P*–*T* conditions above the so-called 'allanite window' (e.g. Wing, Ferry & Harrison, 2003; Janots *et al.* 2007; Krenn & Finger, 2006) making them ideally suited for determining peak metamorphic age. In samples metamorphosed below the staurolite zone, only allanite was observed in the paragenesis. According to Ferry (2000), detrital monazite can entirely disappear during metamorphism and the rare-earth elements originally comprised in its grains be preferentially sited in allanite. Metamorphic allanite is stable only under upper-greenschist-facies conditions above the Bt-in isograd, whereas the crystallization of new metamorphic monazite is related to prograde amphibolite-facies metamorphism (Ferry, 2000; Catlos, Gilley & Harrison, 2002; Wing, Ferry & Harrison, 2003; Gieré & Sorensen, 2004). We emphasize that the amphibolite-facies metamorphic rocks (conditions quantified using Gr–Bt thermometry and GASP barometry: Majka, Czerny & Manecki, 2004) analysed in this study contain monazite but no allanite. Therefore, all dated monazites are interpreted as

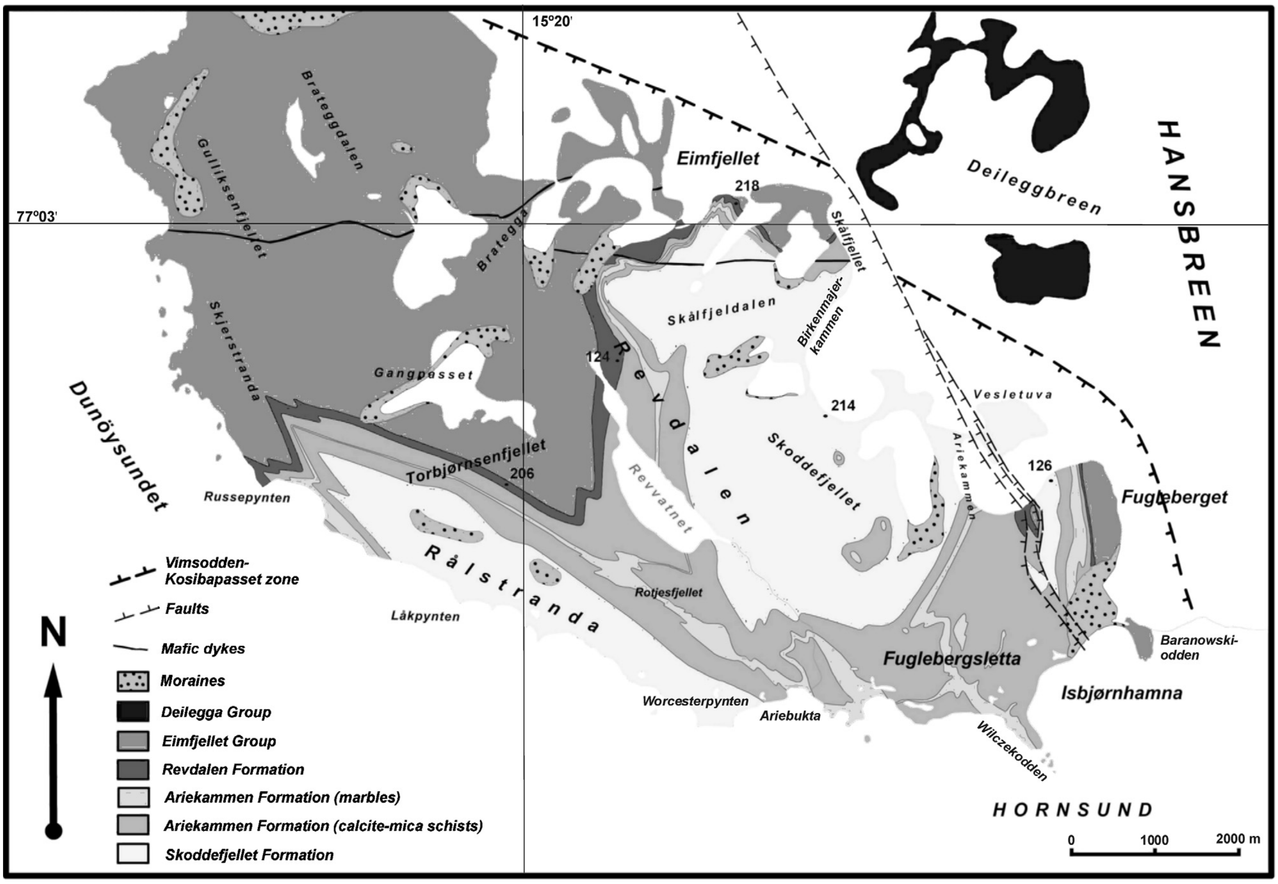

Figure 2. Sample location within the Isbjørnhamna Group.

