72417

Cataclastic Dunite
St. 2, 11.32 g

INTRODUCTION

72417 is a complexly cataclasized dunite that was collected, along with 72415, 72416, and 72418, to sample a 10 cm clast in the impact melt matrix of Boulder 3, Station 2 (see section on Boulder 3, Station 2, Figure 1). It was originally a coarse-grained igneous rock consisting mainly of magnesian olivine. Radiogenic isotope analyses suggest that the dunite crystallized 4.45 Ga ago, but has since suffered a complex history of deformation and excavation. 72417 is an irregular, slabby chip, with many zap pits and a patina on the lunar-exposed face (Fig. 1).

72417 is 1.2 x 2.1 x 3.2 cm, and pale yellowish to greenish gray (5Y 811 to 5 GY 8/1). It is tough, but has a few non-penetrative fractures. It is essentially identical with 72415 both macroscopically and microscopically, consisting dominantly of pale yellow-green olivine fragments in a fine-grained matrix that is also dominantly olivine.

All the early studies of 72417 were conducted under a loosely-knit consortium led by the Caltech group (e.g. Dymek et al., 1975b; Papanastassiou and Wasserburg, 1975a), and the entire sample was allocated to that group for dissection and re-allocation. The details of the dissection are not available, although suballocations to investigators outside of Caltech are documented by mass.

PETROGRAPHY

There are fewer thin sections of 72417 than there are of 72415, and most authors do not distinguish the two samples. Thus the petrographic description of 72415 applies in general to 72417 as well (e.g. Albee et al., 1974a and Dymek et al., 1975b). However, Dymek et al.(1975b) distinguished the composition of metal grains between the two samples (section on 72415, Fig. 5). Bell et al. (1975) gave two microprobe analyses of olivines that were hosts for symplectites, and gave an average composition derived from microprobe analyses of 3 symplectites; their compositions are roughly similar to those in 72415. They also depicted symplectites in 72417. Dymek et al. (1975b) noted that heavy liquid separations of materials in 72417 included a single grain of ilmenite, a phase not identified in thin sections of 72415 or 72417. Ryder (1984b) suggested on the basis of published olivine compositions that 72417 might be a little more iron-rich than 72415.

Lally et al. (1976a,b) made a very detailed optical and electron petrographic study of deformation, recovery, and recrystallization of 72417. They inferred at least four stages of shock deformation and at least two stages of annealing; at least one heating event may have accompanied the shock deformations. Like the study of Richter et al. (1976a) for 72415, the interpretation of 72417 by Lally et al. (1976a,b) is consistent with but more detailed than that of Dymek et al. (1975b). High-voltage electron microscopy was used to define the substructure of crystals and matrix grains (latter defined as less than 50 microns). The olivines are moderately deformed, with planar kink boundaries, undulating extinctions, open and healed fractures, and inclusions. Subgrains in large olivine clasts are bounded by dislocations, and the subgrain sizes are very varied. Symplectites occur in planar boundaries. The matrix contains the most highly-deformed grains, but also some recovery and extensive recrystallization. Annealing followed brecciation, and the matrix has genuine porosity and some genuine sintering. Lally et al. (1976a) infer that the fractures observed by Snee and Ahrens (1975a,b) are probably not from the original shock event that produced the subgrains, as most of these recovered, but are from a later event, or even thermal in origin. A lower limit to the shock pressure is given by the presence of maskelynite and plagioclase melts. Most of the dislocations are probably shock-induced, since such

Figure 1: Pre-allocation photograph of 72417. The sample is about 3 cm long. Part of photograph 5-73-17968.

fractures rarely occur after crystallization and slow cooling. In large olivine crystals, recovery is dominant; in smaller olivines, there is both recovery and recrystallization; in the matrix, recrystallization is dominant. The smallest olivines must have had the greatest dislocation density.

