Devonian Lavas from Solund, West Norway – Field Relationships and Geochemistry

HARALD FURNES & STEPHEN J. LIPPARD

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Devonian volcanic rocks in the Hersvik area, Solund, West Norway are represented by two lava flows occurring close to the base of the Devonian conglomerate. They are composed largely of highly flow-banded and brecciated material. The lavas are of intermediate to acidic composition, the lower flow is trachytic (61–63% SiO_2) and the upper one rhyolitic (67–70% SiO_2). They were strongly altered by hydration and oxidation, probably mainly as a result of hydrothermal activity. Incompatible trace element abundances are very high, and of the same magnitude as in peralkaline acidic rocks, suggesting a continental rift environment for the Hersvik area.

H. Furnes, Geologisk Institutt, Avd. A, Allégt. 41, 5014 Bergen, Norway
S. J. Lippard, Dept. of Earth Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, England

Introduction

The islands of Solund (Fig. 1) consist predominantly of supposed Middle Devonian conglomerates (e.g. Nilsen 1968). The apparent thickness of the conglomerates is 5 km, and they were deposited as alluvial fans (Nilsen 1968, Steel 1976) in a basin dominated by dip-slip tectonics (Steel 1976, 1978). This sequence rests unconformably upon a deformed Lower Palaeozoic volcanic and sedimentary basement (Kolderup 1926, Furnes 1974, Indrevær & Steel 1975). In the lower stratigraphic levels of the conglomerate, about 1 km south of Hersvik (Fig. 1), some rocks of volcanic aspect occur. These were first noted by Kolderup (1926). On petrological and geochemical grounds Kolderup described them as keratophyres and distinguished five units which he suggested were either subaerial flows or shallow intrusives. Later, Nilsen (1968) described keratophyre-filled joints in conglomerate from other parts of the Solund area.

The present account deals with a detailed field and geochemical study of the lavas first described by Kolderup (1926). In this locality two distinct flows have been distinguished; the lower flow is trachytic and the upper one rhyolitic, although they have broadly similar texture and mineralogy.

Description of the lava flows

The lavas outcrop about 1 km south of Hersvik (Fig. 1). The outcrop area is small (about 200 m by 250 m), and they have a maximum thickness of about 40 m. On the northern side of the outcrop only the base is seen, while at the southern end both the upper and the lower contacts are observed (Fig. 2). Here, as well as in the northwestern part, the contact with the sediments is nearly vertical. As the bedding in the conglomerates dips gently southwards, this appears to be an original

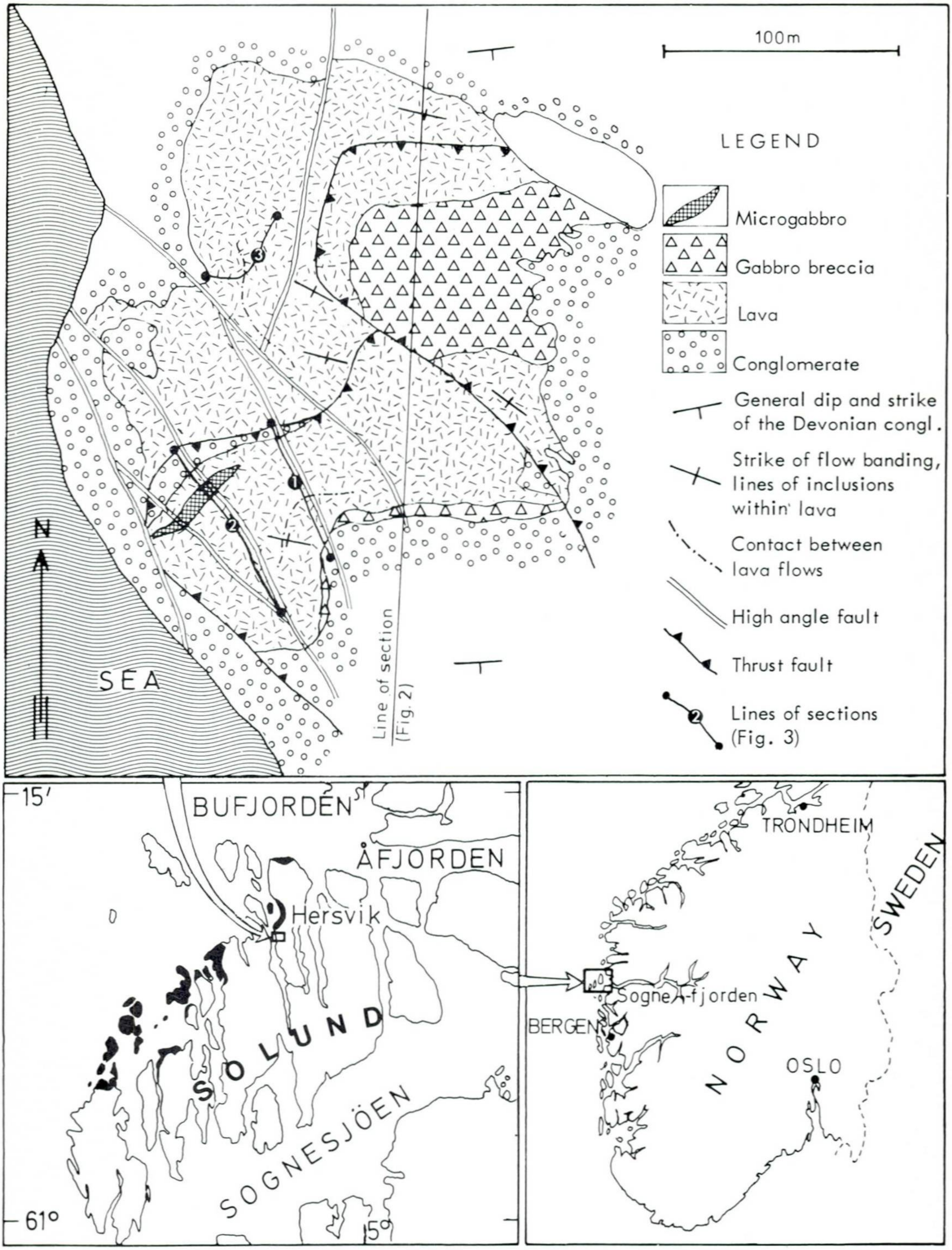

Fig. 1. Geological map of the Devonian lavas south of Hersvik. On the lower left-hand map the dark shaded areas are outcrops of Lower Palaeozoic rocks.

