Grenvillian single-grain zircon Pb age of a granitic rock from the southern island of Hesteskoholmen, Liefdefjorden, northwestern Spitsbergen, Svalbard

YOSHIHIDE OHTA and ALEKSANDR N. LARIONOV

Ohta, Y. & Larionov, A. N. 1998: Grenvillian single-grain zircon Pb age of a granitic rock from the southern island of Hesteskoholmen, Liefdefjorden, northwestern Spitsbergen, Svalbard. *Polar Research 17(2)*, 147–154.

A N–S trending, narrow zone of crystalline basement occurs from Biscayarhalvøya to Holtedahlfonna in northwestern Spitsbergen and is composed of various metasedimentary and igneous rocks, including granites. Previous isotopic age determinations on these rocks are by the K-Ar, Rb-Sr, $^{40}Ar/^{39}Ar$ and conventional zircon U-Pb method and yielded the Caledonian and Grenvillian ages. The single-grain zircon Pb evaporation method has recently been applied to solve complex problems and this is the first report by the method.

A granitic rock, syntectonically intruded into the phyllitic metasediments of the Biscayarhuken formation, which is the uppermost lithotectonic unit in the metamorphic rocks of the zone, was dated on four zircon grains, yielding a narrow age range from 955 ± 4 to 968 ± 9 Ma, 961 ± 4 Ma in average. This age of ca. 960 Ma is considered to be the age of intrusion, based on the occurrence and zircon morphology, which is roughly simultaneous with the formation of the phyllitic cleavages of the surrounding metasediments. The data obtained imply that the Caledonian events did not reset the Pb isotope system of zircon and major metamorphism occurred during the Grenvillian time in the Biscayarhuken formation, accordingly, the protolith age of the metasediments is Mesoproterozoic.

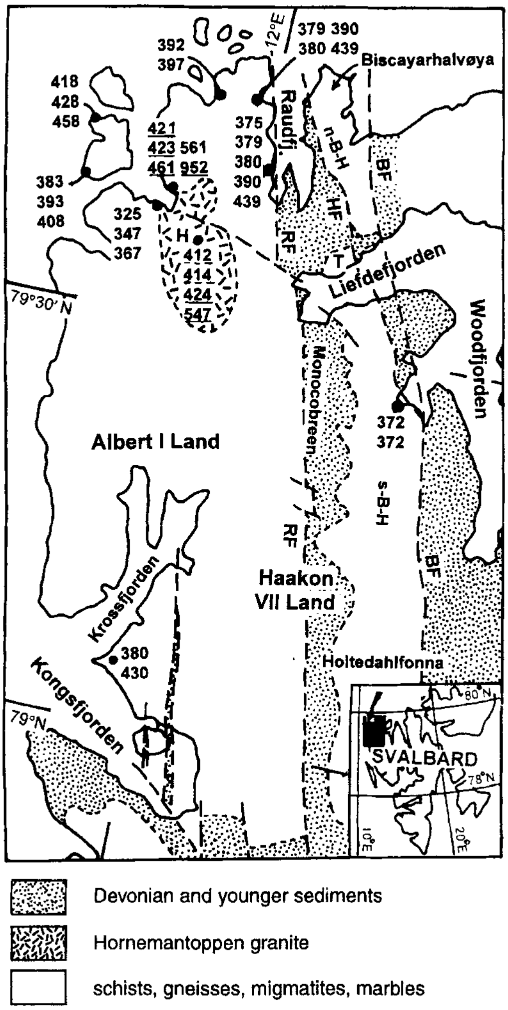
Y. Ohta, Norsk Polarinstitutt, P.O. Box 5072 Majorstua, N-0301 Oslo, Norway; A. N. Larionov, Laboratoriet für Isotopgeologi, Naturhistoriska Riksmuseet, Box 50 007, S-104 05 Stockholm, Sweden.

Introduction

The Precambrian event history of the crystalline basement of northwestern Spitsbergen has earlier been studied based on field observations and petrographical/petrological approaches. However, the time scale for the sequence of geological events has been weakly understood, except for the K-Ar and Rb-Sr ages of Caledonian thermal events (Gayer et al. 1966; Hjelle 1979; Ravich 1979). Isotopic age determination project to study pre-Caledonian history of the rocks was started in 1985, and several results have been published by Peucat et al. (1989), Dallmeyer et al. (1990a) and Balašov et al. (1996), mainly by the conventional U-Pb and $^{40}Ar/^{39}Ar$ methods (Fig. 1). The results suggested the presence of older zircons, possibly back to Archean time. Therefore, the single-grain zircon Pb evaporation method has been applied since 1996. This is the first report of ages obtained by this method from northwestern Spitsbergen.

