Composition and provenance of the Lilljeborgfjellet Conglomerate Haakon VII Land, Spitsbergen

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The Siktefjellet Group of late Silurian or early Devonian age, consisting of the Lilljeborgfjellet Conglomerate and the overlying Siktefjellet Sandstone, is generally accepted as the oldest part of the Old Red Sandstone in Spitsbergen. Most of the clasts of the conglomerate are only slightly rounded and consist of lithologies typical for the underlying basement. A minor component of quartz porphyry clasts is present; these are well-rounded, indicating a longer transport. The provenance of the quartz porphyry clasts is discussed in relation to the known outcrops of quartz porphyry in Svalbard, one occurring in the neighbourhood of the conglomerate, the other ones far away. The quartz porphyry in close proximity is younger than the Lilljeborgfjellet Conglomerate and therefore not a possible source rock. A close petrographic and geochemical comparison with the quartz porphyries at three localities in Nordaustlandet (150–200 km in easterly direction and of probable Grenvillian age) is presented showing many similarities, but enough differences to question their interrelationship. The porphyries of the Hornsund area (300 km in southerly direction and also of probable Grenvillian age) are found to be chemically and petrographically distinctly different from the Lilljeborgfjellet clast porphyry. Metarhyolite reported from the Planetfjella and Harkerbreen Groups in Ny Friesland are not comparable with the clast porphyry. As no unquestionable source rock among the quartz porphyries is known in outcrop, the possibility of a hidden or completely eroded parent rock is considered.

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Introduction

During a sledge expedition in 1909, O. Holtedahl (1926) investigated the Devonian Red Bay series around Raudfjorden. The series which had been reported previously by Nordenskiöld (1892) is confined by north-south trending faults and consists of a basal conglomerate and overlying sandstones of typical Old Red Sandstone (ORS) affinity. In Rabotdalen, on the east side of the fjord, Holtedahl noticed two kinds of conglomerate, one coloured red and yellow and dominated by marble and dolomite clasts, the other more polymictic boulder breccia of grey colour. Although the conglomerates were separated by a distinct fault, Holtedahl considered them to be only different facies of the basal Devonian conglomerate, later named by Friend (1961) the Red Bay conglomerate. Gee & Moody-Stuart (1966) found that the grey breccia, which they named the Lilljeborgfjellet Conglomerate, is the basal unit of a conglomerate-sandstone succession resting unconformably on metamorphic rocks and discordantly overlain by the Red Bay conglomerate. They proposed the name Siktefjellet Group for this succession, restricting the use of the Red Bay conglomerate to the red and yellow marble conglomerate and the overlying red brown quartz chip conglomerate of earlier published studies.

When investigating the Lilljeborgfjellet Conglomerate, the present author noted a striking difference between most of the clasts, which are only slightly rounded and consist of lithologies common in the neighbouring basement; a few are well-rounded and composed of quartz porphyry. The latter are unknown in the basement except for some occurrences in Nordaustlandet and the Hornsund area. These observations raise the question of a very long transport distance of the quartz porphyry clasts versus the possibility of hidden or eroded occurrences of quartz porphyry at a closer distance.

Extent and lithology

Except for some areas which are covered by glaciers, the 150 to 400 m thick Lilljeborgfjellet Conglomerate extends as a continuous unit from the Rabotdalen pass east of Raudfjorden to the Siktefjellet mountain on the northern shore of

