

1N79

**STRONTIUM ISOTOPE INVESTIGATION
OF IGNEOUS ROCKS FROM ICELAND**

By

Dr. S. MOORBATH

and

Dr. G. P. L. WALKER

*(Reprinted from Nature, Vol. 207, No. 4999, pp. 837-840,
August 21, 1965)*

(Reprinted from *Nature*, Vol. 207, No. 4999, pp. 837-840,
August 21, 1965)

STRONTIUM ISOTOPE INVESTIGATION OF IGNEOUS ROCKS FROM ICELAND

By DR. S. MOORBATH

Department of Geology and Mineralogy,
University Museum, Oxford

AND

DR. G. P. L. WALKER

Department of Geology, Imperial College of Science
and Technology, London, S.W.7

THE limited range of variation in the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of basaltic rocks (particularly in oceanic areas) suggests that the source regions of basalts are relatively homogeneous with respect to their Rb/Sr ratios^{1,2}. The average Rb/Sr ratio in the stalic crust is substantially higher than in the source regions of basalts³⁻⁵. On this basis, Faure and Hurley¹ suggested that there is sufficient enrichment of strontium-87 (resulting from the radioactive decay of rubidium-87) in crustal materials to use the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of igneous rocks, at time of crystallization, as a criterion for the origin of the material. Thus the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of an igneous rock formed by remelting of—or contamination with—ancient crustal material may be expected to be measurably higher than that of an igneous rock formed by differentiation of basaltic magma.

Strontium isotope measurements are reported in this article for a small, but reasonably representative, set of basic and acid igneous rocks of Tertiary to Recent age from a number of localities in Iceland (Fig. 1). The rock-types include gabbro, basalt, andesite, basic and acid tuff, pitchstone, obsidian and granophyre. Most of the specimens were collected by one of the authors (G. P. L. W.), but those from the Snaufudal intrusion were collected by A. E. Beswick.

Iceland exhibits many features of unusual geological interest, not least its situation astride the mid-Atlantic ridge, as well as the large-scale, intimate association of basic and acid igneous rocks. The problem of the origin of the acid igneous rocks is of considerable interest. Carmichael⁶, in his investigation of the crystallization of feldspar from volcanic acid liquids, considers those Icelandic rhyolites and pitchstones which he has examined to belong to that class produced by the fractionation of tholeiitic magma. On the other hand, Walker⁷ states

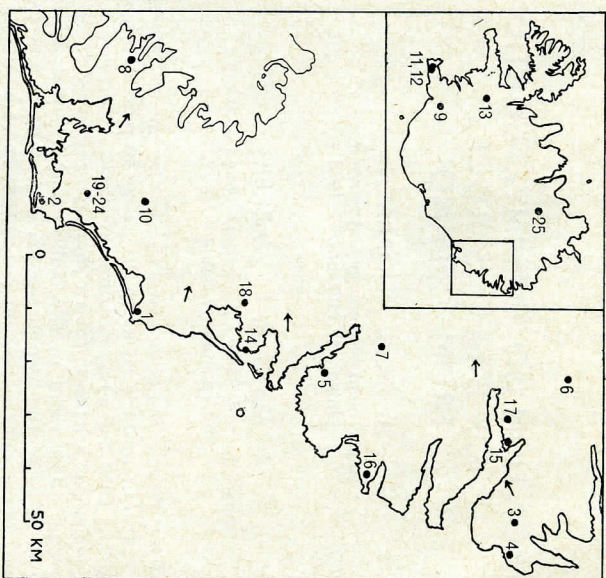


Fig. 1. Sketch map of eastern Iceland showing location of analysed samples. The arrows indicate the direction of younging of the volcanic rocks. Inset map of Iceland showing location of analysed samples of quaternary volcanic rocks.

that "such large amounts of acid (and intermediate) magma seem unlikely to have originated by crystal fractionation of basaltic magma and that a sialic crust seems a more likely source. Recent seismic work in western Iceland by Tryggvason and Baath⁸ has, however, failed to reveal a layer that can be identified as sial, and direct evidence for the existence of a sialic crust below eastern Iceland is lacking; but it may be that the great abundance of acid material in the Icelandic central volcanoes is evidence of its existence." According to Cargill *et al.*⁹ and many later workers, no floor of sial is visible anywhere in Iceland, no 'accidental' xenoliths have been discovered in lavas or intrusions, nor blocks in the volcanic piles; nor is there any evidence in the petrological character of the rocks of the assimilation of sedimentary material.

