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Neoproterozoic pegmatite from Skoddefjellet, Wedel Jarlsberg Land, Spitsbergen: Additional evidence for *c.* 640 Ma tectonothermal event in the Caledonides of Svalbard

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Abstract: Neoproterozoic (*c.* 640 Ma) amphibolite facies metamorphism and deformation have been shown recently to have affected the Isbjørnhamna and Eimfjellet Complex of Wedel Jarlsberg Land in southwestern Spitsbergen. New SHRIMP zircon U-Pb and *in situ* electron microprobe monazite and uraninite U-Th-total Pb ages are presented here on a pegmatite occurring within the Isbjørnhamna metasedimentary rocks. Although the dated zircons are full of inclusions, have high-U contents and are metamict and hence have experienced notable Pb-loss, the new Cryogenian ages are consistent with the age of regional metamorphism of the host metasediments, providing additional evidence for a clear distinction of the Southwestern Province from the other parts of the Svalbard Caledonides.

Key words: Arctic, Svalbard, zircon, monazite, uraninite, geochronology.

Svalbard's Caledonian terranes

The multiphase nature of pre-Caledonian basement evolution in the Svalbard Caledonides implies that unambiguous discrimination of the different tectonic units is problematic. This is particularly the case in southwestern Spitsbergen where the Caledonian complexes are overprinted by Cenozoic folding and thrusting. The first conception of the division of the pre-Devonian rocks on Svalbard into independent Caledonian provinces or terranes was put forward by Harland

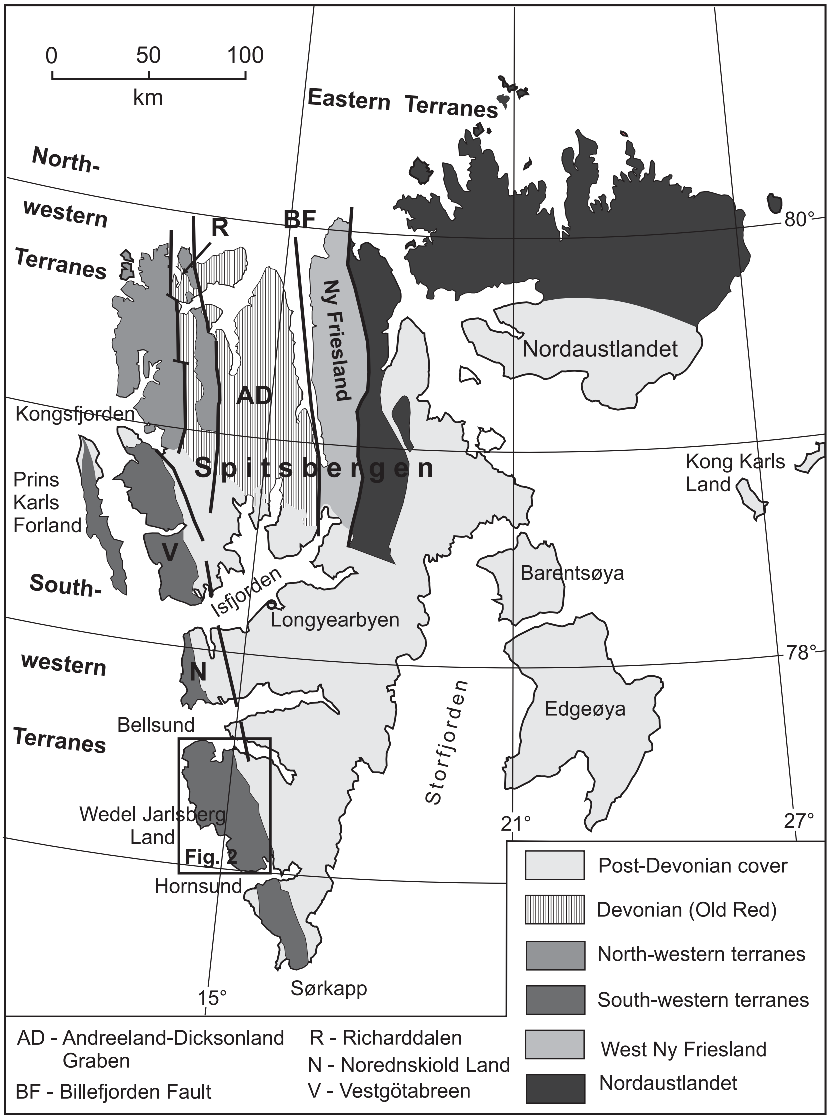

Fig. 1. Geological map of Svalbard (modified from Gee and Tebenkov 2004).

(1972), amplified by Harland and Wright (1979) and later redefined by Harland (1997). In Harland's opinion, it is possible to distinguish three terranes: Eastern, Western and Central. Ohta *et al.* (1989) preferred only two terranes (Western and Northeastern). Gee (1986), Gee and Page (1994) and Gee and Tebenkov (2004) defined three independent groups of terranes: Eastern, Northwestern and South-western (Fig. 1), all of which were shown to be composite and include rock units derived from the pre-Caledonian basement. They are referred to here as provinces and summarized below.

Svalbard's Eastern Province is composed of two "terranes" with different geological histories. Late Grenvillian basement (*c.* 950 Ma) and Neoproterozoic to Ordovician cover of the Nordaustlandet Terrane (Gee *et al.* 1995) is in thrust contact with the Western Ny Friesland Terrane, comprising late Paleoproterozoic (*c.* 1.75 Ga) granites thrust-intercalated with Mesoproterozoic metasedimentary cover (Witt-Nilson *et al.* 1998). Moreover, several granitoid bodies (*c.* 430–410 Ma) intruded the basement of the Nordaustlandet Terrane towards the end of the Caledonian Orogeny (Tebenkov *et al.* 1996; Johansson *et al.* 2002).

The pre-Caledonian basement of the Northwestern Province (located west of the Breibogen-Bockfjorden fault zone and north of the Kongsfjorden fault) revealed both late Grenvillian granites and, locally, in the Richarddalen Complex, unique younger Neoproterozoic (*c.* 660 Ma; Peucat *et al.* 1989; Gromet and Gee 1998) felsic intrusions. These Richarddalen rocks were affected by Caledonian eclogite facies metamorphism (Pecaut *et al.* 1989; Gromet and Gee 1998) and are in fault contact with metasedimentary units and migmatites that did not experienced the HP/HT metamorphism. Post-orogenic Caledonian granites are also present in this province.

