Additional Rb-Sr and single-grain zircon datings of Caledonian granitoid rocks from Albert I Land, northwest Spitsbergen

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Previous K-Ar and Rb-Sr datings of the metamorphic and granitic rocks from the northwestern basement region of Spitsbergen mainly show the cooling time of the rocks, except for a Rb-Sr isochron age of the Hornemantoppen granitoid. New samples were collected during several years of geological mapping in the area and the Rb-Sr whole rock isochron and single-grain zircon evaporation methods were applied to the Hornemantoppen granitoids and the grey granites. A dioritic dyke was also dated by the latter method. The bulk rock chemistry study shows that most of both granitic rocks are of the S-type and probably post orogenic, with distinctive incorporation of crustal materials. The isotopic data also support this interpretation. The results of the Rb-Sr isotope analyses, 412 ± 4.8 Ma and the zircon Pb evaporation age of 424 ± 56 Ma, confirm the previous age of the Hornemantoppen granitoid, 414 ± 10 Ma. An older zircon age of 547 ± 19 Ma is considered to be the minimum age of inherited zircon. Zircons from the grey granites suggest an age of ca. 420 Ma with a large error. Field relations demonstrate that the grey granites are older than the Hornemantoppen granitoids. A minimum inherited zircon age, 952 ± 20 Ma, has been obtained from the grey granites. Three multi-grain Pb ages, 423 ± 22 Ma (2 grains), 461 ± 42 Ma and 561 ± 93 Ma (the last two 3 grains) were considered to be mixed ages. Although no definitive evidence for the presence of Grenvillian granites in this area has been obtained in the present study, preliminary results from the multi-grain zircon evaporation method, carried out in the Russian laboratory at Apatity, infer Paleo- and Mesoproterozoic protoliths for the metamorphic rocks of northwestern Spitsbergen.

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Introduction

Three types of granitic rocks have been known for a long time (e.g., Darocher in Gaimard 1855; Blomstrand 1864; Schetelig 1912; Schenk 1937) in the northwestern part of Spitsbergen, north of Kongsfjorden and west of Raudfjorden-Monacobreen, within a widely developed gneiss-migmatite region (Hoel 1914; Holtedahl 1926; Orvin 1940; Gee & Hjelle 1966; Krasil'ščikov 1973; Hjelle 1974, 1979; Ohta 1969, 1974a, b; Abakumov 1976a, 1976b, 1979; Ravich 1979; Hjelle & Lauritzen 1982) (Fig. 1).

The schists, gneisses and migmatites, primarily Precambrian, in this area have been divided lithostratigraphically into three units by Gee & Hjelle (1966): the Generalfjella Formation, ca. 2 km in thickness, of marble and various schists; the Signehamna Formation, ca. 2–2.5 km in thickness, of thick schists and gneisses derived mainly from areno-argillaceous protoliths with some quartzites; and the Nissenfjella Formation, ca, 1.7 km in thickness, of various gneisses and migmatites including amphibolites.

Abakumov (1976b, 1979) made another division: the Smeerenburgfjorden series of gneisses and migmatites, corresponding to the migmatitic parts of the Nissenfjella Formation of Gee & Hjelle (1966), which is subdivided into the Waggonwaybreen suite and the Kollerbreen suite, and the Krossfjorden series which includes the rest of the lithostratigraphy of Gee & Hjelle. Both authors distinguished the post-orogenic Hornemantoppen granitoids which cut the gneisses and migmatites.

The metamorphic and migmatitic rocks have


88.6°N
11°E
12°E
Amsterdamøya
16-1
Smeereburgfjorden
Svitjodbreen
Smithbreen
Raudfjorden
Ayerfjorden
88.5°N
Danskøya
15-1
SPZ-3
SPZ-4
Bjørnfjorden
14-1
SPZ-5
88.4°N
Reuschhalvøya
14-5
Magdalenefjorden
Smeerenburgbreen
Horneman
14-4
toppen
Raudfjordbreen
15-2
Waggonwaybreen
14-3
14-8
Hoelhalvøya
88.3°N
14-7
14-2
14-6
Sjettebreen
Becquerelbreen
15-3
88.2°N
20-1
Lilliehöökbreen
20-2
Nissenfjella
Cailletetbreen
80 N
SVALBARD
78 N
10 E
20 E
20-3
0
5 km
88.1°N
Lilliehöök
fjorden
15-4
15-5

recorded a complex deformation history in their structures (Hjelle 1974; Ohta 1969, 1974a) and the young enveloping fold structures of Caledonian in age are large scale asymmetric open antiform and synform, probably westwards of vergence, the axes of which plunge gently to the south, with the deeper rocks exposed in the north (Gee & Hjelle 1966; Hjelle 1979). Detailed petrological studies on the marbles by Bucher-Nurminen (1981) and pelitic gneisses by Klaper (1986) showed that the highest metamorphic conditions were 4-6 kb and 600–700°C. Ohta (1974b) also obtained 5.5 kb and 650–700°C. Based on the occurrences of relict kyanite and staurolite, the latter mineral inferred from clusters of a corundum-spinel-cordierite-biotite assemblage (Ohta 1974a), it was considered that the prograde process of metamorphism was of the intermediate-pressure facies series, which was superimposed by high-temperature series reactions (Ohta 1974a; Klaper 1986).

Four main types of granitoid rocks have recently been recognised in this area: (1) concordant layers and veins of foliated granitic-aplitic rocks and the neozomes of the migmatites; (2) gneissose granites containing strongly stretched gneiss-quartzite inclusions; (3) unfoliated grey granites, locally discordant to the schists, gneisses and migmatites; and (4) a batholith of massive, pink-coloured granitoid rocks, intruding all three types mentioned above. In addition there are various small dykes cutting the gneiss-migmatites.

