NORSK GEOLOGISK TIDSSKRIFT

THE GEOCHEMISTRY OF FOUR ICELANDIC BASALTS

BY

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Abstract. The geochemistry of four Icelandic basalts is compared with that of other basalts along the Mid-Atlantic Ridge. The lava from Beruvikurhraun is the only alkali basalt. It has the high Ba and Sr concentrations typical of alkaline rocks. The other three basalts are tholeiites ranging from 49.00 to 50.42 per cent SiO_2 and 0.22 to 0.54 per cent K_2O. In their overall major element chemistry, the Icelandic basalts resemble the Hebridean basalts and Nockolds' average tholeiite. They are more iron rich than average basalts from other localities along the Ridge. A parent magma of a composition similar to the average Hawaiian tholeiites (MACDONALD and KATSURA 1964) could give the high iron, low magnesium basalts of Iceland by early separation of olivine (forsterite). Crustal contamination through any process we know of today is not consistent with many aspects of the chemical composition of the rocks, both with regard to major and trace elements.

The nature of the basaltic rocks along the oceanic ridges has recently received much attention (LE MAITRE 1962, ENGEL and ENGEL 1963, 1964a, b, GAST *et al.* 1964, MUIR and TILLEY 1964), and four papers have discussed restricted aspects, with chemical analyses, of the Icelandic volcanic rocks (WALKER 1963, THORARINSSON and SIGVALDASON 1962, CARMICHAEL 1964, ROBSON and SPECTOR 1962). The localities referred to in Table 1 are shown on the map (Fig. 2). ROBSON and SPECTOR (1962) give some trace element data for the Eldgia and Katla lavas, and HEDGE and WALTHALL (1963) give Rb, Sr concentrations, and initial Sr^{87}/Sr^{86} ratios in two recent Icelandic basalts which agree well with new measurements reported in this paper. After this was written, initial Sr^{87}/Sr^{86} ratios of a suite of Icelandic rocks were published by MOORBATH and WALKER (1965). Their results are in good agreement with those determined by us.

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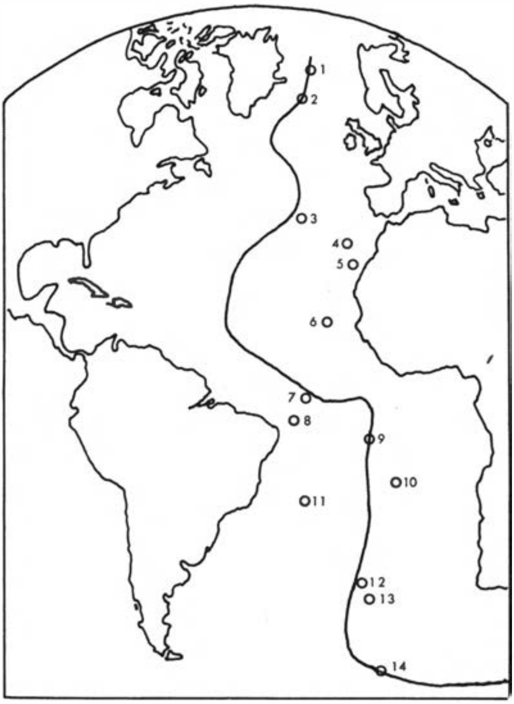

Fig. 1. Sketch map showing the outline of the Mid-Atlantic Ridge: 1. Jan Mayen, 2. Iceland, 3. Azores, 4. Madeira, 5. Canary Islands, 6. Cape Verde Islands, 7. St. Peter and St. Paul's Rocks, 8. Fernando de Noronha, 9. Ascension, 10. St. Helens, 11. Trinidad, 12. Tristan da Cunha, 13. Gough Island, 14. Bouvet Island.

The position of Iceland at the northern end of the Mid-Atlantic Ridge (Fig. 1), together with the observation that Icelandic basalts had been shown to be significantly 'more tholeiitic' and more iron rich than average basalts from other localities along the Ridge, made us undertake tihs investigation of the geochemistry of four specimens of Icelandic basalts kindly provided by Dr. G. E. Sigvaldason of the University Research Institute, Reykjavik. Their locations are shown on the map (Fig. 2).