Strontium isotope measurements were carried out with an A.E.I. MS-2 mass spectrometer with a 60°, 6-in. radius analyser tube and an electron multiplier as the ion-beam detector. A single tantalum-filament, surface ionization technique was used. Full experimental details have been described elsewhere^{10,11}. In order to eliminate unpredictable isotopic fractionation effects, all measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$, in line with the procedure adopted by other workers^{1,2}.

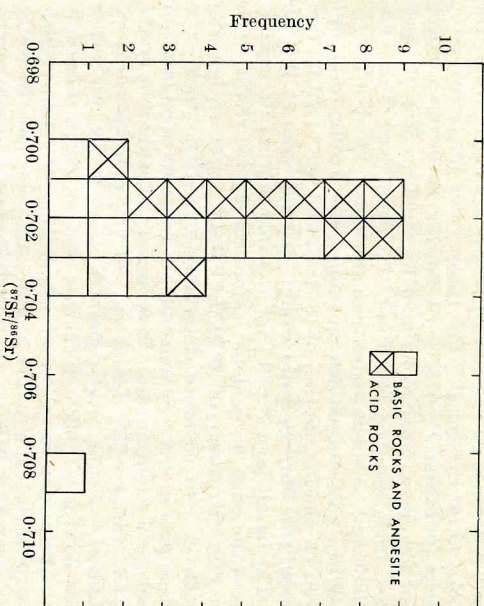


Fig. 2. Histogram of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from Iceland

This also has the effect of improving the reproducibility of replicate measurements. The average $^{86}\text{Sr}/^{88}\text{Sr}$ ratio found in the course of the present work was 0.1183, nearly 1 per cent below the conventional value of 0.1194. It appears, however, from the work of Hedge and Walballe, that the single filament ionization technique can yield slightly lower $^{86}\text{Sr}/^{88}\text{Sr}$ ratios than triple filament ionization. A check on reproducibility was provided by frequent isotopic analysis, during the course of the work, of the Elmer and Amend strontium carbonate standard, circulated internationally by the Massachusetts Institute of Technology group. The mean of eight separate measurements of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio was 0.7076, with a standard deviation of ± 0.0010 . In the 1964 report of the Massachusetts Institute of Technology group¹² it is stated that the normalized values found by several other laboratories for the Elmer and Amend $^{87}\text{Sr}/^{86}\text{Sr}$ ratio lie between 0.7075 and 0.7085. It is considered that in the present work the reproducibility of a single $^{87}\text{Sr}/^{86}\text{Sr}$ measurement is ± 0.0015 at the 66 per cent confidence level. Rubidium and strontium determinations were made by X-ray fluorescence analysis, yielding values to at least ± 10 per cent. The lower detection limit for rubidium was about 5 p.p.m. The Rb/Sr ratio and the geological age of the rocks were too low to necessitate an age correction in the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Measurements were carried out either on powdered, whole rock specimens, or on plagioclase feldspar separates. The results of strontium isotope measurements, expressed as the normalized, initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, are given in Table 1. Fig. 2 is a histogram of the results. It is evident that, with one exception, there is no signifi-

cant difference in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio between any of the rocks so far measured. The mean value for twelve basic rocks (omitting P. 673, see following) is 0.7024 ± 0.0009 and for eleven acid rocks 0.7016 ± 0.0008 . (Six of these acid rock samples are from the same rock unit, see following.) A single andesite measurement yields 0.7029 ± 0.0015 ; this sample has an appreciable Rb/Sr ratio, but even on the assumption of a maximum age of 50 million years, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio would only decrease to 0.7022. The basalt lava P. 673 (No. 7, Table 1) from Breiddalur gives the only 'anomalous' strontium isotope result, with an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7089 ± 0.0010 , representing the mean of two separate determinations. The rock does not appear in any way unusual, but it occurs in an unusual geological environment. It occupies the caldera or crater of the Tertiary Breiddalur central volcano, described by Walker⁷. Below, and separated from it by one other lava flow, is a thick hyaloclastic accumulation, the result of subaqueous eruption of basalt into the lake which occupied the caldera. It appears unlikely that the water was sea-water. (Since the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of sea-water is about 0.708, soaking of the lava in sea-water and resulting element and isotope exchange could account for the comparatively high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the basalt.) However, fumaroles and hot springs are thought to have contributed to the lake, and the rocks now visible beneath the basalt lava consist mainly of highly altered rhyolites and acid pyroclastics, which might have been the source of the slight excess of ^{87}Sr .

