Appendix DR1. Analyses of submarine basalts from the Hilo Ridge

Analyst	Field No.	Sample Description	SiO_2	TiO_2	Al_2O_3	$FeTO_3$	MgO	MnO	CaO	Na_2O	K_2O	P_2O_5	LOI	TOTALS	Total alkalis
	Whole-rock analyses, XRF														
Kimura	K215-1	Talus block, trans. basalt (4032 mbsl)	46.87	2.59	12.17	12.95	12.01	0.17	9.78	2.09	0.54	0.25		99.40	2.63
Kimura	K215-2	Pillow lava, trans. basalt (3999 mbsl)	47.09	2.66	12.35	12.96	11.09	0.15	10.02	2.09	0.64	0.26		99.31	2.74
Kimura	K215-3a	Pillow lava, trans. basalt (3054 mbsl)	46.89	2.65	12.31	13.07	11.62	0.16	9.87	2.18	0.50	0.26		99.49	2.67
Kimura	K215-3b	Pillow lava, trans. basalt (3054 mbsl)	46.71	2.47	11.97	12.81	12.96	0.16	9.49	2.05	0.48	0.25		99.35	2.53
Kimura	K215-4	Pillow lava, trans. basalt (3906 mbsl)	46.68	2.64	12.22	13.21	11.80	0.21	9.82	2.10	0.49	0.26		99.43	2.60
Kimura	K215-5	Pillow lava, trans. basalt (3862 mbsl)	46.81	2.63	12.33	13.02	11.65	0.18	9.94	2.14	0.51	0.26		99.45	2.65
Kimura	K215-6	Pillow lava, trans. basalt (3815 mbsl)	46.58	2.53	11.85	13.09	13.01	0.16	9.56	2.02	0.50	0.25		99.54	2.51
Kimura	K215-7	Pillow lava, picritic basalt (3775 mbsl)	46.16	1.47	8.22	12.19	23.62	0.23	6.46	1.26	0.22	0.15		99.98	1.48
Kimura	K215-8	Pillow lava, picritic basalt (3716 mbsl)	46.44	1.50	8.34	12.18	23.11	0.15	6.49	1.30	0.22	0.15		99.88	1.52
Kimura	K215-9	Pillow lava, picritic basalt (3664 mbsl)	46.28	1.48	8.37	12.12	23.12	0.16	6.56	1.28	0.24	0.15		99.74	1.51
Kimura	K215-10	Pillow lava, picritic basalt (3619 mbsl)	46.31	1.52	8.39	12.29	23.09	0.19	6.57	1.27	0.22	0.15		99.99	1.49
Kimura	K215-11	Pillow lava, picritic basalt (3534 mbsl)	46.68	1.52	8.69	12.04	22.29	0.15	6.72	1.32	0.20	0.15		99.75	1.52
Kimura	K215-12	Pillow lava, picritic basalt (3379 mbsl)	46.58	1.52	8.66	12.09	22.29	0.15	6.92	1.33	0.20	0.14		99.90	1.53
Kimura	K215-13a	Pillow lava, picritic basalt (3289 mbsl)	47.25	1.95	9.67	12.25	17.54	0.22	7.51	1.62	0.34	0.20		98.56	1.96
Kimura	K215-13b	Pillow lava, picritic basalt (3289 mbsl)	47.62	1.92	9.73	12.31	18.44	0.22	7.37	1.59	0.33	0.20		99.73	1.92
Kimura	K215-14	Pillow lava, picritic basalt (3253 mbsl)	47.69	1.99	9.94	12.45	17.51	0.17	7.59	1.61	0.37	0.21		99.52	1.97
Kimura	K215-15	Talus block, picritic basalt (3274 mbsl	46.45	1.66	9.03	12.29	21.14	0.36	7.07	1.44	0.26	0.16		99.84	1.69
Kimura	K215-16	Pillow lava, picritic basalt (3252 mbsl)	46.32	1.50	8.47	12.03	22.78	0.34	6.67	1.35	0.21	0.15		99.82	1.57
Kimura	K215-17	Pillow lava, picritic basalt (3208 mbsl)	47.66	1.98	9.93	12.28	17.70	0.23	7.60	1.67	0.33	0.21		99.59	2.00
USGS	K215-1	Talus block, trans. basalt (4032 mbsl)	47.2	2.64	12.6	13	11.5	0.17	10.1	2.25	0.53	0.31	-0.20	100.1	2.78
USGS	K215-4	Pillow lava, trans. basalt (3906 mbsl)	47.3	2.64	12.8	12.9	11.1	0.17	10.1	2.22	0.51	0.32	0.00	100.06	2.73
USGS	K215-6	Pillow lava, trans. basalt (3815 mbsl)	47	2.53	12.2	13.2	12.3	0.17	9.72	2.19	0.57	0.31	0.07	100.26	2.76