South of the Kongsfjorden fault, the Caledonian terranes of the Southwestern Province are located within the Cenozoic West Spitsbergen fold-and-thrust belt. In the area north from Isfjorden, exotic Ordovician (*c.* 470 Ma) blueschists and eclogites, referred to as the Vestgötabreen Complex (Horsfield 1972; Bernard-Griffiths *et al.* 1993) occur, thrust onto a Vendian tillite-bearing formation. South of Isfjorden, in Nordenskiöld Land, low grade metasedimentary rocks occur, including glaciomarine diamictites and underlying carbonates, phyllites and quartzites (Gosen and Piepjohn 2001). Farther south (Fig. 2), the bedrock of Wedel Jarlsberg Land is dominated by low grade Neoproterozoic diamictites of the Kapp Lyell Formation, inferred to be of glaciomarine origin (Bjørnerud 2010), an interpretation that is not favoured by Birkenmajer (2003), and underlying Sofiebogen (Dunderbukta) and Deilegga (Nordbukta) groups. These two groups are separated by an episode of deformation (Torellian) and a major unconformity (Birkenmajer 1975; Bjørnerud 1990; Birkenmajer 1991), the Deilegga having been tightly folded, uplifted and eroded prior to deposition of the basal conglomerates and overlying phyllites, quartzites and carbonates of the Sofiebogen Group. In eastern Wedel Jarlsberg Land, the Neoproterozoic successions are overlain by Cambro-Ordovician carbonate-bearing formations.

In southwesternmost Wedel Jarlsberg Land (Fig. 3), a major NW-trending shear zone (Mazur *et al.* 2009) separates the Deilegga and Sofiebogen groups from higher grade quartzites, amphibolites and other meta-igneous rocks (gabbros, granites and dolerites) of the Eimfjellet Complex (previously group) and underlying amphibolite-facies schists and marbles of the Isbjørnhamna Group (Birkenmajer 1992; Czerny *et al.* 1993). Both these units were thought to be Mesoproterozoic in age (Birkenmajer 1992; Czerny *et al.* 1993; Ohta 1994), an interpretation that found sup-

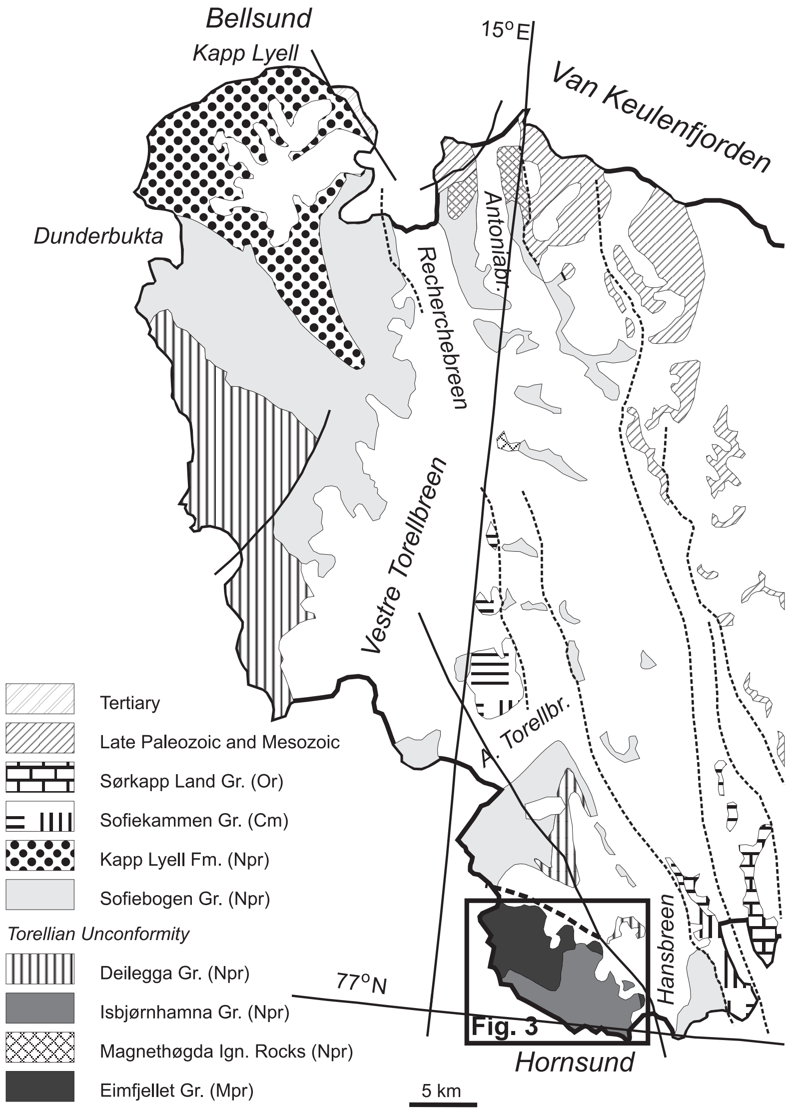

Fig. 2. Geological map of Wedel Jarlsberg Land (modified from Czerny *et al.* 1993 and Dallman *et al.* 1990).

port in the dating of granites within the Eimfjellet Complex, yielding ages of 1.2 Ga (Balashov *et al.* 1995, 1996; Larionov *et al.* 2010). K-Ar and Ar-Ar dating of micas and hornblende from the Isbjørnhamna and the Eimfjellet units yielded surprising Neoproterozoic ages in the time span of 616–575 Ma (Gayer *et al.* 1966; Manecki *et al.* 1998) that were interpreted (Manecki *et al.* 1998) to be an effect of latest Neoproterozoic reheating. Recent age determinations using the U-Th-total Pb method on monazites yielded Cryogenian (643±7 Ma) ages for the amphibolite facies metamorphism of the Isbjørnhamna Group (Majka *et al.* 2008). Moreover, de-