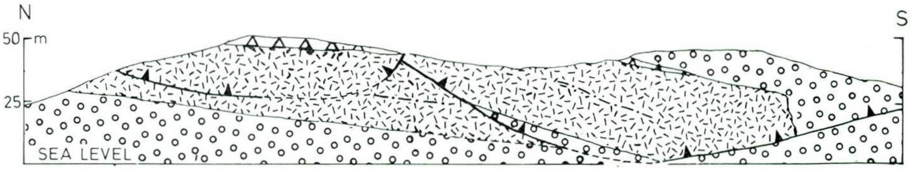

Fig. 2. North-south cross section across the Hersvik lavas. No vertical exaggeration. Symbols as in Fig. 1.

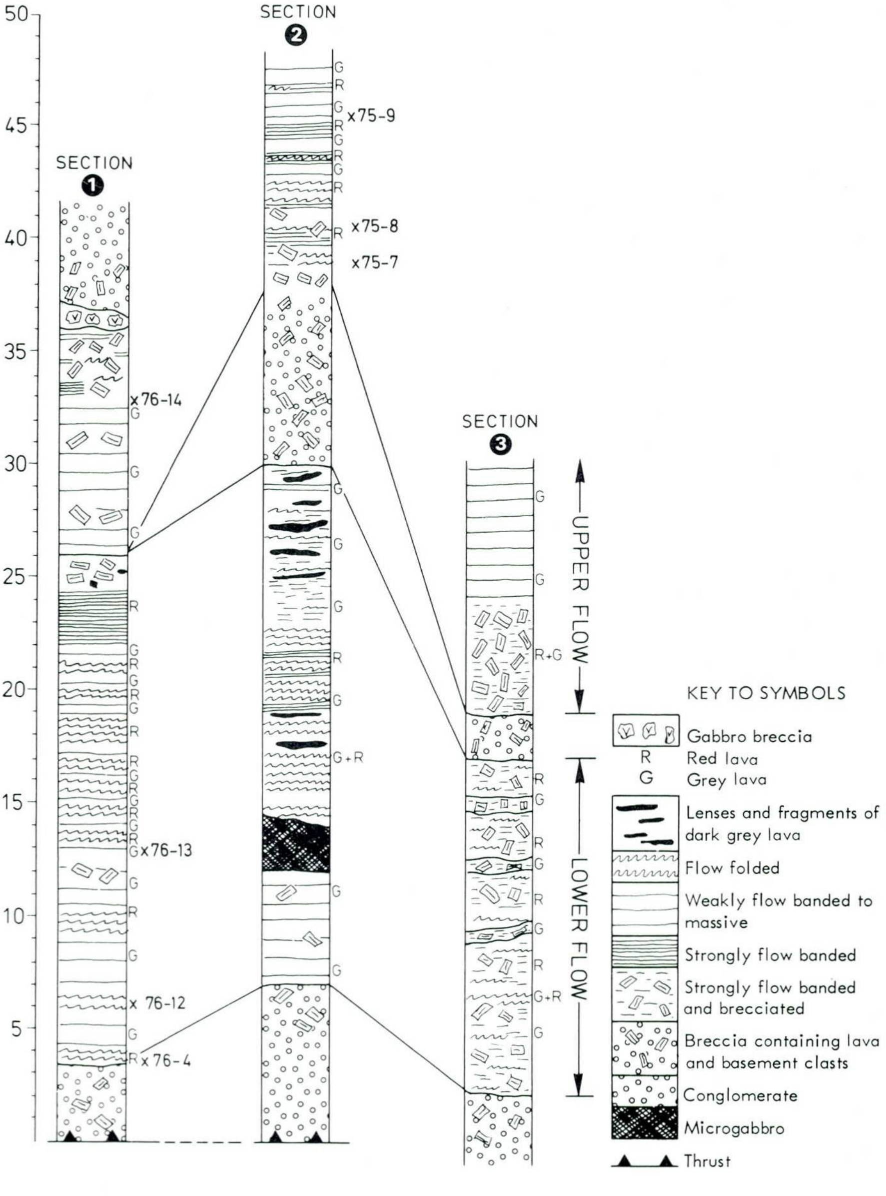

Fig. 3. Vertical column sections through the lavas. Lines of sections shown on Fig. 1.

