THE PRIMITIVE NATURE OF THE LUNAR CRUST AND THE PROBLEM OF INITIAL Pb ISOTOPIC COMPOSITIONS OF LUNAR ROCKS: A Rb-Sr AND U-Th-Pb STUDY OF APOLLO 16 SAMPLES. P. D. Nunes, R. J. Knight, D. M. Unruh, and M. Tatsumoto, U. S. Geological Survey, Denver, Colorado 80225

Rb-Sr data for samples of the black glass rind of anorthosite 60015, a white clast within this rind, and the bulk of the sample (gray plagioclase) are presented in Table 1. The Rb/Sr ratios of the white clast and gray plagioclase are very low and allow us to subtract off ^{87}Sr generated by in-situ decay of ^{87}Rb with very little error in the resulting calculated initial $^{87}Sr/^{86}Sr$ values. Assuming an age of 4.0 b.y., the Rb-corrected initial $^{87}Sr/^{86}Sr$ ratios are 0.69880 ± 0.00004 and 0.69886 ± 0.00007 ($2\sigma m$) for the white clast and gray plagioclase, respectively. These initial $^{87}Sr/^{86}Sr$ ratios agree well within error and are the lowest yet reported for any lunar sample and rank among the most primitive values yet found in our solar system. The $(^{87}Sr/^{86}Sr)_i$ ratio of 60015 indicates melting occurred on the moon very early and indirectly supports an old age of the moon of about 4.65 b.y. (1). The $(^{87}Sr/^{86}Sr)_i$ value of 60015 compares with higher values reported for lunar anorthosites 60025 [0.69906 ± 0.00006 (this report, Table 1) and 0.69894 ± 0.0003 (2)] and 15415 [0.69897 ± 0.00004 (3)] and BABI [0.698976 ± 0.000055 (4)]. The differences between the most extreme of these values are distinct and suggest that the moon formed distinctly earlier (∿5 m.y. earlier, assuming a solar primordial $^{87}Rb/^{86}Sr$ ratio of ∿1.9) than most of the basaltic achondrites. We emphasize that we here report the lowest initial $^{87}Sr/^{86}Sr$ of the moon (LIM) yet measured (0.69885 ± 0.00004) and that LIM should be used rather than BABI for model ages of primitive lunar material such as the lunar soils.

Previously unreported U-Th-Pb data of Apollo 16 samples (Table 2, Fig. 1) emphasize that terrestrial contamination remains a major problem when trying to determine initial Pb isotopic compositions of lunar samples. In particular, our sample of anorthosite 60025 and the <100 mesh fraction of breccia 60018 appear to be contaminated with ∿99% and ∿77% terrestrial Pb, respectively. This contamination occurred prior to our analyses, because Pb blanks were well below the amount of Pb extracted for analysis. An acid leach experiment for the <100 mesh fraction of 60018 revealed that the contaminant Pb was not easily leachable and that the contamination likely occurred by the addition of not easily dissolved solids. Analyses of a "clean" NASA saw blade revealed 10 to 11 ppm Pb in the saw's cutting edge, suggesting that this was the source of contamination. All our unsawed samples show apparent Pb contamination levels of <2%. Apollo 16 samples which were not sawed and which clearly display minimum terrestrial contamination [e.g. 60095 with ∿15 ppm Pb and 60315 with a $^{206}Pb/^{204}Pb$ ratio of >10,000 (5)] fall within error on one line from which we obtained an age of ∿4.0 b.y. and a $(^{206}Pb/^{207}Pb)_i$ of 0.684 (5). Because anorthosite 60015 falls slightly above this line in the direction of terrestrial Pb contamination and because some sawed surface was present on that sample, up to 3% of the Pb we analyzed (5) in that sample may be of terrestrial origin. Thus the model U-Pb age calculations we made (5) for 60015 may be slightly less precise than originally thought. In any case, we think that those model ages of ∿3.6 to 3.8 b.y. continue to approximately

THE PRIMITIVE NATURE OF THE LUNAR CRUST

Nunes, P. D. et al.

reflect the time of Pb introduction into 60015, and agree within error with the ^{39}Ar-^{40}Ar retention age for this rock (O. A. Schaeffer, oral communication, 1974). The Pb data for 60025 [this report and (2)] are not sufficiently precise, owing to terrestrial contamination problems, to calculate model ages--rather, these data emphasize that lunar plagioclase may contain essentially no Pb at all. In any case, the model U-Pb ages calculated for anorthosite 60015 coupled with its primitive $(^{87}Sr/^{86}Sr)_i$ ratio indicate that this anorthosite acquired Pb well after its original crystallization, and the model U-Pb ages for this rock likely reflect one or more metamorphic events rather than differentiation related to original melting.