The bulk rock composition and texture of type (1) granitic rocks show gradational transitions both to the migmatite neozomes and to type (3) grey granites (Hjelle 1974; Ohta 1969, 1974a, b). Type (4) Hornemantoppen granitoids are petrographically biotite-bearing monzonogranites and granites (Streckeisen 1976) with or without hornblende (Hjelle 1974). These three granitoid rocks mentioned above have been known before. Type (2) gneissose granites, newly distinguished, have not been studied chemically, while field evidence shows that they are intruded by the grey granites.

Numerous small dykes and veins of granitic, dioritic, aplitic and pegmatitic compositions occur in this area, type (5), in addition to the main granitoid rocks. Some of the dykes and veins cut the gneiss-migmatites and various granitoid rocks, while some others were deformed together with the host rocks, showing different stages of emplacement.

Petrography of the analysed samples

The dated grey granites and Hornemantoppen granitoids were analysed together with some additional samples from scattered localities for their bulk rock chemical compositions, at the Chemical Laboratory of Kola Science center in Apatity, Russia.

Grey granites

Samples 15-1–15-5 are grey granites from various localities over a wide area, as shown in Fig. 1. Samples SPZ-3 and SPZ-4, used for zircon dating, are from the same locality as 15-1.

The grey granite bodies have mostly concordant, locally discordant, but sharp contacts to the gneiss-migmatites, and the shapes of these bodies are slightly oblique to the structure of the surrounding rocks. The rocks are heterogenous biotite-bearing granodiorite to granite in composition and locally have plagioclase phenocrysts up to 3 cm in length. Rare seams of dark gneissic materials are included.

Sample 15-1 is a coarse-grained biotite granite, having cataclastic texture, containing plagioclase and quartz, both 30%, and K-feldspar and biotite, each about 10%. A few grains of amphibole are also recognised. Secondary chlorite, sericite and zoisite occupy about 15%. Zircon, apatite and barite are accessory minerals.

Samples 15-2, 15-3 and 15-5 are similar to one another and contain 15% K-feldspar, as much as 40% plagioclase (An_{15}), 30% quartz, 10% biotite and 5% hornblende. Zircon, apatite, orthite and sphene are accessories and biotite is locally chloritised. The rocks have a medium-grained, massive mosaic texture.

Sample 15-4 is a medium-grained biotite granite, having 30% each of K-feldspar, quartz and plagioclase (An_{20}) and about 10% biotite. The

Fig. 1. Distribution of the granitoid rocks in northwestern Spitsbergen, with the locations of the analysed samples. Key: Black = grey granites; cross-lined = Hornemantoppen granitoids; dotted areas = schists, gneisses and migmatites; open areas = glaciers; bloken curve = fault.

biotite is completely converted into chlorite and accessories are zircon, apatite, orthite and sphene.

Hornemantoppen granitoids

The dated samples 14-2–14-8 are from various localities in the Hornemantoppen granitoid massif (Fig. 1). These granitoid rocks cut the grey granites and gneiss-migmatites and locally contain angular xenoliths of gneiss-migmatites.

Sample 14-1 is from the northern coast of Bjørnfjorden and is a pink coloured, medium- to coarse-grained rock, similar to the Hornemantoppen granitoids. However, the clearly recognisable boundary between the grey granites and the Hornemantoppen granitoids has been observed about 2 km east of this locality along the northern margin of Smeerenburgbreen. The rocks near the northern boundary of the Hornemantoppen granitoid massif around the locality of sample 14-1 are apparently similar and difficult to discriminate from the grey granites in the field. Sample 14-1 is considered as belonging to the Hornemantoppen granitoids in this article because of its pink colour, but it may be a mixture of the two granitoid rocks. Sample SPZ-5, used for the single-grain zircon dating, was collected from the same locality as 14-1.

Samples 14-3 and 14-5 are biotite granites similar to 14-1, with 50 modal % K-feldspar, 20% plagioclase (An_{15}–An_{20}), 20% quartz and about 10% biotite. Samples 14-1 and 14-5 have trace amounts of hornblende. Magnetite, apatite, sphene, zircon and monazite are common accessories and ilmenite is included in biotite. Chloritisation of mafic minerals and sericitisation of plagioclase with epidote-zoisite grains are often seen.

Sample 14-2 is a medium-grained, hornblende-biotite granite, with K-feldspar, zoned plagioclase (An_{25}–An_{30} in the core and An_{10}–An_{20} at the margin) and quartz equally at 30%, and 10% mafic minerals. Sphene, zircon, apatite and magnetite are accessories. 14-4 is similar to 14-2, but has no hornblende.

Sample 14-6 is a fine-grained, biotite aplitic rock with 60% K-feldspar, 18-19% plagioclase(An_{15}), 20% quartz and 1-2% biotite. Apatite, sphene and hornblende are accessories and biotite is often chloritised.

14-7 is a fine-grained, two-mica aplitic rock, with similar colour as the Hornemantoppen granitoids, having equal amounts (ca. 45%) of K-feldspar and plagioclase (An_{15}), 10% quartz and small amounts of micas. This sample was collected from a dyke cutting the gneiss-migmatites outside the Hornemantoppen granitoid massif to the south; therefore, it is incorporated in the chemical discussion, but not dated.

Sample 14-8 is a pale pink, fine-grained aplitic rock, consisting of roughly equal amounts (30%) of K-feldspar, plagioclase and quartz, with about 10% of biotite and muscovite aggregates. Muscovite exceeds biotite. The accessories are pyrite, apatite, zircon and magnetite. The magnetite grains are sometimes coated by hematite. Secondary minerals are not common, except for rare conversion of biotite into chlorite.

Dioritic dyke

Sample 16-1, dated by zircon, is a dioritic dyke cutting the migmatites on Amsterdamøya (Fig. 1). Dykes of similar composition cut the grey granites at many localities.

