Rb-Sr whole rock and U-Pb zircon datings of the granitic-gabbroic rocks from the Skålfjellet Subgroup, southwest Spitsbergen

YU. A. BALAŠOV, J. J. PEUCAT, A. M. TEBEN'KOV, Y. OHTA, A. N. LARIONOV, A. N. SIROTKIN and M. BJORNERUD

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Recent remapping and new age determinations has shed light on the understanding of Precambrian rocks northwest of Hornsund, southwest Spitsbergen. The Skålfjellet Subgroup has been regarded as the eastern equivalent of the Vimsodden Subgroup, and both of these occur within the Precambrian Eimfjellet Group of southwest Spitsbergen. Although the Eimfjellet Group is considered to be older than the oldest unconformity in the area, the age of the rocks has not been known. The granitic-gabbroic rocks in the Skålfjellet Subgroup have been considered to be the products of granitisation for many years, but recent observations show that they are exotic blocks incorporated into the basic eruptive rocks which are the main constituents of the subgroup. These plutonic rocks have a wide range of compositions, from syenite via granite to gabbroic cumulates, which suggests the existence of a well-differentiated plutonic body at depth.

U-Pb zircon and Pb evaporation datings yielded magmatic ages of ca. 1,100 to 1,200 Ma, and a conformable age has been obtained by Rb-Sr whole rock dating. Detrital zircons from the micaceous schists of the Isbjørnhamna Group, which underlies the Skålfjellet Subgroup, show a poorly defined discordia with an upper intercept age of ca. 2,200 Ma and a lower intercept age of ca. 360 Ma. These dating results define the magmatic age of the granitic-gabbroic rocks as late Mesoproterozoic, early Grenvillian. This age is in broad agreement with that of the metavolcanic rock clasts of the Pyttholmen meta-pyroclastic-conglomeratic unit at Vimsodden, which is considered to be the westernmost occurrence of the Skålfjellet Subgroup.

A Rb-Sr whole rock age determination of the shaly phyllites from the Deilegga Group was performed in order to place constraints on the age of younger Precambrian event; however, no good isochron was obtained.

Yu. A. Balašov and A. N. Larionov, Laboratory of Isotope Geochemistry, Geological Institute of Kola Science Centre, Russian Academy of Sciences, ul. Fersman 14, 184200 Apatity, Russia; J. J. Peucat, Laboratoire de Géochimie Isotopique et de Géochronologie, Géosciences Rennes, F-35042 Rennes Cedex, France; A. M. Teben'kov and A. N. Sirotkin, Polar Marine Geologic Expedition, ul Pobedy 24, 189510 Lomonosov, St. Petersburg, Russia; Y. Ohta, Norsk Polarinstitutt, P.O. Box 5072 Majorstua, N-0301 Oslo, Norway; M. Bjornerud, Geology Department, Lawrence University, Appleton, Wisconsin 54912, U.S.A.

Geological outline

A Precambrian granite-gabbro complex has long been known to the northwest of Hornsund, southwest Spitsbergen (Hoel 1918; Orvin 1940; Birkenmajer & Narebski 1960; Smulikowski 1965 and 1968, Teben'kov 1983; Birkenmajer 1992) (Figs. 1A & 1B). Precambrian rocks in this area have been divided into four groups and two Precambrian tectonic events have been proposed by Birkenmajer (e.g. 1975 and 1992) (Table 1 and Fig. 1A).

The Skålfjellet Subgroup has been considered to be an eastern lithofacies of the Eimfjellet Group, contemporaneous with the Vimsodden Subgroup to the west (Birkenmajer 1992). The Skålfjellet Subgroup consists mainly of meta-eruptive mafic rocks, with felsic rocks being in the minority. The lower part of the eruptive basic sequence contains granitic and gabbroic blocks as much as tens of metres in length. These coarse-grained rocks have been considered the products of granitisation by most previous authors (Orvin 1940; Birkenmajer & Narebski 1960; Smulikowski 1968).

These blocks are confined within three layers of metabasic, eruptive rocks (Fig. 1B). The lowest layer includes mainly granitic-syenitic blocks, the second tonalitic blocks, and the third mostly gabbroic blocks, while some amounts of blocks of

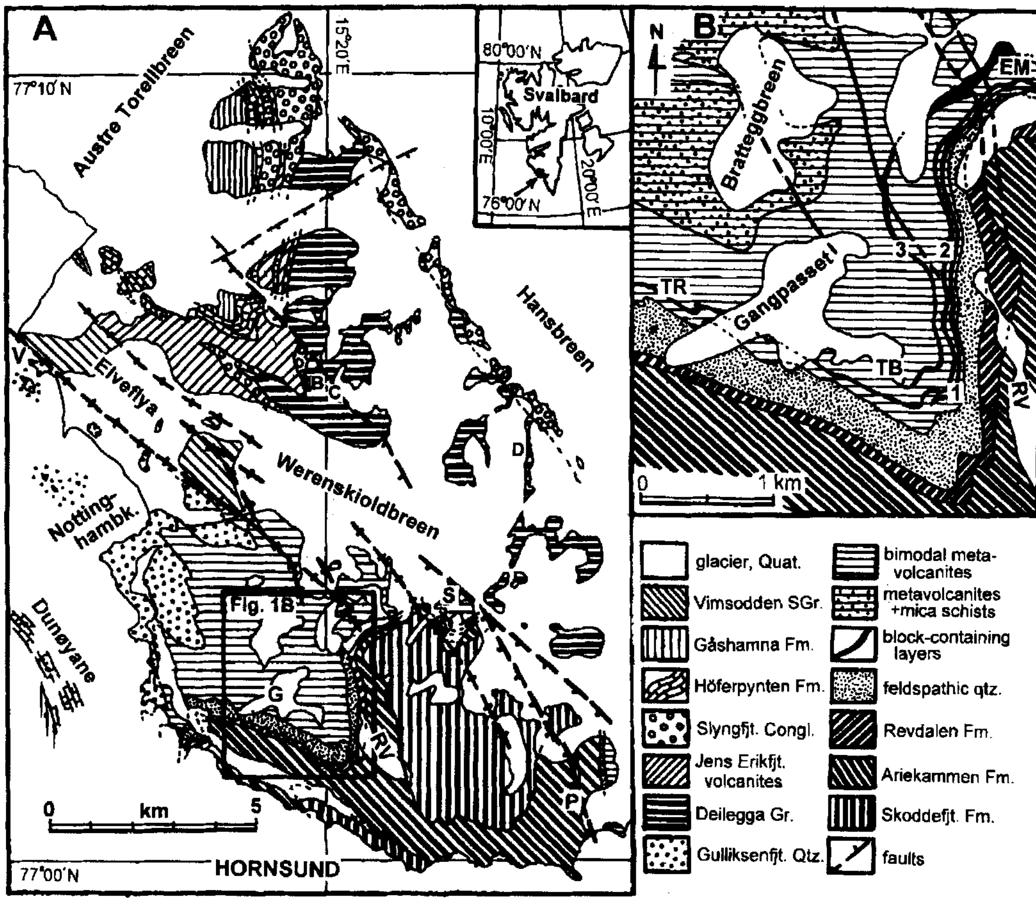

Fig. 1. Geological maps. A: Northwestern Hornsund, with an inset location map, modified from Ohta & Dallmann 1994 (up-dated version 1996). Birkenmajer 1993 and 1994 have not been incorporated because the authors differ with his interpretation. Place names: G = Gangpasset, P = Polish station at Isbjørnhamna, RV = Revdalen, S = Skålfjellet, V = Vimsodden. B, C and D denote localities of metasediment samples of the Deilegga Group. B: Detailed map around Gangpasset. 1 signifies the lowest block-bearing layer, mainly with granite-syenite blocks; 2, second block-bearing layer, mainly with tonalitic blocks; 3, third block-bearing layer, mainly with gabbroic blocks. The analysed samples were collected in the east of Gangpasset. Place names: EM = Eimfjellet; RV = Revdalen; TB = Torbjørnsenfjellet; TR = Trulsenfjellet.

these different lithologies occur mixed in all three layers. The blocks commonly have a subangular outline (Fig. 3A), show a very sharp boundary with the surrounding metaeruptive rocks, and are occasionally cut by thin veins of the latter (Fig. 3C). The blocks have holocrystalline textures and grain sizes that are distinctly coarser than the surrounding rocks, without gradational transition in grain size from block to host rock.

