Preliminary Investigations of some Ordovician Volcanics from Stord, West Norway

STEPHEN JOHN LIPPARD

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Later Ordovician volcanics on Stord, W. Norway, comprise alkaline rhyolite flows and ignimbrites, and ferro-basalt (icelandite) and basaltic andesite lavas. The latter are hy-normative, 'evolved' rocks rich in residual trace elements and low in Ni and Cr. The rhyolites are highly fractionated rocks. They contrast with later intrusions of granite porphyry which are calc–alkaline and poorer in Zr, Nb, Y, and REE, and richer in Ca, Mg and Sr than the rhyolites. Subaerial volcanism of this type suggests an intra-continental, possibly rifted, environment in this part of southwestern Norway in the late Ordovician. Younger dolerite sills and basalt dykes in the area are continental tholeiites and transitional basalts.

S. J. Lippard, Geologisk Institutt, Avd. A, Universitetet, J. Frieles gt. 1, N–5000 Bergen, Norway
Present address: Dept. of Geology, Bedford College, Regents Park, London NW1 4NS, England

Introduction

The northern parts of the islands of Stord and Bømlo, western Tysnesøy and several smaller islands in this part of Hordaland, West Norway (Fig. 1) are composed almost entirely of igneous rocks. This igneous complex has been called the 'Sunnhordland Massif' by Kolderup (1931) and Strand (1972). The southeastern margin of the igneous complex on Stord is a fault (Kvale 1937) which Strand (op. cit.) describes as a thrust, thereby implying that the igneous rocks form a nappe. The first geological map of the area was that of Reusch (1888), who divided the rocks of northern Stord into diorite (altered gabbro in Reush's terminology), granite and stratified greenstones. The area was mapped and described in greater detail by Kvale (1937), who showed that gabbros and granites predominate in the north and extend down the eastern and western sides of the island, while acid and basic volcanics, including lavas, tuffs and agglomerates, crop out mainly in the southern and central parts of the area. Kvale (op. cit.) showed that the original features of the rocks are best preserved in the southeast and that the degree of deformation and grade of metamorphism increase northward and westward. It was therefore decided to make a detailed study of the volcanics in the Katnakken–Tjørndalen region immediately north of the boundary fault.

The southern part of Stord is composed of submarine metasediments and metavolcanics of unknown age (Kiær 1929; Skordal 1948; Strand 1960). A small fault-bounded area of younger rocks on the northwestern edge of this belt comprises late Ordovician-Lower Silurian fossiliferous sediments, pillow lavas and conglomerates known as the Dyvikvågen Group (Færseth & Ryan

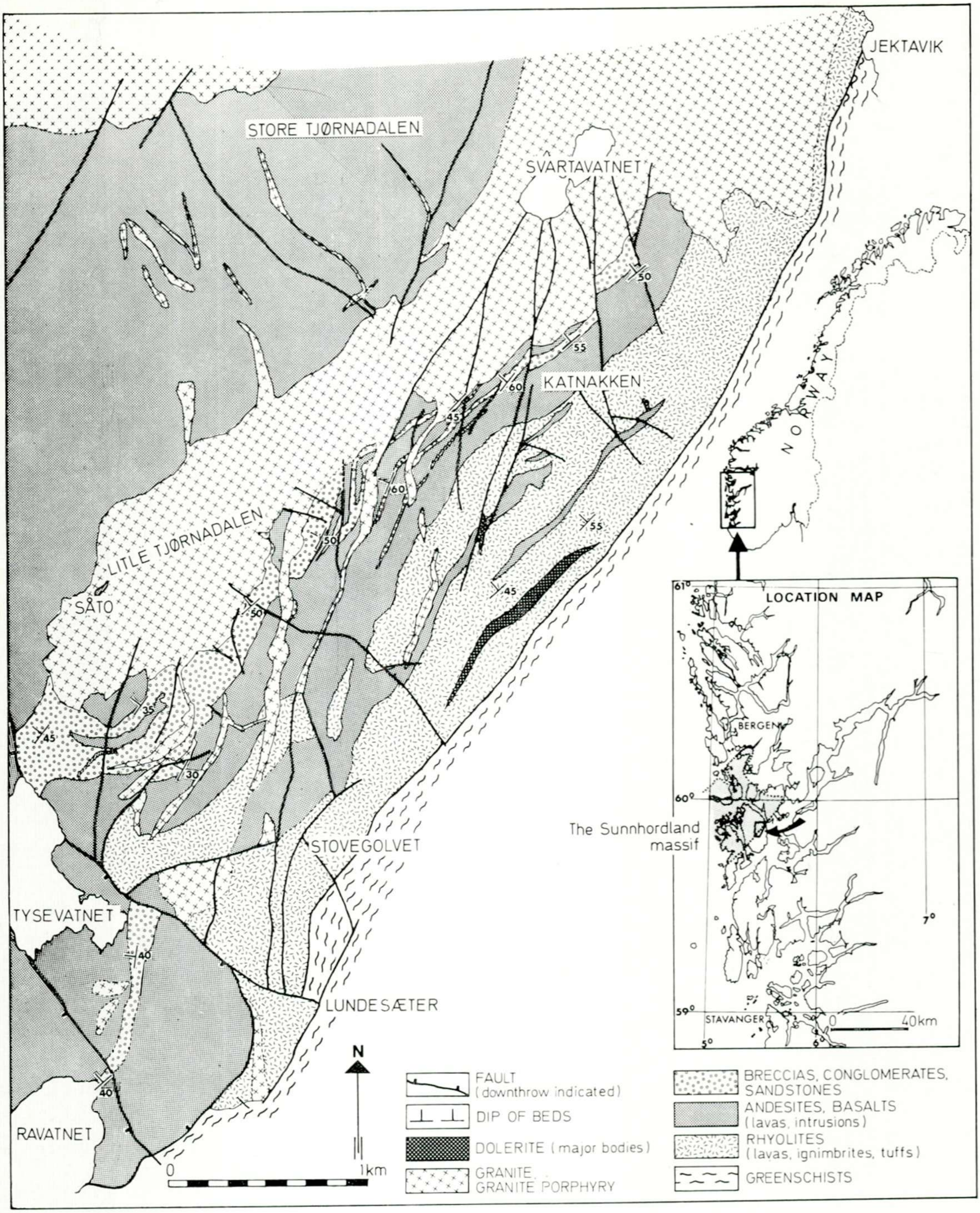

Fig. 1. Geological map of the Katnakken area, Stord, West Norway.

1975). The only evidence for the age of the volcanics north of the boundary fault is a Rb/Sr isochron of 455±5 m.y. (based on $\mathrm{Rb}^{87}-1.39\times10^{-11}\mathrm{y}^{-1}$) for acid volcanics collected from Katnakken (Priem & Torske 1973).

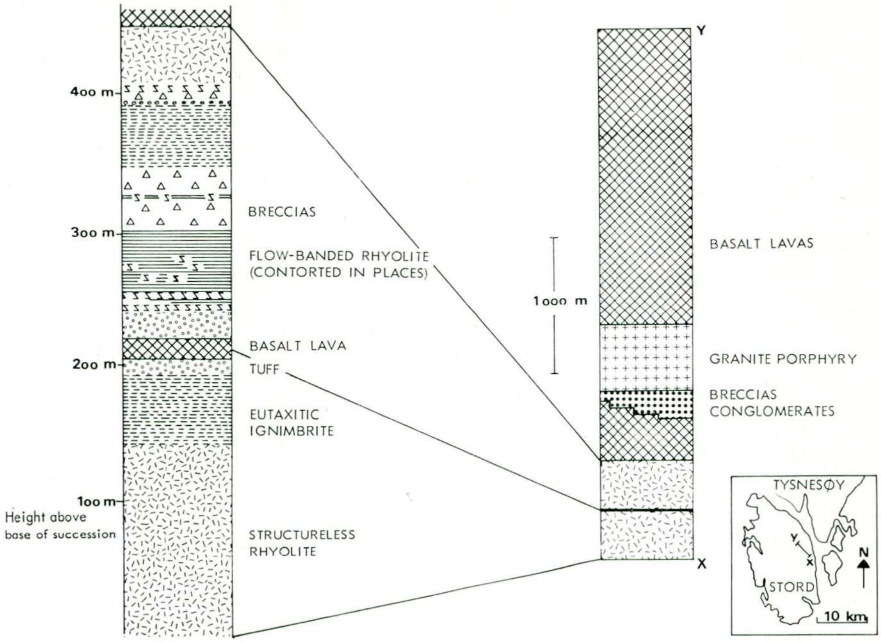

Fig. 2. Volcanic sequence in the Katnakken–Tjørndalen area. Left-hand column shows details of the rhyolite succession on Katnakken.

A geochemical study of the basic metavolcanics from all the rock units on Stord has been made by Furnes & Færseth (1975). Gale (1974) and Gale & Roberts (1974) have carried out reconnaissance geochemical studies on the volcanics on Bømlo (including four analyses from Stord).