Other rocks not dated

Samples 20-1–20-3, which were not analysed isotopically, are from the grey granites to the south of the Hornemantoppen granitoid massif and were analysed for supplementary data of the bulk rock chemistry. Sample 20-1 is a medium-grained biotite granite containing roughly 30% each of K-feldspar, plagioclase (An_{20}–An_{25}) and quartz and 10% biotite. Magnetite, zircon apatite, fluorite and monazite are accessories. Secondary sericite occurs in K-feldsper and plagioclase grains are dusty with calcite and chlorite. Sample 20-2 lacks K-feldspar and is a quartz diorite. Sample 20-3 is similar to 20-1, but has as much as 40% of K-feldspar and about 20% of quartz.

Petrochemistry

Major element analyses of the rocks are shown in Table 1. The compositions of SPZ-3 and SPZ-4 are represented by that of 15-1, and SPZ-5 by 14-1.

The analysed samples are granite, monzonogranite and granodiorite on the Q-P diagram (Fig. 2) (Debon & Le Fort 1983). A trend of slightly higher P-values (K_2O contents) for the grey granites compared to the Hornemantoppen gran-

Table 1. Major element analyses of the granitoid rocks.

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	S	H_2O	Total
14-1	65.91	0.74	15.70	0.84	3.71	0.07	1.68	3.82	3.38	3.20	0.18	0.05	0.98	100.26
14-2	70.69	0.41	14.00	1.32	1.85	0.06	0.70	2.78	3.30	4.12	0.08		0.60	99.91
14-3	74.07	0.15	14.41	0.40	1.31	0.06	0.20	0.58	3.75	4.15	0.05		0.80	99.93
14-4	70.65	0.41	14.38	0.80	2.03	0.05	0.70	2.42	3.62	4.32	0.07		0.54	99.99
14-5	64.61	0.60	16.31	0.98	3.17	0.05	1.60	3.60	3.84	3.48	0.19		0.76	99.19
14-6	75.57	0.06	13.40	0.32	0.95	0.04	0.10	0.53	3.46	4.96	0.05		0.02	99.46
14-7	75.21	0.03	15.82	0.25	0.77	0.04	0.10	0.33	4.70	3.91	0.05		0.38	101.59
14-8	78.00	0.05	12.29	0.11	1.07	0.05	0.10	0.30	3.80	4.00	0.05		0.32	100.14
15-1	69.83	0.66	15.11	0.58	3.23	0.06	0.99	1.85	3.55	4.21	0.11	0.05	1.06	101.29
15-2	69.13	0.52	15.00	0.88	2.99	0.05	0.55	2.23	3.86	4.44	0.06	0.05	0.94	100.70
15-3	67.80	0.55	15.21	0.46	3.59	0.09	1.02	2.84	4.03	4.08	0.12		0.42	100.21
15-4	72.03	0.27	13.90	0.09	2.27	0.08	0.55	1.99	3.09	4.28	0.05		1.20	99.80
15-5	67.01	0.62	14.92	0.31	4.07	0.06	1.41	2.41	3.38	4.16	0.23		1.12	99.70
16-1	55.05	1.31	17.44	3.65	4.61	0.08	4.98	7.38	2.50	1.46	0.32	0.02	1.80	100.60
20-1	67.52	0.75	15.10	0.12	5.02	0.07	1.66	1.80	2.60	3.50	0.14		1.46	99.74
20-2	71.56	0.41	14.53	0.21	2.51	0.04	0.84	2.01	2.40	4.91	0.09		0.46	99.97
20-3	72.22	0.40	14.59	0.26	2.45	0.03	0.40	1.51	3.20	5.09	0.15		0.48	100.78

itoids is seen in this diagram. However, the grey granites have a wide variation of K_2O contents (Ohta 1974b, fig. 7) and this high K_2O tendency is only recognisable within the rocks analysed in this study. The high K_2O (3.2-4.9 wt%) and relatively low Na_2O contents (lower than 4.7 wt%) indicate that all rocks are S-type granites (Chappel & White 1974).

Most rocks plot along the eutectic valley between the albite and K-feldspar fields at various H_2O pressures on the normative Q-Ab-Or diagram (Fig. 3A).

All samples are calcalkaline on the AFM diagram (Fig. 3B), and belong to the high-K series (Fig. 4A) (Ewart 1976). The alkali-lime index is ca. 59 on the total alkalis-SiO_2 diagram (Fig. 4B). On the Sand's diagram (Fig. 5A) the majority of the analysed samples are peraluminous and plot in the CAG (continental arc granitoids) and CCG (continental collision granitoids) fields of Maniar & Piccoli (1989). Some rocks which plot in the metaluminous field contain various amounts of hornblende. The grey granites show a positive relation between the two ratios of this diagram, while the Hornemantoppen granitoids show a slightly negative trend. This difference is possibly caused by the hornblende contents in the latter.

Referring to various diagrams proposed by Maniar & Piccoli (1989), both types of granitic rocks fit with the fields of POG and IAG + CAG + CCG on the Al_2O_3 vs. SiO_2 (Fig. 5B), and with the fields of POG on the FeO* vs. MgO (Fig. 6A), FeO* + MgO vs. CaO (Fig. 6B) and FeO*/(FeO* + MgO) vs. SiO_2 (not shown in this article) diagrams. In Fig. 6B, the grey granites show a slightly negative trend, while the Hornemantoppen granitoids have a weak positive trend.