Analyst	Field No.	Sample Description	Ba ppm	Ce ppm	Cr ppm	Cu ppm	Ga ppm	La ppm	Nb ppm	Nd ppm	Ni ppm	Rb ppm	Sr ppm	U ppm	V ppm	Y ppm	Zn ppm
	Trace elements, XRF																
USGS	K215-1	Talus block, trans. basalt (4032 mbsl)	120	34	648	90	21	15	17	25	417	9	367	2	280	27	122
USGS	K215-4	Pillow lava, trans. basalt (3906 mbsl)	124	27	674	104	21	13	16	8	403	9	369	3	290	27	118
USGS	K215-6	Pillow lava, trans. basalt (3815 mbsl)	114	36	703	89	15	14	16	12	481	10	357	4	274	27	111

Analyst	Field No.	Sample Description	SiO_2	TiO_2	Al_2O_3	FeO	MgO	MnO	CaO	Na_2O	K_2O	P_2O_5	TOTALS	Total alkalis	S, ppm	Cl, ppm
	Glass analyses, by EMP															
Coombs	K215-R1	Talus block, trans. basalt (4032 mbsl)	49.02	3.25	14.21	11.52	6.39	0.17	11.59	2.61	0.58	0.33	99.84	3.20	587	143
Coombs	K215-R3a	Pillow lava, trans. basalt (3054 mbsl)	49.23	3.27	14.19	11.50	6.33	0.17	11.58	2.65	0.59	0.34	100.02	3.24	598	137
Coombs	K215-R4	Pillow lava, trans. basalt (3906 mbsl)	49.09	3.30	14.17	11.48	6.31	0.17	11.57	2.69	0.59	0.34	99.87	3.28	616	144
Coombs	K215-R5	Pillow lava, trans. basalt (3862 mbsl)	49.27	3.35	14.06	11.70	6.13	0.18	11.55	2.68	0.61	0.35	100.04	3.29	625	141
Coombs	K215-R6	Pillow lava, trans. basalt (3815 mbsl)	49.22	3.27	14.21	11.35	6.25	0.17	11.55	2.65	0.58	0.34	99.77	3.24	605	151
Coombs	K215-R8	Pillow lava, picritic basalt (3716 mbsl)	51.72	2.98	13.87	11.09	5.77	0.18	10.33	2.55	0.45	0.31	99.55	3.00	1127	127
Coombs	K215-R11	Pillow lava, picritic basalt (3534 mbsl)	51.75	2.59	14.33	10.15	6.41	0.17	11.09	2.46	0.38	0.26	99.83	2.84	897	85
Coombs	K215-R12	Pillow lava, picritic basalt (3379 mbsl)	51.71	2.60	14.32	10.30	6.36	0.17	11.11	2.42	0.38	0.25	99.87	2.79	917	94
Coombs	K215-R13a	Pillow lava, picritic basalt (3289 mbsl)	52.55	3.58	13.67	11.85	5.08	0.19	9.51	2.42	0.58	0.40	100.12	2.99	1153	161
Coombs	K215-R16	Pillow lava, picritic basalt (3252 mbsl)	51.60	2.59	14.32	10.28	6.36	0.17	11.18	2.36	0.38	0.26	99.73	2.74	889	113
Coombs	S699-1	Pillow lava, picritic basalt (5364 mbsl)	51.60	3.05	13.64	11.84	5.77	0.17	9.86	2.41	0.49	0.30	99.43	2.90	157	1142
Coombs	S699-2	Pillow lava, picritic basalt (5206 mbsl)	51.83	3.13	13.62	11.75	5.78	0.18	9.89	2.43	0.51	0.31	99.68	2.94	109	997
Coombs	S699-3b	Pillow lava, picritic basalt (4976 mbsl)	51.71	3.12	13.61	12.00	5.66	0.16	9.79	2.44	0.51	0.30	99.64	2.96	126	1249

Analysts: Kimura, XRF by Jun Kimura, Shimane University, Japan; USGS, XRF in USGS Denver lab; Coombs, electron-microprobe analyses, at USGS Menlo Park, by Michelle Coombs

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Laboratory Report
U.S. Geological Survey
Lakewood,Colorado

Mineral Resource Program

Energy Resource Program

Job Number
MRP-03669. P. LIPMAN (EDXRF)