ENGEL and ENGEL (1963, 1964a, b) noted that volcanic rocks dredged from submerged parts of the oceanic ridges are largely tholeiitic basalts with low values of K, Ti, P, U, Th, and Pb, whereas the islands and seamounts along these structures are to a large extent built of (or

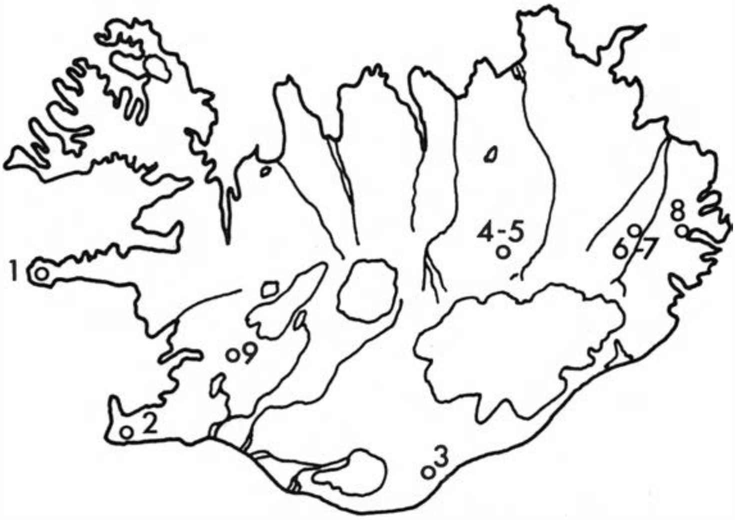

Fig. 2. Map of Iceland indicating the localities of analyzed basalts. 1. Beruvikurhraun, Snæfjellsjökull, 2. Reykjanes, 3. Laki, 4.–5. Askja, 6.–7. Thingmuli, 8. Reydarfjördur, 9. Skjaldbreid.

encrusted by) alkali basalt. The two larger islands (or island groups) of Hawaii and Iceland are clear exceptions to this. Engel and Engel suggested that the alkali basalts are derived from a parent tholeiitic magma by differentiation and that low potassium tholeiites (with about 0.2 per cent K_2O) are the dominant magma erupted from the mantle. It is interesting, therefore, that MUIR and TILLEY (1964) found that basalts dredged from the Mid-Atlantic Ridge at a mean depth of 3,370 m (45° 44′ N, 27° 43′ W) mostly have transitional or slightly alkaline affinities, lower concentrations of silicon and iron, and higher magnesium contents than the dredged samples of Engel and Engel.

ENGEL and ENGEL (1964b) also suggested that oceanic tholeiites can be distinguished from continental tholeiites on the basis of total potassium content, with the discontinuity at 0.3 to 0.5 per cent K_2O by weight. Using this criterion, and regarding the Icelandic basalts as representing a primary, nondifferentiated magma, the basalt from Reykjanes (No. 2, Table 1), and the average Skjaldbreid basalt (No. 9, Table 1) would be classified with the oceanic tholeiites. Neither these nor the average oceanic tholeiites of Engel and Engel are quartz normative. Sample No. 3 (from Laki, 1783 eruption, the greatest extrusion

Table 1

	Iceland								
	1*	2	3	4	5	6	7	8	9
SiO_2	48.29	49.00	49.55	50.42	50.50	47.44	49.31	48.8	47.5
TiO_2	3.59	2.01	2.84	2.78	2.96	2.19	3.13	3.0	2.0
Al_2O_3	14.66	14.10	13.79	12.64	12.75	14.17	12.67	13.6	14.0
Fe_2O_3	3.12	2.64	2.49	3.97	2.38	4.37	4.75	5.5	2.5
FeO	9.59	10.95	11.34	11.62	13.58	7.97	10.31	8.8	10.0
MnO	0.28	0.25	0.25	0.27	0.25	0.20	0.26	0.2	
MgO	4.39	6.96	5.84	4.75	5.09	7.25	4.69	5.2	9.0
CaO	8.87	11.62	10.63	9.05	8.95	11.11	9.10	10.6	12.5
Na_2O	3.80	2.35	2.79	2.85	2.71	2.46	3.01	2.8	1.7
K_2O	1.55	0.22	0.42	0.54	0.66	0.33	0.56	0.5	0.3
P_2O_5	0.93	0.21	0.30	0.24	0.27	0.27	0.57	0.4	0.2
H_2O+	0.29	0.11	0.17	0.13	0.25	1.25	0.68	0.6	
H_2O-	0.14	0.06	0.11	0.14	0.04	0.81	0.76		
CO_2	0.13	0.07	0.11	0.26					
	C.I.P.W. Molecular norm								
Q....	—	—	0.2	4.5	2.2	0.2	4.7	3.8	—
Or ..	9.5	1.5	2.6	3.3	4.0	2.0	3.5	3.0	1.5
Ab...	35.1	21.4	25.6	26.7	25.0	23.0	28.5	26.0	15.5
An...	18.9	27.7	24.4	21.0	21.2	27.5	20.3	24.0	30.2
Ne ..	—	—	—	—	—	—	—	—	—
Ol ...	8.4	2.2	—	—	—	—	—	—	6.6
Hy ..	1.4	17.7	18.0	16.3	21.6	16.4	13.6	9.8	15.2
Di ...	16.4	23.6	22.0	19.4	18.8	22.4	18.4	22.4	25.2
Mt ..	3.3	2.8	2.7	4.3	2.5	4.8	5.1	6.0	2.5
Il ...	5.1	2.8	4.0	4.0	4.2	3.2	4.6	4.4	2.8
Ap...	2.0	0.5	0.6	0.5	0.5	0.5	1.3	0.8	0.5