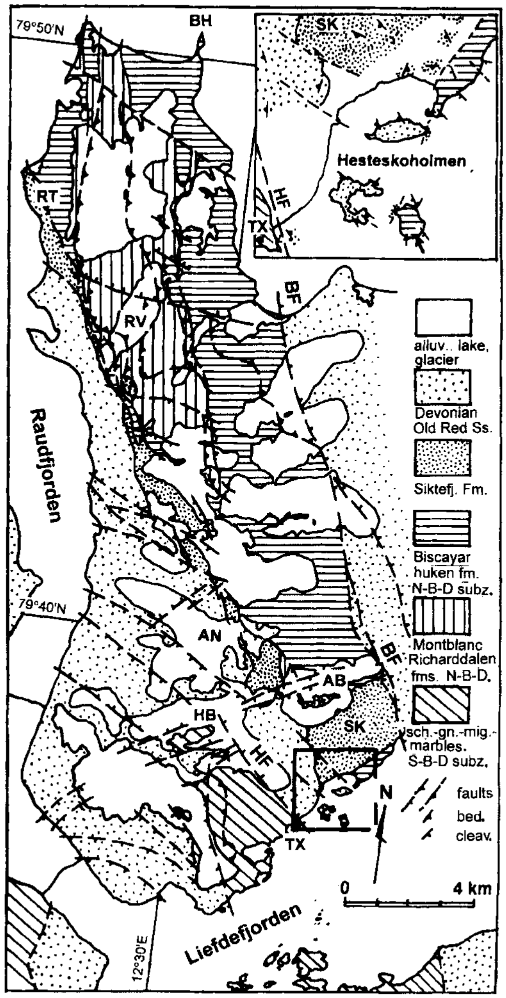
Geological outline

Pre-Devonian crystalline basement rocks are widely exposed in the north-western part of Spitsbergen, i.e. the area north of Kongsfjorden and west of Woodfjorden (Gee & Hjelle 1966; Hjelle 1979; Gjelsvik 1979; Hjelle & Lauritzen 1982). The area is separated by the N–S trending Raudfjorden Fault (RF; Fig. 1). To the west of the fault, a complex of schist-gneiss-migmatites occurs, while Devonian Old Red sandstones unconformably overlie the crystalline rocks in the east of the RF (Gee & Moody-Stuart 1966). The latter crystalline rock area is here referred to as the Biscayarhalvøya-Holtedahlfonna zone (B-H zone) (The place name Biskayerhalvøya has been changed to Biscayarhalvøya in recent maps; therefore, the geological terms including this place name are changed in this paper according to the recommendation of Norwegian Stratigraphic Committee).



BF: Breibogen Fault H: Hornemantoppen
HF: Hannabreen Fault T: Texas Bar hut
RF: Raudfjorden Fault
n-B-H: northern Byscayarhalvøya-Holtedalfonna subzone
s-B-H: southern Byscayarhalvøya-Holtedalfonna subzone

Fig. 1. Geological map of northwestern Spitsbergen, with previously published isotopic ages. The ages obtained from Biscayarhalvøya are not shown, but mentioned in the text.



Faults: BF: Breibogen Fault; HF: Hannabreen Fault
Place names from north to south:
BH: Biscayarhuken AB: Albertbreen
RT: Rivieratoppen HB: Hannabreen
RV: Richardvatnet SK: Siktefjellet
AN: Andréebreen TX: Texas Bar hut

Fig. 2. Geological map of Biscayarhalvøya and Hesteskoholmen (inserted map; the location is shown in the main map). The location of dated sample is shown by an arrow in the inserted map.

The B-H zone, a narrow N–S trending zone of ca. 10–15 km width and ca. 100 km in length, consists of lithologically different metamorphic rocks in the north (n-B-H subzone) and south (s-B-H subzone). The two subzones are separated by an oblique fault, the Hannabreen Fault (HF; Gee & Moody-Stuart 1966; Gjelsvik 1979), extending from Rivieratoppen in the north to Hannabreen in the south (Fig. 2).