The internal structures of the gabbroic blocks in the third block-bearing layer, represented by plagioclase- and mafic-rich compositional layers and shear planes (Fig. 3D), are variously rotated with respect to the structures of the surrounding rocks (Fig. 3B). Some blocks are almost anorthositic in composition, including thin cumulative mafic-rich layers which contain distinct seams of ilmenite concentration. Plagioclase and hornblende in the gabbroic blocks show cumulate textures. The tonalitic rocks from the second block-bearing layer have coarse-grained, equigranular hypidiomorphic textures.

The surrounding metaeruptive rocks are mostly dense, schistose amphibolites, having actinolite-epidote-bearing assemblages with rare relict hornblende and dusty plagioclase grains. Clea-

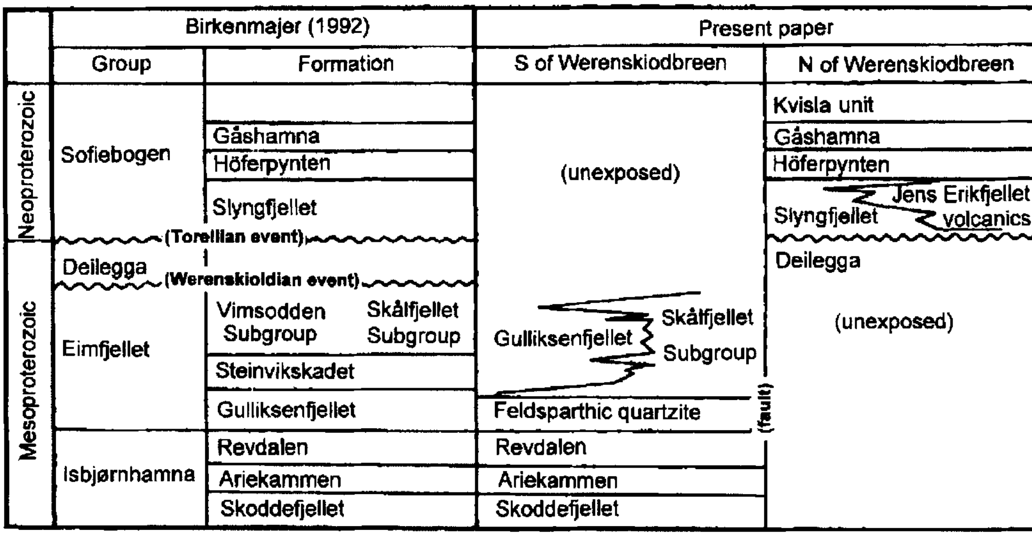

Fig. 2. Lithostratigraphy of the Precambrian rocks north of Hornsund. Second and third columns from the left: Birkenmajer 1993 and 1994 are not incorporated because the authors differ with his interpretation. Fourth and fifth columns: modified from Ohta & Dallmann (1994, up-dated version 1996).

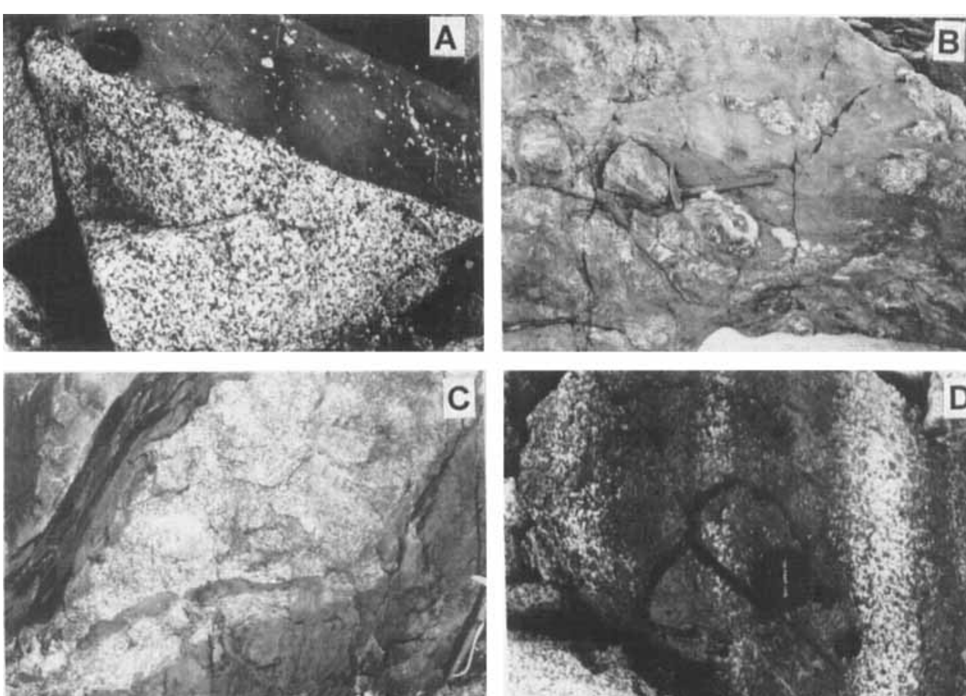

Fig. 3. Photographs showing the occurrences of the granitic-gabbroic blocks in the meta-eruptive rocks of the Skålfjellet Subgroup. Scales: hammer shaft ca. 30 cm, lense-cap ca. 4 cm across. A: Sharp contact between granitic block and meta-eruptive rock with plagioclase phenocrysts and amygdaloidal texture. B: Rotated granitic blocks in the meta-eruptive rocks, with sheared margins. C: A granitic block with partially sheared margin, cut by a vein of eruptive rock. D: Cumulate compositional layers within a gabbroic block.

vages are locally strong, and thin shear planes occur along the boundaries and inside the blocks. Less schistose parts of the metaeruptive rocks locally contain small white plagioclase crystals with prismatic outlines and granulated interiors similar to a protoclastic texture, indicating that they are a primary phenocryst phase. Round white spots consisting of calcite and quartz suggest primary amygdaloidal textures.

The occurrences and lithologies of the blocks and relict-volcanic textures of the surrounding rocks can not be explained by granitisation, and the blocks are considered to be exotic inclusions from underlying plutonic bodies, incorporated into the eruptive rocks. Czerny et al. (1993) made a similar interpretation. The inferred plutonic body seems to have been strongly differentiated, ranging in composition from gabbro-anorthosite cumulates to granitic-syenitic rocks, and was mostly consolidated when the eruptive rocks were extruded. Thus, a sequential magmatic activity, including the formation of both eruptive and plutonic rocks, is inferred from the igenous rocks of the Skålfjellet Subgroup. These observations suggest that these rocks are all of similar age, with the plutonic rocks possibly being older.

The eruptive rock succession of the Skålfjellet Subgroup is underlain by two-mica, locally garnet-bearing, schists of the Isbjørnhamna Group. This group has been divided into three formations by Birkenmajer (1959, 1992; Fig. 2), the middle of which is calcareous and includes some marble layers.

Direct contacts between the Skålfjellet Subgroup and the Isbjørnhamna Group have been observed at more than ten localities and all are conformable. A 3–15 m thick, feldspathic quartzite layer overlies the biotite schists of the Revdalen Formation, the upper division of the Isbjørnhamna Group, with a sharp lithological change, but without any structural discontinuity. Large scale fold structures including the two successions are also conformable.