Similar to rusty rock 66095 (6), breccia 64435 contains excess Pb relative to U; only the concentrations of U, Th, and Pb in 64435 are ∿35 times lower than those in 66095.

Although the glass rind of anorthosite 60015 contains ∿3 times as much Pb as the plagioclase interior (5), it also contains ∿400 times more U, resulting in a severe net loss of Pb relative to U. This indicates that the U-Pb systems of the glass and plagioclase were not equilibrated during glass formation and explains why the 60015 glass plots well below all other Apollo 16 samples. If the initial $^{206}Pb/^{207}Pb$ ratio of this glass was 0.684 [the $(^{206}Pb/^{207}Pb)_i$ of 66095] or slightly higher (e.g. the same as anorthosite 60015), the glass must have lost considerable Pb relative to U about 1 b.y. ago. The high U content of the glass, however, strongly suggests that it contains a significant soil component. A mixture of soil and anorthosite would yield a higher $(^{206}Pb/^{207}Pb)_i$ for the glass, and a younger, more likely, age (<1.3 b.y.) of Pb loss relative to U.

REFERENCES

(1) Tatsumoto, M. (1970) Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta 2, Suppl. 1, p. 1595.

(2) Papanastassiou, D. A., and Wasserburg, G. J. (1972) Earth Planet. Sci. Letters 17, p. 52.

(3) Wasserburg, G. J., and Papanastassiou, D. A. (1971) Earth Planet. Sci. Letters 13, p. 97.

(4) Papanastassiou, D. A., and Wasserburg, G. J. (1969) Earth Planet. Sci. Letters 5, p. 361.

(5) Nunes, P. D., Tatsumoto, M., Knight, R. J., Unruh, D. M., and Doe, B. R. (1973) Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta 2, Suppl. 4, p. 1797.

(6) Nunes, P. D., and Tatsumoto, M. (1973) Science 182, p. 916.

(7) Tatsumoto, M., Hedge, C. E., Unruh, D. M., and Doe, B. R. (1972) The Apollo 15 Lunar Samples (editors, J. W. Chamberlain and C. Watkins), p. 391. The Lunar Science Institute.

THE PRIMITIVE NATURE OF THE LUNAR CRUST

Nunes, P. D. et al.

Table 1. K, Rb, and Sr data from football-sized anorthosite sample 60015 and anorthosite 60025.

Sample	Weight (mg)	Concentration (ppm) K	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ Observed*	Corrected for in-situ Rb decay t = 1.0 b.y.	t = 4.0 b.y.	t = 4.65 b.y.
60015									
Black glass rind	15.8	694	1.910	156.8	0.03520	0.701207 ±0.00006	0.70071	0.69919	0.69886
Plagioclase, 2 mm from rind	30.3	68	0.1353	163.0	0.00240	0.69900 ±0.00007		0.69886	0.69884
Plagioclase interior	2.6	54	0.1221	166.2	0.00212	0.69904 ±0.00006		0.69892	0.69890
Plagioclase clast in glass	28.3	79	0.0810	182.9	0.00128	0.69887 ±0.00003	0.69885	0.69880	0.69878
60025									
Anorthosite whole rock	20.0	60	0.02017	213.6	0.000276	0.69908 ±0.00006		0.69906	0.69906

*These data may be compared to an average of 10 $^{87}Sr/^{86}Sr$ determinations of N.B.S. standard 987: 0.710184 ± 0.000025. All errors are $2\sigma_m$.

Table 2. U-Th-Pb data of some Apollo 16 samples.