The s-B-H subzone has a simple antiform structure with thick pelitic schists, gneisses and marbles on both western and eastern limbs and migmatites and granites along the crestal area. The metamorphic rocks, excluding the migmatites, show distinct brittle thrust duplex structures with an easterly vergence on both the northern and southern sides of Liefdefjorden. These rocks are separated from the Devonian sediments by steep faults on both the eastern and western sides and locally by an unconformity in the west.

The n-B-H subzone is also a horst, but more complex faults occur within the subzone. The metamorphic rocks show large scale thrust duplex structures, verging WSW. The metamorphic rocks have been grouped into three lithotectonic units, the Richarddalen group, Montblanc and Biscayarhuken formations (Gee 1966; Gee & Hjelle 1966; Dallmeyer et al. 1990a), in ascending order and are correlated with the three-fold divisions of caledonised metasediments in the schist-gneiss-migmatite area to the west of the RF.

The Biscayarhuken formation is bounded by moderately east-dipping reverse faults to the amphibolite facies gneisses of the Montblanc formation to the west (Fig. 2). It occupies the eastern half of the n-B-H subzone and consists mainly of phyllitic metasediments derived from psammo-pelitic clastic sediments, including quartzites, and a few marble layers. The exposures of these rocks are interrupted by the sedimentary cover of the Siktefjellet Group at Siktefjellet and reappear along the northern coast of Liefdefjorden.

The southern island of Hesteskoholmen in front of Hannabreen is composed of phyllitic metasediments, quartzite, similar to those of the northern coast of Liefdefjorden, and some interlayered amphibolites. The granitic rock dated in this work occurs in the phyllitic metasediments. Two other islands of Hesteskoholmen and a small sunken rock, ca. 100 m from the western coast of the bay are comprised of the Devonian conglomerates, while the exposures along the western coast of the bay and in the southwest of the alluvial fan of Hannabreen are strongly sheared marbles showing an E-verging duplex extending ca. 4 km to the west. These marbles are continuous to that of the s-B-H subzone across Liefdefjorden to the south, where marbles and pelitic schists/gneisses show similar brittle duplex structures. Thus, the boundary between the s- and n-B-H subzones, the Hannabreen Fault, should be located between the small sunken rock and the coastal exposures west of the bay.

The phyllitic metasediments are unconformably overlain by the basal conglomerates of the Siktefjellet Group on the northern slope of Siktefjellet. These are again overlain unconformably by the basal conglomerates of the Old Red Sandstones, the Wulffberget Formation (Murašov & Mokin 1976) in the eastern part of Andréebreen. The exact age of the Siktefjellet Group is unknown but should be the latest Silurian and/or earliest Devonian.

Previous age determinations

Gayer et al. (1966) reported eleven K-Ar ages from the northern part of Biscayarhalvøya. Metaeclogites and amphibolites from the Richarddalen group and the Montblanc formation yielded ages from ca. 530 to 1,940 Ma. Ages of 431 and 382 Ma were obtained from a biotite and a hornblende, respectively, from the schists of the Biscayarhuken formation. The localities were shown in figure 2 of Dallmeyer et al. (1990a).

$^{40}Ar/^{39}Ar$ datings were carried out by Dallmeyer et al. (1990a) on the rocks of the Montblanc formation and the Richarddalen group. The hornblendes of the Richarddalen group gave ages of ca. 505–538 Ma, while muscovites from the same group yielded ages of ca. 431 and 480 Ma. Ages of 442 and 439 Ma were obtained from the hornblendes of the Montblanc formation.

Rb-Sr age determinations were also made by the same authors, and the muscovite-whole rock systems of both the Richarddalen group and Montblanc formation gave similar age ranges of ca. 420–430 Ma, while biotite-whole rock systems show age range of 402–413 Ma. The difference in the ages between the two systems reflects the closure temperature of the systems, ca. 500°C for muscovite and ca. 300°C for biotite (Jäger 1979).