The schists of the Isbjørnhamna Group contain metamorphic mineral assemblages of garnet-muscovite with or without graphite, garnet-biotite-muscovite and garnet-muscovite-epidote-calcite, all with plagioclase (oligoclase) and quartz. The secondary assemblages include albite, quartz, sericite, chlorite and later calcite. Accessory minerals are tourmaline, zircon, titanite, rutile and pyrite. Some schists contain chloritoid, kyanite and staurolite, indicating metamorphic conditions of middle amphibolite facies of an intermediate-pressure series. These conditions do not provide sufficiently high conditions for granitisation as proposed by previous authors.

Birkenmajer (1975, 1992) placed the Eimfjellet and Isbjørnhamna Groups earlier than his Werenskioldian event (Fig. 2). An angular unconformity has been well established at the base of the Sofiebogen Group, cutting the folded Deilegga Group in the northern Werenskioldbreen area (Fig. 1A). This tectonic break has been named the Torellian event (Fig. 2). The age relationship between the geological units to the north and the south of Werenskioldbreen has not been established because of lack of exposure.

The Pittholmen meta-pyroclastic-conglomerate unit, from which previous U-Pb zircon ages were reported by Balašov et al. (1995), is considered the westernmost occurrence of the upper Skålfjellet Subgroup based on new observations (Ohta & Dallmann 1994), and is separated from the Vimsodden Subgroup of Birkenmajer (1992). A new name, the Kvisla unit, has been introduced for the former Vimsodden Subgroup without Pittholmen unit (Ohta & Dallmann 1994, updated version 1996). The Kvisla unit roughly corresponds to the Kvisla member of the Nottinghambukta Formation plus Elveflya Formation of Birkenmajer (1993, 1994) and the Pyttholmen unit includes the Pyttholmen and Kvislodden members of the same author. The Kvisla unit contains distinct tilloids in front of Werenskioldbreen and in Fig. 2 it is therefore placed in the late Vendian. The boundary between the Pittholmen unit and the Kvisla unit is a fault along the southern coast of Vimsodden, which accompanies many small sheared zones with sulphide mineralisation.

Previous dating

The ages previously reported for the Isbjørnhamna Group are two Cambrian K/Ar apparent ages for biotite from the schists (Gayer et al. 1966). U-Pb zircon ages of the quartz porphyry and rhyolite clasts from the Pyttholmen meta-pyroclastic-conglomerate unit of the Vimsodden Subgroup of Birkenmajer (1992), were reported in Balašov et al. (1995). They indicate a magmatic age of ca. 1.2 Ga, a metamorphic age of ca. 930 Ma and an inherited zircon age of ca. 2.5 Ga. The Rb-Sr whole rock, metamorphic age of the Isbjørnhamna

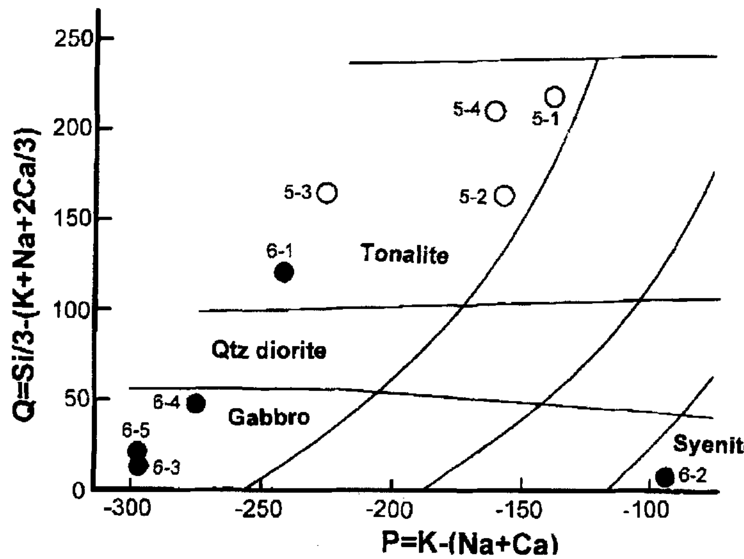

Fig. 4. Classification of the dated samples from the Skålfjellet Subgroup, after Debon & Le Fort (1983). Symbols: open circle, blocks from the second block-bearing layer; filled circles, blocks from the third block-bearing layer. The same symboles are used in Figs. 4 to 9.

schists was also reported to be ca. 930 Ma (Gavrilenko et al. 1993).

Description of the samples

Two sample sets, tonalitic rocks (sample series 5-) and gabbroic rocks (series 6-) of the Skålfjellet Subgroup, one set of schists from the Isbjørnhamna Group (series 4-), and three shaly phyllite samples (from localities B, C and D, Fig. 1A) of the Deilegga Group were collected in 1989. Age determinations for these specimens are reported in this paper.

Petrography

Sample series 5- and 6- were collected from the second and third block-bearing layers, respectively, of the lower part of the Skålfjellet Subgroup, near the eastern part of Gangpasset (Fig. 1B). The samples from the third block-bearing layer are called gabbroic rocks in the field and marked by the same symbol in the figures, but they include a tonalite and a syenite.

Samples 5-1 and -4 are fine-grained, schistose cataclastic tonalitic rock (Fig. 4), consisting of 50% quartz, 35% plagioclase (albite) and 5% biotite. Accessories, which constitute up to 10% of the rock by volume, are orthite, zircon, apatite, pyrite and sphene, and secondary epidote-zoisite, chlorite and carbonates. Sample 5-2 is a tonalite in chemical composition and has a similar texture, but is apparently granodioritic in handspecimen, having less quartz (ca. 30%) and more biotite (ca. 20%). A few grains of hornblende are found, and apatite and opaque grains are accessories. Secondary chlorite represents as much as 15–20% of the rock and some zoisite grains occur. Sample 5-3 is a tonalite and has a similar texture and modal composition to 5-1, but secondary chlorite and carbonates are absent. Octahedral grains of brown-green spinel, up to 0.2 mm in size, are found as an accessory phase.

Sample 6-1 is a rare tonalitic block in the third block-bearing layer, which is dominated by gabbroic blocks. The rock is coarse-grained and has 40–60% plagioclase (albite), 20–25% quartz and 10–20% hornblende. Secondary epidote-zoisite constitutes ca. 10%, and accessories are biotite, chlorite, zircon, apatite and opaques. The rock is massive and has a prismatic-mosaic texture. Samples 6-3, 6-4 and 6-5 are coarse-grained, massive hornblende gabbros with or without biotite, having prismatic mosaic-textures. Major consituents are albitised plagioclase (as much as 60%), amphiboles (light green hornblende and actinolite, 20–30%) and biotite (up to 10%). Secondary minerals including chlorite, epidote-zoisite and carbonates make up the remaining 10–20%. Accessories are rutile, sphene, pyrite, ilmenite and zircon.

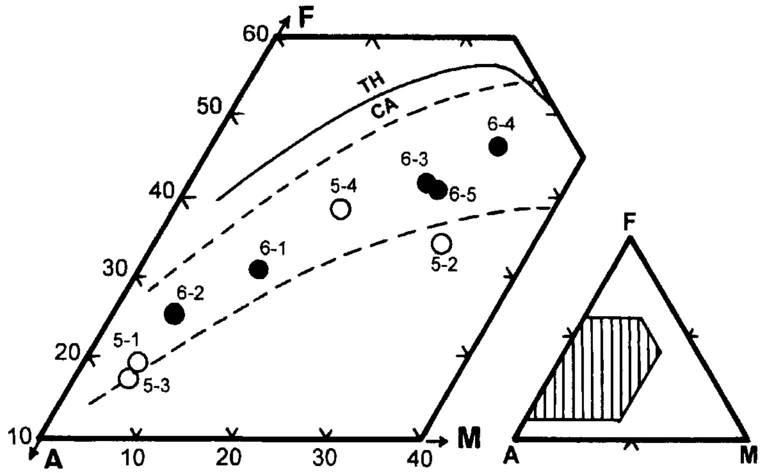

Fig. 5. AFM diagram. Solid curve indicates the tholeiite-calcalkaline division (Irvine & Baragar 1971); broken curve, common calcalkalic rock field (Ringwood 1974).