metamorphic, based on their morphology and internal structure. Detrital monazite, if originally present, likely underwent complete dissolution or recrystallization during M1 metamorphism and actively participated in prograde mineral reactions.

In the studied rocks, monazites occur in micaceous S1 foliation planes and as inclusions in garnet and staurolite porphyroblasts which are synkinematic with the foliation described above (Fig. 3). Monazites from subhedral to anhedral blasts do not exceed about 70 μm in length, and are locally surrounded by aggregates of apatite or apatite–allanite coronas (Majka & Budzyń, 2006). Some monazite grains reveal a 'swiss cheese'-like internal structure characteristic of metamorphic growth. Most of the analysed monazites do not reveal any zoning in BSE imaging. Only sporadically tiny, patchy zoning was observed. Both structural position of analysed monazites and pervasive lack of zoning lead us to conclude that all the monazites likely grew during a single-stage metamorphic event.

In situ analyses were made of polished thin-sections using the Cameca SX-100 electron microprobe at the Electron Microanalysis Department of the Geological Survey of Slovak Republic in Bratislava. Details of analytical methodology and recalculations are as described by Konečný *et al.* (2004). The age calculation is based on the formulation of Montel *et al.* (1996), which is considered as effective and satisfactory when a single age population of homogeneous monazites is analysed (Williams *et al.* 2006). Briefly, the model ages are calculated for each analysis and presented in the form of a histogram. From all results, the model weighted average and standard deviation are calculated according to the statistical procedure described by Montel *et al.* (1996). The age is calculated using the Microsoft Excel add-in program DAMON that reads the data, calculates the model and weighted averaged ages, and constructs the histograms and isochrons (Konečný *et al.* 2004). The isochrons are not used to determine the age. The fact that all results plot on the very same isochron is additional evidence that supports our interpretation that the population of dated monazites is homogeneous and formed during a single metamorphic event.

The EMP analyses were performed using 100 nA beam current and 15kV accelerating voltage. The beam diameter varied from 1 to 3 μm. Background level was determined using linear fit. The counting time (peak + background) for Si, Al, Ca, P and As was 20 seconds, for REE 25 seconds, for Th and Y 35 seconds, for U 65 seconds and for Pb 150 seconds. The following standards were used for analysed elements: Si – wollastonite, Al – Al_2O_3, Ca – wollastonite, Pb – PbS, Th – ThO_2, U – UO_2, P – apatite, As – $GaAs_2$, REE and Y – REE and Y phosphates. Si, Al and As were measured with the use of a TAP crystal; Ca, Pb, U, Th, Y and P were measured with the use of a LPET crystal, and REE with the use of a LLIF crystal. For