The history of 72417 as inferred by Lally et al. (1975a) is given in Table 1. Its main difference from that of Dymek et al. (1975b) is the matrix recrystallization, which cannot be seen optically. The recrystallization might result from the inclusion of the dunite in the melt matrix of Boulder 3, Station 2. The large grains of olivine have an unusual heterogeneity of sizes. Shock event IIa (Table 1) produced a coherent rock, with well-recovered and recrystallized olivine and pyroxenes equilibrated at less than 810 degrees C. The present structure of the sample was produced in shock event HIa, at 50 to 100 kb, without the production of maskelynite.

CHEMISTRY

Among the chemical analyses are for 72417 given in Table 2, none can be particularly said to represent bulk rock. The data from Laul and Schmitt (1975a) in Table 2 are weighted means of 9 different subsamples that were chosen to sample the visual variety of materials composing 72417, and which themselves show a wide range in compositions (Table 3). The 9 subsamples range from 70 to 130 mg. Nonetheless, this mean corresponds reasonably with the analyses given for 72415, and corresponds with a magnesian dunite with low abundances of incompatible and felsic elements. The rare earth elements for the individual samples and the mean are shown in Figure 2; their main feature is the consistent flat pattern of light rare earth elements and changing slope of heavy rare earth elements among subsamples. Laul and Schmitt (1975a,b) attempted to calculate the composition of the parent magma, which in essence must be enriched in rare earths (cf. chondrites) and comparatively more enriched in light rare earths (e.g. La 14 x chondrites, Lu 7 x chondrites; Fig. 3). However, such calculations are very model dependent. Laul and Schmitt (1975a) explored several possible models, favoring garnet in the history to produce the light rare earth element enrichment. They suggested that the parent magma was a second-stage product, needing a previous history in which the products of melting of a gabbrosc anorthosite was mixed with an earlier Mg-rich cumulate in some form of magma pool from which the dunite crystallized. McKay et al. (1979) used the data of Laul and Schmitt (1975a,b) to reinvestigate the composition of the parent magma; using updated coefficients and a trapped liquid model, they suggested a parent magma with rare earth abundances only about half of those of Laul and Schmitt (1975a) but with a similar overall pattern. The inferred magma had Ca/Al less than

Table 1: Mechanical and thermal history of dunite 72417 (Lally et al., 1976a).

Stage	Nature of events	Resulting fabric
I	Initial crystallization, accumulation of dunite; slow cooling.	Coarse-grained; presumably cumulate or modified cumulate texture.
IIa	*Shock deformation*: plastic deformation of olivine; melting of plagioclase; and injection of plag melt. Introduction of crack porosity.	
IIb	*Recovery and local recrystallization*: Crystallization of injected plag glass. Sintering of crack porosity.	Texture unknown; probably cohesive and massive.
IIIa	*Shock deformation*: brecciation, cataclastic deformation; plastic flow especially in fine-grained material. Consolidation (?)	Present breccia fabric; state of consolidation unknown.
IIIb	*Recovery and local recrystallization*: Possibly responsible for contributing to consolidation.	
IV	*Incorporation* in melt (72435) of cohesive breccia fragments; heating by melt.	Present breccia texture
V	Excavation of Boulder 3 to present location. Little or no effect on dunite fabric.	Present breccia texture

Table 2: Chemical analyses of "whale rock" 72417 samples.