Conventional U-Pb age determinations and Sr and Nd isotope analyses were carried out by Peucat et al. (1989), using the samples from the Richarddalen group. A meta-porphyritic granite, mostly changed into augen gneisses with distinctive amount of garnet, yielded a lower intercept age of 965 Ma and an upper intercept age of 3.234 Ga, the latter with a large error. A corona gabbro showed an upper intercept age of 955 Ma. An eclogitic rock (Gee 1966) and a felsic neozome in a gneiss yielded zircon ages of 620 and 661 Ma, respectively. The last two ages were considered to be mixing age by Peucat et al. (1989).

Recent works of the sphene U-Pb ages and Pb evaporation ages of single-grain zircon ages by Gromet & Gee (in press) argued that the ages of 620–660 is a magmatic event associated with the rifting of paleo-Atlantic and that a high-grade metamorphism occurred in Middle Ordovician, ca. 455 Ma, approximately at the same time the high-pressure metamorphism was established in west-central Spitsbergen (Ohta et al. 1984; Dallmeyer et al. 1990b).

The Sr initial ratios and εNd suggest that the ages of 965 and 955 Ma are crustal reworking ages. These results, together with that of Dallmeyer et al. (1990a) are interpreted in a way that a distinctive igneous event occurred ca. 960 Ma ago, while the 3.2 Ga data suggest the presence of older detrital/inherited zircons.

The Caledonian thermal events up to ca. 500° – possibly subdivided into two phases, ca. 470 and 430 Ma as established in the west-central coast of Spitsbergen (Ohta 1992) – were superposed on all metamorphic-igneous rocks of the n-B-H subzone with different metamorphic grades on the rock units separated by WNW verging thrusts.

The dated rock

The dated granitic rock was collected on the southern shore of the southern island of Hesteskoholmen (Fig. 2). A dark-coloured conglomerate, probably belonging to the Siktefjellet Group, occurs at the northern tip of the island which is in contact with phyllitic metasediments by a NE striking steep fault. The phyllitic rocks are derived from sandy to shaley sediments and have strong cleavages defined by chlorite and sericite, striking NNW–SSE to N–S with dips of 30 to 60°W. Thin quartzite layers are interbedded in the northeast and at the southeastern to southwestern coasts, and thin schistose amphibolites occur at the northeastern and western coasts. These phyllitic metasediments with quartzites and amphibolites are very similar to those along the northern coast of Liefdefjorden, immediately to the east of Hesteskoholmen. The structures are also similar, though the strikes are more westerly on the northern coast. The lack of amphibolite is one of the lithological criterias of the Biscayarhuken formation (Gee & Hjelle 1966) which has not thoroughly been mapped in the southern n-B-H subzone. However, based on the assumption of structural continuity, these rocks are considered to be the southernmost exposure of the Biscayarhuken formation.

The dated granitic rock occurs in eight concordant/subconcordant layers each 1–3 m thick, in the sericite-chlorite phyllites on the southern coast of the southern island (Fig. 3). The rock is strongly sheared by brittle fractures emphasised by chlorite, showing spaced cleavages. Large feldspar grains, up to 1 cm long, are distinct in the hand specimens. The outlines of the granitic layers locally show low angle interfingering with the surrounding phyllitic metasediments along the margins. This suggests slightly oblique primary boundaries, though primary contact is completely disturbed by phyllitic cleavages. The development of a cleavage in the granitic rock is distinctly weaker than in the phyllitic metasediments.

Under the microscope, a primary coarse-grained mosaic of plagioclase and quartz has been granulated in an irregular network, locally showing weak preferred orientation. Biotite flakes were converted into green chlorite and aggregates of vermiculite and have been locally torn off into

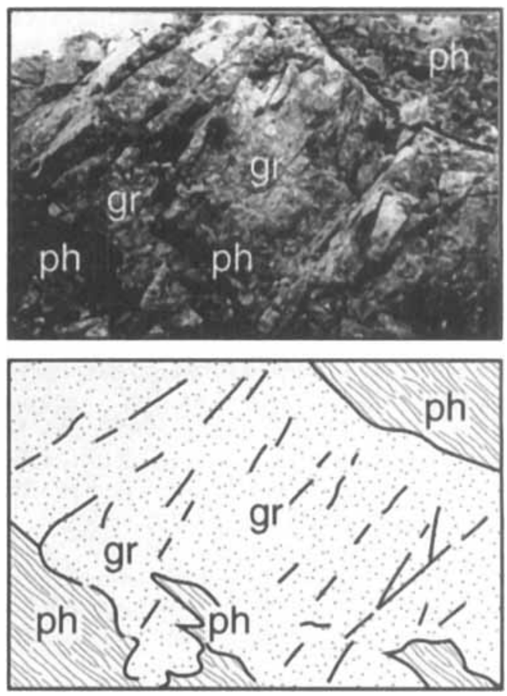


Fig. 3. Occurrence of the dated granitic rock, a photo and its sketch: gr = granitic rock; ph = phyllite.

