Geophys. J. R. astr. Soc. (1980) **60**, 37–52

$^{40}Ar/^{39}Ar$ dates of eastern Iceland lavas

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Received 1979 May 8; in original form 1978 April 24

Summary. Twenty-two plateau ages obtained by the $^{40}Ar/^{39}Ar$ step-heating method span most of the time of formation of eastern Iceland. With one exception the dates are consistent with the stratigraphy, the exception having a very unusual argon release pattern. It is concluded that the $^{40}Ar/^{39}Ar$ step-heating method can give correct dates on hydrothermally altered samples the total fusion ages of which are not correct; however, it is not possible to conclude from the results obtained that the method is inherently more accurate than the conventional method using carefully selected samples.

Though it is known from geological evidence that minor irregularities of spreading have occurred the results show that, within the resolution of the dates, spreading has been steady and symmetrical; in particular, neither a large eastward jump nor repetitive westward jumps can have occurred. The average half spreading rate for the period 2 Myr to 12 Myr ago was 0.78 ± 0.16 cm yr^{-1}.

1 Introduction

The purpose of the work described in this paper was two-fold: to establish empirically the validity of the $^{40}Ar/^{39}Ar$ step-heating method of dating on basaltic lavas, and then to use it to investigate the chronology of the eastern Iceland lava pile.

Prior to the inception of this work K–Ar dating had established that the oldest exposed rocks in the area are *c.* 12.5 Myr old, and that generally ages were less, the nearer the lava to the present active zone. However, there were considerable inconsistencies between determinations on rocks of substantially the same age and even on the same sample (see Palmason & Saemundsson 1974, for a summary).

Because of these inconsistencies it was thought that the $^{40}Ar/^{39}Ar$ step-heating method might produce better results, but as this method itself was not proven for basaltic lavas which have suffered hydrothermal alteration it was decided to test the dates by stratigraphic consistency.

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A preliminary account of this work has been published (Ross & Mussett 1976); this paper differs in giving a fuller account, especially of the analytic method, and in containing more and better data.

2 Geology

The particular interest of Iceland arises because it is part of the Mid-Atlantic Ridge, and being above water is more accessible to observation. However, since it is anomalous in being subaerial rather than submarine, the mode of spreading may be atypical as well (Palmason & Saemundsson 1974; Walker 1975). Radiometric dating can clearly be used to test possible spreading patterns.

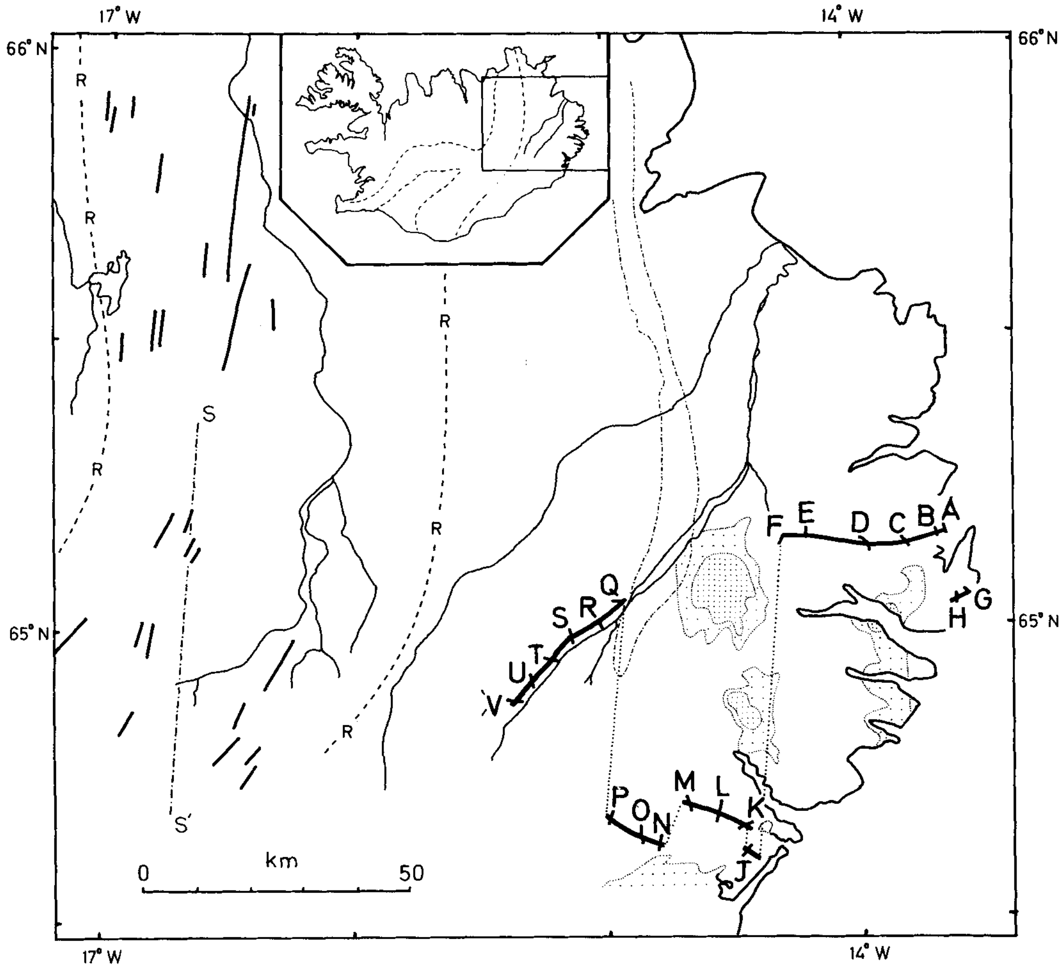

Figure 1. Map of eastern Iceland. The larger letters show the locations of sections sampled by Dagley *et al.* (1967), from whose collection the dating samples were taken. The line SS′ approximates the centre of the present active zone and is used for calculating spreading rates. The dashed lines ---R--- denote the limits of the present active zone and the heavy lines within this zone signify post-glacial fissure eruptions. The line ·—·—·— encloses a flexure zone, a region of anomalously high westward dips. The closely dotted areas show the cores of the Tertiary eruptive centres, and the less closely dotted areas show associated alteration.