Of the acid rocks, the six samples from the Slaufudal granophyre stock (Nos. 19-24, Table 1) of Eastern Iceland are of particular interest. This is the largest known intrusive mass in Iceland, with an outcrop covering an area of 15 km² and with a volume of at least 10 km³. The structure and petrology of this intrusive have been described by Cargill *et al.*⁸, and further details will be published elsewhere by A. E. Beswick. Although many of the principal plutonic intrusions of Eastern Iceland are composite masses, mainly composed of gabbro, granite and granophyre, the Slaufudal stock consists of acid rock only. A potassium-argon determination on whole rock sample A. 39 yielded an age of 6.5 ± 1.1 million years. Even allowing for a plausible maximum of about 20 per cent loss of argon from potash feldspar, this puts the age of intrusion of the stock very late in the Tertiary. This unexpectedly young age explains why the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios all agree within the limits of experimental error, despite the fact that the Rb/Sr ratios of the six samples range from 0.4 to 2.3.

Samples No. 16, 17 and 18 (Table 1) are feldspar crystals obtained from interbasaltic acid tuff horizons. These tuffs are the products of explosive eruptions of acid magma, during which feldspar phenocrysts became separated from the acid magma. Being in a protected

Table 1. STRONTIUM ISOTOPE RESULTS FROM ICELAND

Map No. (Fig. 1)	Specimen No.	Rock type	Locality	Stratigraphic age	Sample form	Rb* (p.p.m.)	Sr* (p.p.m.)	($^{87}\text{Sr}/^{86}\text{Sr}$ + initial)
1	E. 718	Gabbro	Austurhorn intrusion (ref. 9)	Tertiary	Whole rock	n.d.	393	0.7029 (1)
2	E. 737	"	Litla-horn, Vesturhorn intrusion (ref. 9)	"	"	n.d.	460	0.7026 (1)
3	E. 469	Olivine-basalt lava	Vikurvattn group (ref. 18), Vindhalstindur, Reydarfjörður	"	"	n.d.	323	0.7022 (1)
4	E. 413	Tholeiitic basalt	Lava above Bardartangi tuff (ref. 18), Gerpir, Reydarfjörður area	"	"	5	243	0.7021 (1)
5	E. 704	Feldspar-porphyrific basalt lava	Kollur group (ref. 18), Gautavik, Berufjörður	"	"	n.d.	289	0.7032 (1)
6	P. 701	Olivine-basalt lava	Near summit of Skagafell, N.W. of Reydarfjörður	"	"	n.d.	238	0.7021 (1)
7	P. 673	Basalt lava	North nose of Berufjardartindur, Breiddalur (ref. 7)	"	"	n.d.	187	0.7089 (2)
8	R. 314	Basic tuff	Vidbordsdalur	Pleistocene	Bytownite	n.d.	692	0.7016 (1)
9	R. 341	Olivine-basalt lava	460 ft. on S.W. corner of Ingolfssfjall	(? Inter-glacial)	Whole rock	n.d.	150	0.7033 (1)
10	R. 298	Tholeiitic basalt lava	Columnar basalt at base of Dalsheidi palagonite breccia mass	Pleistocene	"	5	169	0.7033 (2)
11	R. 153	Basalt lava	Afstapahraun, W. of Hafnarfjörður, Reykjanes peninsula	Recent	"	n.d.	118	0.7028 (1)
12	R. 162	"	6 km W.S.W. of Grindavik, Reykjanes	Recent	"	n.d.	122	0.7004 (1)
13	R. 257	Feldspar-porphyrific basalt cinder	Cinder cone, Bifrost	"	Bytownite	n.d.	451	0.7012 (1)
14	P. 868	Hornblende-rich porphyritic dyke	Melrakkane	Tertiary	Whole rock	81	228	0.7029 (1)
15	E. 461	Pitchstone top of rhyolite lava	Holmahals, Reydarfjörður	"	Oligoclase	n.d.	504	0.7015 (1)
16	E. 779	Acid tuff	500 ft. on Mosfell, S. of Stodvarfjörður	"	"	n.d.	872	0.7014 (2)
17	E. 459	"	720 ft. in Ljosa, N. of Reydarfjörður	"	Andesine	n.d.	777	0.7013 (1)
18	R. 106	"	N. side Geithellnadalur	"	Oligoclase	n.d.	877	0.7007 (1)
19	A. 31a	Granophyre	Slaufudal intrusion (ref. 9), 1,550 ft. altitude, S.W. side of Skeggtind	Late Tertiary	Whole rock	78	194	0.7010 (1)
20	A. 35	"	Ditto, 1,100 ft. altitude, S.W. side of Skeggtind	"	"	93	40	0.7014 (1)
21	A. 39	"	Ditto, 1,430 ft. altitude, N. side of Upper Slaufudal	"	"	96	72	0.7033 (1)
22	A. 77	"	Ditto, 1,630 ft. altitude, S.E. of Bleikitind summit	"	"	83	184	0.7012 (1)
23	A. 102	"	Ditto, 190 ft. altitude. Bottom of Endalausidal valley	"	"	104	102	0.7026 (1)
24	A. 115	"	Ditto, 1,280 ft. altitude. Bottom of Upper Slaufudal	"	"	100	50	0.7024 (1)
25	OWR-1	Obsidian	Hrafninnuhryggur, near Myvatn (refs. 13-15)	Pleistocene or Recent	"	70	106	0.7017 (2)