Split	(a)	,1	,9018a	,9018b	,9018c	,13	,1,1(c)	,1,7(d)
wt %								
SiO_2								
TiO_2								
Al_2O_3	1.3							
Cr_2O_3	0.34							
FeO	11.9							
MnO	0.113							
MgO	45.4							
CaO	1.1							
Na_2O	0.0186							
K_2O	0.0030							
P_2O_5								
ppm								
Sc	4.3							
V	50							
Co	55							
Ni	160	411	538	650	314			
Rb		0.027						
Sr	8.2							
Y								
Zr								
Nb								
Hf	0.10							
Ba	4.1							
Th								
U		0.0028	0.0024	0.0006	0.0051		0.002	0.002
Cs		0.0141						
Ta								
Pb								
La	0.15							
Ce	0.37							
Pr								
Nd								
Sm	0.080							
Eu	0.061							
Gd								
Tb	0.017							
Dy	0.11							
Ho	0.023							
Er								
Tm								
Yb	0.074							
Lu	0.012							
Li							2.3	
Be								
B								
C								
N								
S								
F								154
Cl							6.69(b)	
Br		0.0272					0.028(b)	
Cu								
Zn		9.8	2.5	2.1	9.6	2.3		
ppb								
Au		2.55	3.9	5.1	3.3	3.2		
Ir		3.13	0.048	0.050	0.46	<0.010		
I							0.9	
At								
Ga								
Ge		261	349	542	186	270		
As								
Se		5.1	31	5.4	9.0	3.0		
Mo								
Tc								
Ru								<3
Rh								
Pd								
Ag		30.2	14.5	5.0	46			
Cd		0.85	5.2	4.0	26			
In			0.72	0.21	<0.25			
Sn								
Sb		2.81	1.78		3.4			
Te		0.56						
W								
Re		0.099	0.0007	0.002	0.022	<0.04		
Os			<0.043	<0.025	0.71		<0.8	1.2(e)
Pt								
Hg							2.2	
Tl		0.033	0.103	0.101	1.04			
Bi		1.24	2.8	<2	0.89			
	(1)	(2)	(3)	(3)	(3)	(3)	(4)	(4)

(1) Laul and Schmitt (1975a); INAA, RNAA
(2) Higuchi and Morgan (1975a,b);RNAA
(3) Morgan and Wandless (1988); RNAA
(4) Jovanovic and Reed (1974a,1975c); RNAA

Notes:
(a) Mass weighted mean of 9 (70-130 mg) samples from different locations of 72417 from Caltech consortium samples.
(b) combined leach and residue values.
(c) interior.
(d) exterior.
(e) =/-0.7 ppb

chondritic, and this and other non-chondritic aspects probably could not be derived by fractional crystallization of a chondritic parent.

Higuchi and Morgan (1975a) and Morgan and Wandless (1979) inferred that the siderophile and volatile elements were of indigenous, not meteoritic, origin. Continued analyses of small subsamples by Morgan and Wandless (1988) showed that the 72417 samples generally had higher siderophiles and volatiles than 72415, and confirmed that the siderophiles were indigenous; for instance, the refractory siderophiles Os,Re, and Ir do not correlate with other siderophiles. Ni, Co, and Ge correlate with each other, suggesting that Ge acted as a siderophile and that all three elements reside mainly in Fe-metal. Morgan and Wandless (1988) infer a source magma for the dunite that had about 6 x the volatiles of a mare basalt.

The data of Jovanovic and Reed (e.g. 1974a) includes separate leach and residue data for Cl and Br. Although most of their data is presented with little discussion, they claim that the Ru/Os ratio is roughly chondritic, but that is a sign of primitiveness rather than contamination. Such a ratio is much lower than that of mare basalts (about 24). For Hg they present some temperature release (<130 degrees C) data.

RADIOGENIC ISOTOPES

Papanastassiou and Wasserburg (1975a,b, 1976b) gave a detailed description of analyses of subsamples of 72417 for Rb and Sr isotopic ratios (Table 4). The subsamples were varied chips and splits of 50 to 150 mg chosen for their distinctive characters, and the analyses included handpicked olivine and symplectite fragments. None specifically represent bulk rock. 'Me data define a precise age