The volcanic rocks form rugged mountain country between 300 m and 700 m a.s.l. with high points at Katnakken (724 m) and Stovegolvet (703 m). The area mapped in detail covers about 15 km^2.

Grid references referred to in the text refer to the 1:50.000 map sheets 1114 I (Fitjar) and 1214 IV (Onarheim).

Succession and lithologies

The sequence begins with acid volcanics, mainly rhyolites, about 450 m thick (Fig. 2). This formation contains both lavas and pyroclastic rocks, including ignimbrites. These are overlain by lavas of mainly basic composition, at least 3000 m thick. Volcanic sediments, breccias, conglomerates and some sandstones occur within the lava pile. The sequence is subaerial throughout. There are intrusions of granite porphyry, dolerite and basalt dykes, emplaced in that order, cutting the volcanics.

EXTRUSIVE ROCKS

Rhyolites

The rhyolites outcrop along the southeast-facing scarp between Jektavik and

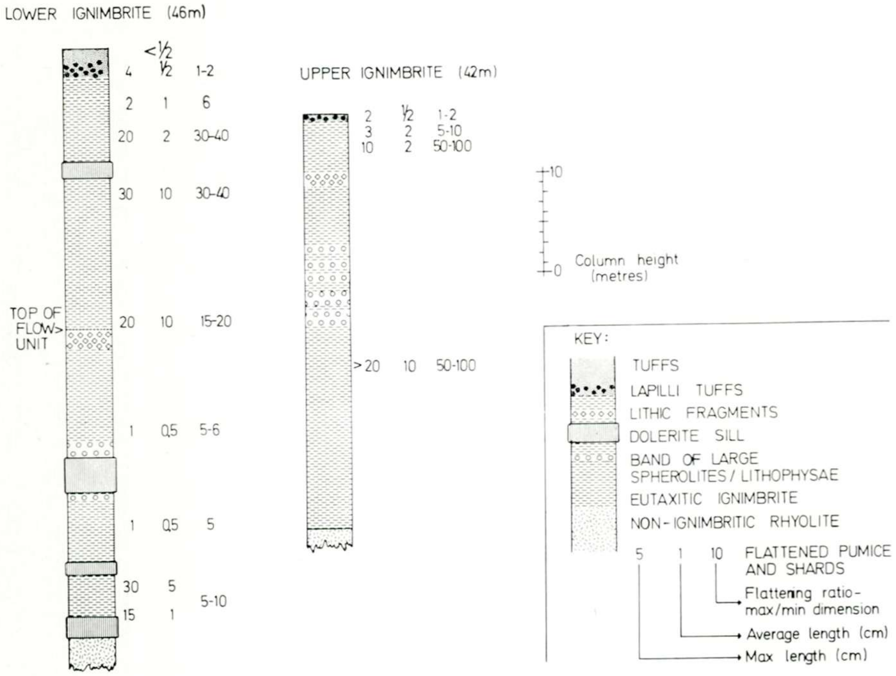

Fig. 3. Detailed sections through the two ignimbrites in the Katnakken section.

Stovegolvet. They do not extend far to the southwest; beyond Lundesæter they are cut out by faulting. The maximum thickness is about 450 m in the Katnakken section, which is described in detail below.

The *lover rhyolite* (200 m thick – base not seen) comprises 150 m of structureless rhyolite overlain by 50 m of eutaxitic ignimbrite. The latter contains two flow units, and at the top there is a 2–3 m thick layer of non-flattened lapilli tuff. The lower and middle rhyolites are separated by a basalt lava.

The *middle rhyolite* (160 m) is composed in the lower part of 20 m of bedded tuffs. These are overlain by a rhyolite flow approximately 100 m thick and then by more tuffs and breccias towards the top.

The next member of the succession is an andesitic-dacitic ignimbrite, which is described in some detail below.

The *upper rhyolite* (60 m), which has thin tuffs and breccias at its base, is mainly a structurless rhyolite showing local flow banding. It probably represents a single lava flow.

Ignimbrites: The ignimbrites are recognised primarily by the presence of

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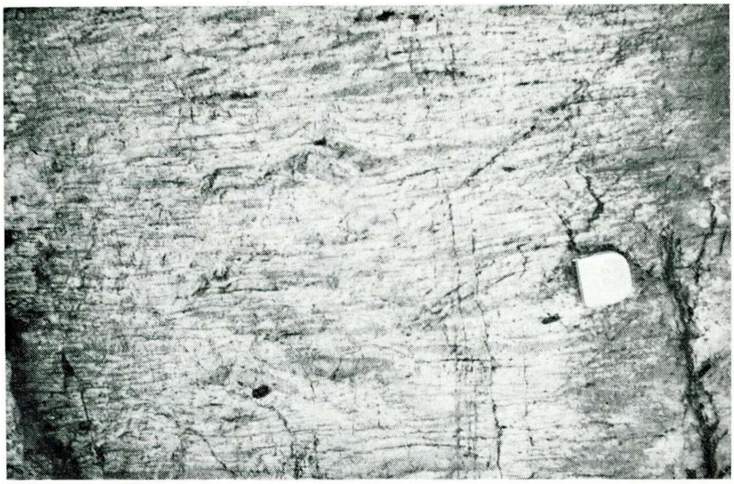
Fig. 4. A) Eutaxitic ignimbrite from the upper part of the lower rhyolite. Scale 5 mm across. *B)* Contact of two ignimbrite flow units. The lower unit contains angular lithic blocks at the top. The upper unit is free from lithic inclusions and shows a greater degree of flattening of the shards as compared with the lower. Scale bar 15 cm.

C) Highly flattened parataxitic rhyolitic ignimbrite. Later-formed spherulites have grown across the flattened shards. Pencil approximately 15 cm long.



a)

b)

c)

eutaxitic and paratixitic textures (Martin 1959; Ross & Smith 1961; Boyd 1961) (Fig. 4). Variations in the degree of flattening and in the sizes of the dark lenticular fiamme are indicated on Fig. 3.

The lower ignimbritic rocks in the succession are rhyolitic in composition (Fig. 5). These contain abundant dark fiamme (30–40% vol.) set in a pale matrix. Sparse quartz and feldspar phenocrysts form about 1% of the mode. Lithic fragments are absent except in a few bands; these are highly altered.

The structureless rhyolite forming the greater part of the lower rhyolite is believed to be ignimbritic for the following reasons: 1) the contact with the overlying eutaxitic is sharp; 2) there is an absence of weathering or tuff deposition at the boundary; and 3) the whole of the lower rhyolite displays chemical homogeneity. Complete homogenisation may have obliterated the fragmental texture in the lower part, as has been observed in the central zones of thick Tertiary ignimbrite sheets in the U.S.A. (Smith 1960). The entire lower rhyolite (200 m) may be the upper part of a single ignimbrite cooling unit (Ross & Smith 1961).

The upper ignimbrite in the succession is thinner than the lower and is andesitic to dacitic in composition (Table 4). It contains 5–10% of phenocrysts of plagioclase and pseudomorphs after ferromagnesian minerals, dark fiamme and 20–30% of small angular fragments of basalt and andesite. The lithic chips are absent from the upper 3–4 m of the deposit from which the analysed dacite sample was taken.

Acid ignimbrites have been described from Bømlo by Songstad (1971).

Tuffs: Air-fall bedded tuffs constitute about 10% of the Katnakken section. They are mainly fine-grained, thin-bedded, pumice tuffs with occasional bands rich in crystals and pumice and lithic fragments. Some bands are composed of rain-drop accretionary lapilli (Wentworth & Williams 1932). The fine-grained tuffs have generally recrystallised to a hard, flinty felsite. Despite this, delicately preserved textures are recognisable, particularly on weathered surfaces. The same is true of the ignimbrites.

Lava flows: The rhyolite flows in the middle and upper units are distinguished by the presence of flow folding and flow banding (Rutten 1963). Autobreccias are also found, being particularly well displayed at the top of the middle rhyolite, for example at grid reference 040428.

Basic lavas

The basic lavas are massive, dark grey to green, aphanitic, aphyric and plagioclase-phyric rocks. Although there are some flows interbedded within the rhyolites near the base of the succession, the majority overlie the rhyolites and the total thickness measured between Katnakken and Tjørndalen is 3000 m. They are divided into two groups by the sedimentary formation described below. The lower lava unit is slightly less than 1000 m thick and can be traced from Ravatnet to 1 km northeast of Katnakken (grid reference 041438). The upper formation is more than 2000 m thick and crops out over the greater part of the map area. These rocks were recognised as a pile of lava flows by Kvale (1937) and variously described as diabases, grennstones and diabase porphyries. Kvale (op. cit.) also recognised several amygdaloidal types. When viewed from a distance the topography shows well-defined trapp features particularly on the southwest side of Tysevatnet and around Ravatnet. Locally the lavas are vesicular and amygdaloidal. Flow tops can be recognised by highly vesicular, brecciated and oxidised zones. Massive outcrops of columnar jointed lava represent the central parts of thicker flow units. Several hundred flow units are considered to be present, the majority between 10 m and 20 m thickness. The absence of pillow structures and the presence of columnar jointing, weathered flow tops and interbedded subaerial sediments indicate that the lavas are of subaerial origin.

