Single-grain zircon dating of the metamorphic and granitic rocks from the Biscayarhalvøya–Holtedahlfonna zone, north-west Spitsbergen

Yoshihide Ohta, Alexander N. Larionov & Alexander M. Tebenkov

The Biscayarhalvøya–Holtedahlfonna zone (BHZ) in north-western Spitsbergen is a north–south trending, narrow horst, with crystalline basement rocks exposed under a Devonian unconformity. Previous K–Ar, $^{40}Ar/^{39}Ar$ and Rb–Sr analyses have confirmed the occurrence of Caledonian thermal events, and Grenvillian ages have been obtained by conventional zircon U–Pb and single-zircon Pb evaporation methods. A total of 55 zircon grains from three samples (an augen metagranite, a micaceous schist and a granitic neosome of migmatite) have been analysed by the single-zircon Pb evaporation method. The grains with the age range of ca. 950 - 1100 My (million years) are the major component in all three samples, suggesting tectono-thermal activity in that period. The detrital versus resorption orgin of the rounded shapes of these grains from the granitic neosome is not clear yet. Therefore, the ages of the migmatization and of the sedimentary protoliths are not concluded. The youngest presumed detrital grain from the granitic neosome is 1060 My old. The metagranite, cutting the Richarddalen unit, yielded grains with an age of ca. 950 Mya. A granite dyke with an age range of 955 - 968 My cuts the Biscayarhuken unit in the northern Liefdefjorden area. These indicate the sedimentary protoliths of the Richarddalen and Biscayarhuken units are pre-Neoproterozoic. The youngest detrital zircon ages of ca. 940 My indicate Neoproterozoic sedimentary protoliths of the Solanderfjellet micaceous schists. A significant population of zircon grains with an age range of 1600 - 1900 My in all three samples suggests a wide exposure of these rocks in the source areas during Meso- and Neoproterozoic times. Several Archean ages have also been obtained. The results are generally conformable with those obtained from north-western Spitsbergen.

Y. Ohta, Norwegian Polar Institute, c/o IASC, Box 5158 Majorstua, NO-0302 Oslo, Norway, yoshihide.ohta@npolar.no; A. N. Larionov, Centre of Isotope Research, Geological Institute, Sredniy prospect 74, 199106 St. Petersburg, Russia; A. M. Tebenkov, Polar Marine Geological Expedition, ul. Pobedy 24, Lomonosov, 189510 St. Petersburg, Russia.

Pre-Devonian crystalline basement rocks exposed along the western and northern parts of the Svalbard archipelago are distributed in two north–south trending zones in north-western Spitsbergen. The Biscayarhalvøya–Holtedahlfonna zone (BHZ) (Gee & Hjelle 1966; Gee & Moody-Stuart 1966; Gjelsvik 1979; Hjelle & Lauritzen 1982), which is bounded by the Raudfjorden–Monacobreen Fault in the west and the Breibogen Fault in the east, is the subject of the present contribution

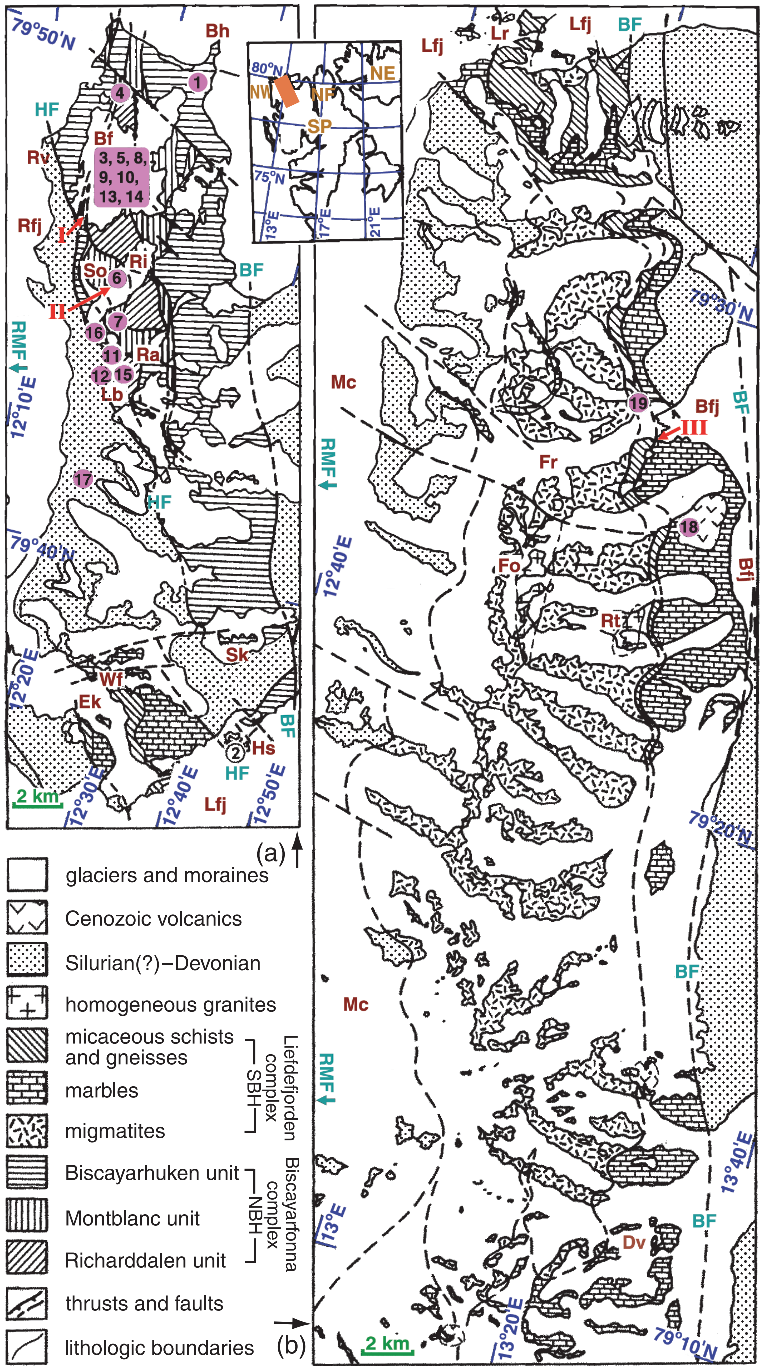


Fig. 1. Geological map of the Biscayarhalvøya–Holtedahlfonna zone (BHZ), indicating the sample localities (I, II and III) and those of the previously dated samples (numbers 1 - 19; see Table 1). (a) Map of Biscayarhalvøya, mainly the northern subzone (NBH) of the BHZ. (b) map of the southern subzone (SBH) of the BHZ, south of Liefdefjorden. Map (b) is a southward continuation of map (a). Names of faults are abbreviated this way: Breibogen Fault–BF; Hannabreen Fault–HF; Raudfjorden–Monacobreen Fault–RMF. Place names are abbreviated thusly: Biscayarfonna–Bf; Biscayarhuken–Bh; Bockfjorden–Bfj; Dovrefjell–Dv; Erikbreen–Ek; Fred Olsenfjellet–Fo; Friedrichbreen–Fr; Hesteskoholmen–Hs; Lernerøyane–Lr; Lilljeborgfjellet–Lb; Liefdefjorden–Lfj; Monacobreen–Mc; Rabotdalen–Ra; Raudfjorden–Rfj; Richarddalen–Ri; Rv–Richardvatnet; Rt–Rivieratoppen; Rt–Ryptind; Sikteflellet–Sk; Solanderfjellet–So; Wulffberget–Wf. Place names on the small index map are abbreviated thusly: Spitsbergen–SP; Nordaustlandet–NE; north-west Spitsbergen migmatite region–NW; Ny-Friesland–NF. The orange rectangle on the index map indicates the study area, in the north-west Spitsbergen migmatite region.

(Fig. 1). Crystalline rocks occur along the north–south trending anticline axis, and are unconformably overlain by latest Silurian (?)/Devonian sediments (Friend & Moody-Stuart 1972; Gee 1972).

In the southern BHZ, the crystalline rocks consist of psammo-pelitic phyllites, schists, gneisses and migmatites with a distinct marble unit on the top. These rocks are intruded by unfoliated granites. The schists and gneisses of the northern BHZ are associated with metagranitic and metamafic rocks. Except for the augen metagranites and retrogressed eclogites which are present in the BHZ (Gee 1966a), the rocks in the BHZ are very similar to those in the north-western Spitsbergen basement area, west of the Raudfjorden–Monacobreen Fault (Gee & Hjelle 1966; Hjelle & Ohta 1974). This suggests lithological correlation. Single-zircon Pb evaporation dating studies of the rocks in the north-western basement rocks have recently been presented by Balašov et al. (1996b) and Ohta et al. (2002). The present article reports the dating results by the single-zircon Pb evaporation method on the rocks of the BHZ.

Geological outline

The 7 - 10 km wide BHZ extends from the northern coast of Biscayarhalvøya, via Liefdefjorden, southwards to Holtedahlfonna (south of the area shown in Fig. 1), over a distance of ca. 100 km. The zone is structurally subdivided into two—the northern (NBH) and the southern (SBH) subzones—by the Hannabreen Fault, which runs SSE–NNW from the northern coast of Liefdefjorden to Rivieratoppen on the eastern coast of Raudfjorden (Gee 1966a; Gjelsvik 1979). The Hannabreen Fault displays a hinge fault geometry. In its southern reaches, Silurian (?)–Devonian rocks in the east are downfaulted. In its northern reaches (north of Lilljeborgfjellet), the western side is downfaulted.