Sample 6-2 is a porphyroblastic rock rarely found in the third, gabbro block dominating layer. K-feldspar megacrysts, ca. 60 modal percent and up to 7 mm in size, replaced the matrix of albitised plagioclase (20%), hornblende (10%) and biotite (10–15%). Plagioclase is also partly

Table 1. Chemical compositions of the granitic (nos. 5-) and gabbroic (nos. 6-) rocks of the Skålfjellet Subgroup. Sample nos. 5- are from the second block-bearing layer and samples nos. 6- are from the third block-bearing layer. Blank boxes mean not determined.

	5-1	5-2	5-3	5-4	6-1	6-2	6-3	6-4	6-5
SiO_2	73.78	63.10	71.13	69.91	65.22	61.29	51.52	50.72	52.63
TiO_2	0.35	0.71	0.22	0.54	0.78	0.74	0.73	0.78	0.92
Al_2O_3	14.52	15.23	17.68	14.34	17.30	18.85	21.38	18.30	20.07
Fe_2O_3	0.65	1.44	0.43	1.25	1.95	1.60	2.37	2.11	2.30
FeO	0.93	3.81	1.15	2.44	1.36	2.66	3.95	6.03	4.38
MnO	0.06	0.05	0.05	0.06	0.05	0.07	0.10	0.14	0.10
MgO	0.47	4.65	0.44	1.55	1.22	0.92	3.60	5.11	4.40
CaO	1.36	2.15	1.09	4.23	5.73	2.86	10.34	8.79	9.41
Na_2O	4.42	4.30	6.51	3.26	4.82	5.29	4.07	3.83	4.47
K_2O	1.44	0.98	0.24	0.98	0.77	6.01	0.85	0.23	0.68
P_2O_5	0.01	0.11	0.08	0.02	0.07	0.13	0.01	0.05	0.03
CO_2		0.05							
H_2O^-	0.00	0.22	0.04	0.08	0.16	0.08	0.10	0.16	0.16
S	0.07		0.05	0.05	0.05	0.05	0.05	0.05	0.05
H_2O^+	0.56	2.94	0.60	0.70	0.86	0.62	1.36	1.78	1.50
Total	98.62	99.74	99.71	99.41	100.34	101.17	100.43	98.08	100.70
Rb	38	15	13	20	14	63	14	39	15
Sr	86	135	191	268	385	174	494	532	477
Ba	170	100	200	280	250	2910	190	620	190
Zr	281	1230	372	363	435	452	36	68	88
V	7	10	20	20	110		140	140	160
Zn	12	35	24	24	15	47	36		36
Co		30		10			25	30	30
Nb	97	133	203	32	18	56	8	15	12
Y	94	91	124	32	58	41	8	14	13
Ni	8	25	10	10	9	10	40	40	30
Cr	190	20	40	120	110	50	120	110	120
Cu	10	8	20	9	10	10	20	15	10

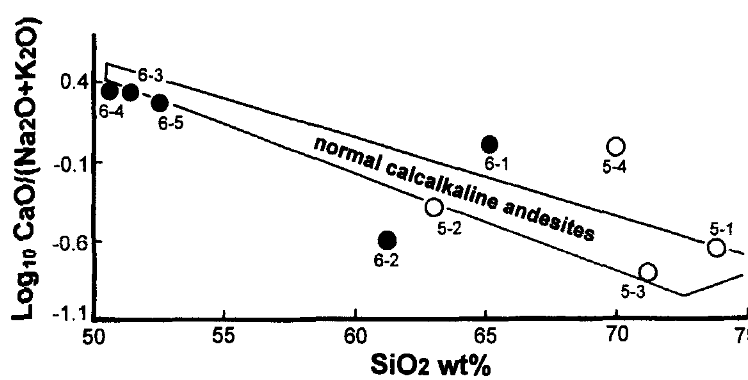

Fig. 6. Log_{10} CaO/total alkalis vs. SiO_2 diagram. Calc-alkaline andesite field from Brown (1982).

replaced by quartz. Secondary chlorite and epidote-zoisite are common, and apatite and zircon are the accessories.

The samples from the Isbjørnhamna Group are various garnet-mica schists. Sample 4-1 is a fine-grained schist with garnet porphyroblasts. It consists of 15% garnet, 5–7% plagioclase, 10–15% quartz, 20–25% muscovite and 35–40% chloritoid. The chloritoid grains contain streaky graphite, and kyanite occurs between chloritoid grains. The schistosity is marked by muscovite flakes. Accessories are tourmaline, zircon, orthite, apatite and opaques, and secondary chlorite and sericite occur in small amounts. Samples 4-2 to 4-5 are medium-grained, garnet-two-mica schists consisting of 15–30% quartz, 10–20% plagioclase, 5–20% muscovite, 5–20% biotite and 5–10% garnet. Accessories are the same as in 4-1 with the addition of sphene (up to 2–3%). Secondary chlorite represents ca. 2–10%. Samples 4-3, 4-4 and 4-5 contain secondary epidote-zoisite and carbonates.

All three metasediment samples from the Deilegga Group came from sites close to the Deilegga/Slyngfjellet unconformity (Fig. 1A) and are fine-grained, phyllitic rocks derived from calcareous and shaly protoliths. Mineral assemblages in all samples indicate low-grade, sub-greenschist facies metamorphism. Samples B and C are from the western limb of a major N-S anticline. The former sample is a calcareous shale containing white mica, quartz, dolomite and opaques, while the latter is more pelitic and lacks dolomite. Sample D, collected from the eastern limb, is a pure dolomitic marble. All three samples include carbonate veins, but these are excluded from the materials used for the Rb-Sr analyses.

Petrochemistry

Major and trace elements of the dated rocks were analysed by the X-ray fluorescence method on the KRF-18 device at the SEVZAP GEOLOGIJA laboratory in St. Petersburg (Table 1).

Samples 6-3, 6-4 and 6-5 are gabbros, while 5-1, -2, -3, -4 and 6-1 are tonalites and 6-2 is a syenite (Fig. 4; Debon & Le Fort 1983). In the Streckeisen & Maitre (1979) classification, 5-1 is a granodiorite, while the rest are in the same categories as shown in Fig. 4. The rocks are classified as granites to tonalites and gabbros in the R2 vs. R1 diagram of La Roche et al. (1980). Sample 6-2 has a syenitic composition in all three classifications mentioned above and is similar in appearance to the blocks in the lowest block-bearing layer, which have not been analysed in

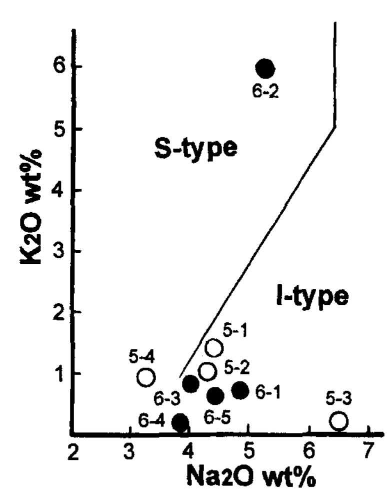

Fig. 7. K_2O vs. Na_2O diagram. The I-type and S-type granite fields are from Chappell & White (1974).