Some small plugs of a fine-grained basic rock have been observed cutting the lavas and may have been feeding necks for some of the flows. A nearly circular body at grid reference 023422 was emplaced through the sediments and locally contains blocks of sediment along its margins.

The sediments interbedded in the lavas consist mainly of massive breccias and conglomerates (max. clast size 40 cm) with local sandstones and shales. The clasts are of locally derived rhyolite, basalt and porphyry. Near Såto these deposits are 350 m thick but they thin rapidly to the NE and SW and then consist of a series of thin sediment lenses with interbedded lavas. The majority are poorly sorted with a predominance of angular clasts; these are interpreted as scree and mud-flow deposits in an area of high volcanic relief. Towards the top of the succession there are some better sorted cross-bedded and flat-badded fluvial sandstones and conglomerates with a few thin shale horizons.

INTRUSIVE ROCKS

Granite porphyries

A number of sills, dykes and plugs of massive, light-coloured, granite porphyry intrude the volcanics in the Katnakken–Tjørndalen area. The largest body is a 400 m-thick conformable sheet trending NE-SW between Svartavatnet and Såto intruded into the middle of the basic lavas just above the sedimentary unit. Porphyry dykes between 10 m and 100 m thick protrude into the lavas from both the base and the top of the sheet. Those above the sheet trend NW-SE, and those below it N-S to NE-SW. There are, in addition, several isolated plugs and sheets of the same rock-type distributed throughout the area. The upper and lower margins of the main porphyry sheet are deformed and foliated by later tectonic movements. The porphyries show no chilled margins, changes of grain-size or variation in phenocryst content within individual bodies. On the map of Kvale (op. cit. 1937) the porphyries are not distinguished from the rhyolites and are shown as acid effusives.

Dolerites

Dolerite sills have intruded the volcanics and the porphyries and trend NE-SW. The swarm is most intense in the southeast between Stovegolvet and Katnakken, where it forms about 15% of the outcrop area, and dies out northwestwards. The northwesternmost sill occurs at grid reference 026424. The largest body is laccolithic and has a maximum thickness of 70 m. The majority are 1–3 m thick sills that can be traced for long distances along the strike. There are some irregular bodies of dolerite which trend N-S, for example at grid reference 033418, where the dolerites are intruded along a fault-line.

Basalt dykes

Northwest of Stovegolvet three fine-grained basalt dykes, 1–2 m in thickness, transect the dolerites. Two of them trend N-S, the third approximately E-W. These are the youngest rocks in the area which have been affected by the Caledonian metamorphism.

A few NW-SE-oriented camptonite dykes occur on Stovegolvet and cut across the boundary fault. They are unmetamorphosed and probably Upper Palaeozoic to Mesozoic in age. None of the other intrusive rocks occurs south of the fault.

Petrographic notes

Rhyolites: The rhyolites contain sparse phenocrysts of quartz and heavily sericitised alkali feldspar. The groundmass is a cryptocrystalline felsite in which quartz, microcline and albite have been identified by X-ray diffraction. Sericite, chlorite, calcite, epidote, haematite, sphene, zircon and apatite occur in minor amounts. Quartz/feldspar spherulites occur on all scales up to 3–4 cm across. Recrystallisation under low-grade metamorphism has produced this low temperature mineral assemblage. These rocks were almost certainly originally composed largely of glass and pumice.

Basic lavas: Most of these rocks are fine-grained to aphanitic. Some are sparsely porphyritic with up to 10% of plagioclase phenocrysts. These are heavily altered but occasionally have fresh cores showing strong zoning. The average composition of these is labradorite–andesine in the range $An_{52\text{-}44}$ (measured by $\alpha \wedge (010)$ on pars of Carlsbad/albite twins using the determine curve of Calkins & Hess (1947)). The largest phenocrysts seen are 2 mm long. The groundmass is generally microcrystalline, pilotaxitic and heavily impregnated with opaque dust. The mineralogy is entirely secondary due to low-grade (greenschist) metamorphism and comprises albite, quartz, chlorite, actinolite, epidote, sphene and titanomagnetite–ilmenite. The titanomagnetite–ilmenite intergrowths are very fine-grained and all the grains are mantled with sphene; some are completely replaced by the latter mineral. The quartz occurs in irregular granular patches and contains numerous fine needles, probably of apatite. Autobreccias consist of angular lava blocks separated by veins of granular epidote and quartz. Amygdales contain the same minerals together with penninite and sometimes a later infilling of carbonate. Quartz and carbonate veins are common.

Granite porphyries: These rocks are conspicuously porphyritic with between 10% and 35% of phenocrysts of quartz, orthoclase microperthite and albite–oligoclase, and microphenocrysts of biotite and pyroxene. The quartzes show sub-grain development and undulose strain extinction. Both types of feldspar are altered to sericite and clay minerals, while the ferromagnesian minerals are pseudomorphed by chlorite and opaque iron–titanium oxides. All these effects are due to the greenschist facies metamorphism and deformation. The quartz phenocrysts are anhedral with embayed margins, while the feldspars tend to be subhedral. In some porphyry bodies the phenocrysts average 5 mm across, but 1–2 mm is more typical. The groundmass is microcrystalline to cryptocrystalline 'felsitic' and locally spherulitic, and is composed of quartz, perthite, chlorite, muscovite, iron oxides and sphene. Some deformed specimens have a schistose matrix of sericite and chlorite containing oriented phenocrysts and fragments of porphyry. In these rocks the quartz phenocrysts have an overgrowth of unstrained granular quartz.

Dolerites: The rocks show sub-ophitic and intergranular textures and retain some of their primary mineralogy which comprises labradorite, augite, titanomagnetite, ilmenite and apatite. The plagioclase and pyroxene are partly replaced by a greenschist facies mineral assemblage – albite, chlorite, actinolite, epidote. The ilmenite and titanomagnetite occur as rod-shaped and skeletal grains up to 5 mm in length, and as coarse intergrowths and individual grains. Interstitial quartz is present, some of which appears to be secondary. There are also some possible pseudomorphs after olivine in some specimens. The grain size, as measured by the lengths of plagioclase laths, in the thicker sills and irregular sheets reaches 0.5mm, but in the majority of the sills it is 0.1–0.2 mm.

Metamorphism and structure

The mineralogies of the rocks indicate recrystallisation under greenschist facies conditions (quartz–albite–biotite–chlorite subfacies), although locally, in the cores of phenocrysts and in the dolerites, original igneous calcic–plagioclases and pyroxenes are preserved.

Throughout the area the rocks dip to the northwest at between 30° and 70°. Some of the rocks have a flat-lying cleavage dipping to the northwest. The fact that the cleavage consistently has a lower dip than the bedding could be taken to indicate a possible inversion of the sequence. Further work on the significance of the cleavage in the northern Stord is being undertaken.

There are several high-angle faults with two predominant strike directions (NNE–SSW and NW–SE). Two of the largest trend NW–SE along the sides of Tysevatnet (Fig. 1), the one on the northeast side having a downthrow to the southwest of about 1 km. Near Lundesæter this fault swings through 90° towards Ravatnet to parallel the NE–SW boundary fault. The latter is a high-angle fault with little associated cataclasis.

The joint patterns in the area are complex with nearly all possible strike directions represented, probably owing to the superimposition of tectonic joints on cooling structures. Columnar jointing is characteristic of the dolerite sills.

Geochemistry

METHODS

The chemical analyses were performed on a Phillips PW1450 automatic X-ray fluorescence spectrometer in the Geologisk Institutt, Avd. A, Universitetet i Bergen.

Fused glass beads, prepared according to the method of Padfield & Gray (1971), were used for the major element analyses and pressed powder briquettes for the trace element and sodium determinations. For the major elements twenty-eight international standards and the recommended values of Flanagan (1972), refined by least squares procedures and matrix corrections, were used for calibration. For the trace elements eighteen standards were employed and background and interfering element corrections applied.

Water and carbon dioxide were determined by conventional techniques, ferrous iron by titration with potassium dichromate. In addition, some duplicate Na_2O and K_2O values were obtained by flame photometry.