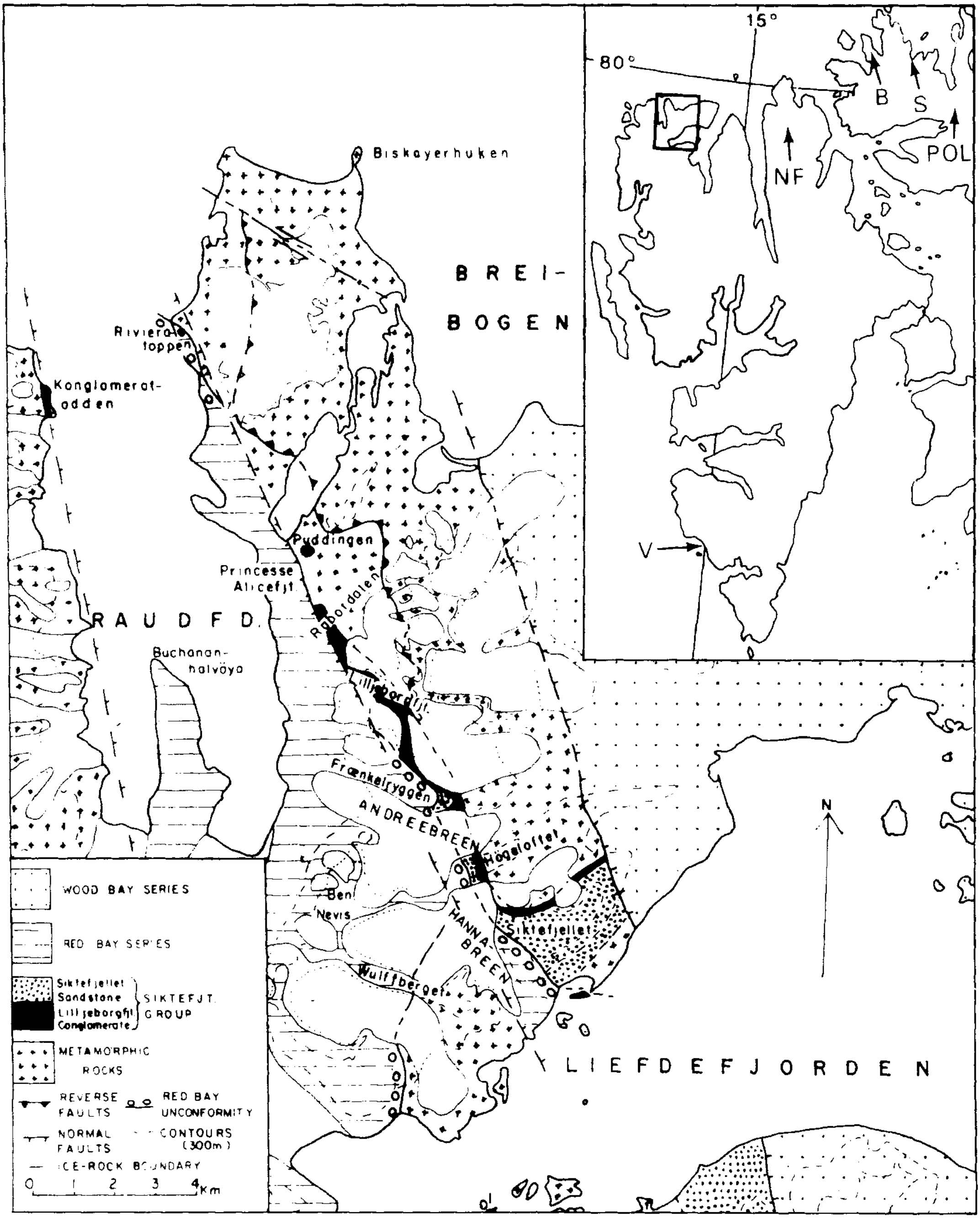


Fig. 1. Geological sketch map, extracted from Gee & Moody-Stuart (1966, fig. 1). Locations of Nordaustlandet quartz porphyries: B = Botniahalvøya, S = Sabinebukta, POL = Prins Oscars Land (Rijpdalen). Location north of Hornsund: V = Vimsodden, NF = Ny Friesland.

Liefdefjorden (Fig. 1), a distance of 14 km. It generally dips 30–50° WSW. In Puddingen, to the north of Rabotdalen, an isolated outlier of "a red quartz conglomerate" was found by Holtedahl (1926, p. 11) who considered that it belonged to the Red Bay conglomerate series. However, Gee & Moody-Stuart (1966, p. 62) included it in the Siktefjellet Group. This author has found two additional, isolated occurrences of the same conglomerate on either side of the Hannabreen glacier tongue in Liefdefjorden. Gee & Moody-Stuart (1966) also considered the possibility that the marble conglomerate at the promontory of Konglomeratodden on the western side of Raudfjorden might be a separate unit of the Siktefjellet Group, without giving conclusive evidence.

At its northern end in Rabotdalen (Fig. 1), the Lilljeborgfjellet Conglomerate tapers out with a basal breccia resting on an irregular basement of schists and gneisses. When visible, the contact is mostly sharp, in part tectonically disturbed by steeply west-dipping shear planes. In other places, the immediately underlying basement is coloured red by a network of small, hematite-bearing veins down to a depth of 20–30 m below the unconformity. Also, the basal part of the conglomerate comprises numerous clasts of gneiss containing the same hematite vein system. In one place Holtedahl (1926, p. 12) also noted a transitional layer of huge, angular pieces of crystalline rocks between the conglomerate and the basement rocks.

The breccia in Rabotdalen consists of very coarse (up to 1 m), angular clasts of gneiss, marble, and metabasites (Fig. 2), many of which are garnet-bearing and of medium to high metamorphic grade. Similar lithologies occur in small areas of the adjacent crystalline rocks (Gee 1966, chap. 6). Both stratigraphically upwards and laterally southwards the conglomerate clasts generally become more rounded, the proportion of quartzite increases, and especially in the transition zone to the overlying Siktefjellet Sandstone the clasts diminish to form a pebble conglomerate interbedded with arkosic sandstone. In the intermediate and lower levels the clasts are still mostly massive, and particularly in the basal part angular clasts of crystalline schists or gneisses are ubiquitous. Clasts of coarse-grained marble are also common, but dolomite marble, which is so frequent in the Red Bay conglomerate, is very rare. Less common, but nearly always present, are the well-rounded clasts of quartz porphyry. These are much better rounded than the clasts of other lithologies (Fig. 3). In most cases they make up only 1% or less of the clasts. In one place, however, as much as 5–10% has been observed. The size ranges from a few cm to 1.5 m, but most clasts are small. The subordinate matrix of the Lilljeborgfjellet Conglomerate consists mostly of small pieces of the same rock types as in the larger clasts, perhaps with a greater proportion of mica-rich schists and gneisses.

Unfortunately, this study lacked the necessary logistic support for a detailed sedimentologic

Fig. 2. Angular clast of augen gneiss (below center) in massive Lilljeborgfjellet Conglomerate, Rabotdalen.

Fig. 3. Well-rounded clast of quartz porphyry, 1 m long, in Lilljeborgfjellet Conglomerate, eastern border of the snout of Hannabreen.

investigation of the Lilljeborgfjellet Conglomerate from Rabotdalen all the way to Siktefjellet. Most of the observations are from exposures in the vicinity of Raudfjorden in the north and Liefdefjorden in the south. The conglomerate is to a great extent covered by debris or snow; the best exposures are either inaccessible or too hazardous for field observations. Thus, it was not possible to investigate whether there are any internal stratigraphic relationships defined by the quartz porphyry clasts. Nor was it possible to measure any lateral variation in their frequency distribution.

The lithology and angular to subrounded shape of the clasts, except for the small number consisting of quartz porphyry and perhaps for the most rounded quartzites, indicate a short transport of the components of the Lilljeborgfjellet Conglomerate. All lithologies, again with the exception of the quartz porphyry, are comparable with those of the underlying or adjacent metamorphic rocks (Holtedahl 1926; Harland 1961; Gee & Moody-Stuart 1966). It should be especially noted that exposures of garnet-bearing, medium to high-grade metabasites in Spitsbergen are restricted to the adjacent Richarddalen Complex (see map, fig. 3 in Peucat et al. 1989). On the other hand, the quartz porphyry clasts present an enigma, at least a contradiction. Their well-rounded shape, despite the tough and hard composition, testifies of a longer transport than for the other clasts. However, quartz porphyry has nowhere been observed in the Hecla Hoek successions of northwestern Spitsbergen.

Exposures of quartz porphyries in Svalbard

Quartz porphyry outcrops have been reported from five areas in Svalbard. The one nearest to the Lilljeborgfjellet Conglomerate is located on the Frænkelryggen ridge in Raudfjorden, only about 2–3 km southwest of Lilljeborgfjellet. Three other outcrops are located 150–200 km to the east, on the island of Nordaustlandet (Fig. 1). Quartz porphyry has also recently been found on the western coast of Spitsbergen, a little to the north of Hornsund.