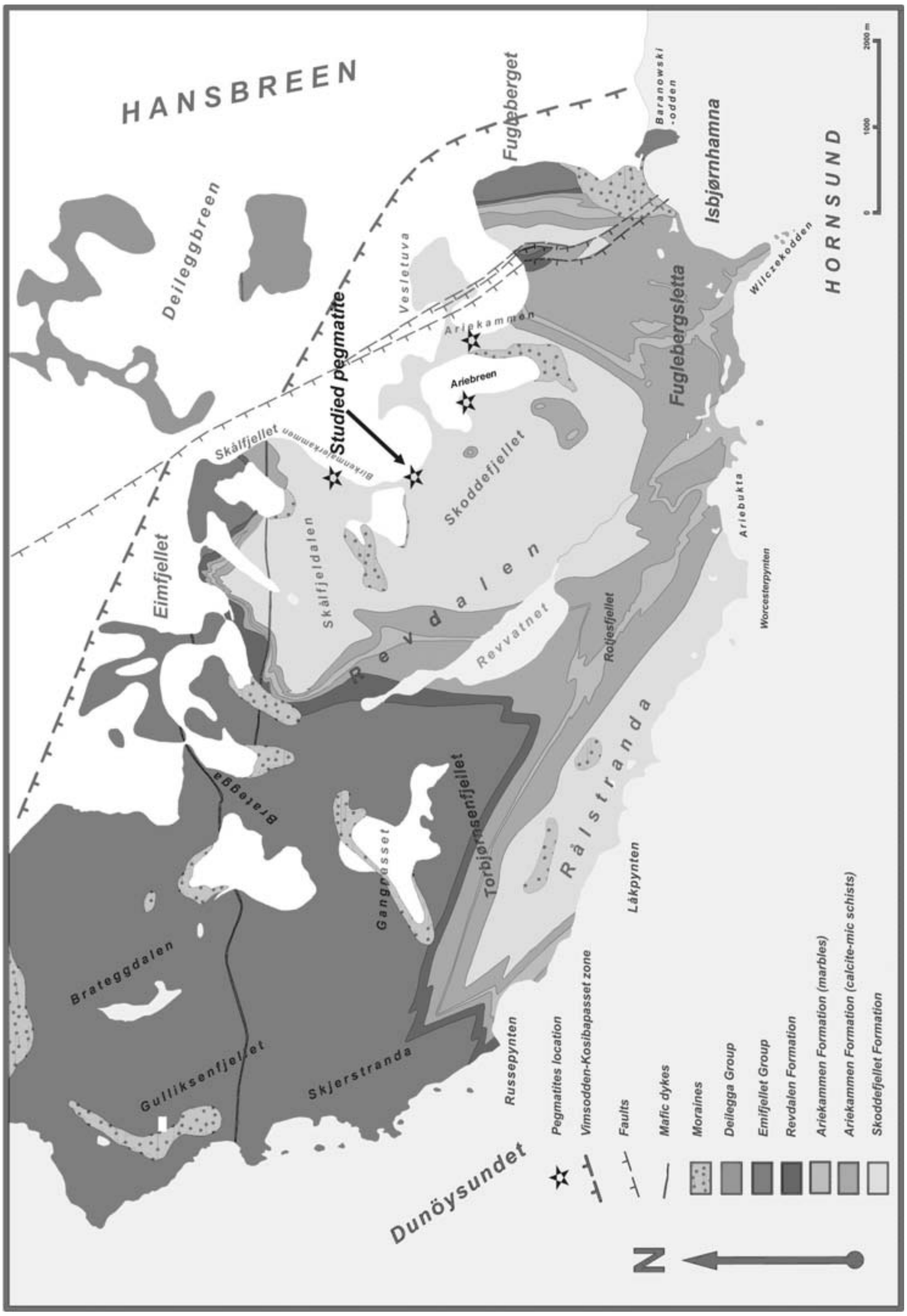

Fig. 3. Geological map of the SW part of Wedel Jarlsberg Land (modified from Czerny *et al.* 1993). Pegmatite locations are marked with stars.

trital zircon dating of the Isbjørnhamna meta-turbidites yielded Neoproterozoic (Tonian and Cryogenian) ages (Larionov *et al.* 2010), demonstrating this group to be younger than previously thought. The pegmatite investigated in this study occurs in the Isbjørnhamna schists.

Geological position of the pegmatites

Several pegmatites were found within the Isbjørnhamna Group (Czerny *et al.* 1993) during geological mapping of the area north of Hornsund and west of Hansbreen (Fig. 3). They occur mostly on the Ariekammen ridge within the pelitic and psammitic schists of the Skoddefjellet Formation. Several are located in the highest grade, garnet-, staurolite-, kyanite-bearing metasediments in the core of the Skoddefjellet dome at the deepest exposed structural levels (*e.g.* on Birkenmajerkammen, Skoddefjellet and Ariekammen, Fig. 3).

The pegmatites are up to a couple of meters thick and occur both concordantly within the dominating schistosity and discordantly, cutting the latter and the early isoclinal folds in the host rocks. Many veins are isoclinally folded and, in the limbs of these folds, they are often fragmented into lenticular bodies.

The dated pegmatite crops out on the northeastern slope of Skoddefjellet, above Tuvbreen, at an altitude of *c.* 560 m. It is *c.*1.5 m thick and can be followed along the mountainside for about 500 m (Fig. 4), being cut by minor faults and, in places, dismembered into isolated lenses. It cuts early isoclinal folds and is deformed by younger folding related to the major refolding of the tectonostratigraphy.

Mineral composition of the Skoddefjellet pegmatite

The Skoddefjellet pegmatite has a core dominated by blocky quartz and a margin dominated by sugary albite. The main minerals are medium grained quartz, fine to medium grained K-feldspar, fine-grained albite and laths of muscovite and biotite.

A rare earth element (REE) mineralization occurs in the blocky zone and also in the zone of sugary albite. Nests of allanite-(Ce) occur frequently, being usually altered to the REE-bearing epidote and clinozoisite. Synchysite-(Ce) occurs inside the allanite-(Ce) grains as an alteration product. Titanite was identified together with allanite-(Ce). It is chemically zoned with variable content of Nb and Ta. It is also frequently altered to the mixture of chlorite, Nb-and Ta-bearing rutile and calcite. Nb- and Ta-bearing ilmenite occurs sometimes together with rutile. Fluorapatite was found in accessory amounts, usually in association with allanite-(Ce). It contains inclusions of xenotime-(Y), thorite and, occasionally, monazite-(Ce) and uraninite. Both, monazite-(Ce) and uraninite are primary phases, overgrown by fluorapatite. Monazite does not show any compositional zoning. Monazite forms grains up to 100

Fig. 4. Overview picture of studied pegmatite (a) and its relationship to the country rocks (b). J. Pršek as a scale. Star shows the sampling site.

μm in width. Uraninite does not exceed several micrometers in diameter. Due to high luminescence of the latter, tracing of the zoning was impossible. Importantly, such monazite and uraninite were chosen for dating reported herein.

Xenotime-(Y) and thorite frequently form small grains up to 200 μm in diameter disseminated in quartz, albite, apatite and zircon. An intermediate composition between thorite and xenotime sometimes occurs. Xenotime-(Y) may be rimmed by fluorapatite and hingganite-(Y) coronas. These coronas were observed exclusively in the beryl-bearing samples (see also Majka *et al.* 2011). Beryl forms grains up to 0.5 cm usually, intimately intergrown with K-feldspar and quartz. Y-bearing silicates were observed in beryl and spessartine-bearing samples. They usually form small zoned crystals, which fill the fissures in the spessartine grains. Keiviite-(Y), gadolinite-(Y) and hingganite-(Y) were identified within the spessartine crystals.