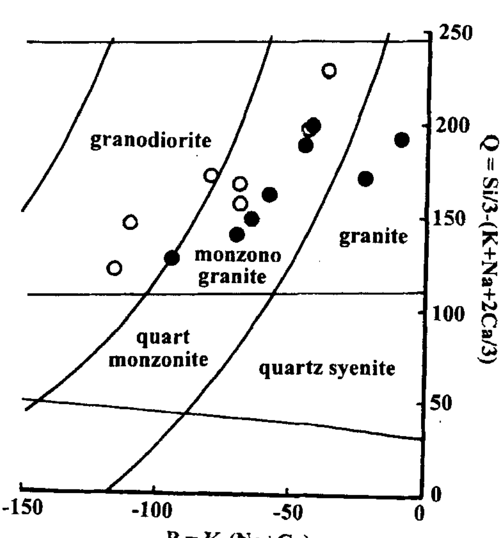

Fig. 2. Chemical classification of the analysed rocks on the Q-P diagram of Debon & Le Fort (1983). Legend (common for Figs. 2–6): solid circles = grey granites; open circles = Hornemantoppen granitoids.

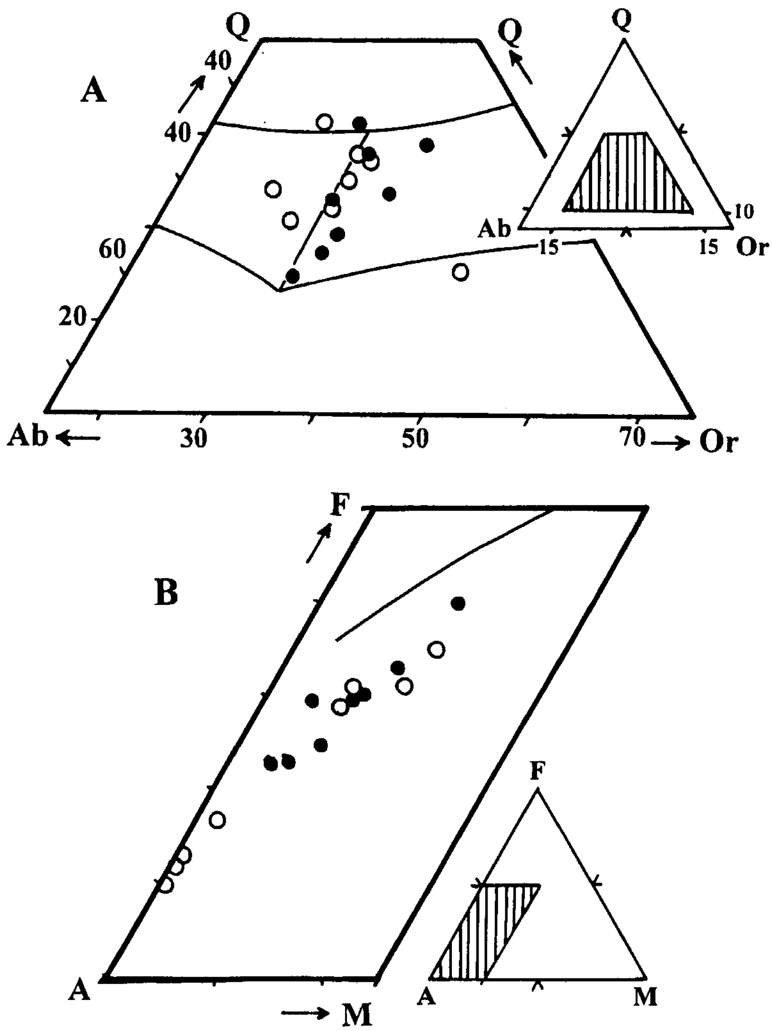

Fig. 3. Felsic and mafic ratios of the rocks. A: Normative Q-Ab-Or diagram. Solid curves are eutectic valleys at various H_2O pressures. B: AFM diagram. Solid curve: division of tholeiite and calcalkalic rocks (Irvine & Baragar 1971).

This is due to the larger amounts of hornblende in the latter, the same reason as in Fig. 5A.

Although there are slight differences between the grey granites and the Hornemantoppen granitoids in their bulk rock chemistry, the two types of granitoids have nearly the same composition and belong to similar differentiation trends typical for post-tectonic granitoids in their later stage.

Previous isotopic dating

The gneisses and migmatites in northwestern Spitsbergen have been considered as Caledonian products since the time of Holtedahl (1926). However, Krasil'ščikov (1973) and Abakumov (1976b, 1979) proposed that these rocks were the basement to the Caledonian rocks and are Paleoproterozoic Karelian basement reworked by Caledonian tectonothermal events.

K-Ar whole rock and biotite ages from this area were summarised by Gayer et al. (1966) and mainly fall in the range of 380-450 Ma, with the estimated main thermal event at around 430 Ma. The K-Ar biotite ages are around 400 Ma, and these ages and K-Ar whole rock ages in the range of 375-340 Ma are considered to be cooling ages. A Rb-Sr whole rock isochron age of the Hornemantoppen granite has been reported by Hjelle (1979) at 414 ± 10 Ma. Ravich (1979)