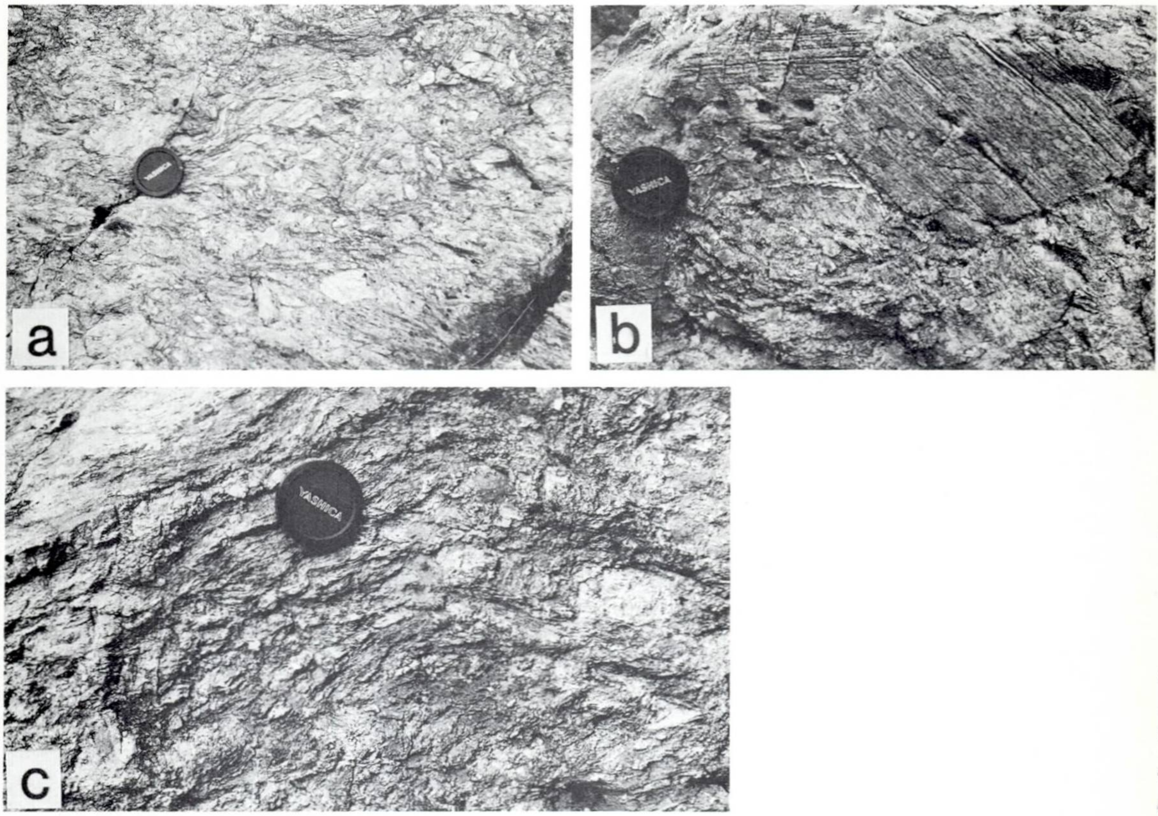

Fig. 4. a. Red rhyolitic autobreccia. Near base of upper flow.
b. Grey rhyolitic autobreccia. Upper flow.
c. Flow-folded red trachyte. Middle part of lower flow.

feature and may represent the sides of a steep-sided valley similar, for example, to the lava-filled dry gorges ('barrancos') in the Canary Islands (Fuster 1968).

Detailed sections through the lavas (Fig. 3) show that the rock is extremely variable in character. For the most part it is strongly flow banded and brecciated (Fig. 4), varying in colour from red to grey. The red variety is clearly the more altered and oxidised rock. It can sometimes be seen veining the grey material (Fig. 5a). The banding developed is on a fine scale (0.1–2 mm) and can be both planar, especially in the more central portions of the flows, and contorted. The strike and orientation of the blow banding and breccia fragments is predominantly E–W to NW–SE.

The sediments immediately underlying the lowest lava flow consist of a mixture of trachyte blocks and substrate material (Fig. 5b). This bed is recognised everywhere at the base of the volcanics and varies in thickness from 3 m to 5 m. The presence of weathered trachyte fragments in this horizon indicates that older lava flows existed in the region before the emplacement of the lower flow. The fact that some of the trachyte fragments were veined (Fig. 5b) before incorporation