+ Including 0.16% BaO + SrO calculated as CaO in the norm.

1. Beruvikurhraun, crater on the flank of Snæfjellsjökull.
2. Reykjanes peninsula, close to road to Grindavik.
3. Laki (1783 eruption), greatest lava production on the Earth in historic time; 60 km from South end of fissure.
4. Askja caldera, 1961 eruption.
5. Askja average of three lava flows (THORARINSSON and SIGVALDASON 1962).
6. Ol-tholeiite, Thingmuli volcano, average of 3 (CARMICHAEL 1964).
7. Tholeiite, Thingmuli volcano, average of 7 (CARMICHAEL 1964).
8. Tholeiitic andesite lava, Reidarfjördur, average of 6 (WALKER 1963).
9. Skjaldbreid basalts, average of 6 (WAGER 1956).

of lava in historic time) and the olivine tholeiites from Thingmuli (No. 6) are barely quartz normative and fall in the 'potassium gap' of Engel and Engel. The tholeiites from Askja (Nos. 4 and 5), Thingmuli (No. 7), and Reidarfjördur (No. 8) all contain more than 0.5 per cent K_2O.

CHAYES (1964) used a TiO_2 content of 1.75 per cent to distinguish between oceanic (above 1.75 per cent) and circumoceanic (less than 1.75 per cent) basalts. The Iceland basalts were specifically omitted from his discussion as being continental rather than oceanic (Thulean province). We do not know the general TiO_2 content of continental tholeiites, but judging from the compilation of WALKER and POLDERVAART (1949) TiO_2 concentrations of less than 1.75 per cent seem to be common. Using the TiO_2 criterion, the tholeiitic basalts dredged from the Mid-Atlantic Ridge area (ENGEL and ENGEL 1964a, MUIR and TILLEY 1964) should be designated 'circumoceanic', while those from the islands are 'oceanic'.

In their overall major element chemistry, the Icelandic basalts resemble the Hebridean basalts (WAGER 1956) and the average tholeiite of NOCKOLDS (1954). This provokes the question of whether Icelandic basalts have been contaminated by or interacted with continental materials. CHAYES (1963) for this reason excluded the Icelandic basalts (as well as those from the United Kingdom) in his survey of oceanic volcanic rocks. No process we know of today would derive a basalt composition, similar to that from Iceland, from a primitive basalt magma of a composition as suggested by ENGEL and ENGEL (1964b), by contamination with crustal materials. It is possible however that the Icelandic basalts could be derived from a more primary basaltic magma by magmatic fractionation, and the rocks Nos. 2, 3, and 4 could well represent different fractionation stages of a common magma. Geochemical parameters more sensitive than major element chemistry alone are available for the study of crustal contamination of mantle material. The use of initial Sr^{87}/Sr^{86} ratios in such problems has been discussed repeatedly (HEDGE and WALTHALL 1963, GAST 1960, FAURE and HURLEY 1963), and it was recently used in a study of volcanic rocks from Gough and Ascension Islands (GAST *et al.* 1964). Initial Sr^{87}/Sr^{86} ratios of basalts from Iceland are given in Table 2. The variation from the mean of $0.7028_{(5)}$ of all the samples is probably not significant. The ratio is lower than the most frequent published value in basaltic rocks (0.704 to 0.705, HEIER *et al.* 1965) and is similar