Fig. 1 shows the position of the present neovolcanic fissure zone and the location of the lava sections dated in the present study. The lavas in eastern Iceland form a thick pile of subaerial flows which dip at between 2° and 12° to the west, towards and beneath the present neovolcanic zone. It is clear from the work of Walker (1959, 1960, 1964, 1974) that eruptions from this zone were essentially continuous during the last 13 Myr, producing this thick lava pile. However, the eruption of lavas along the length of the zone at any particular time was probably not uniform. During the Quaternary, eruptions have been strongly localized and such eruptive centres are regions of intense hydrothermal activity; the presence of local swarms of dykes cutting the older lavas indicates that this concentration of eruptive activity is not just a recent feature. The dyke swarms clearly define older eruptive centres which are also regions of intense hydrothermal alteration.

Stratigraphic sampling was concentrated along latitude 65° N, but to avoid areas of intense alteration, the central portion of the stratigraphic traverse (section J–P) was sampled some 50 km to the south. Key stratigraphic marker horizons were used to link the various sections and detailed descriptions of these can be found in Watkins & Walker (1977).

3 Analytical technique

3.1 METHOD

The samples used had been collected for palaeomagnetic measurements (Dagley *et al.*, 1967). Cores 2.5 cm in diameter and *c.* 7 cm long were drilled *in situ*; from these, solid samples 1–2 cm^3 in volume and weighing 3–6 g, were cut for dating. All the lava samples have been buried to some depth and as a consequence experienced deuteric alteration, including zeolitization (Wood & Gibson 1976). In general, alteration increases with depth of burial but there is local variation and the least altered were selected after thin-section examination; in particular, amygdales were avoided as far as possible.

The essence of the $^{40}Ar/^{39}Ar$ method is to convert ^{39}K, the common isotope of potassium, to ^{39}Ar by fast-neutron irradiation. Provided the proportion converted is known, a measurement of the $^{40}Ar/^{39}Ar$ ratio is equivalent to $^{40}Ar/^{40}K$, the ratio used in 'conventional' K–Ar dating. Samples were irradiated in the Herald Reactor, Aldermaston, to a total integrated flux of between 1.2 and 1.8×10^{17} neutrons cm^{-2}, without shielding of thermal neutrons, over a period of a few hours. The flux was calibrated using 'standard' biotite samples which were alternated with samples along the length of the irradiation can. The standard used was the Bern biotite 4B, for which a mean age and standard deviation of 16.4 ± 0.2 Myr has been calculated from published data (Steiger 1964; Armstrong, Jäger & Eberhardt 1966; Armstrong 1969; for decay constants used see Table 1).

In the earliest irradiations the can was put near the centre of the core of the reactor where the flux gradient perpendicular to the can is small, but later (and not at first appreciated by us) irradiations took place at mid-face of one side where a large transverse gradient exists. This variation is not monitored by the standards which are distributed only along the length of the can, but it is known that the flux difference across samples could be 18 per cent. Once the problem was appreciated the effect was minimized by having the can rotated 180° about its axis at mid-irradiation and by taking care that standards and samples were co-linear. This has reduced errors due to transverse flux gradients to a fraction of a per cent, but in earlier samples it may have reached 4 per cent.

To correct for interfering reactions which produce ^{40}Ar and ^{39}Ar from potassium and calcium (Mitchell 1968; Brereton 1970, 1972) pure salts were irradiated. CaF_2 gave a $^{39}Ar/^{37}Ar$ ratio of $6.20 \pm 0.02 \times 10^{-4}$, and a $(296\ ^{36}Ar - ^{40}Ar)/^{37}Ar$ ratio of 0.0683 ± 0.0003. K_2SO_4 gave a $^{40}Ar/^{39}Ar$ ratio 0.0126. KCl was used but results were rejected because of the production of ^{36}Ar from the chlorine, as has been found by Berger & York (1970). This suggests that the presence of chlorine in rocks might interfere with the correction for air contamination which is based upon the amount of ^{36}Ar measured, and chlorine has been reported in Icelandic basalts (Sigvaldason & Oskarsson 1976). However, no attempt has been made to assess this possibility.

As correction for interference is a somewhat complicated procedure independent checks are desirable. These were carried out in two ways: first by analysing a sample from the 1973 eruption of Vestmannaeyjar volcano, Iceland. The gas was released in four temperature steps; corrections were small except for the last step which changed an uncorrected age from -0.94 Myr to 0.06 ± 0.06 Myr. Although correction on one step produced a small positive age (possibly due to small amounts of hydrocarbons, probably from the sample, which were observed during this run) the mean and standard deviation of the summed steps was 0.10 ± 0.13 Myr. The second way was to observe the consistency of the apparent ages before and after correction but this is complicated by other effects, as will be discussed in Section 3.3. However, in general, correction improved the agreement of the step ages.