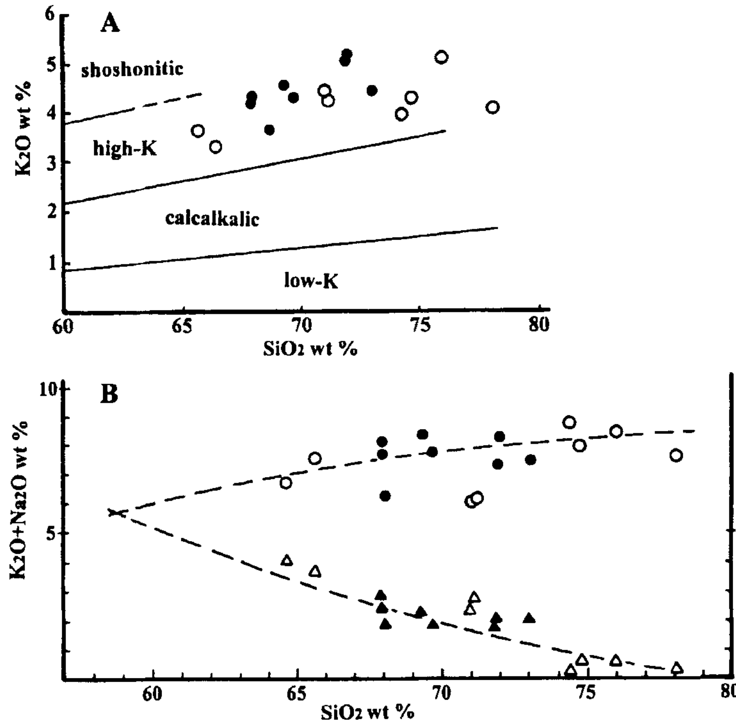

Fig. 4. Alkali contents of the rocks. A: K_2O vs. SiO_2 diagram. Division lines, Ewart (1976). B: Total alkalis and CaO vs. SiO_2 diagram. Circles = K_2O. Triangles = CaO.

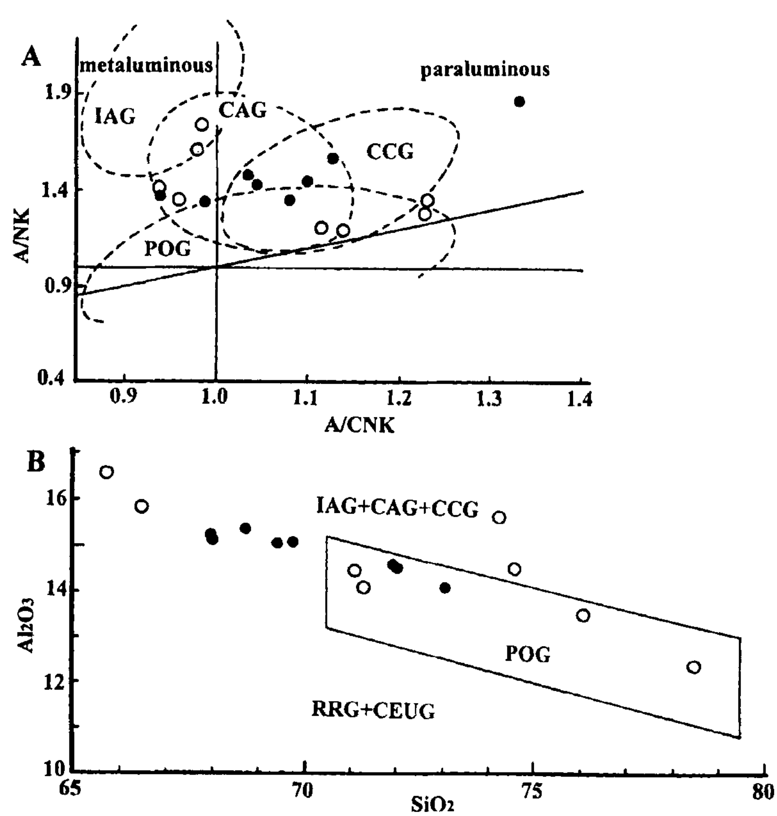

Fig. 5. Al_2O_3-contents of the rocks: A: Al-saturation of the rocks. A = Al, N = Na, K = K, C = Ca. CAG = continental arc granitoids, POG = post orogenic granitoids, CCG = continental collision granitoids, IAG = island arc granitoids (Maniar & Piccoli 1989). B: Al vs. SiO_2 diagram. Classification by Maniar & Piccoli (1989). RRG = rift-related granitoids, CEUG = continental epeirogenic uplift granitoids. Other abbreviations are the same as Fig. 5A.

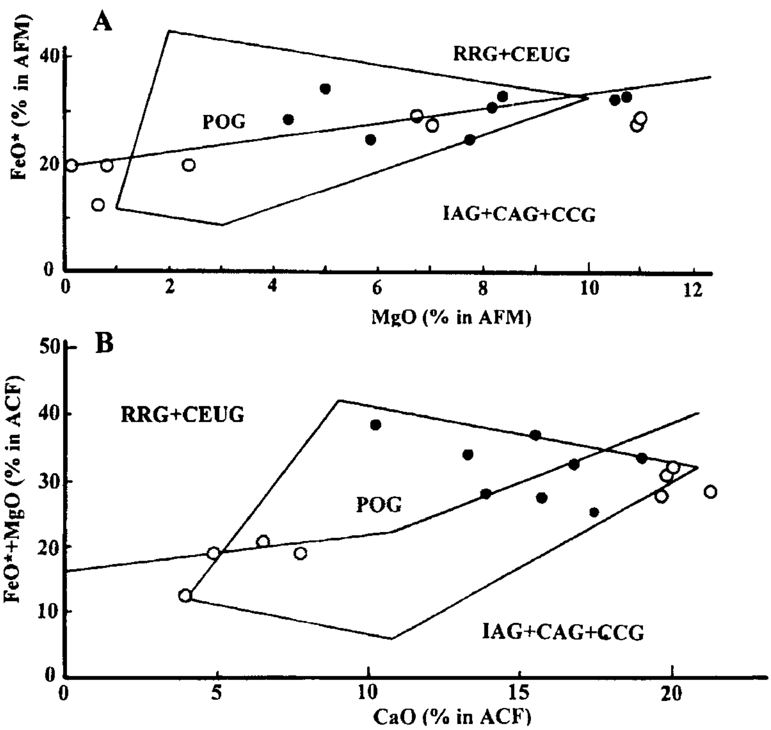

Fig. 6. Fe* (total Fe), Mg and Ca contents of the rocks. Abbreviations are the same as for Figs. 5A and B (Maniar & Piccoli 1989). A: FeO* vs. MgO diagram. B: FeO*+MgO vs. CaO diagram.

made two additional K-Ar whole rock datings on a gneiss and a leuco-granite from the north of Kongsfjorden, which gave ages of 430 and 380 Ma, respectively.