The NBH subzone was first mapped by Gee (1966a) and successively studied by Gayer et al. (1966), Peucat et al. (1989), Dallmeyer et al. (1990), Hesbøl (1996), Gromet & Gee (1998) and Ohta & Larionov (1998). The SBH was first visited by Hoel (1914) and Holtedahl (1914a, b). A regional map was presented by Gjelsvik (1979). The northern part of the SBH was recently studied by Pipjohn & Thiedig (1994, 1995, 1997), and Wyss et al. (1998) worked in the west of Bockfjorden. Russian geologists have studied throughout the BHZ since the 1960s, but no publication has been issued on the crystalline rocks.

The NBH subzone consists of five to six thrust duplex units, which run north–south to NNW–SSE and dip moderately and/or steeply eastward. Each duplex unit is a few km wide and verging to the west. These units consist of different lithotectonic units (Gee 1966a; Gee & Hjelle 1966; Peucat et al. 1989; Dallmeyer et al. 1990), which are summarized below in structurally ascending order, from the west to the east (some are repeated).

These lithological divisions are hereafter termed "complex" and "units", since their stratigraphic definitions are unclear. Place names that formerly began with "Biskayer" have been changed to "Biscayar-", in accordance with recent official topographic maps.

Biscayarfonna complex

The Richarddalen unit comprises various gneisses, agmatitic diorite, garnet-bearing schists and gneisses, porphyritic meta-granite, small amphibolites with retrograded eclogites and marbles.

The Montblanc unit is mainly banded schists and gneisses and some amphibolites.

The Biscayarhuken unit consists of various phyllites with quartzite and a small amount of marbles.

The Wulffberget and Erikbreen areas on the northern coast of Liefdefjorden, west of the Hannabreen Fault (SBH), comprise a 4 km wide zone of east verging thrust duplexes consisting of marbles, with a 0.5 km thick package of phyllite and schists in the middle (Ilys et al. 1995; Ohta et al. 1995). These marbles extend south across Liefdefjorden and form the western limb of a major anticline structure of the SBH. The same marbles occur on the eastern limb.

Three lithological units—marbles, pelitic schist, gneisses and migmatites—are recognized in the pre-Devonian Liefdefjorden Complex (Gjelsvik 1979; Piepjohn & Thiedig 1995; Wyss et al. 1998), in the SBH, structurally descending in the following order.

The migmatites occupy the crestal part of the regional anticline. Both the marbles and pelitic schists and gneisses are involved in a complex thrust duplex of a brittle nature, although the marbles are often ductile, and east verging structures are well developed in both limbs of the anticline (Piepjohn & Thiedig 1995, 1997; Ohta et al. 1995), with thrust surfaces dipping to the east in the eastern limb. The migmatites locally show intrusive contacts to the pelitic gneisses, and the latter are included as randomly rotated angular enclaves in heterogeneous granitic neosomes. The neosomes locally have flow structures.

A homogeneous granite, similar to the grey granite in north-western Spitsbergen, intrudes the migmatites in the crestal part of the anticline in the eastern Fred Olsenfjellet and around Ryptind, west of Bockfjorden (Wyss et al. 1998). All varieties of metamorphic and migmatitic rocks described above from the SBH are included in the granite as xenoliths.

The axis of the regional anticline plunges gently to the south, so that the top-seated marbles cover the anticline crest and both limbs in the southernmost part of the SBH.

The three-fold lithotectonic divisions in the NBH and SBH subzones have been correlated with the Generalfjella, Signehamna and Nissenfjella units of north-western Spitsbergen (Gee & Hjelle 1966; Hjelle & Ohta 1974; Hjelle 1979; Hjelle & Lauritzen 1982; Harland 1997).

Cenozoic volcanic rocks and hot springs are roughly aligned along the Breibogen Fault, near the western side of Bockfjorden. The basaltic rocks contain a large number of ultramafic, upper mantle enclaves and lower crustal granulitic rocks of Grenville age (Amundsen et al. 1987; Skjelkvåle et al. 1989), and they imply the presence of high grade metamorphic rocks in the abyss and depth of the Breibogen Fault.

Previous geochronological studies in the BHZ

Several isotopic dating studies have been carried out on the rocks of the BHZ, especially in the NBH, which are characterized by the occurrence of retrogressed eclogites (Gee 1966b; Ohta et al. 1989; Hesbøl 1996). The results are summarized in Table 1.

The K–Ar, $^{40}Ar/^{39}Ar$, Rb–Sr, U–Pb sphene and single-zircon Pb/Pb methods have yielded Caledonian ages. Late Caledonian ages of ca. 435 - 400 My (million years) have been obtained from all lithotectonic units of the BHZ (Gayer et al. 1966; Dallmeyer et al. 1990), while Early Caledonian ages of 480 My (muscovite from augen granite; Dallmeyer et al. 1990), 465 My (biotite from corona gabbro; Dallmeyer et al. 1990) and ca. 455 My (U–Pb sphene age; Gromet & Gee 1998) were obtained only from rocks of the Richarddalen unit. The last age has been argued to date the eclogite facies metamorphism in the NBH by Gromet & Gee (1998), while Dallmeyer et al. (1990) argued that the high P metamorphism was 504 - 552 My old based on $^{40}Ar/^{39}Ar$ hornblende age. Several K–Ar hornblende and clinopyroxene ages of 500 - 1939 My (Gayer et al. 1966) and $^{40}Ar/^{39}Ar$ ages of 505 - 550 My of hornblende (Dallmeyer et al 1990), obtained from the retrograded eclogites and gneissose amphibolites, have been difficult to explain.

Zircon U–Pb ages of ca. 620 - 660 My have been obtained from the rocks of the Richarddalen unit by Peucat et al. (1989) and Gromet & Gee (1998), and interpreted as the igneous protolith age of the retrogressed eclogitic rocks.

Meta-granite and corona gabbro in the Richarddalen unit were dated by conventional U–Pb and single-zircon methods and yielded ages of 955 - 965 My (Peucat et al. 1989; Gromet & Gee 1998). Similar ages were obtained from the zircon xenocrysts from Devonian tuffites (Hellman et al. 1998) and from the granulite xenoliths within Cenozoic volcanic rocks (Amundsen et al. 1987), both in the SBH.

A granitic dyke with the single-zircon age of 961 My cuts the phyllites of the Biscayarhuken unit on the northern coast of Liefdefjorden, and thus sets the youngest limit of the sedimentary protolith of the unit (Ohta & Larionov 1998). The 950 My old metagranite cuts the gneissosity of the Richarddalen unit and contain enclaves of folded marbles from the unit (Peucat et al. 1989), demonstrating that the sedimentary protoliths of the unit are also pre-Neoproterozoic.

Zircon xenocrysts from Devonian tuffites yielded two Mesoproterozoic age groups: 1353 - 1370 My and 1509 - 1586 My, while a late Palaeoproterozoic age of ca. 1737 My was obtained from the quartz porphyry clasts of the Lilljeborgfjellet conglomerate, the basal conglomerate of the Siktefjellet Group (latest Silurian ?) (Hellman et al. 1998). The presence of inherited Archean zircon, ca. 3.2 Gy old, within the 950 My old metagranite has been suggested by the concordia upper intercept age (Peucat et al. 1989).

Analytical method

Zircon grains were analysed by the Pb evaporation method, following Kober (1986, 1987). Each zircon grain was mounted in a canoe-shaped rhenium (Re) filament and its Pb isotope composition analysed in a Finnigan MAT 261 mass spectrometer at the Laboratory for Isotope Geology of the Natural History Museum in Stockholm. Zircon ($ZrSiO_4$) is decomposed by heating into ZrO_2 (baddeleyite) and SiO_2; this decomposition front moves from the surface of the grain inwards. To avoid the influence of lead as a contaminant on surfaces, in cracks and in metamict domains, the grain is pre-heated from 1350 to 1500 °C, whereas the lead content from unaltered inner domains is evaporated in several steps from 1550 to 1600 °C. The evaporated lead is precipitated on an ionization filament at the opposite side of the Re filament, together with silica. Each heating step takes 3 - 10 min to get an adequate quantity of lead for the isotope analysis. After each analysis, the heating is repeated, with a temperature increment of 10 - 30 °C, if required. The lead isotope composition of each step is ana-

Table 1. Previous isotopic ages from the Biscayarhalvøya–Holtedahlfonna zone. Ages in My (million years). See Fig. 1 for the locations of the sites listed by number in the first column. Numbers 1 and 2 are in the Biscayarhuken unit, 3 - 8 from the Montblanc unit, 9 - 15 from the Richarddalen unit and 18 and 19 are Devonian volcanics.