Sample no.	Description	P/C	Weight (mg)	Concentration (ppm) U	Th	Pb	$^{232}Th/^{238}U$	$^{238}U/^{204}Pb$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$
									Atomic ratios corrected for analytical blank+				
60025	anorthosite whole rock	P	95.6						18.67	15.78	38.37	0.8456	2.056
		C_1	74.4	0.000594	0.00152	0.0652	2.64	0.581	18.83	15.74	--	0.8361	--
		$*C_2$	113.7	0.000502	0.00108	0.0936	2.22	0.340	18.54	15.65	--	0.8440	--
60018 (1)	breccia whole rock	P	49.3						643.2	357.1	627.7	0.5552	0.976
		*C	208.9	0.801	3.160	1.722	4.08	1,378	1,356	732.9	--	0.5405	--
(2)	<100 mesh	P	49.3						26.02	19.65	45.58	0.7551	1.752
		C_1	48.7	0.796	3.021	6.643	3.92	9.552	26.00	19.62	--	0.7546	--
		$*C_2$	180.5	0.381	1.398	1.3F9	3.79	190.0	239.0	132.0	--	0.5523	--
(3)	hand-picked glass	P	71.9						298.2	163.0	307.4	0.5466	1.031
		*C	32.3	0.694	2.588	1.827	3.86	353.4	405.5	274.2	--	0.6762	--
(4)	magnetics	P	32.5						52.12	32.94	72.35	0.6319	1.388
		C	29.8	0.433	1.544	1.657	3.68	34.9	50.82	32.04	--	0.6306	--
(5)	hand-picked dark gray	P	40.9						151.7	79.60	173.0	0.5248	1.141
		C	39.6	1.055	3.584	2.623	3.51	161.6	174.2	90.32	--	0.5185	--
(6)	hand-picked light gray	P	109.2						247.2	117.8	249.5	0.4765	1.009
		*C	88.4	1.209	4.469	2.520	3.82	230.3	227.7	106.8	--	0.4799	--
(7)	hand-picked white	P	40.37						43.78	29.84	67.96	0.6816	1.552
		C	19.11	0.1123	0.5430	0.7104	5.006	19.35	43.53	29.58	--	0.6795	--
64435	breccia whole rock	P	71.0						223.5	283.8	204.8	1.2562	0.9166
		C_1	58.4	0.0226	0.0917	0.354	4.19	39.2	221.1	277.4	--	1.2543	--
		$*C_2$	145.6	0.0299	lost	0.397	--	35.6	170.6	215.4	--	1.2630	--
60015 (A)	anorthosite black glass rind	P	168.5						251.8	236.0	245.2	0.9373	0.9738
		*C	108.0	0.409	1.539	0.566	3.89	628.4	345.6	324.1	--	0.9376	--
		*C	92.4	0.398	1.466	0.621	3.81	364.1	217.9	206.8	--	0.9491	--
(B)	"glassy" white boundary	P	60.0						94.89	104.0	102.7	1.0958	1.0819
		*C	80.0	0.0421	0.1567	0.3881	3.85	24.36	81.65	89.48	--	1.0959	--
(C)	plagioclase, 2 mm from boundary	P	126.4						71.20	91.60	79.66	1.287	1.119
		*C	115.2	0.0023	0.0060	0.171	2.70	4.32	107.9	144.5	--	1.339	--
(D)	plagioclase clast included in black glass rind	P	117.7						33.15	31.34	50.82	0.9454	1.533
		*C	87.7	0.0077	0.0248	0.1486	3.33	6.29	41.14	40.74	--	0.9902	--

+Analytical total Pb blanks were 1.15 ng for anorthosite 60025 analyses and ranged from 0.5 ng to 2.2 ng for the remaining analyses.

*Total spiked samples.

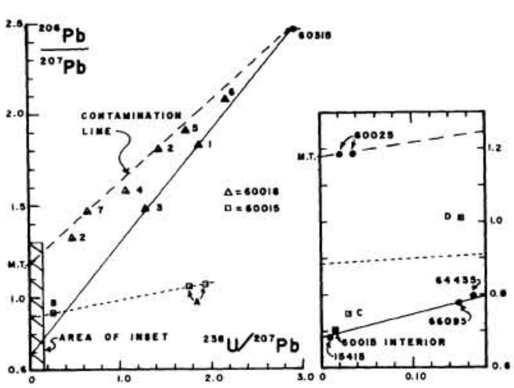

Fig. 1. Numbers and letters correspond to numbered and lettered analyses in Table 2. Data of 60315 and 60015 interior (5), 66095 (6), and 15415 (7) are plotted for comparison. Data corrected for blanks only.