Table 2a

	Sr^{87}/Sr^{86}	Sr/Rb	K/Rb	Th/K × 10^4	U/K × 10^4	Th/U	Co/Ni
1	0.7026	17	406	2.6	1.2	2.1	>3.0
2	0.7034	40	500	2.7	1.0	2.7	0.7
3	0.7031	28	450	2.9	1.0	2.9	1.2
4	0.7029	14	354	3.6	0.9	3.4	1.6

Table 2b

	Th ppm	U ppm	Ba ppm	Sr ppm	Rb ppm	Co ppm	Ni ppm	Cr ppm	V ppm	Zr ppm
1	3.4	1.6	900	539	32	32	tr.	tr.	235	290
2	0.54	0.20	80	161	4	50	70	190	390	120
3	1.2	0.42	110	225	8	50	43	75	375	180
4	1.6	0.47	130	182	13	47	30	25	460	180

1. Beruvikurhraun. 2. Reykjanes. 3. Laki 1783. 4. Askja 1961.
Th and U by gamma-ray spectrometry.
Rb, Sr, and Zr by X-ray spectrography.
Ba, Co, Ni, Cr, and V by optical spectrography.
Sr-isotope ratios determinations by a technique of voltage peak switching which gave the following results for the M.I.T. standard strontium carbonate (E A) normalized for $Sr^{86}/Sr^{88} = 0.1194$

	1	2	3	4	5	6
Sr^{87}/Sr^{86}	0.7080	0.7082	0.7082	0.7083	0.7084	0.7083
Sr^{84}/Sr^{86}	0.05660		0.05668		0.05657	0.05657

to the value determined by GAST *et al.* (1964) for basalts from Ascension Island but lower than their Gough Island basalts. Contamination of basaltic magma with crustal materials would tend to increase this ratio by the addition of radiogenic strontium.

The K : Rb ratio in basalt is in some state of controversy at the moment. Recent publications quote high ratios for oceanic basalts (GAST 1960, LESSING *et al.* 1963), and 500 is a typical ratio in tholeiites and low potassium alkali lavas from Hawaii. This is similar to what we find for basalts from Reykjanes (No. 2). The lower K : Rb ratio of the other tholeiitic rocks examined could reflect contamination by crustal material (average K : Rb ratio of 230), but in view of the other chemical evidence we suggest that it is related to the degree of differentiation of these basalts. Progressive enrichment of Rb relative to K has been widely observed in magmatic differentiation series.

K : Rb ratios calculated from the analyses reported by LE MAITRE (1962) and MUIR and TILLEY (1964) indicate wide variation (K : Rb between 140 and 700) in the tholeiitic basalts examined by them. The variation is not related in any way to potassium content or to any other chemical or petrographic parameters of the rocks, and this would suggest that the Rb data are not sufficiently precise for a useful comparison of K : Rb ratios.

Increase in the Co : Ni ratio is a useful indicator of differentiation in magmatic rocks. In the Icelandic basalts, the ratio indicates the same trend as discussed above. The Co : Ni ratios of these rocks are considerably lower than in rocks at similar stages of fractionation at Hawaii, but similar to those of the British Tertiary province and Hakone volcanic rocks (NOCKOLDS and ALLEN 1956). The dredged samples from the Mid-Atlantic Ridge (MUIR and TILLEY 1964), as well as the early basalt types from Gough Island (LE MAITRE 1962), have characteristically much lower Co : Ni ratios. Similar comments can be made about the concentrations of Cr and V in the Icelandic basalts.

The relations between thorium, uranium, and potassium in basaltic rocks have been studied by HEIER and co-workers (1963, 1964, 1965). The Th : K ratios in the basalts from Iceland are very similar to those found in basaltic rocks from many different environments, but uranium is relatively enriched in the Icelandic rocks (by a factor of about 2). The U : K ratio is similar to that in continental dolerites from Tasmania (HEIER *et al.* 1965), but in these the Th : K ratio is high as well (about 5×10^{-4}). This difference between U and Th in Icelandic basalts compared with other basaltic provinces cannot be explained before a better knowledge of radioactive element concentrations in basaltic rocks is obtained. In the Hawaiian group, the data available show the basalts from Kuai to have significantly higher Th/K and U/K ratios than those from Oahu and Maui (HEIER *et al.* 1964). As a result of the relatively higher U concentrations, the Th/U ratios are low in the Icelandic basalts. The tendency towards an increase in the Th/K ratios with increasing potassium content in the three Icelandic tholeiites (Nos. 2, 3, 4, Table 1) is in qualitative agreement with the trend in magmatic differentiation series.