Frænkelryggen area

In the Frænkelryggen area, two beds of "welded tuff", each 4 m thick, are interbedded in the Frænkelryggen Sandstone which is situated in the middle of the Red Bay Group (Murašov et al. 1983). Besides phenocrysts of quartz and feldspar in a microfelsitic groundmass, the welded tuff contains about 30% clastic fragments and might rather be called a tuffite. In this way it differs from the quartz porphyry clasts and the Nordaustlandet quartz porphyries, none of which contain extraneous clastic components. Plagioclase phenocrysts make up 3–5% of the rock, orthoclase 1–2%. The sizes are 0.2–0.4 mm and 0.1–0.2 mm respectively. Orthoclase phenocrysts are completely altered to clay minerals. The groundmass is excessively replaced by carbonate, mica and chlorite. The rock is mottled with a carbonate mineral, a phase which also occurs in

Table 1. Chemical composition (anhydrous) of quartz porphyry from Frænkelryggen and from the Vimsodden conglomerate, and of posttectonic granite from northwestern Spitsbergen.

No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
1	71.15	0.18	17.27	1.32	0.79	0.11	1.51	1.85	1.60	4.06	0.13	99.97
2	76.69	0.22	14.00	1.16	0.71	0.06	1.20	1.93	1.45	2.50	0.13	100.00
3	73.91	0.20	15.64	1.24	0.75	0.09	1.36	1.89	1.53	3.28	0.13	99.99
4	70.01	0.22	12.73	4.19	0.65	0.02	0.60	1.59	0.23	9.59	0.11	99.99
5	62.22	0.18	14.67	2.72	1.60	0.41	1.31	5.45	0.30	10.97	0.16	100.00
6	66.12	0.20	13.70	3.46	1.13	0.22	0.96	3.52	0.27	10.28	0.14	100.00
7	70.94	0.31	15.07	0.49	2.06	0.04	0.59	1.87	3.15	4.44	0.07	99.83

No. 1 Welded tuff, Frænkelryggen, upper layer.
No. 2 Welded tuff, Frænkelryggen, lower layer.
No. 3 Average of 1 and 2
No. 4 Porphyric clast, Vimsodden conglomerate, Hornsund.
No. 5 Aphanitic clast, Vimsodden conglomerate, Hornsund.
No. 6 Average of 4 and 5.
No. 7 Average of 8 samples of granite dikes, northwestern Spitsbergen (Hjelle in Hjelle & Ohta 1974, table 3).

numerous microfissures. The upper bed has a 10 cm thick sole with quartz and orthoclase phenocrysts up to 5 mm in length. Two major element chemical analyses, one from each bed (Murašov et al. 1983, p. 98), are recalculated to 100% (anhydrous) and presented as no. 1 and 2 in Table 1.

Hornsund area

Smulikowski (1968, pp. 108–111) reported the presence of slightly metamorphosed rhyolite clasts in a Proterozoic, polymict conglomerate at Vimsodden (V in Fig. 1). According to his description, the clasts only contain phenocrysts of potash feldspar, maximum 2 × 5 mm in size, imbedded in an aphanitic, dark grey matrix and usually exhibiting preferred orientation concordant with the elongation of the pebbles. The matrix consists mainly of quartz and microcline with minor amounts of secondary biotite, sericite and chlorite. Some of the phenocrysts are crushed and deformed, resulting in the crystallization of quartz, biotite and carbonate in internal fissures and along the grain boundaries. The chemical compositions of one porphyric and one aphanitic rhyolite pebble (Smulikowski 1968, table 2), recalculated to an anhydrous composition, are reproduced in Table 1 (nos. 4 and 5). The rhyolite clasts described by Smulikowski do not contain phenocrysts of quartz. However, according to Y. Ohta (pers. comm.) both rhyolite and quartz porphyry lenses have been found in the adjacent Skålfjell amphibolite complex (Birkenmajer & Narebski 1960, fig. 1) which is probably of Grenvillian age (Peucat pers. comm. 1991). Like the rhyolite pebbles of the Vimsodden conglomerate, the chemical composition of these acid vulcanites is characterized by extremely high potash and very low sodium contents.

Nordaustlandet areas

Quartz porphyries occurring on Nordaustlandet (Fig. 1) appear in the form of massive bodies, plugs and dikes in Botniahalvøya (B) and Sabinebukta (S), whereas in Prins Oscars Land (POL) they are strongly foliated and appear as folded sheets. The massive rocks are only slightly altered, mainly by sericitization of the plagioclase phenocrysts and the groundmass, whereas in the POL sheets intense sericitization and carbonate replacement have often led to a complete destruction of the feldspar phenocrysts (Flood et al. 1969; Ohta 1984). However, the metamorphic processes have not obliterated the typical porphyric texture of the rocks nor the characteristic late magmatic corrosion features of the quartz phenocrysts. The Botniahalvøya quartz porphyry has been dated by the Rb/Sr whole rock isochron method to 766 Ma by Gorochov et al. (1977), and has been recalculated by the same authors to a model age of 970 Ma. The quartz porphyry clasts in the Lilljeborgfjellet Conglomerate resemble the Nordaustlandet rocks, both in the frequency and in the composition of the various phenocrysts (Table 2). The feldspar phenocrysts have not been separated in Table 2 due to the complex

Table 2. Proportions of matrix and phenocrysts.

Location	n	Matrix	Phenocrysts	
			quartz	Feldspar
Haakon VII Land (LC clasts)	13	55–81	3–26	12–25
Botniahalvøya (B)	6	59–75	3–13	14–25
Sabinebukta (S)	2	64–67	10–13	20–24
Prins Oscars Land (POL)	3	80–89	6	0–11
Total Nordaustlandet	11	59–89	3–13	0–25

The percentages from Nordaustlandet are calculated from Ohta (1984, table 2c).

intergrowth of the alkali feldspars in the clasts, to be described below. The apparent lithologic similarity between quartz porphyry clasts of the Lilljeborgfjellet Conglomerate and the Nordaustlandet quartz porphyries prompted a detailed petrographic and geochemical study of the former as a basis for comparison with the relevant data of the latter (Flood et al. 1969; Ohta 1984).

Petrography

In both the Lilljeborgfjellet and the Nordaustlandet suites, the size of the quartz phenocrysts is mostly between 2 and 5 mm; the feldspars are a little larger. However, in one of the clast samples the feldspar phenocrysts measure up to 2.5 cm.

