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6. ^{39}Ar-^{40}Ar ANALYSIS ON BASALTIC LAVA SERIES OF VAVILOV BASIN, TYRRHENIAN SEA (OCEAN DRILLING PROGRAM, LEG 107, HOLES 655B AND 651A)[1]

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ABSTRACT

Six whole rocks from the basaltic lava series drilled in the Vavilov basin have been analyzed by ^{39}Ar-^{40}Ar stepwise heating method. One sample from the upper part of the Hole 655B basement gave a plateau-age at 4.3 ± 0.3 Ma whereas the other ones showed disturbed age spectra caused by alteration processes. The weighted averages of ages measured at low and intermediate temperatures on these five samples are concordant (1) one to each other and (2) with independent estimates deduced from paleontological and paleomagnetical arguments. Ages of 4.3 ± 0.3 Ma and from 3 to 2.6 Ma may represent reasonable estimates of the crystallization ages of the basaltic lava series of the Holes 655B and 651A, respectively. These ages must be taken with caution because they correspond to argon released from secondary phases characterized by low argon retention.

INTRODUCTION

The Tyrrhenian sea is interpreted as a back-arc basin developing behind an active subduction zone. The central area is subdivided into two basins, the Vavilov and Marsili basins which are floored with basaltic crust. Paleontological, paleomagnetical, and geochronological arguments suggest that the Marsili Basin is younger than the Vavilov Basin and therefore that the Tyrrhenian Sea has grown southeastward toward the subduction zone (Kastens et al, 1988; Mascle et al, 1988). One of the goals of Leg 107 (Ocean Drilling Program) was to determine more precisely the age of this basaltic crust. A previous geochronological study (by the conventional K-Ar method) of basaltic lavas drilled by Site 373 (Leg 42) of the Deep Sea Drilling Project gave ages trending from 7.5 to 3 Ma (Barberi et al, 1978; Kreuzer et al, 1978; Savelli et al, 1978). We performed ^{39}Ar-^{40}Ar stepwise heating analysis on basaltic lava series drilled on the Holes 651A and 655B located in the Vavilov basin. The approximate location of the dated samples in the series is indicated on Figure 1.

Hole 651A is located on the eastern flank of a north-south oriented basement swell which crosses the Vavilov Basin. The basement is covered by Pliocene-Pleistocene sediments and has been drilled through 134 m. From the top to the bottom, it consists of 4 units: (1) 78 m of a basaltic series, (2) 28 m of a thick assemblage of dolerite, metasediment, and metadolerite, (3) 30 m of basalt and basaltic breccia, and (4) 30 m of serpentinized peridotite (Kastens et al, 1988). Calcareous ooze and calcareous claystone located immediately above the oldest sedimentary unit have been biostratigraphically and paleomagnetically dated (1.67–2.1 Ma) (Kastens et al, 1988). An age of 2.2–3 Ma has been suggested from nannofossils found in sedimentary cracks (R. Sprovieri, pers. comm. in Sartori, this volume). We selected three basalts belonging to the units (1) (651A-046R-01, 075-080 and 651A-049R-01, 081-084), and (3) (651A-053R-02, 117-119) which are described in detail by Bertrand et al. (this volume). These samples are named D, E, and F, respectively, in the text.

Hole 655B is located on a narrow north-south oriented ridge near the assumed limit between continental and oceanic crust.