D. Siems, 11-Oct-01

Lab No.	**Field No.**	**Sample Description**	**Ba** ppm	**Ce** ppm	**Cr** ppm	**Cu** ppm	**Ga** ppm	**La** ppm	**Nb** ppm	**Nd** ppm	**Ni** ppm	**Pb** ppm	**Rb** ppm	**Sr** ppm	**V** ppm	**Y** ppm	**Zn** ppm	**Zr** ppm
C-198927	K215-1	Pillow lava outcrop olivine basalt (4032 mbsl)	120	34	648	90	21	15	17	25	417	<3	9	367	280	27	122	164
C-198928	K215-4	Pillow lava outcrop olivine basalt (3906 mbsl)	124	27	674	104	21	13	16	8	403	<3	9	369	290	27	118	166
C-198929	K215-6	Pillow lava outcrop olivine basalt (3815 mbsl)	114	36	703	89	15	14	16	12	481	<3	10	357	274	27	111	160

Appendix DR2

$^{40}Ar/^{39}Ar$ Analytical techniques

Analytical techniques for the submarine Hilo Ridge samples are nearly identical to those reported previously for underwater basalt from Kilauea (Calvert and Lanphere, 2006). Grey, crystalline portions of pillow interiors were separated for dating. Samples were crushed, ultrasonicated and sized to 250-350μm. Dense, clean groundmass was concentrated using a Frantz magnetic separator and careful handpicking under a binocular microscope. For irradiation, 180-190 mg groundmass sample were packaged in Cu foil and placed in a cylindrical quartz vial, together with fluence monitors of known age and K-glass and fluorite to measure interfering isotopes from K and Ca. The quartz vials were wrapped in 0.5 mm-thick Cd foil to shield samples from thermal neutrons during irradiation. The samples were irradiated for two hours in the central thimble of the U.S. Geological Survey TRIGA reactor in Denver, Colorado (Dalrymple et al., 1981). The reactor vessel was rotated continuously during irradiation to avoid lateral neutron flux gradients. Reactor constants determined for these irradiations were indistinguishable from recent irradiations, and a weighted mean of constants obtained over the past five years yields $^{40}Ar/^{39}Ar_K = 0.000\pm0.004$, $^{39}Ar/^{37}Ar_{Ca} = 0.000706\pm0.000051$, and $^{36}Ar/^{37}Ar_{Ca} = 0.000281\pm0.000009$. TCR-2 sanidine from the Taylor Creek Rhyolite (Dalrymple and Duffield, 1988) was used as a fluence monitor with an age of 27.87 Ma. This monitor is a secondary standard calibrated against the primary intralaboratory standard, SB-3, that has an age of 162.9 ± 0.9 Ma (Lanphere and Dalrymple, 2000). Data in this study were recalculated to a Fish Canyon sanidine age of 28.02 using R = 1.00655217±0.0005853. Fluence monitors were analyzed using a continuous CO_2 laser system and mass spectrometer described by Dalrymple (1989). Argon was extracted from groundmass and mica separates using a Mo crucible in a custom resistance furnace modified from the design of Staudacher et al. (1978) attached to the above mass spectrometer. Heating temperatures were monitored with an optical fiber thermometer and controlled with an Accufiber Model 10 controller. Gas was purified continuously during extraction using two SAES ST-172 getters operated at 4A and 0A.

Mass spectrometer discrimination and system blanks are important factors in the precision and accuracy of $^{40}Ar/^{39}Ar$ age determinations of Pleistocene lavas because of low radiogenic yields. Discrimination is monitored by analyzing splits of atmospheric Ar from a reservoir attached to the extraction line and for these samples $D_{1amu} = 1.007504 \pm 0.000279$. All isotopic ratios are mass discrimination corrected using $^{40}Ar/^{36}Ar = 295.5$ (Steiger and Jager, 1977). A recent determination of atmospheric argon ($^{40}Ar/^{36}Ar = 298.56 \pm 0.31$; Lee et al., 2006) is more precise, but acceptance is controversial and that ratio has no impact on this study because normalizing to a different value does not change the age. Typical system blanks including mass spectrometer backgrounds were 1.5×10^{-18} mol of m/z 36, 9×10^{-17} mol of m/z 37, 3×10^{-18} mol of m/z 39 and 1.5×10^{-16} mol of m/z 40, where m/z is mass/charge ratio.