3.2 ERRORS

All analyses were carried out using an A.E.I. MS10 mass spectrometer with the 0.18 tesla (small) magnet, connected to a conventional argon extraction system (Purdy *et al.* 1972). Sensitivity is *c.* 58 μA torr^{-1}. Peak heights of the argon isotopes were recorded by a chart recorder and no systematic change of peak height was observed during a scan, while tailing of one peak into adjacent ones was negligible under the conditions of the analyses. Linearity of the recording system was better than ½ per cent.

The measured atmospheric ratio varied from 284 to 292 during the course of the measurements, but changed only slowly and semisystematically so that the error in the mass discrimination is estimated at 0.3 per cent.

Errors in peak heights (amounts) of the various isotopes were significant only for mass-36, the effect upon the date depending upon the fraction of the argon which was atmospheric, which ranged from 45 to 90 per cent for the steps used to determine the dates. This was the chief source of (random) error in the dates and the chief reason why the errors vary.

Errors in the correction for interference by potassium-derived isotopes are negligible since even a doubling of the correction factor would change the date by only 0.5 per cent, given the isotope ratios observed in the samples. Errors in correction for calcium-derived isotopes are negligible for all but the highest temperature steps since, except for these, corrections do not exceed 10 per cent. For the highest temperature step the correction can be as large as 80 per cent (of the mean value of the corrected steps), but even so the resulting error is only *c.* 0.5 per cent.

The irradiation at the samples could be interpolated to ± 2 per cent along the length of the can.

The age of the standard has been computed at 16.4 ± 0.2 Myr so that systematic error from this source is unlikely to exceed 1.2 per cent (this does not include uncertainties in the decay constants of ^{40}K, used to determine the value of 16.4 Myr).

3.3 INTERPRETATION OF STEP AGES

Dates were computed for the gas released during each heating step of a sample. In general they were not the same and the problem arises of how to interpret them.

Little is known definitely about how argon is released at different temperatures but probably several mechanisms are involved (Mussett 1969). In practice, it is assumed that gas from different sources is retained in sites of different energy and so will be released at different temperatures. Such sites probably are not different positions within a single crystal lattice because of the difficulty of removing atoms from a loose site past those trapped in tight ones, but instead they may be due to surface adsorption, crystal imperfections of various kinds or be due to the presence of different minerals.

Fitch, Miller & Mitchell (1969) have described release patterns that might be expected in different circumstances and have supported their arguments by measurements on artificial samples, but it is not known if they hold for natural samples.

Interpretation is made more complex by effects arising from the irradiation itself. Turner & Cadogan (1974) have evidence that the recoil energy of formation of a ^{39}Ar atom may displace it a considerable distance, even outside its parent lattice, so that the temperature release pattern of such atoms will differ from the radiogenic argon in the crystal. The effect will depend upon the grain sizes present but often will produce low apparent ages at high temperature and vice versa.

Dalrymple & Lanphere (1974) have suggested that lighter isotopes may be released preferentially by diffusion; as the effect will be most marked for small released amounts, they advised against accepting apparent ages involving less than 2 per cent of the ^{39}Ar released. It is also known that irradiation can damage the lattice, changing the release pattern (Mussett 1969); this is probably the cause of loss of ^{39}Ar and ^{40}Ar from a few samples at room temperature even after the usual overnight bake-out of the system following the loading of a sample.

Because of these complications and uncertainties theory needs to be backed by empirical testing. The test used was whether a plateau age – several steps having the same apparent age – is the true age of the sample, checked by self- and stratigraphic consistency.

A fully objective definition of a plateau age cannot be formulated but to avoid basing a plateau upon a short section of what is really a curve, or, by contrast, upon a few large steps which may have averaged out variations, the following criteria were adopted: a plateau must have at least four consecutive steps none of which differ from the mean plateau age by more than their standard deviation, and must comprise at least half of the ^{39}Ar released. There remains the possibility that when errors of individual steps are large genuine variations will not be detected (see problem of sample K9 in Section 4.1).

The error of the plateau age was computed from the component steps in two ways. The first weighted the step ages according to the inverse of their variances. As it can be objected that small steps should not have as much weight as large ones a second method weighted steps by their amounts of ^{39}Ar. In practice there was little difference between the two results (as reported in Ross & Mussett 1976) so the first method, being the one in general use, is used hereafter. The agreement of the two methods suggests they are not independent, perhaps because small steps have large measuring errors associated with them.

4 Results

4.1 STEP-HEATING DATA

Thirty-three samples were irradiated. Of these, 22 gave plateaux as defined previously, six failed to give plateaux, while the remaining five were rejected because less than four steps were obtained, for various technical reasons. The results are given in Table 1.

Among samples that yielded plateaux deviations were usually confined to first and last steps. First steps more commonly gave high rather than low ages (e.g. Fig. 2(a)), but among those that were low (e.g. Fig. 2(b)) were some that were negative; as the amounts of gas

Table 1. Step-heating data.

