Geochemistry of the late Proterozoic Kapp Hansteen igneous rocks of Nordaustlandet, Svalbard

YOSHIHIDE OHTA

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Proterozoic igneous rocks occur in three areas in Nordaustlandet, Svalbard, and are found in the upper part of the Lower Hecla Hoek succession, the Botniahalvøya Supergroup. The rocks have been called porphyrites in Botniahalvøya, metadiabases in Prins Oscars Land and quartz porphyries in both areas as well as in the Sabinebukta area. All rocks have been metamorphosed under the greenschist facies conditions.

The porphyrites are calc-alkaline acid andesites and dacites of medium to high K_2O type, possibly showing a transition to tholeiitic series. The quartz porphyries are calc-alkaline rhyolites of high K_2O type. The metadiabases are subdivided into two: the basic dykes of low K_2O type and relatively high Fe tholeiite series, while the main bodies are acid andesites of medium to high K_2O and low Fe tholeiite series. The basic dykes fall in the oceanic rock field of the TiO_2-K_2O-P_2O_5 diagram, and are most likely belonging to the island arc type volcanism. The metadiabases of main bodies and the porphyrites, and possibly the quartz porphyries, are chemically continuous. The medium to high K_2O contents, and their TiO_2-K_2O-P_2O_5 ratios suggest that these three rock groups are non-oceanic and resemble the rock associations of the areas having thick continental crust. This conclusion agrees with the reported high initial $Sr^{87/86}$ ratios and the existence of a distinct unconformity at the base of this volcanogenic succession.

Yoshihide Ohta, Norsk Polarinstitutt, Rolfstangveien 12, 1330 Oslo Lufthavn, Norway; *May 1984 (revised October 1984).*

Introduction

A distinct igneous succession has long been recognized in the Precambrian Lower Hecla Hoek successions of Nordaustlandet (Hjelle & Lauritzen 1982; Lauritzen & Ohta 1984). A metaporphyrite unit was first described by Kulling (1934) in Botniahalvøya, then similar rocks were reported from Sabinebukta by Sandford (1950), and a third locality was found in southern Prins Oscars Land by Flood et al. (1969) (Fig. 1). Flood et al. defined the Kapp Hansteen Formation to the volcanogenic succession in the Botniahalvøya Group. A revision of the stratigraphy was made by Ohta (1982) as shown in Table 1 and this paper will use these new terms.

The Kapp Hansteen Group in the Botniahalvøya area consists of both porphyrite and quartz porphyry, but in Sabinebukta of quartz porphyry alone, and in Prins Oscars Land of metadiabase and quartz porphyry. These igneous rocks comprise the upper part of the Botniahalvøya Supergroup (= Lower Hecla Hoek), being overlain by the cyclic clastic sediments of the Murchisonfjorden Supergroup (= Middle Hecla Hoek) and underlain by an areno-argillaceous succession of the Brennevinsfjorden Formation. The igneous succession has been correlated with the lower Planetfjella Group of the Stubendorffbreen Supergroup of Ny Friesland, northeast Spitsbergen (Harland et al. 1966; Ohta 1982) (Table 1).

This paper presents the modes of occurrence, petrography, and the bulk rock chemistry of these igneous rocks with some consideration on their tectonic circumstances.

Modes of occurrence

The three distribution areas of the Kapp Hansteen igneous rocks are shown in the three maps of Fig. 2, with the localities of analysed rocks: P-porphyrites, Q-quartz porphyrites, D-metadiabases.

1. The Botniahalvøya area (Figs. 1 and 2a)

A clear unconformity has been found at the base of the Kapp Hansteen Group in the southern part of the peninsula and a similar relationship was inferred in the northern part; the Brennevinsfjorden Formation occurs below the group (Ohta 1982 and Table 1). The upper boundary of the

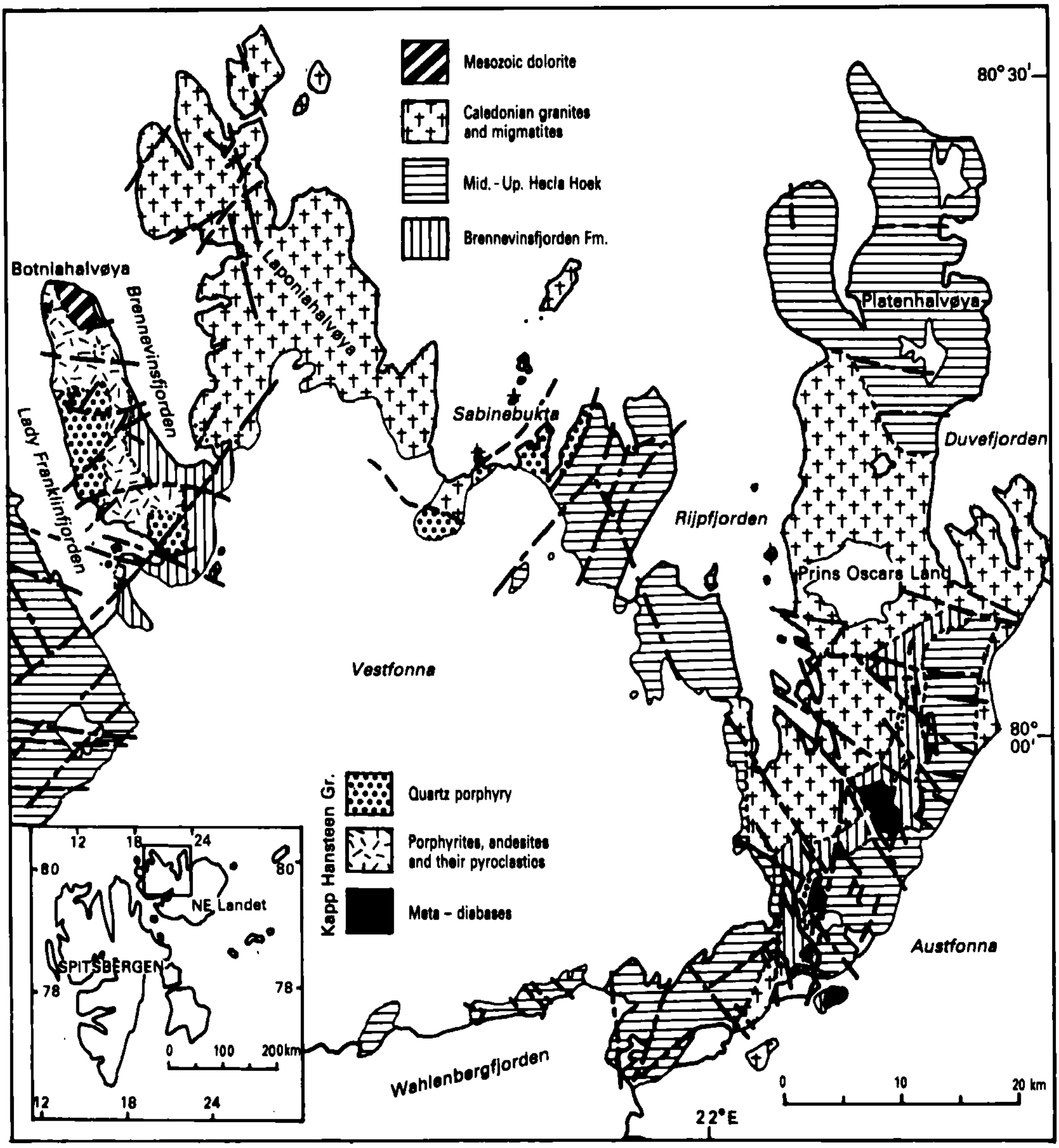


Fig. 1. Distribution of the Kapp Hansteen igneous rocks in Nordaustlandet.

group is not clear, although a small exposure of conglomerate with quartz porphyry boulders occurring just north of the Horgenkollen quartz porphyry mass may indicate the base of the overlying Murchisonfjorden Supergroup (Flood et al. 1969; Ohta 1982).

A little less than half the peninsula area, excluding the areas of the Brennevinsfjorden Formation and the Mesozoic dolerite, is occupied by the quartz porphyry which intruded as stocks and dykes into the rocks of the Botniahalvøya Supergroup. Flood et al. (1969) excluded the quartz porphyry from their stratigraphic column. This rock never cuts the Murchisonfjorden Supergroup and has been found as boulders in the possible basal conglomerate of the latter; therefore, it is considered to belong to the Kapp Hansteen Group.

Table 1. Stratigraphy of the Hecla Hoek successions in Nordaustlandet (Ohta 1982), with the correlation to that of Ny Friesland (Harland et al. 1966). Radiometric ages are from Edwards & Taylor (1976) and Gorochov et al. (1977).

Ny Friesland			Nordaustlandet					
Supergroup	Group	Thickness (m)	Supergroup	Group	Thickness (m)			
					Murchisonfj.	Wahlenbergfj.	Sabinebukta	Pr. Oscars L.
Hinlopenstr.	Oslobreen Polarisbreen	1197+	Hinlopenstr. (U.H.H.)	Kapp Sparre Sveanor	1500	225+		
Lomfjorden	Akademikerbreen	2490	Murchisonfjorden (Mid Hecla Hoek)	Roaldtoppen	1250	400+		
	Veteranen	3800		Celsiusberget	2140	1650	1250+	
				Franklinsundet	1775	1150	1380+	1717
Stubendorffbreen	Planetfjella	4750		Meyerbukta/ Austfonna	1200+	1365	650+	1630+
			Botniahalvøya (Low Hecla Hoek)	Kapp Hansteen	(766 Ma) ext: c. 2000		ext. 200-300 intr: c. 2000	
				Brennevinsfjorden ?	c. 3000		c. 3000	
	Harkerbreen	4100		meta-supracrustals ?	Up: amph-ls-bg. Lw: pelitics } schists and gneisses in migmatites			
	Finnlandveggen	2700						
			Basement		granite-gneiss clasts = 1275±45 Ma			

Pyroclastic block deposits with locally sorted, coarse-grained eruptive materials, account for more than 80% of the exposed rocks in the Kapp Hansteen Group here, and the amount of massive lavas is very small. Various lithological units have been distinguished in this group: basal conglomerates (locally monomictic with quartzite pebbles, but mainly bimictic with quartzite and volcanogenic rocks), massive porphyrite with well developed columnar joints, massive andesites, boulder pyroclastics, stratified tuff-breccias, volcanogenic sandstones, and local shale/sandstone lenses. Comprehensive mapping of these units has not yet been achieved. Possible late magmatic hydrothermal activities are revealed by jasper veins in the massive andesites and boulder pyroclastics. The pyroclastic blocks show a distinct crust of deep coloured margins, caused by oxidation, as described in detail by Flood et al. (1969), probably by subaerial weathering, while some coarse-grained stratified rocks indicate shallow water action during their deposition. These lithological variations and their impersistent spatial extension infer a rough surface topography with volcanic hills and lakes/shallow sea.