Zircon forms usually homogenous grains up to 500 μm in length disseminated in quartz and albite. It frequently occurs in aggregates of crystals usually overgrown by pyrochlore group minerals. Sometimes, zircon associates with thorite and xenotime-(Y). Zircon is highly metamict and commonly contains abundant fine inclusions of uraninite, thorite and xenotime-(Y).

The Nb-Ta minerals are typical accessory phases in the Skoddefjellet pegmatite (see also Pršek *et al.* 2010). Minerals of the columbite and pyrochlore group were identified. They form small grains up to 1mm in diameter with a complicated zoning. Minerals of the columbite group are represented by Fe- and Mn-varieties. They are sometimes replaced by yttropyrochlore and fersmite. Except yttropyrochlore, minerals of the pyrochlore group are represented by uranpyrochlore, plumbopyrochlore, betafite, yttrobetafite and plumbobetafite. Sometimes, they are replaced by fersmite and Fe-hydroxides. Usually they contain inclusions of uraninite and thorite.

The analysed pegmatite is cut by various hydrothermal veins, usually containing carbonates (calcite, Fe-dolomite) and sulphides (pyrite, chalcopyrite and galena). Veins with allanite-(Ce), together with pyrite, rutile, ilmenite and Fe-dolomite have been also observed.

Dating methods

Zircon separation and analysis. — Crushed whole rock samples were sieved to a fine fraction and heavy minerals were separated using the heavy liquid, flourbromomethane. The heavy fraction was imaged using stereoscopic microscope and scanning electron microscope (SEM) for manual separation of zircon grains (*c.* 130 grains). From these, the best were hand-picked and mounted in epoxy resin together with chips of the TEMORA (Middledale Gabbroic Diorite, New South Wales, Australia, Black *et al.* 2003) and 91500 (Wiedenbeck *et al.* 1995) reference zircons. None of the grains exceeded *c.* 200 μm in length and *c.* 50 μm in width. The grains were sectioned approximately in half and polished. Reflected and transmitted light photomicrographs and cathodoluminescence (CL) SEM imaging have been done for all zircons. The CL images were used to reveal the internal structures of the grains and to target specific areas within these zircons.

The U-Pb analyses of the zircons were performed using the Sensitive High Resolution Ion Microprobe (SHRIMP-II) at the Center of Isotopic Research, VSEGEI, St. Petersburg, Russia. Each analysis consisted of 5 scans through the 196–254 AMU mass range; the diameter of *c.* 6 nA primary beam was about 20 μm. The data have been reduced in a manner similar to that described by Williams (1998, and references therein and Larionov *et al.* 2004), using the SQUID 13a Excel Macro of Ludwig (2005a). Uncertainties are given for individual analyses (ratios and ages) are at the one σ level; however the uncertainties in calculated concordia ages are reported at two σ level. The Tera-Wasserburg concordia plot has been constructed using ISOPLOT/EX (Ludwig 2005b).

Monazite and uraninite dating. — The monazite and uraninite analyses were made in polished thin sections using the Cameca SX-100 electron microprobe (EMP) at the Electron Microanalysis Department of the Geological Survey of Slovak Republic in Bratislava. Both, monazite and uraninite can be dated using the non-istopic method, because they generally do not incorporate so-called common Pb into their structure; thus, the measured Pb must be radiogenic. The age calculation is based on the formula of Montel *et al.* (1996). The age has been calculated using the Microsoft Excel add-in program DAMON that reads the data and calculates the model and weighted average ages (Konečný *et al.* 2004). We used a similar dating protocol for both, monazite and uraninite.

The EMP analyses were performed using a 100 nA beam current and 15kV accelerating voltage. The beam diameter was focused in the range from 3 up to 5 μm. The background levels were determined using a linear fit. The counting time (peak and 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 the analyzed 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, As were measured with the use of TAP crystal, Ca, Pb, U, Th, Y, P were measured with the use of LPET crystal whereas REE with the use of LLIF crystal. For determination of the Si, Al, Ca and P content, the Kα line was measured; for La, Ce, Gd, Tb, Tm, Yb, Y and As, the Lα line was measured; for Pr, Nd, Sm, Eu, Dy, Ho, Er and Lu the Lβ line was measured; for Pb and Th, the Mα line was measured and for U, the Mβ line was measured. PAP corrections were applied throughout. All errors are reported, depicted, and discussed in this paper at the 2σ level (95% confidence limits). Two monazite grains and one uraninite grain were dated in this study.

Results of dating

17 U-Pb SIMS analyses were made on 13 zircons. All the obtained results are discordant to various degrees (Table 1). A regression line (Fig. 5) trough all the 17