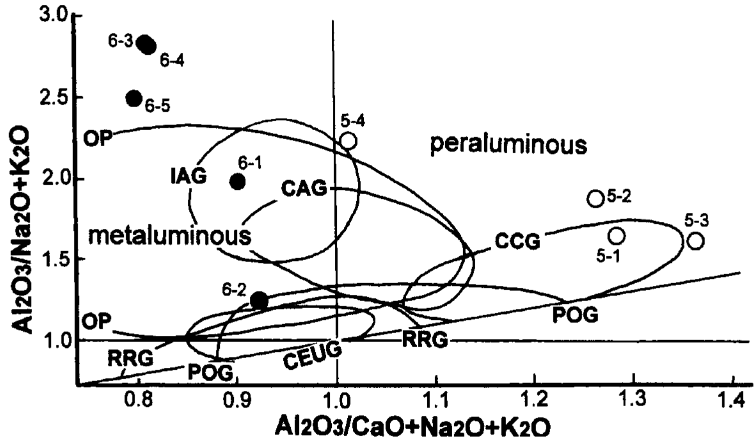

Fig. 8. Al_2O_3-saturation diagram. Classification after Maniar & Piccoli (1989): CAG, continental arc granites; CCG, contineta1 collision granites; CEUG, contineta1 epeirogenic uplift granites; IAG, island arc granites; OP, plagiogranites; POG, post-orogenic granites; RRG, rift-related granites.

this study. The high K_2O content of this rock reflects the K-feldspar replacement as mentioned in the petrographic description of the samples. Most samples are in the calcalkaline field on the AFM diagram (Fig. 5), and plot within or near the field of modern calcalkaline andesite-dacites of Brown (1982) (Fig. 6) . The Na_2O vs. K_2O diagram (Fig. 7; Chappell & White 1974) shows that most samples, except for 5-4 and 6-2, are in the field of I-type granite.

The tonalitic rocks are of the trondhjemite-tonalite series in the normative Or-Ab-An diagram of Barker (1979), and have slightly higher Or contents than oceanic plagiogranite (Maniar & Piccoli 1989). Sand's diagram of Maniar & Piccoli (1989) shows that the majority of tonalitic rocks are peraluminous, and all gabbros plot in the metaluminous field, owing to the existence of hornblende (Fig. 8). No tectonic setting can be estimated from this figure. The high Al contents in the tonalitic rocks can be explained by the existence of chlorite and epidote which were formed during later metamorphism. This inference is consistent with the fact that six of the nine analysed samples are projected outside the igneous spectrum on the total alkalis vs. 100

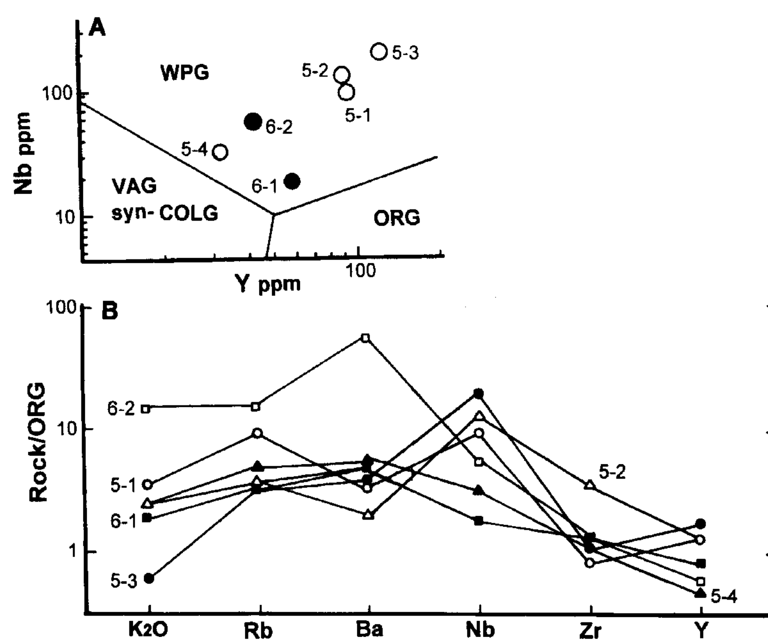

Fig. 9. Trace element ratios of the samples with more than $SiO_2 = 60\%$. A: Nb vs. Y diagram after Pearce et al. (1984). VAG = volcanic arc granite; syn-COLG, syn-collision granite; WPG = within plate granite; ORG = ocean ridge granite. B: Spider diagram of the trace elements, normalised by ocean ridge granites (ORG).

Table 2. U and Pb isotopic compositions of the granitic-gabbroic rocks of the Skålfjellet Subgroup (nos. 5- and 6-) and the schists of the sbjørnhamna Group (nos. 4-), analysed by the U-Pb dissolution method. Sample fraction 5-2-1 is imperfect because of bad quality of measurements. Abbreviations: rad., radioactive; com., common.

Sample	Weight	Pb rad.	Pb com.	U	Measured						Radiogenic ratio						Age, Ma.		
					$^{206}Pb/^{204}Pb$	error	$^{206}Pb/^{207}Pb$	error	$^{206}Pb/^{208}Pb$	error	$^{207}Pb/^{206}Pb$	error	$^{207}Pb/^{135}U$	error	$^{206}Pb/^{235}U$	error	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{207}Pb/^{238}U$
fraction	mg	ppm	ppm	ppm		%		%		%		%		%		%			
4-1-1	1.8	105.3	19.3	1083	306	0.82	7.138	0.14	5.217	0.05	0.0959	0.46	1.266	0.58	0.0958	0.29	1545+/-9	831	590
4-1-2	0.9	155.8	12.7	1453	643	0.96	8.010	0.88	7.910	0.82	0.1040	1.10	1.517	1.16	0.1058	0.34	1697+/-20	937	648
4-1-3	7.5	146.7	17.4	1239	448	5.20	7.310	0.15	6.592	0.07	0.1070	1.52	1.714	1.71	0.1162	0.31	1749+/-28	1014	709
4-3	2.5	63.7	8.2	344	435	5.80	7.974	0.08	4.798	0.20	0.0938	2.00	2.275	2.28	0.1760	0.32	1503+/-39	1205	1045
5-2-1	11.9				4084	6.40	12.379	0.27	2.783	0.50	0.0844						1300		
6-1-1	7.2	29.6	1.1	140	1430	3.00	11.360	0.86	5.215	0.70	0.7826	1.05	2.128	1.68	0.1972	1.30	1154+/-21	1158	1160
6-2-2	20.4	137.8	3.7	635	2052	5.00	12.200	0.40	5.013	0.40	0.0751	0.64	2.076	0.74	0.2004	0.32	1072+/-13	1141	1178

K_2O/total alkali diagram of Hughes (1973), suggesting metamorphic modifications.

Trace element ratios have been used to determine the tectonic settings of the rocks (Pearce et al. 1984). All tonalitic rocks plot in the WPG field on the Nb vs. Y diagram (Fig. 9A). A spider diagram (Fig. 9B), normalised to ORG, shows several times higher K_2O, Rb, Ba, and Nb than ORG.

Isotopic datings

Three methods of isotopic age determination have been applied in this study: (1) The classical U-Pb zircon dissolution method of Krogh (1973), for sample series of 4- and 6-, with an imperfect analysis of sample 5-2; (2) The single-grain Pb evaporation method of Kober (1986) on zircon grains from samples 5-3, 6-1 and 6-2; and (3) Rb-Sr whole rocks dating on sample series 5- and 6-. Three samples of shaly phyllites from the Deilegga Group were commercially analysed by this method in U.S.A.