In the massive quartz porphyries of Nordaustlandet the alkali feldspar phenocrysts are composed of homogeneous orthoclase or finely lamellar perthite (Fig. 4). In the Lilljeborgfjellet Conglomerate (LC) porphyry clasts, the alkali feldspar phenocrysts display a coarse, patchy intergrowth of potash feldspar and sodic plagioclase (Fig. 5). The uniform extinction of the potash feldspar domains in the plagioclase host crystal indicates that the pattern is formed by exsolution rather than by replacement. Sometimes the potash feldspar forms an outer rim or follows the cleavage directions in the host crystal. In both cases the plagioclase phenocrysts are composed of oligoclase which in Nordaustlandet is evenly and densely clouded by sericite. In the LC porphyry clasts they are replaced by more coarse-grained sericite in irregular patches, along veins or in the marginal zones of the grains.

The matrix of the Nordaustlandet quartz porphyries is microcrystalline and mostly granular, evidently due to recrystallization. Equigranular quartz and feldspar crystals, usually less than 0.02 mm, mixed with scaly sericite, are the main constituents. In a few cases a primary texture of platy, radial feldspar in a spherulitic pattern is

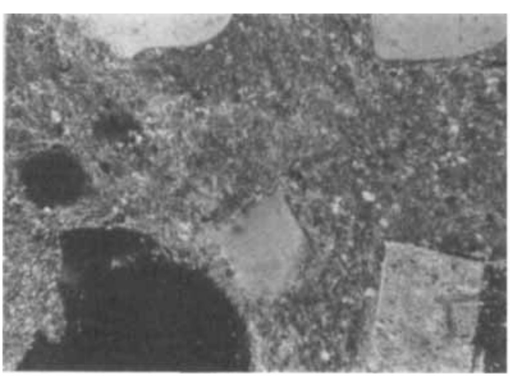


Fig. 4. Quartz porphyry. Botniahalvøya, Nordaustlandet. Phenocrysts: quartz, plagioclase (rhomboidal), perthite (lower left, extinct). 32×.

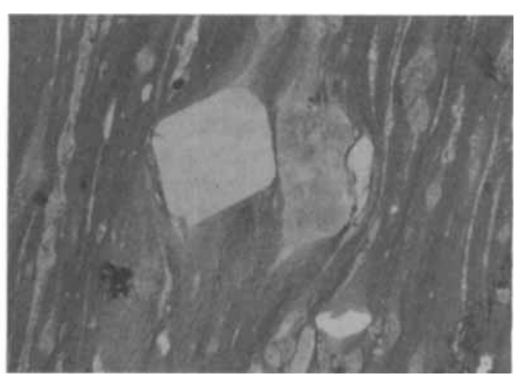


Fig. 5. Sericitized, foliated quartz porphyry, POL (Rijpdalen). Phenocrysts: quartz, (left center, diamond shaped), sericitized potassium feldspar (right center). 13×.

Fig. 6. Rounded phenocryst with intergrowth of plagioclase (white) and potassium feldspar (dark) in clast porphyry from Lilljeborgfjellet. Note jagged border of the phenocryst due to recrystallization of the groundmass. 13×.

observed, indicating devitrification. In the POL rocks, the sericite is sometimes slightly coarser and concentrated in densely foliated bands (Fig. 6). The contact of the phenocrysts appears mostly sharp and smooth, although under high magnification it can be seen that the sericite crystals intersect the margins. Stronger recrystallization of quartz, chlorite, muscovite, and sometimes calcite is seen in strain shadows of the phenocrysts.

In the LC porphyry clasts recrystallization of the matrix is more advanced than in the Nordaustlandet porphyries (except perhaps, for some in POL). A granular texture dominates, the grain size of the groundmass is usually in the range of 0.04–0.1 mm, i.e. twice as coarse. The matrix minerals are the same as in Nordaustlandet: quartz, feldspar and sericite. Potash feldspar seems to be the most abundant feldspar, making up perhaps 30% of the matrix. The phenocrysts are strongly indented by the matrix minerals, including chlorite and sometimes calcite. Iron ore is present in clusters of large, often idiomorphic crystals together with chlorite and calcite in cross-cutting veins and as tiny crystals in the matrix. In one of the clast samples, some plagioclase phenocrysts are encrusted by an opaque rim indicating quick, subaerial cooling. They also have a peculiar glomerophyric texture not observed in the other samples (Fig. 7). At the same time the matrix often shows a spherulitic texture. The source rock of this clast would be of pyroclastic origin. Both in the porphyry clasts and in the Nordaustlandet porphyries, clusters of coarse crystals of quartz, calcite, muscovite, sphene, and iron ore are seen, perhaps representing more or less recrystallized amygdales. Chlorite, muscovite and iron ore also occur, derived through replacement of larger biotite crystals.

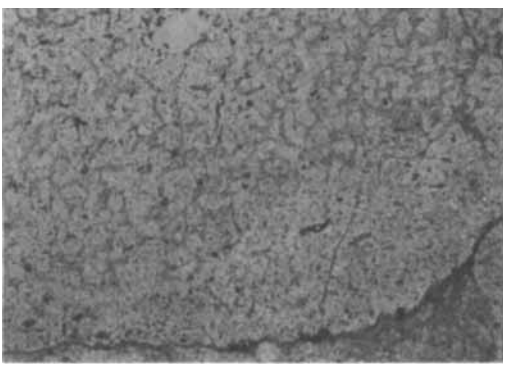


Fig. 7. Glomeroporphyric feldspar with opaque seam along the margin. Clast porphyry, Lilljeborgfjellet. 13×.

To sum up the petrographic evidence, the quartz porphyry of the LC clasts porphyry is in most respects similar to those in Nordaustlandet. The main difference is found in the structure of the alkali phenocrysts and the generally more advanced recrystallization of the former. The two associations both comprise subvolcanic and pyroclastic units which have been metamorphosed in greenschist facies.

Geochemistry

The major element composition of the LC porphyry clasts is given in Table 3, which also provides the average (Av.) compositions of the various oxides. According to the TAS classification all the analysed rocks are high-K rhyolite (Le Maitre 1989, figs. B14 and 15), although a few are close to the borderlines of dacite and trachyte, respectively. The average compositions of the Nordaustlandet porphyries are included in the table for comparison. There is good agreement for most of the elements, the main differences being lower Al and P, much higher Fe^{3+}, and a little higher Ca in the LC clast porphyry. The SiO_2 content of the clast porphyry agrees with the porphyry of Botniahalvøya. However, the latter has an even spread of SiO_2 between 70 and 75%, whereas the clast porphyry has two distinct concentrations of 70 and 74%. K is nearly the same as in the Botniahalvøya area, but dis-

Table 3. Major element composition (anhydrous base) of quartz porphyry clasts in Lilljeborgfjellet Conglomerate.

Sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
78-Gj.111C	73.78	0.37	12.83	2.14	0.46	0.01	0.62	1.67	2.16	6.52	0.04	100.00
78-Gj.151A	73.69	0.48	12.83	1.92	1.13	0.02	0.72	0.94	3.23	4.84	0.06	99.99
78-Gj.151B	73.24	0.43	12.87	1.57	1.11	0.02	1.09	0.31	1.65	7.65	0.06	100.00
78-Gj.157A	70.22	0.67	13.26	3.61	1.31	0.03	1.35	1.49	3.40	4.50	0.13	99.98
78-Gj.157B	70.05	0.63	12.83	4.59	1.15	0.03	0.44	1.50	2.86	5.78	0.14	99.99
78-Gj.157C	70.19	0.78	13.27	2.16	3.06	0.07	1.37	1.36	3.49	4.11	0.15	100.01
78-Gj.159A	70.38	0.72	12.93	4.11	1.08	0.02	1.37	1.69	2.80	4.73	0.14	99.97
78-Gj.159B	74.09	0.32	11.81	0.55	1.34	0.03	1.73	2.67	1.96	5.43	0.04	99.97
78-Gj.159C	71.53	0.58	13.10	3.73	0.78	0.02	0.63	0.95	3.30	5.25	0.12	99.99
78-Gj.159E	74.11	0.41	12.84	0.43	2.05	0.03	0.50	0.91	2.84	5.82	0.05	99.99
78-Gj.177D	73.51	0.43	12.78	2.56	0.28	0.02	0.27	1.70	3.32	5.06	0.06	99.99
78-Gj.182	73.41	0.66	12.89	1.64	1.75	0.03	1.60	0.78	3.07	4.04	0.12	99.99
78-Gj.191D	72.12	0.31	11.20	1.81	0.47	0.03	0.33	5.77	1.53	6.39	0.04	100.00
Av. (13)	72.33	0.52	12.74	2.37	1.66	0.03	0.92	1.63	2.75	5.31	0.09	
Av. B(7)	72.77	0.30	15.06	0.57	1.44	0.02	0.51	1.09	2.82	5.16	0.23	
Av. S(3)	73.82	0.29	14.81	0.37	1.51	0.02	0.79	0.78	3.44	3.94	0.19	
Av. POL(8)	75.13	0.32	14.54	0.80	1.68	0.03	0.81	1.06	1.49	3.91	0.21	

Sample no. 78-Gj.111C is collected near the Høgeloftet ridge north of Liefdefjorden. The other samples are from the area between Rabotdalen and Lilljeborgfjellet on the eastern side of Raudfjorden.

tinctly higher than in the two other areas in Nordaustlandet. In Figs. 8–11 the distribution of the elements of the LC clast porphyry is shown by crosses in the various oxide variation diagrams given by Ohta (1984, pp. 85–88, 90) for the Nordaustlandet rocks. Fig. 8A shows that the total alkali content of the LC clast porphyry is in the same range, or slightly higher range, as that of Botniahalvøya. In the alkali variation diagrams (Fig. 9C) it is seen that especially the K_2O content of some samples is higher, although most of the samples are within the same range as the Botniahalvøya rocks. Since the LC clast porphyry has been subjected to extensive sericitization of the matrix as well as the feldspar phenocrysts, it is conceivable that some K has been introduced. However, the Al diagram (Fig. 9C) shows that the Al_2O_3 content of the LC porphyry clasts is consistently lower than the content of the clasts of Nordaustlandet. Moreover, the Al content of the former lies in the range of representative rhyolites of the andesite-rhyolite family (Carmichael et al. 1974, table 2–2). These relationships suggest that the source rock of the clast porphyry initially has a high amount of potash feldspar, rather than being subjected to potash metasomatism at a later stage. The relevant diagrams in Fig. 9C demonstrate that the trends of FeO, MgO and CaO in the clast porphyry are the same as in the Nordaustlandet rocks. However, both Fe and Ca have been mobilized and perhaps introduced during the recrystallization of the clast porphyry, as shown by the vein-like or cleavage-related distribution of iron oxides in some samples, and by the numerous cross-cutting calcite veins. Because of the latter, one very high Ca figure was discarded from the diagram.

According to the data for Al and the alkalis given by Carmichael et al. (1974), Mueller & Saxena (1977), and Wilson (1989), the LC clast porphyry compares better with the acid derivates of continental tholeiitic flood basalts and other continental rhyolites than with oceanic and volcanic arc rhyolites. Accordingly, the clast porphyry is most probably derived from a continental source.

Trace element data on the LC porphyry clasts are given in Table 4. Ohta (1984, table 6) provided trace element data only for Sr, Ni, Co and Cr for the Nordaustlandet quartz porphyries, classified as H-K and M-K CA rhyolites. Compared with his figures, Sr in the clast porphyry is similar to the M-K CA rhyolite, but much higher than the H-K rhyolite. Ni and Cr are much lower than in both kinds of the Nordaustlandet rhyolites; Co is also lower. The content of P_2O_5 is distinctly lower in the clast porphyry (Fig. 11A), and the Ni/Cr proportions are also different (Fig. 11B). Trace