Table 1. Major element compositions of the Katnakken rhyolites and porphyries, and average of rhyolites from Nockolds (1954)

	1	2	3	4
SiO_2	73.89	72.09	73.66	74.57
Al_2O_3	12.74	13.95	13.45	12.58
TiO_2	0.26	0.30	0.22	0.17
Fe_2O_3	1.07	0.29	1.25	1.30
FeO	1.52	1.82	0.75	1.02
MgO	0.27	0.49	0.32	0.11
CaO	0.86	1.22	1.33	0.61
Na_2O	4.02	3.10	2.99	4.13
K_2O	4.90	6.04	5.35	4.73
MnO	0.03	0.05	0.03	0.05
P_2O_5	0.01	0.08	0.07	0.07
Loss on ignition	0.33	0.35	0.78	0.66

1 Average Katnakken rhyolite (27 analyses)
2 Average porphyry (5 analyses)
3 Average calc-alkaline rhyolite (Nockolds (1954))
4 Average alkaline rhyolite (Nockolds, op. cit.)
All averages recalculated to 100 % for direct comparison with Nockolds' data.

Table 2. Means (x) and standard deviations (s) of trace element contents of the Katnakken rhyolites and porphyries

	A	B	C	D
	$\bar{x}$ (s)	$\bar{x}$ (s)	$\bar{x}$ (s)	$\bar{x}$ (s)
Zr	548(9.80)	461(29.3)	772(52.7)	244(11.95)
Nb	55(2.75)	54(2.71)	52(15.34)	33(3.04)
La	74(1.97)	80(7.15)	62(6.22)	57(8.99)
Ce	129(4.35)	129(8.47)	111(13.64)	102(2.92)
Nd	73(3.36)	75(5.05)	64(7.23)	50(4.18)
Y	118(3.90)	127(8.06)	120(40.73)	64(10.55)
Rb	228(33.88)	279(49.45)	205(40.73)	242(23.17)
Sr	51(18.20)	20(3.21)	31(10.29)	110(43.94)

A Lower Katnakken rhyolite (12 analyses)
B Middle Katnakken rhyolite (7 analyses)
C Upper Katnakken rhyolite (6 analyses)
D Granite porphyry (5 analyses)
All values in parts per million. Analyst S. J. Lippard.

RESULTS

Rhyolites (27 analyses)

The average Katnakken rhyolite (Table 1) has a composition intermediate between Nockold's (1954) calc–alkaline and alkaline rhyolite types in terms of Al_2O_3, CaO and MgO, and a total alkali content similar to the alkaline rhyolite. Na_2O/K_2O varies between 0.40 and 1.27, but the majority of values (22) fall between 0.68 and 0.93.

The middle rhyolite is the most acid of the three units in the Katnakken

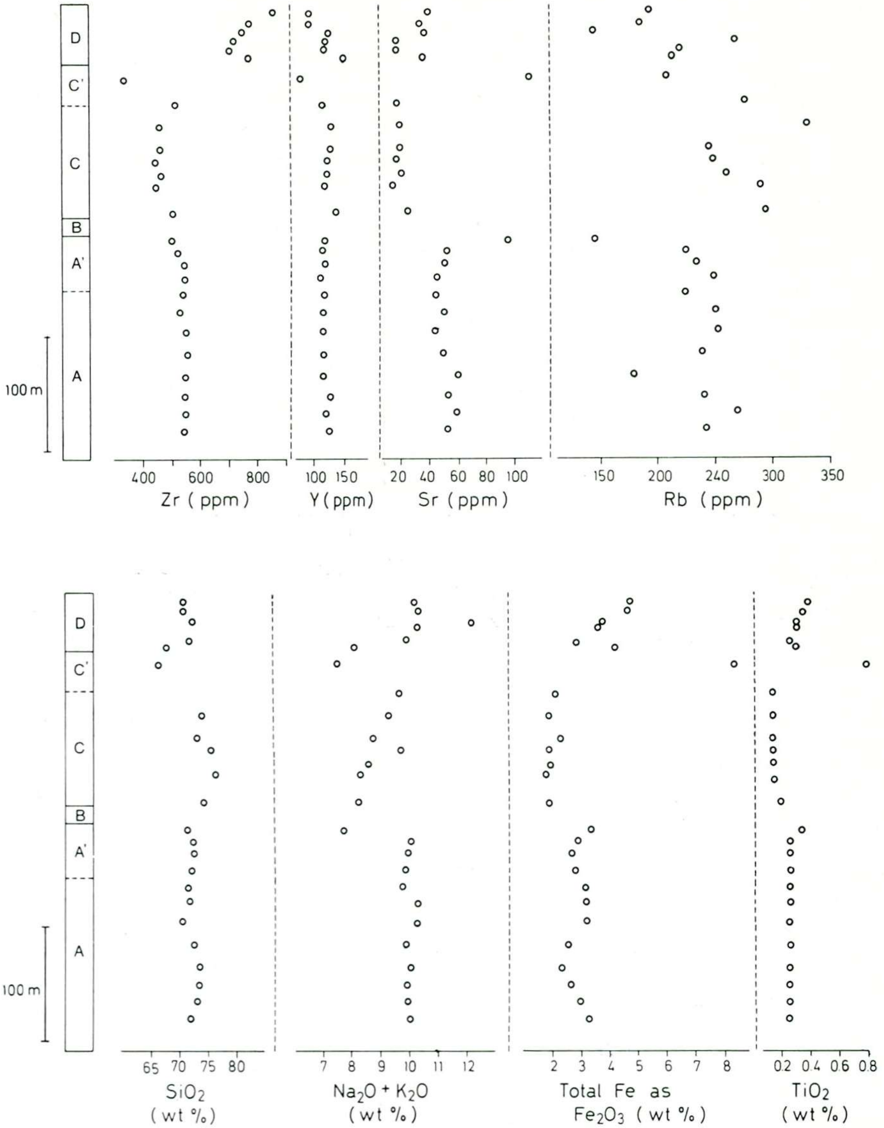


Fig. 5. Chemical variations in the Katnakken rhyolites. A – lower rhyolite; A′ – eutaxitic ignimbrite; B – basalt lava (analysis not shown); C – middle rhyolite; C′ – dacitic ignimbrite; D – upper rhyolite.

section with higher SiO_2 and lower MgO, CaO, total Fe and TiO_2 than the upper and lower members (Fig. 5). In the middle unit Mg assumes trace abundance and is frequently below the level of detection of the analytical method ($MgO < 0.01\%$). The tuffs and the lower part of the flow in the middle unit are depleted in alkalies, particularly Na_2O, compared to the rest of the section (Fig. 5).

The Katnakken rhyolites have a high Zr content of 450–865 ppm. The Zr contents of the lower, middle and upper rhyolites are each distinct (Table 2).

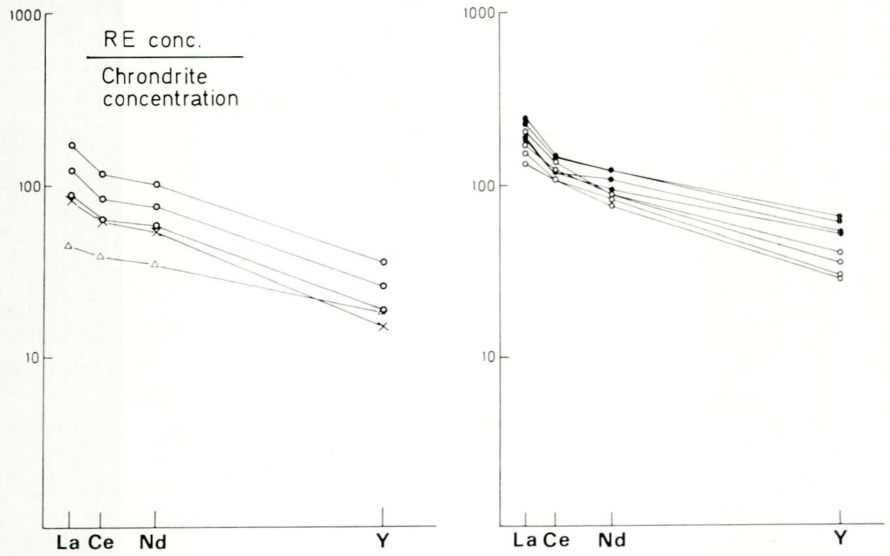


Fig. 6. Normalised rare-earth patterns for the Katnakken volcanics. Left-hand diagram: open circles – basic lavas (maximum, minimum and average values); crosses – dolerites (average values); triangles – basalt dyke. Right-hand diagram: closed circles – rhyolites; open circles – porphyries.

On the other hand, Nb (c. 50 ppm), Y (100–120 ppm) and the light rare-earth elements (La, Ce, Nd) are remarkably constant in abundance throughout the sequence. Sr follows Ca and is lower in the middle rhyolite (average 20 ppm). Rb is variable throughout (150–350 ppm) and shows no systematic variation. K/Rb varies from 161 to 267.

Porphyries (5 analyses)

The porphyries have higher average Al_2O_3, MgO and CaO than the rhyolites (although the ranges overlap) corresponding to Nockold's (1954) calc–alkaline rhyolite type values (Table 1). The Na_2O/K_2O ratio in the porphyries is 0.51–0.61, with one anomalously low value 0.3, lower than in almost all the rhyolites. The porphyries seem uniform in their trace element contents (there are only a limited number of analyses), except for Sr, which is much lower in one sample (S49) than in the others.