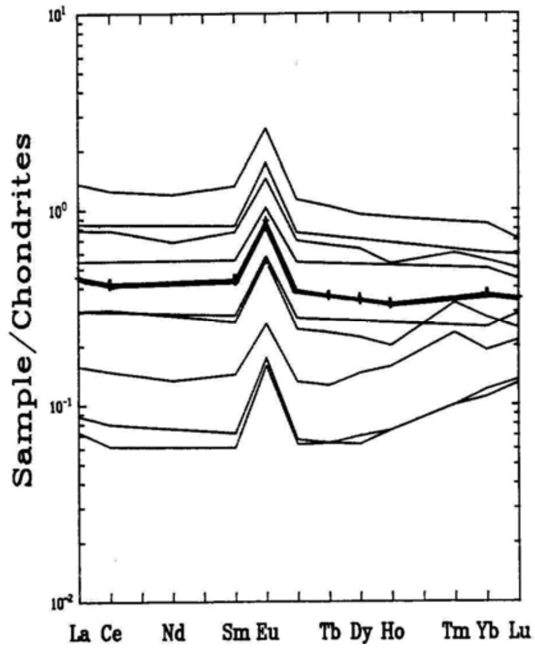

Figure 2: Rare earth elements in small subsamples (70 to 130 mg) of 72417 (lighter lines), from Laul and Schmitt (1975a). The weighted mean is included (heavier line with strokes).

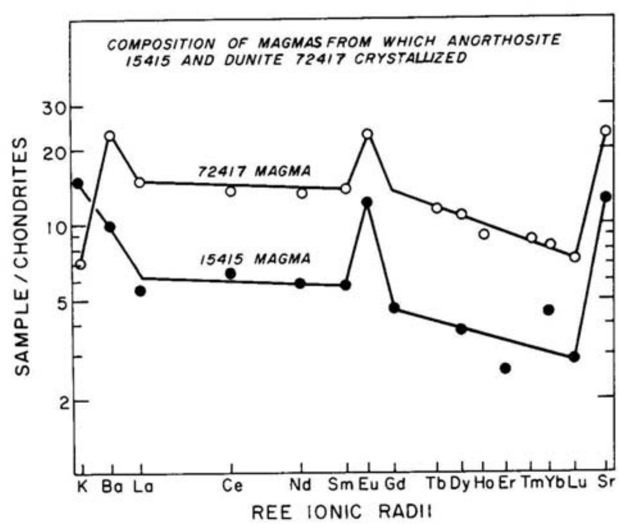

Figure 3: Calculation of abundances of incompatible elements in the parent magma of 72417 according to one of the models of Laul and Schmitt (1975, their Fig. 7), and a calculated parent for anorthosite 15415.

of 4.47 +/- 0.10 Ga (decay constant for ^{87}Rb =1.42 x 10-^{11}1yr), with an initial 87Sr/86Sr of 0.69900 +1-7 (Fig. 4). A few of a the points fall are several millimeters in size, so the data establish the time of isolation of the isotopic systems at this scale. The array is a primary isochron, and is not merely a mixture of two components (Figs. 5 and 6). The variation in Rb/Sr is not attributable to specific phases. The very low K/Rb ratio eliminates contamination as a contributing factor. The data thus define a very ancient crystallization event The initial ^{87}Sr/^{86}Sr is indistinguishable from BABI Papannastassiou and Wasserburg (1975a) document the severe effects that leaching of dunite samples with organic liquids has on the Rb/Sr isotopic systems, with preferential removal of Rb and the obliteration of any time information.

Dymek et al. (1975b) quoted ^{4O}Ar-^{39}Ar data from Huneke (pers. comm.) that suggested a complicated release pattern but that indicated Ar loss at 3.89 +/- 0.1 Ga (assuming original quote of 3.95 Ga