Analytical methods

The U-Pb zircon analysis was performed at the Isotope Geochemistry Institute of Kola Science Centre, Apatity, Russia, using an MI 1201-T mass-spectrometer (Balašov et al. 1995). The lead and uranium blanks are less than 0.5 ng and 0.05 ng, respectively. The analytical errors of the isotope composition measurements of Pb and of the isotope dilution analyses of Pb and U, using ^{208}Pb and ^{235}U spike, are shown in Table 2. The analytical procedures were assessed by running the IGFM-87 and NBS-981 standards, and the calculations have been done using the programs of Ludwig (1991a, b).

The single grain zircon evaporation analyses were performed at the Isotope Laboratory of Rennes University, France, following the procedure proposed by Kober (1986), using a Finnigan MAT 262 mass-spectrometer, except for sample 6-2 which was analysed by a Cameca TSM 206 mass spectrometer. Correction for mass fractionation was 0.10% per AMU and the common lead used for correction had an isotopic composition corresponding to an age of 1,150 Ma, following the Stacey & Kramers (1975) two-stage model.

The Rb-Sr whole rock analyses for the Skålfjellet granite-gabbros were carried out in

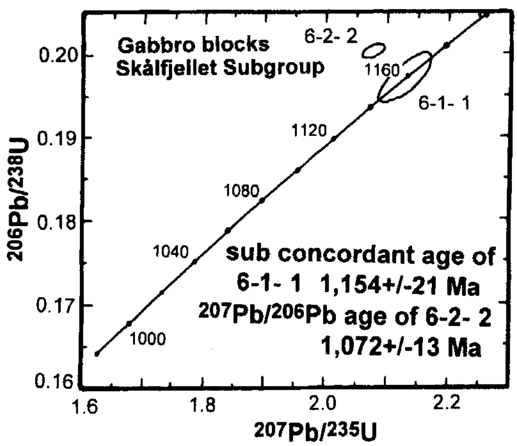

Fig. 10. U-Pb concordia diagram for the gabbroic samples, 6-1 and 6-2.

the same laboratory at Apatity (Teben'kov et al. 1996). The samples were dissolved in HCl + HF + $HClO_4$, the residue was dissolved in HCl and put in a column with Dowex 50x3 (200–400 mesh) resin. Rb and Sr contents were determined by isotope dilution and mass-spectrometry. The Sr isotope compositions were determined by an MI 1201-T mass spectrometer. The blanks of Rb and Sr are 2 and 8 ng, respectively. The analytical error for $^{87}Rb/^{86}Sr$ is assumed to be 1.5% and that of $^{87}Sr/^{86}Sr$ 0.04%. The age calculation was made using the program of Ludwig (1991b).

Samples of the Deilegga Group were analysed for Rb-Sr whole rock dating by Geochron Laboratories of Krueger Enterprises INC., Cambridge, Massachusetts, U.S.A. The samples, made as free of carbonate vein material as possible, were crushed and homogenised to –80 mesh whole rock powders prior to analysis. Errors on Rb and Sr concentrations, analysed by XRF, are approximately ±0.5%, and those of $^{87}Sr/^{86}Sr$ are given as 2 sigma in Table 4. The Sr analyses were normalised to $^{86}Sr/^{88}Sr$ = 0.11940. Analyses of the NSB 987 standard gave 0.710240 (±10) during the period.

Description of zircons

The zircon grains used for the U-Pb dissolution analyses, from samples 5-2 (from the second block-bearing layer), 6-1 and 6-2 (from the third layer) of the Skålfjellet Subgroup, show similar shapes, eu- to subhedral shapes with facets (111) and 110), often flattened along one of the (110) faces and having smooth surfaces. Most grains are zoned. Pink coloured, transparent grains were handpicked for the analyses.

Zircons from samples 5-3, 6-1 and 6-2 were used for the single-grain Pb evaporation analyses. They are similar in shape, eu- to subhedral, but range in colour from yellow (sample 5-3) to pink (sample 6-1). Prism facets (100) are better developed than (110), and (101) pyramidal facets are dominant over (211), corresponding to the S 24-25 type of Pupin (1980). These are characteristics of high temperature zircons like those found in calcalkaline series rocks. They do not exhibit any visible core, and the clearest grains are entirely inclusion free.

Zircon grains were also separated from two micaceous schists of the Isbjørnhamna Group (3 fractions from 4-1; and one fraction from 4-3). All grains are anhedral to subhedral, with round shapes and rough surfaces. The zircon grains from 4-1 are dark grey to black, due to graphite inclusions. Those of 4-3 are less rounded, rose to light rose in colour, and translucent due to cloudy outer parts. Some grains are weakly zoned. The character of zircons from the schists suggests a detrital origin. Zircons from sample 4-3 may be primarily magmatic judging from their idiomorphically zoned structure.

Results and interpretation

Zircon ages. – The results of isotopic analyses by the U-Pb dissolution method are shown in Table 2. One zircon sample from specimen 6-1-1 (a tonalitic rock from the third block-bearing layer) is almost concordant and defines a $^{207}Pb/^{206}Pb$ age of 1,154 ± 21 Ma (Fig. 10). The zircon of 6-2-2 (a syenite from the third block-bearing layer) plots above the concordia, suggesting possible U-loss during processing sample or reversely discordant fraction due to U loss or Pb gain in nature. Thus the $^{207}Pb/^{206}Pb$ age of 1,072 ± 13 Ma for this sample is assumed to be the minimum age. Sample 5-2 (a tonalite from the second layer) exhibits a $^{207}Pb/^{206}Pb$ age of ca.1,300 Ma by the U-Pb dissolution method (Table 2).

A three-grain Pb evaporation analysis was performed on sample 6-1 (Fig. 11F and G). The two-heating steps provide similar results, taking

Table 3. Pb isotope ratios of the granitic-gabbroic rocks of the Skålfjellet Subgroup, analysed by the Pb evaporation method. Analyses 2 of 5-3 were not calculated because of bad quality of measurements. Sample 6-2 was analysed using a CAMECA TSM 206 mass spectrometer, while the others were performed using a Finnigan MAT 262 mass spectrometer. Abbreviations in the second column from the left: numbers = analysis number, eh = euhedral, br = brown colour. Third column: a, b, c, etc., signify different blocks of the same evaporation step.

Samples	Analysis zircon	Step (ampere)	$^{206}Pb/^{204}Pb$ (measured)	$^{207}Pb/^{206}Pb$ (measured)	Error (2 sigma)	$^{207}Pb/^{206}Pb$ (corrected)	Age, Ma	Error (2 sigma)
5-3	1, eh,br,	2.6, a	5324	0.08055	3	0.07811	1150	3
		2.6, b	5326	0.08078	6	0.07836	1156	7
		2.6, total	5325	0.08067	5	0.07822	1153	7
		2.8, a	17056	0.07815	4	0.07744	1133	2
		2.8, b	17018	0.07836	6	0.07765	1138	1
		2.8, c	17238	0.07839	2	0.07770	1139	2
		2.8, d	17345	0.07840	3	0.07772	1139	2
		2.8, e	17324	0.07836	5	0.07766	1138	1
		2.8, total	17214	0.07833	2	0.07684	1138	3
		3.0, a	39714	0.07845	3	0.07819	1152	2
		3.0, b	38731	0.07836	3	0.07809	1149	3
		3.0, c	37975	0.07811	2	0.07794	1145	2
		3.0, total	38806	0.07834	3	0.07807	1149	3
5-3	2, eh,br,	2.6, a	125976	0.07929	9			
		2.6, b	124053	0.07929	8			
		2.6, c	120834	0.07926	9			
		2.6, d	1230476	0.07920	6			
		2.6, e	116139	0.07939	11			
		2.6, f	113776	0.07952	10			
		2.6, total	120210	0.07933	4	0.07928	1179	6
		2.8, a	117020	0.07900	30	0.07889	1169	15
		2.8, b	132122	0.07870	33	0.07851	1162	17
		2.8, c	140763	0.07866	24	0.07866	1163	14
		2.8, d	143423	0.07852	24	0.07852	1161	12
		2.8, e	79336	0.07839	23	0.07839	1154	13
		2.8, total	122533	0.07865	13	0.07865	1161	13
6-1	1, eh,	2.8, a	14184	0.08080	23	0.07994	1196	12
		2.8, b	14258	0.08032	15	0.07941	1182	8
		2.8, c	13954	0.08011	13	0.07919	1177	8
		2.8, d	13891	0.08013	10	0.07918	1177	6
		2.8, e	13958	0.08033	9	0.07939	1182	5
		2.8, total	14049	0.08034	9	0.07935	1181	9
		3.0, a	23818	0.08007	11	0.07955	1185	5
		3.0, b	25891	0.08117	19	0.08061	1212	8
		3.0, c	27032	0.08009	26	0.07960	1187	13
		3.0, d	27469	0.08060	41	0.08017	1201	30
		3.0, total	26798	0.08062	24	0.08023	1203	20
6-2	1, eh, br,	2.6	1731	0.08551	12	0.07722	1127	12
		2.8	10512	0.07887	31	0.07752	1135	19