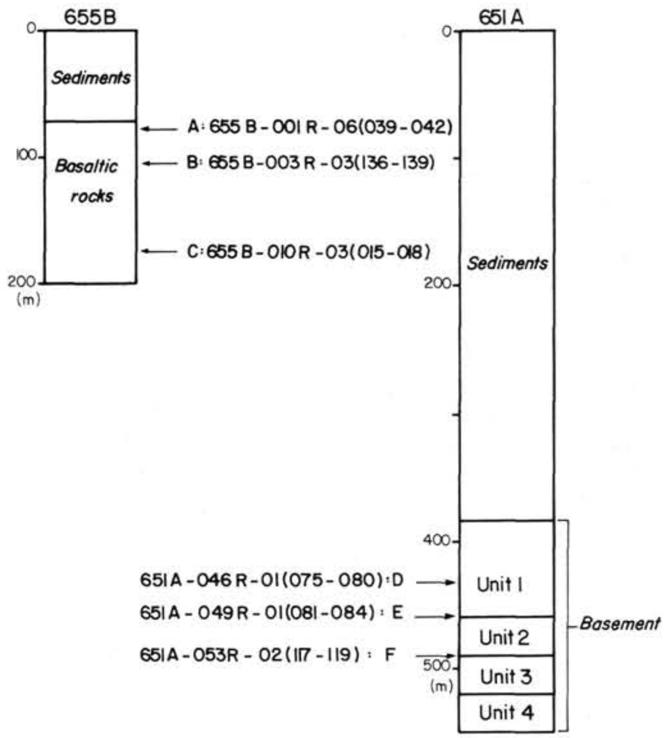

Figure 1. Location of the dated samples into the drilled series. The four units of the Hole 651A basement are described by Kastens et al. (1988).

The basement consists of 115 m of pillow-basalt flows described in detail by Bertrand et al. (this volume). They are covered by upper Pliocene sediments. Planktonic foraminifers (zone MPl-4; 3.1–3.6 Ma) and nannofossils (zone NN15; 3.5–3.6 Ma), within carbonate-cemented fractures in the basalt, and the observation that the basalt is entirely reversely magnetized, suggest that the age of the basalt is 3.4–3.6 Ma (Kastens et al, 1988). Three samples have been selected for dating, they are 655B-001R-06, 039-042, 655B-003R-03, 136-139, and 655B-010R-03, 015-018 from the top to the bottom of the series. These samples are named A, B, and C, respectively, in the text.

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RESULTS

In spite of a first selection made by the Leg 107 team, all the dated samples are strongly altered and do not correspond to the usual criteria of suitability for K-Ar whole rock dating. The main secondary phases are chlorite, serpentine, K-feldspar, clays, and calcite, and the glass is completely devitrified. Primary and secondary phases of these volcanics are given by Bertrand et al. (this volume).

The analytical procedure is described elsewhere (Féraud et al., 1982). The samples were irradiated in the Melusine reactor (Centre d'Etudes Nucléaires de Grenoble). The mass spectrometer is composed of a 120° MASSE tube and a Bauer-Signer source, working for these experiments on a Faraday cup. The weight of analyzed samples is between 2 and 2.5 g. We used the biotite 4B as a monitor with an age of 17.25 Ma. The results are given in Table 1 and the age spectra in Figures 2 and 3. The criteria we have used to define a plateau are: (1) the plateau of the age spectrum should include at least 70% of the ^{39}Ar released; (2) there should be at least three steps in the plateau, and (3) the individual fraction ages should agree within 2 σ limits with the "integrated age" (the weighting factor is the percentage in argon 39 released) of the plateau.

Hole 655B

For the three samples A, B, and C, most of the argon is released at low temperature: at least 64% of ^{39}Ar is released below 750°C. The only plateau-age (4.3 ± 0.3 Ma) is given by the sample A for the steps 550°–890° (corresponding to 77% of ^{39}Ar). The samples B and C gave disturbed age spectra with different trends. The sample B gave two ages near 5.5 Ma (steps 730°–810°C) which are sensibly discordant with more homogeneous results obtained at lower (650°C) and higher (from 890° to 1130°C) temperatures. For the steps 650°–1130°C, we obtained a weighted average of 4.4 ± 0.8 Ma for the whole steps and 4.0 ± 0.8 Ma if we exclude the two higher ages obtained at 730° and 810°C. The sample C gave an age spectrum nearly similar to the age spectra given by the sample A and characterized by a strong decrease of ages (as young as 2.0 Ma) at high temperature. The intermediate temperature steps (590°–950°) give a weighted average of 4.0 ± 0.2 Ma. These ages (and the integrated total ages of 4.3 ± 0.3 Ma (A), 4.1 ± 0.8 Ma (B), and 4.0 ± 0.1 Ma (C)), are concordant within the error bars.

Hole 651A

The three samples D, E, and F gave ages which are younger than for the Hole 655B. Their integrated ages, which are 2.10 ± 0.03 Ma, 2.15 ± 0.03 Ma, and 2.55 ± 0.03 Ma, respectively, are concordant with their relative location into the series. Nevertheless, these ages are not reliable because the age spectra are very disturbed without showing any plateau. We observe the same kind of age spectra for the samples A and C, with (1) a very strong decrease of ages (as young as 0.5 Ma) at high temperature, then a slight increase for the last steps, and (2) concordant mean ages (weighted average) calculated from the low and intermediate temperature steps. From the top to the bottom of the series, these weighted averages are 2.58 ± 0.07 Ma (sample D, steps 450°–810°, ^{39}Ar = 66%), 2.6 ± 0.1 (sample E, steps 430°–950°, ^{39}Ar = 65%), and 3.01 ± 0.09 Ma (sample F, steps 750°–1050°, ^{39}Ar = 40%).