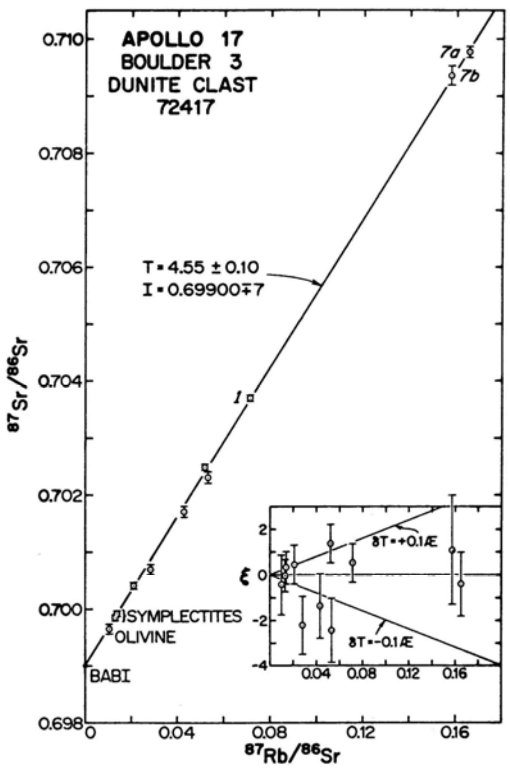

Figure 4: Rb-Sr evolution diagram for mechanically separated samples of the dunite 72417.The age is determined for decay constant for ^{87}Rb =1.39 X 10-^{11}1yr; for decay constant for ^{87}Rb =1.42 x 10-^{11}/yr, age is 4.47 Ga. Inset shows deviations in pans of 10^4 from the best fit line (Papanastassiou and Wasserburg, 1975a).

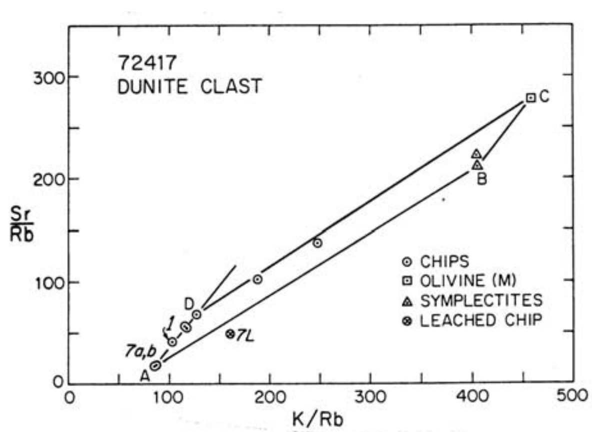

Figure 5. Element correlation diagram for dunite 72417 samples. The distinctly low K/Rb data fall along line AD. These data require the presence of at least three different phases with distinct Rb/Sr values (Papanastassiou and Wasserburg, 1975a).

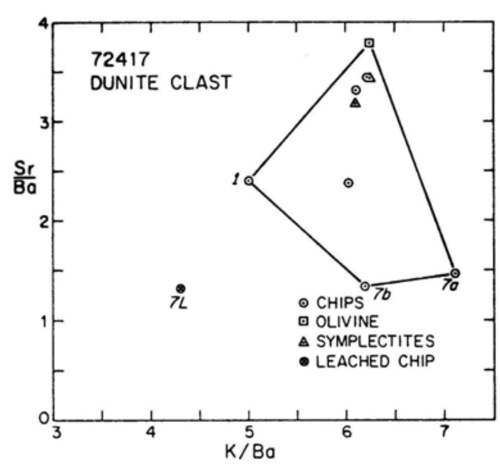

Figure 6: Element correlation diagram for dunite 72417 samples. These data require the presence of at least three different phases The olivine appears to be sampling phases distinct from the handpicked coarse symplectites. (Papanastassiou and Wasserburg, 1975a).

used the old decay constant), which is the same age as that of the host melt_ However, no details were published. Tera et al. (1974b) reported some limited Pb isotopic data that also suggested a somewhat younger age than 4.6 Ga and might indicate a disturbed system. The Pb is distinctly radiogenic.

STABLE ISOTOPES

Clayton and Mayeda (1975a,b) and Mayeda et al. (1975) reported isotopic analyses of oxygen in 72417 splits, with little discussion (Table 5). The delta ^{Ig}o values for olivines are in the middle of the range for lunar olivines.

PROCESSING

The sample was entirely allocated to the Caltech group for study and further allocation, and the details of the subdivisions are not generally available. Allocations to investigators outside of Caltecb are documented by mass.

Table 3: Chemical analyses of small subsamples of 72417 (70 to 130 mg) from Laul and Schmitt (1975x); the weighted average is included in Table 2.