Table 1. Modal (%) and chemical compositions (wt%) of the dated granitic rock.

Modal composition (%) of the dated granitic rock											
	qt	pl	K-f	mafics							
granulated part	38	49	5	8							
blastoporphyritic part	27	44	22	7							
Chemical composition (wt%, Fe_2O_3 = total iron)											
SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	Total
74.18	0.29	12.33	2.46	0.04	0.38	1.24	4.89	2.33	0.07	1.54	99.75

small flakes showing a cleavage. Large grains of K-feldspar with C-twins and local myrmekitic margins are well preserved. Some large plagioclase grains show polysynthetic twins and are strongly saussuritised. Small idiomorphic apatite and zircon grains occur scatteredly, and pyrite and carbonates are secondary minerals. The granulated parts of the rock apparently have granodioritic modal compositions and the identification of plagioclase and K-feldspar is not accurate: While the blastoporphyritic parts have quartz monzonite composition, the bulk modal composition ranges from granite to granodiorite (Table 1). The chemical composition is a calcalkalic, peraluminous granite and has moderate K_2O, I type characteristics (Chappell & White 1974). The rock plots in the field of Post Orogenic granites in the SiO_2-FeO/FeO + MgO and SiO_2-Al_2O_3 diagrams of Maniar & Piccoli (1989) (Table 1). A weaker cleavage development than that in the surrounding phyllitic rocks is confirmed by microscopic observations.

The locality of these rocks is situated ca. 1 km east from the supposed position of the Hannabreen Fault between the n-B-H and s-B-H subzones. The overlying Devonian conglomerates show different bedding directions from place to place in the two northern islands. This means that the Hannabreen fault moved later than the deposition of the Devonian sediments and some brittle deformation might have occurred around this area, resulting a part of the cataclastic texture of the granitic rocks.

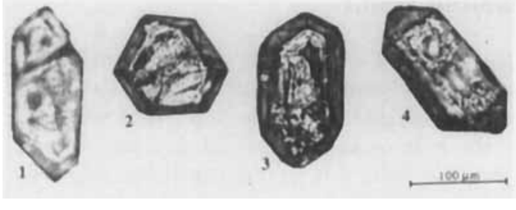


Fig. 4. Dated zircon grains.

The occurrence and petrography of the granitic rock suggest that the rock intruded subconcordantly along the cleavage surfaces of the phyllitic metasediments, while later brittle shearing gave the rock cataclastic, gneiss-like texture. It is considered that the intrusion occurred during or in a later time of the development of phyllitic cleavages. Therefore, the age of the granitic rock is expected to define the youngest limit of the metamorphic/deformation event of the Biscayarhuken formation.

Zircons

Zircon grains were separated by standard techniques, using the Wilfley table, heavy liquids and the Frantz isodynamic separator. The morphology and structure were examined under the optical microscope. Four zircon grains, most transparent, less fractured and inclusion-free grains, were hand-picked for the single-grain isotopic analysis (Fig. 4).

The analysed zircon grains are non-magnetic, sub- and euhedral, short to moderately prismatic in outlines, with pink to light brown colours. Most grains have facets of (100) and (101), with or without (110) and (221). Grains 2 and 3 are flat in shape. The surfaces are usually smooth. Ideomorphic oscillatory zoning concordant to the crystal outline is clearly seen. No discordant core has been observed. Small black flakes and transparent inclusions are common. Grain 1 is fractured. These characteristics of the zircon grains imply a magmatic origin.

Analytical notes

The step-wise, single-grain zircon Pb-evaporation method was applied, following standard techniques of Kober (1986; 1987). All analyses were

Table 2. Isotopic data. Abbreviations: M, moderately prismatic; S, short prismatic, ft: flat shape; P = pink, lB = light brown, T = transparent, F = fractured, Z = zoned, +Ib = with black inclusions; +It = with transparent inclusions.