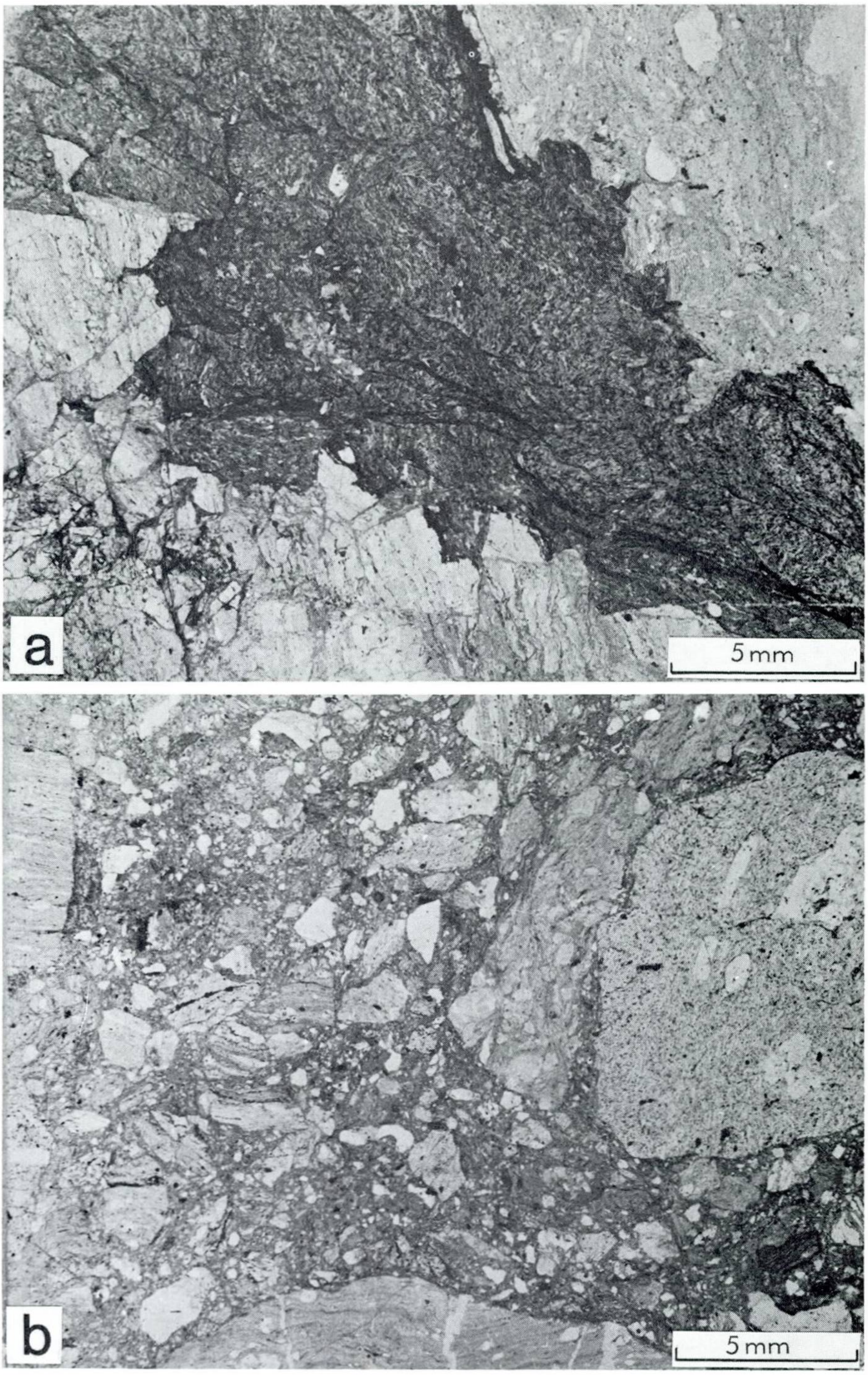

Fig. 5 a. Grey autobreccia with vein of dark (red) flow-banded and flow-folded rhyolite. Scale bar 1 cm long. Photographed by shadow master.
b. Basal breccia. Composed largerly of fragments of various types of both red and grey-coloured and broken feldspar crystals. Scale bar 1 cm long. Photographed by shadow master.

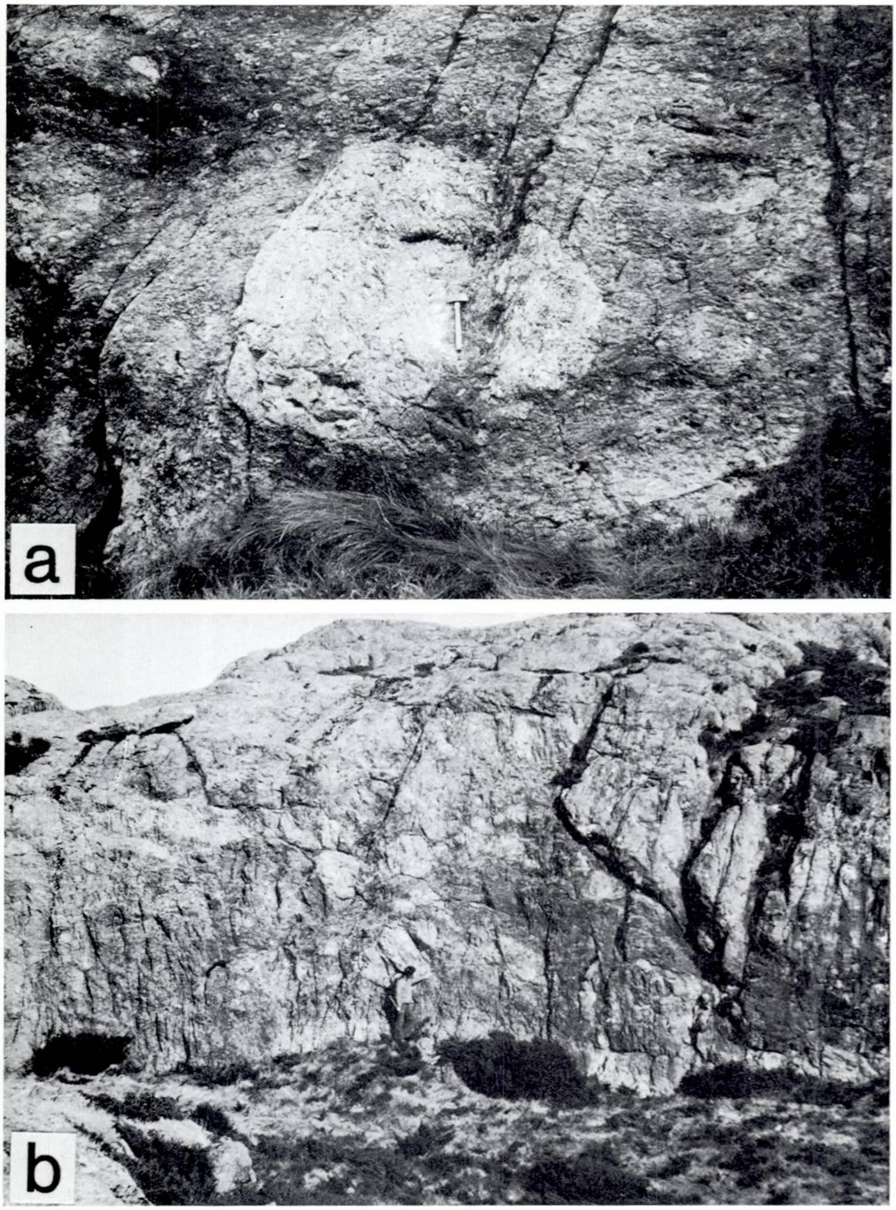

Fig. 6 *a.* Large block of grey trachyte (about 3.5m across) in red trachyte breccia. Near base of lower flow.
b. Section through lower part of the lower flow. The base of the flow is 2–3m below the figure. Dominantly red trachyte with relics of grey material passes up into massive grey rock.

in the sediment makes it unlikely that they were derived from the explosive break-up of the overlying flow. However, the contact between the breccia bed and the overlying trachyte is gradational, and the upper part of the breccia may represent the base of the flow with incorporated basement material. The lower part of the flow is chaotically brecciated and highly reddened. Above this the red material can be seen penetrating up into and including blocks of grey trachyte (Fig. 6). This zone passes up into a more massive, dominantly grey-coloured rock. The relationships, however, are complex with reddened layers and irregular cross-cutting bands continuing throughout the unit. The maximum thickness of the lower flow is 20 m. At the top of the lower flow there are red-coloured breccias containing fragments and lenses of dark grey lava. This is overlain by 0–8 m of breccia containing a mixture of trachyte and substrate clasts. This lithology is similar to that underlying the lower flow. A second rhyolite flow overlies this and is broadly similar to the first except that it is more massive in the central part. Its maximum thickness is about 15 m (Fig. 3).