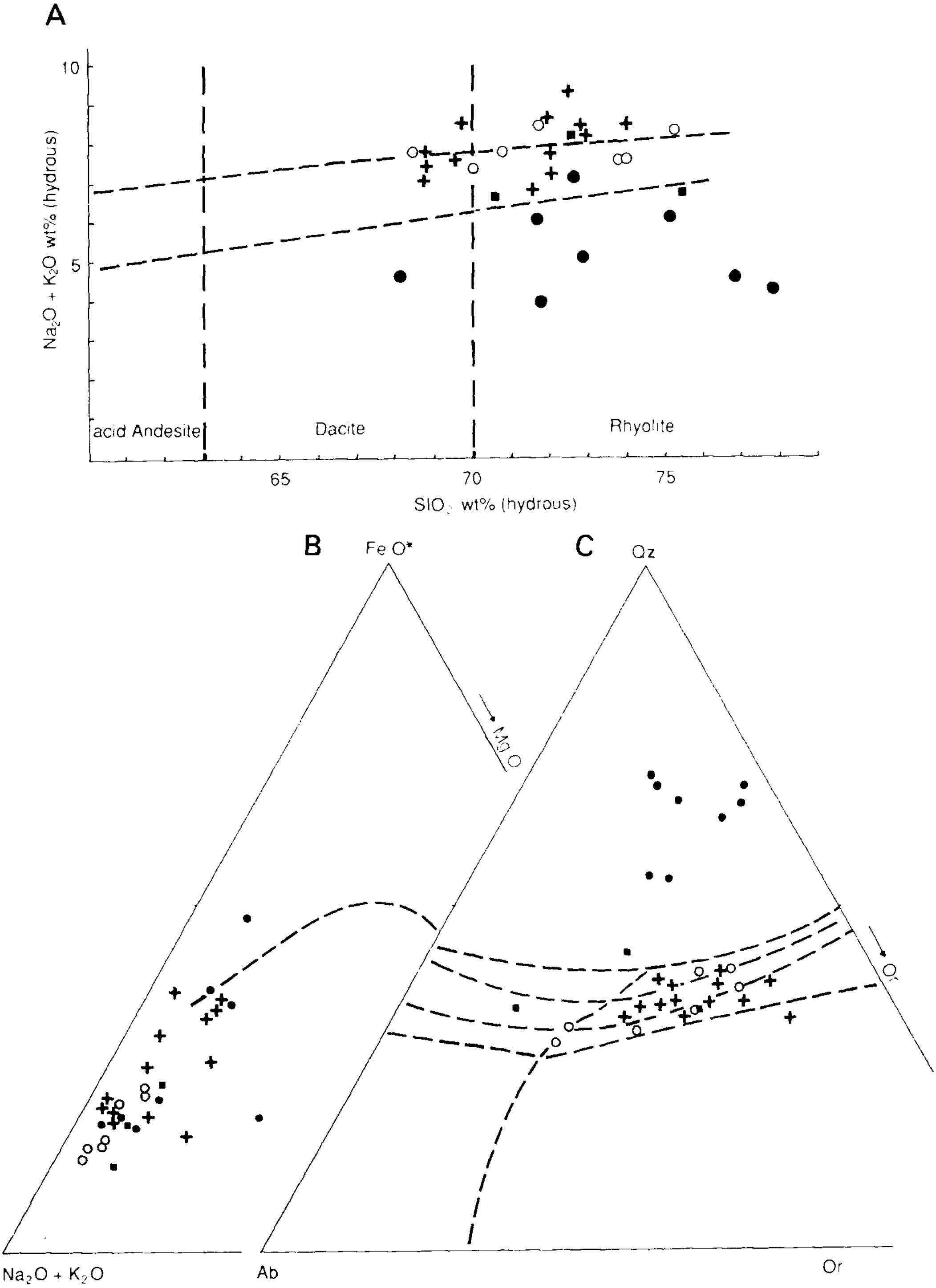
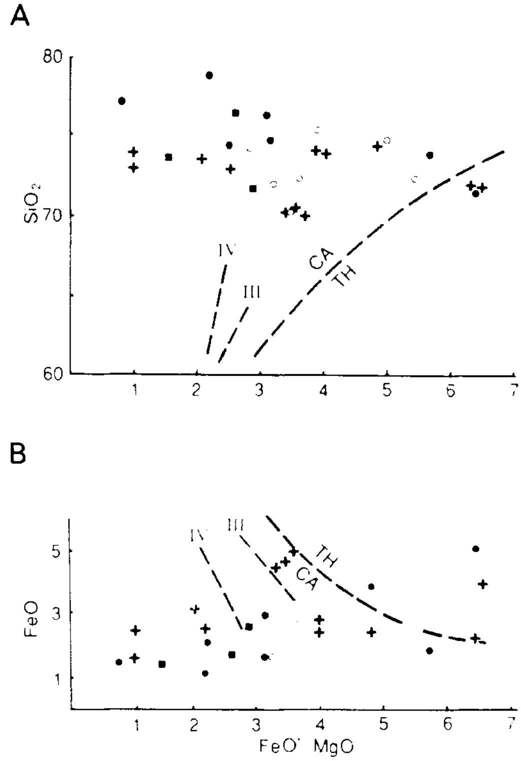


Fig. 8. A. Alkali—SiO_2 diagram (hydrous). B. AFM diagram. C. Normative Qz-Ab-Or diagram. Symbols: Open circles = Botniahalvøya; solid squares = Sabinebukta; solid circles = Prins Oscars Land; crosses = Lilljeborgfjellet Conglomerate clast porphyry. Reference for dividing lines in Ohta (1984, fig. 9).



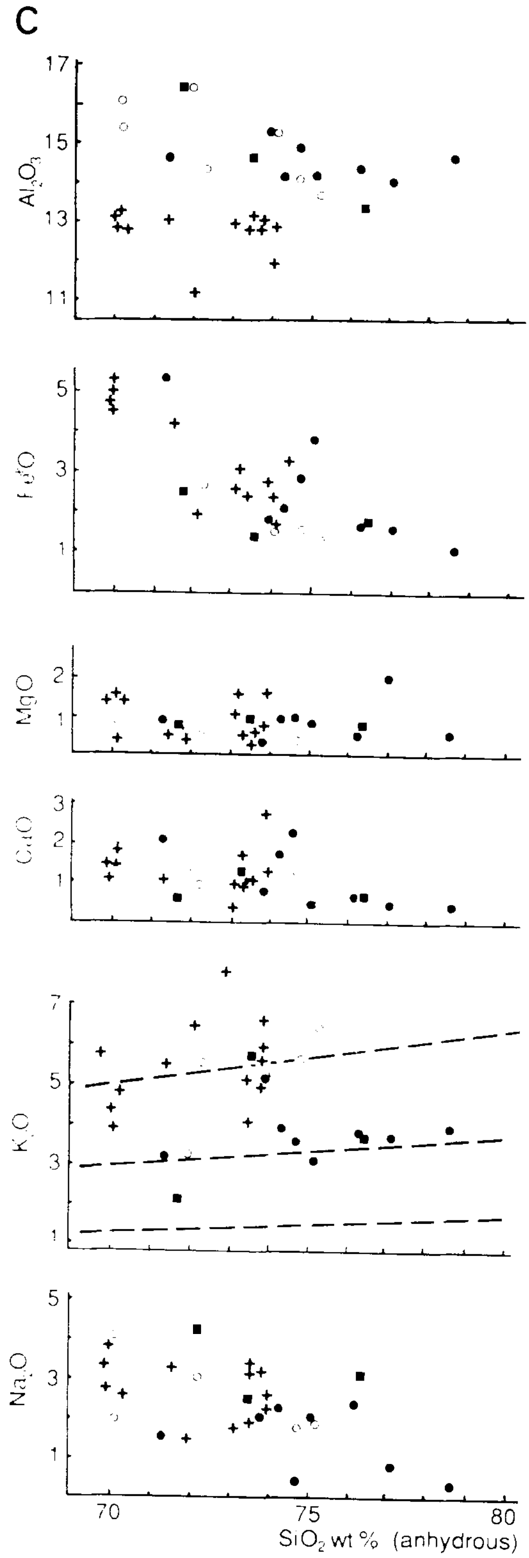


Fig. 9. A. SiO_2–FeO/MgO diagram. B. FeO–FeO/MgO diagram. C. Harker variation diagrams. Symbols as for Fig. 8. Reference for dividing lines in Ohta (1984, fig. 10)