* Determined by X-ray fluorescence; n.d. = not detectable.

† Normalized by adjusting $^{86}\text{Sr}/^{88}\text{Sr}$ to 0.1194 and the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratio by half this amount. The figure in parentheses after the ratio indicates the number of analyses performed for each specimen.

K/Ar age on sample A. 39 whole rock is 6.5 ± 1.1 million years (analyst, D. C. Rex).

environment, surrounded by soft and loose buffaceous material, these crystals are usually free from fractures and in a very fresh condition.

The well-known postglacial obsidian from Hrafninnubryggur (No. 25, Table 1) was first described and chemically analysed by Wright¹³ and later by Carmichael^{14,15}.

The strontium isotope results suggest that these relatively few acid rocks from Iceland so far investigated are ultimately derived from the same source region as the basic rocks, presumably the upper mantle. The acid rocks were formed either by the fractional crystallization of basic magma⁶ or by some process of partial melting of basic rocks. The possibility that they were produced by the partial or complete remelting of an ancient stalic crust beneath Iceland with anything like the average crustal Rb/Sr ratio is excluded by the isotopic data. If such a crust exists—and there is no direct evidence for it—then, either, it has not contributed any significant amounts of material to the acid rocks investigated in this study, or it is not older than about 100 million years. Clearly, many more strontium isotope measurements on Icelandic rocks are needed. However, if none of the acid rocks is found to contain a significant enrichment of strontium-87 over basalts, it would provide rather strong circumstantial evidence for the absence of ancient, stalic crust beneath Iceland. The presence or absence of such a crust would have an important bearing on reconstructions of the northern land masses prior to (hypothetical) continental drift. It is inherent in the present interpretation of the isotope results that there is some mechanism by which comparatively large volumes of acid magma can accumulate at depth by derivation from the same source regions as basalt magmas, or from basalt magma itself. This may have happened at various times during the Tertiary geological history of Iceland.

It is of interest that the average $^{87}\text{Sr}/^{86}\text{Sr}$ value for the Icelandic rocks is significantly lower than for the basic rocks of at least some of the continental areas of the North Atlantic Tertiary igneous province. An average value of 0.7058 ± 0.0010 has been reported for basic rocks from the Isle of Skye, north-west Scotland¹¹, while the average value for the basic rocks of the Skaergaard intrusion, East Greenland, is 0.7065 ± 0.0021 . However, the mass spectrometer used in the present study gave an average $^{87}\text{Sr}/^{86}\text{Sr}$ value for the Finner and Amend standard which is about 0.0020 lower than that obtained with the mass spectrometer used in the Skye and East Greenland investigations. (There is something to be said for correcting the measured $^{87}\text{Sr}/^{86}\text{Sr}$ from all laboratories to an agreed value of this standard.) Nevertheless, even allowing for instrumental differences, there still appears to be a significant difference of about 0.002–0.003 between the Icelandic results and those from Skye and East Greenland.

This difference is in accord with the findings of previous workers^{11,2} that the $^{87}\text{Sr}/^{86}\text{Sr}$ values for oceanic basalts are, on the whole, slightly lower and less variable than those of continental basalts. Hedge and Waltham² report an average of 0.703 for oceanic basalts, while two Recent basalts from Iceland measured by them gave an average of 0.7025. The values for continental basic volcanic rocks appear to lie in the range 0.702–0.710^{1,2}.

