

The Opaque Mineralogy of Surtsey

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The opaque mineralogy of the Surtsey rocks is of interest because it affords insight into the relationship between volcanic gases and the magma from which they exsolved. Furthermore, in a general way changes in the oxidation state of the cooling melt and rock are reflected in the oxide minerals.

In the following the minerals will be briefly described, some analyses reported, and conclusions drawn.

Earlier work on the opaque minerals in Surtsey is scant. From modal analyses of samples representing different degrees of crystallisation Steintthórsson (1966) found that a small percentage (0.4–0.8) of “opaques” was consistently present in the rock, remaining at that low level until more than 60% of the melt had crystallised. Then the percentage started to grow, increasing with degree of crystallisation to about 10% in fully crystalline samples. Jakobsson (1968, 1969) briefly described the ore minerals in some samples from the Vestmann Islands (including Surtsey). According to him the ores consist of magnetite, ilmenite and chrome-spinel, and may reach 12% by volume. Chrome-spinel occurs included in olivine, and when present in the groundmass it is heavily zoned towards magnetite. A preliminary microprobe analysis revealed 35–40% of hercynite in the chromite.

OPTICAL OBSERVATIONS

The four samples inspected optically are described below. They are listed in Table I.

In sample SU 32 opaques amount to some 5%. *Titanomagnetite* is dominant. The crystals tend to be equidimensional xenomorphic and fre-

TABLE I
Samples inspected.

SU 32	First lava, flowed April 1964, about 1 m below surface of flow. Coll. S. Jakobsson, August 1964. For analysis, see Steintthórsson (1966).
SU 11	Lava, flowed April–May 1965. Coll. S. Jakobsson.
SU 18	Lava, flowed August 1966, from surface of flow. Coll. S. Jakobsson.
1242	Bomb from Jólnir (August 1966). Coll. B. Johnsen.

quently skeletal, 0.05–0.1 mm in diameter. They are homogeneous, showing no oxyexsolution. *Ilmenite* crystals constitute less than 10% of the opaques. The grains are frequently skeletal and tend to be acicular in shape. Comparatively large grains measure 0.7x0.001 or 0.002 mm. *Chrome-spinel* is only found included in olivine. Grains situated near the crystal margin or on cracks are zoned towards titanomagnetite. The crystals show equidimensional cubic form, less than 0.025 mm in diameter (Plate I, a).

SU 11: Opaques estimated about 5%. *Titanomagnetite* dominates. The grains are less than 0.1 mm in diameter, xenomorphic, showing pronounced skeletal texture. Oxyexsolution of ilmenite is quite pronounced (Plate I, b). *Ilmenite* occurs both as discreet acicular crystals (< 10% of opaques) and as the product of exsolution in the titanomagnetite. *Chromite* only occurs included in olivine phenocrysts, where it frequently shows zoning in colour from dark grey to