There are significant trace element differences between the rhyolites and the porphyries (Table 2). The former are richer in Zr (by a factor of 1.8–3.1), Nb (1.6) and Y (1.7–2.0). Rb, Sr, La, Ce and Nd are not significantly different, however. The normalised REE patterns (Fig. 6) show that there is an enrichment in heavy REE (represented by Y) relative to light REE (La, Ce, Nd) in the rhyolites, compared to the porphyries. Both the rhyolites and the porphyries are, however, markedly enriched in the light REE, especially La, compared to the chrondrite norm. This is typical of nearly all granitic rocks (Haskin et al. 1966). The K/Rb values of he porphyries (161–210) fall within the range found in the rhyolites.

Table 3. Chemical compositions of andesites and dacites from the Katnakken section

	S_9	S_{10}	S_{11}	S_{46}
SiO_2	56.71	59.19	66.27	65.69
Al_2O_3	15.04	14.35	14.04	14.76
TiO_2	2.07	1.87	0.79	1.54
Fe_2O_3	4.66	4.60	3.30	4.92
FeO	7.56	7.00	3.95	2.23
MgO	2.38	1.92	0.56	1.47
CaO	5.54	4.49	2.35	1.62
Na_2O	3.17	3.39	2.23	0.68
K_2O	2.58	2.58	5.19	4.44
MnO	0.18	0.15	0.12	0.05
P_2O_5	0.75	0.60	0.22	0.26
H_2O (total)	0.69	0.68	0.38	1.75
CO_2	n.d.	n.d.	n.d.	0.35
Total	100.79	100.72	99.40	99.58
Zr	186	197	346	329
Nb	21	21	34	33
Sr	221	168	112	66
Rb	89	90	209	209
La	41	40	48	35
Ce	77	83	96	66
Nd	50	53	53	40
Y	51	51	80	62
Cu	8	7	7	11
Zn	131	125	118	92

n.d. Not determined
Analyst S. J. Lippard
Major element values in weight per cent.
Trace element values in parts per million.

Dacites (2 analyses)

Out of a total of 80 analyses made of the volcanic rocks from the area, only two fall in the range of dacites (62–68% SiO_2) as defined by Taylor (1969) (Table 3). Sample S11 comes from the upper part of the upper ignimbrite. Also included in Table 3 are samples S9 and S10, which come from the lower and middle portions of the flow respectively. These specimens contain abundant inclusions of basic lavas. The second dacite (S46) is from the pumice tuffs and shows a deficiency of Na_2O and probably also CaO.

The dacites are poorer in Zr, Nb, Y and REE compared to the rhyolites, by an average factor of 0.6–0.7. The Sr, Rb, Cu and Zn values are not different.

Basic lavas (34 analyses) (Table 4)

The basic lavas from the Katnakken area are divided on the basis of FeO* (total iron oxide recalculated as FeO) into an iron-rich type (27 analyses) (FeO* $>$ 9.5) and an iron-poor type (7 analyses) (FeO* 6.5–8.0). The Al_2O_3 (lower in the iron-rich group) and P_2O_5 (higher in the iron-rich group) contents of the two types are significantly different. Taking the basic lavas as

Table 4. Chemical composition of the basic lavas, Katnakken area

	Type 1 (icelandites)		Type 2 (basaltic andesites)	
	Average (27 analyses)	Range	Average (7 analyses)	Range
SiO_2	55.35	51.39–58.96	56.60	54.22–57.71
Al_2O_3	14.78	13.13–15.38	16.26	15.73–17.53
TiO_2	1.84	1.64– 2.83	1.54	1.16– 2.34
Fe_2O_3	3.91	2.24– 7.09	2.28	1.53– 5.09
FeO	7.28	4.84– 9.59	5.06	3.32– 6.58
MgO	2.67	1.80– 3.52	2.95	1.84– 4.65
CaO	6.00	3.19– 8.54	6.44	3.21– 9.81
Na_2O	3.31	2.95– 4.58	3.11	2.24– 4.07
K_2O	2.24	1.31– 3.74	2.08	0.96– 2.86
MnO	0.17	0.13– 0.25	0.14	0.08– 0.20
P_2O_5	0.43	0.28– 0.74	0.23	0.15– 0.43
H_2O (total)	0.72	0.33– 1.74	0.93	0.58– 1.13
CO_2	0.42	0.10– 2.06	0.27	0.05– 0.75
Total	99.12		98.89	
FeO*	10.80	9.87–12.96	7.11	6.82– 7.87
Zr	221	183 – 377	250	199 – 382
Nb	24	21 – 28	23	17 – 35
Y	50	42 – 58	44	32 – 70
La	41	36 – 48	41	33 – 57
Ce	74	62 – 89	74	61 – 104
Nd	48	40 – 55	44	34 – 61
Sr	242	181 – 281	218	159 – 398
Rb	92	58 – 126	86	20 – 136
Zn	121	113 – 132	107	88 – 132
Cu	9	6 – 13	9	4 – 17
Ni	13	10 – 14	20	11 – 36
Cr	21	15 – 30	54	13 – 103

CIPW norms: Analysts: S. J. Lippard

Type 1 average: q 11.0; or 13.2; ab 28.0; an 18.9; di 4.5; hy 11.5; mt 5.2; il 3.5; ap 1.0; c 1.0.

Type 2 average: q 12.8; or 12.3; ab 26.3; and 24.3; di 3.6; hy 9.8; mt 4.8; il 2.9; ap 0.5; c 0.6.

a whole, CaO, K_2O and P_2O_5 vary by factors greater than three, and TiO_2, Fe_2O_3, FeO, MgO, Na_2O and MnO by more than two. The FeO* content can reach as much as 13% and FeO*/MgO up to 6.5. The CIPW norms (Table 4) contain q and hy and the normative plagioclase composition is andesine.

The Katnakken basic volcanics contain high 'residual' element contents and low Ni, Cu and Cr (Table 4). The REE/chrondrite normalised plots show a strong enrichment i nthe light REE (Fig. 6).

Dolerite (8 analyses)

The dolerites are uniform in composition over the limited number of samples taken (Table 5). The average composition is a typical quartz tholeiite, closely comparable, for example, to the average Palisades (Walker 1969) or Karroo

Table 5. Chemical compositions and CIPW norms of the younger dolerite sills and one basalt dyke

	Dolerite (average composition of 8 analyses)	Basalt dyke (S 107)
SiO_2	51.51	49.40
Al_2O_3	15.28	15.29
TiO_2	1.78	1.63
Fe_2O_3	1.83	2.17
FeO	8.51	7.93
MgO	4.73	7.25
CaO	8.74	10.03
Na_2O	2.75	2.20
K_2O	1.57	0.85
MnO	0.16	0.16
P_2O_5	0.25	0.19
H_2O (total)	0.90	0.96
CO_2	0.22	0.13
Total	98.33	98.29
Zr	163	183
Nb	17	13
Y	32	46
La	29	16
Ce	63	32
Nd	36	21
Sr	370	266
Rb	59	29
Zn	105	85

CIPW norms: Analysts: S. J. Lippard

Dolerite: q 2.88; or 9.28; ab 23.27; an 24.71; di 15.37 (wo 7.90; en 4.75; fs 2.73); hy 20.96 (en 13.31; fs 7.65); mt 3.155 il 3.09; ap 0.44; c 0.10.

Basalt: q 0.95; or 5.02; ab 18.62; an 29.61; di 14.06 (wo 7.10; en 3.53; fs 3.43); hy 16.29 (en 8.25; fs 8,04); mt 2.65; il 3.38; ap 0.58: c 0.05.

dolerite (Walker & Poldervaart 1949). The 'residual' trace element contents of the dolerites are comparable to those of Continental tholeiites (Condie et al. 1970) but higher than those of oceanic tholeiites (Table 6). The REE/chrondrite normalised patterns show light REE enrichment (Fig. 6).

Basalt dyke (1 analysis)

The one analysis of a basaltic dyke shows the rock to be somewhat more basic than the dolerites. It is only just q-normative, but rich in hy (> 20%) and therefore tholeiitic. Except for Zr and Y the 'residual' element contents are lower in the basalt dyke compared to the dolerites. The REE/chrondrite plot is 'flatter', showing much less marked light REE enrichment (Fig. 6).