In the incremental-heating experiments, the extraction line is isolated from pumping systems and the sample is heated to a specified temperature for 10 minutes, cooled for 3-5 minutes, and transferred to an isolated mass spectrometer. The gas is exposed to getters during the entire extraction. Isotopic ratios are measured and corrected for instrumental blanks, mass discrimination and interfering isotopes generated in the reactor. In these experiments we separated and loaded enough material to do 12-18 steps on each unknown in order to carefully characterize the argon release. The incremental heating data are plotted both as an age spectrum diagram and as an isotope correlation (isochron) diagram. For the age spectrum, apparent ages are calculated assuming that non-radiogenic Ar is atmospheric ($^{40}Ar/^{36}Ar = 295.5$) in composition and are plotted against the cumulative ^{39}Ar released during the experiment. In cases with several contiguous steps yielding ages within analytical error, we calculate and report plateau ages by weighing individual ages by the inverse of their analytical error. Most groundmass age experiments do not yield identical ages across the entire spectrum due to minor alteration, recoil of ^{39}Ar during irradiation or modest excess ^{40}Ar. Generally accepted criteria for a meaningful incremental heating age are: (1) well-defined plateau (horizontal age spectrum) for more than 50% of the ^{39}Ar released; (2) well-defined isochron for the plateau gas fractions; (3) concordant plateau and isochron ages; and (4) $^{40}Ar/^{36}Ar$ isochron intercept not significantly different from 295.5.

For isochron plots, data are not corrected using an atmospheric ratio. Isochron ages include plateau steps on well-behaved samples or a subset of data that yield a reasonable goodness of fit. We show normal isochron plots for these low-radiogenic rocks because the data are easier to visualize. Inverse isochron results are indistinguishable. Isochron ratios are particularly vulnerable to mobilization of argon isotopes during irradiation, particularly in fine-grained volcanic rocks. ^{39}Ar produced from ^{39}K in the reactor recoils ~0.1μm causing different degassing rates during analysis (Huneke and Smith, 1976). Recoil moves ratios along the x-axis of isotope correlation plots with low-T steps moved to lower values (loss of ^{39}Ar) and high-T steps moved toward higher values (deeply implanted ^{39}Ar). In this case, the isochron line becomes shallow, yielding a high $^{40}Ar/^{36}Ar$ ratio and young isochron age. We interpret this as an irradiation artifact. The most reliable results generally include gas from the middle of the release spectrum with consistent K/Ca ratios and concordant isochron data with $^{40}Ar/^{36}Ar$ intercepts within error of air. Ages and isotopic ratios reported below are 1σ.

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Hilo Ridge $^{40}Ar/^{39}Ar$ tabulated data

K215-2 Basalt

Temp(°C)	Age(ka)	%40Ar*	K/Ca	K/Cl	moles 40Ar*	∑39Ar	40Ar	39Ar	38Ar	37Ar	36Ar
550	1,161±99	5.09	0.2	1639	8.07E-15	0.09	5.178498±0.010406	0.144994±0.000296	0.005349±0.000071	0.384960±0.004180	0.016741±0.000046
575	1,076±120	3.96	0.15	2012	6.09E-15	0.16	5.021460±0.010267	0.118159±0.000242	0.004821±0.000065	0.413938±0.006226	0.016436±0.000046
600	1,252±139	4.01	0.11	1699	6.78E-15	0.23	5.526504±0.011277	0.113158±0.000232	0.005099±0.000069	0.529411±0.006250	0.018102±0.000051
625	1,141±140	3.5	0.09	2331	5.63E-15	0.3	5.253218±0.010730	0.103266±0.000212	0.004730±0.000064	0.612146±0.006907	0.017327±0.000044
650	1,453±138	4.53	0.07	1456	6.51E-15	0.36	4.692509±0.009609	0.093738±0.000193	0.004323±0.000053	0.690832±0.004669	0.015354±0.000040
725	1,096±105	4.65	0.05	911	6.37E-15	0.43	4.474216±0.009019	0.121852±0.000249	0.004853±0.000070	1.172917±0.004970	0.014767±0.000043
760	1,260±97	5.93	0.05	793	6.68E-15	0.5	3.683547±0.007480	0.111238±0.000228	0.004237±0.000054	1.087616±0.003919	0.012032±0.000038
800	1,077±91	5.81	0.05	931	5.56E-15	0.57	3.130714±0.006375	0.108392±0.000222	0.003772±0.000063	1.104009±0.004547	0.010290±0.000037
850	1,088±90	5.89	0.05	816	5.27E-15	0.63	2.923037±0.005960	0.101498±0.000208	0.003590±0.000059	1.009554±0.012080	0.009593±0.000034
900	1,155±95	5.68	0.06	696	4.63E-15	0.68	2.664407±0.005443	0.084031±0.000173	0.003195±0.000060	0.706428±0.004343	0.008703±0.000028
975	2,395±98	11.78	0.06	724	8.70E-15	0.73	2.413802±0.004942	0.076088±0.000157	0.002783±0.000066	0.670953±0.004787	0.007395±0.000028
1075	2,763±451	7.42	0.01	1241	5.79E-14	1	11.336304±0.097797	0.199233±0.000407	0.010032±0.000066	7.413394±0.016467	0.037600±0.000327