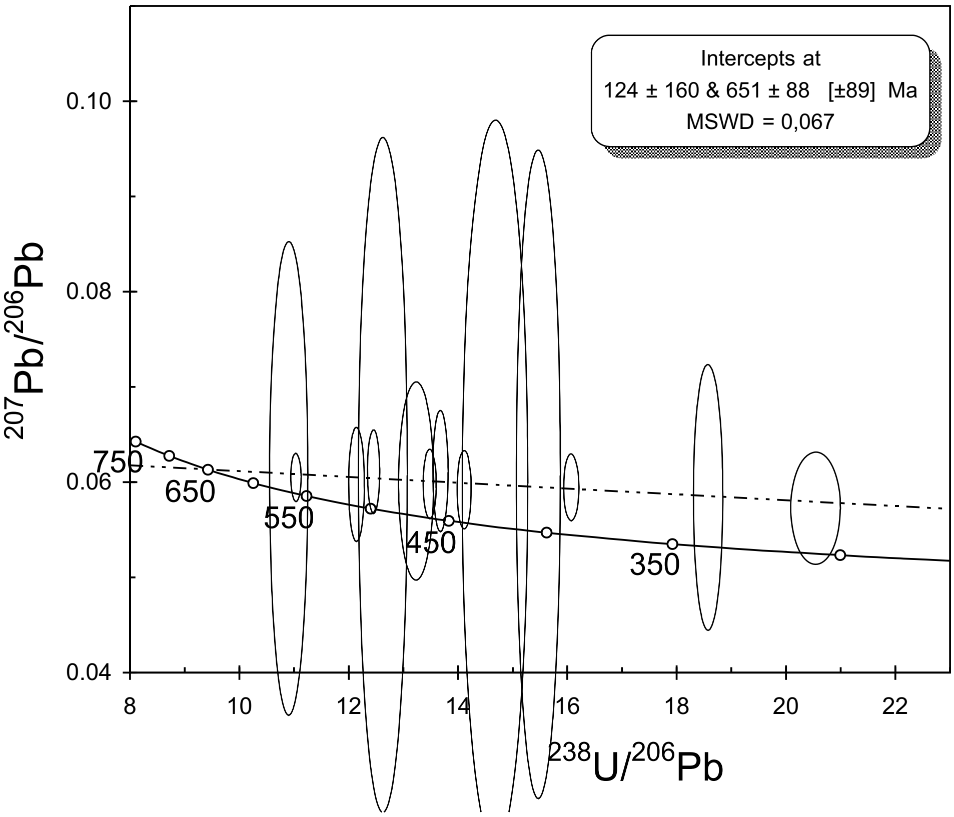

Fig. 5. Tera-Wasserburg concordia diagram of zircon dating results. Three most discordant measurements are excluded.

analyses has an upper intercept at 615±63 Ma and a lower one at 9±160 Ma (MSWD = 0.41). Excluding the three most discordant analyses results in a discordia line that intersects the concordia at 651±88 Ma (MSWD = 0.067) and 124±160 Ma. This result is regarded as more trustworthy, since it is based on the results from the least disturbed zircons. The observed Th/U ratios in range of 0.01–0.06, suggest low thorium mobility, caused by the pegmatite chemistry; alternatively Th may not have been available at the time of zircon growth due to prior consumption by other minerals (*e.g.* monazite in this case). The most likely explanation may be a combination of both these reasons, considering the range of variability of the Th concentrations of (15 to 490 ppm; average = 23). The elevated U concentrations of 1200–4000 ppm have negative correlation with the $^{206}Pb/^{238}U$ age, implying that the degree of metamictization is produced by U decay, probably causing substantial Pb-loss.

Considering the large uncertainty of the SHRIMP zircon age, additional analyses of monazite and uraninite have been made using U-Th-total Pb method. Two grains of monazites yielded ages of 662±19 Ma and 681±16 Ma, respectively, i.e.

Table 1

Zircon dating results

Spot name	$^{204}Pb/^{206}Pb$	±, %	% $^{206}Pb_c$	ppm U	ppm Th	$^{232}Th/^{238}U$	ppm ^{206}Pb*	Age $^{206}Pb/^{238}U$ M.y.	±	Age $^{207}Pb/^{206}Pb$ M.y.	±	%D	$^{238}U/^{206}Pb^*$	±, %	$^{207}Pb^*/^{206}Pb^*$	±, %	$^{207}Pb^*/^{235}U$	±, %	$^{206}Pb^*/^{238}U$	±, %	err corr
.1.1	0.00715	2	13.37	3101	37	0.01	149.8	307	3	508	92	66	20.529	0.9	0.057	4.2	0.39	4.3	0.0487	0.9	0.212
.2.1	0.00698	8	13.05	2207	119	0.06	102.9	297	4	547	351	84	21.200	1.3	0.058	16.1	0.38	16.1	0.0472	1.3	0.078
.3.1	0.00162	16	3.03	2355	51	0.02	112.5	338	2	552	212	63	18.551	0.6	0.059	9.7	0.44	9.7	0.0539	0.6	0.061
.3.2	0.00047	18	0.88	1794	21	0.01	115.7	463	2	602	53	30	13.439	0.4	0.060	2.5	0.62	2.5	0.0744	0.4	0.142
.4.1	0.00387	18	7.24	1614	30	0.02	118.8	493	7	648	501	32	12.582	1.4	0.061	23.3	0.67	23.4	0.0795	1.4	0.062
.5.1	0.00088	7	1.64	1244	15	0.01	98.9	562	2	627	37	12	10.986	0.4	0.061	1.7	0.76	1.8	0.0910	0.4	0.208
.5.2	0.00265	4	4.95	1563	46	0.03	100.4	442	2	581	61	31	14.078	0.4	0.059	2.8	0.58	2.8	0.0710	0.4	0.136
.6.1	0.00946	2	17.70	4095	181	0.05	165.3	245	1	888	137	263	25.863	0.5	0.069	6.7	0.37	6.7	0.0387	0.5	0.069
.7.1	0.00154	4	2.87	1822	27	0.02	129.9	500	2	649	62	30	12.408	0.4	0.061	2.9	0.68	2.9	0.0806	0.4	0.127
.8.1	0.00067	12	1.25	2531	22	0.01	137.3	390	1	590	52	51	16.035	0.4	0.060	2.4	0.51	2.4	0.0624	0.4	0.155
.9.1	0.00435	6	8.13	1797	76	0.04	127.4	471	5	614	152	30	13.194	1.0	0.060	7.0	0.63	7.1	0.0758	1.0	0.143
.9.2	0.00274	6	5.12	1939	96	0.05	145.1	512	2	601	88	17	12.100	0.5	0.060	4.1	0.68	4.1	0.0826	0.5	0.114
.10.1	0.00366	3	6.84	1810	24	0.01	122.4	456	2	650	91	42	13.637	0.4	0.061	4.2	0.62	4.2	0.0733	0.4	0.101
.11.1	0.01069	4	20.00	4001	490	0.13	147.9	218	2	719	349	230	29.062	1.1	0.063	16.5	0.30	16.5	0.0344	1.1	0.069
.12.1	0.00512	15	9.58	1720	56	0.03	111.7	426	7	620	548	46	14.636	1.7	0.060	25.4	0.57	25.5	0.0683	1.7	0.066
.13.1	0.00971	6	18.17	1546	62	0.04	149.5	568	7	626	359	10	10.860	1.3	0.061	16.6	0.77	16.7	0.0921	1.3	0.079
.13.2	0.00984	4	18.40	2068	91	0.05	141.1	405	4	649	481	60	15.436	1.1	0.061	22.4	0.55	22.4	0.0648	1.1	0.047

Errors are 1-sigma; Pbc and Pb* indicate the common and radiogenic portions, respectively
Error in 91500 Standard calibration was 0.22% (average of 18 analyses)
(1) common Pb corrected using measured 204Pb
D% – discordance, %
Grey rows – rejected analyses during second calculation of the age

an inferred age of 675±25 Ma. Additionally, a uraninite single analysis yielded an age of 685±5.5 Ma (Table 2).