Discussion

RHYOLITES AND PORPHYRIES

Effects of metamorphism on the geochemistry of the acid rocks

As already noted, there is a chemical distinction between the rhyolites and the

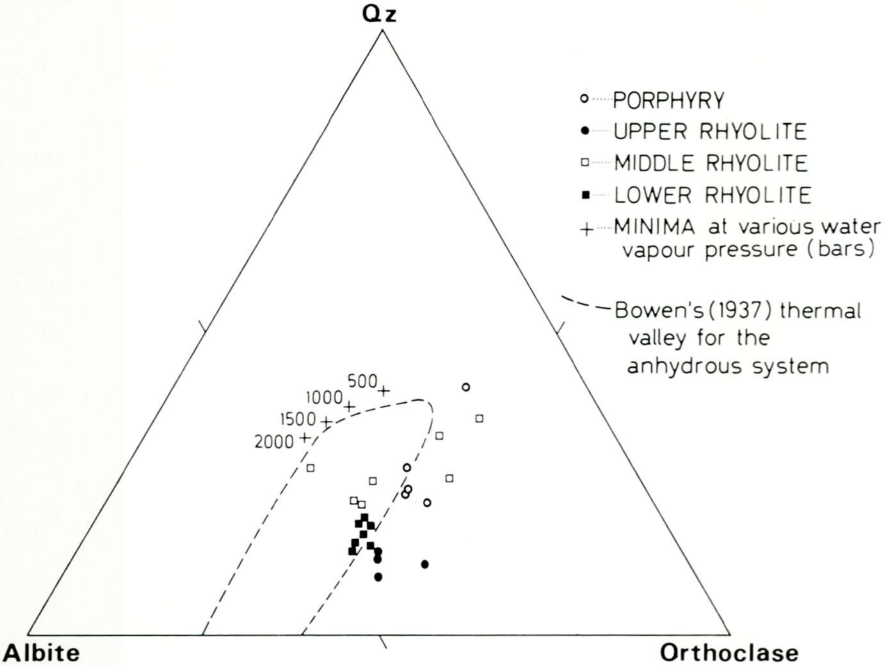


Fig. 7. Q–Or–Ab plot of the acid rocks from the Katnakken area.

porphyries on the basis of their Na_2O, K_2O and CaO contents. However, these elements are those most likely to be affected during deuteric and hydrothermal alteration and low-grade metamorphism (Battey 1955; Scott 1966). The analyses show a considerable scatter on the Q–Or–Ab triangular plot (Fig. 7) where most of the rhyolites and all of the porphyries fall to the potassic side of Bowen's (1937) thermal valley. These high K_2O/Na_2O ratios may be due to sericitisation of the feldspar. Several analyses from the rhyolitic bedded tuffs have exceptionally low values of Na_2O and CaO. These rocks, prior to recrystallisation, were probably particularly susceptible to hydrothermal leaching of these elements, owing to their high porosity.

Rb may be either enriched or depleted during deuteric and hydrothermal alteration and low-grade metamorphism (Hart 1969; Cann 1969). The variability of Rb in the rhyolites is high and follows K. 'Residual' elements such as Zr, Nb, Y and REE are known to be rather stable up to greenschist-facies conditions in basic rocks (Pearce & Cann 1973), but little is known about their behaviour in acid volcanics. The internal consistency of the present results and a comparison with published data on Tertiary–Recent rhyolites do, however, suggest immobility of these trace elements in the metamorphosed rhyolites. For example, the three rhyolite units mapped in the field can be effectively distinguished by their Zr contents, which correspond to less significant differences in SiO_2, total Fe, TiO_2, MgO and Sr (Fig. 5). The uniformity of the Nb, Y and REE contents also suggest that these elements have not been significantly affected by post-emplacement alteration or metamorphism, even in rocks that are strongly depleted in alkalies.

A geochemical comparison with other acid volcanics

The average rhyolite from the Taupo volcanic zone, North Island, New Zealand (Ewart et al. 1968) is closely comparable to the average Katnakken rhyolite except for lower K_2O, and several published analyses from the Andes (Zeil & Pichler 1967) and Yellowstone Park, U.S.A., correspond almost exactly. Ordovician rhyolites from North Wales (Tremlett 1969) have variable total alkali contents and Na/K ratios similar to those of the Katnakken rocks.

Only limited trace element data are available on rhyolites from New Zealand (Ewart et al. 1968), the Andes (El-Hinnawi et al. 1969), California (Jack & Carmichael 1969) and Kamchatka and the Kurile Islands (Markinen & Sapozhnikova 1962). In addition, Chao & Fleischer (1960) have published Zr contents of rhyolites from the Aleutians and several areas in the western U.S.A. The Zr contents of the Andean, northern Cascade and Kamchatka rocks are comparable to those from Katnakken. They are much higher than average granite values of Turekian & Wedepohl (1961) and Taylor (1964). The New Zealand rhyolites have low contents of trace elements, a feature which Taylor et al. (1968) attributed to an origin by partial melting of Palaeozoic greywackes.

The rhyolites from Katnakken can also be compared to the leucogranites from the Snowy Mountains, Australia (Kolbe & Taylor 1964) and the Sierra Navada (Towell et al. 1965), which they resemble in major element chemistry. These rocks contain much lower trace element abundances (except Rb) than the Katnakken rocks.

Jack & Carmichael (1969) found variability in the geochemistry of the Californian rhyolites (for example, Nb varied from 5 to 65 ppm, Y from 15 to 90 ppm). They demonstrated the chemical uniqueness of each eruptive centre, particularly in terms of Zr, Sr and Ba.

The Katnakken rhyolites have the trace element abundances of highly differentiated rocks – high residual element contents and low Sr (20–60 ppm) and MgO (<0.01–0.4%). These concentrations are most readily explained by extensive fractional crystallisation (Noble et al. 1969). The porphyries have less extreme trace element abundances, although they are poorer only in certain residual elements (Zr, Nb and Y and not Rb, La or Ce). It seems most likely that these differences in trace element compositions reflect differences between the original magma compositions – an alkali rhyolite in the case of the lavas, and a calc-alkaline rhyolite for the porphyries. Similar differences between alkali granites (higher in Zr, Nb, Y, lower in Sr) and calc-alkaline granites have been described from North Wales (Tremlett 1972).

DACITES

The dacites contain about 60% of the Nb, Y and REE contents of the rhyolites and are substantially poorer in Zr. Chao & Fleischer (1960) reported systematic increases of Zr in the series dacite-rhyodacite-rhyolite from several areas. Markinen & Sapozhnikova's (1962) average dacite contains 390 ppm Zr and that of El-Hinnawi et al. (1969) 215 ppm. The former value is similar to those of the Katnakken dacites.

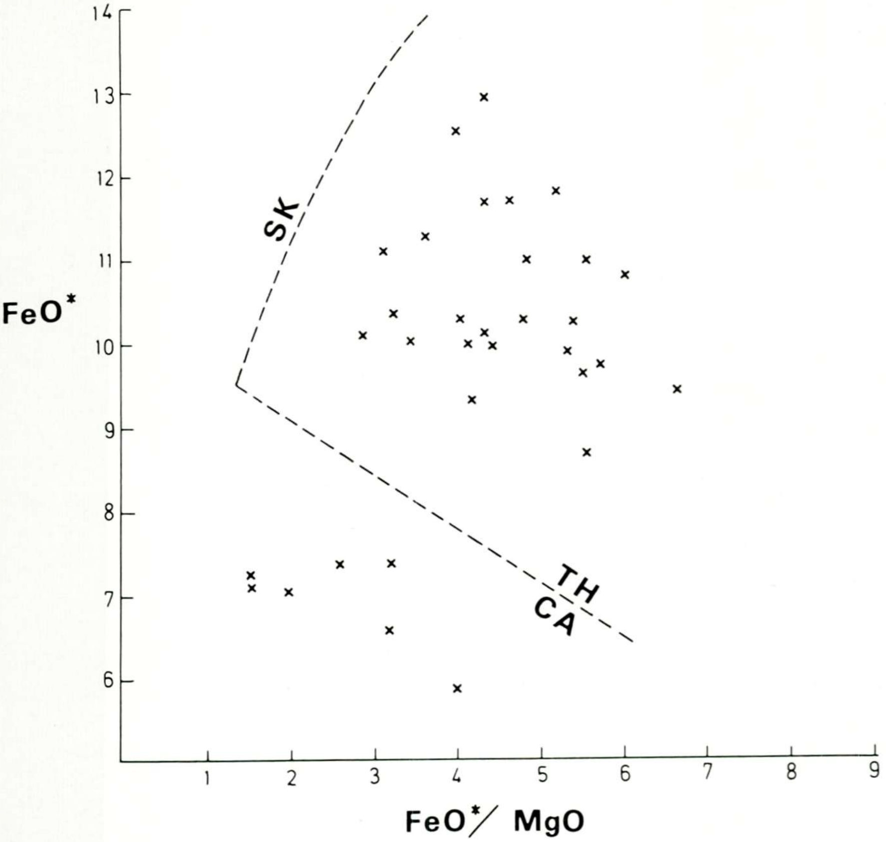


Fig. 8. FeO* versus FeO*/MgO plot for the basic lavas, Katnakken area. Upper dashed line (SK) represents Skærgaard liquid trend; lower line separates tholeiitic (TH) from calc-alkaline (CA) series (both lines redrawn from Miyashiro (1974)).