Packet IRR233-SG, Experiment #06Z0204, 0.1907 g Basalt, all errors ±1 sigma
J = 0.00034922±4.74E-07

40Ar* is radiogenic argon, isotopes in volts (6.88e-14 moles/volt), corrected for blank, background, discrimination, and decay
Calculated K2O = 0.28%wt., Calculated CaO = 7.68%wt., Calculated Cl = 0.3ppm

Total Gas Age = 1465 ± 67 ka

Weighted Mean Plateau Age = 1158.5 ± 33.4 ka (±1 sigma, including ±J), 68.2% 39Ar released
Weighted Mean Plateau Age = 1158.5 ± 33.4 ka (A priori, without ±J)
MSWD = 0.93 (Good fit, MSWD < 2.11)
Steps 10 of 12 (550,575,600,625,650,725,760,800,850,900°C)

Isochron Age = 925.6 ± 144.567 ka (±1 sigma, including ±J)
Isochron Age = 925.6 ± 127.530 ka (A Priori Errors, including ±J)
Isochron Age = 925.6 ± 327.001 ka (95% confidence, including ±J)
MSWD = 1.29 (Good fit, MSWD < 2.19)
40Ar/36Ar intercept = 298.6 ± 1.9 (±1 sigma)
40Ar/36Ar intercept = 298.6 ± 1.7 (A Priori)
40Ar/36Ar intercept = 298.6 ± 4.3 (95% confidence)
Steps 10 of 12 (550,575,600,625,650,725,760,800,850,900°C)

K215-6 Basalt

Temp(°C)	Age(ka)	%40Ar*	K/Ca	K/Cl	moles 40Ar*	∑39Ar	40Ar	39Ar	38Ar	37Ar	36Ar
550	1,018±90	5.45	0.17	1517	6.00E-15	0.09	3.600618±0.007307	0.119223±0.000244	0.004021±0.000041	0.357512±0.002895	0.011622±0.000041
600	1,159±113	4.71	0.1	1371	6.03E-15	0.18	4.182930±0.008471	0.105418±0.000216	0.004209±0.000061	0.532881±0.003008	0.013638±0.000043
650	1,231±110	4.83	0.07	1574	7.16E-15	0.27	4.839060±0.009783	0.117977±0.000241	0.004761±0.000056	0.885322±0.008426	0.015833±0.000042
700	1,152±93	5.18	0.05	1289	8.28E-15	0.38	5.230929±0.010567	0.146151±0.000298	0.005521±0.000069	1.420308±0.008229	0.017185±0.000042
750	1,078±87	5.39	0.05	938	7.92E-15	0.5	4.800814±0.009707	0.149398±0.000305	0.005497±0.000049	1.562733±0.009591	0.015810±0.000043
800	1,206±84	6.46	0.05	910	7.71E-15	0.6	3.897254±0.007954	0.129973±0.000266	0.004609±0.000077	1.447800±0.012247	0.012743±0.000038
850	1,036±103	4.76	0.05	810	5.11E-15	0.68	3.508551±0.007177	0.100220±0.000206	0.003946±0.000062	1.046462±0.005182	0.011603±0.000038
900	1,311±120	5.15	0.06	609	5.13E-15	0.74	3.254463±0.006669	0.079451±0.000164	0.003540±0.000052	0.651302±0.007812	0.010629±0.000035
950	1,861±136	7.8	0.06	521	5.16E-15	0.78	2.161057±0.004483	0.056220±0.000117	0.002450±0.000052	0.469263±0.005529	0.006875±0.000033
1025	3,427±174	8.03	0.02	356	2.50E-14	0.9	10.177325±0.020514	0.150094±0.000308	0.009711±0.000084	4.046640±0.022661	0.032812±0.000078
1025	3,149±284	8.96	0.01	623	2.77E-15	0.91	1.010265±0.002183	0.018290±0.000066	0.000956±0.000051	0.767681±0.005187	0.003328±0.000021
1150	1,646±2,288	4.74	0.01	1420	9.07E-15	1	6.259438±0.012678	0.116525±0.000239	0.005775±0.000040	7.484736±0.016591	0.022283±0.001460

Packet IRR233-SH, Experiment #06Z0205, 0.1809 g Basalt, all errors ±1 sigma
J = 0.000338321±4.59E-07