No.	Rock	Single zircon	Zircon U–Pb	Sphene U–Pb	Hb $^{40/39}$Ar	Ms $^{40/39}$Ar	Rock Ms Rb/Sr	Rock Bt Rb-Sr	Hb K–Ar	Micas K–Ar
1	phyllite									439 ± 20 [a]
2	granite	955 ± 4 - 968 ± 9 [h]								
3	mica schist			230.2 ± 2.8 [f]						
4	amphi- bolite				506.1 ± 2.1 [e]				389 ± 12 [a]	
5	grt-hb schist				4414.3 [e]					
6	mica schist				442.1 ± 2.3 [e] 538.5 ± 2.4 [e]	430.7 ± 0.9 [e]	428 ± 11 [e]	402 ± 8 [e] 413 ± 8 [e]		
7	hb schist				439.3 ± 2.8 [e]					
8	grt-hb gneiss	647 ± 4 - 667 ± 4 [f]		425.1 ± 15 - 458.3 ± 2.4 [f]	538.2 ± 2.4 [e]				428 ± 17 [b] 436 ± 17 [b]	
9	grt amphi- bolite				552.6 ± 2.7 [e]	454.9 ± 0.7 [e]				
10	retro. eclogite north	653 ± 9 [f] 655 ± 10 [f]	620 + 2, −5 [e]	431.3 ± 4.4 - 483.4 ± 3.5 [f]	504.7 ± 2.5 [e]	443.3 ± 6 [e]	430 ± 9 [e]		397 ± 10 - 550 ± 24 [a] 780 ± 50 [a] 1939 ± 12 [a]	399 ± 5 [a]
11	retro. eclogite south				529.4 ± 1.7 [e]				529 ± 15 [a]	
12	meta- granite		3234 ± 43 [d] 965 ± 1 [d]			480.4 ± 0.6 [e]	420 ± 10 [e]	410 ± 8 [e]		
13	agmatitic diorite		661 ± 2 [d]				423 ± 11 [e]			
14	pegmatite						418 [e]			433 ± 22 [a]
15	corona gabbro		955 ± 1 [d]					465 ± 9 [e]		
16	quartz porphyry	1735 ± 4 - 1739 ± 5 [g]								
17	tuff	439 ± 6 [g] 932 ± 15 - 952 ± 18 [g] > 1353 ± 7 - 1370 ± 7 [g] 1509 ± 45 [g] > 1586 ± 18 [g]								
18	granulite enclave						ca. 980 [b]			basalt ca. 3.0 [c]
19	schist/ gneiss									ca. 365 [a]

[a] Data from Gayer et al. 1966.
[b] Data fromAmundsen et al. 1987.
[c] Data fromSkjelkvåle et al. 1989.
[d] Data from Peucat et al. 1989.
[e] Data from Dallmeyer et al. 1990.
[f] Data from Gromet & Gee 1998.
[g] Data from Hellman 1998.
[h] Data from Ohta & Larionov 1998.

lysed in peak-jumping mode, using the electron multiplier. The measured isotope ratios are corrected for common Pb using the obtained $^{206}Pb/^{204}Pb$ ratio and following the model of Stacey & Kramers (1975). No correction for fractionation was made.

Pb evaporation age is calculated from the corrected $^{207}Pb/^{206}Pb$ ratio for each block of 10 scans, and the average age for each heating step is computed. If several steps (minimum 2 steps) have a similar age, a weighted average $^{207}Pb/^{206}Pb$ age (plateau age) is calculated for these steps using Ludwig's (1991) ISOPLOT program. This age is taken to indicate the age of crystallization of the zircon. The initial steps may often show a deviating lower age, as lead is first released from outer parts that may bear younger overgrowth or from metamict parts of the zircon crystal that may have undergone Pb loss or may be enriched in common Pb. Some zircon grains may show a steady increase in age to the final step, indicating the presence of older cores. Only a minimum age for the crystallization of the zircon core is available in such cases.

Samples, dating results and comparisons with previous data

Zircon grains were picked from two samples from the NBH and one from the SBH for dating. Two samples from the NBH are from the same localities as those described in Dallmeyer et al. (1990a) and Peucat et al. (1989), and one sample from the SBH has been collected from the area where the sample of Gayer et al. (1966) was taken (Fig. 1, Table 1).

Metagranite of the Richarddalen unit from south-west Biscayarfonna, NBH

A gneissose, porphyritic granite occurs at the south-western corner of Biscayarfonna, forming a north–south trending 200 m wide zone. It extends discontinuously to SSE for ca. 6 km to the north-west of Rabotdalen (Fig. 1). The metagranite contains K-feldspar augen, up to several centimetres long, and several modal percentages of garnet. In the Rabotdalen area, the metagranite displays a massive porphyritic texture. This metagranite includes enclaves of tightly folded marbles and gneisses of the Richarddalen unit, and appears as augen gneiss and mylonites, while a vein of fine-grained, corona gabbro cuts the gneissosity of metegranite. The contacts with the coarse-grained, garnet-biotite and hornblende-biotite gneisses of the Richarddalen unit to the east is concordant, but sheared. These field relations suggest a syntectonic emplacement of primary porphyritic granite and successive metamorphism into augen gneisses and mylonites (Peucat et al. 1989).

The analysed sample is a high K, S-type adamellite (Table 2), containing a significant modal amount of garnet, with biotite and large K-feldspar augen emphasizing its gneissosity. Accessories are allanite, apatite, rutil and zircon.

The majority of the zircon grains are euhedral in shape, with magmatic zoning, and inclusions are common (Fig. 2). However, ca. 10 %, are anhedral grains, with small aspect ratios of 1.5 - 2.0, rarely 4, and rounded outlines. They are transparent with smooth or rough surfaces and are considered to be inherited grains. Cathode luminescence images show core–mantle relations in these grains, indicating different degrees of overgrowth. Cores are evidently rounded and discordant to the mantle.

Nine anhedral zircon grains were selected in order to obtain the protolith age (Table 3a, Fig. 2). These are rounded with rough or relatively smooth surfaces; some are multi-faceted and have almost spherical outline. Grain E (dated to 964 ± 4 Mya) is subhedral with a pyramidal shape, suggesting overgrowth. All analysed grains were transparent, pink or yellow in colour, and grain H (dated to >2539 Mya) shows a definite core. The rounded xenocrystic shapes of the dated zircon grains are interpreted to result from metamorphic resorption and mechanical corrosion, during the conversion from primary porphyritic granite to garnet-bearing augen gneiss and mylonite. The foliation of the augen gneisses and mylonites are cut by the corona gabbro which yielded an U–Pb zircon age of ca. 955 My (Peucat et al. 1989).

Five grains from the metagranite (grains E, F, I, J and K) yielded plateau ages between 937 ± 14 and 976 ± 5 My, with an average of 960 ± 17 My. These ages are consistent with the conventional U–Pb age (965 ± 1 My) of Peucat et al. (1989), which was interpreted as a magmatic age. These ages are comparable to the single-grain zircon ages of the Hesteskoholmen granite sheets (bulk composition in Table 2), which have an average age of ca. 961 My (Table 1), intruding into the Biscayarhuken unit (Ohta & Larionov 1998).

Fig. 2. Age evaporation step results. Also shown, cathode luminescence images of two grains (not those analysed) from the metagranite of the Richarddalen unit (locality I, see Fig. 1).

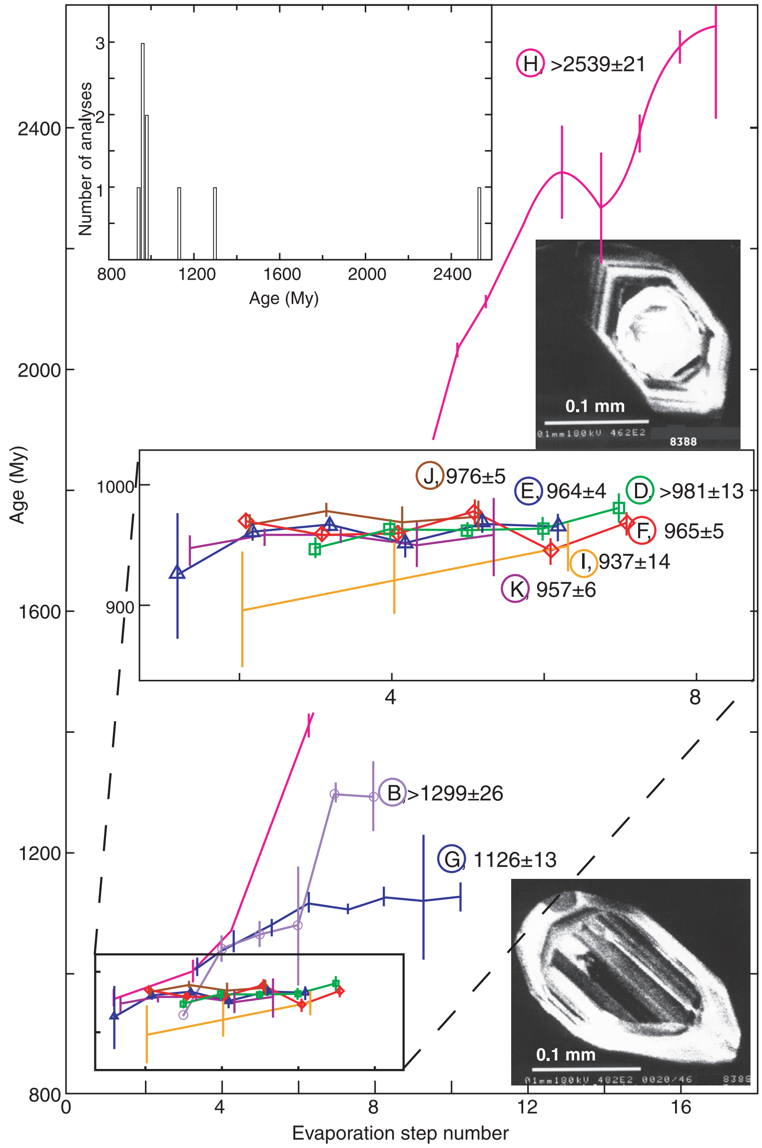


Table 2. Bulk rock compositions of the samples from which analysed zircon grains were picked.

	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ig loss	Total
1 [a]	73.92	0.13	13.11	0.62	0.03	0.29	1.45	2.84	6.54	nd	1.34	100.14
2 [b]	74.18	0.29	12.33	2.46	0.04	0.38	1.24	4.89	2.33	0.07	1.54	99.46
3 [c]	65.97	0.83	15.55	6.09	0.09	1.69	1.69	2.76	3.44	0.10	1.50	98.88

[a] Metagranite of the Richarddalen unit, south-western Biscayarfonna.

[b] Granite dyke cutting the Biscayarhuken unit on the southern island of Hesteskoholmen, northern Liefdefjorden (Ohta & Larionov 1998).

[c] Granitic neosome from the west of Bockfjorden.