DISCUSSION

The six analyzed samples from Holes 655B and 651A gave one plateau-age at 4.3 ± 0.3 Ma only, corresponding to 77% of ^{39}Ar released (sample A, Hole 655B). The other five samples gave disturbed age spectra which are in most cases characterized by (1) low temperature steps with weighted averages giving con-

Table 1. ^{39}Ar-^{40}Ar results of whole rock samples from Holes 655B and 651A. $^{40}Ar/^{39}Ar$ = radiogenic $^{40}Ar/^{39}Ar$ from K, $^{37}Ar/^{39}Ar$ = ^{37}Ar from Ca/^{39}Ar from K. The values are corrected for K- and Ca-derived Ar isotopes. The errors are quoted in 1 σ. We used the decay constants recommended by Steiger and Jäger (1977). The samples are named A, B, C, D, E, and F in the text.

Temperature (°C)	Atmospheric contamination (%)	^{39}Ar (%)	$^{37}Ar/^{39}AR$	$^{40}Ar/^{39}AR$	Apparent age (Ma)
655B-001R-06(039-042) (A)					
350	100.0	0	—	8.75	16 ± 69
450	98.4	11.31	2.20	2.47	4.7 ± 1.6
550	93.9	20.46	6.54	2.21	4.2 ± 0.4
650	75.9	24.42	25.93	2.23	4.3 ± 0.2
730	58.5	13.55	42.32	2.32	4.4 ± 0.2
810	65.7	11.94	38.31	2.46	4.7 ± 0.3
890	60.9	6.87	36.62	2.00	3.8 ± 0.5
970	80.5	2.38	30.94	1.49	2.9 ± 0.9
1050	77.4	2.98	38.50	1.61	3.1 ± 0.7
1130	88.7	2.46	177.66	1.22	2.3 ± 1.2
1250	92.3	2.14	556.11	1.72	3.3 ± 3.2
FUSE	98.4	1.55	490.11	5.21	9.9 ± 4.7
				Total age =	4.3 ± 0.2
655B-003R-03(136-139) (B)					
350	99.6	0	—	—	0 —
450	100.0	3.85	2.43	—	0 —
550	99.7	5.10	2.07	0.989	1.8 ± 3.4
650	97.1	44.15	6.24	2.16	4.0 ± 0.7
730	92.5	11.66	20.01	3.33	6.2 ± 0.4
810	86.2	6.77	16.57	3.06	5.7 ± 0.3
890	48.2	8.57	7.99	2.28	4.23 ± 0.09
970	37.9	5.04	5.45	2.14	4.0 ± 0.2
1050	33.0	8.34	5.59	2.09	3.88 ± 0.08
1250	74.3	1.71	222.4	2.35	4.3 ± 1.1
FUSE	91.4	0.83	304.9	3.06	5.7 ± 1.6
				Total age =	4.1 ± 0.4
655B-010R-03(015-018) (C)					
350	99.7	2.0	1.89	0.91	1.7 ± 2.9
450	92.9	4.16	1.61	3.10	5.9 ± 0.7
510	91.8	12.74	3.41	2.49	4.7 ± 0.4
590	76.9	18.27	7.49	1.88	3.6 ± 0.2
670	57.8	17.66	17.78	2.07	3.9 ± 0.1
750	55.7	17.95	34.43	2.18	4.2 ± 0.2
850	62.3	11.03	40.61	2.27	4.3 ± 0.3
950	65.3	5.45	34.87	2.31	4.4 ± 0.5
1050	79.6	4.12	28.05	1.07	2.0 ± 0.3
1150	82.9	2.58	78.11	1.48	2.8 ± 0.9
1250	89.8	1.79	342.8	1.69	3.2 ± 2.4
FUSE	83.8	2.24	362.6	2.98	5.7 ± 1.8
				Total age =	4.0 ± 0.1
651A-046R-01(075-080) (D)					
350	89.6	4.3	0.87	1.64	3.1 ± 0.3
450	88.2	7.8	1.35	1.28	2.4 ± 0.2
550	68.6	19.6	2.51	1.28	2.44 ± 0.06
650	39.3	20.4	4.99	1.38	2.63 ± 0.04
730	48.1	9.7	6.67	1.40	2.6 ± 0.06
810	47.9	8.5	6.57	1.48	2.81 ± 0.09
890	75.4	6.4	3.89	0.914	1.74 ± 0.07
970	81.3	8.4	2.04	0.457	0.87 ± 0.08
1050	77.7	8.2	2.10	0.279	0.53 ± 0.06
1130	100.0	1.2	4.04	—	0 ± —
1210	95.8	2.4	4.87	0.542	1.0 ± 0.4
1350	96.6	2.0	4.92	0.310	0.6 ± 0.6
FUSE	95.8	1.2	5.16	1.62	3.1 ± 0.8
				Total age =	2.14 ± 0.03
651A-049R-01(081-084) (E)					
350	100.0	0.4	0.244	—	0 ± —
430	97.9	3.2	0.286	1.06	2.0 ± 0.5
510	93.2	11.8	0.366	1.19	2.3 ± 0.2
590	84.3	13.4	0.663	1.55	2.9 ± 0.08
670	86.6	8.1	1.93	1.47	2.8 ± 0.1
750	81.8	9.5	3.18	1.35	2.58 ± 0.08
850	85.2	9.0	2.33	1.32	2.52 ± 0.08
950	86.4	10.0	1.18	1.32	2.51 ± 0.09