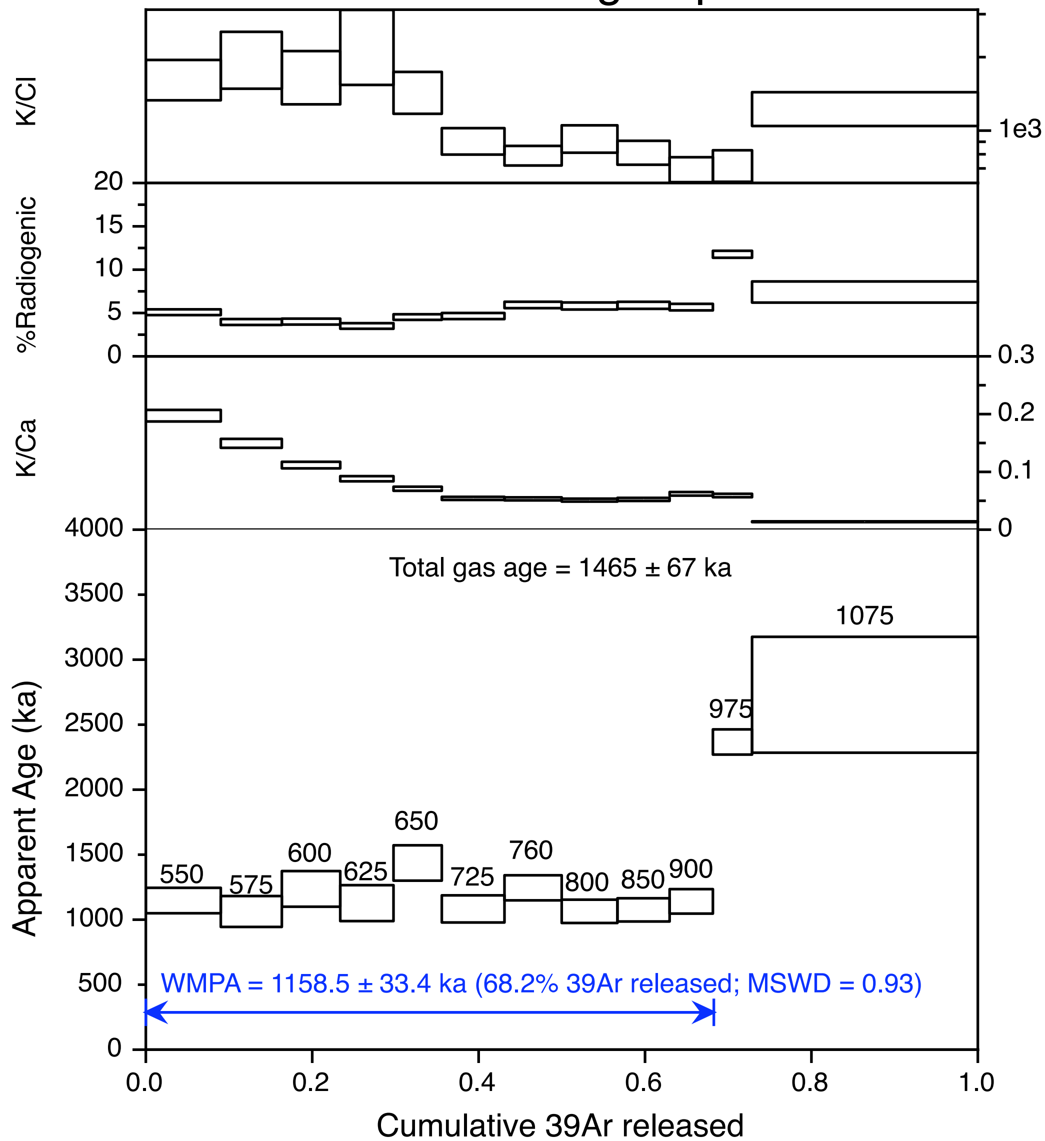
40Ar* is radiogenic argon, isotopes in volts (3.06e-14 moles/volt), corrected for blank, background, discrimination, and decay
Calculated K2O = 0.25%wt., Calculated CaO = 9.29%wt., Calculated Cl = 0.3ppm