Grain D shows somewhat higher minimum age of >981±13 My, possibly due to inherited old core. Two grains, B and G, yielded ages of >1299±26 My and 1126±13 My, respectively, suggesting the existence of older core.

Grain H started from ca. 950 My and finally showed a minimum age of >2539±21 My. This suggests an Archean inherited core in the grain, consistent with the upper intercept U–Pb age (multi-grain, 3234±43 My; Peucat et al. 1989; Table 1).

No Caledonian age has been recorded in the U–Pb isotope system of these zircon grains. The inherited ages are widespread and they may point to detrital zircon grains from incorporated sediments.

Table 3. $^{207}Pb/^{206}Pb$ single-zircon dating results from the Biscayarhalvøya–Holtedahlfonna zone (BHZ). Table continues opposite page.

Grain (number of steps on plateau in parentheses)	Measured				Age±2σ (My)	
	$^{207}Pb/^{206}Pb$±2σ%		$^{206}Pb/^{204}Pb$±2σ%			
3a. Metagranite of the Richarddalen unit, south-western Biscayarfonna (locality I in Fig. 1)						
B. Euhedral, round corners, brown, transparent (2)	0.085029	1.23	25697	69.60	>1299	26
D. Subhedral, rounded, pink, transparent	0.072141	0.95	63839	119.8	>981	13
E. Subhedral, pink, transparent (6)	0.071627	0.48	66904	40.45	964	4
F. Anhedral, flat, round, pink, transparent, inclusion (5)	0.071725	0.60	41414	32.59	965	5
G. Multifaceted, subhedral, pink, transparent (3)	0.076735	2.36	72897	35.05	1126	13
H. Anhedral, rounded, pink, transparent	0.169920	0.67	27302	101.1	>2539	21
I. Subhedral, rounded, resorbed, pink, transparent (3)	0.070646	2.58	14449	32.41	937	14
J. Multifaceted, subhedral, pink, transparent (3)	0.072035	0.59	39355	60.76	976	5
K. Anhedral, rounded, pink, semi-transparent (4)	0.072451	0.99	10264	79.06	957	6
3b. Micaceous schists from south-east Solanderfjellet, northern subzone (NBH) of the BHZ (locality II in Fig. 1)						
A. Moderately rounded, brown, transparent (2)	0.099698	1.95	7075	19.01	1610	8
B. Slightly rounded, zoned, pink, transparent (2)	0.071206	0.21	40340	15.35	949	6
C. Well-rounded, flat, pink, transparent (5)	0.108869	0.22	220958	31.02	1779	2
D. Well-rounded, flat, pink, transparent (3)	0.112487	3.56	15015	71.98	1855	10
E. Well-rounded, brown, transparent	0.117927	3.75	4066	20.89	>1888	46
F. Prism, slightly rounded, pink, transparent(3)	0.070797	0.20	60718	22.79	938	4
G. Rounded, fractured, pink (5)	0.083796	0.23	72232	20.91	1294	3
H. Slightly abraded, prismatic, pink, transparent (2)	0.070990	0.14	76247	11.85	952	2
I. Well-rounded, flat, brown (2)	0.075994	0.41	30467	27.39	1080	7
J. Rounded, pink, transparent (2)	0.090543	1.02	29015	90.53	1416	7
K. Broken, slightly rounded, pink, transparent	0.077730	0.84	21858	46.91	>1120	15
L. Slightly rounded, elongated, pink, transparent (5)	0.101077	0.25	95698	61.81	1646	3
M. Non-abraded, broken, pink, transparent (2)	0.072189	0.70	85386	54.53	985	8
N. Rounded, zoned, brown, semi-transparent (6)	0.070777	0.16	159611	31.36	947	3
O. Rounded, pink, transparent (3)	0.074327	0.44	123485	35.42	1047	5
P. Rounded, flat, pink, transparent (2)	0,090454	0.11	244688	18.27	1431	3
Q. Well-rounded, flat, pink, transparent (3)	0.119856	0.17	142085	50.35	1950	2
R. Well-rounded, pink, transparent, flat (4)	0.181826	0.12	181660	18.40	2669	2
S. Rounded, pink, transparent (4)	0.106407	0.21	122421	25.90	1735	4
T. Rounded, pink, transparent (3)	0.112245	0.43	80832	113.1	1834	3
U. Rounded, flat, pink, transparent (4)	0.113497	0.17	115310	26.64	1854	3
V. Rounded, flat, pink, transparent (4)	0.112192	0.15	336383	38.44	1830	3
W. Rounded, flat, fractured, brown, transparent (3)	0.085172	1.71	40194	35.59	1326	4
X. Slightly rounded, flat, pink, transparent (4)	0.101111	0.25	221063	34.53	1642	2
Y. Non-abraded, multifaceted, pink, transparent (3)	0.103356	0.38	50724	60.80	1677	5
Z. Well-rounded, pink, semi-transparent (4)	0.113593	0.85	58689	73.41	1858	4

Micaceous schists from Solanderfjellet, Montblanc unit, NBH

Micaceous schists with a small amount of schistose amphibolite form a lenticular body, 1.5 km wide and 2.5 km long, in Solanderfjellet, north-west of Richardvatnet (Fig. 1). A north-west striking reverse fault zone bounds this body at its north-eastern margin. Several small thrust duplex units, each less than 1 m thick, are developed in the reverse fault zone, illustrating westward stacking. The south-western boundary of the schist body is a thrust dipping moderately to north-east, and the north-western border is the vertical Hannabreen Fault. The Richarddalen unit occurs both structurally above and below the schists, which have been assigned to the Montblanc unit (Gee 1966a, b; Gee & Hjelle 1966; Peucat et al. 1989; Dallmeyer et al. 1990).

Two-mica schists dominate, associated rocks are hornblende-, garnet- and epidote-bearing amphibolites. Meso- and micro-structures are characterized by a fine- to medium-grained, lepidoblastic texture, and represent a single metamorphic recrystallization.

Caledonian $^{40}Ar/^{39}Ar$ and Rb–Sr ages have previously been recorded from the mica schist collected from the same locality sampled here. The $^{40}Ar/^{39}Ar$ ages are 442.1 ± 2.3 My (hornblende) and 430.7 ± 0.9 My (muscovite), and the Rb–Sr age is 413 ± 8 My (biotite) (Dallmeyer et al. 1990; Table 1).

Zircon grains were separated from a garnet-bearing, two-mica schist, sampled along the north-west coast of Richardvatnet, at the south-eastern foothill of Solanderfjellet. The sample schist displays a well developed cleavage and its metamorphic grade is not higher than lower amphibolite facies, judging from the metamorphic mineral assemblages with garnet, chlorite, muscovite, biotite, epidote and pale green amphibole. All zircon grains from this sample can therefore be considered detrital.

Analysed zircon grains differ in shape, aspect ratio, degree of abrasion, colour and internal structure, and some are fragmental, which is typical for detrital grains (Table 3b, Fig. 3). Most grains are transparent or semi-transparent and have relatively light colours. Less rounded grains could be considered to be derived from their primary sources, while more rounded grains could have experienced several sedimentary cycles, or alternatively, derived from remote sources. Cathode luminescence observations revealed a bright, thin, sometimes discontinuous rim. This might be a signature of later metamorphic / hydrother-

3c. Granitic neosomes of migmatite from west of Bockfjorden, southern subzone (SBH) of the BHZ (locality III in Fig. 1)						
R. Anhedral, abraded, pink, transparent (2)	0.075577	1.71	37605.1	32.40	> 1097	9
W. Subhedral, sharp corners, prism reduced, brown, transparent (3)	0.182249	0.45	32371.8	33.70	2683	3
X. Subhedral, sharp corners, core, pink, transparent (2)	0.102451	2.42	18348.9	57.47	1685	11
Y. Anhedral, abraded, flat, brown, semi-transparent (4)	0.101514	0.46	43378.3	150.73	1636	4
Z. Subhedral, sharp corners, multifaceted, transparent (3)	0.326849	0.38	33540	70.44	3604	4
A. Subhedral, fractured, zoned, brown, translucent (2)	0.072789	0.54	6109.8	9.04	942	8
B. Subhedral, long prismatic, zoned, core, brown, translucent (3)	0.071175	0.41	22101.3	12.56	946	6
E. Subhedral, zoned, pink, semi-transparent (5)	0.071201	0.25	162928	45.32	959	3
F. Subhedral, multifaceted, flat, pink, transparent (3)	0.194336	0.57	16617.1	14.00	2775	4
G. Anhedral, rounded, flat, smooth, pink, transparent (2)	0.075262	0.70	103591	79.67	1063	16
I. Subhedral, multifaceted, flat, round corners, brown, transparent (3)	0.085516	0.84	26672.8	22.29	1319	14
K. Anhedral, flat, smooth, pink, transparent	0.093320	4.80	125166	140.10	> 1509	17
M. Anhedral, rounded corners, pink, semi-transparent	0.105456	1.09	43339.2	31,85	> 1714	15
N. Subhedral, zoned, core?, one vertex, dark brown, semi-transparent (2)	0.108443	1.23	36336.1	72.76	> 1793	34
O. Subhedral, rounded corners, healed fracture, zoned, light brown, transparent (3)	0.070163	1.81	152570	68,87	947	4
P. Subhedral, prismatic, flat, zoned, pink, transparent (4)	0.070417	1.13	41036.4	54.02	944	6
Q. Subhedral, rounded, flat, core, brown, transparent	0.102813	0.87	62610.7	96.78	> 1667	17
T. Subhedral, flat, sharp corners, pink, transparent (2)	0.101500	0.27	121056	86.12	1645	5
U. Anhedral, abraded, fine zoning, pink, transparent (4)	0.099014	2.61	53461.0	55.75	1636	5
V. Subhedral, scratched, broken vertex, brown, semi-transparent (2)	0.106841	1.15	26473.1	97.11	1750	5