the analytical errors in account (Table 3). The first step at 2.8 amperes yielded a mean age of 1,181 ± 9 Ma, and the highest temperature step at 3.0 amperes gave an age of 1,203 ± 20 Ma. The correction of primary and contaminant common Pb is limited in this sample because it has a high $^{206}Pb/^{204}Pb$ ratio. A single grain from sample 6-2 was also analysed (Fig. 11H and K) by two-step heating and yielded similar ages of 1,127 ± 12 and 1,135 ± 19 Ma (Table 3).

Two single-grain analyses of sample 5-3 were made by the Pb evaporation method. The first grain yielded ages of 1,153 ± 7 Ma, 1,138 ± 3 Ma and 1,149 ± 3 Ma in three heating steps at 2.6A, 2.8A and 3.0A, respectively (Fig. 11A, B and C). The second grain shows slightly older ages from 1,179 ± 6 Ma to 1,161 ± 13 Ma by the 2.6A and 2.8A heating steps (Fig. 11D and E).

Zircon grains were handpicked from two Isbjørnhamna schists, three fractions from 4-1

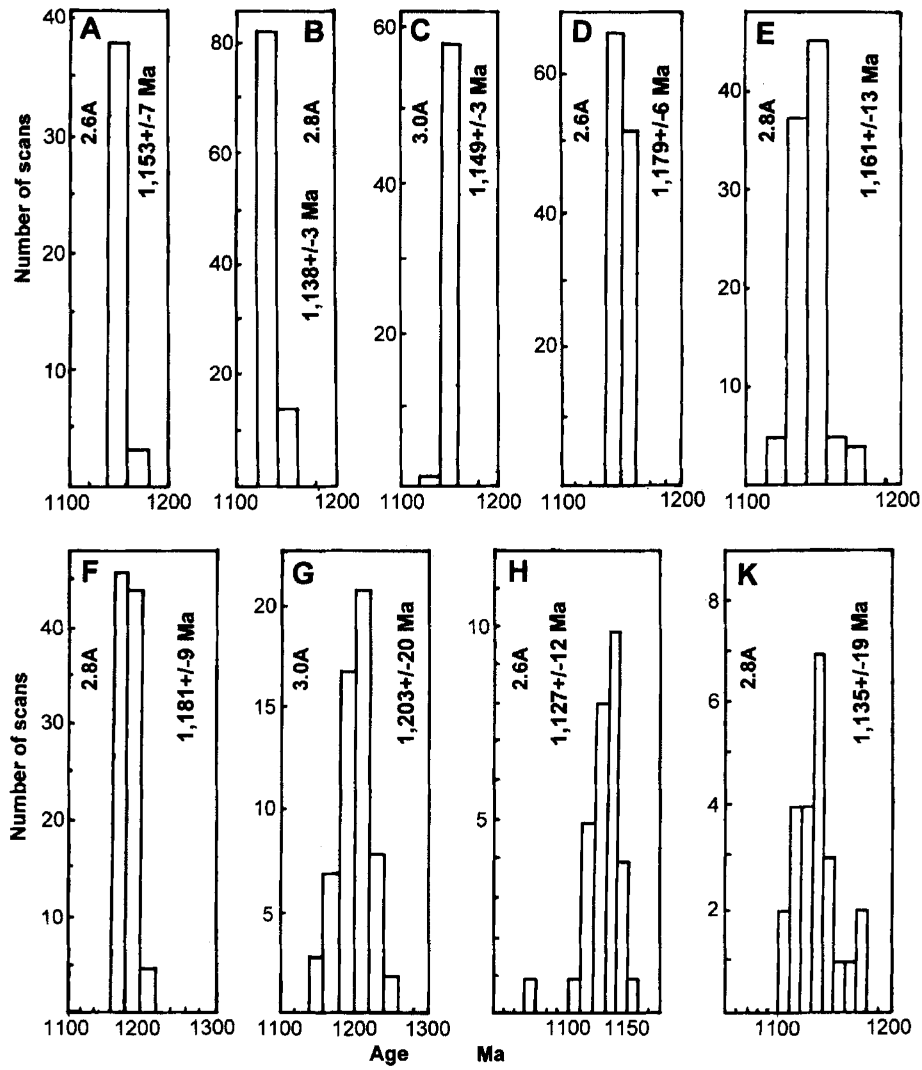

Fig. 11. Histograms of Pb isotope ages, analysed by the zircon evaporation method. A, B and C: Sample 5-3, the first grain. D and E: Sample 5-3, the second grain. F and G: Sample 6-1, 3-grains together. H and K: Sample 6-2, single grain.

and one from 4-3, and analysed by the U-Pb dissolution method (Fig. 12). The $^{207}Pb/^{206}Pb$ ages of 4-1 range from 1,503 to 1,749 Ma (Table 2). Assuming the three fractions from sample 4-1 form a coherent system, it is possible to draw a discordia approximately between 2,300 Ma and 360 Ma, but the error is very high. The zircons from sample 4-3 plot away from the discordia which is defined by the 4-1 fractions. The 4-3 zircon grains have a more magmatic morphology than the 4-1 grains. The common Pb content of this zircon sample is also distinctly lower, 8.2 ppm, than those of the 4-1 fractions, which range from 12.7 to 19.3 ppm. The $^{207}Pb/^{206}Pb$ age of sample 4-3 is 1,503 ± 39 Ma.

Rb-Sr whole rock age. – Nine rocks from the Skålfjellet Subgroup were analysed for Rb and Sr isotopes, including 5 tonalites, 1 syenite and 3

Table 4. Whole rock Rb and Sr isotopic compositions of the granitic-gabbroic rocks of the Skålfjellet Subgroup (nos. 5- and 6-) and the metasediments of the Deilegga Group (B, C, D). Normalisation factor: $^{87}Sr/^{86}Sr$ = 10 and $^{86}Sr/^{88}Sr$ = 0.1194.