Total Gas Age = 1510 ± 208 ka

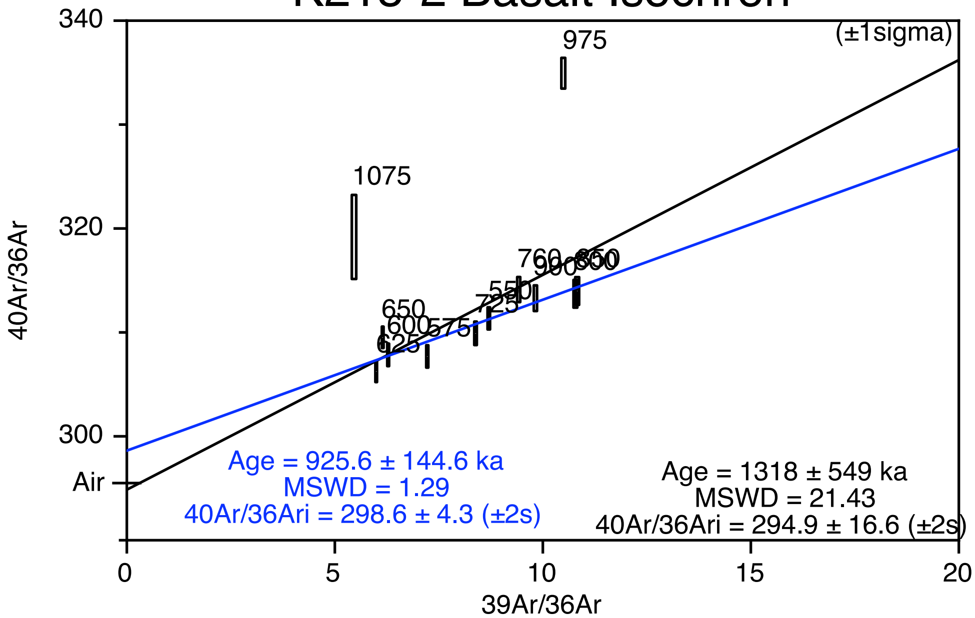
Weighted Mean Plateau Age = 1138.5 ± 34.2 ka (±1 sigma, including ±J), 73.9% 39Ar released
Weighted Mean Plateau Age = 1138.5 ± 34.2 ka (A priori, without ±J)
MSWD = 0.96 (Good fit, MSWD < 2.29)
Steps 8 of 12 (550,600,650,700,750,800,850,900°C)

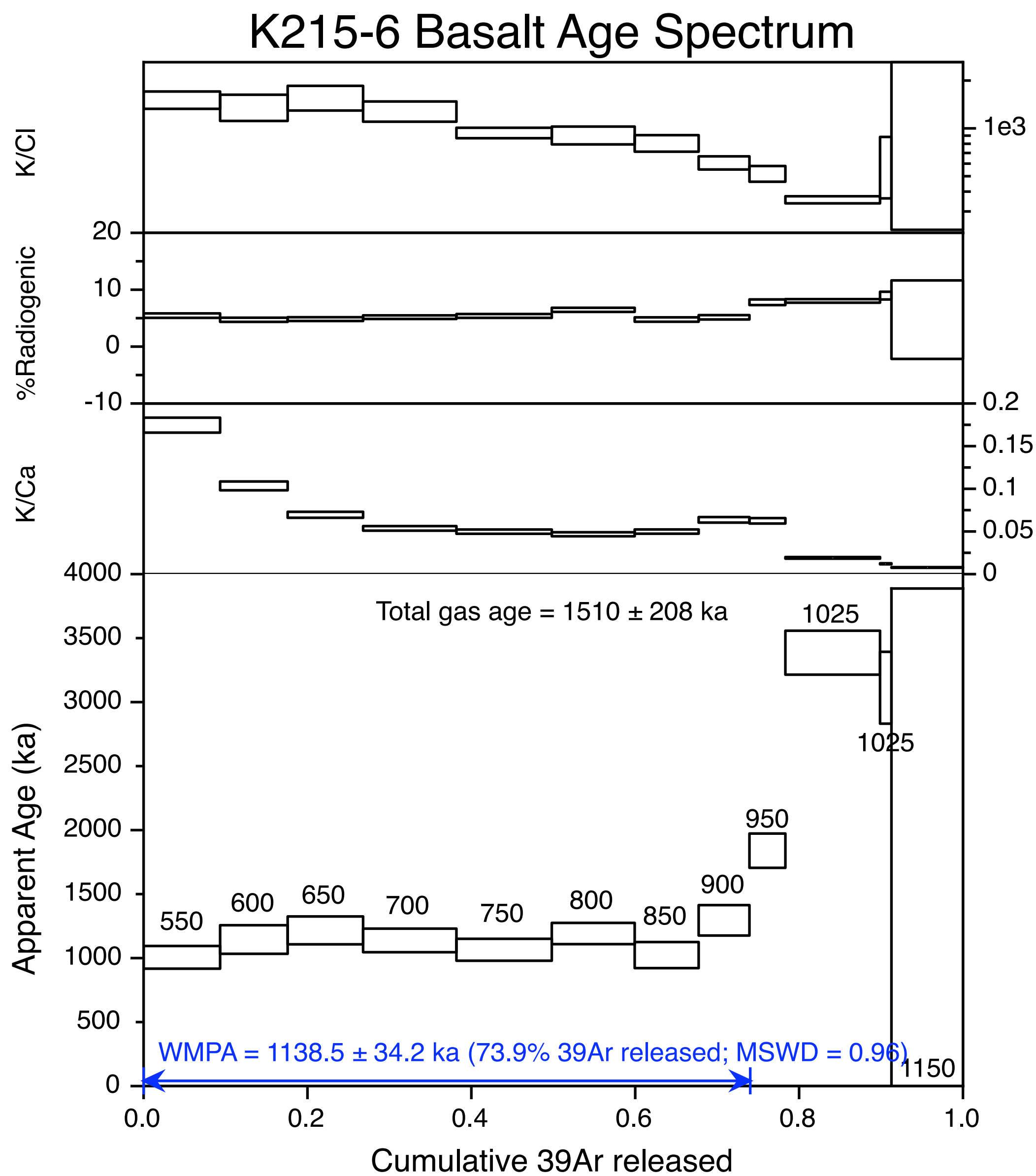
Isochron Age = 1024.2 ± 285.083 ka (±1 sigma, including ±J)
Isochron Age = 1024.2 ± 271.490 ka (A Priori Errors, including ±J)
Isochron Age = 1024.2 ± 644.852 ka (95% confidence, including ±J)
MSWD = 1.10 (Good fit, MSWD < 2.77)
40Ar/36Ar intercept = 297.2 ± 4.1 (±1 sigma)
40Ar/36Ar intercept = 297.2 ± 3.9 (A Priori)
40Ar/36Ar intercept = 297.2 ± 9.3 (95% confidence)
Steps 6 of 12 (600,650,700,750,800,850°C)