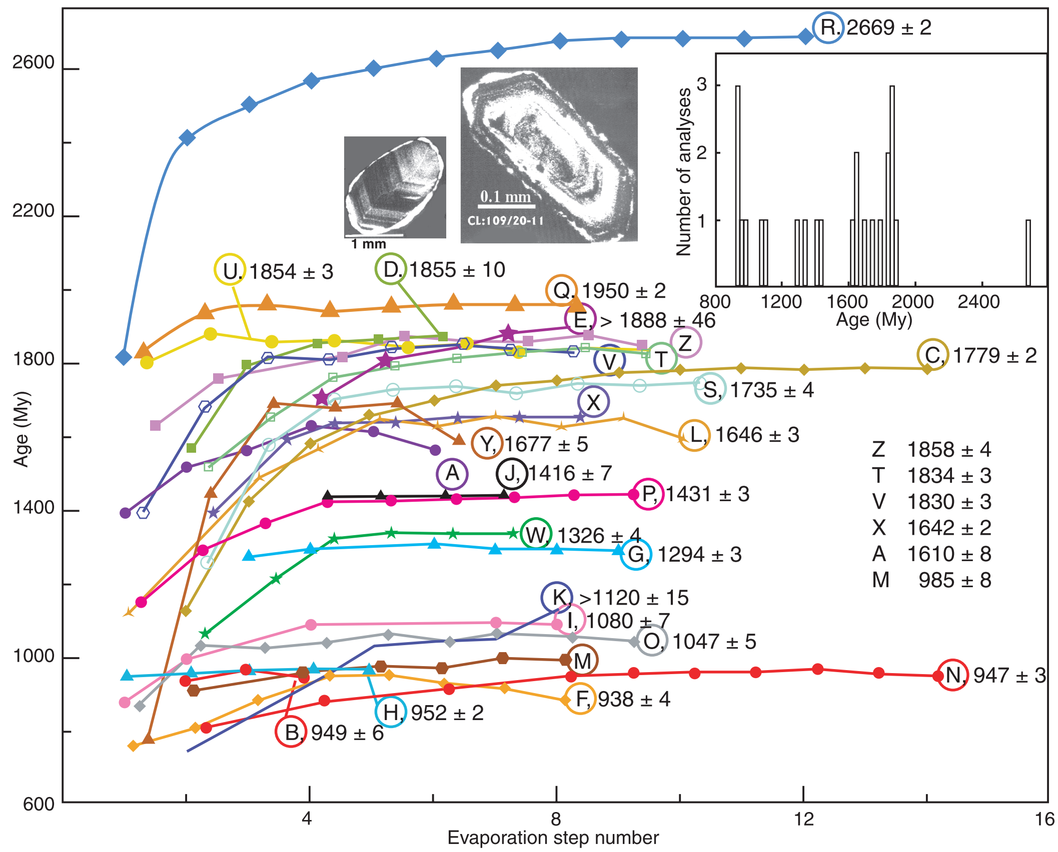


Fig. 3. Age evaporation step figure and some cathode luminescence images of zircons from the micaceous schist (locality II; see Fig. 1) from Solanderfjellet.

mal resorption events.

The 26 analysed zircon grains can be grouped into four age groups (Fig. 3, Table 3b), as follows. (1) Seven grains (B, F, H, I, M, N, O) are dated to 938±4 - 1080±7 Mya. (2) Four grains (G, J, P, W) are dated to 1294±3 - 1431±3 Mya, and one grain (K) has a minimum age of 1120±15 My. (3) Twelve grains (A, C, D, L, Q, S, T, U, V, X, Y, Z) are dated to 1610±8 - 1950±2 Mya, and one grain (E) with a minimum age of 1888±46 My. (4) One grain (R) has an Archean age of 2669±2 My.

Age group 1. Three grains (F, K, N) in this age group show ages as young as 740 My in their early evaporation steps. Then ages moderately or gently increase with successive evaporation steps. This suggests Pb loss probably due to the Caledonian imprint around the margins. Grain N shows metamict alteration.

Grains of this age group comprise ca. 24% of the analysed grains of this sample. This suggests a significant exposure of Grenvillian rocks in the source areas of the protoliths. This age group may have two ill-defined age clusters: younger than 985 My and older than 1047 My, separated by a 60 My interval.

Age group 2. The four grains of this age group can be subdivided into two subgroups with ages overlapping roughly within the error ranges in each subgroup. Subgroup 2a comprises: grain G, dated to 1294±3 Mya; grain W, dated to 1326±4 Mya; and possibly grain K, dated to >1120 Mya. Grain K is metamictic. Subgroup 2b includes: grain J, dated to 1416±7 Mya; and grain P, dated to 1431±3 Mya.

These two age subgroups represent two separate thermal events. Except for grain W, all these grains are strongly abraded, implying a lengthy sedimentary history. Ages similar to those of subgroup 2a have been reported from the zircon xenocrysts of the Devonian tuffites, ca. 6.5 km south

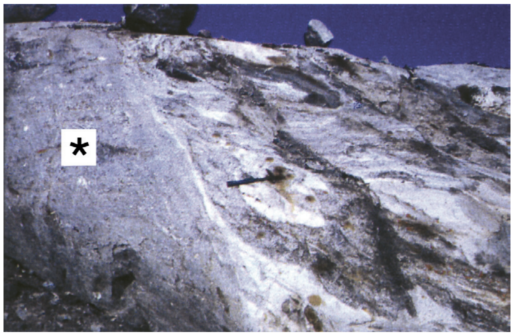


Fig. 4. Occurrence of the migmatite at the mouth of Friedrichbreen, south-western coast of Bockfjorden. The asterisk marks the dated granitic neosome. The shaft of the hammer in the centre of the photograph is 30 cm long.

of this locality in the north-western part of SBH (Fig. 1, Table 1; Hellman et al. 1998).

Age group 3. Circa 50 % of the grains in the whole population are 1600 - 1950 My old, though with a wide age range of 340 My, suggesting a wide exposure of the latest Palaeoproterozoic crystalline rocks in the source areas.

Some grains have overlapping ages within the error rages: grain X (1642 ± 2 My) and grain L (1646 ± 3 My); grain V (1830 ± 3 My) and grain T (1834 ± 3 My); and grain U (1854 ± 3 My) and grain Z (1858 ± 4 My), probably derived from the same sources. As the zircon grains with ages from 1830 to 1950 My are less abraded and grain Y (1677 My) is even non-abraded, their derivation from primary sources is inferred. The rest of the grains are all well rounded, except for grains S (dated to 1735 Mya) and D (1855 Mya). The age of grain S is similar to the age of the ca. 1740 My old quartz porphyry clasts from the Lilljeborgfjellet Conglomarate (Hellman et al. 1998; Table 1).

Almost all grains in age group 3 show ages as young as ca. 800 My at their early evaporation steps, suggesting later disturbance of the Pb isotope system, but Caledonian influence may be very weak.

Age group 4. Grain R, with the Archean age, of 2669 ± 2 My, is very well rounded, suggesting that it could have experienced several depositional episodes. A weak mantle overgrowth in the latest Paleoproterozoic is inferred on the basis of the young ages at the earliest evaporation step of this grain.

Granitic neosome of migmatite from the west of Bockfjorden, SBH

The eastern limb of the SHB major anticline west of Bockfjorden consists of marbles, pelitic schists and gneisses and granitic migmatites, in structurally descending order. The heterogeneous granitic neosomes of the migmatites often contain scattered plagioclase porphyroblasts and show local distinct flow foliation. They cut agmatitic migmatite and contain a large amount of strongly assimilated enclaves of pelitic schists, gneisses and marbles (Fig. 4). A massive homogeneous, leucocratic granite, similar to the grey granite of north-western Spitsbergen (Balašov et al. 1996b; Ohta et al. 2002), cuts all other metamorphic and migmatitic rocks.

Zircon grains were separated from a heterogeneous granitic neosome, sampled at the mouth of Friedrichbreen. This sample is a medium-grained, weakly gneissose rock, containing ovoidal plagioclase centimetre-sized grains which are partly enclosed by deep brown biotite flakes. Both plagioclase and K-feldspar are thickly overgrown by small sericite flakes, and myrmekite texture developes between them. Quartz is interstitial and shows mylonitic bleb shapes. Cordierite grains are strongly replaced by flakes of muscovite and irregular cracks are pinitized. Thin needles of sillimanite are included in plagioclase. The rock has an adamellitic composition, with high K, calc-alkaline, S-type characteristics (Table 2), and plots in the field of IAG+CAG+CCG of the SiO_2 vs FeO*/FeO*+MgO diagram of Maniar & Piccoli (1989).

Zircon grains from this sample are euhedral to anhedral; some have fragmental appearences and overgrowth (Table 3c, Fig. 5a). A number of grains have rounded edges and scratched surfaces, which suggests that the zircon population is heterogen.

Cathode luminescence images reveal complex core structures of the euhedral and subhedral grains (Fig. 5a). The sharp edges and smooth surfaces are mostly due to overgrowth. The cores are discordant to the mantle and the boundaries between them are abrupt or diffused, suggesting possible resorption before or in the very beginning of overgrowth. Cathode luminescence-darkness of the mantle is due to the U enrichment, which, in turn, could correspond to the mantle growth during a migmatization event (Cornell et al. 1998).