Sample	Alteration no.*	Plateau data			Isochrons		Total fusion age	Other dates on section
Section, lava core, cylinder		No. of steps	% ^{39}Ar in plateau	Plateau age (Myr)	Age (Myr)	Intercept		
1	2	3	4	5	6	7	8	9
G21-1a	2	5	70†	12.92 ± 0.14	12.36 ± 2.21	348 ± 187		12.5 ± 0.2[1]
G21-1a	2	4	80†	13.19 ± 0.10	13.07 ± 0.60	297 ± 3		
H								14.5 ± 3.9[5], 18.1 ± 4.5[5]
B19-1a	3	6	95†	11.98 ± 0.78	12.94 ± 1.28	283 ± 9		11.46 ± 0.24[2]
B19-1a	3	4	60†	12.10 ± 0.71	14.68 ± 2.01	282 ± 8		
C60-3a	–	5	99	12.30 ± 0.48	12.36 ± 0.27	292 ± 1	11.47 ± 0.25	5 dates 10.81–11.81[3]
D								11.9 ± 0.3[1] 10.26 ± 0.10[3], 11.07 ± 0.16[3]
E14-2a	2–	6	85†	9.52 ± 0.56	10.52 ± 1.01	286 ± 6		8.95 ± 0.14[2], 9.36 ± 0.16[2] 9.64 ± 0.10
F46-2a	–	No plateau obtained			N.a.		21.04 ± 0.51	9 dates 8.40–9.73[3]
J1-2a	–	4	85	10.30 ± 1.00	10.90 ± 0.28	290 ± 1		
K9-1	3+	5	79	12.04 ± 0.84	12.15 ± 0.79	295 ± 1	39.8 ± 4.8	10.07 ± 0.20[2]
K36A-1a	2	5	87	10.18 ± 0.22	9.90 ± 0.70	300 ± 13	10.62 ± 0.43	
K36A-2a	2	5	91	10.11 ± 0.27	10.38 ± 0.48	290 ± 8	10.39 ± 0.35	
	2	6	100	9.39 ± 0.54	9.52 ± 0.35	294 ± 2	9.45 ± 0.51	

L33C-1a	–	5	92	8.19 ± 0.72	8.83 ± 0.77	281 ± 10	8.62 ± 0.52	9.5 ± 0.6[1]
M								22 ± 12[5]
N1-1a	3+	4	60	7.83 ± 0.11	7.83 ± 0.34	296 ± 5	} 6.25 ± 0.90	13.26 ± 0.21[2]
N20-2a	3	9	99	6.48 ± 0.73	6.48 ± 0.46	296 ± 2	6.25 ± 0.90 }	
P14-1a	3+	5	80†	5.68 ± 0.17	4.72 ± 1.17	306 ± 12		
P29-2a	3–	No plateau obtained			N.a.		6.27 ± 0.48	
Q5-1a	2	No plateau obtained			N.a.		32.1 ± 4.3 }	{ 6.97 ± 0.13[2]
Q13-1a	3–	4	90	5.81 ± 0.16	5.62 ± 0.60	298 ± 6	6.14 ± 0.65 }	{ 10 samples 3.90–6.53[4]
R5-2a	2–	4	93	5.63 ± 0.06	5.68 ± 0.28	291 ± 12	5.43 ± 0.14	
R16-2a	2	4	77	5.26 ± 0.15	5.13 ± 0.47	299 ± 9	6.35 ± 0.37	
R20A-2a	2	5	82	4.33 ± 0.63	3.67 ± 0.66	305 ± 8	3.72 ± 0.79	
S19-1a	–	5	95†	4.38 ± 0.46	3.98 ± 0.12	297 ± 1		
T17A-2a	2	5	100	3.31 ± 0.72	3.91 ± 0.57	286 ± 5	3.14 ± 0.47	
V8-3a	2–	5	98	2.42 ± 0.12	2.52 ± 0.08	290 ± 5	2.48 ± 0.06	

* Following scheme of Mussett *et al.* (1973): samples assigned a number from 1 to 5 denoting increasing alteration.
† Estimated, as first step not measured.
[1] Moorbath *et al* (1968).
[2] Unpublished work of this Lab.
[3] McDougall *et al.* (1976b).
[4] McDougall *et al.* (1976c).
[5] Dagley *et al.* (1967).
Constants used: $^{40}K/K = 1.9 \times 10^{-4}$ (atom ratio); ^{40}K: $\lambda = 5.30 \times 10^{-11}\ yr^{-1}$; ^{40}K: $\lambda_e = 0.585 \times 10^{-11}\ yr^{-1}$; ^{37}Ar: $\lambda = 6.48\ yr^{-1}$.
If constants recommended by Steiger & Jäger (1977) are used ages should be increased by 2.7 per cent.

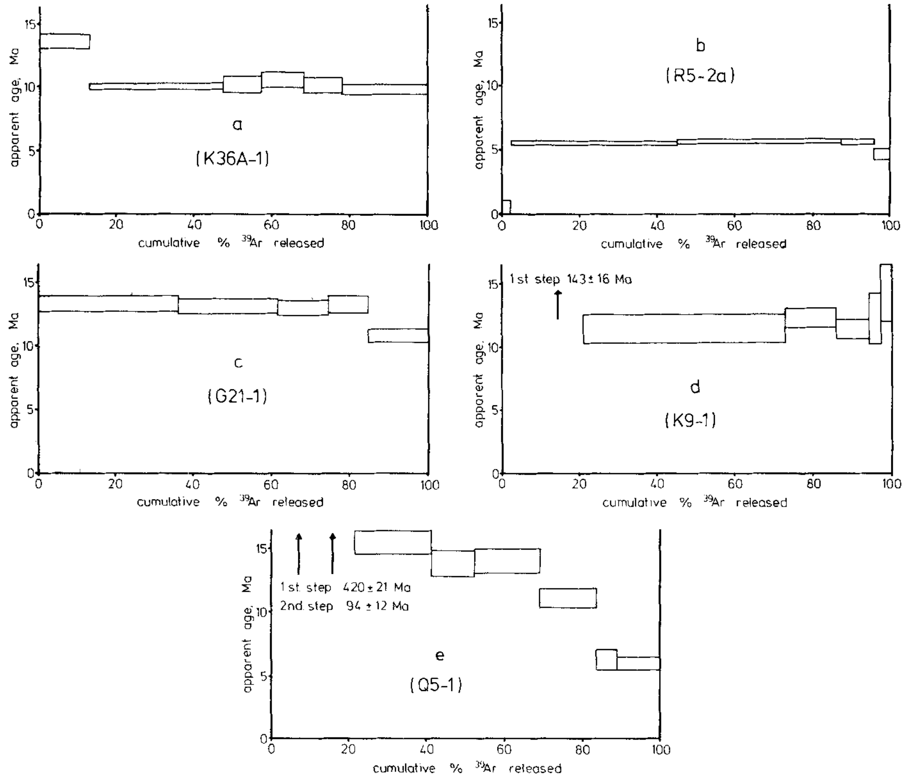

Figure 2. Selection of age spectra. The horizontal dimension of each rectangle denotes the relative amount of ^{39}Ar released in the step, and the vertical dimension the analytical error. For further details see text.