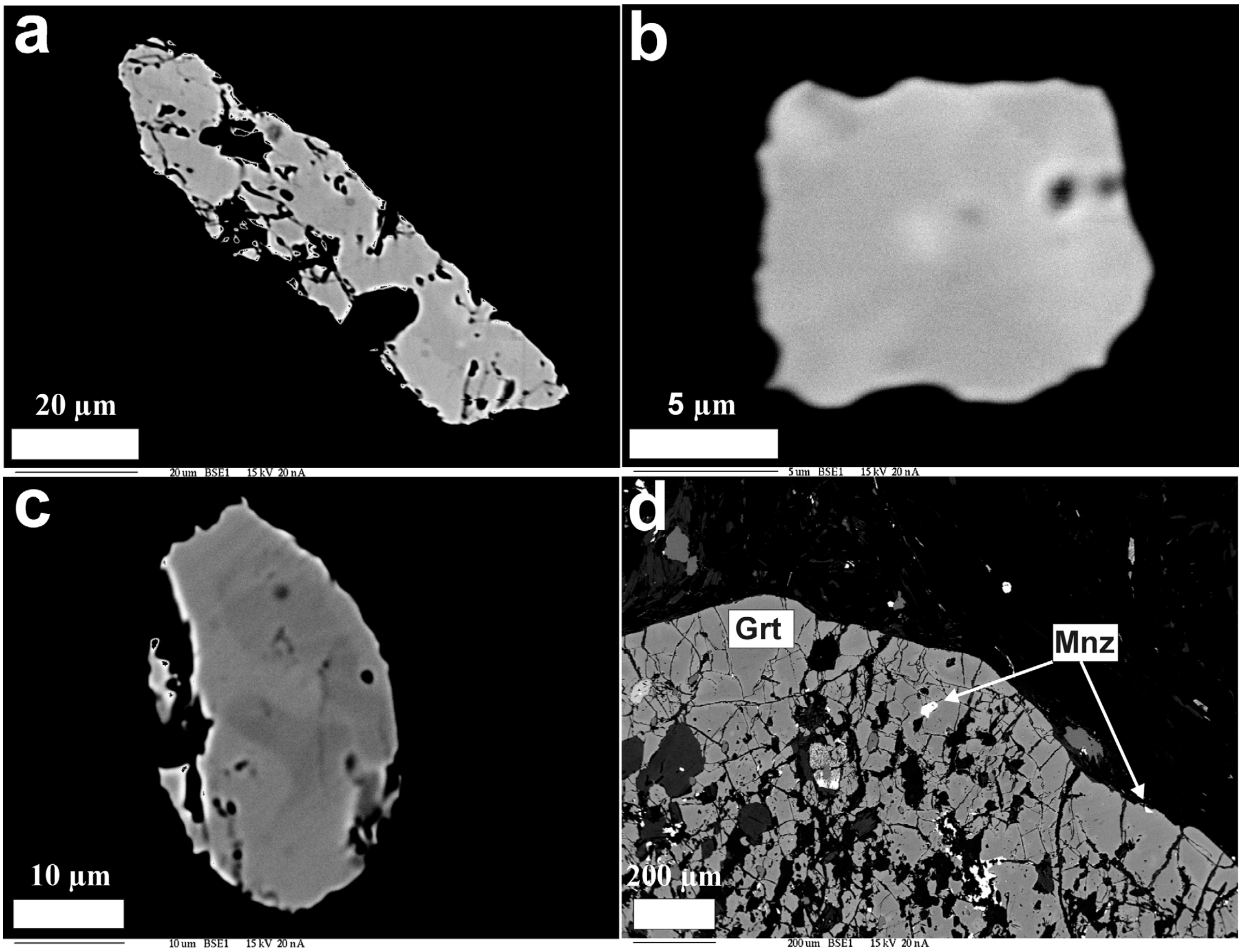

Figure 3. (a) Typical subhedral monazite. (b) Typical anhedral monazite. (c) Anhedral monazite with sectoral zoning. (d) Monazite grains enclosed in garnet porphyroblast.

determination of the content of Si, Al, Ca, P, the Kα line was measured, for La, Ce, Gd, Tb, Tm, Yb, Y, As the Lα line was measured, for Pr, Nd, Sm, Eu, Dy, Ho, Er, Lu the Lβ line was measured, for Pb and Th the Mα line was measured, and for U the Mβ line was measured. ZAF corrections were applied throughout. All errors are reported, depicted and discussed in this paper at the 2σ level (95 % confidence limits).

4. Results

Chemical U–Th–total Pb dating performed on all monazite grains (n=61; table of supplementary material available online at http://journals.cambrige.org/geo) span a 130 Ma interval between 580 and 710 Ma (Fig. 4), with an average statistical uncertainty (2σ) of approximately ± 36 Ma for a single age determination. The distribution of analytical results on the isochron indicates that all dated monazites belong to the same population (Fig. 5), with the weighted average age being 643 ± 9 Ma. There is no age difference between matrix monazite grains and those forming inclusions in garnet. A uniform age is also characteristic for discrete domains within individual monazite grains revealed with BSE imaging and monazites showing secondary alterations apparent as allanite–apatite coronas (Majka & Budzyń, 2006).