2. The Sabinebukta area (Figs. 1 and 2b)

Sandford (1950) recognized the rocks of his Cape Hansteen Formation at then head of the bay, and Flood et al. (1969) found that the rocks are all quartz porphyry. Four occurrences of quartz porphyry are known in this area:

(1) Small nunataks of massive quartz porphyry in the south of Laponiahalvøya.
(2) Sabineberget, where the quartz porphyry includes a larger number of silicified argillaceous rock fragments, probably from the underlying Brennevinsfjorden Formation. The contact to the Caledonian porphyritic granite (post-tectonic) on the northern slope is sharp and interfingered. The granite contains many angular xenoliths of both quartz porphyry and silicified argillaceous hornfels.
(3) In front of Maudbreen, where the quartz porphyry and argillites, both of which silicified and hornfelsed, form a narrow zone along the shore. Their SW and N sides are intruded by the porphyritic granite.
(4) Both sides of Carolusbukta, with massive quartz porphyry showing well developed

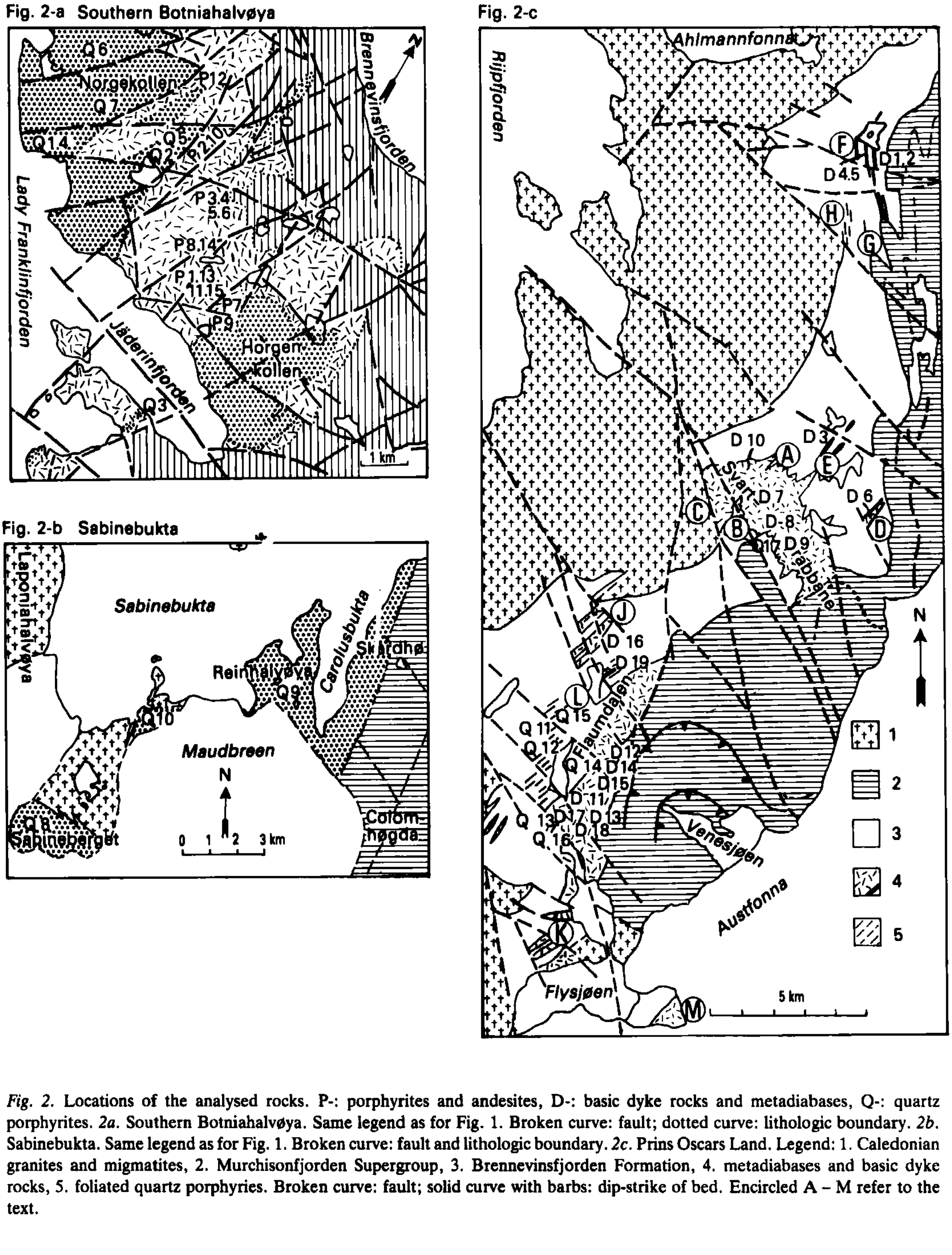


Fig. 2. Locations of the analysed rocks. P-: porphyrites and andesites, D-: basic dyke rocks and metadiabases, Q-: quartz porphyrites. *2a.* Southern Botniahalvøya. Same legend as for Fig. 1. Broken curve: fault; dotted curve: lithologic boundary. *2b.* Sabinebukta. Same legend as for Fig. 1. Broken curve: fault and lithologic boundary. *2c.* Prins Oscars Land. Legend: 1. Caledonian granites and migmatites, 2. Murchisonfjorden Supergroup, 3. Brennevinsfjorden Formation, 4. metadiabases and basic dyke rocks, 5. foliated quartz porphyries. Broken curve: fault; solid curve with barbs: dip-strike of bed. Encircled A – M refer to the text.

joints. The eastern border is a fault against the slate of the Austfonna Group, and the rocks on both sides of the fault are shattered for a few tens of metres.

Thus, the quartz porphyry suffered thermal metamorphism and silicification from the Caledonian granite in the northwest, while the quartz porphyry itself gave a similar effect to the argillites of the Brennevinsfjorden Formation. The quartz porphyry is free from thermal metamorphism and contamination in the eastern part around Carolusbukta.

3. Prins Oscars Land (Figs. 1 and 2c)

Metadiabase and quartz porphyry were found during the traverses of this area in 1965 (Flood et al. 1969) and were correlated with the Kapp Hansteen volcanogenic rocks of Botniahalvøya, based on their lithological similarities.

The main masses of these rocks occur in the Svartrabbane and the Flaumdalen areas and some minor occurrences were found to the north and south of the main masses (Ohta 1982). These rocks occur as thick piles of sheet-like layers in the areno-argillaceous succession underlying the basal quartzite formation of the Austfonna Group. The areno-argillaceous succession itself has been correlated with the Brennevinsfjorden Formation of Botniahalvøya.

The Svartrabbane mass consists mainly of diabasic rocks of about 2 km width, and its outline shows an apparently conformably curved structure with the folded structures of the Murchisonfjorden Supergroup to the southeast. The western side of the mass is cut by a NNW-SSE trending fault. Strong cleavages have developed in the rocks, especially along the margins and along some sheared zones cutting through the mass with the NE-SW strikes. These cleavages and sheared zones are sub-parallel to the eastern border of the granite-gneiss complex occurring to the west, and have modified the margins of the mass into zigzag interfingering contacts to the surrounding meta-sediments. The central part of the mass often shows massive texture.

A small impure limestone lense occurs at the contact in the northwest of the mass (A in Fig. 2c) where the rock recrystallized into epidote-bearing skarn and is included as small angular xenoliths in the diabasic rock. A local conglomerate lens with dolomitic matrix occurs on the southwestern margin (B in Fig. 2c). Sheet-like lenses of diabasic rocks, less than 5 m thick, are included in the porphyritic gneiss to the west and the margins of the lenses were converted into hornfels for some decimetres (C in Fig. 2c).

A 100 m thick metadiabase occurs on the west side of Kjedevatna, being overlain by a conglomerate with angular boulders of shale (D in Fig. 2c). Several basic dykes less than 5 m thick, cut folded meta-sediments about 1.5 km northeast of the Svartrabbane mass, and the meta-sediments were backed and hardened for about 10 cm at the contact (E in Fig. 2c). Similar narrow dykes of basic rocks occur in the south and north of the middle stretch of Beistfaret farther north (F in Fig. 2c). There the basic rocks have cleavages at the margins, in the conformable direction with those in the surrounding meta-sediments, but the centres are massive. These dykes abruptly terminate against the basal quartzite bed of the Austfonna Group in the West of Flóttesjøen (G in Fig. 2c), indicating an unconformity at the base of the latter (Ohta 1982).

The quartz porphyry is always strongly foliated, the cleavages being concordant with those in the surrounding meta-sediments. A sheared zone in the Svartrabbane metadiabase mass is followed by this rock. Two thin foliated quartz porphyry layers occur isolated in the north (H in Fig. 2c).

The Flaumdalen metadiabase mass is distributed on the eastern side of the middle stretch of the valley and a quartz porphyry lies mainly on the western side. Some dyke-like diabasic rocks occur to the north and south (J and K in Fig. 2c) of the main metadiabase mass. These rocks generally display structures conformable with the Venesjøen syncline of the Franklinsundet Group to the east (Ohta 1982). Both the diabasic and quartz porphyritic rocks are strongly foliated, and together with many thin layers of areno-argillaceous sediments of the Brennevinsfjorden Formation, they form thick piles of thin layers. Central parts of the thicker layers are massive. Well preseved pyroclastic block structures were observed in the easternmost part of the metadiabase mass, representing local extrusive activity. An intrusive occurrence of quartz porphyry along the joints of meta-sediments was observed on the western side of the river (L in Fig. 2c). The quartz porphyry also occurs on the eastern side of the river as thin foliated layers in the diabasic rocks, and occupies about 25% of the whole igneous rock areas on both sides of the river. The diabasic rocks in the north of the Flaumdalen mass (J in Fig. 2c) are massive and one is in contact with the granite, being converted into hornfels. The diabasic rocks to the south of the main mass are massive, they have suffered silicification from the granite occurring on the northern side of Flysjøen, and are included as xenoliths in the latter. A massive, medium-grained hornblende gabbro occurs on the east coast of Flysjøen and is intercalated with some black slate layers bounded by faults (M in Fig. 2c).

Summarizing the occurrences, the Kapp Hansteen igneous rocks underlie the Murchisonfjorden Supergroup and are themselves underlain by or intruded into, the Brennevinsfjorden Formation of the Botniahalvøya Supergroup. The quartz porphyry is younger than the porphyrites and the metadiabases, but it is safely considered to be older than the Murchisonfjorden Supergroup. The Rb/Sr isochron age of the quartz porphyry in Botniahalvøya is 766 ± 87 Ma, or possibly 970 Ma on their assumption taking the initial $Sr^{87/86}$ ratio as 0.705, instead of the obtained value 0.7259 ± 0.0088, and its K/Ar age is 472 Ma (Gorochev et al. 1977).

Table 2. Modal compositions of the analysed rocks. Sample numbers refer to Tables 3, 4, 5, and 6 and the figures. *2a*, Porphyrites and andesites of Botniahalvøya.

	porph	andesites			
	3	6	7	13	14
Pl (pheno.)	7.4	19.5	33.9	11.0	15.3
Pl (matrx.)	71.1	45.0	42.2	59.6	55.6
Quartz	1.1	—	—	—	—
Sericite	5.4	20.4	3.2	9.1	6.4
Chlorite	0.2	—	—	5.9	4.5
Epidote	6.2	2.0	2.3	2.8	3.6
Carbonates	0.7	—	13.2	1.8	6.7
Sphene	3.5	9.6	2.6	7.6	5.1
Opaques	4.4	3.4	2.8	2.5	2.9
Total	100.0	99.9	100.2	100.3	100.1
Total Pl	78.5	64.5	76.1	70.6	70.9
Total Mafics	15.0	15.0	20.9	20.6	22.8
Groundmass	77.6	65.4	45.4	68.7	62.0

2b, Basic dyke rocks and metadiabases from Prins Oscars Land.

	basic dykes (D-1)		Svartrabbane (D-2)		Flaumdalen (D-2)	
	1	4	7	8	12	18
Plagioclase	35.2	17.7	62.9	52.9	54.6	59.1
Quartz	—	—	+	+	—	—
Graphic Int.	—	—	1.6	22.0	—	—
Groundmass	—	—	—	—	14.3	13.2
Amphiboles	26.4	29.4	9.9	—	14.7	6.2
Chlorite	18.1	8.8	11.4	12.0	10.0	11.5
Sericite	—	—	3.9	1.7	—	—
Epidote	15.5	28.7	4.1	4.7	1.6	7.3
Carbonates	—	3.8	1.8	1.0	1.4	0.5
Sphene	3.1	9.5	2.7	4.7	0.7	0.2
Opaques	1.7	2.2	2.1	1.1	3.1	2.0
Total	100.0	100.1	100.4	100.1	100.4	100.0
Total Mafics	64.8	8.24	32.0	23.5	31.5	27.7

2c, Quartz porphyries from the three localities.