	Biweight mean on measured ratios[1]				
Step No + Number of scans	$^{206}Pb/^{204}Pb$	$\pm 2\sigma\%$	$^{207}Pb/^{206}Pb$	$\pm 2\sigma\%$	Age, Ma $\pm 2\sigma$[2]
Grain 1: moderat. prism., pink, transp, fract., black inclus., ?zoned					
2 + 20	20000	8.0	0.07192	0.15	963 ± 4.0
3 + 20	32400	15.0	0.07203	0.28	974 ± 7.0
4 + 20	28700	18.0	0.07118	0.24	947 ± 6.0
5 + 20	61400	13.0	0.07154	0.18	966 ± 4.0
6 + 20	16900	9.0	0.07212	0.18	965 ± 4.5
7 + 20	44800	7.0	0.07160	0.21	965 ± 4.5
8 + 20	37000	14.0	0.07139	0.17	957 ± 4.0
Weighted average					**962 ± 6.5**
Grain 2: short prism., light brown, flat, transp, fract.					
1 + 10	2740	9.0	0.07608	0.54	952 ± 5.5
3 + 20	6340	9.0	0.07368	0.27	970 ± 7.0
4 + 20	11900	10.0	0.07217	0.54	954 ± 9.5
Weighted average					**959 ± 13**
Grain 3: moderat. prism., pink, flat, transp, fract., black inclus., zoned					
1 + 20	7920	10.0	0.07277	0.36	956 ± 6.5
2 + 10	34200	9.0	0.07193	0.26	973 ± 6.5
3 + 10	27200	10.0	0.07252	0.32	985 ± 6.0
4 + 10	6110	5.4	0.07335	0.15	958 ± 5.0
5 + 20	40800	6.0	0.07187	0.17	972 ± 3.0
6 + 20	17810	4.3	0.07206	0.21	965 ± 4.5
7 + 20	43600	13.0	0.07150	0.22	965 ± 4.5
Weighted average					**968 ± 9.0**
Grain 4: moderat. prism., pink, flat, transp, fract., transp. inclus.					
1 + 20	830	36.0	0.07953	0.54	952 ± 17
2 + 10	7640	11.0	0.07304	0.48	962 ± 10
3 + 20	44000	25.0	0.07124	0.39	954 ± 9.0
4 + 20	390000	35.0	0.07131	0.29	956 ± 6.0
5 + 20	370000	46.0	0.07129	0.67	944 ± 12
Weighted average					**955 ± 4.0**
		Average of the four grains			**961 ± 4.0**

[1]Results shown in the table are biweight mean of measured ratios scan-by-scan, error is sown in percentage as 2σ;
[2]Age for each step calculated as biweight mean on the scans. Age for each grain and for that of the whole population are weighted average on the step results.

performed at the Laboratory for Isotope Geology (LIG), Swedish Museum of Natural History, using a Finningan MAT 261 mass-spectrometer.

Data were collected in a peak-jumping mode, using a secondary electron multiplier in a sequence of ^{206}Pb-^{207}Pb-^{208}Pb-^{206}Pb-^{204}Pb. No correction for mass-fractionation was made. The correction for common lead was done using the measured $^{206}Pb/^{204}Pb$ ratio and initial lead isotope ratios of Stacey & Kramers (1975).

The lead emission was observed at temperatures of ca. 1470–1520°C. Scan-by-scan data were recorded and the age for each scan was calculated, using the software designed by Torsten Persson at the LIG. The age for each evaporation step has been calculated as Biweighted Mean of 10 to 20 scans, applying the Histogram procedure of the 'ISOPLOT' program of Ludwig (1991) with the tuning constant 6 to decline outliers out of 6σ error limit. The age of each grain and the age of the zircon population have been calculated with Weight Average procedure of the 'ISOPLOT' (Ludwig 1991), using the results from all evaporation steps of the four zircon grains.

Dating results

The results of the analyses are shown in Table 2 and Fig. 5. None of the analysed grains shows an increase of age from step to step. This implies that if the host rocks experienced any later thermal overprint, there was no thermal/fluid-acting event high enough to reset the U-Pb isotope system of the zircons after the crystallisation of these grains.