5. Discussion

The age of 643 ± 9 Ma obtained for metamorphic monazite from the Isbjørnhamna Group provides the first direct evidence for late Neoproterozoic metamorphism of the Hecla Hoek succession in SW Spitsbergen. Previous geochronological results of K–Ar dating, reported by Gayer *et al.* (1966) and Ar–Ar dating of micas and hornblende (Manecki *et al.* 1998), indicated a late Neoproterozoic cooling within the same time span. We consider the fact that monazite grains enclosed in garnet yield the same age as matrix monazite grains as strong evidence for a progressive Barrovian metamorphic event having taken place around 640 Ma.

Zircon ages reported by Gavrilenko *et al.* (1993) and Balashov *et al.* (1995, 1996) potentially reveal an older Grenvillian metamorphic event, probably under sub-amphibolite-facies conditions, which took place in the southern part of Wedel Jarlsberg Land. However, no

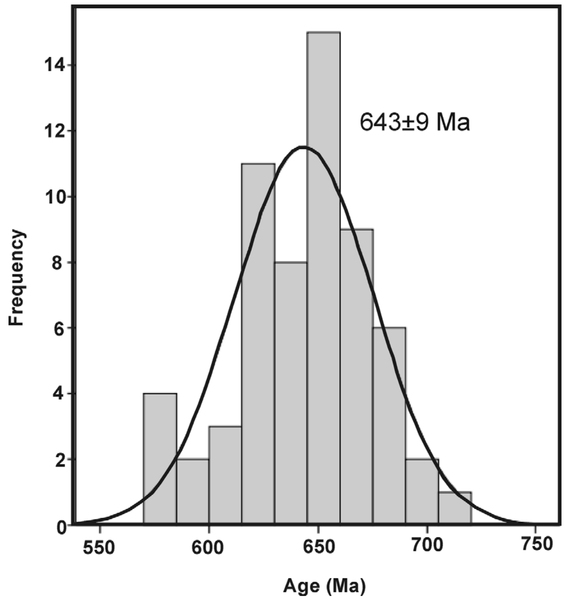

Figure 4. Histogram of monazite ages from the Isbjørhamna Group.

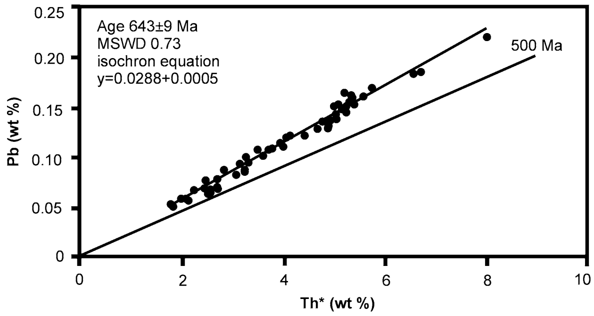

Figure 5. Isochron of monazite age from the Isbjørnhamna Group.

structural or mineral relicts of this event are preserved in rocks of the Isbjørnhamna Group. Essentially, the *c.* 930 Ma zircon age of the metarhyolites from the Eimfjellet Group is based on a discordia lower intercept (Balashov *et al.* 1995) and thus remains poorly constrained. The earlier determined Rb/Sr ages of the Isbjørnhamna rocks (Gavrilenko *et al.* 1993) are based on a small pre-selected population of samples. Furthermore, the Rb–Sr method itself is not fully reliable in the case of rocks subjected to a prolonged polyphase metamorphic evolution.

The *c.* 640 Ma peak metamorphic age of the Isbjørnhamna Group compares well with the ages of igneous and high-pressure metamorphic events in the Richarddalen Complex of NW Spitsbergen dated at *c.* 660 and 620 Ma, respectively (Peucat *et al.* 1989). These ages were interpreted to represent the time of magmatic crystallization of a felsic intrusive phase and probably of high-grade (eclogite) metamorphism (Peucat *et al.* 1989). Thus, they were considered as evidence of a significant high-pressure tectonothermal episode in latest Neoproterozoic times. This interpretation received further support from 540–500 Ma Ar/Ar cooling ages for the Richarddalen Complex (Dallmeyer, Peucat & Ohta, 1990). Nevertheless, the age of high-pressure metamorphism of the Richarddalen eclogites was subsequently reinterpreted as Early to Middle Ordovician and correlated with the Caledonian collisional cycle (Gromet & Gee, 1998). Accepting the original interpretation of Peucat *et al.* (1989), our new monazite ages from the Isbjørnhamna Group convincingly support the connection between SW Spitsbergen and NW Spitsbergen recently postulated by Gee & Tebenkov (2004). Although not a favoured model in their interpretation, we note that Gromet & Gee (1998) did allow the possibility of two tectonically distinct metamorphic events, a latest Neoproterozoic eclogite facies event followed by a pervasive Ordovician event at mid-amphibolite grade.