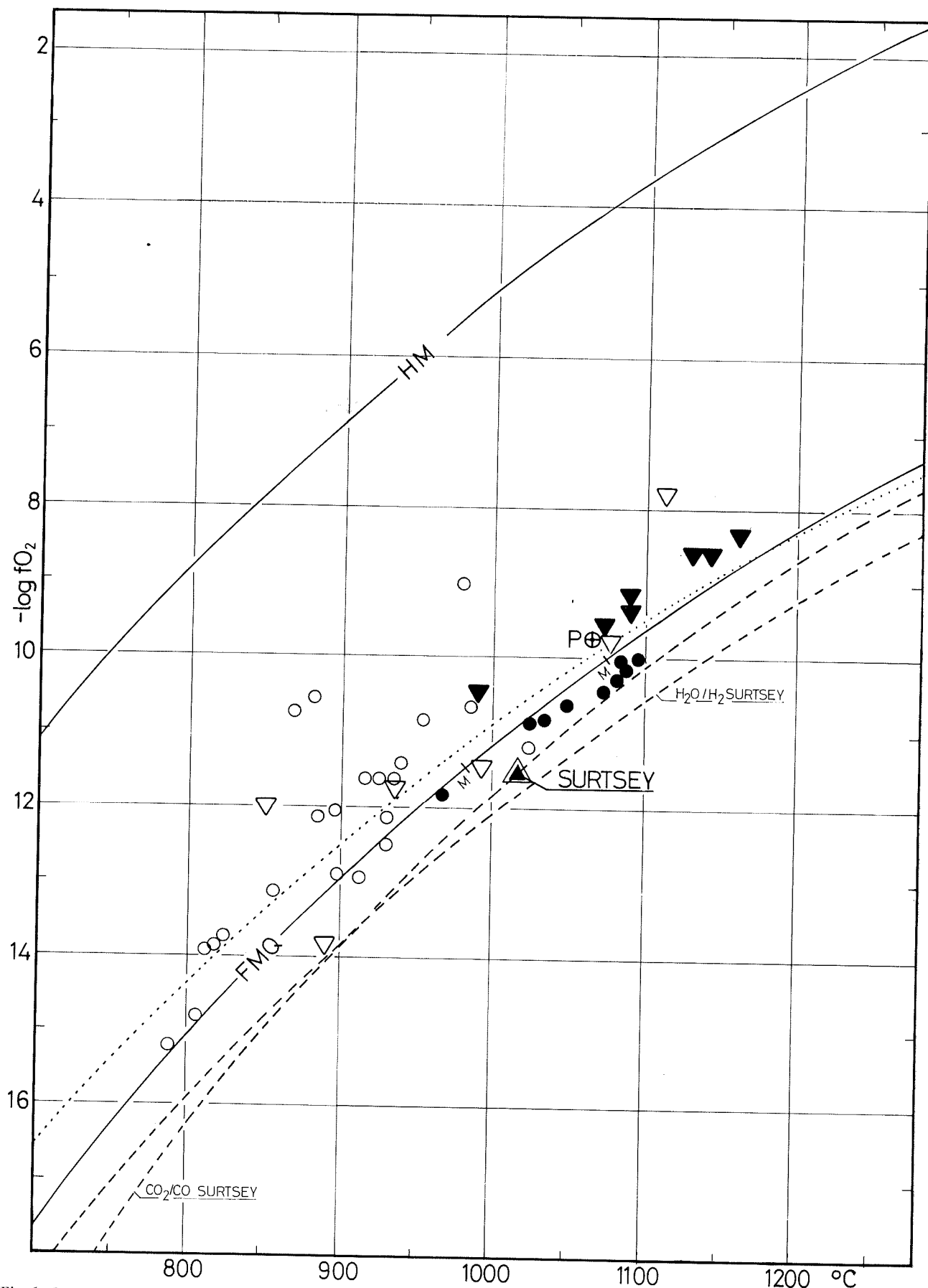


Fig. 1. Oxygen fugacities ($-\log f_{O_2}$) plotted against temperature showing the relationship between f_{O_2} , calculated from an analysis of volcanic gas from Surtsey (dashed curves), and that obtained from the analysis of Fe-Ti oxides in the lava (triangle). The buffer assemblages HM and FMQ are plotted for reference. Dotted curve: volcanic gas from Hawaii (Heald et al., 1963). Circle P: a direct measurement in Kilauea lava lake, Hawaii (Peck & Wright, 1966). Curve M—M: the curve followed during the cooling of the Makaopuhi lava lake (from Fe-Ti oxide analyses, Evans & Moore, 1968). Filled circles and inverted triangles: basaltic lavas, respectively, from E. Iceland and elsewhere (Carmichael & Nicholls, 1967) and from Tristan da Cunha (Anderson, 1968). Open circles and inverted triangles: acid and intermediate volcanics, as above (Carmichael & Nicholls, 1967, and Anderson, 1968).