Table 1 (continued).

Temperature (°C)	Atmospheric contamination (%)	^{39}Ar (%)	$^{37}Ar/^{39}AR$	$^{40}Ar/^{39}AR$	Apparent age (Ma)
651A-049R-01(081-084) (E)					
1050	51.9	19.6	0.979	0.892	1.70 ± 0.02
1150	67.1	10.7	1.44	0.431	0.82 ± 0.02
1250	90.3	1.2	9.30	0.331	0.63 ± 0.09
FUSE	92.6	3.1	22.89	0.560	1.1 ± 0.1
				Total age =	2.15 ± 0.03
651A-053R-02(117-119) (F)					
350	94.0	0	—	—	0 ± —
450	99.5	.4	5.0	1.03	1.9 ± 1.03
550	100.0	1.9	—	—	0 ± —
650	95.1	6.9	1.29	1.21	2.3 ± 0.1
750	87.9	8.2	2.11	1.61	3.1 ± 0.1
850	83.9	11.1	3.57	1.59	3.04 ± 0.07
950	88.1	9.7	3.27	1.58	3.02 ± 0.09
1050	87.2	10.6	1.66	1.54	2.93 ± 0.07
1150	66.3	35.5	1.38	1.27	2.42 ± 0.02
1250	75.6	8.6	2.77	0.784	1.50 ± 0.03
FUSE	78.2	7.0	19.00	1.48	2.8 ± 0.1
				Total age =	2.55 ± 0.03

cordant ages in agreement with independent estimates of the age of the volcanic series and (2) strong decrease of ages at high temperatures (sample B excepted). This last phenomenon is frequently observed on submarine basalts (Ozima et al., 1977; Dalrymple and Clague, 1976; Saito and Ozima, 1977), but has never been clearly explained.

Hole 655B

The samples A and C have similar degassing trends of ^{39}Ar (corresponding to potassium sites) with a large peak of argon between 500° and 800°C, approximately, whereas the sample B shows a sharper ^{39}Ar release pattern near 650°C (Fig. 4). The age spectra (Fig. 2) shows such a similarity between A and C and a difference with B. This behavior may be correlated with the microscopic observation of the rocks: the samples A and C show abundant yellow secondary phases which may represent the alteration of glass (palagonite), whereas the sample C seems more crystallized (doleritic structure) with different alteration products. These secondary phases have generally high potassium content because (1) they are issued from late crystallized phases and (2) they may be affected by K enrichment from seawater during alteration.

These observations lead us to the following suggestions:

1. The low and intermediate temperature ages (approximately 550°-950°) given by the samples A (plateau at 4.3 ± 0.3 Ma) and C (no plateau, weighted average at 4.0 ± 0.2 Ma) correspond to K-rich secondary and late crystallized phases.