		Botniahalvøya						Sabinebuk.		Prins Oscars Land		
		2	3	5		6		9		12	14	16
phenocry	K-feld	1.7	—	8.3	11.1	4.7	7.5	10.3	15.3	3.5	—	1.7
	Plagioclase	23.6	20.7	10.3	4.6	9.2	7.8	13.6	4.4	7.0	—	5.6
	Quartz	6.9	3.6	12.6	12.6	9.3	8.9	10.4	13.2	5.7	6.0	5.7
ground mass	Q + F	53.8		40.1						27.0		45.1
			71.4		70.8	74.8	71.5	63.6	67.1		89.1	
	Sericate	5.0		26.1						53.2		41.0
Garnet		0.8	—	—	—	—	—	—	—	—	—	—
Bi./Chl.		3.7	2.5	1.3	0.9	—	1.8	—	—	1.3	—	—
Epidote		+	0.4	+	+	—	—	+	—	+	+	+
Carbonates		—	—	—	+	—	+	+	+	0.5	4.6	0.5
Apatite		+	0.2	+	+	+	+	+	+	—	—	—
Sphene		4.0	+	0.8	—	+	—	—	—	1.1	—	—
Opaques		0.8	1.2	0.7	+	2.0	0.8	2.3	+	0.9	0.3	0.5
Total		100.3	100.0	100.2	100.0	100.0	98.3	100.2	100.0	100.2	100.0	100.1

Petrography of the analysed rocks

1. Porphyrites of Botniahalvøya (Table 2a)

Idiomorphic and angular fragments of plagioclase phenocrysts, acid andesine-albite composition and 2–5 mm in size, range from 7.5 to 34 modal % in these rocks. They are well twinned and zoned, partly tacoblastic, and often show sharp oscillatory zoning at the margins. Mafic phenocrysts have been totally decomposed into aggregates of chlorite, epidote, carbonates, leucoxene and opaque grains; occasional short prismatic outlines of the aggregates infer primary hornblende and/or pyroxenes. Some rocks have a groundmass of small plagioclase laths with micro-phenocrysts, while many others have a very fine-grained, microcrystalline groundmass of recrystallization origin. Cavities and flow structures are inferable by the distribution of tiny mafic grains, and quartz is probably present in the groundmass. Extrusive emplacement of these rocks is indicated by the large amount of groundmass, 45–77 modal %, the oscillatory zoning and fragmentation of the phenocrysts. A distinct size contrast between the phenocrysts and groundmass indicates primary andesitic texture, although the rocks have been called porphyrites because of their crystalline groundmass of secondary origin. Glomero-porphyritic and amygdaloidal textures are also present. Detailed descriptions of the pyroclastic blocks are given in Flood et al. (1969).

2. Metadiabases of Prins Oscars Land (Table 2b)

Two petrographic groups are recognized in this area: 1) metadiabases of Svartrabbane (2a, below) and Flaumdalen (2b), and 2) the basic dykes (2c) to the north of Svartrabbane.

2a. Svartrabbane metadiabases. – Most rocks in this mass seem to be primarily holocrystalline and have less size-contrast between sub-ophitic phenocrysts (average 3 mm) and groundmass. Some may have had small laths of basic plagioclase in the groundmass, but if so, they have been converted into granular aggregates of acidic plagioclase, epidote and quartz, with chlorite, leucoxene and opaques. Micrographic intergrowth of plagioclase and quartz occurs in the interspaces of large grains. Short prismatic plagioclase phenocrysts, acid andesine-oligoclase in composition, 53–63 modal % and up to 5 mm in size, have partial zoning, well developed twin lamellae, and tacoblastic inclusions. They often have large amounts of secondary sericite and carbonates. Mafic minerals, possibly hornblende and pyroxene primarily, were totally decomposed into aggregates of actinolite, chlorite, epidote, zoisite, carbonates, sphene/leucoxene and opaques, the latter often showing skeletal shape with sphene rim.

2b. Flaumdalen metadiabases. – The texture of these rocks ranges from sub-ophitic to porphyritic with fine-grained groundmass. Plagioclase phenocrysts, some of which are glomero-phenocrysts and radial aggregates of up to 15 mm, have large amounts of secondary epidote and sericite. They rarely include microcline grains. Hornblende has been preseved in some rocks, but is mostly converted into secondary mafic aggregates. Short prismatic domains of secondary aggregates within the hornblende grains may have been pyroxene originally. Granular groundmass occupies less than 15 modal % of the rocks and has poorly preserved graphic and spherulitic textures and small plagioclase laths.

A weakly foliated basic rock from northern Flaumdalen (No. 19) has a large amount of clear idiomorphic plagioclase glomero-phenocrysts of up to 20 mm, and no secondary mafic aggregate. The plagioclase shows chess-board twins and strong tacoblastic texture. Some fragmental 1 mm quartz grains occur in the groundmass and show round and corroded outlines. The groundmass is cut by cleavages revealed by sericite flakes and quartz lenses around the margins of phenocrysts. A sub-ophitic, irregularly shaped small rock fragment is included in the groundmass. This rock may be an extrusive representative of metadiabasic rocks, and has transitional petrographic characteristics between metadiabase and porphyrite.

2c. Basic dykes. – Idiomorphic, strongly zoned and tacoblastic long prisms of plagioclase form an ophitic texture, while mafic aggregates, primarily hornblende up to more than 60 modal %, have interstitial xenomorphic shapes. Margins of plagioclase grains are recrystallized into clear granular albite, while the cores are acid andesine-oligoclase in composition and strongly dusty with sericite, epidote and carbonates. Outlines of primary hornblende are well preserved in the central parts of the dykes and have been converted into pale green aggregates of actinolite, chlorite and granular epidote, and all are strongly clouded by leucoxene and opaques. Opaques are often rimmed by sphene. Relatively large amounts of apatite occur in the plagioclase phenocrysts of some rocks. Groundmass occurs in the marginal parts of the dykes, 20–50 modal %, and is composed of granular plagioclase and epidote, flaky chlorite and sericite, some carbonates and quartz. Epidote occasionally forms clots in the groundmass.

3. *Quartz porphyries (Table 2c)*

The quartz porphyry has been described in relative detail by Flood et al. (1969) and Gorochov et al. (1977). Although the present groundmasses are crystalline, the primary ones were presumed to be glassy and cryptocrystalline, and this suggests that the rocks were originally nevaditic and liparitic rhyolites. Most tiny sericite flakes counted under the microscope are a secondary product from the groundmass and are thus included in the model groundmass in Table 2-c.

3a. Botniahalvøya. – Feldspar phenocrysts make up 14–25% of the rocks, which is a larger and more fragmental amount than quartz. The K-feldspar and plagioclase ratios differ very much. Most quartz phenocrysts (7-12.6 modal %) have idiomorphic outlines, but the edges are rounded and show strong corroded texture. K-feldspar phenocrysts, partly corroded, are weakly dusty orthoclase and include mafic grains and small graphic textured blocks. Fragments of graphic intergrowth of quartz-feldspar occur also as phenocrysts. Plagioclase phenocrysts, acid oligoclase to albite in composition, are always strongly clouded with sericite. Brown biotite flakes have occasionally been preserved, up to 4 modal %, but have mostly been converted into chlorite, leucoxene and opaques, and there are associated apatite needles.

Small clear grains of garnet were found in the secondary mafic aggregates. The groundmasses, 59–75 modal %, show microcrystalline texture, and secondary sericite flakes mark patterns of polygonal glass cracks, flow and spherulitic textures. Thus, primary glassy groundmasses are inferred.

Table 3. Major element analyses of the porphyrites and andesites from Botniahalvøya.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	57.67	60.23	60.46	61.68	62.50	62.72	62.75	62.86	62.97	63.13	64.44	64.67	65.04	65.87	67.67
TiO_2	0.81	0.78	1.07	1.06	0.82	0.80	0.75	0.84	0.83	0.84	0.92	0.74	0.75	0.77	0.71
Al_2O_3	17.00	16.23	17.99	16.73	17.24	19.47	16.43	15.97	18.32	16.72	17.79	15.51	17.59	16.91	15.09
Fe_2O_3	5.04	0.97	6.73	2.07	1.87	0.09	0.93	3.06	1.13	1.66	3.85	1.81	1.07	1.35	5.31
FeO	2.71	5.63	2.12	6.65	4.63	5.72	5.02	4.94	5.21	5.66	1.20	4.53	5.56	5.27	1.07
MnO	0.14	0.14	0.10	0.16	0.09	0.14	0.08	0.08	0.08	0.08	0.11	0.11	0.11	0.13	0.08
MgO	3.93	5.33	1.38	4.23	2.77	1.83	2.97	2.61	2.98	4.09	1.98	3.12	2.56	2.51	1.15
CaO	6.65	7.01	2.36	3.37	4.52	2.03	4.38	4.83	2.01	3.17	3.66	4.07	1.84	1.68	3.88
Na_2O	3.41	2.00	0.88	1.57	2.73	3.90	0.71	1.58	2.89	1.30	2.45	2.92	2.07	2.40	1.60
K_2O	1.39	1.60	6.73	2.34	2.67	3.06	5.79	3.10	3.38	3.21	3.53	2.34	3.23	2.94	3.26
P_2O_5	0.20	0.08	0.17	0.14	0.14	0.23	0.17	0.12	0.19	0.12	0.07	0.17	0.17	0.16	0.16
Total	98.95	100.00	99.99	100.00	99.98	99.99	99.98	99.99	99.97	99.98	100.00	99.99	99.99	99.99	99.98

3b. Sabinebukta. – Modal ratios of phenocrysts are similar to those of the Botniahalvøya rocks, while the groundmasses have been strongly recrystallized into microcrystalline to granular textures in this area. Plagioclase phenocrysts were strongly sericitized and orthoclase grains were partly converted into microcline. Biotite flakes were totally decomposed into chlorite and opaque aggregates. Small round aggregates of chlorite, sericite, leucoxene and opaques indicate former garnet grains.

3c. Prins Oscars Land. – Strongly foliated textures and large amounts of very fine-grained groundmasses are characteristic in these rocks. Quartz phenocrysts show strong corroded texture and feldspar phenocrysts are missing in some rocks. Despite strong cleavages, flow structure was observed between the cleavage planes in some rocks, where the groundmass texture is cryptocrystalline. Cleavages are emphasized by strong preferred orientation of sericite flakes and elongated quartz lenses to form lepido- and granoblastic textures in many rocks.

Major elements

1. Porphyrites of Botniahalvøya (Table 3)

The SiO_2 values range from 57.6 to 67.7% (anhydrous base) among 15 analysed rocks, including two from Flood et al. (1969); acid andesite ($57 < SiO_2 < 63\%$) = 9 and dacite ($63 < SiO_2 < 70\%$) = 6 (Fig. 3a). Rocks with more than 65% SiO_2 have larger amounts of groundmass and are andesitic in texture. One rock (No. 2) is di-normative, while all others have normative qz, hy and c. The alkali-SiO_2 diagram (Fig. 3a) shows that all rocks are sub-alkaline and the calc-alkali index (Peacock 1931) is about 57, i.e., calc-alkaline. Some rocks are plotted in the field of high-Al series (Kuno 1960) and six rocks have more than 16.5% Al_2O_3 (on a hydrous base). This is mainly related to large amounts of plagioclase phenocrysts.

Two thirds of Tebenkov's analyses (Tebenkov 1983), small dots in Figs. 3a and b, are in the acid andesite SiO_2 range, two are a little basic, and three are in the range of basalt. These data are probably on a hydrous base (his paper presented no numerical data), so the majority would lie in the acid andesite range on an anhydrous base. His most basic rock plots in the alkaline field, with very high total alkali, about 7.5%.

The AFM (Fig. 3b) and FeO^*/MgO ($FeO^* = FeO + 0.9Fe_2O_3$) variation diagrams (Figs. 4a, b and c) reveal that most of the rocks are of the calc-alkaline rocks series. Some are in the tholeiite field in these diagrams: Nos. 3, 4, 6, 8 and 15. Nos. 6 and 15 are the most silicic rocks (Fig. 3a), and Nos. 3 and 15 have somewhat pyroclastic textures. Nos. 4 and 8 have relatively high contents of opaque grains. Three quarters of Tebenkov's analyses plot in the tholeiitic field, having similar FeO^* enrichments as Nos. 3, 4, 8 and 15 of the present analyses. There is some evidence of secondary fumarole activities having formed jasper veins in this area and this could have modified primary calc-alkaline rocks into slightly tholeiitic ones. If Tebenkov's rocks are free from such secondary effects, his data indicate a transition from tholeiitic to calc-alkaline series.