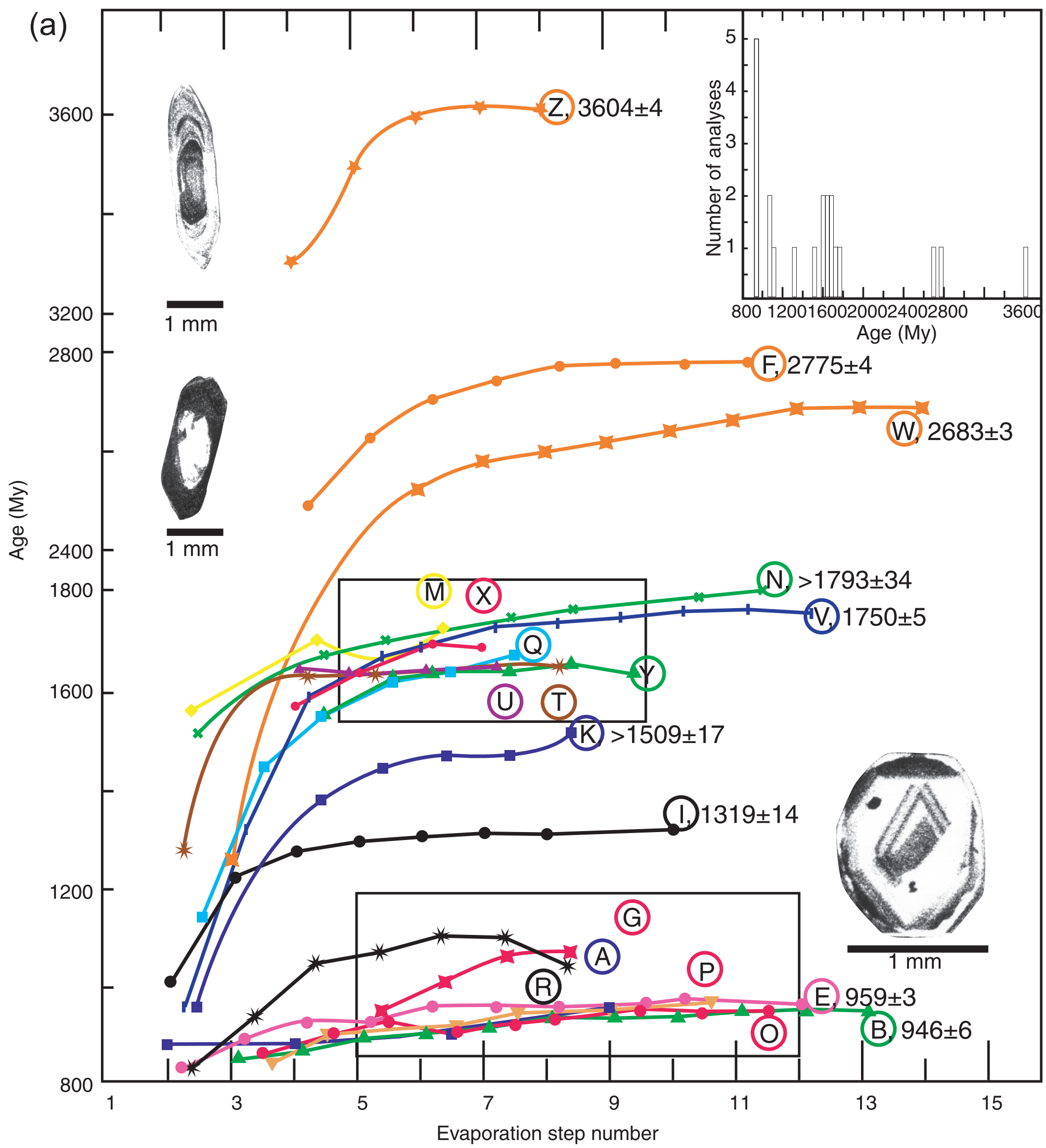
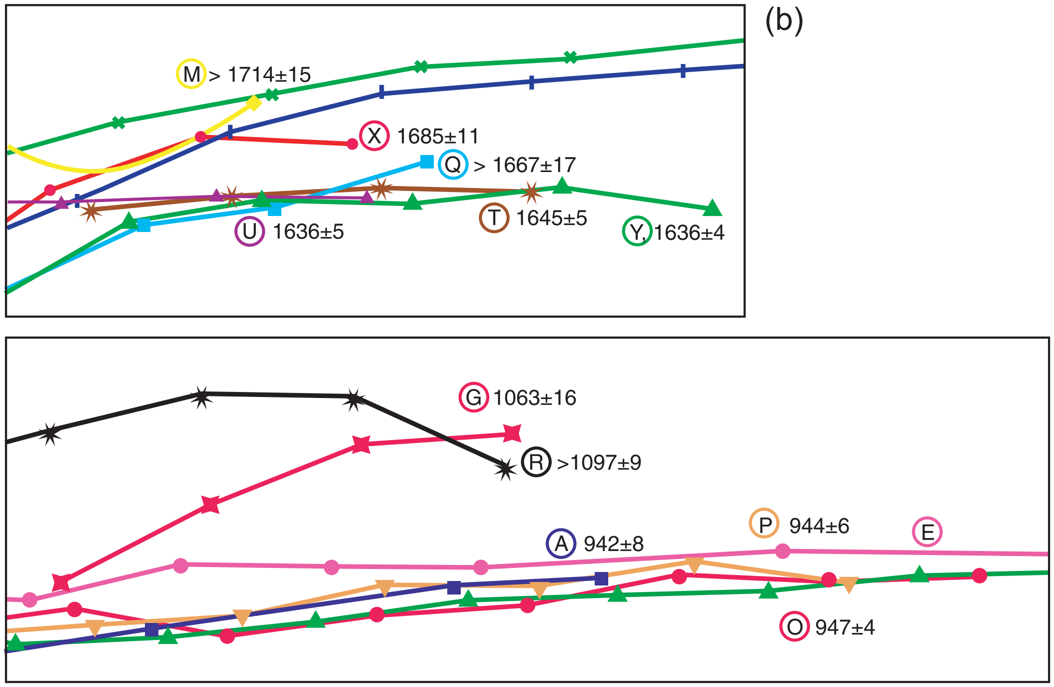


Fig. 5. (a) Age-evaporation step results and some cathode luminescence images of zircon grains from the granitic neozome from the west of Bockfjorden (locality III, see Fig. 1). Rectangles indicate sections enlarged in (b), opposite page.

Four age groups are recognized among the 20 analysed zircon grains (Fig. 5, Table 3c), as follows. (1) Six grains (A, B, E, G, O, P), comprising 40% of the analysed grains, are dated to 942±8 to >1063±1 Mya, and one grain (R) has a minimum age of >1097±9 My. (2) One grain (I) is dated to 1319±14 Mya. (3) Five grains (T, U, V, X, Y), i.e. 25% of the analysed grains, are dated to 1636±4 to 1793±34 Mya, and four grains (K, M, N, Q) have minimum ages from >1509 to >1793 Mya. (4) Three grains (F, W, Z) have ages older than ca. 2683 My.

Evaporations of the beginning steps for the outer parts of grains were usually not measured. However, in some cases $^{207}Pb/^{206}Pb$ ratios correspond to 560-850 Mya, suggesting partial reset of the U–Pb system by later thermal events on the surface of older grains.



Age group 1. Two clusters of ages may be recognized in this age group. Cluster 1a includes five grains (A, B, E, O, P) dated to 942 - 959 Mya. Cluster 1b includes one grain (G) dated to 1063 Mya, and a second grain (R) with a minimum age of 1097 Mya.

Grains A (dated to 942 ± 8 Mya), B (946 ± 6 Mya) and P (944 ± 6 Mya) of the 1a age cluster are subhedral, while two others—E (959 ± 3 Mya) and O (947 ± 4 Mya)—have rounded edges and pinnacles. All five grains have clear oscillatory zoning and small inclusions of acicular, short prismatic and dot shapes. Grain B contains a rounded core, and possible inherited cores are observed in some of the other grains.

These ages indicate that the major zircon crystallization from the granitic melt occurred ca. 950 Mya. This age range corresponds to the second-dominant age cluster of the Solanderfjellet micaceous schist.

Grain G (1063 My old) of the 1b age cluster has a rounded outline, without overgrowth, suggesting a detrital origin. This is the youngest age of apparently detrital grains. Optical microscopy and cathode luminescence observation do not permit the determination of whether the rounded outlines of the ca. 950 My old grains E and O are products of detrital abrasion or magmatic resorption. If grain G is detrital in origin and the grains of the 1a age cluster are metamorphic, the sedimentary protoliths of the gneissic enclaves in the granitic neosome are younger than 1063 My and older than 959 My. No evidence of Caledonian zircon growth has been detected in the present study, though a date of ca. 365 Mya has been yielded by the K–Ar method from a rock collected in the same area as the present sample (Gayer et al. 1966; Table 1).

Age group 2. The short, prismatic, flat grain (I) of this age group has well developed facets, and gave a well defined plateau age of 1319 ± 14 My. Comparable ages (1353 - 1370 My) have been reported from the xenocrystic zircons of the tuffites interbedding in the Devonian sediments (Hellman et al. 1998; Table 1).