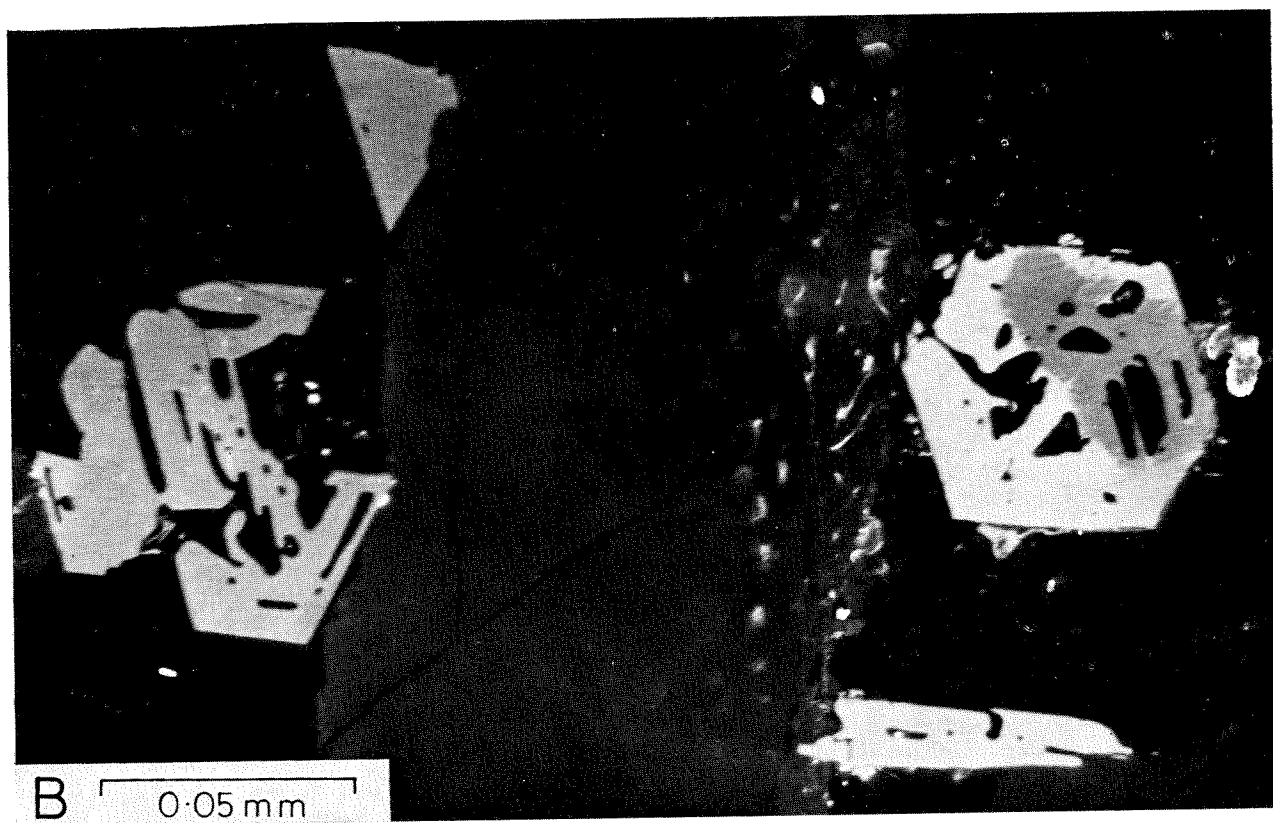
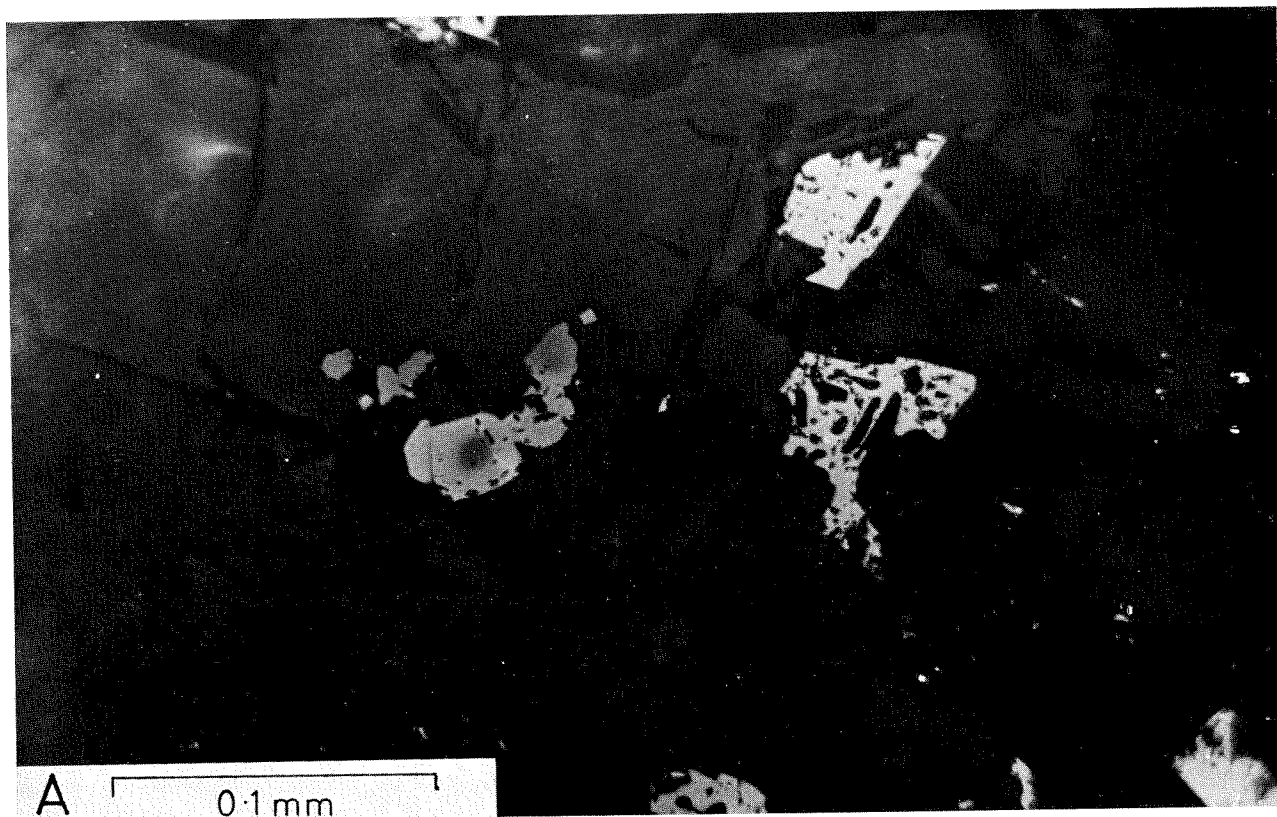