Sample	Wt. mg	Al_2O_3 %	Al_2O_3* %	FeO %	MgO %	CaO %	Na_2O ppm	K_2O ppm	MnO %	Cr_2O_3 %	Sc ppm	V ppm	Co ppm	Ba ppm
1 I	78	4.0	3.9	11.4	43.0	3.0	430	65	0.109	0.200	5.9	50	43	—
1 R	77													8.3
2 I	69	2.5	2.2	11.6	42.5	1.6	270	40	0.114	0.790	5.1	80	72	—
3 I	135	2.2	2.1	12.0	43.8	1.7	220	40	0.117	0.284	5.3	50	50	—
3 R	122													5.1
4 I	86	1.6	1.5	11.7	46.9	1.2	160	28	0.116	0.320	4.6	50	50	—
5 I	210	0.90	0.80	12.4	48.7	0.80	100	—	0.114	0.240	4.1	40	60	—
5A I	89	—	—	12.4	—	—	80	18	—	0.242	4.1	—	—	—
5AR	89													2.0
5B I	108	0.90	0.80	12.3	—	0.82	80	18	0.116	0.240	4.1	40	—	—
6 I	77	0.90	0.77	12.0	48.1	0.85	100	20	0.116	0.310	4.0	50	54	—
7 I	69	0.41	0.36	11.5	50.0	0.44	70	6 ± 1	0.116	0.116	3.3	40	45	—
7 R	69							5.3						0.75
8 I	106	0.40	0.28	11.6	45.3	0.41	30	7 ± 1	0.107	0.300	3.3	40	47	—
8 R	104							5.4						(2)
9 I	118	0.55	0.21	11.7	45.6	0.60	30	7 ± 2	0.110	0.830	4.1	80	84	—
9 R	117							6.4						(1.0)
Mass weighted mean		1.3	1.2	11.9	45.4	1.1	130	24	0.113	0.34	4.3	50	55	4.1
Mass weighted mean[b]		1.2	—	11.4	45.5	1.2	~200	25	~0.11	~0.11	—	—	—	4
BCR-1		13.7	—	12.3	—	6.9	32000	17000	0.174	—	32	420	36	650

Sample	Sr ppm	La ppm	Ce ppm	Nd ppm	Sm ppm	Eu ppm	Tb ppm	Dy ppm	Ho ppm	Tm ppm	Yb ppm	Lu ppm	Hf ppm	Ni ppm	Au ppb
1 I	—	0.45	—	—	0.24	0.18	—	—	—	—	0.17	0.024	0.20	130	—
1 R	25	0.45	1.1	0.72	0.24	0.18	0.049	0.30	0.064	0.026	0.17	0.024			
2 I	—	0.28	—	—	0.15	0.12	—	—	—	—	0.12	0.020	0.13	550	3.0
3 I	—	0.26	—	—	0.15	0.10	—	—	—	—	0.12	0.017	0.1	130	—
3 R	15	0.26	0.69	0.41	0.14	0.10	0.031	0.20	0.037	0.018	0.11	0.017			
4 I	—	0.18	—	—	0.10	0.071	—	—	—	—	0.10	0.015	0.1	130	—
5 I	—	0.10	—	—	0.055	0.042	—	—	—	—	0.07	0.009	<0.05	230	1.5
5A I	—	0.10	—	—	0.050	0.039	—	—	—	—	0.07	—	—	—	1.3
5AR	5.9	0.10	0.27	—	0.048	0.038	0.011	0.070	0.014	0.010	0.056	0.0084			
5B I	—	0.10	—	—	0.055	0.042	—	—	—	—	0.06	0.009	—	—	—
6 I	—	0.10	—	—	0.052	0.040	—	—	—	—	0.05	0.01	<0.04	250	1.0
7 I	—	0.055	—	—	0.023	0.025	—	—	—	—	0.03	—	0.06	100	—
7 R	2.2	0.052	0.13	0.080	0.026	0.018	0.0059	0.046	0.011	0.007	0.038	0.0073			
8 I	—	0.030	—	—	0.012	0.014	—	—	—	—	0.02	—	<0.04	180	1.4
8 R	1.9	0.029	0.070	—	0.013	0.012	0.0030	0.022	0.0052	0.003	0.022	0.0044			
9 I	—	0.023	—	—	—	0.013	—	—	—	—	0.02	—	<0.04	650	4.0
9 R	1.2	0.024	0.054	—	0.011	0.011	0.0030	0.020	0.0052	0.003	0.024	0.0046			
Mass weighted mean	8.2	0.15	0.37	—	0.080	0.061	0.017	0.11	0.023	—	0.074	0.012	0.10	160	—
Mass weighted mean[b]	8.0 11[d]	—	—	—	—	—	—	—	—	—	—	—	—	150–410[c] 173[d]	0.2–2.5[c]
BCR-1	330	25.0	53	29	6.70	1.90	1.1	6.30	1.2	0.52	3.40	0.42	4.7	—	—