New datings

Rb-Sr dating

Five samples of the grey granites, 15-1 to 15-5, and seven samples of the Hornemantoppen granitoids, 14-1 to 14-6 and 14-8, were analysed by the whole rock Rb-Sr method.

Analytical method. – The whole rock samples were dissolved in HF and $HClO_4$ and residue was dissolved in HCl and put in a column with Dowex 50 × 3 (200–400 mesh) resin. The Sr isotope compositions were determined by the MI-1201-T mass-spectrometer at the laboratory of Kola Science Centre, Apatity, Russia. Rb and Sr blanks were 2 ng and 8 ng, respectively. Rb and Sr contents were determined by the XRF method. Analytical errors (2 sigma) are assumed to be 1.5% for $^{87}Rb/^{86}Sr$ and 0.04% for $^{87}Sr/^{86}Sr$. The age calculation was carried out using the program of Ludwig (1991).

Table 2. Rb and Sr isotope compositions. From the left to right: column 1, sample no.: columns 2 and 3, Rb and Sr contents in ppm.; column 5, 1.5% error; column 6, normalised to $^{86}Sr/^{88}Sr = 0.1194$; column 7, 2 sigma error in the last degits. Sample nos. 4- = Hornemantoppen granitoids; nos. 5- = grey granites.

No.	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	Error	$^{87}Sr/^{86}Sr$	Error
14-1	107	462	0.684	0.010	0.71251	10
14-2	149	293	1.412	0.021	0.71655	10
14-3	161	97	4.653	0.070	0.73573	13
14-4	162	278	1.621	0.024	0.71741	16
14-5	168	44	0.923	0.014	0.71477	9
14-6	168	44	10.525	0.158	0.77035	9
14-8	246	18	10.561	0.158	0.77045	20
15-1	165	168	2.727	0.040	0.73669	15
15-2	227	196	3.221	0.048	0.73116	13
15-3	236	332	1.982	0.030	0.71943	8
15-4	184	166	3.091	0.046	0.74486	12
15-5	132	498	0.740	0.011	0.71221	10

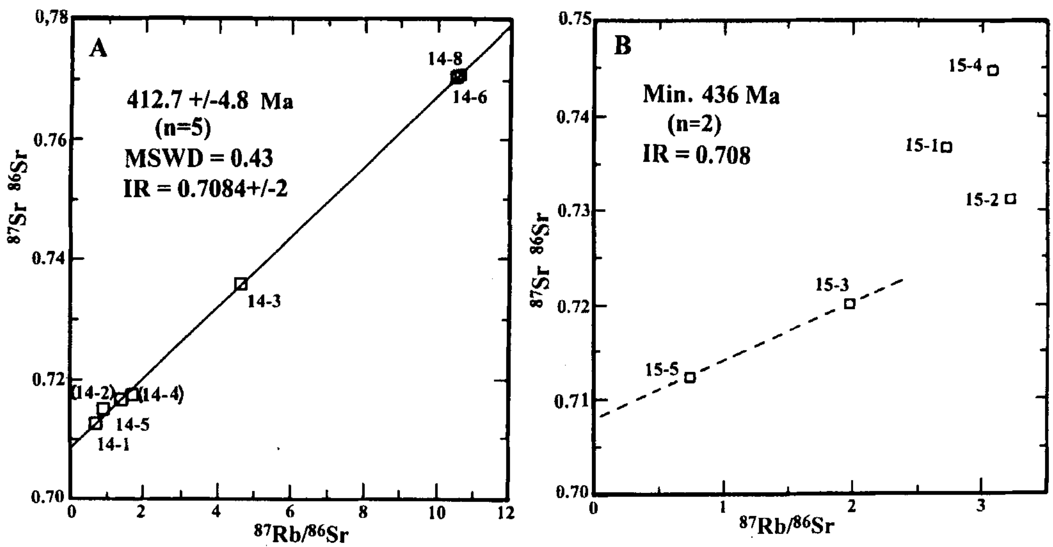

Fig. 7. Rb/Sr isotope diagrams. A: Hornemantoppen granitoids. Samples in parenthesis have been excluded from the age calculation. B: Grey granites.

Results. – Seven samples of the Hornemantoppen granitoids from various localities within the massif (Fig. 1) and five samples of the grey granites from widely separated localities were analysed and the results are shown in Table 2.

The age from all seven samples of the Hornemantoppen granitoids is 419 ± 11 Ma and MSWD is 4.43. Five samples excluding 14-2 and 14-4 provide a good isochron, giving an age of 413 ± 5 Ma with MSWD = 0.43, and the initial $^{87}Sr/^{86}Sr$ ratio = 0.7084 ± 2 (Fig. 7A). Sample 14-2 is slightly higher and 14-4 is slightly lower than the isochron for unknown reason and have been excluded from calculation.

The Rb-Sr isotopic results of the grey granites scatter widely and do not show any isochron (Fig. 7B). A line through points 15-3 and 15-5 only corresponds to an age of 436 Ma.

Single- and multi-grain zircon ages

Two grey granite samples, SPZ-3 and SPZ-4, one Hornemantoppen granitoid and one dioritic dyke rock, were analysed by the single- and multi-grain Pb evaporation method.

Analytical method. – The separated zircon grains were analysed by the Pb evaporation method described by Kober (1986) at the isotope chemistry laboratory of the University of Rennes, France, using the Cameca TSN 206 mass spectrometer. Correction for mass fractionation was 0.10% per AMU, following analyses of the NBS 981 and 983 standards. The common lead used for the correction had an isotopic composition corresponding to an age of 1,150 Ma, following the two-stage model of Stacey & Kramers (1975). Two steps of evaporation were made for each sample.