Age group 3. This age group can be divided into two age clusters, separated by an interval of ca. 40 My. Three younger grains—T (dated to 1645 ± 5 Mya), U (1636 ± 5 Mya) and Y (1636 ± 4 Mya)—of this age group show a short range of ca. 10 My and the error ranges are almost overlapping. However, grains T and U display prismatic, subhedral outlines, with slightly rounded edges and rough spots on the facets, while grain Y is distinctly abraded. The morphology suggests a detrital nature of these grains. Grain K (dated to

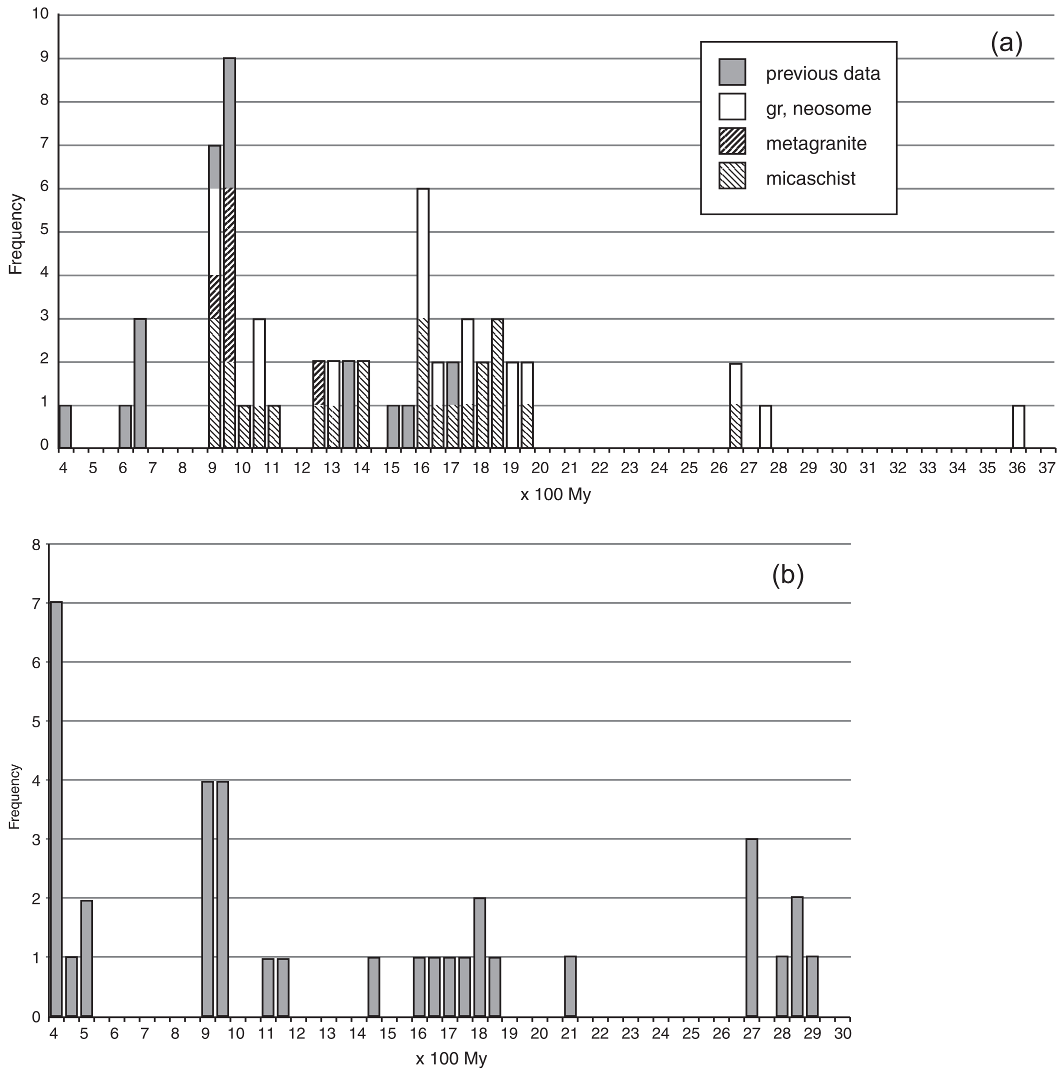


Fig 6. Histograms of the single-zircon Pb ages from north-western Spitsbergen. Only plateau ages are used. (a) Biscayarhalvøya–Holtedahlfonna zone (45; this paper). (b) North-west migmatite region (36; Ohta et al. 2002).

>1509±17 Mya), with smooth surfaces and sharp edges, may belong to this age cluster of the latest Palaeoproterozoic.

Grains V (dated to 1750±5 Mya), X (1685±11 Mya) and three minimum ages of M (>1714±15 Mya), N (>1793±34 Mya) and Q (>1667±17 Mya) are grouped into a late Palaeoproterozoic age cluster. Grain N could be older. Grain Q may belong to this age cluster. All grains of this age cluster have subhedral outlines with relatively sharp edges and smooth facets. This suggests the presence of younger overgrowth, which is supported by the low $^{207}Pb/^{206}Pb$ ratios in the beginning stages of analyses giving ages as young as ca. 950 Mya (Fig. 5).

Age groups 4. Three Archean ages have been obtained. They show at least two age subgroups. Subgroup 4a comprises grain W, dated to 2683 Mya, and grain F, dated to 2775 Mya. Subgroup 4b consists of grain Z, dated to ca. 3600 Mya. The last one is the oldest single-zircon age so far obtained in Svalbard. All grains are short prismatic with well-developed smooth facets and sharp edges due to younger overgrowth.

Discussion

In all, 54 zircon grains have been analysed by the single-grain zircon Pb evaporation method in this study (Fig. 6a). Previous isotopic dating results are incorporated in this discussion (Table 1). The regional discussion takes into account recent dating results from north-west Spitsbergen (Fig. 6b).

A topographic horst today, the BHZ was a graben during latest Silurian (?)–Devonian time. Some K–Ar ages of ca. 370 My (Gayer et al. 1966) may reflect the activity of faults and the formation of the anticline structure during the Svalbardian event in late Devonian (Orvin 1940).

The Hannabreen Fault is the boundary between the east verging SHB and the west verging NHB subzones. Together with the Hannabreen Fault—the two boundary faults of the graben—the Raudfjorden–Monacobreen and Breibogen faults, form an N-shaped pattern, suggesting a late post-Devonian dextral faulting. The oppositely verging duplex structures of the two subzones are evidently older than the deposition of the Siktefjellet group. Caledonian thermal events, ca. 400 - 480 Mya, have been detected by the K–Ar (Gayer et al. 1966), $^{40}Ar/^{39}Ar$, Rb–Sr (Dallmeyer et al. 1990) and U–Pb sphene dating methods (Gromet & Gee 1998) in this zone. However, no Caledonian plateau age has been obtained by the present method.

Caledonian and older events relating to the NBH and SBH are discussed below.

NBH

Three lithotectonic units of this subzone—the Richardalen, Montblanc and Biscayarhuken units—are repeatedly thrust to the WSW direction, and are thought to get younger in the following order (Gee & Hjelle 1966; Gjelsvik 1979).

Biscayarhuken unit. The low grade psammitic phyllites of this unit are intruded by subconcordant sheets of ca. 961 My old granite on the southern island of Hesteskoholmen, northern Liefdefjorden (Ohta & Larionov 1998). The granite is brittly sheared, and has local oblique contacts to the cleavages of the host phyllites. Accordingly, the sedimentary protoliths of the phyllites of the Biskayarhuken unit are older than ca. 961 My, i.e. Mesoproterozoic. The older age limit of the protoliths is unknown. Imprint of the Caledonian thermal event is indicated by a biotite K–Ar age of ca. 431 My in the north-eastern part of the subzone (Gayer et al. 1966), but this event did not disturbed the U–Pb isotope system.

Montblanc unit. This unit occupy the middle structural position among the three lithotectonic units of NBH.

The Solanderfjellet micaceous schists studied in this work have been correlated with the Montblanc unit (Gee 1966a; Gee & Hjelle 1966; Peucat et al. 1989; Dallmeyer et al. 1990). The youngest detrital zircon from the analysed micaceous schist is 938 My old; accordingly, the age of the sedimentary protoliths of the schist is Neoproterozoic. There is no sign of Vendian tilloids and thick lower Palaeozoic carbonate rocks in this unit.

Zircon grains with the Grenvillian ages from the Solanderfjellet micaceous schist (938 - 1080 My; 28 % of the analysed grains) may show two age clusters, separated by a 60 My interval from 985 Mya to 1047 Mya. Ohta et al. (2002) argued for two phases of zircon formation during the Grenvillian period in Svalbard: an early igneous event (the Vimsodden quartz porphyry and rhyolite, >1100 Mya, in south-west Spitsbergen; Balašov et al. 1995; and the Kapp Hansteen quartz porphyry, 950 Mya, in north-western Nordaustlandet; Johansson et al. 1996) and a later metamorphic event (Isbjørnhamna schists, 930 Mya, south-west Spitsbergen; Barašov et al. 1996b; and the Kontaktberget granite, 939 Mya, in north-west Nordaustlandet; Gee et al 1995). The age clusters inferred in the present samples are conformable with subdivision inferred for other areas of Svalbard.

The grains with the Grenvillian ages, in the broad sense (ca. 940 - 1080 Mya), and late Palaeoproterozoic ages (ca. 1600 - 1950 Mya) constitute 28 and 52 %, respectively, of the analysed grains. This suggests that the source areas consist of the rocks with these ages. The Grenvillian zircon grains show a low degree of abrasion, suggesting a single depositional process and relatively short transport, while the grains with older ages are strongly abraded.

Late Caledonian thermal records, from ca. 400 - 440 Mya, have been provided by $^{40}Ar/^{39}Ar$ and Rb–Sr ages (Dallmeyer et al. 1990), although no Early Caledonian ages (ca. 460 - 480 My; e.g. Ohta et al. 1979) have been reported from this unit, except for a 458.3 ± 2.4 My sphene U–Pb age (Gromet & Gee 1998). Two $^{40}Ar/^{39}Ar$ hornblende ages—506 and 538 My—were reported by Dallmeyer et al. (1990), but their geological meaning is unknown.

The lithological correlation of the Solanderfjellet schists with those of the prototype Montblanc unit, exposed in the Montblanc area ca. 3 km east of Solanderfjellet (Gee 1966a), is uncertain.