[a] I = INAA, R = RNAA. Errors in INAA are cited by Laul *et al.* (1974). Overall errors in RNAA are 2–10%.
Al_2O_3* values are corrected for Cr-spinel (Al_2O_3/Cr_2O_3 = 0.41) from Albee *et al.* (1974).
[b] Albee *et al.* (1974).
[c] Higuchi and Morgan (1975) values for Ni and Au in two 72415 fragments.
[d] LSPET (1973).

Table 4: Analyses of subsamples of 72417 for Rb and Sr isotopic ratios.

Sample[a]	Weight (mg)	K ppm	Ba ppm	Rb (10^{-8} mole/g)	^{88}Sr (10^{-8} mole/g)	$^{87}Rb/^{86}Sr$[b] $\times 10^2$	$^{87}Sr/^{86}Sr$[c]	Sr/Rb[d]	Sr/Ba[d]	K/Rb[d]	K/Ba[d]	Ref.[e]
Chip-1	203	7.3	1.213	0.0830	2.712	7.14	0.70370 ± 6	40.58	2.37	103	6.02	1
-2	255	8.2	1.642	0.0827	3.713	5.19	0.70249 ± 6	55.76	2.40	116	4.99	2
-3	45	9.3	—	0.0931	4.075	5.33	0.70231 ± 10	54.35	—	117	—	2
-4	54	8.9	—	0.0817	4.438	4.29	0.70171 ± 10	67.45	—	127	—	2
-5	53	16.9	2.77	0.1053	8.651	2.838	0.70070 ± 9	102.0	3.31	188	6.10	
-6	170	19.9	3.20	0.0938	10.37	2.110	0.70041 ± 6	137.2	3.44	248	6.22	
-7a[f]	114	4.7	0.664	0.0645	0.910	16.53	0.70977 ± 10	17.53	1.46	85	7.1	
-7b	63	4.9	0.787	0.0661	0.979	15.75	0.70936 ± 17	18.40	1.32	87	6.2	
Sym I-1	125	29.1	4.66	0.0843	15.08	1.304	0.69985 ± 5	222.1	3.43	404	6.24	1
-2	151	31.3	5.14	0.0905	15.38	1.372	0.69992 ± 5	211.0	3.18	405	6.09	2
Olivine	138	10.6	1.70	0.0271	6.074	1.041	0.69965 ± 9	278.3	3.79	458	6.24	2

[a] All samples were obtained by mechanical means only, except chip-1 which was rinsed in acetone prior to crushing.
[b] Uncertainty in concentrations is 0.4% for Rb and 0.1% for ^{88}Sr.
[c] Errors correspond to last significant figures and are $2\sigma_{mean}$.
[d] Elemental ratios are calculated by weight.
[e] Ref. 1: Albee *et al.* (1974); Ref. 2: Papanastassiou and Wasserburg (1975).
[f] Sample 7a represents a quarter split of a homogenized sample after crushing to less than 75 μm; 7b is an eight split of the same original sample.

Table 5: Oxygen isotopic analyses for samples of 72417 (Clayton and Mayeda,1975a,b; Mayeda et al., 1975).

Split	description	delta ^{18}O	delta ^{17}O
,9011	dunite	4.77	2.52
,9011	dunite	5.20	2.55
,9011	mx in dunite	4.82	
,9010	ol in dunite	5.09	