BASIC LAVAS

Much of the variability in major element composition in the basic lavas can be ascribed to the greenschist-facies metamorphism (Smith 1960; Cann 1969). Petrographic evidence of silication, hydration and carbonation must be taken into account when attempting to determine the original compositions from the analyses. As a result, the SiO_2, alkali (including Rb), CaO and Sr values are treated with caution, and some conventional plots, such as the total alkali versus silica and FMA diagrams, have not been used.

The FeO*/MgO ratios of the lavas are higher than of most basalts (Manson 1968) and are more similar to those of andesites (Chayes 1969). The Fe/Mg ratio is commonly taken as an index of differentiation or degree of fractionation (Kuno 1959; Thompson et al. 1972), therefore the Katnakken lavas are somewhat 'evolved'rocks. The Fe/Mg ratio should not be affected by low-grade metamorphism (Pearce 1975). As already noted, on the FeO*/MgO versus MgO plot (Fig. 8) the analyses fall into two groups; one in the calc-alkaline field, and the other in the tholeiite field (Miyashiro 1974).

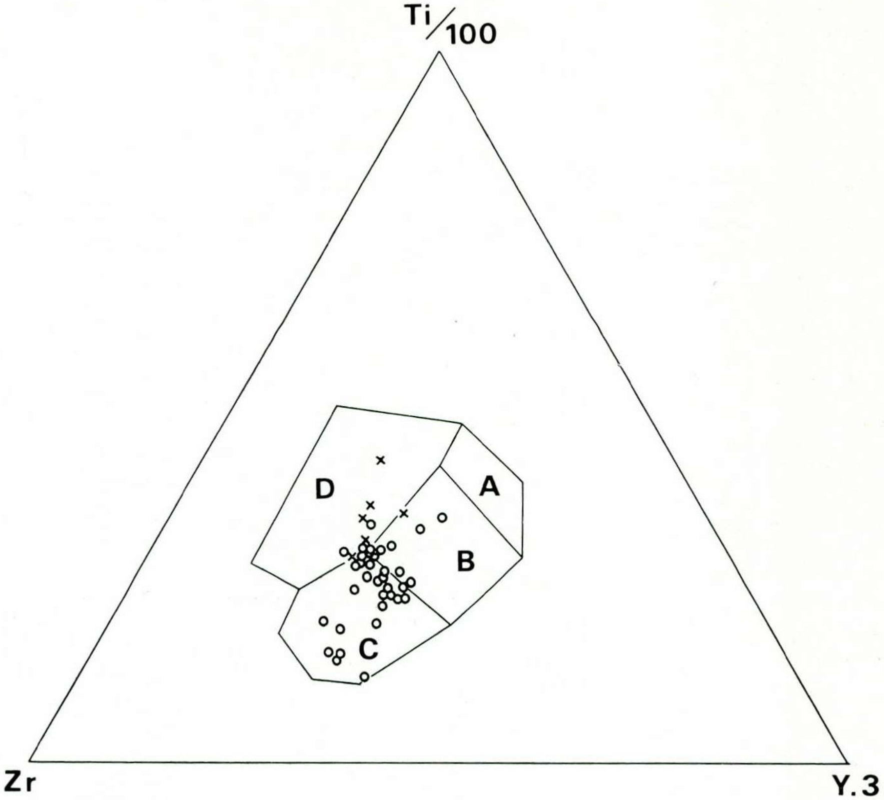


Fig. 9. Ti–Zr–Y plot for the basic rocks from the Katnakken area. D – 'within-plate' basalts; A + B – low-potassium tholeiites; C + B – calc-alkaline basalts; B – ocean-floor basalts. Open circles – basic lavas; crosses – dolerites and basalt dyke.

The 'low-iron' group (calc-alkaline) with 6.5–8% FeO* are high-alumina basaltic andesites; the 'high-iron' group (10–13% FeO*) are low-alumina ferro-basalts or icelandites (Carmichael 1964). The latter most closely compare to the basic icelandites from the Galapagos Islands (McBirney & Williams 1969). Judging from the generally high P_2O_5 and TiO_2 contents neither of these types is likely to be island arc tholeiites or calc-alkaline andesites (Chayes 1964; Jakes & White 1972).

The 'stable' trace elements (Zr, Nb, Y, REE) may be used to characterise basalts according to their tectonic setting and petrological type (Pearce & Cann 1973). This is particularly important where the rocks are metamorphosed. It is arguable, however, that the Katnakken rocks are too fractionated to be treated in this way. This is borne out by the fact that on the Ti–Zr–Y diagram (Fig. 9) the analyses plot in fields B, D and C of Pearce & Cann (op. cit.). The results are therefore no distinctive. On the Ti–Zr plot (Fig. 10) they fall outside all fields (A to D). This indicates that they are unlikely to be altered low-potassium tholeiites, calc-alkaline basalts or ocean floor basalts. The Y/Nb ratio is about 2, corresponding to 'transitional' basalts, according to the scheme of Pearce & Cann (1973). The Nb contents are below the values given by

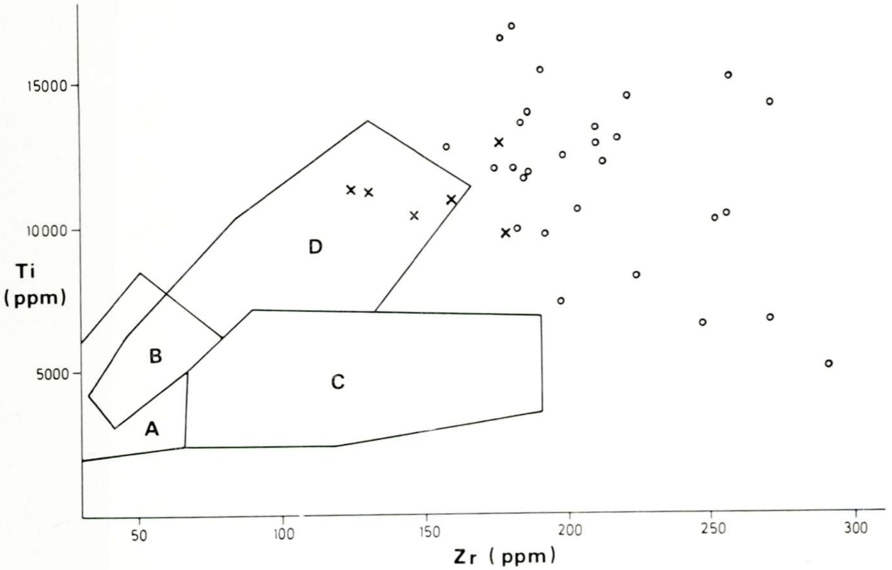


Fig. 10. Ti–Zr plot for the basic rocks from the Katnakken area. B + D – ocean-floor basalts; A + B – low-potassium tholeiites; B + C – calc-alkaline basalts. Symbols as in Fig. 9.

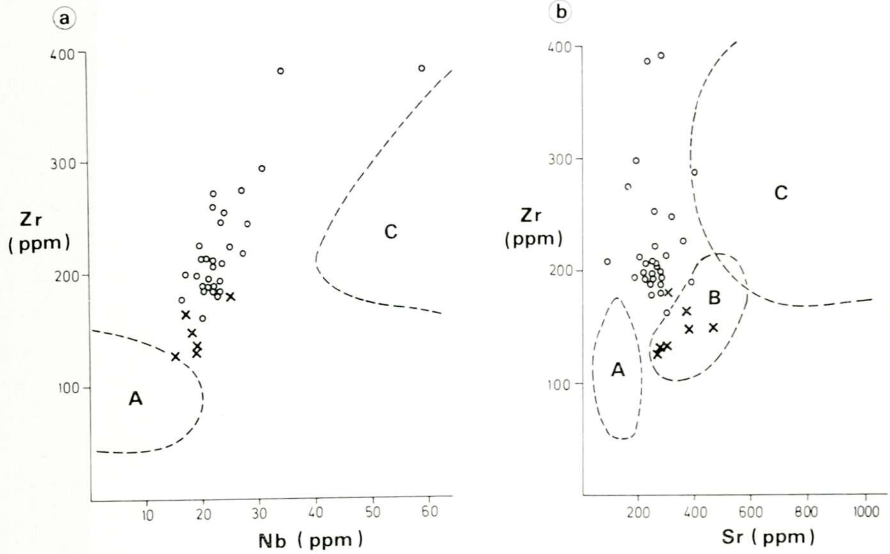


Fig. 11. Zr/Nb and Zr/Sr plots for the basic rocks from the Katnakken area. A – ocean-ridge basalts; B – ocean island tholeiites; C – alkali basalts. Symbols as in Fig. 9.