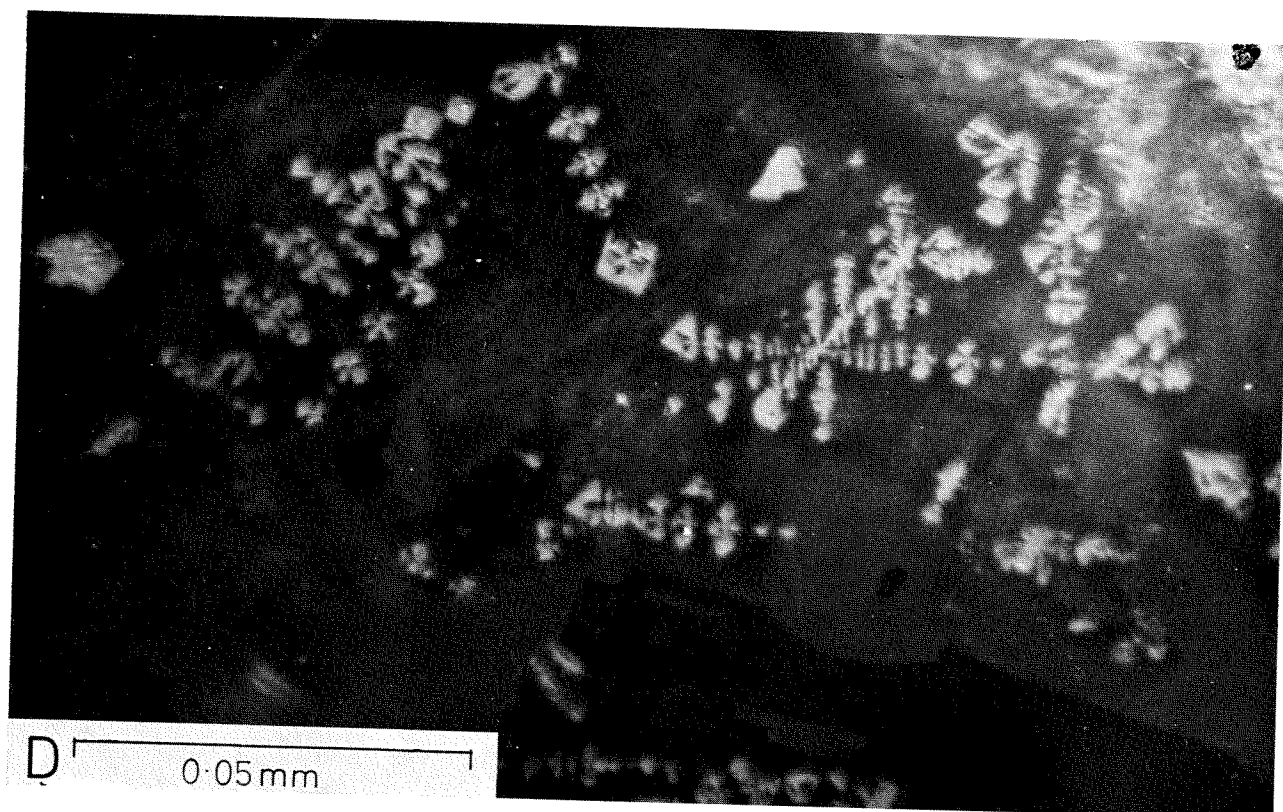