Table 2

Monazite and uraninite dating results

Sample	Th	U	Pb	Y	Th*	Age	Error
Mnz 1	7.3425	0.1530	0.2343	0.3421	7.85	662	19.0
Mnz 2	8.6190	0.2171	0.2868	0.4034	9.34	681	16.5
Urn	0.5001	13.2013	1.3668	0.3563	44.64	685	5.5

Discussion

The validity of the zircon age. — Zircons in pegmatites are often high in U, metamict due to radiation damage, and full of channels, promoting Pb loss. In case of the Skoddefjellet pegmatite in the Isbjørnhamna Group, the discordant points are inferred to result from Pb-loss, possibly triggered by post-650 Ma events. Although, the 2σ error is ±88 Ma, the SHRIMP data clearly favour a Neoproterozoic age. The inferred ion microprobe zircon age is *c.* 20 Ma younger then that obtained by the dating of monazite and uraninite, presented here; however the large error of the zircon age and ±25 Ma error of the monazite age allow them to be interpreted as similar. It should be also pointed out that the monazite and uraninite dating results are based on a small amount of analytical points. Usually, tens of grains of monazite and uraninite should be dated to obtain an unquestionable age, using the chemical dating method. In the case of the Skoddefejellet pegmatite this was not possible, due to the very scarce occurrence of monazite and even scarcer occurrence of uraninite. Taking these into account, the ages of monazite and uraninite should be rather considered as an indication of Cryogenian timing of their formation, than absolute ages. Although the zircon age is associated with a large error, it should be considered as more reliable, since it is based on more numerous analytical data. It must be also emphasized here that the Skoddefjellet pegmatite cuts the foliation of the host rocks, timing of which is well defined as 643±9 Ma (Majka *et al.* 2008).

Pegmatite forming scenario. — The Isbjørnhamna metasedimentary rocks, which host the Skoddefjellet pegmatite, underwent Barrovian amphibolite facies metamorphism under conditions of up to *c.* 670°C and *c.* 11 kbar (Majka *et al.* 2010). Taking into account the age (*c.* 645 Ma) of this metamorphic event (Majka *et al.* 2008) and ages reported herein, the investigated pegmatite probably formed under similar or slightly lower P-T. This is also suggested by the pegmatite mineralogy, which allows its classification as muscovite-rare element class, MSREL-REE subclass of pegmatites (Černy and Ercit 2005). According to these authors, MSREL-REE pegmatites are formed under moderate to high amphibolite facies

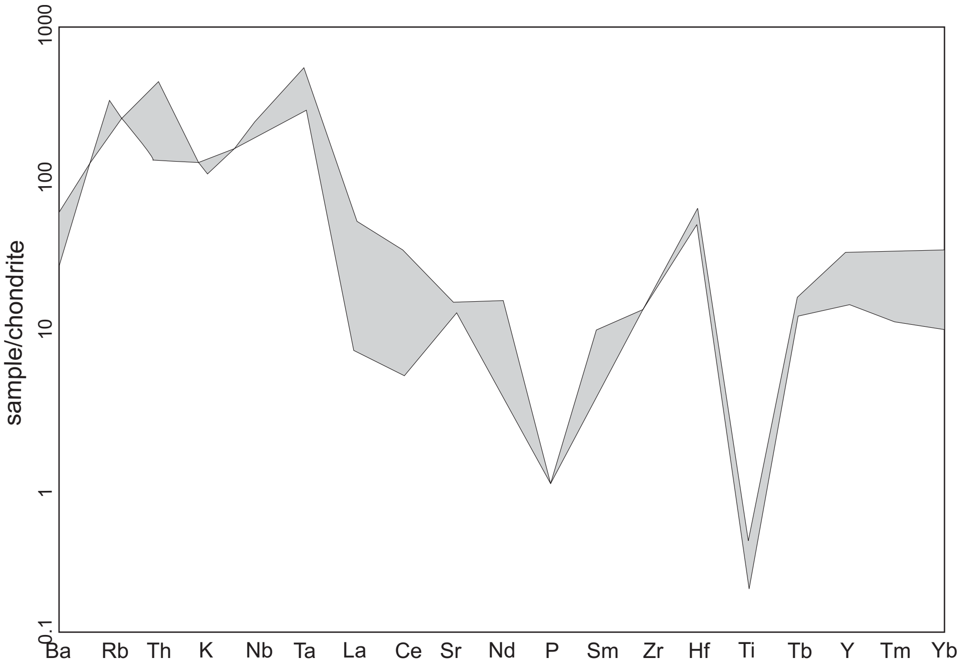

Fig. 6. Spider diagram of the studied pegmatite confirming its affinity to the NYF type (based on two samples).

conditions and their relation to possible parental granites is usually poorly defined. Moreover, MSREL-REE pegmatites, including the one that has been analysed, usually can be ascribed to so-called NYF-type pegmatites. The bulk trace-elements chemistry of the studied rock shows strong enrichment in Nb and Y and REEs (Fig. 6).

Regional implications. — K-Ar biotite ages of the Isbjørnhamna mica-schists reported by Gayer *et al.* (1966) and Ar-Ar dating results of muscovite and hornblende reported by Manecki *et al.* (1998) indicated a probable Neoproterozoic thermal episode. The recently reported age of 643±9 Ma by Majka *et al.* (2008) for metamorphic monazite from the same rocks led to the conclusion that this was the age of Barrovian metamorphism, providing the first evidence of Neoproterozoic regional metamorphism in the Svalbard's Caledonides. The geochronological data on the pegmatite reported here provide additional evidence for the age of this tectonothermal event. In this context, it is of interest that Larionov and Tebenkov (2004) have reported similar ages (*c.* 630 Ma) from granitic pebbles in the Kapp Linne diamictite, south from Isfjorden and north from Bellsund.

The Neoproterozoic and early Paleozoic successions elsewhere in other parts of the Svalbard Caledonides (*e.g.* Nordaustlandet) provide excellent evidence of continuous deposition in a generally shallow marine environment. The evidence of late Neoproterozoic metamorphism within the Caledonian basement of southwestern Svalbard suggests significant separation from the rocks in the rest of Svalbard. Correlation of Svalbard's Southwestern Province with Pearya Terrane of northern Ellesmere Island has long been advocated based on the similarities in tectonostratigraphy (*e.g.* Trettin 1987; Harland 1997; Trettin 1998; Gee and Tebenkov 2004). On the other hand, Mazur *et al.* (2009) suggested that the entire basement of Wedel Jarlsberg Land located north from the Vimsodden-Kosibapasset shear zone could be formerly a part of the Pearya Terrane, while southern tectonic unit, comprising the Isbjørnhamna and Eimfjellet units, could be a northwesternmost continuation of the late Neoproterozoic Timanide Orogen. This model required *c.* 600 km of strike-slip displacement. Here we prefer the more straightforward interpretation of previous authors and suggest that, the new evidence from the Southwestren Province of Svalbard favours correlation with the Timanide Orogen of northeastern Baltica. The latter could have continued along the Laurentian northern margin prior to the Iapetus opening. In such a case, neither the correlation with Pearya nor with the Timanides requires substantial strike-slip displacement along the axis of the Caledonide Orogen. Recent reports from Pearya of late Neoproterozoic detrital zircon signatures in the Paleozoic succession (Malone and McClelland 2010) provide support for this interpretation.