Bass et al. (1973) as typical for alkali basalts (Fig. 11a). The 'residual' elements, particularly the light REE, show high abundances in the Katnakken basic lavas compared to most basic and intermediate rocks (Table 6). These can be accounted for in highly fractionated rocks because the concentrations of these elements in the common phenocryst minerals in volcanic rocks are less

Table 6. Comparison of trace element contents of the basic lavas, dolerites and basalt dyke from the Katnakken area with average values of trace elements in continental tholeiites, ocean-floor tholeiite and calc–alkaline andesites

	1	2	3	4	5	6	7
Zr	221	250	163	183	96	224	110
Nb	24	23	17	13	5	20	4
Y	50	44	32	46	34	53	21
La	41	41	29	16	5	25	12
Ce	74	74	63	32	18	66	24
Nd	48	44	36	21	13	37	13
Sr	242	218	370	266	125	428	385
Rb	92	86	59	29	2	36	31

1. Basic lava type (1) icelandite (Table 4)
2. Basic lava type (2) basaltic andesite (Table 4)
3. Average dolerite (Table 5)
4. Basalt dyke (Table 5)
5. Average ocean ridge tholeiite
6. Average continental tholeiite
7. Average calc–alkaline andesite

5 & 6 compiled from Condie et al. (1970), Bass et al. (1973) and Haskin et al. (1966).
7 taken from Taylor (1969).

than those of the groundmass or matrix (Schnetzler & Philpotts 1970). The REE pattern in the Katnakken rocks (Fig. 6) is similar to those of continental tholeiites (Haskin et al. 1966; Osawa & Goles 1970) and alkali basalts (Schilling & Winchester 1967; Gast 1968).

The Ni and Cr contents of the Katnakken lavas are low for basaltic rocks, most of which contain at least 100 ppm Ni and 200 ppm Cr (Taylor 1969). This is further support for their fractionated nature and is in agreement with the high Fe/Mg, P_2O_5 and 'residual' element contents. The low Ni and Cr abundances in both types are consistent with early fractionation of olivine (Thompson et al. 1972). The differences between the two types may possibly be accounted for by the varying role of plagioclase fractionation; this being important in producing the high-iron, low-alumina icelandites, but less so in the formation of the low-iron, high-alumina basaltic andesites.

Lava types similar to those from the Katnakken area have been described from the Craters of the Moon lava field on the margin of the Snake River Plains, U.S.A. (Leeman et al. 1975). There the lava types range from andesine–normative olivine ferro-basalts to quartz–normative ferro-latites. The ferro-basalts have high 'residual' element contents, high Fe/(Fe + Mg) and low Ni, Co and Sc contents which '... are consistent with derivation ... (of the ferro-basalts) ... from the Snake River Plain olivine tholeiite magma by fractional crystallisation of some 50–60% olivine + plagioclase + magnetite + apatite ...' (Leeman et al. 1975, abstract).

DOLERITES AND BASALT DYKES

As noted earlier, the major element compositions show that these rocks are of tholeiitic composition. These sills and dykes are more basic than the lavas they

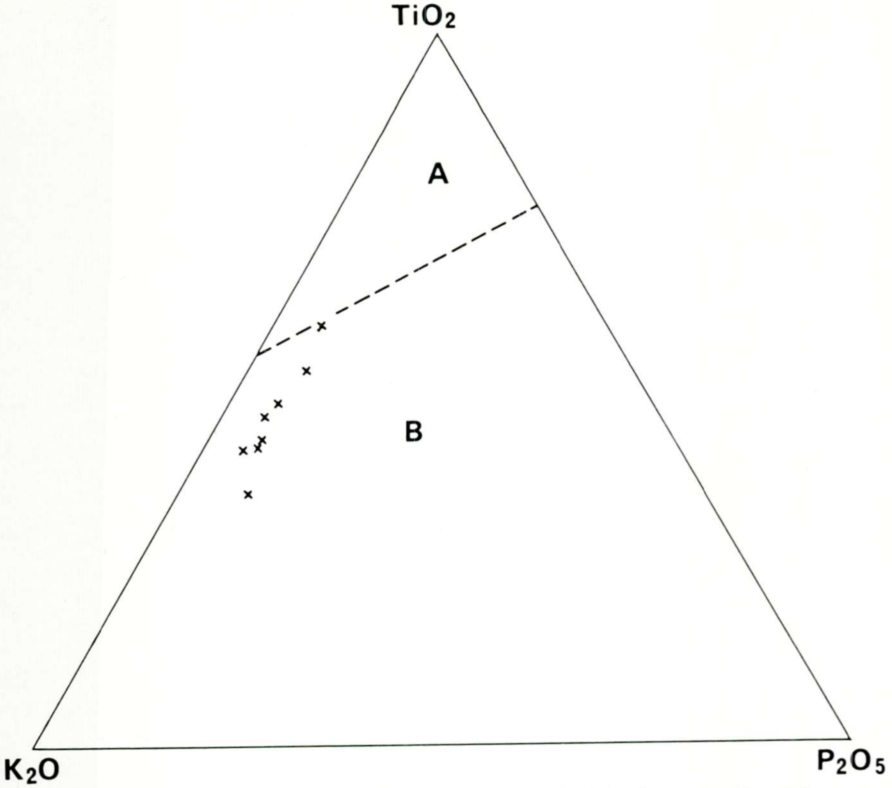


Fig. 12. TiO_2–K_2O–P_2O_5 plot for the dolerites and basalt dyke from the Katnakken area. Field A – oceanic tholeiites; field B – continental tholeiites.

intrude and it is a more valid exercise to plot them on the various basalt discrimination diagrams. On the Zr–Sr plot (Fig. 11b) they plot in the field of ocean island tholeiites (as distinct from ocean floor tholeiites and oceanic alkali basalts) (Bass et al. 1973); on the Ti–Zr–Y plot (Fig. 9) in the field of within-plate basalts (Pearce & Cann 1973); and on the TiO_2–P_2O_5–K_2O diagram (Fig. 12) they fall in the field of continental tholeiites (as distinct from oceanic tholeiites (Pearce et al. 1975). The REE patterns show differences between the dolerites and the basalt dyke (Fig. 6). The dolerite pattern is enriched in the light REE and similar to that of alkaline basalts (Schilling & Winchester 1967; Gast 1968), while the basalt pattern shows much less light REE enrichment (tholeiitic). This distinction is reinforced by the difference in Y/Nb ratios; 1.4–1.9 for the dolerites (alkaline to transitional basalt), 3.0–3.5 for the basalt (tholeiitic) (Pearce & Cann 1973). From the geochemical data it would appear that the late dolerite sills and basalt dykes are representative of intra-plate, probably continental, magmas.

Conclusions

The weight of the geological and petrochemical evidence presented above suggests that the Upper Ordovician volcanics in the Katnakken area are of intra-continental derivation. They form a bimodal association of high-silica alkaline rhyolites and voluminous tholeiitic iron-rich basalts, icelandites and basaltic andesites. They can be closely compared to the Yellowstone Park–Snake River Plains volcanics in the northwestern U.S.A. (Boyd 1961; Leeman et al. 1975), which have been related to a mantle-derived plume presently situated below the Yellowstone area (Matthews & Anderson 1973). The initial Sr^{87}/Sr^{86} ratio of 0.7071 obtained by Priem & Torske (1973) is within the range of continental rhyolites.

The Katnakken rhyolites are similar in age, appearance and petrochemistry to the Caradocian acid volcanics in North Wales (Rast 1969; Tremlett 1969). Jeans (1973) suggested that these particular rocks were formed by melting of continental crust by a separate fault-controlled heat source, possibly, but not necessarily, rising from a subduction zone at depth (cf. Fitton & Hughes 1970).

The dolerite sills and basalt dykes are typical continental tholeiites and, possibly, transitional to mildly alkaline basalt intrusives emplaced as the last event in the Caledonian magmatic cycle in the region. Similar 'late' Caledonian dolerites are widespread in North Wales (Shackleton 1959).

An intra-continental environment in SW Norway in the late Ordovician is strongly suggested by the Katnakken volcanics. The late Ordovician–Lower Silurian marine sediments and pillow lavas in the Dyvikvågen Group (Færseth & Ryan, in press) must be incorporated into this model. Furnes & Færseth (1975) have shown that the Silurian basic volcanics have the trace element geochemistry of ocean floor basalts and they suggest that they were probably formed in a back-arc basin spreading region. It may well be that this basin developed on or near the site of the earlier-faulted Baltic continental plate through which the Katnakken volcanics were erupted. The distance between these rock units may have been considerably foreshortened by later faulting, although much of the pebble material in the conglomerates which overlie the pillow lavas (Færseth & Ryan op. cit.; Færseth & Steel, in press) appears to have been derived from the igneous complex. Sturt & Thon (in press) have stressed the importance of a pre-Moberg Conglomerate unconformity in the Bergen Arcs where Ashgill and younger rocks rest on an older metamorphic basement indicating an early Caledonian orogenic event in this area. The age-determinations of Priem & Torske (1973) show that the Katnakken volcanics may well be post-orogenic with respect to this orogenic event.

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