Plate 1. All the photographs are taken using a x25 oil-immersion objective and plane polarised light. A) Chrome-spinel included in olivine has a thick rim of titanomagnetite. Unexsolved xenomorphic and skeletal titanomagnetite in the ground-mass (sample SU 32). B) Skeletal titanomagnetite showing exsolution of ilmenite (SU 11). C) Grains of chrome-spinel included



in olivine and showing zoning to titanomagnetite. Tiny grains of skeletal titanomagnetite in groundmass (surface of lava, Búdahraun, Snaefellsnes). D) Skeletal titanomagnetite at surface of lava, as in SU 18. (Present photograph of Búdahraun, Snaefellsnes.)

lighter grey at the margin. This may reflect substitution of Al for Cr in the structure. One *sulphide* crystal (pyrite?) was observed associated with chromite.

SU 18: Opaques constitute less than 1%. Chromite is mostly associated with the olivine as inclusions, but is also found in the glassy groundmass. The largest chromite crystal was observed in the groundmass and measured 0.1x0.05 mm. A very thin veneer of lighter grey or yellowish was observed on some of the chromite crystals. Titanomagnetite occurs in tiny skeletal forms all over the groundmass, presumably lending the dark colour and opacity to the sideromelane at the lava surface (Plate I, d).

1242: Tiny crystals ($d = 0.02$ mm) of chromite occur both within olivine phenocrysts and without. The groundmass is sideromelane glass which is quite opaque, but shows red internal reflections — probably due to haematite.

These samples represent four different degrees of crystallisation and oxidation. The latter is of twofold nature: (a) Progressive oxidation takes place in the crystallising melt due to the buildup of volatile concentration and the selective removal of ferrous iron into olivine and pyroxene, and (b) the sample is oxidised due to exposure to the atmosphere (SU 18, 1242).

The least crystalline state is represented by sample 1242, in which chromite occurs in the glass. In sample SU 18 it is suggested that the crystallisation is slightly more advanced, with a hercynite-rich composition forming on the margin of the Cr-spinel (cf. Evans & Moore, 1968, pp. 103–104). Sample SU 32 is crystalline, but the titanomagnetite is homogenous and unoxidised. Only Cr-spinel protected within olivine phenocrysts (analysis 6 in Table II) has survived the peritectic reaction with augite (cf. Irvine, 1967, p. 76). Finally, in SU 11 the titanomagnetite shows subsolidus oxidation with the exsolution of ilmenite.

The sequence of crystallisation in a basaltic melt is dependent of the oxidation state. In particular, low oxidation state (high FeO/Fe₂O₃ ratio) favours the early formation of olivine, whereas high oxidation state brings about the crystallisation of titanomagnetite. Cr is very insoluble in basaltic melts (cf. Irvine, 1967, p. 72), and if present chromite will be the first mineral to form at normal oxygen pressures. From the mineralogy of the samples it is evident that chrome-spinel was the first mineral to crystallise, closely followed by olivine in which it is included. The iron-titanium oxides crystallised last.

Apparently there was a hiatus in the crystallisation of the oxides after the initial formation of the chromite, until the activity of ferric iron in the melt was high enough to stabilise titanomagnetite. The available chromite reacted with the liquid and disappeared.

TABLE II

Electron microprobe analyses of coexisting titanomagnetite and haemoilmenites (1–5) and one chrome-spinel (6) from Surtsey dolerite sample 1088. The mineral compositions are recalculated according to the methods of Carmichael (1967) (C) and Anderson (1968) (A).