released were small isotopic enrichment as suggested by Dalrymple & Lanphere (1974) may be operating, and affecting the atmospheric correction.

Three samples (R5-2a and both samples of G21-1a) gave plateaux but had a low age for the final step (e.g. Fig. 2(b), (c)). One possible cause is recoil of some ^{39}Ar atoms into sites with a lower release temperature, and one way in which this can occur is recoil into an adjacent grain of different composition. If this were the case, the three samples should be finer grained than the rest, but this is not observed. However, as the recoil effect can also operate by inhomogeneities within a grain it cannot be ruled out, though in the case of R5-2a there was no evidence of a compensatory higher age at low temperatures (Fig. 2(b)).

One sample, K9, behaved differently from all the others (Fig. 2(d)). Though it yielded a 4-step plateau comprising 77 per cent of the released ^{39}Ar the age is clearly too large for its stratigraphic position (Table 2). The sample was unusual in having a final step of higher age than the plateau, unlike other samples that deviated in the last step, but the most remarkable feature was a first step of 143 Myr, and comprising 21 per cent of released ^{39}Ar. A roughly U-shaped age spectrum has been found in other rocks and attributed to excess argon, but they have not yielded plateaux (Kaneoka 1974; Dalrymple, Grommé & White 1975); however, Pankhurst *et al.* (1973) found plateaux ages which were clearly high, so a U-shaped age spectrum is not fully diagnostic of excess argon. The result for K9 is disquieting for it shows that the plateau criteria are not sufficiently stringent, though in this particular case the very high initial age would arouse suspicion; also errors on the individual steps were high and it is possible that the plateau would disappear with increased precision.

All six samples that were rejected by the plateau criteria had high initial ages (relative to their stratigraphic position) followed by progressively lower ones (e.g. Fig. 2(e)).

It is implicit in the above results that the only non-radiogenic argon present is air argon, which can be corrected for using the amount of ^{36}Ar measured. This assumption can be checked to some extent by plotting a correlation diagram ('isochron plot') of $^{40}Ar/^{36}Ar$ versus $^{40}K/^{36}Ar$ in which the intercept gives the isotopic composition of contaminant argon and age is deduced from the slope (deduced from a least squares fit, with points weighted by the inverse of their variances). Results of isochron plots of the plateau steps are given in Table 1, columns 6 and 7. In seven cases the intercept differs by more than one standard deviation from the air ratio. Of these, two (C60, J1) differ by more than two standard deviations but in both cases the standard deviation is probably unrealistically small since it is based only upon the scatter of the points and takes no account of the errors of the points themselves. There is therefore no convincing evidence of contaminant argon with ratios differing from that of air. As the slope ages agree with the plateau ages within one standard deviation the latter values will be used in the rest of this paper.

A secondary advantage of the step-heating method is the reduction of contaminant argon, for this is preferentially released at the lowest, and to a lesser extent, the highest temperatures. In all cases there was a reduction but not a large one: on average the amount of atmospheric contamination was reduced by 12 per cent, with no apparent correlation with the percentage contamination.

The accuracy of a date does not seem to correlate with the degree of alteration as judged by the scale of Mussett *et al.* (1973) based upon feldspars, (though in this study there was only a small range of alteration). This agrees with earlier conclusions (Mussett *et al.* 1973).

4.2 REPLICATION AND STRATIGRAPHIC CONSISTENCY

As pointed out earlier, part of the object of this work was to test the validity of using plateau dates. This was done in two ways.

Replicate ages were determined for two samples from the same core in three cases (G21, B19, and K36A; Table 2), with a date on an additional core from Lava K36A. All agree at the 95 per cent confidence level (2σ).

A second test is to use stratigraphic consistency. Table 1 lists the dates in stratigraphic order, while Fig. 4a and b display them in related ways. It is seen that ages decrease monotonically with position in the column, as required (with the exception of K9, noted above).

Whether the departure from linearity is due to inaccuracies in the age or to irregularity in lava extrusion cannot be determined without precise knowledge of the ages of all the lavas *a priori*. For instance, we can make any of the following assumptions: that age increases linearly with distance from the present active zone either corrected or uncorrected for the shape of the lava pile (see Section 5), that the thickness of the pile increases uniformly with time, or that the rate of lava extrusion is uniform. In each case a line of regression can be calculated and the deviation of individual dates from the line measured. For any of these plots some ages lie a considerable distance from the line, suggesting that they are incorrect, but these apparently incorrect dates are not the same in the different plots. It is probable, of course, that in detail age does not vary linearly with any simple parameter of the lava pile.