All the rocks are in the non-oceanic field in the TiO_2-K_2O-P_2O_5 diagram (Fig. 3c) (Pearce & Cann 1973).

In the Harker variation diagrams (Fig. 5) a relatively constant Al_2O_3, high MgO and low Na_2O are conformable with the calc-alkaline rock series. It is difficult to discriminate the two rock series on the basis of CaO (Gill 1981). The genrally high FeO^* and TiO_2 of the present rocks are probably related to the secondary leucoxene and opaques. However, even with this secondary addition of Fe, most rocks fall within the calc-alkaline field of the AFM diagram (Fig. 3b). The K_2O variation shows that rocks with less than 61% SiO_2 are medium K_2O andesites, while those with more than 61% SiO_2 are high K_2O andesites. These K_2O contents are comparable with the Andes and Cascade andesites. The former have the highest K_2O contents among recent orogenic andesites (Miyashiro 1974). Two (Nos. 3 and 7) have even higher K_2O contents.

2. Metadiabases of Prins Oscars Land (Table 4)

The nineteen analysed rocks can be divided into two groups by their SiO_2 contents (Fig. 6a): rocks of basic dykes, the D-1 group, of basaltic SiO_2 range (triangles of Figs. 6, 7 and 8), and the D-2 group rocks from the Svartrabbane metadiabase mass (solid circles), and the Flaumdalen mass (open circles) of mostly acid andesites, except for the most silicic ones which have dacitic composition. One diabase analysis of Tebenkov (1983)

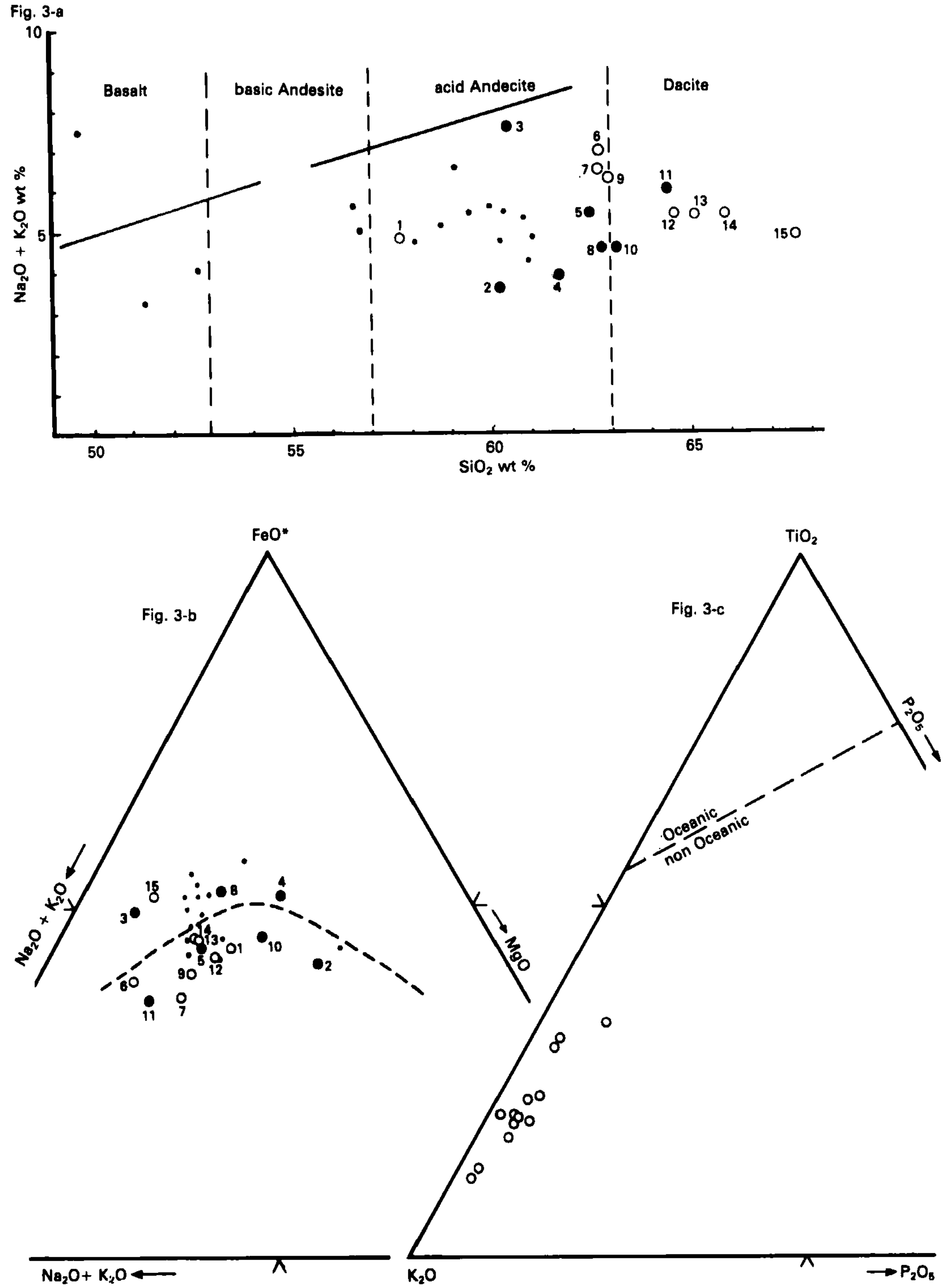


Fig. 3. Porphyrites and andesites from Botniahalvøya. Nos refer to Table 3 (anhydrous base). Solid circles: porphyrites; open circles: andesites; small dots: analyses of Tebenkov (1983), possibly on a hydrous base. *3a.* Alkali-SiO_2 diagram. Division curve: Irvine & Barager (1971). *3b.* AFM diagram. Division curve: Irvine & Barager (1971). *3c.* TiO_2-K_2O-P_2O_5 diagram. Division line: Pearce & Cann (1973). Same symbol for both porphyrites and andesites.

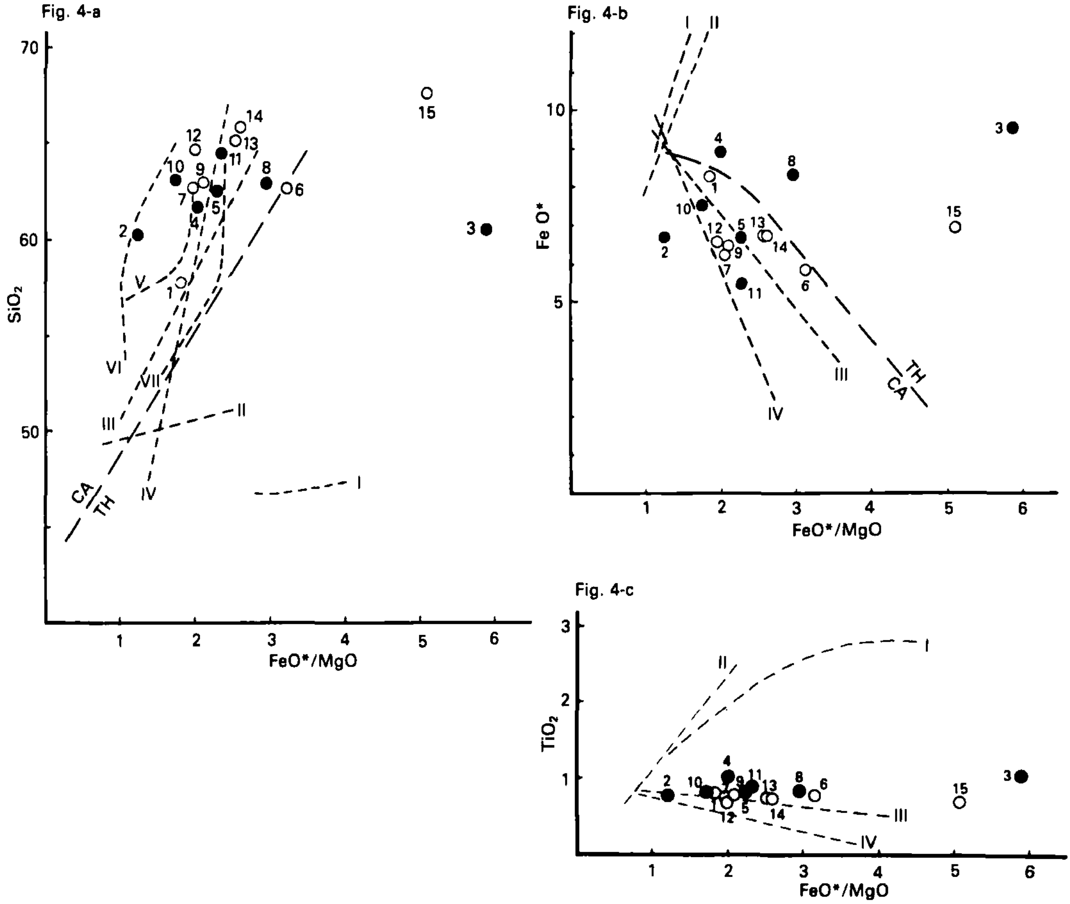


Fig. 4. FeO*/MgO variation diagrams for the porphyrites and andesites (anhydrous). Symbols as for Fig. 3. Reference curves: I. Skaergaard igneous rocks; II. abyssal basalts; III and IV. calc-alkaline rocks of Japan. TH/CA division line, all above from Miyashiro (1974 and 1975); V. high K_2O andesites; VI. medium K_2O andesites; VII. low K_2O andesites, the last three from Gill (1981). *4a.* SiO_2-FeO*/MgO diagram. *4b.* FeO*-FeO*/MgO diagram. *4c.* TiO_2-FeO*/MgO diagram.

falls in the D-1 group. The total lack of basic andesite is characteristic.

Sixteen rocks among the present analysis are qz normative, two from the D-1 group (Nos. 2 and 3) have very small amounts of normative qz (1.12 and 0.7%, respectively) and relatively large amounts of normative di (20 and 14%, respectively). The three rocks free from normative qz (No. 1 of the D-1 group and Nos. 12 and 13 of the D-2 group) have varying amounts of normative ol (0, 8.5, and 3.7%, respectively). The latter two are mainly due to high contents of normative ab.

Most rocks in Fig. 6a are sub-alkaline, while two (Nos. 12 and 13) have about 1.8% higher alkali than the division curve (Irvine & Barager 1971). The latter might be caused by secondary albitization since they have high normative ab. The calc-alkali index is about 56, i.e., around the boundary between the alkali-calc and calc-alkali series, for the D-2 group, while that of the D-1 group is difficult to estimate due to a large scatter of CaO contents.