element data of rhyolites elsewhere are scarce, even rarer for quartz porphyries. According to tables in the textbooks of Carmichael et al. (1974) and Wilson (1989), Cr, Ni, Ba, Rb and Zr in the LC clast porphyry compare well with those of the rhyolites in continental, tholeiitic flood basalt provinces. But Sr is somewhat lower, as are P_2O_5 and TiO_2.

Discussion and conclusion

The chemical and mineral compositions of the welded tuffs in the Frænkelryggen Sandstone Formation differ considerably from that of the LC quartz porphyry clasts. According to the description by Murašov et al. (1983), the alteration of the tuffs also seems to be greater. If they were to be the source rocks, it would also imply an inversion of the succession since the Siktefjellet Group underlies the Red Bay Group. As there is

Table 4. Trace elements of quartz porphyry clasts.

Sample no.	Ba	Co	Cr	Cu	Nb	Ni	Rb	Sr	Y	Zn	Zr
78-Gj.111C	985	29	16	17	55	1.1	274	39	103	24	418
78-Gj.151A	1066	41	2	7	60	6.9	122	72	111	24	508
78-Gj.151B	883	40	25	3.5	58	1.9	226	37	115	38	468
78-Gj.157A	825	33	14	15.6	53	10.1	107	26	127	48	636
78-Gj.157B	1192	62	7	9	58	8.6	125	100	132	36	676
78-Gj.157C	1124	36	48	5.5	57	2.6	99	93	128	116	684
78-Gj.159A	695	37	20	7.1	49	5.7	125	21	111	30	628
78-Gj.159B	781	49	27	22.4	45	5.1	151	51	86	30	341
78-Gj.159C	1274	57	13	4.3	48	4.8	154	66	104	67	548
78-Gj.159E	1124	29	12	1.6	51	—	183	61	109	41	405
78-Gj.177D	1992	40	—	0.7	47	4.1	143	84	99	20	421
78-Gj.182	690	36	7	1.5	55	3.4	101	84	102	48	507
78-Gj.191D	776	26	60	—	45	0.9	187	127	91	12	349
Average(x)	1331	40	19	6	53	4	153	66	109	41	506
o.n.		10	17			3		30			

For sample locations see Table 3.

no indication of an inversion here, this alternative can be ruled out with some confidence.

Bulk chemistry and petrography of the LC clast porphyry are in many respects similar to that of Nordaustlandet. The main petrographic difference is the structure of the alkali phenocrysts and, at least in relation to the quartz porphyries of B and S, a more advanced recrystallization of the LC porphyry clasts. Both associations comprise subvolcanic and pyroclastic units which have been subjected to metamorphism in greenschist facies. In most respects there is also good correlation between the chemical composition of the quartz porphyry clasts and that of the Nordaustlandet quartz porphyries, especially those of Botniahalvøya. But there are deviations particularly in the amounts of Al, Cr and Ni, which speaks against the possibility of the Nordaustlandet quartz porphyries being the source rocks of the LC quartz porphyry clasts. This alternative also raises other objections. Not only is the transport distance from Nordaustlandet to Haakon VII Land very long, but the direction is transverse to the general structural trend of the basement, which would probably create topographic barriers for river transport. Considering the large size of some of the clasts, it is especially difficult to reconcile the idea of such a long transport

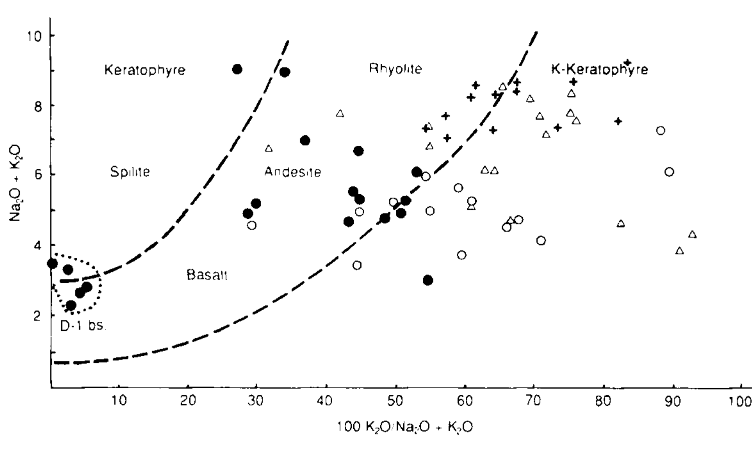


Fig. 10. Alkalis vs. 100 K_2O/Na_2O+K_2O diagram. Symbols as for Fig. 8. Reference for dividing lines in Ohta (1984, fig. 12).