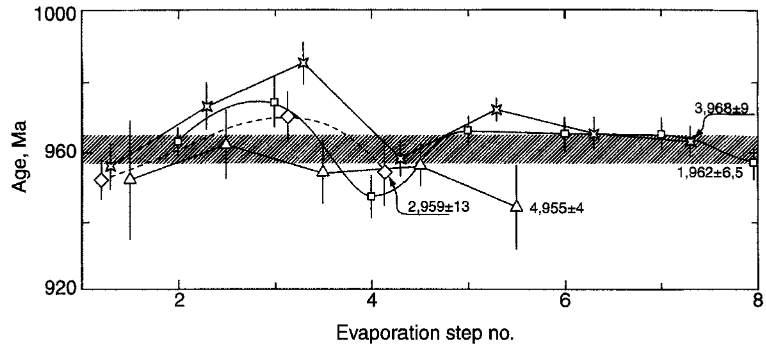


Fig. 5. Step evaporation diagram. First number before comma refers to Fig. 4. Shadowed area gives average of the four grains.

Some upward scattering of the results, e.g. grains 1 and 3, may suggest the presence of older (inherited) domains within the grains, though no recognisable discordant core has been noted. the lower age of grain 4 may have resulted from partial lead loss due to its metamict structure.

The ages obtained are: grain 1: 962 ± 6.5 Ma (7 steps), grain 2: 959 ± 13 Ma (3 steps), grain 3: 968 ± 9 Ma (7 steps) and grain 4: 955 ± 4 Ma (5 steps). The biweighted mean of 21 steps, excluding grain 3 scan 3 due to a large deviation, from all four grains is 961 ± 4 Ma.

Interpretation of the results

The phyllitic rocks surrounding the dated granitic rock are considered to be part of the Biscayarhuken formation, the uppermost structural unit of metamorphic rocks in the n-B-H subzone. The granitic rock intruded into the phyllitic rocks and the primary igneous texture was converted into cataclastic gneissose textures subsequent to the formation of the cleavages in the phyllitic rocks. Petrographic and field observations suggest that the granitic rock was emplaced subconcordantly along the cleavages of phyllitic rocks as locally oblique sheets. The morphology and structure of the analysed zircon grains do not show any clear evidence of abrasion by detrital processes and their concentric zonal structures suggest a magmatic origin; therefore, the obtained ages, 961 ± 4 Ma in average, are considered to be the age of intrusion.

Accordingly, it is concluded that the formation of the phyllitic cleavages of the Biscayarhuken formation is older than, or simultaneous with, the intrusion age of the granitic rock, ca. 960 Ma. This is consistent with the igneous ages obtained from the metagranite and corona gabbros from the north of Richardvatnet by Peucat et al. (1989). The age of the sedimentary protoliths of the metamorphic rocks of the Biscayarhuken formation in the n-B-H subzone is Mesoproterozoic.

No evidence of supposed rift-related igneous activity around 620–660 and high-grade metamorphism around 455 Ma argued in the rocks of the Richarddalen group by Gromet & Gee (in press) can be detected in the zircon grains studied in this work, and the conditions during the Caledonian events were not high enough to reset the U-Pb isotope system of zircon in the Biscayarhuken formation. This implies that the thrust duplex structures presently observed within the n-B-H subzone were developed after the Middle Ordovician metamorphic event of Caledonian.

Acknowledgements. – Laboratory for Isotope Geology, Swedish Museum of Natural History kindly offered the opportunity to carry out isotopic analyses. The field information given by A. N. Sirotkin and A. M. Teben'kov, Polar Marine Geological Expedition, Lomonosov, Russia, and T. Gjelsvik of Norwegian Polar Institute is deeply acknowledged.

References

Balašov, Ju. A., Peucat, J. J., Teben'kov, A. M., Ohta, Y., Larionov, A. N. & Sirotkin, A. N. 1996: Additional Rb-Sr and single-grain zircon datings of Caledonian granitoid rocks from Albert Land, northwest Spitsbergen. *Polar Res. 15(2)*, 153–165.

Chappell, B. W. & White, A. J. R. 1974: Two contrasting granite types. *Pacific Geol. 8*, 173–175.