Resting on the upper flow is a sedimentary breccia, whose contact with the volcanics is irregular but undisturbed. This unusual bed is composed almost entirely of weathered metagabbro fragments set in a fine-grained, red, micaceous sandstone matrix. A few trachyte clasts are present in this sediment, and in some cases it also seems to be cut by veins and small irregular intrusive bodies of trachyte. The metagabbro clasts are generally small (1–10 cm) but range up to several decimetres across. This bed is up to 7 m thick, although it is only developed locally.

A fine-grained gabbro sill (3–4 m thick) is intruded into the lower flow (Figs. 1 & 3) in the southwestern part of the area.

Mode of emplacement

The following are the main features of the Hersvik flows:

a) flow banding; b) extensive brecciation on all scales; c) complex relations between the grey and red-coloured rock; d) complete lack of vesiculation and gas cavities.

The flow banding indicates that the mechanism of emplacement was by slow, viscous flowage typical of acid lavas. The brecciation is believed to be largely the result of movements of extremely viscous material when the mass was almost totally solified (autobreccia), or when the lava flowed over a steep slope or cliff. The strongly oxidised (reddened) rock was formed by hydrothermal action shortly after, or possibly during the later stages of consolidation of the lava. The veins and bands of reddened rock in the lower part of the flows represent channelways along which the hydrothermal agents passed. These might be expected to preferentially attack the more strongly flow-banded and brecciated rock, and this is what is generally observed. The lack of vesiculation shows that the lava must have been somewhat dry. This would in part account for the high viscosity which gave rise to the flow banding and autobrecciation.

Structure

The lava flows seem to define a broadly conformable sheet within the conglomerate (about 40–50 m above the Lower Palaeozoic basement) which, in the area immediately to the south of Hersvik, dips gently at about 5° to the SSE. Low-angle,

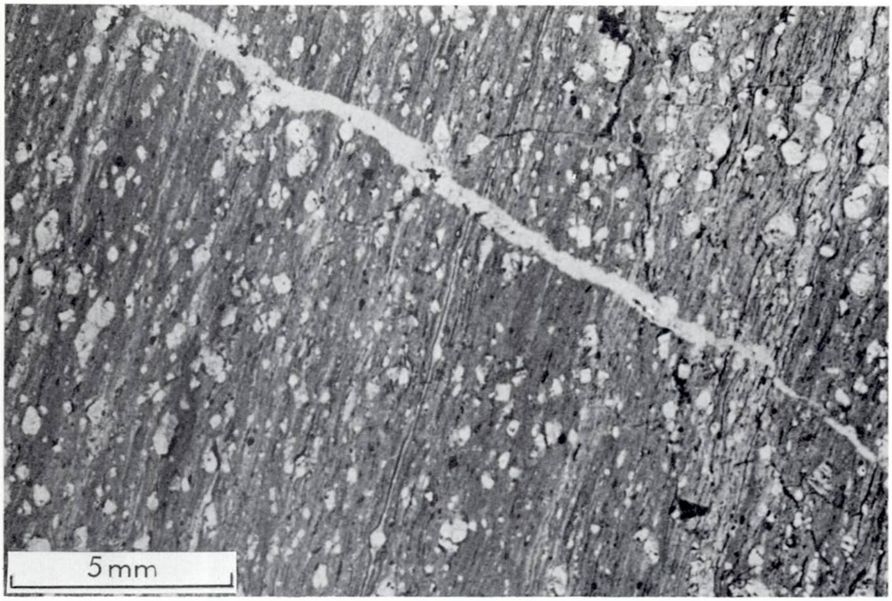

Fig. 7. Flow-banded porphyritic rhyolite. Upper flow. Scale bar 1 cm. Photographed by shadow master.

mainly southward dipping, shear zones and ultramylonite bands 0.5–40 cm thick, give evidence of minor thrusting (Fig. 2), the rocks having been locally thrust northwards, movements that may be related to the overlying major thrust on the nearby Husefjell (about 1 km ENE of the mapped area) (D.M. Ramsay & B.A. Sturt, pers.comm. 1982). A nearly vertically dipping, approximately ESE-WNW-trending crenulation cleavage is developed in the flow-banded lava and those autobrecciated fragments which were suitably orientated. Vertical N–S and NW–SE trending faults, along which minor movements have taken place, are common.

Petrography

The trachytes are porphyritic rocks with 10–20% phenocrysts of alkali feldspar. The phenocrysts occur generally as single subhedral crystals up to 3–4 mm in length and have equant, rectangular shapes. The rocks are commonly banded and the banding is bent around the phenocrysts (Fig. 7) which are often marginally granulated, stretched and aligned in the direction of the banding. The feldspar is a low-temperature albite antiperthite with a host albite which has spindle-shaped twin lamellae partly replaced by grey untwinned potash feldspar. The crystals exhibit signs of strain, notably undulose extinction and bent twin lamellae.

The matrix is fine-grained, microcrystalline to crypto-crystalline. It is dominantly quartzo-feldspathic in the grey variety of the trachyte, with minor amounts of sericite, chlorite and opaques. Alternating bands of different texture define the flow banding, which is an early fabric imposed during emplacement of the flows is it predates the autobrecciation and hydrothermal veining. The opaque material (dominantly hematite), comprising about 5% by volume, occurs as isolated grains, bands and streaks elongated in the banding, and minute flakes of sericite and chlorite are aligned parallel to the banding. Accessory carbonate, sphene and (?)zircon are present. In the reddish trachyte the matrix is largely composed of chlorite and hematite. All gradations between grey and red trachyte can be seen, with intermediate stages of selective alteration along certain bands and around the edges of blocks, although locally where the red material intrudes the grey the contact can be sharp (Fig. 5a).