Richarddalen unit

The gneisses of this unit were intruded by a porphyritic granite (age range of 937 - 981 My), which were later metamorphosed into augen gneisses and mylonites, before the intrusion of the 955 My old, unfoliated corona gabbro (Peucat et al. 1989). Rounded shapes of the dated zircon grains from the metagranite sample can be explained by this metamorphism. Therefore, a magmatic age of the porphyritic granite of ca. 981 My and the metamorphic age of ca. 955 My are inferred. Zircon grains with these ages show similar ages at all evaporation steps of analyses (Fig. 2), indicating that they are free from inherited inclusion in the core. The age of the sedimentary protoliths of the Richarddalen gneisses is older than 981 My, i.e. Mesoproterozoic or older.

There are many uncertainties regarding the presence of an Early Caledonian record in the rocks of the Richarddalen unit (Dallmeyer et al. 1990; Gromet & Gee 1998), which contains retrogressed eclogites (Gee 1966a, b; Hesbøl 1996). There are a few relicts of eclogite facies minerals, but most rocks were strongly reworked at high pressure granulite facies conditions (S. Elvevold, pers. comm.). Late Caledonian reworking is demonstrated by the K–Ar, $^{40}Ar/^{39}Ar$ and Rb–Sr mica whole rock ages (Gayer et al. 1966; Dallmeyer et al. 1990).

To summarize the NBH: the Richarddalen and Biscayarhuken units have Mesoproterozoic or older sedimentary protoliths. Both were intruded by 960 - 980 My old granites and variously metamorphosed during the Grenvillian period. Difference in structural levels during and after Grenvillian times may explain their different lithological characteristics. The Richarddalen unit, being intruded by basic and felsic rocks around 620 - 660 My ago (Peucat et al. 1989), was metamorphosed under high P–T conditions in a deep crust during Early Caledonian phase, older than ca. 455 - 480 Mya (Gromet & Gee 1998). In contrast, the Biscayarhuken unit, which was not intruded by basic igneous rocks, has no record of Caledonian metamorphism higher than lower amphibolite facies, which is conformable with the K–Ar and Rb–Sr isotope closure temperatures, 350 - 500 °C (Hames & Bowring 1995; Dickin 1997).

The Solanderfjellet micaceous schists have Neoproterozoic sedimentary protoliths. However, the correlation of the schists with the Montblanc unit at the type locality is uncertain and the protolith age of the Montblanc unit there is unknown.

Thus, the three lithotectonic units of the Biscayarfonna complex have different histories and were brought into the present duplex configuration by west verging compressions after the middle Silurian during the Late Caledonian period, before the sedimentation of the Siktefjellet group in the latest Silurian (?) to the earliest Devonian time.

SBH

The mesoscopic structures of the pre-Devonian rocks within both limbs of the anticline in the SBH are complex brittle duplexes in the pelitic schists and gneisses and ductile isoclinal folds in the marbles, both verging to the east (Piepjohn & Thiedig 1994, 1995, 1997; Ohta et al. 1995). The tectonic transport direction is opposite to that of the NBH. Some brittle shear boundaries of the duplex units penetrate into the migmatites, while thin aplite veins of Caledonian grey granite affinity cut slightly oblique to the foliation of the gneisses within the duplex units but do not cut the brittle shear boundaries. Devonian strata thrust onto the duplex structures and postdate the latest felsic igneous activity.

On the middle island of Lernerøyane in southern Liefdefjorden, the migmatites have feldspar porphyroblastic textures and show a rapid transition from the schists and gneisses in the west. In contrast, abrupt transition from schists and gneisses to agmatitic migmatites is characteristic of the eastern contacts, though the contacts are often sheared. This asymmetric transition reflects the eastward verging tectonics of the SBH and generally observed in the west of Bockfjorden. Definitely younger, unfoliated grey granite sharply cuts the migmatites.

The sample rock used for the present zircon dating cuts the migmatites (Fig. 4), and is itself cut by a tourmaline-bearing pegmatitic dyke, which is an affinity of the grey granite. It is not clear from field relations whether the sample rock is mobilized neosome of the migmatite or a grey granite contaminating significant amount of migmatitic material.

Caledonian ages

Ages around 560 - 850 My, obtained from the beginning steps of evaporation, indicate Caledonian overgrowth or Pb-loss of zircon around the grain margins. The latest Caledonian thermal event was accompanied with the emplacement of grey granite in the anticlinal crest, ca. 410 - 430 Mya in adjacent north-western Spitsbergen (Ohta et al. 2002). No sign of an Early Caledonian phase has been obtained in the SBH.

Grenvillian ages

Circa 942 - 1097 My old zircon grains from the granitic neosome are the most numerous of the grains analysed: 40 % of obtained plateau ages. These have clear igneous growth zoning and inclusions of euhedral crystals and liquid and/or gas, and these ages could represent crystallization of the zircon from a granitic melt during high grade Grenvillian regional metamorphism. Accordingly, the age of the sedimentary protoliths of the schists, gneisses and migmatitic paleosomes is considered to be older than ca. 940 My.

However, if the presence of a core in one of these grains (grain B with a plateau age of 946 ± 6 My) and rounded outlines of others (grains E, 959 ± 3 My and O, 947 ± 4 My) indicate that these grains are detrital, then the protoliths can be Neoproterozoic, similar to the Solanderfjellet schists in the NBH. Grain G (1063 My old) is evidently rounded and may be the youngest detrital grain so far obtained, though later Caledonian resorption origin of the outline is not negligible. To solve the problem of migmatization age, more detailed Cathode luminescence examination and ion microprobe spot analysis are needed.

Two age clusters may be recognized in the Grenvillian age range: ca. 950 My (metamorphism) and ca. 1080 My (igneous) phases, consistent with the zircon grains of the Solanderfjellet micaceous schist.

The age of the marbles overlying the schists and gneisses is unknown. However, they are involved in the same mesoscopic structures as the schists and gneisses and are included as enclaves in the granitic neosomes, hence their protolith age is considered to be Mesoproterozoic. No Neoproterozoic zircon age younger than 942 My has been obtained in the SBH.

Mesoproterozoic ages

An igneous event can be recognized from the ages of ca. 1320 My in the granitic neosome sample. This grain has a subhedral shape, due to either overgrowth or weak abrasion during sedimentation. A grain with the age of > 1509 My (grain K) belongs to an older thermal event.

A group of zircon grains with ages of ca. 1353 - 1370 My has been reported from the lower Devonian tuffites (Hellman et al. 1998; Table 1), suggesting Mesoproterozoic rocks below the surface of north-western SBH.

Latest Palaeoproterozoic and older ages

The age group of 1636 - 1750 My is another large zircon age population, constituting 33 % of obtained plateau ages. Grains older than 1636 My show rounded outlines (detrital features), while some are subhedral, due to various degree of overgrowth.

A notably high proportion of dated zircon grains are in this age range, similar to the same characteristics of the NBH and north-western Spitsbergen gneissose migmatites (Fig 6) (Balašov et al. 1996b; Ohta et al. 2002). Granitoids in the western half of Ny-Friesland, ca. 60 km east of the BHZ, are dated to ca. 1750 Mya (e.g. Gee et al. 1994; Johansson et al. 1995; Johansson & Larionov 1996). Such areas could be candidates for the sources of zircon grains with these ages.

Two Archean age groups can be seen among the obtained ages: ca. 2.6 - 2.8 Gya and ca. 3.6 Gya. A minimum age of >2.9 Gya was obtained from a migmatite neosome of Hamiltonbukta, north-western coast of Raudfjorden, ca. 1.5 km west of the Raudfjorden–Monacobreen Fault (Ohta et al. 2002). The oldest zircon age (grain Z, 3.6 Gya) from the granitic neosome sample is a relatively good plateau age; this is the oldest single-zircon age so far obtained in Svalbard.

Conclusions

The following general conclusions can be drawn from the single-zircon Pb ages obtained by this study and previous dating results.

(1) Zircon grains with Grenvillian ages constitute the largest population among the analysed grains, indicating thermal events in that period.

(2) Caledonian growth of zircon is limited to minor overgrowth on older grains.

(3) In the NBH, the sedimentary protoliths of the Richarddalen and Biscayarhuken units are Mesoproterozoic, while that of the Solanderfjellet schists of the Montblanc unit is Neoproterozoic. The correlation between the Solanderfjellet micaceous schists and the prototype Montblanc unit is questioned.

(4) The Richarddalen unit is intruded by the porphyritic granites, which were successively metamorphosed into augen gneisses and mylonites during the Grenvillian period.

(5) The Biscayarhuken unit was metamorphosed under low grade conditions during the Grenvillian period, as the cleavages are cut by the 955 My old granite, and has not experienced any higher metamorphism since that time, though it was involved in the Caledonian deformations.

(6) The protolith age of the schists, gneisses, migmatites and marbles in the SBH is possibly of Mesoproterozoic, although a Neoproterozoic age can not be ruled out, since the origin of the rounded shapes of the zircon grains is unclear.

(7) Extensive exposures of latest Palaeoproterozoic crystalline rocks are inferred to be the source areas of all the sedimentary protoliths.

(8) The population frequency of the obtained ages from the BHZ (Fig. 6a) is generally similar to that of the north-western Spitsbergen (Fig. 6b) (Ohta 1992; Balašov et al. 1996b; Ohta et al. 2002), but markedly different from the western half of Ny-Friesland, which comprise latest Palaeoproterozoic granitoids and lack Grenvillian rocks.

Acknowledgements.—The Swedish Museum of Natural History, Stockholm, kindly provided the isotopic analysis facility, and the Mineralogical–Geological Museum, University of Oslo, provided the bulk rock analyses. We have benefited from many critical discussions have been made by German and Russian colleagues who worked in this area. We are grateful to M. Bjornerud, Laurence University, Wisconsin, and Synnøve Elvevold, Norwegian Polar Institute, for language improvements. Many constructive comments and language corrections by the referees are also acknowledged.

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