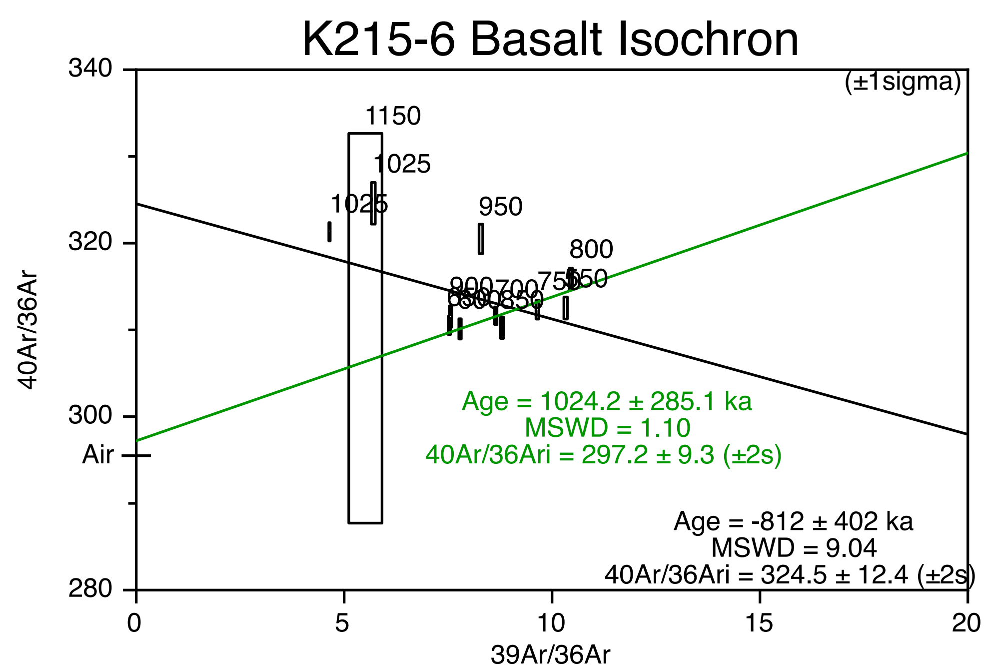
K215-2 Basalt Age Spectrum



K215-2 Basalt Isochron




K215-6 Basalt Age Spectrum
K/Cl
1e3
20
10
0
-10
%Radiogenic
K/Ca
0.2
0.15
0.1
0.05
0
4000
3500
3000
2500
2000
1500
1000
500
0
Apparent Age (ka)
Total gas age = 1510 ± 208 ka
1025
1025
950
900
550
600
650
700
750
800
850
1150
WMPA = 1138.5 ± 34.2 ka (73.9% 39Ar released; MSWD = 0.96)
0.0
0.2
0.4
0.6
0.8
1.0
Cumulative 39Ar released


K215-6 Basalt Isochron
(±1sigma)
340
320
300
Air
280
40Ar/36Ar
1150
1025
1025
950
800
900
700
750
650
850
Age = 1024.2 ± 285.1 ka
MSWD = 1.10
40Ar/36Ari = 297.2 ± 9.3 (±2s)
Age = -812 ± 402 ka
MSWD = 9.04
40Ar/36Ari = 324.5 ± 12.4 (±2s)
0
5
10
15
20
39Ar/36Ar