2. Because (a) these ages are concordant one to each other within error bars and (b) they are in reasonable agreement with ages (3.4-3.6 Ma) suggested by planktonic and nannofossils found into the lava series (Kastens et al., 1988), these ^{39}Ar-^{40}Ar ages may be close to crystallization ages of the lava flows.

3. In that case, we must admit that (a) most of the secondary phases of the samples A and C are formed immediately after crystallization and (b) the alteration which affected the rocks between the crystallization time and the present disturbs the K-Ar chronometer in relative low proportion only. Nevertheless, this later alteration may produce a loss of radiogenic ^{40}Ar, an enrichment of K as a result of exchange with seawater, or a ^{39}Ar loss during the irradiation. These phenomena would lead to a decreasing or an increasing of the measured ages, and we have no argument for choosing between these hypotheses. Note that the geochemistry analysis do not show a significant enrichment in potassium by alteration processes (Bertrand et al., this volume).

4. The weighted average of the ages given by the steps 650°-1130°C of the sample B, excluding the discordant results of the steps 730° and 810°C, is concordant with the previously mentioned ages of A and C and therefore may represent a value close to the crystallization age.

5. In conclusion, the age of 4.3 ± 0.3 Ma given by a low and intermediate temperature plateau of the sample A from the upper part of the lava series may represent a reasonable estimate of the cooling age of the rock. The age of the lower part of the lava series (up to Core 010R) may be included into this time period.

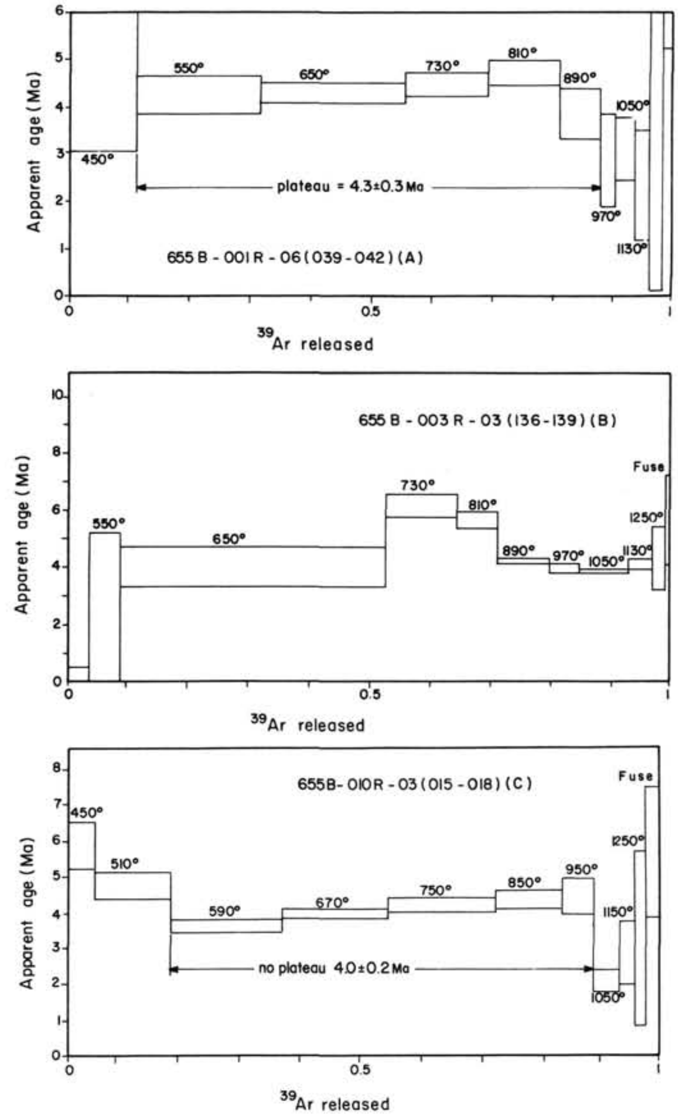

Figure 2. ^{39}Ar-^{40}Ar age spectra as a function of ^{39}Ar released on samples A, B, and C (see text for their complete name) from Hole 655B. The plateau age is calculated with 2 σ errors.