It is interesting to compare the results of this paper with a recent investigation by McDougall *et al.* (1976a) using the conventional K–Ar method. They collected 17 carefully selected samples from sections C, D, E & F. Although they found a generally increasing age with depth in the stratigraphic column, clearly some dates are in error by up to several standard deviations and if a line of regression of age against position in the pile is calculated the standard deviation of the scatter of the dates from the line is *c.* 0.3 Myr, whereas the analytical errors are only *c.* 0.1 Myr. This inaccuracy is apparent only because of the high analytical precision; the precision of the present study is lower on the whole and so may conceal genuine inaccuracies.

Lava C60 was common to both studies and results were 12.3 ± 0.5 Myr (this study) and 11.5 ± 0.1 Myr (McDougall, Watkins & Kristjansson 1976a) which therefore do not agree at the 1σ level.

From these considerations we conclude that the $^{40}Ar/^{39}Ar$ step-heating method gives plateau ages which are self-consistent and consistent with the stratigraphy. It is to be noted that these dates were made on material not primarily selected for dating and which, it is clear from Table 1, column 8, in many cases would have given incorrect results if a total fusion age had been used (as had been found in earlier investigations). Whether it is superior to conventional determination on carefully selected material cannot be determined at present, but the requirement of a plateau does seem to provide a useful test of reliability where stratigraphic checks are absent.

5 Interpretation of results

A major use for the dates given in this paper is to deduce spreading rates for Iceland, but to do this it is necessary to take into account the considerable extent of any lava. Fig. 3 shows an idealized cross-section of a spreading ridge. At the left lavas are extruded from a fissure and flow downhill away from it on both sides, thinning as they do so. At the right is shown the final section of the pile: some such shape is a necessary corollary to steady and continuous spreading, being the only way of accommodating indefinitely the succession of lavas. The transition from the left- to the right-hand profile takes place as a result of subsidence. Obviously individual lavas do not thin in such a regular way but may do so on average. Therefore it is convenient to refer to lava 'wedges' which are merely all the lavas formed within some interval long enough to include a representative selection of lavas, probably at least several hundred thousand years. In Fig. 3 the wedges all represent the same interval: their boundaries are therefore isochrons spaced equally in time, and in space too if spreading is uniform.

Because of the lateral extent of lavas it is not sufficient to plot age of a sample against its distance from the spreading ridge to deduce spreading rates; instead positions have to be corrected to a common reference height in the pile. Ross & Mussett (1976) did this by first assuming that on average lavas thin according to:

$$Z = Z_0 \exp(-Kx) \quad (1)$$

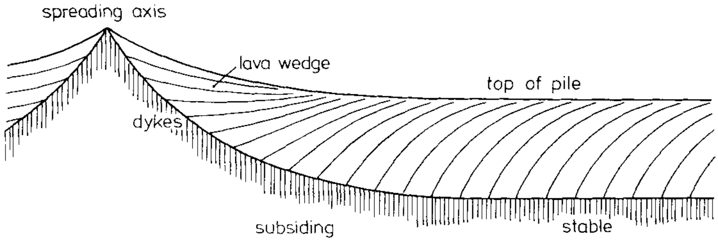

Figure 3. Idealized section of east Icelandic lava pile. Lavas are extruded downhill from fissures within the active zone and spread out to some limit. As spreading proceeds subsidence occurs burying the parts of lavas nearest the axis until finally the pile settles into the form at the right. Vertical scale exaggerated. Adapted from Palmason & Saemundsson (1974).

where x is measured perpendicularly to the spreading axis, Z_0 is the thickness of a lava at the spreading axis and Z is the thickness a distance x away. It follows that the profile of a lava wedge in the stable pile (Fig. 3, right) is:

$$d = d_0 \exp(-Kx) \tag{2}$$

where d_0 is the depth of the reference level below the surface of the pile. (This formula neglects that strictly x ought to be measured along the curve of the profile rather than horizontally.)

The justification for the use of these two equations is that they predict that larvas thin away from the spreading axis at constant proportional rate, and that the dip in a vertical section of the pile should decrease upwards at a regular rate. Both of these are observed and Ross & Mussett (1976) were able to deduce a value for K of about 0.1 km^{-1}. Near the surface of the pile the model breaks down for it assumes that the lavas taper to infinity. Though this implausibility is easily removed by truncating the lavas at some suitable average distance, great enough for their thickness to be small, it means that the corrections will be least reliable where they are largest.

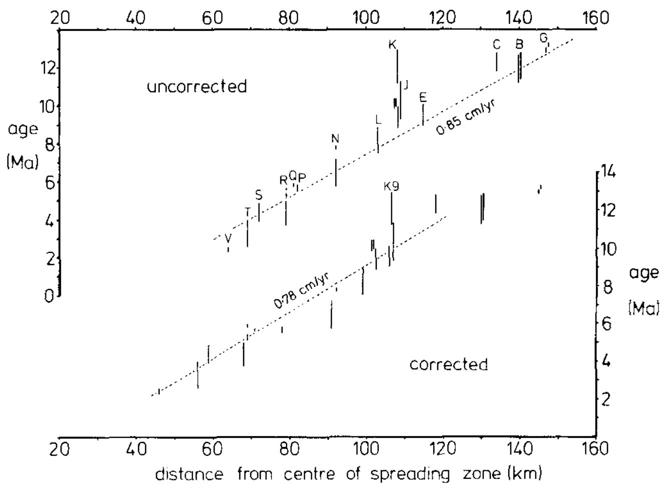

Figure 4. Spreading rates. (a) uncorrected plot of age versus distance from line S–S′ of Fig. 1. (b) similar plot but with distances corrected to a reference height of 1.7 km below inferred pile surface, assuming an exponential lava surface characterized by $K = 0.1$. For further details see text. The dashed lines are least-squares fits, weighted by the inverse of the variances in the ages only.