Table 3. *Comparison between gamma-ray spectrometric* (γ) *and neutron activation* (*n.a.*) *determinations of Th and U*

	Th ppm	U ppm
Laki (γ)	1.11–1.37	0.42
Laki (n. a.)	1.13	0.374 ± 3 %
Askja (γ)	1.55	0.47
Askja (n.a.)............	1.52	0.457

The U and Th concentrations were first determined by gamma-ray spectrometry using the 2.62 MeV peak for Th (the Tl^{208} peak in the Th series) and the 1.76 MeV peak for U (the Bi^{214} peak in the U series). Th and U in the two most recent basalts (Laki, 1783; Askja, 1961) were thereafter determined by a neutron activation method. The results are compared in Table 3, and the close agreement between the two sets of results demonstrates that radioactive equilibrium may obtain in very recent lavas.

The alkaline affinities of the basalt from Beruvikurhraun is reflected in the high Ba and Sr concentrations. High concentrations of these elements are also characteristic of plutonic alkaline rocks (HEIER and TAYLOR 1964) and pose an interesting geochemical problem. This rock is strikingly different from the tholeiitic basalts from Iceland listed in Table 1. It should be compared with the lava of Elgjá and Katla in the southeastern part of the Iceland graben (ROBSON and SPECTOR 1962). MUIR and TILLEY (1964) pointed to the alkaline affinities of those basalts. The analysis of the Beruvikurhraun rock compares well with MACDONALD and KATSURA'S (1964) average Hawaiite. The Hawaiite is more fractionated with respect to Ca and Na but less with respect to Mg and Fe. Two of the eight Hawaiites listed by Macdonald and Katsura have normative hypersthene.

Conclusions

The purpose of this investigation has been to draw attention to the specific chemical peculiarities of the Icelandic basalts when they are compared with other basalts along the Mid-Atlantic Ridge. With the possible exception of the alkali basalt No. 1, much of the chemical evidence is consistent with the Icelandic basalts being inter-related through a liquid line of descent from a common magma type. A parent magma of a composition similar to the average Hawaiian tholeiites of MACDONALD and KATSURA (1964) could yield the high iron, low magnesium basalts of Iceland by early separation of olivine (forsterite).

The special position of the Icelandic basalts has often been explained by assuming 'continental' affinities, and thereby suggesting 'Crustal contamination' as affecting the primary basaltic magma composition. We have endeavoured to show that crustal contamination through any process we know of today is not consistent with many aspects of the chemical composition of the rocks, both with regard to major and trace elements. Recent seismic surveys have failed to detect any sign of a sial-layer under Iceland (TRYGVASON and BATH 1961), and, at least in eastern Iceland, no material of such composition has been found in the volcanic agglomerates (WALKER 1963). We therefore feel that the role of contamination may well have been overemphasized as an explanation of the diversity of these basaltic magmas, and we would rather postulate primary differences in the source material(s) or variations in the physical conditions of magma generation.

APPENDIX

PETROGRAPHY

Beruvikurhraun: Microphenocrysts of basic feldspar (zoned around An_{60}) up to 3 mm long with olivine less common and rare clinopyroxene and oxide mineral. Groundmass consists of plagioclase (An_{40}–An_{43}) with sub-trachytic texture with olivine and very fine intergranular titaniferous clinopyroxene, oxide minerals, and apatite needles. Plagioclase constitutes approximately 60 per cent of rock. No separate alkali feldspar phase has been observed.

Reykjanes: Microphenocrysts of olivine make up a few per cent of this rock; microphenocrysts of bytownite and clinopyroxene are more abundant and generally show sub-ophitic relations. The groundmass is intergranular and made up of roughly equal amounts of basic labradorite and clinopyroxene.

Laki: Generally aphyric, intergranular texture with approximately equal amounts of clinopyroxene and plagioclase (An_{60}–An_{64} in groundmass). Olivine is a very minor constituent.

Askja: Exceedingly fine grained with occasional small phenocrysts (less than 0.3 mm) of plagioclase (An_{60}) and clinopyroxene.

(Plagioclase compositions by beta-index.)

REFERENCES

Carmichael, I. S. E. 1964. The petrology of Thingmuli, a Tertiary volcano in eastern Iceland. Jour. Petrology 5: 435–460.