Conclusions

The age, structural position and mineralogical and geochemical characteristics of the studied pegmatite allow the following conclusions:

- The zircon U-Pb 651±88 Ma age and monazite 675±25 Ma (aver.), and uraninite 685±11 Ma U-Th-total Pb ages are in accord with the 643± 9Ma age of the Barrovian amphibolite facies metamorphic event reported for the Isbjørnhamna Group (Majka *et al.* 2008) and the overlying Eimfjellet Complex.
- The occurrence of minerals typical for MSREL-REE pegmatites and the chemical composition typical for NYF-type pegmatites indicates that the studied rock was formed during the metamorphism, under amphibolite facies conditions.
- The evidence of a late Neoproterozoic tectonometamorphic event within Svalbard's Sothwestern Province not only emphasizes the differences between this composite unit and the rest of the Svalbard Caledonides, but also indicates affinities with the Timanides and the possibility of testing correlation with the Pearya Terrane.

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References

BALASHOV Yu.A., TEBENKOV A.M., OHTA Y., LARIONOV A.N., SIROSTKIN A.N., GANNIBAL L.F. and RYUNGENEN G.I. 1995. Grenvillian U-Pb zircon ages of quartz porphyry and rhyolite clasts in a metacoglomerate at Vimsodden, southern Spitsbergen. *Polar Research* 14: 291–302.

BALASHOV Yu.A., TEBENKOV A.M., PEUCAT J.J., OHTA Y., LARIONOV A.N. and SIROSTKIN A.N. 1996. Rb-Sr whole rock and U-Pb zircon dating of the granitic-gabbroic rocks from the Skålfjellet Subgroup, southwest Spitsbergen. *Polar Research* 15: 167–181.

BERNARD-GRIFFITHS J., PEUCAT J.J. and OHTA Y. 1993. Age and nature of protoliths in the Caledonian blueschist-eclogite complex of western Spitsbergen; a combined approach using U-Pb, Sm-Nd and REE whole-rock systems. *Lithos* 30: 81–90.

BIRKENMAJER K. 1975. Caledonides of Svalbard and plate tectonics. *Bulletin of the Geological Society of Denmark* 24: 1–10.

BIRKENMAJER K. 1991. The Jarlsbergian unconformity (Proterozoic/Cambrian boundary) and the problem of Varangian tillites in South Spitsbergen. *Polish Polar Research* 12: 269–278.

BIRKENMAJER K. 1992. Precambrian succession at Hornsund, south Spitsbergen: A lithostratigraphic guide. *Studia Geologica Polonica* 98: 7–66.

BIRKENMAJER K. 2003. The Kapp Lyell diamictite (Late Proterozoic), Bellsund, Spitsbergen: sedimentological evidence for its non-glacial origin. *Bulletin of the Polish Academy of Sciences: Earth Sciences* 51: 65–78.

BJØRNERUD M. 1990. Upper Proterozoic unconformity in northern Wedel-Jarlsberg Land, southwest Spitsbergen: lithostratigrapby and tectonic implications. *Polar Research* 8: 127–140.

BLACK L.P., KAMO S.L., ALLEN C.M., ALEINIKOFF J.N., DAVIS D.W., KORSCH R.J. and FOUDOULIS C. 2003. TEMORA 1: a new zircon standard for Phanerozoic U-Pb geochronology. *Chemical Geology* 200: 155–170.

ČERNY P. and ERCIT T.S. 2005. The calssification of granitic pegmatites revisited. *Canadian Mineralogist* 43: 2005–2026.

CZERNY J., KIERES A., MANECKI M. and RAJCHEL J. 1993. *Geological map of the SW part of Wedel Jarlsberg Land, Spitsbergen 1:25000.* Scientific editor A. Manecki. Institute of Geology and Mineral Deposits, University of Mining and Metallurgy. Cracow: 1–61.

DALLMANN W.K., HJELLE A., OHTA Y., SALVIGSEN O., MAHER H.D., BJØRNERUD M., HAUSER E.C. and CRADDOCK C. 1990. *Geological map of Svalbard 1:100,000, B11G Van Keulenfjorden.* Norsk Polarinstitutt Temakart No. 15. With explanatory text, 58 pp.

GAYER R.A., GEE D.G., HARLAND W.B., MILLER J.A., SPALL H.R., WALLIS R.H. and WINSNES T.S. 1966. Radiometric age determinations on rocks from Spitsbergen. *Norsk Polarinstitutt Skrifter* 137: 1–39.

GEE D.G. 1986. Svalbard's Caledonian terranes reviewed. *Geologiska Föreningens Stockholm Förhandlingar* 108: 284–286.

GEE D.G. and PAGE L.M. 1994. Caledonian terrane assembly on Svalbard: New evidence from $^{40}Ar/^{39}Ar$ dating in Ny Friesland. *American Journal of Science* 294: 1166–1186.

GEE D.G. and TEBENKOV A.M. 2004. Svalbard: a fragment of the Laurentian margin. *In*: D.G. Gee and V. Pease (eds) The Neoproterozoic Timanide Orogen of Eastern Baltica. *Geological Society, London, Memoirs* 30: 191–206.

GEE D.G., JOHANSSON Å., OHTA Y., TEBENKOV A.M., KRASILŠČHIKOV A.A., BALASHOV Y.A., LARIONOV A.N., GANNIBAL L.F. and RYUNGENEN G.I. 1995. Grenvillian basement and a major unconformity within the Caledonides of Nordaustlandet, Svalbard. *Precambrian Research* 70: 215–234.

GOSEN W. and PIEPJOHN K. 2001. Thrust tectonics north of van Keulenfjorden. *Geologisches Jahrbuch* 91: 247–272.

GROMET L.P. and GEE D.G. 1998. An evaluation of the age of high-grade metamorphism in the Caledonides of Biskayerhalvøya. *GFF* 120: 199–208.