Before the correction is applied it is also necessary to correct for irregularities in the pile due to uneven uplift long after its formation. This is done by observing the zeolite zones within the pile, which are believed to be closely parallel to the original surface of the pile (Walker 1960). Since Ross & Mussett (1976) made their correction, improved data have been published (Wood & Gibson 1976) and have been used in this paper.

Fig. 4 shows both corrected and uncorrected age versus distance plots. Correction has a systematic effect because, in general, the younger lavas were sampled nearer the surface of the pile. It seems reasonable to fit a straight line to the data, apart from the easternmost sections B and G. The value of K used is not critical, except if the samples are very near to the top of the pile; with $K = 0.10\ km^{-1}$ the average spreading rate is $0.78 \pm 0.16\ cm\ yr^{-1}$.

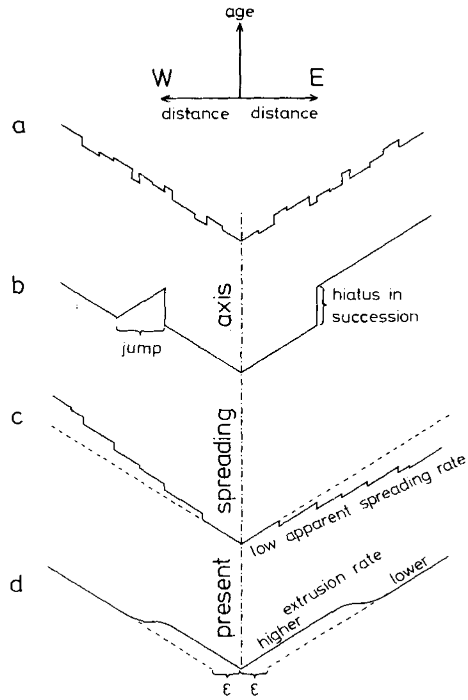

Figure 5. Some variations in spreading. (a) small random jumps of spreading axis, (b) single large eastwards jump of axis, (c) small westward jumps of axis, producing low apparent spreading rate on east side, high on west, (d) constant spreading rate but with change in the rate of extrusion.

5.1 ACTIVE ZONE OF FINITE WIDTH

We shall next consider some variants of the above model. The first is that the spreading axis jumps randomly back and forth within an active zone, such as the rift zone that exists in Iceland.

Obviously the apparent spreading rate measured between a remote point and the axis will vary discontinuously every time the axis jumps, so that the age versus distance plot will have steps, either upwards or downwards, on it (Fig. 5(a)). However, one can still define an average rate of spreading, provided a sufficiently long interval is used. In addition to evidence that at present the spreading axis moves about within an active zone, the bunching of dykes in older sections indicates that jumping occurred in the past (Walker 1964), with bunchings up to 10 km apart, which is equivalent to roughly a million years. Such jumps may account for the irregularities in Fig. 4 but the resolution is not sufficient to be sure.

Presumably only the spreading axis jumps, while the plates move steadily. In principle, this could be checked by measuring the spreading rate between two points one either side of the spreading ridge, but the data available are not adequate to test this.

5.2 ASYMMETRIC MOVEMENT OF THE SPREADING ZONE

This can take place in several ways: as a single large jump, as a succession of small jumps always in the same sense, or as a backward and forward jumping as before, but with overall migration in one direction. All of these will affect the age versus distance plot.

In 1971 Ward postulated a large eastward displacement of the spreading axis, with the resulting hiatus (see Fig. 5(b)) in eastern Iceland being predicted to be between 4 and 8 Myr (Saemundsson 1974) or 3 and 7 Myr (Wilson & McElhinny 1974), the discontinuity probably lying between sections P and Q. Fig. 4 clearly rules out such a large gap, nor did McDougall *et al.* (1976b) find a gap in western Iceland during the period 2 to 7 Myr ago.

Walker (1975) proposed the existence of several dormant and extinct zones in addition to the present active zone. Of these proposed zones, some were to the east of the present active zone, implying a westward migration of the spreading axis. If the jumps were small and frequent enough the resulting steps might not be discernible in Fig. 4, but should also produce an asymmetry of spreading (Fig. 5(c)). McDougall *et al.* (1976a) found a spreading rate, for the interval 2 to 7 Myr ago, of 0.8 cm yr^{-1}, which is not significantly different from the value deduced from this study (0.78 ± 0.16 cm yr^{-1}). Moreover, Johnson *et al.* (1972) found rates of 0.82 and 0.77 for the eastern and western sides of the Kolbeinsey Ridge to the north of Iceland, and though they indicate some asymmetry of spreading it is small. The rate for Reykjanes Ridge to the south is less well determined at 0.94 cm yr^{-1} (Talwini, Windisch & Langseth 1971).

A second part of Walker's argument, that the spreading rate is several times that of the adjacent submerged ridge and of northern Iceland, poses problems of accommodating the resultant wedging action, as has been pointed out by Searle (1976).

Thus it seems there is little support for asymmetric spreading, though asymmetry within the errors cannot be ruled out.

5.3 VARIABLE RATE OF EXTRUSION

In this case it is assumed that the spreading rate remains constant but the volume or thickness of lavas extruded in a given time changes. Fig. 6 illustrates an increase from low to high rate. Palmason (1977) has produced a model in which dyke intrusion and lava deposition around the spreading axis each follow Gaussian distributions, with different standard deviations. He has pointed out that the dip at a given depth in the lava pile depends only slightly on the lava production rate. This 'self-compensation' effect will be investigated for the model used in this paper, which is similar to Palmason's except close to the spreading axis; this is because a Gaussian distribution tends to an exponential away from its axis of symmetry.