Alteration and metamorphism

The trachytes have a pervasive low-temperature mineralogy comprising albite antiperthite, quartz, sericite, chlorite and hematite. This mineral peragenesis probably reflects the effects of both hydrothermal alteration and low-grade (lower greenschist facies) metamorphism, which is also indicated by the presence of chlorite in the sandstone matrix of the overlying gabbro breccia. The red alteration of the rock occurred shortly after, and possibly during emplacement, as a result of permeating gases and fluids. This alteration was overprinted by a low-grade regional metamorphism accompanied by deformation which occurred beneath a thick (5 km, according to Nilsen (1968) cover of Devonian sediments but complicated by the affects of thrusting at the base of the sediment pile.

Geochemistry

The major element analyses were carried out by X-ray fluorescence (XRF) using glass beads. Twenty international standards and recommended values of Flanagan (1973) were used for calibration. The calibration curves were refined be least squares procedures and matrix corrections. The trace elements were similarly determined on XRF using pressed powder pellets. Ferrous iron was determined titrimetrically; water and carbon dioxide by standard procedures.

Major and trace elements analyses and CIPW norms are presented in Table 1. The stratigraphic locations of the samples are shown on the sections (Fig. 3). There is a clear chemical difference between the two flows, particularly with respect to SiO_2, Al_2O_3, TiO_2, P_2O_5, Zr, Y, La, Ce and Nd. These differences are attributed to the original compositions, particularly as certain of these elements are known to be relatively stable under greenschist facies metamorphism and other low-temperature alteration processes. This applies particularly to TiO_2, Zr and Y (Cann 1970). The upper flow is more differentiated than the lower with higher SiO_2, Zr, Y and LREE, and generally lower TiO_2, P_2O_5 and Al_2O_3 contents. The lower flow is trachytic and the upper rhyolitic in composition.

The strong correlations between SiO_2 and Al_2O_3, TiO_2 and P_2O_5 (all negative) and between SiO_2 and Zr, Y, La, Ce and Nd (positive) (Fig. 8) are taken to reflect fractional crystallization. Mobilization of alkalies is indicated by the recrystallization and replacement textures of the alkali feldspar and the presence of secondary

Table 1. Major oxides, norms, and trace elements of the trachytes

	Lower flow			*Upper flow*			
	76–4	*76–12*	*76–13*	*75–7*	*75–8*	*76–14*	*75–9*
SiO_2	61.23	61.77	63.22	67.17	66.78	68.78	70.19
Al_2O_5	16.11	18.65	16.19	14.81	15.15	14.88	14.10
TiO_2	0.81	1.10	0.73	0.43	0.42	0.50	0.39
Fe_2O_3	2.97	1.97	2.29	2.44	1.88	2.38	0.83
FeO	2.67	1.00	2.24	2.57	2.75	0.85	1.91
MgO	3.66	0.59	3.07	3.78	2.07	1.03	0.59
CaO	1.66	1.15	0.90	0.52	1.44	0.43	0.66
Na_2O	3.72	5.43	3.86	3.29	5.52	5.71	4.12
K_2O	4.18	6.72	5.77	3.24	3.23	4.56	5.90
MnO	0.10	0.04	0.15	0.10	0.10	0.51	0.10
P_2O_5	0.10	0.17	0.08	0.01	0.04	–	0.01
H_2O	2.07	0.72	1.42	2.32	0.98	0.55	0.49
CO_2	–	–	–	–	0.37	–	0.35
Sum	99.28	99.31	99.92	100.68	100.73	100.18	99.63
Q	14.28	1.60	11.82	29.45	15.90	15.80	21.26
Or	24.70	39.71	34.10	19.15	19.09	26.95	34.86
Ab	31.48	45.95	32.66	27.84	46.71	48.32	34.86
An	7.58	4.59	3.94	2.35	4.54	1.50	1.00
Mt	4.31	0.17	3.32	4.00	2.72	2.95	1.19
Hm	–	1.86	–	–	–	0.34	–
Il	1.54	2.09	1.39	0.80	0.80	0.95	0.74
Hy	10.39	1.47	8.94	11.06	8.15	2.34	3.84
Di	–	–	–	–	–	0.49	–
Ap	0.23	0.39	0.18	0.12	0.09	–	–
C	2.69	0.76	2.15	5.20	0.19	–	0.57
Zr	873	761	1116	1439	1328	1426	1361
Nb	45	43	61	53	52	67	61
Y	63	64	71	91	95	81	85
La	77	66	89	98	87	130	123
Ce	133	103	143	174	153	237	205
Nd	69	59	75	92	84	106	103
Rb	105	111	98	105	84	87	104
Sr	168	121	76	80	73	41	64

sericite. The distributions of MgO, FeO^t, FeO and Fe_2O_3 are extremely erratic in the analysed samples. There is petrographic evidence that this is the result of the uneven development of secondary chlorite and the formation of hematite veins. The concentration of these oxides is higher in the red-coloured rock. The presence of corundum and hematite in the norms point to the effects of oxidation and hydration.