Figs. 6b and 7a, b and c show that both groups belong to the tholeiitic series. The D-1 group tends to have a high Fe concentration, while the D-2 group shows a moderate one (Fig. 6b), except for two (Nos. 10 and 18). The latter two have abnormally high FeO*/MgO ratios (13.9 and 11.7, respectively) and are considered to be strongly altered. The rocks from the Svartrabbane mass tend to have less total alkali (Fig. 6a), and

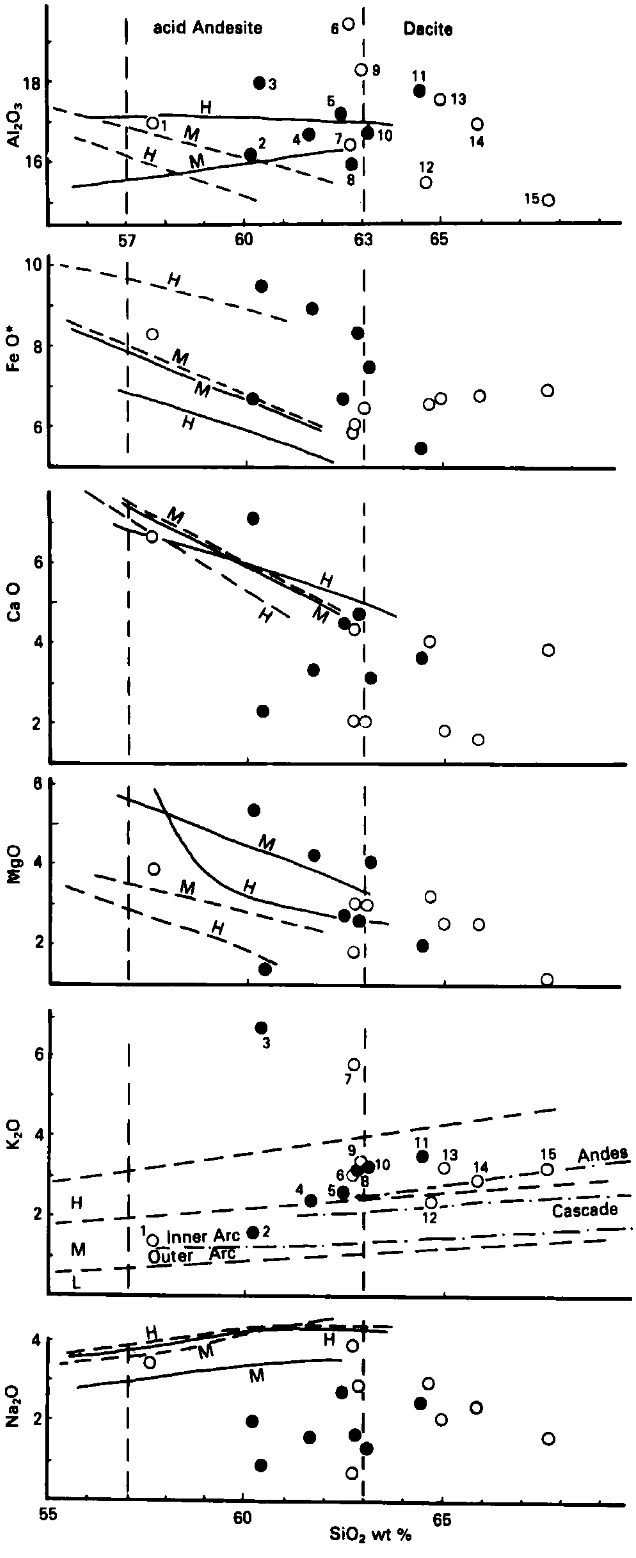


Fig. 5. Harker variation diagrams for the porphyrites and andesites (anhydrous). Symbols as for Fig. 3. Reference curves (all simplified from Gill 1981): solid curves: calc-alkaline rocks; broken curves: tholeiitic rocks; H: high K_2O type; M: medium K_2O type. Division lines in the K_2O variation diagram: Gill (1981); Andes, Cascade and inner/outer arcs: Miyashiro (1974).

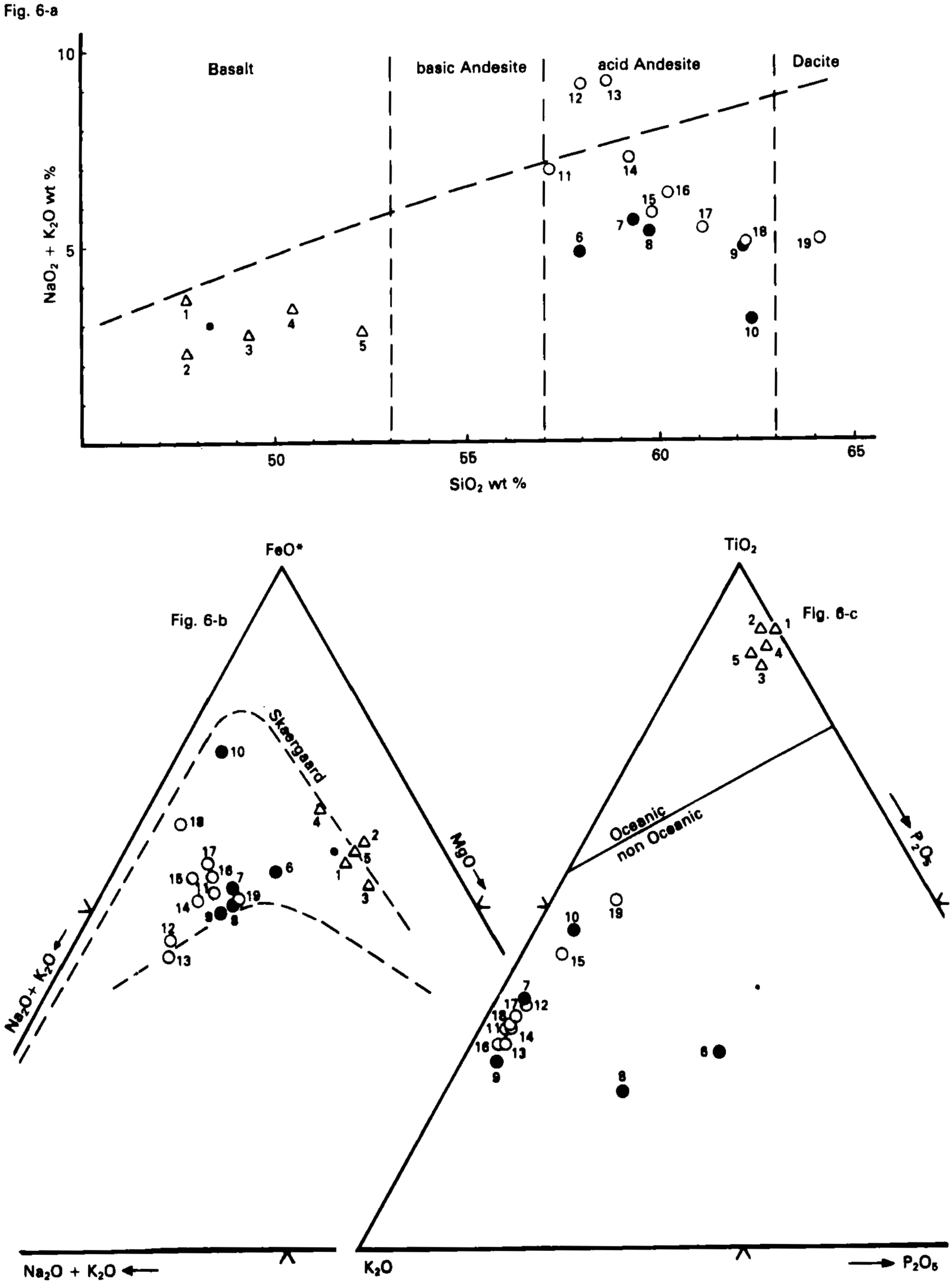


Fig. 6. Metadiabases of Prins Oscars Land (anhydrous). Triangles: D-1 basic dyke rocks; solid circles: D-2 metadiabases from the Svartrabbane mass; open circles: D-2 metadiabases from the Flaumdalen mass; small dots: diabase of the Tebenkov's analysis, the last one may be on a hydrous base. *6a.* Alkali-SiO_2 diagram. *6b.* AFM diagram. *6c.* TiO_2-K_2O-P_2O_5 diagram.

Table 4. Major element analyses of the basic dyke rocks and metadiabases from Prins Oscars Land.

	Basic dyke rocks (D-l)					Svartrabbane metadiabases (D-2)				
	1	2	3	4	5	6	7	8	9	10
SiO_2	47.70	47.75	49.32	50.47	52.30	57.93	59.34	59.76	62.15	62.40
TiO_2	3.26	3.44	2.49	2.91	2.70	1.55	1.52	1.18	0.98	1.64
Al_2O_3	16.42	13.46	15.13	16.55	15.44	15.37	15.72	16.56	18.77	18.05
Fe_2O_3	2.80	3.35	3.09	5.08	3.34	1.74	1.60	1.77	1.99	1.41
FeO	12.87	11.29	9.28	12.77	11.25	9.88	8.54	7.08	5.42	9.25
MnO	0.21	0.20	0.18	0.30	0.21	0.16	0.16	0.13	0.19	0.16
MgO	8.11	7.32	7.71	6.03	7.46	4.38	3.12	3.09	2.50	0.78
CaO	4.63	10.61	9.68	2.11	4.16	2.35	4.18	3.82	2.91	3.00
Na_2O	3.66	2.22	2.65	3.37	2.73	2.73	3.14	2.60	2.54	1.71
K_2O	0	0.07	0.12	0.08	0.16	2.08	2.48	2.78	2.38	1.38
P_2O_5	0.33	0.28	0.29	0.31	0.25	1.78	0.15	1.18	0.15	0.17
Total	99.99	99.99	99.94	99.98	100.00	99.95	99.95	99.95	99.98	99.95

	Flaumdalen metadiabases (D-2)								
	11	12	13	14	15	16	17	18	19
SiO_2	57.16	58.00	58.65	59.24	59.80	60.22	61.15	62.25	64.17
TiO_2	1.54	1.47	1.43	1.35	1.46	1.52	1.36	1.34	1.24
Al_2O_3	17.42	15.63	15.70	16.04	16.13	15.79	16.69	16.79	14.96
Fe_2O_3	1.86	1.89	1.80	1.76	0.87	1.81	1.65	1.67	1.32
FeO	9.23	8.22	7.51	8.72	8.48	9.00	8.18	8.33	7.72
MnO	0.15	0.13	0.12	0.15	0.17	0.14	0.14	0.14	0.07
MgO	3.09	2.69	2.85	2.72	1.83	2.57	2.02	0.85	3.11
CaO	2.37	2.66	2.52	2.57	5.27	2.44	3.18	3.33	2.06
Na_2O	3.88	6.64	6.07	4.59	1.75	2.99	3.02	2.52	4.15
K_2O	3.09	2.47	3.13	2.67	4.06	3.33	2.46	2.60	0.99
P_2O_5	0.18	0.18	0.20	0.16	0.17	0.17	0.15	0.16	0.20
Total	99.97	99.98	99.98	99.97	99.99	99.99	99.98	99.98	99.99

can be considered as earlier differentiates than those from the Flaumdalen mass. Two rocks (Nos. 9 and 19) are in the calc-alkaline field of Fig. 7a, but this degree of deviation can be expected in any weakly metamorphosed rocks like the present ones.

All FeO*/MgO variation diagrams (Fig. 7) show that the D-1 group has a similar trend to those of the Skaergaard igneous rocks and abyssal basalts (Miyashiro 1974). The TiO_2 content is remarkably high (Fig. 7c) and it is noteworthy that these rocks plot in the oceanic tholeiite field of Fig. 6c. Since very high Fe concentration in the middle stage has not been observed in Fig. 6b, the D-1 group appears similar to the island arc tholeiites of Jakes & Gill (1970).

The D-2 group rocks show a large FeO*/MgO increase in the SiO_2 range of 58–62% (Fig. 7a) and this is in good agreement with the high K_2O tholeiites of Gill (1981), i.e., K_2O = 2.5% and FeO*/MgO = 3.2 at SiO_2 = 57.5%. Fig. 7b shows a moderate Fe concentration tholeiite for the D-2 group. Some (Nos. 15 and 17), having higher FeO*/MgO values than typical tholeiites such as the Karroo dolerites and the British Tertiary volcanics (VIII and IX of Fig. 7b, respectively) show weak pyroclastic textures and their composition might be modified.

In the Harker variation diagrams (Fig. 8) the D-1 group is characterized by high FeO*, with high TiO_2 (Fig. 7c), and very low K_2O. The rocks from the margins of the dykes have lower FeO* and higher CaO than those from the central parts, and this and the existence of groundmass in the former parts indicate chilled margins. The CaO values in three of the rocks are very low.