	1	2	3	4	5	6
FeO	53.40	53.48	42.87	42.29	43.52	15.10
Fe ₂ O ₃	13.88	13.23	4.03	4.33	2.51	3.60
TiO ₂	26.98	27.39	50.48	50.44	51.50	0.67
Al ₂ O ₃	3.92	3.14	0.09	0.05	0.20	39.76
MgO	1.83	1.74	0.84	1.10	0.91	15.74
MnO	0.87	0.85	1.01	1.09	1.15	0.17
Cr ₂ O ₃	0.03	0.04	0.02	0.01	0.05	25.06
CaO	—	—	—	—	—	0.04
SiO ₂	—	—	—	—	—	0.29
Total	100.91	99.88	99.34	99.31	99.84	100.43

C) Usp₇₉Mt₂₁ Usp₈₀Mt₂₀ Hm₄Im₉₆ Hm₄Im₉₆ Hm₃Im₉₇
A) Usp₇₆Mt₂₄ Usp₇₈Mt₂₂ Hm₄Im₉₆ Hm₅Im₉₅ Hm₃Im₉₇

TABLE III

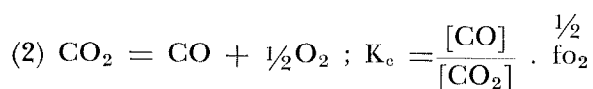
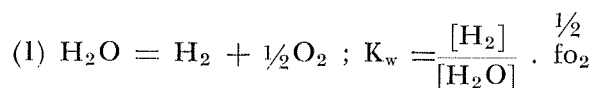
°K	K _w	log f _{O₂} from eq. 1	K _c	log f _{O₂} from eq. 1
1000	—10.07	—17.60	—10.22	—18.14
1100	— 8.89	—15.24	— 8.88	—15.46
1200	— 7.90	—13.26	— 7.77	—13.24
1300	— 7.07	—11.60	— 6.82	—11.34
1400	— 6.35	—10.16	— 6.02	— 9.74
1500	— 5.73	— 8.92	— 5.32	— 8.34
1600	— 5.18	— 7.72	— 4.71	— 7.12
1700	— 4.70	— 6.86	— 4.17	— 6.04

Equilibrium constants K_w (eq. 1) and K_c (eq. 2), calculated on the basis of data in the JANAF Tables (1965, 1966), (from H. D. Holland, 1970, unpublished) and oxygen fugacities calculated from a gas analysis from Surtsey: H₂O = 86.13, H₂ = 4.58, CO₂ = 5.54, CO = 0.39 (Febr. 21, 1965, Sigvaldason & Elisson, 1968).

CHEMISTRY

Coexisting titanomagnetite and haemoilmenite were analysed in one sample with the electron microprobe (for description of sample 1088, see Steinthórsson, 1966). The sample is of well-crystallised ophitic dolerite, in which the titanomagnetite shows abundant exsolution. The analyses are reported in Table II. They have been recalculated according to the method of Carmichael (1967), whereas the composition of the minerals was recalculated both as described by Carmichael (1967) and Anderson (1968). Applying the composition $\text{Usp}_{77}\text{Mt}_{23}$ and $\text{Hm}_4\text{Im}_{96}$ to the curves of Lindsley (Buddington & Lindsley, 1964) the temperature and f_{O_2} of last equilibration is obtained: $T = 1020^\circ\text{C}$, $\log f_{\text{O}_2} = -11.5$. This point is plotted as a triangle in fig. 1.

These results may be compared with those obtained from the analyses of volcanic gases in Surtsey, reported by Sigvaldason & Elísson (1968). The f_{O_2} of the gas is calculated from the ratios $\text{H}_2/\text{H}_2\text{O}$ and CO/CO_2 , which are governed by the reactions



In Table III are listed the values of the two equilibrium constants at various temperatures, and the corresponding f_{O_2} 's. The $f_{\text{O}_2} - T$ curves are plotted in fig. 1.

The two curves intersect at $T = 900^\circ\text{C}$, $\log f_{\text{O}_2} = -14$ atm. Taking these numbers at face value the gases equilibrated down to 900°C whereas the oxide minerals in this particular lava-sample stopped reacting at 1020°C . There is, however, an excellent agreement between the gas-analyses and the results obtained from the oxide minerals. The Surtsey magma, accordingly, was rather more reducing than basalts hitherto reported, as seen in fig. 1, where the results of Carmichael & Nicholls (1967) and Anderson (1968) for basaltic rocks are plotted.

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