An interesting feature of the chemistry of these rocks is the unusually high concentrations of some of the incompatible trace elements (Zr, Y, Nb, LREE and Rb). In Fig. 9 Nb, Y, La and Rb have been plotted against Zr, and compared with some typical metaluminous ($Al > Na+K$) trachytes and rhyolites as well as peralkaline ($Al < Na+K$) comendites and pantellerites. Although the present chemical composition of the Hersvik lavas is not peralkaline, they have incom-

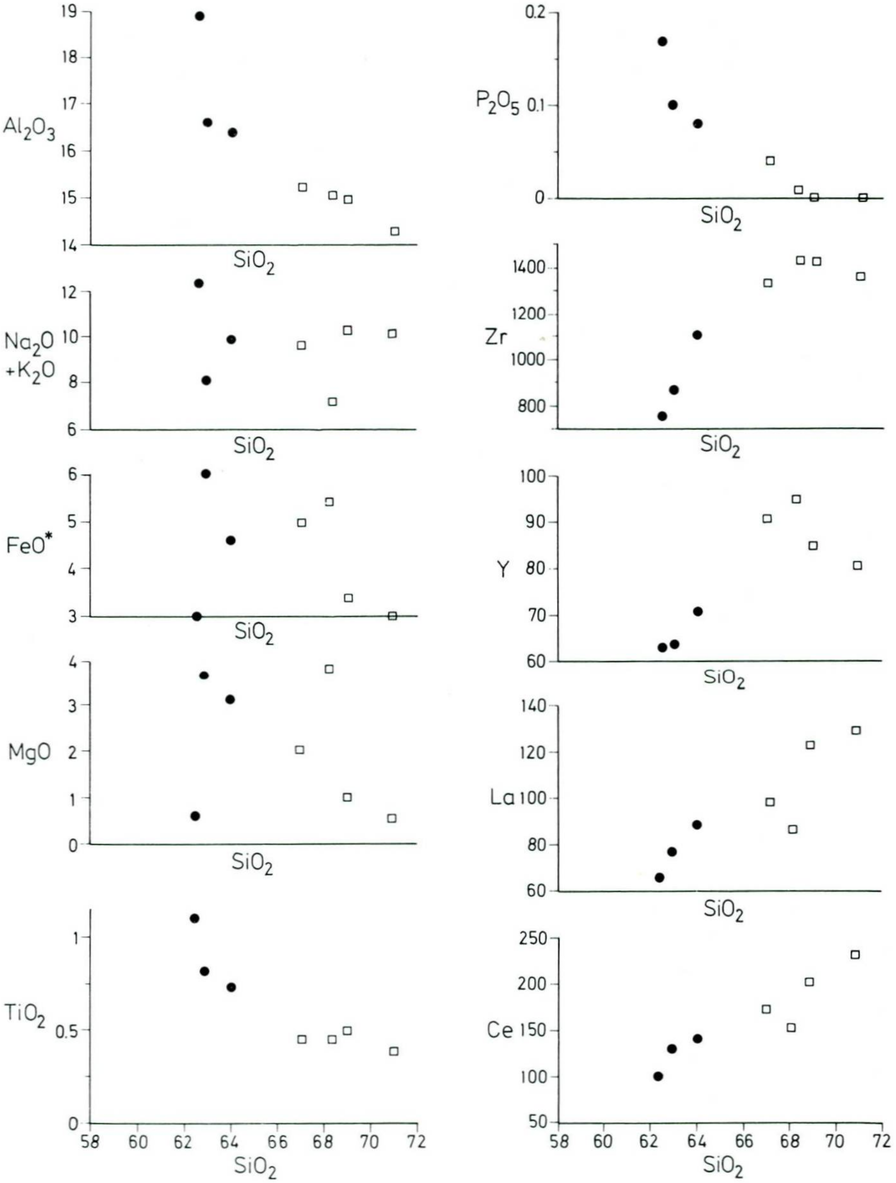

Fig. 8. Major oxide and trace element versus SiO_2 plots for the lavas. Dots–lower flow; squares upper flow.

patible trace element abundances of the same magnitude as some of the peralkaline acidic rocks (Fig. 9). Therefore, taking into consideration the possible loss of the alkalies during alteration, whereas Al_2O_3 may have remained relatively constant, they may, on this basis, have lost the original peralkaline character. The immobile trace element abundances may therefore, in fact, be more informative than the major elements.

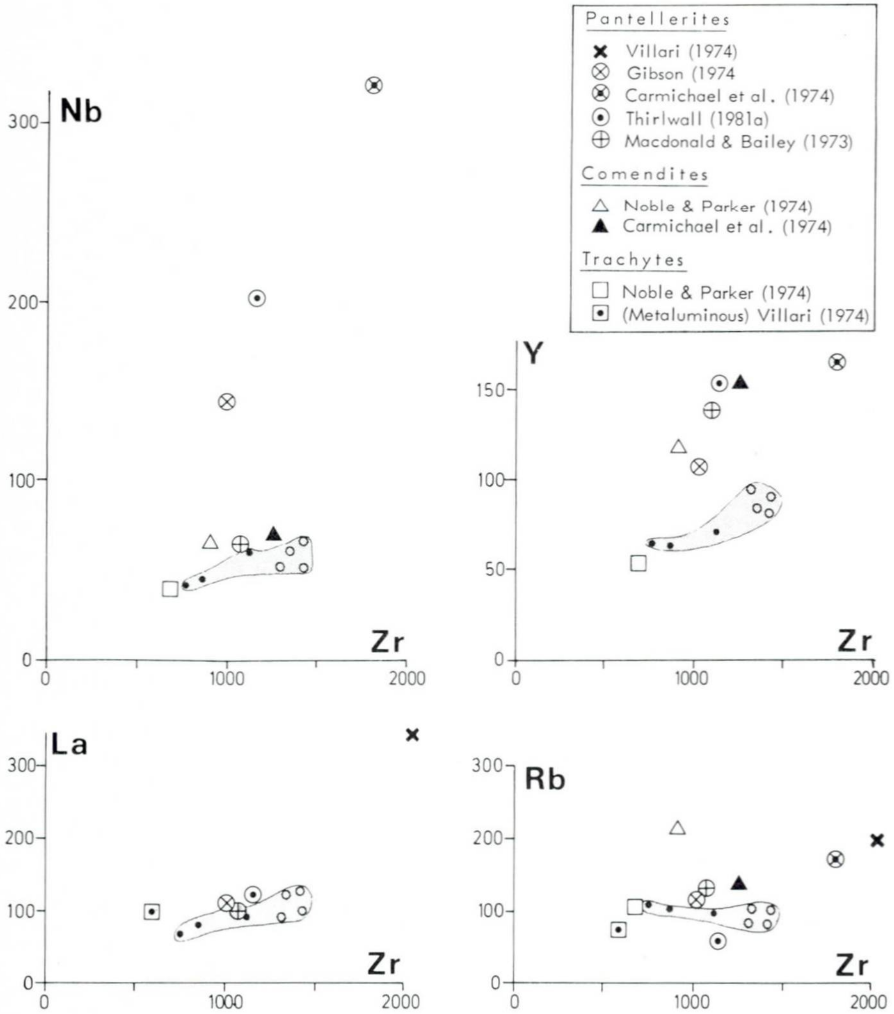

Fig. 9. The Hersvik lavas (shaded area) compared with various trachytes, comendites and pantellerites. Dots–lower flow; open circles–upper flow.