HARLAND W.B. 1972. Early Palaeozoic faults as margins of Arctic plates in Svalbard. *Proceedings of the 24th International Geological Congress, Montreal*: 230–237.

HARLAND W.B. 1997. The Geology of Svalbard. *Geological Society of London Memoirs* 78: 452 pp.

HARLAND W.B. and WRIGHT N.J.R. 1979. Alternative hypothesis for the pre-Carboniferous evolution of Svalbard. *Norsk Polarinstitutt Skifier* 167: 89-117.

HORSFIELD W.T. 1972. Glaucophane schists of Caledonian age from Spitsbergen. *Geological Magazine* 109: 29–36.

JOHANSSON A., LARIONOV A.N., TEBENKOV A.M., OHTA Y and GEE D.G. 2002. Caledonian granites of western and central Nordaustlandet, northeast Svalbard. *GFF* 124: 135–148.

KONEČNÝ P., SIMAN P., HOLICKY I., JANAK M. and KOLLAROVA V. 2004. Metodika datovania monazitu pomocou elektronoveho mikroanalyzatora. *Mineralia Slovaca* 36: 225–235.

LARIONOV F.N. and TEBENKOV A.M. 2004. New SRIMP-II U-Pb zircon age data from granitic boulders in Vendian tillites of southern coast of Isfjorden, West Spitsbergen. *Abstract and Proceedings of the Geological Society of Norway* 2: 88–89.

LARIONOV A. N., ANDREICHEV V. A. and GEE D. G. 2004. The Vendian alkaline igneous suite of northern Timan: ion microprobe U-Pb zircon ages of gabbros and syenite. *In*: D.G. Gee and V.L. Pease (eds) *The Neoproterozoic Timanide Orogen of Eastern Baltica. Geological Society, London, Memoirs* 30: 69–74.

LARIONOV A.N., TEBENKOV A.M., GEE D.G., CZERNY J. and MAJKA J. 2010. Recognition of Precambrian tectonostratigraphy in Wedel-Jarlsberg Land, southwestern Spitsbergen. *NGF Abstracts and Proceedings*: 106.

LUDWIG K.R. 2005a. SQUID 1.13a A User's Manual. A Geochronological Toolkit for Microsoft Excel. *Berkeley Geochronology Center Special Publication*. 22 pp. http://www.bgc.org/klprogrammenu.html

LUDWIG K.R. 2005b. User's Manual for ISOPLOT/Ex 3.22. A Geochronological Toolkit for Microsoft Excel. *Berkeley Geochronology Center Special Publication*. 71 pp. http://www.bgc.org/klprogrammenu.html

MAJKA J., CZERNY J., MAZUR S., HOLM D.K. and MANECKI M. 2010. Neoproterozoic metamorphic evolution of the Isbjørnhamna Group rocks from south-western Svalbard. *Polar Research* 29: 250–264.

MAJKA J., MAZUR S., MANECKI M. CZERNY J. and HOLM D. 2008. 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. *Geological Magazine* 145: 822–830.

MAJKA J., PRŠEK J., BUDZYŃ B., BAČIK P., BARKER A. and ŁODZIŃSKI M. 2011. Fluorapatite-hingganite-(Y) reaction coronas as products of fluid induced xenotime-(Y) breakdown in the Skoddefjellet pegmatite (Svalbard). *Mineralogical Magazine* 75: 159–167.

MALONE S.J. and MCCLELLAND W.C. 2010. Detrital zircon geochronology of Neoproterozoic and Paleozoic units of the Pearya Terrane, Ellesmere Island, Canada. *Geological Society of America meeting:* paper no. 243-3.

MANECKI M., HOLM D.K., CZERNY J. and LUX D. 1998. Thermochronological evidence for late Proterozoic (Vendian) cooling in southwest Wedel Jarlsberg Land, Spitsbergen. *Geological Magazine* 135: 63–69.

MAZUR S., CZERNY J., MAJKA J., MANECKI M., HOLM D.K., SMYRAK A. and WYPYCH A. 2009. A strike-slip terrane boundary in Wedel Jarlsberg Land, Svalbard, and its bearing on correlations of SW Spitsbergen with the Pearya terrane and Timanide belt. *Journal of the Geological Society of London* 166: 529–544.

MONTEL J.M., FORET S., VESCHAMBRE M., NICOLLET CH. and PROVOST A. 1996. Electron microprobe dating of monazite. *Chemical Geology* 131: 37–53.

OHTA Y. 1994. Caledonian and Precambrian history in Svalbard – a review, and an implication of escape tectonics. *Tectonophysics* 231: 183–194.

OHTA Y., DALLMEYER R.D. and PEUCAT J.J. 1989. Caledonian terranes in Svalbard. *Geological Society of America Special Paper* 230: 1–15.

PEUCAT J.J., OHTA Y., GEE D.G. and BERNARD-GRIFFITHS J. 1989. U-Pb, Sr, and Nd evidence for Grenvillian and latest Proterozoic tectonothermal activity in the Spitsbergen Caledonides, Arctic Ocean. *Lithos* 22: 275–285.

PRŠEK J., MAJKA J., UHER P. and CHUDIK P. 2010. Nb-Ta minerals from the Skodefjellet pegmatite (Svalbard): mineralogy, chemistry and compositional trends. *Neues Jahrbuch für Mineralogie – Abhandlungen* 187: 235–248.

TEBENKOV A.M., OHTA Y., BALASHOV Y.A. and SIROTKIN A.N. 1996. Newtontoppen granitoid rocks; their geology chemistry and Rb-Sr age. *Polar Research* 15: 67–80.

TRETTIN H.P. 1987. Pearya: a composite terrane with Caledonian affinities in northern Ellesmere Island. *Canadian Journal of Earth Sciences* 24: 224–245.

TRETTIN H.P. 1998. Pre-Carboniferous geology of the northern part of the Arctic islands. 4: Geology of Pearya. *Geological Survey of Canada Bulletin* 425: 108–192.

WIEDENBECK M., ALLÉ P., CORFU F., GRIFFIN W.L., MEIER M., OBERLI F., VON QUADT A., RODDICK J.C. and SPIEGEL W. 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. *Geostandards Newsletter* 19 :1–23.

WILLIAMS I.S. 1998. U-Th-Pb Geochronology by ion microprobe. *In*: Applications in microanalytical techniques to understanding mineralizing processes. *Reviews in Economic Geology* 7: 1–35.

WITT-NILSSON P., GEE D.G. and HELLMAN F. 1998. Tectonostratigraphy of the Caledonian Atomfjella Antiform of northern Ny Friesland, Svalbard. *Norsk Geologisk Tidsskrift* 78: 67–80.

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