Dallmeyer, R. D., Peucat, J. J. & Ohta, Y. 1990a: Tectonothermal evolution of contrasting metamorphic complexes in northwest Spitsbergen (Biscayarhalvøya): Evidence from $^{40}Ar/^{39}Ar$ and Rb-Sr mineral ages. *Geol. Soc. Am. Bull. 102*, 653–663.

Dallmeyer, R. D., Peucat, J. J., Hirajima, T. & Ohta, Y. 1990b: Tectono-thermal chronology within a blueschist-eclogite complex, west-central Spitsbergen, Svalbard: Evidence from $^{40}Ar/^{39}Ar$ and Rb-Sr mineral ages. *Lithos 24*, 291–304.

Gayer, R. A., Gee, D. G., Harland, W. B., Miller, J. A., Spall, H. R., Wallis, R. H. & Winsnes, T. S. 1966: Radiometric age determinations on rocks from Spitsbergen. *Norsk Polarinst. Skr. 137*, p. 39.

Gee, D. G. 1966: A note on the occurrence of eclogite in Spitsbergen. *Norsk Polarinst. Årbok 1964*, Oslo. 240–241.

Gee, D. G. & Hjelle, A. 1966: On the crystalline rocks of northwest Spitsbergen. *Norsk Polarinst. Årbok 1964*, Oslo. 31–45.

Gee, D. G. & Moody-Stuart, M. 1966: The base of the Old Red Sandstone in central north Haakon VII Land, Vestspitsbergen. *Norsk Polarinst. Årbok 1964*. 57–68.

Gjelsvik, T. 1979: The Hecla Hoek ridge of the Devonian graben between Liefdefjorden and Holtedahlfonna, Spitsbergen. *Norsk Polarinst. Skr. 167*, 63–71.

Gromet, L. P. & Gee, D. G. in press: An evaluation of the age of high-grade metamorphism in the Caledonides of Biskayerhalvøya, NW Svalbard. *Geol. For. Förhandl.* 120.

Hjelle, A. 1979: Aspects of the geology of northwest Spitsbergen. *Norsk Polarinst. Skr. 167*. 37–62.

Hjelle, A. & Lauritzen, Ø. 1982: Geological map of Svalbard 1:500,000, sheet 3G Spitsbergen, northern part. *Norsk Polarinst. Skr. 154-C*, 1–15.

Jäger, E. 1979: Introduction to geochronology. In Jäger, E. & Hunziker, J. C. eds. *Lectures in isotope geology. 1-12*. Springer Verlag, Berlin, Germany.

Kober, B. 1986: Whole-grain evaporation for $^{207}Pb/^{206}Pb$-age-investigations on single zircons using a double-filament thermal ion source. *Contr. Miner. Petrol. 93(4)*, 482–490.

Kober, B. 1987: Single-zircon evaporation combined with Pb+emitter bedding for $^{207}Pb/^{206}Pb$-age investigations using thermal ion mass-spectrometry, and implications to airconology. *Contr. Miner. Petrol. 96(1)*, 63–71.

Ludwig, K. R. 1991: ISOPLOT – a plotting and regression program for radiogenic isotope data, version 2.56. *U.S. Geol. Surv. Open File Rep.*, 91–445.

Maniar, P. D. & Piccoli, P. M. 1989: Tectonic discrimination of granitoids. *Bull. Geol. Soc. Am. 101*, 635–643.

Muravšov, L. G. & Mokin, Ju. I. 1976: Stratigrafičeskoe rasčlenenie devonskih oženij o. špicbergen. (Stratigraphic subdivision of Devonian deposits of Spitsbergen) In: *Geologija Sval'barda*. Leningrad. 78–91.

Ohta, Y. 1992: Caledonian and Precambrian history in Svalbard: a review, and an implication of escape tectonics. *Tectonophysics 231*, 183–194.

Ohta, Y., Hiroi, Y. & Hirajima, T. 1984: Additional evidence of pre-Silurian high-pressure metamorphic rocks in Spitsbergen. *Polar Res.*, N.S., 1, 215–218.

Peucat, J. J., Ohta, Y. & 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.

Ravich, M. G. 1979: Is there an early Precambrian granite-gneiss complex in northwestern Spitsbergen. *Norsk Polarinst. Skr. 167*, 9–28.

Stacy, J. S. & Kramer, J. D. 1975: Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth Planet Sci. Lett. 26*, 207–221.