The D-2 group shows high FeO* with a negative relation to SiO_2 while the CaO content is lower

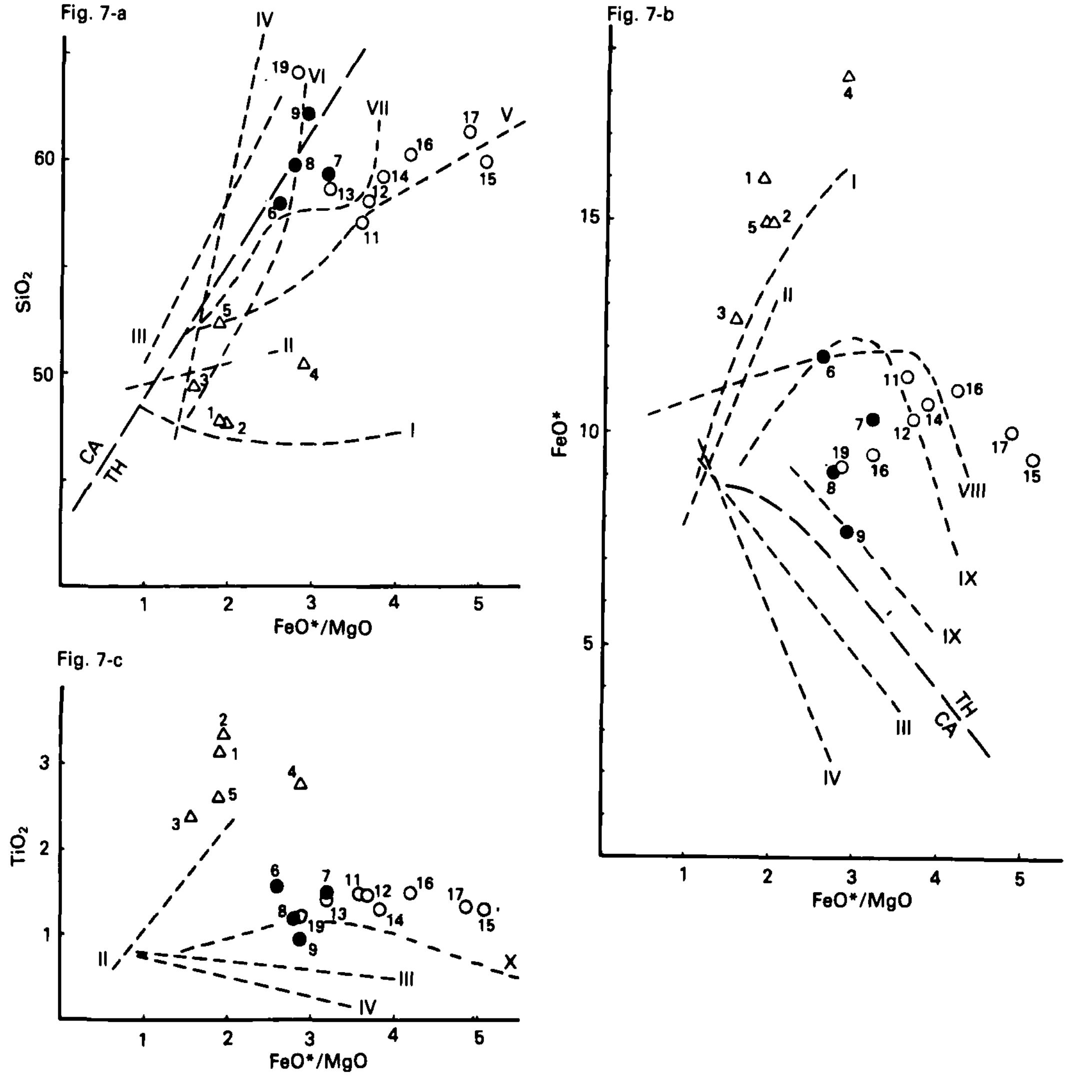


Fig. 7. FeO*/MgO variation diagrams for the metadiabases (anhydrous). Symbols as for Fig. 6. Reference lines and curves are the same as in Fig. 4. Nos. 10 and 18 are not in the diagrams, since their FeO*/MgO ratios are too high. *7a.* SiO_2-FeO*/MgO diagram. *7b.* FeO*-FeO*/MgO diagram. Reference curves: VIII. Karroo dolerites; IX. tholeiites of British Tertiary volcanics, calculated from Kuno (1968). *7c.* TiO_2-FeO*/MgO diagram. Reference curve: X. tholeiites of IZU-Hakone volcanos, Japan (Kuno 1968).

than that commonly present in tholeiitic rocks (Gill 1981). Relatively low MgO and high TiO_2 (Fig. 7c) fit with the tholeiitic trend, but the negative relations of Na_2O and K_2O to SiO_2 is difficult to explain by magmatic differentiation. Five high Na_2O rocks (Nos. 11, 12, 13, 14 and 19) are from the Flaumdalen mass and belong to a relatively later stage of differentiation.

It is evident that all D-1 group rocks are of low K_2O basalts. Among the D-2 group rocks, those less silicic than 60% SiO_2 tend to be of high K_2O types, while more silicic rocks are of a medium K_2O type. Most high K_2O rocks, with high Na_2O and low CaO, are from the Flaumdalen mass in which the rocks occur as thin layers, often possessing relatively strong cleavages. These rocks have abundant sericite flakes and some secondary albite.

A weak positive relation of Al_2O_3 to SiO_2, low CaO and lower K_2O and Na_2O in more silicic

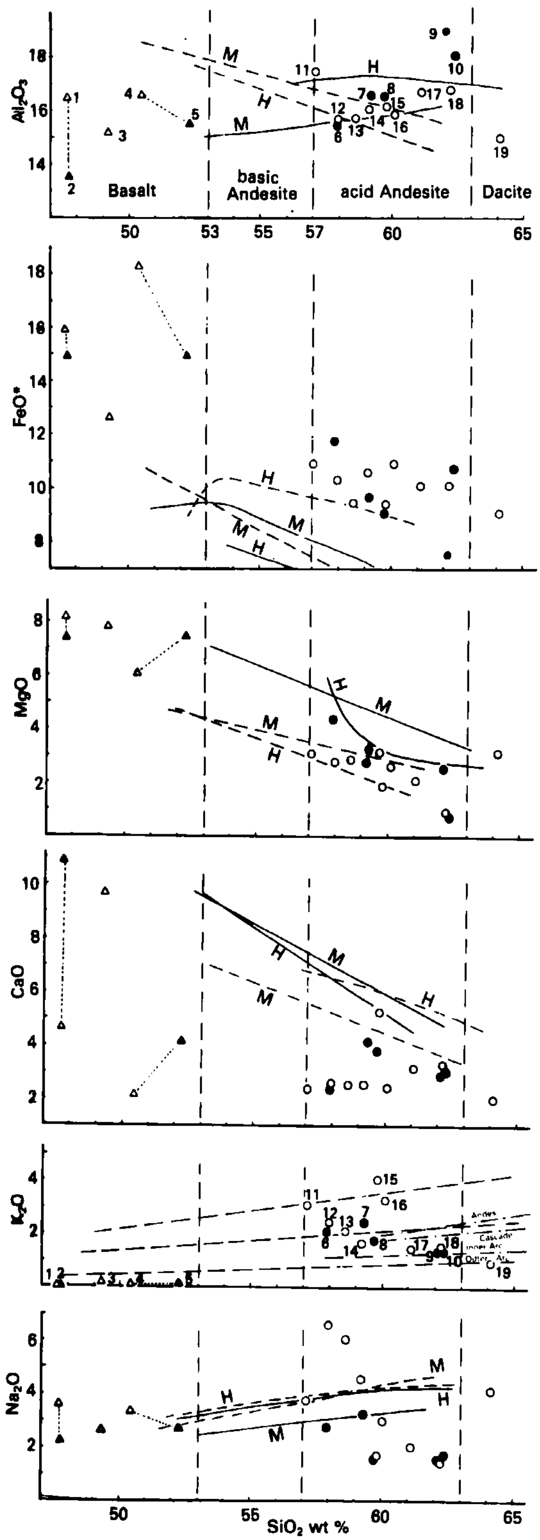


Fig. 8. Harker variation diagrams for the metadiabases (anhydrous). Symbols as for Fig. 6, except for open triangles: core of the dykes; solid triangles: margin of the dykes, both from the D-1 group; Dotted tie lines: from the same dyke. Reference curves are the same as in Fig. 5.

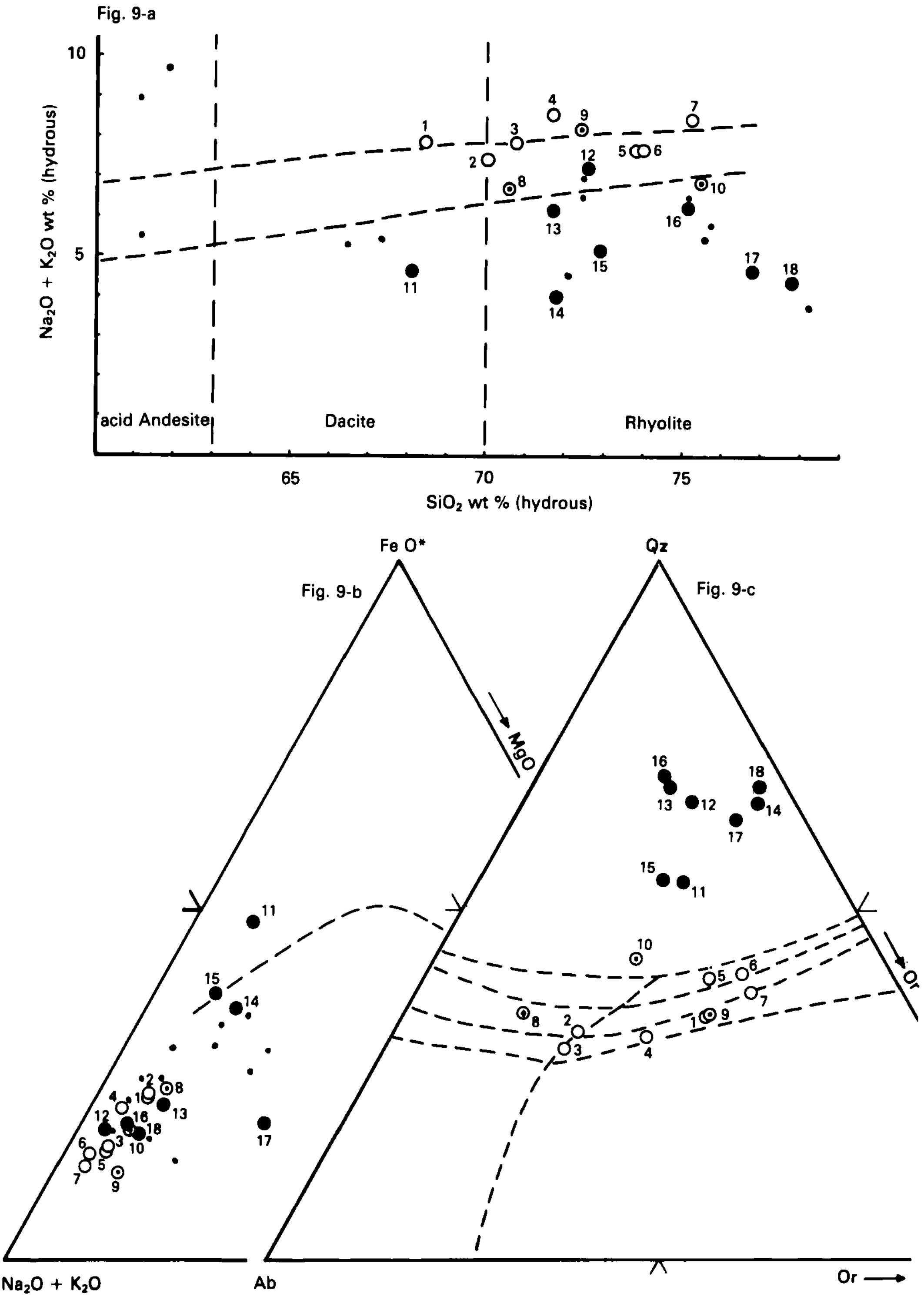


Fig. 9. Quartz porphyries. Open circles: rocks from Botniahalvøya; open circles with dot: Sabinebukta; solid circles: Prins Oscars Land; small dots: Tebenkov's analyses (1983). *9a.* Alkali-SiO_2 diagram (hydrous). Reference curves: Kuno (1968). *9b.* AFM diagram. *9c.* Normative Qz-Ab-Or diagram.