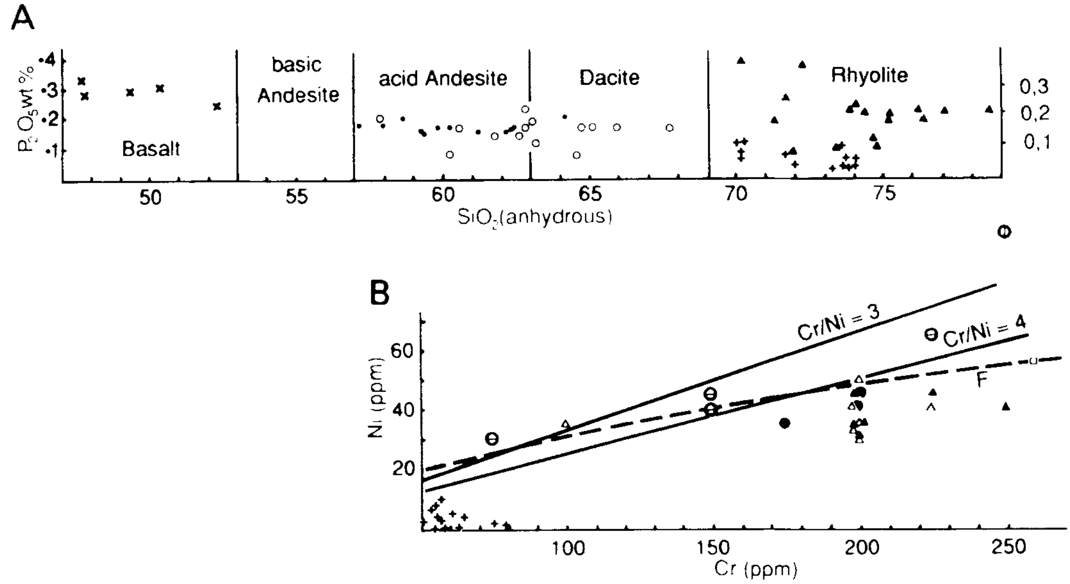


Fig. 11. A. P_2O_5–SiO_2 diagram. Symbols: x = basic dike rocks, Nordaustlandet; open circles = porphyrite and andesite, Nordaustlandet; solid circles = metadiabase, Nordaustlandet; solid triangles = quartz porphyries, Nordaustlandet; crosses = LC clast porphyry. Dividing lines from Ohta (1984, fig. 11a). B. Ni–Cr diagram. Symbols: open circles with horizontal lines = high K_2O calc alkaline rocks; open triangle = medium K_2O tholeiites; solid triangles = high K_2O tholeiites; crosses = LC clast porphyry. Reference for broken curve, Ohta (1984, fig. 11c).

distance. On the other hand, the rounding of the clasts suggests that they are not derived from the adjacent basement rocks.

The quartz porphyries in the Hornsund area are also unlikely to be the source of the LC clasts, since the chemistry as well as the petrology of the two types are very different. The distance between them, 300 km, is also very long, but it might have been less prior to possible strike slip movement along the western Spitsbergen fold belt direction.

Also from Ny Friesland (NF on Fig. 1), the northeastern peninsula of Spitsbergen, rocks thought to be derived from acid volcanics have been reported (Gayer & Wallis 1966; Wallis 1969). They occur both in the basal part of the Planetfjella Group and in the upper formations of the underlying Harkerbreen Group; they mostly comprise massive, feldspar-rich beds, now present as augen-gneisses. They are considered to be reworked, acid pyroclastics (Gayer & Wallis 1966). Some smaller beds consisting of crenulated schists with "megacrysts" of feldspar (up to 5 mm in length), set in a fine-grained groundmass, are called meta-acid-tuffs. They have not been reported to contain relics of quartz phenocrysts. No chemical data on these rocks has been published, and their origin is uncertain (Wallis 1969). Recent zircon U/Pb dating (Gee 1991, unpubl. data from Peucat & Tebenkov 1990; Ohta in press) has shown that the Harkerbreen Group belongs to the Sveco-Karelian period, whereas the Planetfjella Group may be of Grenvillian age. The rocks have been subjected to orogenic deformation and recrystallization in amphibolite facies, and the feldspar "megacrysts" occurring in both groups could be a product of Caledonian or older events. Whatever their origin, they are not similar to the LC quartz porphyry.

Thus, none of the known outcrops of quartz porphyry in Svalbard satisfy the petrological and chemical criteria for the source rock. Most of the clasts in the LC can readily be matched with lithologies in the adjacent basement. Other alternatives must therefore be considered, such as quartz porphyry bodies which have been completely eroded. The adjacent area of northwestern Spitsbergen consists of amphibolite facies gneisses, migmatites and granite. At originally higher stratigraphic levels, extrusive or subvolcanic rhyolite might have occurred. As referred to above, "welded tuff" of quartz porphyric composition is interbedded in the Frænkelryggen Formation of the Red Bay Group which was deposited in the early Gedinnian (Blieck et al. 1987) at about 400–410 Ma. However, the source rock in question would have to have been formed earlier. Acid igneous activity (including the Hornemantoppen granite) in northwestern Spitsbergen started somewhat earlier, a related vulcanite might have provided a source. However, the interrelationship of the deep-seated granites of north-western Spitsbergen and the welded quartz porphyric tuff in Frænkelryggen is still an open question. Although the correspondence of most elements in the two rock types is good (Table 1), it is less so for the alkalis and Mg. The correspondence is somewhat better for these critical elements when comparing the post-tectonic granites and porphyry of the LC clasts, but the Al_2O_3 contents of the former are more than 2% higher (Table 1). In 21 samples of syntectonic granites (> 68% SiO_2) from the Smeerenburgfjorden area, the average Al_2O_3 value is more than 3% higher (calculated from Ohta, table 5, pp. 94–95 in Hjelle & Ohta 1974).

In any case, because of the deep erosion, the tectonic setting, and the high metamorphic grade of the rocks to the north of Kongsfjorden, a possible source rock on the western side of the Devonian Graben could only be expected south of Kongsfjorden. Despite high mapping activity in recent years on the western coast of Spitsbergen, no quartz porphyry outcrop has been reported north of Bellsund. The same is the case for the anticlinal Hecla Hoek horst in the Raudfjord Devonian Graben.

Other possible source rocks could be hidden under the sediments of the Devonian Graben, under large ice caps, or under the sea off the northern coast of Spitsbergen. So far, no quartz porphyry pebbles have been reported from the shelf, but very little sampling has been done. The northern shelf is perhaps not a probable source area, since it would imply a transport direction in Devonian time from north to south, opposite or transverse to what is believed by Orvin (1940, p. 15) and Friend & Moody-Stuart (1972, p. 17). The conclusions of their studies, however, are based on sedimentological investigations of the Red Bay/Wood Bay Groups, and the paleogeographical situation during deposition of the Siktefjellet Group might have been different. The seemingly increased degree of rounding southwards of most clast lithologies in the latter indicates a source area to the north of the present location. This does not apply for the quartz porphyry clasts, however, which are equally rounded everywhere.

It may be concluded that the present information is insufficient to give a definite answer to the question of the provenance of the quartz porphyry clasts. Isotope dating of zircons from these clasts may provide a useful constraint on the potential alternatives.

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