No.	Rb ppm	Sr ppom	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Error
5-1	10	78	1.3160	0.7477	2
5-2	15	135	0.3267	0.7109	8
5-3	13	191	0.1858	0.7109	4
5-4	20	268	0.2185	0.7097	9
6-1	14	385	0.1154	0.7088	8
6-2	63	174	1.0874	0.7259	7
6-3	14	494	0.0837	0.7074	10
6-4	39	532	0.2189	0.7103	9
6-5	15	477	0.0927	0.7073	10
B	61	125	1.4173	0.7291	7
C	144	44	9.6062	0.7961	7
D	148	43	10.0726	0.8051	8

gabbros (classification after Fig. 4) (Table 4, Fig. 13). No isochron can be defined by the whole rock Rb-Sr isotope data, probably due to different degrees of partial resetting by later metamorphism. The datapoints for rocks with $^{87}Rb/^{86}Sr$ ratios between 0.1 and 0.4 are scattered and suggest an open system. One tonalite, 5-1 (with the highest SiO_2 content) and one syenite, 6-2 (with the highest K_2O content) have $^{87}Rb/^{86}Sr$ ratios of more than 1.0. An errochron including all samples yields an age of 1,259 ± 170 Ma with MSWD = 34 (Fig. 13). Another errochron using 5 points

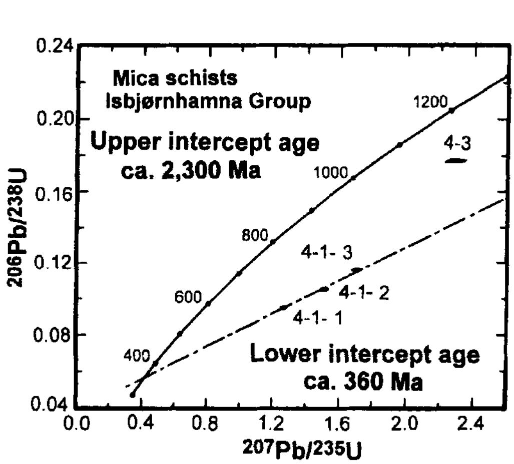

Fig. 12. U-Pb concordia diagram of the Isbjørnhamna schists.

(samples 6-2, -3, -4, -5 and 5-4) yields 1,278 ± 100 Ma, with MSWD = 10.2 and initial $^{87}Sr/^{86}Sr$ ratio = 0.7060 ± 7 (Fig. 13). The obtained Rb-Sr whole rock errochron age is apparently older than the zircon ages, but has a large error. Within the range of this error, it is conformable with most of the zircon ages.

The Rb/Sr whole rock isotope analyses of the phyllites of the Deilegga Group do not give a good isochron (Table 4, Fig. 14). The best estimated age is about 600 Ma, with a very large error (MSWD = 70, 2-sigma error = ±450 Ma). The initial $^{87}Sr/^{86}Sr$ ratio corresponding to this age is 0.716 ± 51.

Discussion and conclusions

The Eimfjellet Group and Isbjørnhamna Group have been considered older than the oldest regional Precambrian tectonic event, the Werenskioldian, by Birkenmajer (e.g., 1992), but no age has been known for this event.

The granite-gabbro complex in the Skålfjellet Subgroup of the Eimfjellet Group has been considered to be the product of granitisation, but new observations on field relations and petrography show that these rocks are exotic blocks incorporated into the eruptive rocks, which make up most of the subgroup. The chemical compositions of the tonalitic rocks indicate that they are I-type, calcalkalic, within-plate-granite.

The felsic volcanic clasts in the Pyttholmen unit at Vimsodden (Fig. 1A), which is the lateral equivalent of the upper Skålfjellet Subgroup, has been dated by the U-Pb zircon dissolution method (Balašov et al. 1995), and preliminary Rb-Sr whole rock age determinations were made for the Isbjørnhamna schists (Gavrilenko et al. 1993). The results suggest a felsic magmatism at ca. 1,200 Ma, and an inherited zircon age of ca. 2,500 Ma, and a greenschist-amphibolite facies metamorphism at ca. 930–936 Ma.

The present age determinations for the Skålfjellet granitic-gabbroic rocks by the zircon dissolution and evaporation methods yielded reasonably consistent results. The zircons of sample 6-1 are subconcordant with an age of 1,154 ± 21 Ma in the U-Pb diagram and the error of this determination overlaps with the most reliable evaporation zircon age, of 1,181 ± 9 Ma from the same rock. The old age with the smallest error from sample 5-

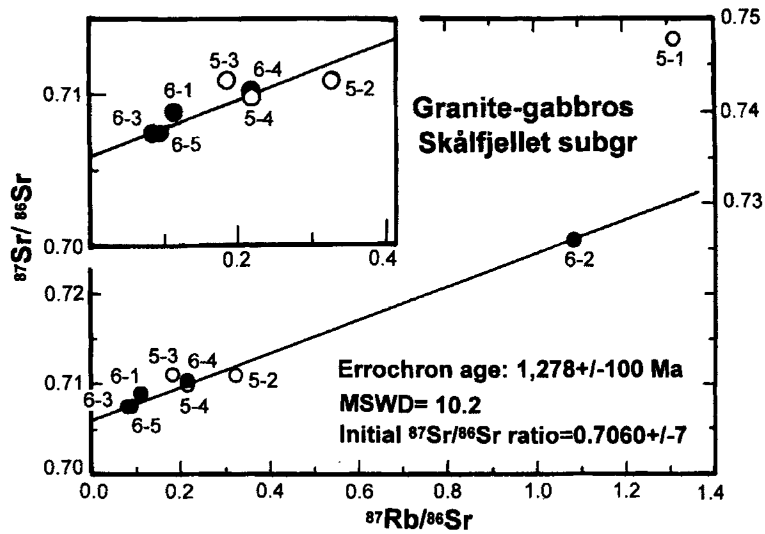

Fig. 13. Rb-Sr errochron of the Skålfjellet granitic-gabbroic rocks.

3, 1,179 ± 6 Ma, is similar. These ages are conformable with previous results from the felsic volcanic clasts of Vimsodden and constrain the magmatic age of the granitic-gabbroic rocks of the Skålfjellet Subgroup. The blocks of the granitic-gabbroic rocks are considered to be consolidated when the host eruptive rocks were exploded. The present results can not distinguish the time difference between these two events and may suggest that there is no recognisable age difference between them.

Slightly younger ages, around 1,130–1,150 Ma, were obtained from samples 6-2, a gabbro, and 5-3, a tonalite. These probably reflect discordant zircons.

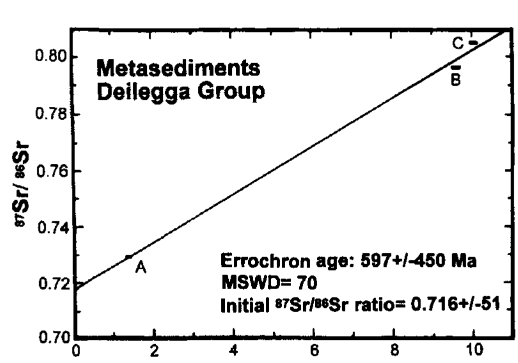

Fig. 14. Rb-Sr errochron of the metasediments from the Deilegga Group.

An Rb-Sr errochron yielded an age of 1,278 ± 100 Ma which is in rough agreement with the zircon ages. The age of 1,300 Ma from sample 5-2 (Table 2) remains debatable. It could reflect older radiogenic lead.

The poorly constrained U-Pb zircon upper intercept age for the Isbjørnhamna schists, ca. 1,503–1,750 Ma, as old as 2,300 Ma, suggests the presence of Paleoproterozoic detrital material, similar to the earlier results of Balašov et al. (1995). The lower intercept age of ca. 360 Ma suggests Caledonian or younger readjustments. The sedimentary protoliths of the Isbjørnhamna schists are possibly of Mesoproterozoic age, containing Paleoproterozoic zircons as detrital grains, and metamorphosed during the Grenvillian time, as suggested by the Rb-Sr whole rock age obtained by Gavrilenko et al. (1993) and Balašov et al. (1995).

The apparent latest Neoproterozoic Rb-Sr whole rock age of the Deilegga Group phyllites, ca. 600 Ma, can be explained as partial readjustment of the Proterozoic isotope system by low grade metamorphism during the Caledonian event. It is evident that this group is overlain by the Slyngfjellet Conglomerate (Fig. 2) with a distinct angular unconformity, but its age-relationship to the Eimfjellet and Isbjørnhamna Groups is still unknown.

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