Throughout the Neoproterozoic and early Palaeozoic, stratigraphic successions in Svalbard, East Greenland and Scandinavia indicate essentially continuous deposition on a rifted continental margin (e.g. Flood *et al.* 1969; Kumpulainen & Nystuen, 1985; Henriksen, 1985). Significantly, the Laurentian Cambro-Ordovician faunal provinciality of Svalbard and East Greenland is in clear contrast with that of Scandinavia. Thus, rifting of a Neoproterozoic supercontinent and the independent development of Laurentian and Baltic passive margins appear substantiated (Gromet & Gee, 1998). At the same time, Neoproterozoic metamorphism and/or granitoid magmatism are practically unknown from the Scandinavian Caledonides and the underlying basement of the Baltic shield (Gorbatschev, 1985), as well as from East Greenland (e.g. Henriksen, 1985) and eastern Svalbard (e.g. Gee & Tebenkov, 2004). Therefore, if *c.* 640 Ma metamorphic ages from the Isbjørnhamna Group represent a phase of orogenic development in the Neoproterozoic, they are difficult to reconcile with a quiescent non-tectonic regime inferred from the occurrence of rift-drift sequences on the Baltic and Laurentian passive margins. Instead, our new monazite ages imply an exotic origin of the pre-Devonian basement exposed in SW Spitsbergen and support models of terrane assembly postulated for the Svalbard Archipelago (e.g. Harland & Gayer, 1972; Harland, 1985; Ohta, Dallmeyer & Peucat, 1989; Gee & Page, 1994).

More work needs to be done to better elucidate the tectonothermal evolution of the study area and to better understand its potential origin as an exotic terrane. Speculatively, we note that the time span of 580–710 Ma overlaps ages of many of the Pan-African orogenic belts widespread across the Gondwana supercontinent. However, a Gondwanan derivation of the SW part of Spitsbergen is inconsistent with recent plate reconstructions for the Neoproterozoic, which place Gondwana opposite to the Laurentian passive margin (e.g. Hoffman, 1991; Torsvik *et al.* 1996; Dalziel, 1997). Instead, a more likely solution seems to be the correlation of SW Spitsbergen with the Timanide orogen of the North Urals, which also records Neoproterozoic tectono-magmatic activity (e.g.

Kuznetsov *et al.* 2007). Nevertheless, such speculation contradicts the Laurentian affinity characteristic of the majority of the pre-Devonian basement of Svalbard (with important exceptions of foreign terranes along the west coast of central Spitsbergen) and the postulated large-scale separation between Laurentia and Baltica in the late Neoproterozoic and early Palaeozoic (e.g. Gee & Tebenkov, 2004). Therefore, our results call for an essential reconsideration of large-scale tectonic models explaining the assembly of Svalbard terranes.

6. Conclusions

The U–Th–total Pb monazite dating presented here allows the following interpretation of the Isbjørnhamna Group from the southern part of the Wedel Jarlsberg Land north of the Honsund Fjord:

(1) Monazite U–Th–total Pb ages reported herein unequivocally indicate, in line with previous K/Ar and Ar/Ar data (Gayer *et al.* 1966; Manecki *et al.* 1998), that peak amphibolite-facies conditions of a progressive Barrovian-type metamorphic event occurred around 640 Ma.
(2) A preceding Grenvillian metamorphic event, if it occurred, most likely took place under sub-amphibolite-facies conditions.
(3) Later greenschist-facies alteration reported by Manecki *et al.* (1998) can be attributed to the effects of Caledonian tectonism.
(4) Wedel Jarlsberg Land comprises a Proterozoic basement block consisting of a lithostratigraphic profile and metamorphic history unique at the scale of the Svalbard Archipelago. A record of Neoproterozoic orogenic development may suggest an affinity to either Pan-African or Timanide orogens.
(5) The unique characteristics of this basement block confirm its exotic provenance and support terrane models postulated for the Svalbard Archipelago.

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