Hole 651A

The degassing trend of radiogenic ^{40}Ar of the sample D (Fig. 5) is about similar to the degassing trends of ^{39}Ar of the sample A and C (Fig. 4) whereas the ^{39}Ar released from the sample D shows clearly a degassing peak approximately between 900° and

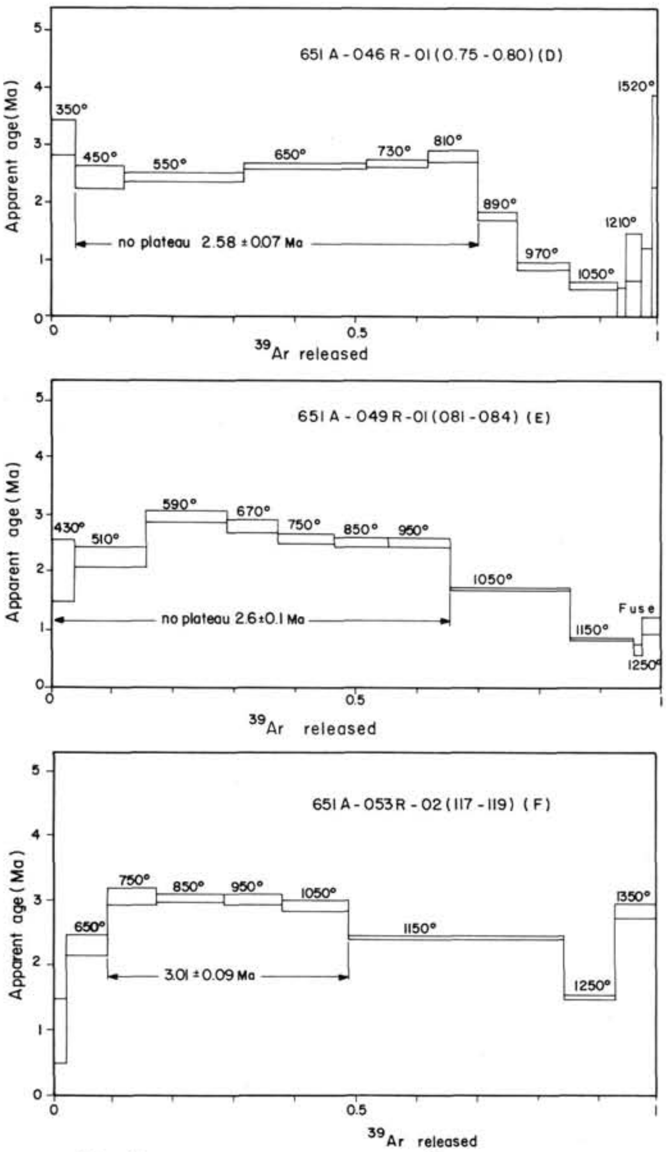

Figure 3. ^{39}Ar-^{40}Ar age spectra as a function of ^{39}Ar released of samples D, E, and F from Hole 651A.

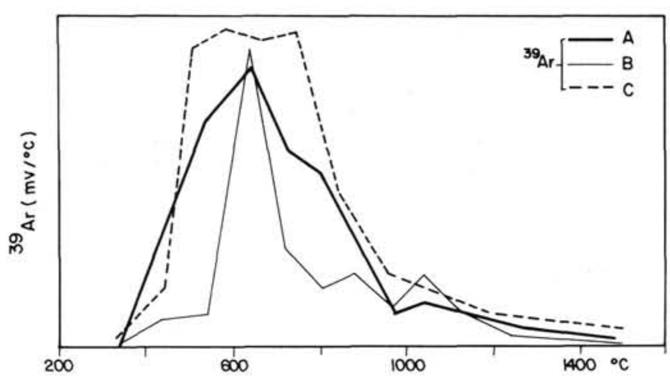

Figure 4. ^{39}Ar (from K) degassing trends vs. temperature for the samples A, B, and C from Hole 655B. On the ordinate is plotted the ^{39}Ar signal (from K) in millivolt per °C, and the scale may be different for the three samples.

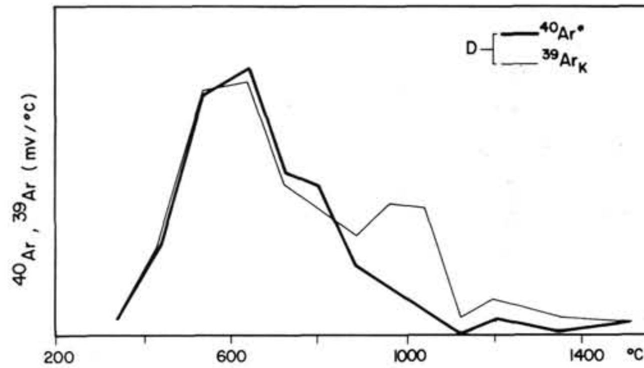

Figure 5. ^{39}Ar (from K) and radiogenic ^{40}Ar degassing trends vs. temperature for the sample D (Hole 651A). Same legend as Figure 4.