It was mentioned above that the high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7089 ± 0.0010 for the Breiddalur basalt, P.673, might be due to some superficial process such as leaching and isotopic exchange. Nevertheless, the possibility must be kept in mind that this is a true, primary ratio, indicating local inhomogeneities in the Rb/Sr ratio of the basaltic source regions. More work is in progress on this problem. It is of interest to note that Faure and Hurley¹ reported a single $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7101 ± 0.0004 for a Recent olivine basalt of unspecified locality from Iceland. Those authors have recently revised all their originally published $^{87}\text{Sr}/^{86}\text{Sr}$ values downwards by about 0.003, but in either case the quoted value is close to that of the Breiddalur Tertiary basalt. Clearly, the suspicion is justified that not all the basic rocks of Iceland have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios as low as 0.702–0.703.

It is important not to carry the analogy between the acid igneous rocks of Iceland and of the Tertiary igneous centres of north-west Scotland too far. While there may be some general similarities in field relationships and mode of occurrence, the ultimate origin of the granitic material may be quite different in the two cases. This emerges already from recent investigations of the feldspars in certain volcanic acid liquids by Carmichael⁶, as well as from geochemical and trace element studies on natural acid glasses from the North Atlantic Tertiary province by the same author^{14,15}. Indeed, Carmichael¹⁴ considers that "the acid magma available for eruption in Iceland, as represented by the pitchstones, shows little variation in composition throughout perhaps as much as 60 million years".

The general uniformity of the Icelandic strontium isotope results contrasts strongly with the results from two large Tertiary plutonic igneous centres in the Isle of Skye, north-west Scotland, where it has been shown¹¹ that the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of granitic and related rocks are significantly higher (about 0.713) than those of nearby basaltic rocks. This suggested that the granitic and related rocks were produced by partial melting of ancient Lewisian rocks (>1,600 million years) which form the underlying basement at no great depth in Skye. This interpretation was in agreement with conclusions drawn from other recent, totally independent, experimental lines of evidence^{6,11}.

There are clearly several ways in which granitic magma can be formed, even within a single volcanic province.

It is to be hoped that strontium isotope investigations, in addition to the more conventional geological, geochemical, petrological and mineralogical criteria, will provide a clue to the mode of origin in any particular case. We thank our colleagues for their advice. The work at Oxford forms part of the programme of age and isotope studies directed by Prof. L. R. Wager.

- ¹ Faure, G., and Hurley, P. M., *J. Petrol.*, **4**, 1 (1963).
- ² Hedge, C. E., and Walthall, F. G., *Science*, **140**, 1214 (1963).
- ³ Polge, A., in *Chemistry of the Earth's Crust*, Geol. Soc. Amer. Spec. Paper, **62**, 119 (1955).
- ⁴ Turekian, K. K., and Kulp, J. L., *Geochim. Cosmochim. Acta*, **10**, 245 (1956).
- ⁵ Horstman, E. L., *Geochim. Cosmochim. Acta*, **12**, 1 (1957).
- ⁶ Carmichael, I. S. E., *Quart. J. Geol. Soc. Lond.*, **119**, 95 (1963).
- ⁷ Walker, G. P. L., *Quart. J. Geol. Soc. Lond.*, **119**, 29 (1963).
- ⁸ Tyceevason, E., and Barth, M., *J. Geophys. Res.*, **66**, 1913 (1961).
- ⁹ Carrill, H. K., Hawkes, L., and Ledebor, J. A., *Quart. J. Geol. Soc. Lond.*, **84**, 505 (1928).
- ¹⁰ Giletti, B. J., Moorbath, S., and Lambert, R. St. J., *Quart. J. Geol. Soc. Lond.*, **117**, 233 (1961).
- ¹¹ Moorbath, S., and Bell, J. D., *J. Petrol.*, **6**, 37 (1965).
- ¹² Hurley, P. M., Fairbairn, H. W., Pinson, W. H., and Hughes, H., *Twelfth Ann. Prog. Rep. M.I.T.-1351-12* (1964).
- ¹³ Wright, F. E., *Bull. Geol. Soc. Amer.*, **26**, 255 (1915).
- ¹⁴ Carmichael, I. S. E., *Geol. Mag.*, **94**, 253 (1962).
- ¹⁵ Carmichael, I. S. E., and McDonald, A., *Geochim. Cosmochim. Acta*, **25**, 189 (1961).
- ¹⁶ Hamilton, E. I., *J. Petrol.*, **4**, 383 (1963).
- ¹⁷ Brown, G. M., *Min. Mag.*, **33**, 533 (1963).
- ¹⁸ Walker, G. P. L., *Quart. J. Geol. Soc. Lond.*, **114**, 367 (1959).