Results. – The analytical results are shown in Table 3 and Figs. 8A–8E. Sample SPZ-5 is tentatively considered to be a Hornemantoppen granitoid as mentioned for 14-1. This is not typical Hornemantoppen granitoids, however, it was only possible to collect a sample from this locality when we visited in 1985. Three morphotypes of zircon have been found in this rock: (1) elongated, euhedral grains having an overgrowth of an orange-pink coloured margin around a round core; (2) orange-transparent, euhedral crystals, similar to the overgrowth of morphotype 1, but without a core; and (3) round, orange-coloured crystals similar to the overgrowth of morphotype 1. Morphotypes 1 and 3 were analysed, the former provided a $^{207}Pb/^{206}Pb$ age of 547 ± 19 Ma (Fig. 8A) and the latter gave a age of 424 ± 56 Ma (Table 3; not shown in Fig. 8 because of large errors).

Sample SPZ-4 is a sample from the grey

Table 3. Pb isotope analyses. Column 2 from the left: first numbers are the number of analysis. Two-lettered abbreviations: eh = euhedral = st, stocky = el, elongated, or = orange, br = brown, yl = yellow, tr = transparent.

Sample	Analysis, Zircon	Step (ampere)	$^{206}Pb/^{204}Pb$ (measured)	$^{207}Pb/^{206}Pb$ (measured)	Error (2 sigma)	$^{207}Pb/^{206}Pb$ (corrected)	Age, Ma. ($^{207}Pb/^{206}Pb$)	Error (2 sigma)
SPZ-3	1: eh,el,yl,tr	2.7	676	0.0799	10	0.0589	561	62
	2: eh	2.7	est. 3000	0.0598	3	0.0553	423	11
	3: eh	2.8	9123	0.0577	4	0.0562	461	17
SPZ-4	1: eh,st,br,tr	2.9	2020	0.078	2	0.0708	952	7
SPZ-5	1: eh,el,or,tr	2.8	5422	0.0612	2	0.0585	547	9
	2: eh,el,or,tr	2.8	583	0.0799	8	0.0553	424	40
16-1	1: eh,br	2.6	16428	0.0563	3	0.0552	421	15
	2: eh,br	2.8	23000	0.0556	17	(not calculated)		

granites and the analysed zircon is a brown-coloured, stocky euhedral crystal, rich in inclusions and with a large core visible. The lead isotope age recorded is 952 ± 20 Ma (Fig. 8B).

Sample SPZ-3 is a grey granite and has zircons with yellow-transparent, euhedral shape, frequently having small, irregularly zoned cores. Due to the small size of the grains, several grains were used: one analysis with 2 grains and two analyses with 3 grains. The 2-grain analysis yielded an age of 423 ± 22 Ma (Fig. 8D), while the 3-grain analyses gave ages of 461 ± 42 Ma (Fig. 8C) and 561 ± 93 Ma (Table 3).

Sample 16-1 is a dioritic dyke rock. Analysis of one zircon gave an age of 421 ± 36 Ma (Fig. 8E).

Interpretation of the obtained ages

Hornemantoppen granitoids

The Rb-Sr age, 413 ± 5 Ma, shows a good agreement with the previously reported Rb-Sr age, 414 ± 10 Ma (Hjelle 1979).

Sample SPZ-5, a pink granite which was collected as a representative of the Hornemantoppen granitoids in the field, yielded two zircon ages, the younger one being 424 ± 56 Ma, which is in agreement with the Rb-Sr isochron age.

The older age obtained from a non-transparent single zircon grain of SPZ-5, 547 ± 19 Ma is considered to correspond to the minimum age of inherited zircon. The high $^{87}Sr/^{86}Sr$ initial ratio, 0.708, and the existence of a core in the zircon grain, indicate the incorporation of old crustal material during the formation of this granite.

Grey granites

The Rb-Sr data scatter widely. Calculations back to 450 Ma yielded initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.707 to 0.725, suggesting crustal contributions in the genesis of these rocks.

The oldest single grain zircon age, 952 ± 20 Ma, is interpreted to be an inherited zircon age. The old ages obtained by the 3-grain analyses of SPZ-3, 561 Ma and 461 Ma are uncertain with errors of ± 93 Ma and ± 42 Ma, respectively. However, they also suggest the existence of some inherited material. The 2-grain age of SPZ-3, 423 ± 22 Ma is considered to be less contaminated by inherited lead and thus closer to the crystallisation age of the zircon. The younger age obtained from SPZ-5, as well as the age obtained on the granodiorite dyke 16-1, are similar to this age, though both have large errors.

Discussion

Other preliminary studies of zircons have been carried out by the multi-grain Pb evaporation method at the laboratory of Kola Science Centre in Apatity, Russia, from the late 1980s, and the results were summarised by Teben'kov in 1993 (unpubl.). One sample from the Hornemantoppen granitoids from the same locality as samples 14-1 and SPZ-5 gave ages of ca. 780, 565 and 500 Ma. The last two ages are similar to the older age obtained from SPZ-5, while the first one is still older. Multi-grain analyses of zircon from the same locality as a grey granite sample 15-1 provided ages of 1,136 and 1,050 Ma, not far from the age of SPZ-4, which is from a different sample