Table 5. Major element analyses of the quartz porphyries from the three localities.

	Botniahalvøya							Sabinebukta		
	1	2	3	4	5	6	7	8	9	10
SiO_2	70.16	71.12	71.90	72.26	74.04	74.69	75.21	71.70	73.43	76.34
TiO_2	0.37	0.47	0.29	0.34	0.19	0.23	0.20	0.50	0.20	0.16
Al_2O_3	15.39	16.09	16.38	14.36	15.35	14.15	13.72	16.42	14.65	13.36
Fe_2O_3	1.63	0.47	0.29	0.80	0.27	0.53	0.03	0.27	0.41	0.43
FeO	1.23	2.11	1.38	1.82	1.22	1.00	1.34	2.29	0.98	1.28
MnO	—	0.03	—	—	0.03	0.02	0.01	0.03	0.01	0.02
MgO	0.77	0.70	0.51	0.46	0.50	0.29	0.35	0.87	0.87	0.64
CaO	2.05	1.25	1.23	0.95	0.48	1.23	0.47	0.75	0.96	0.62
Na_2O	2.01	4.12	4.59	3.02	2.26	1.87	1.89	4.69	2.54	3.10
K_2O	6.00	3.40	3.36	5.62	5.42	5.80	6.55	2.19	5.81	3.83
P_2O_5	0.39	0.23	0.09	0.38	0.24	0.11	0.22	0.26	0.10	0.20
Total	100.00	99.99	100.02	100.01	100.00	99.92	99.99	99.97	100.01	99.98

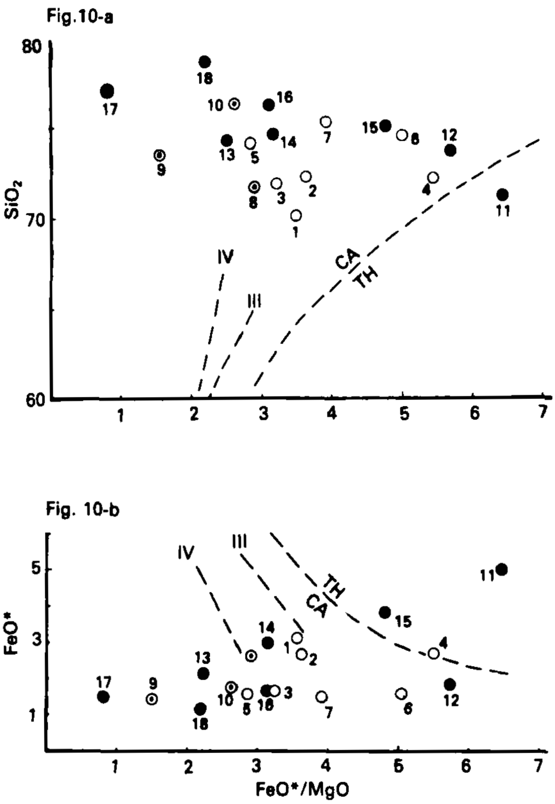
	Prins Oscars Land							
	11	12	13	14	15	16	17	18
SiO_2	71.31	73.84	74.28	74.66	75.08	76.21	77.02	78.62
TiO_2	0.77	0.30	0.26	0.21	0.25	0.24	0.30	0.21
Al_2O_3	14.71	15.41	14.18	14.88	14.17	14.34	14.02	14.62
Fe_2O_3	1.38	0.81	1.22	0.55	0.98	0.70	0.51	0.28
FeO	3.88	0.95	0.82	2.31	2.74	0.92	1.04	0.80
MnO	0.06	0.01	0.10	—	0.06	0.02	0.02	—
MgO	0.82	0.29	0.86	0.90	0.77	0.50	1.86	0.49
CaO	2.01	0.79	1.70	2.29	0.47	0.52	0.38	0.33
Na_2O	1.62	2.09	2.29	0.38	2.04	2.37	0.80	0.30
K_2O	3.22	5.24	4.06	3.71	3.22	3.94	3.81	4.09
P_2O_5	0.19	0.23	0.22	0.13	0.20	0.23	0.22	0.23
Total	99.97	99.96	99.99	100.02	99.95	99.99	99.98	99.97

rocks than 60% SiO_2, may indicate that the D-2 group approaches the calc-alkaline series in the range of acid andesite to dacite, and is possibly gradational to the porphyrites of Botniahalvøya.

3. Quartz porphyries (Table 5)

The SiO_2 contents range from 70.1 to 78.6% (anhydrous) and all rocks can be called rhyolite. Fig. 9a (hydrous base) shows that most rocks are sub-alkaline, except for four (three of them are from Flood et al. 1969) which have slightly higher alkali than the division curve of Kuno (1968). The calc-alkali index is about 59–62, i.e. the calc-alkali group. Most rocks from Botniahalvøya and Sabinebukta (BS area) plot in the high Al_2O_3 field of Kuno (1960), while those from Prins Oscars Land (POL area) have lower alkali than the former. This relation is well confirmed by the difference in model feldspar phenocrysts (Table 2c).

Tebenkov's data (1983) have a much larger range of SiO_2 contents than the present ones, from 61 to 84.5%, while a distinct gap exists around $62 < SiO_2 < 66\%$. This gap covers almost the whole dacite range on the anhydrous base. Tebenkov's three most basic rocks, although their localities are unknown to the present author, could be grouped in the porphyrites, since in Botniahalvøya they are difficult to discriminate in the field. All the rest of the Tebenkov's data have low alkali contents similar to those of the POL area.



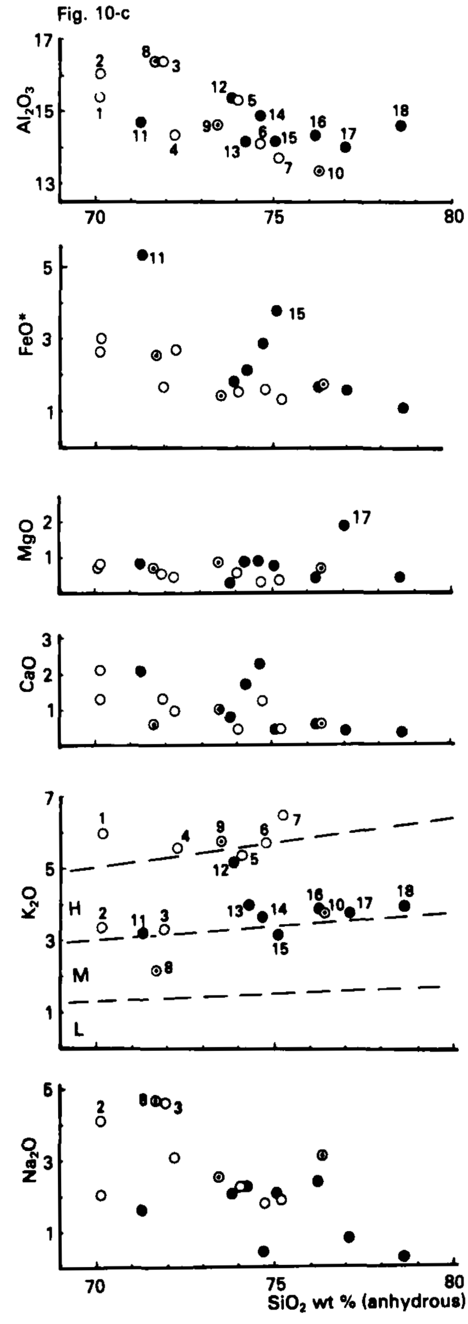


Fig. 10. FeO*/MgO and Harker variation diagrams for the quartz porphyries (anhydrous). Symbols as for Fig. 9, and reference curves as for Figs. 4 and 5, except for TH/CA division curves in 10a and b, where the curves have been extended using the data of Kuno (1968). *10a.* SiO_2-FeO*/MgO diagram. *10b.* FeO*-FeO*/MgO diagram. *10c.* Harker variation diagrams.

In Fig. 9b, most rocks, including those of Tebenkov, belong to the calc-alkaline series, except for two (No. 11, with some degree of pyroclastic block structure, and No. 15, strongly foliated) and another isolated plot, No. 17, is also a strongly foliated rock.

All the present rocks have normative qz (21–57%), hy (1.35–6.55%) and c (3.52–10.93%), but have no normative di. All rocks from the BS area plot in the eutectic valleys of various H_2O pressures in the Qz-Ab-Or diagram (Fig. 9c), while those from the POL area are far from the valleys and have very large normative qz contents. The latter probably resulted from a large addition of secondary quartz to the groundmass during the formation of foliated cleavages.

The FeO*/MgO variation diagrams (Fig. 10), with modified division curves referring to the data of Kuno (1968), show that most rocks are of the calc-alkaline series, except for two (Nos. 11 and 15) as in Fig. 9b. Wide variations of the FeO*/MgO ratio in a relatively small range of SiO_2 and FeO* are quite different from basaltic and andesitic rocks.

On the Harker variation diagrams (Fig. 10c) most rocks show smooth curves, with a few exceptions. The Al_2O_3 contents show a weak negative relation to SiO_2. The tree rocks with high Al_2O_3 (Nos. 2, 3, and 8) also have high Na_2O contents, thus, these are due to large modal plagioclase phenocrysts (Table 2c). Two rocks (Nos. 11 and 15) have higher FeO* (Figs 9b and 10b) than the other ones revealing a smooth negative curve to SiO_2. CaO plots show relatively large variations with a negative relation, while MgO and TiO_2 (Table 5) have small variations and keep constant values in this SiO_2 range. A rock with strong secondary cleavages (No. 17) has a specially high MgO content (Fig. 9b). Rocks showing large deviations from the general trend of FeO*, MgO and CaO are all from the POL area where the rocks always have a certain degree of foliated structure.

Na_2O shows a weak negative, while K_2O has a weak positive relation to SiO_2. The rocks from the POL area tend to have lower values of both contents than those from the BS area, i.e., the former are more calc-alkaline than the latter. Sixteen among the eighteen present rocks are plotted in the high K_2O field of Eward (1982). The rocks from the POL area form a relatively low trend and those from the BS area make a relatively high K_2O trend, except for four rocks (Nos. 2, 3, 8 and 10) which are compensated by high Na_2O values (Fig. 10c).

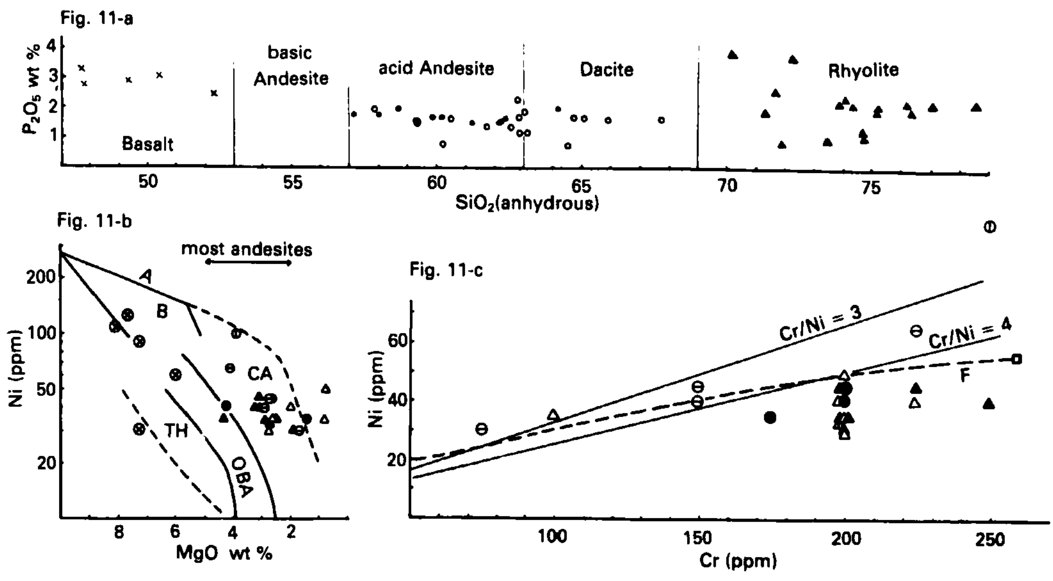


Fig. 11. Trace elements. 11a. $10P_2O_5$-SiO_2 diagram. Crosses: D-1 basic dyke rocks; dots: D-2 metadiabases; open circles: porphyrites and andesites; triangles: quartz porphyries. Nos. 6 and 8 of the metadiabases are excluded due to their too high P_2O_5 contents. *11b.* Ni-MgO diagram for the rocks of basalt-andesite composition range. Open circles with cross: D-1 basic dyke rocks; circles: Botniahalvøya; triangles: Prins Oscars Land; open circles: medium K_2O tholeiites; solid circles: high K_2O tholeiites; open circles with vertical line: medium K_2O calc-alkaline rocks, open circles with horizontal line: high K_2O calc-alkaline rocks; open triangles: medium K_2O tholeiites; solid triangles: high K_2O tholeiites; open triangle with vertical line: medium K_2O calc-alkaline rocks. Reference line: A. liquid in equilibrium with mantle peridotite olivine; B area. MORB and within-plate basalts; OBA zone. orogenic basalts and andesites; TH area. tholeiites; CA area. calc-alkaline rocks, all references are from Gill (1981). *11c.* Ni-Cr diagram for the rocks of andesite composition range. Symbols as for Fig. 11b. Broken curve: fractional crystallization trend with least differentiation (Gill 1981).