If we assume that the lavas, on average, thin at the same rate regardless of the extrusion rate then K in equation (1) will be the same throughout, but if we take Z_0 to be the thickness of a lava wedge at its thicker or lower end clearly Z_0 will be less when the extrusion

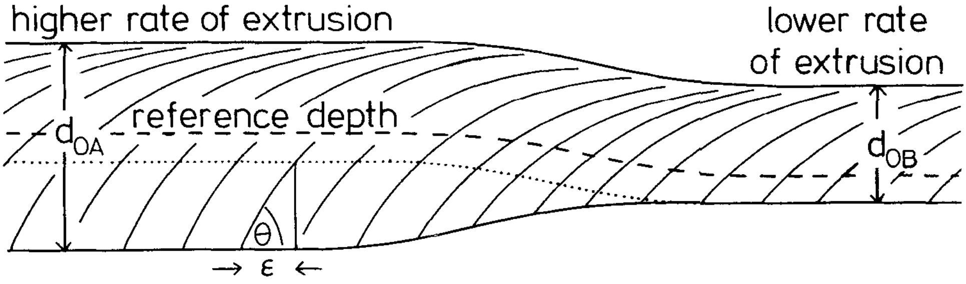

Figure 6. Change in extrusion rate. A change in the volume of lavas extruded in unit time changes the thickness of the pile but does not affect the cross-section of the upper parts of the pile. ϵ is the error in correcting positions of lavas to a constant depth in the pile rather than to the base of the lavas.

rate is less. As before, the profiles of the wedges will be characterized by:

$$d_A = d_{AO} \exp(-Kx), \qquad d_B = d_{BO} \exp(-Kx). \tag{3}$$

This shows that the wedges have to be stacked more steeply when they are thicker, i.e. angle θ in Fig. 6 is larger, but, viewed or sectioned down from the top, the piles will appear identical; the only difference is that, measured from the top, the lavas will extend to greater depths where the pile is thicker. Thus detecting changes in the rate of extrusion is impossible unless the depth to the base of the pile can be found, which requires techniques beyond the scope of this paper.

The effect upon the apparent spreading rate will be less extreme. To obtain correct spreading rates, positions should be referred to the base of the pile or to a level parallel to it, rather than one parallel to the surface. The error introduced by using a fixed depth below the top of the pile will be ϵ in Figs 5(d) and 6; ϵ can be determined from the equation

$$d_{OA} = d_{OB} \exp(-K\epsilon). \tag{4}$$

Even if $d_{OA}/d_{OB} = 2$, ϵ is only 7 km, which represents about 1 Myr and therefore the effect of variable extrusion rate upon the apparent spreading rate is not detectable with the data available. Of course, this assumes that the rate of thinning lavas, defined by the parameter K, is not affected by the rate of extrusion, an assumption that may not be true since, for instance, the composition of the lavas might be different when the extrusion rate is low.

5.4 POSITION OF SPREADING AXIS

The intercept of Fig. 4(b) does not coincide with the line taken as the present spreading axis, but is about 25 km to its east. This difference is not considered a significant failure of the model because of several factors that could introduce errors. The corrections used to derive Fig. 4(b) from Fig. 4(a) depend upon the shape chosen for the lava profile, which can be defined only approximately; in addition, if corrections had been referred to the base of the lava pile – the most physically meaningful reference height – all points on Fig. 4(b) would be displaced a few km to the left. Other errors depend upon the detailed mechanism of spreading. The model assumes spreading from a line, with the thickness of extruded lava decreasing exponentially with distance from the line; clearly, this is over-simplified and Palmason (1977), assuming a Gaussian distribution, deduces that the lava accretion zone has a standard deviation width of 15–20 km. Even this does not take into account probable displacements of the spreading axis, nor that the line SS′ on Fig. 1 may be a poor approximation to the present spreading axis, since a single line had to be chosen to suit all the lava sections dated.

6 Conclusions

It is clear that (with the exception of the doubts surrounding sample K9) the $^{40}Ar/^{39}Ar$ step-heating method can provide useful dates, when the samples would give erroneous values using total fusion methods. The use of age plateaux provides a semi-objective criterion of reliability independent of stratigraphic or other external evidence. With the evidence available it is not possible to tell if the method has an *accuracy* superior to that of the conventional method using carefully selected samples.

It is not possible to resolve the discontinuities of spreading which are known, from field evidence, to have occurred. Hiatuses as large as 1 Myr may possibly exist though they are likely to be smaller, but the postulated large westward jump (Ward 1971; Wilson & McElhinny 1974) cannot be accommodated within the data. Nor is there any support for asymmetric spreading as suggested by Walker (1975), though a small degree of asymmetry could escape detection.

The dates presented in this paper are consistent with uniform spreading in the interval 2.5 to 11 Myr ago, when averaged over periods of 2 Myr or more. The corresponding spreading rate has a minimum value of $0.78 \pm 0.16\,cm\,yr^{-1}$ which is not significantly different from the value for western Iceland or adjacent parts of the ridge, so far as these are known. For the period 11–13 Myr ago the rate may have been considerably more.

Acknowledgments

The samples used for the paper belong to a larger collection originally made jointly between workers from the Universities of Iceland and Liverpool (see Dagley *et al.* 1967). We are indebted to the Icelandic Science Foundation, and to the British Natural Environment Research Council, for funding that collection.

We wish to thank Mr R. Peacock for making some of the age determinations, Professor R. L. Wilson for suggesting the project and Dr J. Purdy for initiating it, Dr G. Palmason for an abstract of his 1977 paper, and NERC for the cost of the neutron irradiations.

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