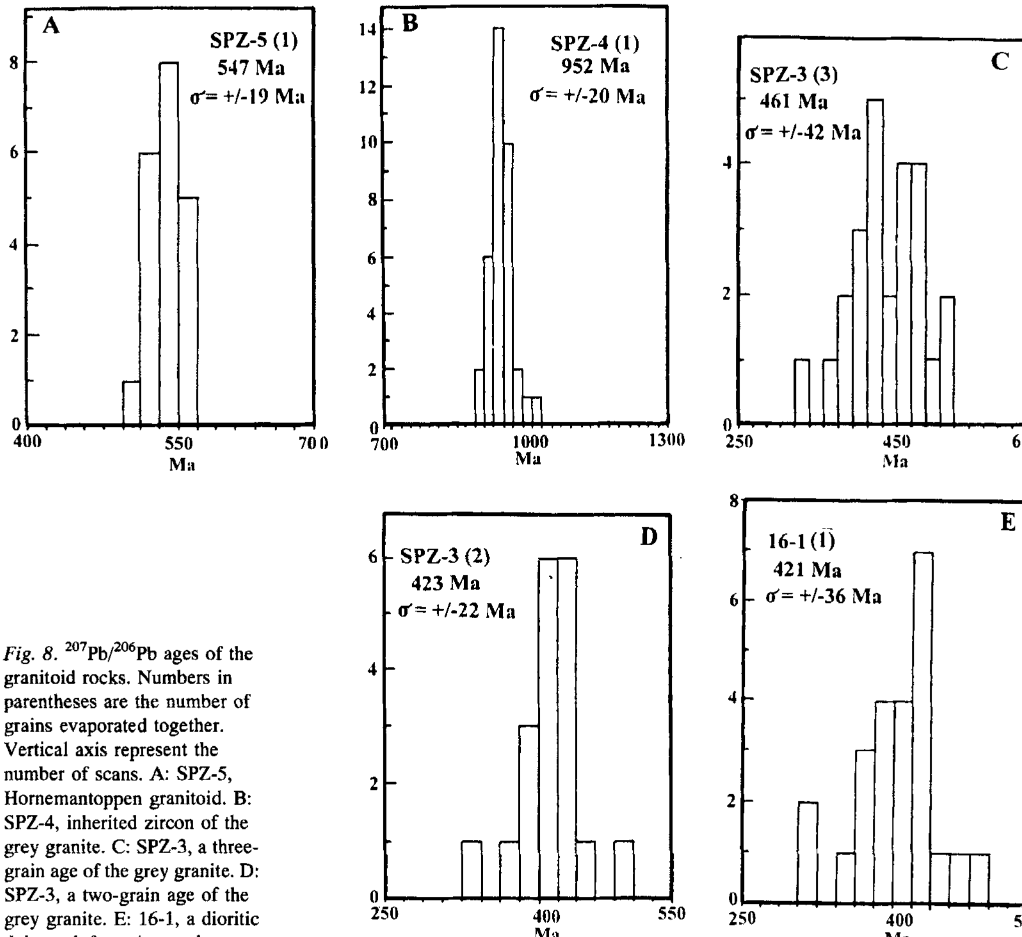

Fig. 8. $^{207}Pb/^{206}Pb$ ages of the granitoid rocks. Numbers in parentheses are the number of grains evaporated together. Vertical axis represent the number of scans. A: SPZ-5, Hornemantoppen granitoid. B: SPZ-4, inherited zircon of the grey granite. C: SPZ-3, a three-grain age of the grey granite. D: SPZ-3, a two-grain age of the grey granite. E: 16-1, a dioritic dyke rock from Amsterdamøya.

but from the same grey granite body. The relatively good agreement between these preliminary multi-grain analyses and the present results suggest that the former data are useful for general considerations at the present situation of knowledge where the amount of age data is very limited.

A weakly metamorphosed gabbro diorite from the same locality as sample 16-1, but from a different dyke, gave multi-grain evaporation ages of 502 and 445 Ma. These ages are higher than the present result, 421 ± 36 Ma, from 16-1. It is natural that the latter is a dyke.

Six multi-grain analyses were also attempted on the zircons from the schists of the Signehamna Formation to the east of Krossfjorden, resulting in ages ranging from 1,645 to 1,660 Ma. Six multi-grain evaporation analyses were made on zircons from the gneisses of the Kongsvegen Formation in the middle of Brøggerhalvøya to the south of Kongsfjorden, and the results gave a wide age range from 1,720 to 960 Ma. No younger age than 960 Ma has been obtained. These ages from both areas must be detrital zircon ages. These results from the schists and gneisses of the northwestern and western regions of Spitsbergen suggest that the provenance materials to the sedimentary protoliths of these metamorphic rocks are Paleo- to Meso-proterozoic in age, and that these rocks were first metamorphosed during the Grenvillian period, ca. 1,100 to 950 Ma ago.

Conclusions

Bulk rock chemistry of the analysed samples shows that both the grey granites and the

Hornemantoppen granitoids are S-type, continental, post-orogenic granitoids.

New Rb-Sr whole rock isochron age of the Hornemantoppen granitoids, ca. 413 ± 5 Ma, conforms with the previous result of Hjelle (1979). One of the single-grain zircon $^{207}Pb/^{206}Pb$ ages of the rocks is conformable with the Rb-Sr age within the error range, while the other suggests the presence of some inherited component.

The youngest single-grain zircon ages of the grey granites are identical, ca. 424 and 423 Ma, to that of the Hornemantoppen granitoids. while another grain indicates an minimum inherited age as old as ca. 950 Ma.

The dioritic dyke cutting the migmatites in Amsterdamøya has an age similar to the grey granites and is possibly older than the Hornemantoppen granitoids.

The present dating results, together with previous data, show that both types of granitoid rocks were emplaced during the Caledonian period, and the Hornemantoppen granitoids are younger than the grey granites based on observed cutting relation in the field, though the Rb-Sr and zircon data are identical. Although there is a single-grain zircon result from the grey granites, which suggests a Grenvillian age, pre-Caledonian basement has not been proven by the present data. The zircon grain showing a 952 ± 20 Ma age may be derived from deep-seated basement or from detrital grains in the protolith, and in both cases Grenvillian rocks must have existed within or near the area where these grey granites were formed. Peucat et al. (1989) reported a Grenvillian metamorphic age from Biskayerhalvøya, about 20 km east of the present area. Preliminary multi-grain zircon data also suggest Grenvillian and older basement in the northwestern Spitsbergen.

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