Minor and trace elements (Table 6)

The P_2O_5 content of the rocks in the composition range of acid andesite-dacite, both from Botniahalvøya and Prins Oscars Land, is nearly constant (Fig. 11a) relative to SiO_2, with some variations, and that of the quartz porphyrites show separated, negative, correlation. These tendencies indicate a calc-alkaline series.

Sr shows a large variation (Table 6). The D-1 basalts and the Botniahalvøya porphyrites have higher Sr contents than the average MORB (120 ppm), while the rocks of the D-2 group from the POL area have similar level of Sr concentration to the latter. This difference is controlled by fractional crystallization as revealed by the amounts of plagioclase phenocrysts.

Pb was measured only for the D-1 basalts and the values vary randomly from 0 to 50 ppm.

Co contents are very high (100 ± 30 ppm) compared with the average MORB (40 ppm), and remain constant throughout the whole range of SiO_2.

Two other compatible elements, Ni and Cr, are shown in Figs. 11b and c. Ni contents are higher relative to MgO, thus all acid andesites plot in the calc-alkaline field of Fig. 11b. Gill (1981) concluded that high Ni indicates eruption through thick crust as in Andes and Cascade, and the high K_2O contents of the present rocks agree with this presumption. Cr/Ni relation (Fig. 11c) shows an essentially fractional crystallization for the andesitic rocks. Ni contents of the D-1 basalts have a concentration level (88–90 ppm) lower than the average MORB (129 ppm) and show tholeiitic and orogenic basalt-andesite trends (Fig. 11b).

Secondary modifications

Since alkalis are most sensitive to the decomposition of feldspars and development of cleavage with secondary phyllosilicates, the chemical data were examined on the total alkali versus K_2O/total alkali diagram (Fig. 12). Three foliated quartz porphyries from Flaumdalen (Nos. 14, 17,

Table 6. Trace elements.

	Basalts		Acid andesites										
	POL area		porph.- and. Botniahalvøya					Metadiabases. POL area					
	L-K. TH		M-K. TH		H-K. TH		M-K. CA	M-K. TH		H-K. TH		H-K. CA
	n = 5		n = 4		n = 3		n = 1	n = 5		n = 5		n = 1
	x̄	σn	x̄	σn	x̄	σn		x̄	σn	x̄	σn	
Sr	200	115	174	167	228	39	145	142	37	125	31	170
Pb	27	28	—	—	—	—	—	—	—	—	—	—
Ni	83	38	45	15	40	5	100	38	7	38	6	35
Co	106	23	88	33	122	19	110	78	9	101	23	80
Cr	305	96	150	61	192	14	250	205	112	213	21	200

	Dacites						Rhyolites			
	M-K. TH	H-K. TH	M-K. CA		H-K. CA		M-K. CA		H-K. CA	
	n = 1	n = 1	n = 2		n = 2		n = 3		n = 8	
			x̄	σn	x̄	σn	x̄	σn	x̄	σn
Sr	60	405	76	35	108	4	58	67	11	17
Ni	35	40	35	7	33	4	27	3	23	5
Co	80	115	70	28	108	18	72	20	56	29
Cr	200	100	150	0	100	0	108	14	90	29

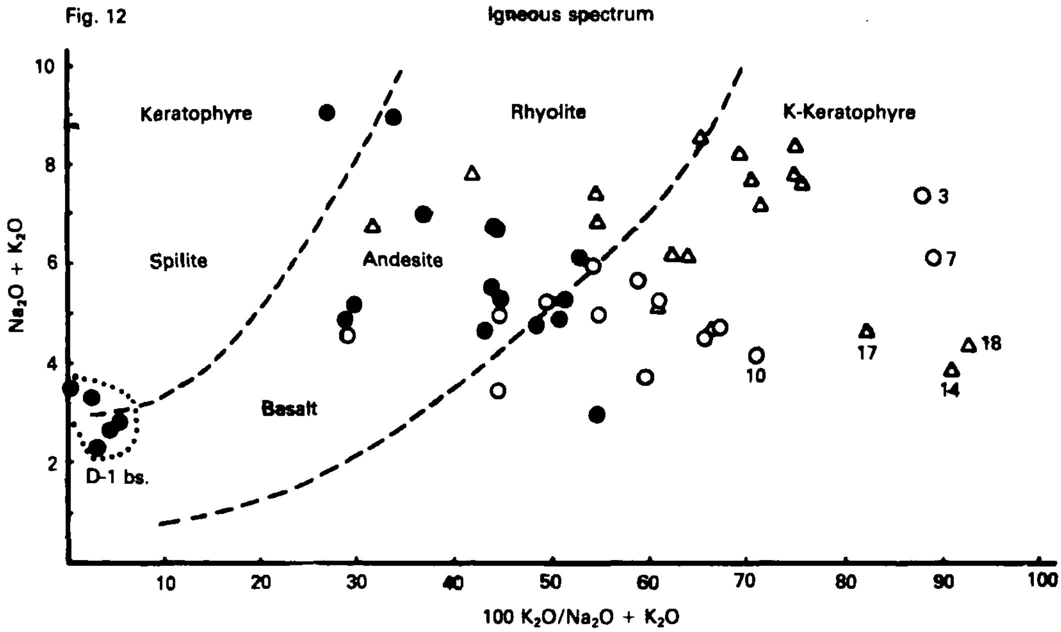


Fig. 12. Alkali-100 K_2O/Alkali diagram for the examination of secondary modification of the rocks. Open circles: porphyrites and andesites; solid circles: metadiabases and basic dyke rocks; triangles: quartz porphyries. Nos. refer to Tables 3, 4 and 5. Igneous spectrum: Hughes (1973).

and 18, having pyroclastic blocky structure or strong cleavage) and three porphyrites from Botniahalvøya (Nos. 3, 7 and 10, blocks from pyroclastic rocks or possible tuff breccia) have very high ratios of K_2O/total alkali. About half of all the analysed rocks plot in the igneous field of Hughes (1973), while the rest are in the K_2O rich field of K-keratophyre composition.

The microscopic observations show that most analysed rocks reveal definite igneous textures without any xenolitic matter, except for the case of some pyroclastic rocks. This means that the addition of K_2O, Al_2O_3 and FeO* might have happened through the assimilation of underlying rocks, i.e., the areno-argillites of the Brennevinsfjorden Formation and micaceous metamorphic rocks of crystalline basement, in the stage of magma, observed as digested xenoliths of shales in Sabineberget, the xenocrysts of microcline in plagioclase phenocrysts in a Flaumdalen metadiabase and garnet in the quartz porphyries of Botniahalvøya. Introduction of these elements had certainly occurred during the formation of cleavage, in the form of sericite.

Summary and discussion

The Kapp Hansteen igneous rocks, the Caledonian geosynclinal volcanic rocks of the Lower Hecla Hoek succession in Nordaustlandet, are possibly older than 766 Ma (Gorochov et al. 1977), but not older than 1275 Ma (Edwards & Taylor 1974). Petrographically, these rocks are primarily basalts, andesites and rhyolites. The metadiabasic rocks are mainly intrusive with a small amount of extrusives, while the porphyrites and andesites are extrusive, accompanied by large amounts of pyroclastic rocks and volcanogenic sediments. The quartz porphyries intruded into them, forming a thick pile of thin layers in southern Prins Oscars Land and stocks and dykes in Botniahalvøya. All rocks are probably covered unconformably by the Murchisonfjorden Supergroup.

Evidence of assimilation in a depth is commonly observed, thus, the modification of the original nature of magma is evident, and a fractional crystallization process took place from such assimilated magmas.

The geochemical characteristics of these rocks can be summarized as follows, if a certain degree of secondary modification is taken into consideration:

Metadiabases:

D-1 group: Basalts of low K_2O type and relatively high Fe tholeiite series.

D-2 group: Mainly acid andesites of low Fe tholeiite series and medium-high K_2O type.

Porphyrites: Acid andesites and dacites of medium-high K_2O type and calc-alkaline series, possibly showing a transition from tholeiitic series.

Quartz porphyries: Rhyolites of high K_2O type and calc-alkaline series.

The FeO* enrichment trend of the D-1 group basalts seems to be similar to the island arc tholeiites of Jakes & Gill (1970) and their TiO_2-K_2O-P_2O_5 ratios show an oceanic nature (Fig. 6c). No confirming evidence for their oceanic emplacement has been found in their occurrences.

The D-2 metadiabases show least evidence of assimilation. They are tholeiitic and tend to approach the calc-alkaline series in their silicic varieties. On the other hand, the porphyrite-andesites may show a transition from the tholeiitic to calc-alkalic series. The quartz porphyries are the latest differentiates of the calc-alkaline rock series. Thus, the three rock groups can be considered as the products of one series of fractional crystallization, even though the localities are spread over more than 60 km across the general structural trend of Caledonian folded zone. Since detailed trace element data, such as REE analyses, are lacking at the present stage of study, it is impossible to discuss repeated partial melting of mantle and basement.

The tholeiitic metadiabases seem to possess relatively primary chemical characteristics and the calc-alkaline porphyrite/andesites and quartz porphyries are more modified representatives of assimilation. All these rocks are non-oceanic in terms of their TiO_2-K_2O-P_2O_5 ratios.

The large volume of acid andesites and rhyolites and their high K_2O contents are conformable with recent volcanic associations of active continental margins, i.e., in Andes and Cascade, where the continental crust developed very thickly (Miyashiro 1974; Gill 1981). The high initial $Sr^{87/86}$ ratio of possible basement granite-gneiss; 0.72172 ± 0.00056 (Edwards & Taylor 1974) and that of the quartz porphyry, 0.7259 ± 0.0088 (Gorochov et al. 1977) may reveal that there were old crustal rocks below, though these values are also controlled very much by fractional crystallization.

Thus, it seems probable that thick crust existed in this part of the Caledonian geosyncline during the period of Kapp Hansteen igneous activities. An unconformity found in the southern part of Botniahalvøya shows that the volcanogenic basal conglomerate of the Kapp Hansteen Group lies on strongly folded shale/sandy quartzite beds of the Brennevinsfjorden Formation, thus indicating a distinct Precambrian deformation. The inferred thick continental crust could have been formed during this deformation period, or even earlier.

To the west in Ny Friesland, NE Spitsbergen, where the standard stratigraphy of the Hecla Hoek geosynclinal succession was established, no discontinuity has been reported from the corresponding part of the succession (Harland et al. 1966). However, Krasil'scikov (1979) proposed a major break in the upper Lower Hecla Hoek, and considered that the high grade metamorphic rocks of the Harkerbreen and the Finnlandveggen Groups belong to the crystalline basement. Present study of the igneous rocks infers a positive evidence for the existence of Precambrian continental crust in Nordaustlandet.

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