Chayes, F. 1963. Relative abundance of intermediate members of the oceanic basalt-trachyite association. Jour. Geophys. Res. 68: 1519—1534.

— 1964. A petrographic distinction between Cenezoic volcanics in and around the open oceans. Jour. Geophys. Res. 69: 1573–1588.

Engel, C. G. and **Engel**, A. E. J. 1963. Basalts dredged from the northeastern Pacific Ocean. Science 140: 1321–1324.

Engel, A. E. J. and **Engel**, C. G. 1964a. Composition of basalts from the Mid-Atlantic Ridge. Science 144: 1330–1332.

— — 1964b. Igneous rocks of the East Pacific Rise. Science 146: 477–485.

Faure, G. and **Hurley**, P. M. 1963. The isotopic composition of strontium in Oceanic and Continental basalts. Application to the origin of igneous rocks. Jour. Petrology 4: 31–50.

Gast, P. W. 1960. Limitations on the composition of the Upper Mantle. Jour. Geophys. Res. 65: 1287–1297.

Gast, P. W., **Tilton**, G. R. and **Hedge**, C. 1964. Isotopic composition of lead and strontium from Ascension and Gough Islands. Science 145: 1181–1185.

Hedge, C. E. and **Walthall**, F. G. 1963. Radiogenic strontium-87 as an index of geologic processes. Science 140: 1214–1217.

Heier, K. S., **Compston**, W. and **Mc Dougall**, I. 1965. Thorium and uranium concentrations, and the isotopic composition of strontium in the differentiated Tasmanian dolerites. Geochim. et Cosmochim. Acta 29: 643–659.

Heier, K. S., **McDougall**, I. and **Adams**, J. A. S. 1964. Thorium, uranium and potassium concentrations in Hawaiian lavas. Nature 201: 254–256.

Heier, K. S. and **Rogers**, J. J. W. 1963. Radiometric determination of thorium, uranium and potassium in basalts and in two magmatic differentiation series. Geochim. et Cosmochim. Acta 27: 137–154.

Heier, K. S. and **Taylor**, S. R. 1964. A note on the geochemistry of alkaline rocks. Norsk geol. tidsskr. 44: 197–204.

Le Maitre, R. W. 1962. Petrology of volcanic rocks, Gough Island, South Atlantic. Geol. Soc. America Bull. 73: 1309–1340.

Lessing, P., **Decker**, R. W. and **Reynolds**, L. P. J. 1963. Potassium and rubidium distribution in Hawaiian lavas. Jour. Geophys. Res. 68: 5851–5855.

Macdonald, G. A. and **Katsura**, T. 1964. Chemical composition of Hawaiian lavas. Jour. Petrology 5, 82–133.

Moorbath, S. and **Walker**, G. P. L. 1965. Strontium isotope investigation of igneous rocks from Iceland. Nature 207: 837.

Muir, I. D. and **Tilley**, C. E. 1964. Basalts from the northern part of the Rift Zone of the Mid-Atlantic Ridge. Jour. Petrology 5: 409–434.

NOCKOLDS, S. R. 1954. Average composition of some igneous rocks. Geol. Soc. America Bull. 65: 1007–1032.

NOCKOLDS, S. R. and ALLEN, R. 1956. The geochemistry of some igneous rock series. Part III. Geochim. et Cosmochim. Acta 9: 34–77.

ROBSON, G. R. and SPECTOR, J. 1962. Crystal fractionation of the Skaergaard type in modern Icelandic magmas. Nature 193: 1277–1278.

THORARINSSON, S. and SIGVALDASON, G. E. 1962. The eruption in Askja, 1961. A preliminary report. Am. Jour. Sci. 260: 641–651.

TRYGVASON, E. and BATH, M. 1961. Upper crustal structure of Iceland. Jour. Geophys. Res. 66: 1913–1925.

WAGER, L. R. 1956. A chemical definition of fractionation stages as a basis for comparison of Hawaiian, Hebridean, and other basic lavas. Geochim. et Cosmochim. Acta 9: 217–248.

WALKER, G. P. L. 1963. The Breiddalur Central volcano, eastern Iceland. Quart. Jour. Geol. Soc. (London) 119: 29–63.

WALKER, G. P. L. and POLDERVAART, A. 1949. Karroo dolerites of the Union of South Africa. Geol. Soc. America Bull. 60: 591–706.

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