Tectonic environment of the Hersvik lavas

Although peralkaline trachytes and rhyolites, as well as their intrusive equivalents, are common on oceanic islands, they are particularly characteristic of non-orogenic continental volcanism, especially rift valleys (Turner & Verhoogen 1960, Macdonald 1974). The association with continental sediments deposited in a deep, fault-bounded basin (Nilsen 1968, Steel 1978) may therefore fit well with the petrochemical character of the Hersvik lavas.

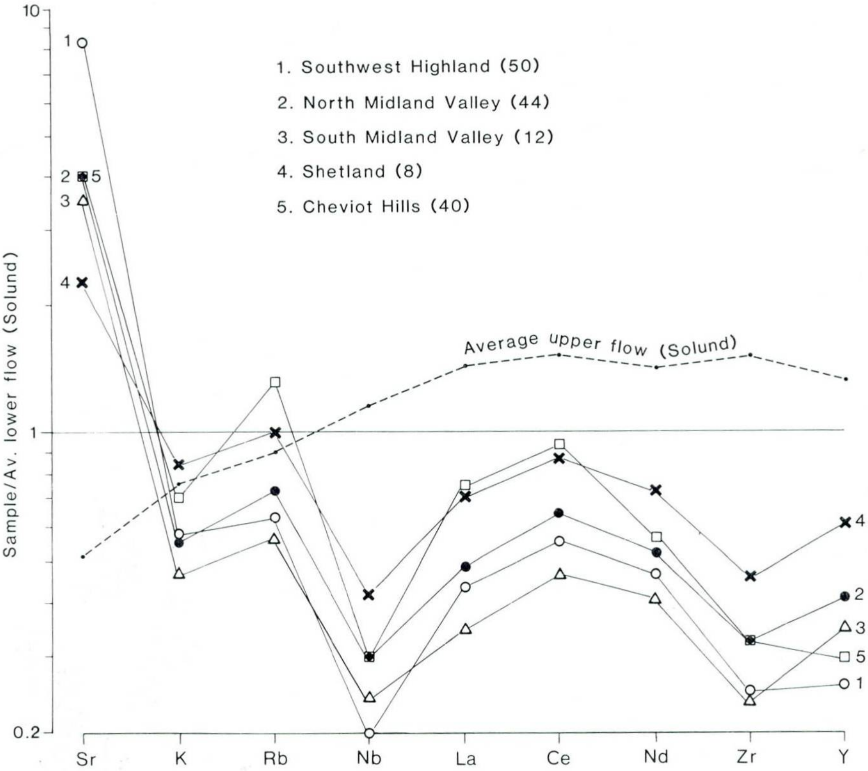

Fig. 10. The Hersvik lavas compared with average (no. of analyses in parentheses) acid Devonian volcanics from northern Britain and Shetland. The British analytical data are taken from Thirlwall (1981b).

Comparison with other Devonian volcanics in the N. Atlantic region

Devonian volcanics, predominantly acid lavas and pyroclastics, but including some basic lavas, occur in the Middle Devonian of W. Shetland (Miller & Flinn 1966, Flinn et al. 1968), and more extensively in S.E. Greenland (Noe-Nygaard 1937, Haller 1971), where the volcanics are of Middle and Upper Devonian age. Lower Devonian volcanicity is extensively developed in northern Britain (Turner & Verhoogen 1960).

The authors do not know of any modern petrochemical studies on the S.E. Greenland volcanics; however, they appear to include rocks of both alkaline and calc-alkaline affinities (Rittmann 1940). A large number of geochemical analyses has recently been carried out on the north British and Shetland volcanics (Groom & Hall 1974, Thirlwall 1981b). According to Thirlwall (1981b) the Lower Devonian volcanics of their region are dominantly calc-alkaline and related to subduction. He draws analogies with the calc-alkaline volcanics of the continental margin of the western USA. On Fig. 10 the acidic lavas of northern Britain and Shetland have been normalized against the average lower trachyte flow from

Solund. It is obvious from this diagram that the volcanics from the two provinces are distinctly different with respect to total abundances as well as most ratios of incompatible elements.

It should be mentioned, however, that the Solund lavas may not be of the same age as the volcanics in northern Britain. The exact age of the Devonian rocks in Solund is not known, but in the nearby Kvamshesten, Buelandet–Værlandet and Hornelen areas plant fossils and fish remains indicate a Middle Devonian age (Kolderup 1904, 1915a, b, 1916, Nathorst 1915, Kiær 1918). If the Solund rocks are of the same age, the Hersvik volcanics may be younger than those in northern Britain.

Summary

The volcanic rocks of the Hersvik area of Solund occurs as flow-banded, autobrecciated, subaerial lava flows interbedded with the lower part of the Devonian conglomerate. Two flows, the lower one trachytic and the upper rhyolitic, can be distinguished both in the filed and by their chemical compositions, Syn- to post-emplacement hydrothermal alteration and later lower greenschist facies metamorphism converted the rock to an albite antiperthite–quartz–chlorite–hematite assemblage. Tectonic activity is reflected in minor thrusting as well as the development of a steep crenulation cleavage. Geochemically the rocks can be classified as peralkaline with trace element (Zr, Y, Nb, LREE, Rb) contents that are high and comparable to those of some peralkaline acid rocks formed in continental rift environments.

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