1100°C which does not exist for the radiogenic ^{40}Ar (Fig. 5). The phases released at this temperature domain may have been affected by (1) a radiogenic ^{40}Ar loss and/or (2) adding of potassium after cooling of the lava. Whatever the hypothesis chosen, these phenomena correspond to an alteration process happening markedly after cooling of the rock. The samples E and F also show a high temperature degassing peak of ^{39}Ar at about 1050° and 1150°C, respectively (see 39% on the table), but at the difference with the sample D, it corresponds to a significant amount of radiogenic ^{40}Ar released. In all cases this high temperature domain is characterized by a very disturbed age spectrum (Fig. 3).

Therefore we suggest the following conclusions.

1. The high temperature steps (starting at 890°, 1050°, and 1150° for the samples D, E, and F, respectively) correspond to the degassing of phases affected by alteration processes which happened between the crystallization time and the present, more or less continuously (probably mostly very recently for the sample D which does not show high temperature degassing of radiogenic ^{40}Ar corresponding to a ^{39}Ar degassing peak). These high temperature phases may correspond to alteration products in the plagioclases (zeolites and/or K-feldspars). These secondary minerals have been observed in plagioclases of several basalts of the Hole 651A (R. Bertrand and C. Mevel, pers. comm.).

2. The low and intermediate temperature steps do not give any plateau age. Although these domains correspond to a lower amount of ^{39}Ar released (maximum 65% of total ^{39}Ar released) than for the samples A, B, and C, the weighted averages of these ages are concordant (a) one to each other in the stratigraphic series and (b) with the ages suggested by paleontological evidences (this volume). Following the same arguments for the samples A, B, and C, we suggest that the low and intermediate temperature weighted averages of 2.58 ± 0.07 Ma, 2.6 ± 0.1 Ma, and 3.01 ± 0.09 Ma for the samples D, E (unit 1), and F (unit 3), respectively, may be close to crystallization ages. This age difference between the units 1 and 3 may be significant because these two units are characterized by distinct chemical features (Bertrand et al., this volume).

3. As for the samples from Hole 655B, these ages are from secondary and late crystallized phases and are probably affected by argon loss (^{40}Ar and/or ^{39}Ar) and/or potassium addition from seawater during alteration processes. Although the geochemistry does not show evidence of secondary enrichment in potassium (Bertrand et al., this volume), we are unable to estimate the importance of the eventual disturbances on the K-Ar chronometer.

CONCLUSIONS

The six analyzed samples are affected by strong alteration phenomena and do not satisfy the usual criteria of suitability for K-Ar dating.

Nevertheless, the results show one plateau-age at 4.3 ± 0.3 Ma (sample A, Hole 655B) and low and intermediate temperature ages with weighted averages (no plateau) which are reasonably concordant (1) one to each other and (2) with paleontological evidences. These results lead us to suggest that the crystallization ages of the basaltic series of Holes 655B and 651A may be close to 4.3 ± 0.3 Ma and from 3 to 2.6 Ma, respectively. These ages must be taken with caution because the argon is from secondary phases characterized by low argon retention.

To accept the peculiar hypothesis of deducing crystallization ages from low and intermediate temperature steps and not from high temperature data, we must admit that (1) the high temperature ages are produced by primary phases which have been altered markedly after the cooling of the lavas (possibly from secondary K-feldspars included into the plagioclases), (2) the low and intermediate temperature ages are at least partly produced by secondary products formed immediately after the crystallization of the rocks, and (3) these low and intermediate temperature ages are only slightly disturbed by later alteration phenomena.

These data are consistent with the youngest ages measured by the K/Ar conventional method on lavas from Site 373 (Barberi et al., 1978; Kreuzer et al., 1978; Savelli et al., 1978). They do not sensibly modify the previous estimates of the age of the Vavilov basaltic series which were used in the geodynamic models described by Kastens et al. (1988) and Mascle et al. (1988).

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