10017
Ilmenite Basalt (high K)
973 grams

Figure 1: Close-up photo of dusted surface of 10017,81 N1 face. Sample is 4 cm across. NASA #76-25451.

Introduction

10017 is the largest rock sample returned by Apollo 11. It is a fine-grained, vesicular, ilmenite basalt of the high-K variety (figure 1). The original crystallization age was determined as 3.6 b.y.

10017 was used for the study of solar- and cosmic-ray interaction with the lunar surface (Shedlovsky et al. 1970, SHRELLDALFF 1970). Shedlovsky et al. determined the orientation by radiation counting and found that *"most photographs made in the preliminary examination were in what we now consider a position inverted relative to its orientation on the moon."* Overall, 10017 was found to have a high level of cosmic-ray-induced radioactivity with an exposure age of 480 m.y.

Photos of 10017 taken before it was broken show that all sides are rounded and covered with micrometeorite craters and patina indicating that this sample "tumbled" while on the lunar surface (figures 2 and 3). However, one side is flatter and turned out to have been the surface that was most recently exposed on the Moon (from ^{56}Co activity). Depth profiles of cosmic-ray-induced nuclear tracks were found on both the top and bottom sides of the sample. The sample has not always been in the orientation that it was found, and it is not

Figure 2: Original photo of rounded, dust-covered, surface of 10017,0. NASA S69-47573. Note micrometeorite craters and vesicles. This was originally thought to be the "top" surface untill 56Co was found on the other side (figure 3).

the most suitable sample for the separation of the nuclear effects caused by solar-ray and cosmic-ray radiation.

Petrography

There is a variability to the texture of 10017, even within a given thin section, which is due to apparent mineral segregations and differences in grain size (French et al. 1970; Dence et al. 1970). For this reason, and because petrologists were not familiar with high Ti basalts, a wide variety of descriptions and names were applied to Apollo 11 basalts. All investigators were surprised by the lack of any alteration. Mesostasis is glassy.

Schmitt et al. (1970) originally described 10017 as a "poikiloblastic olivine basalt (very fine-grained, vesicular, vuggy, glass-bearing)." James and Jackson (1970) listed 10017 as "hornfelsic, intersertal basalt" where ilmenite and pyroxene "occur in mosaics of equant interlocking grains and plagioclase forms coarse poikiloblastic crystals" (figure 4). Dence et al. (1970) describe the texture of 10017 as "intergranular", Brown et al. (1970) describe the texture as "hypidiomorphic granular" and McGee et al. (1977) described the texture as "intersertal."

Adler et al. (1970), French et al. (1970), Brown et al. (1970), Kushiro and Nakamura (1970), Dence et al. (1970), McGee et al. (1977), Beaty and Albee (1978) and others have provided detailed petrographic descriptions of 10017. 10017 is a fine- to medium-grained basalt composed primarily of clinopyroxene, plagioclase and ilmenite, with minor mesostasis including high-K glass. Plagioclase megacrysts ate typically poikilitic and enclose anhedral pyroxene and ilmenite crystals. The rock is vesicular, with both circular and irregular vesicles about 0.2 to 0. 5 mm in size, which make up only a few percent of the sample. In 10017, pyroxenes are often granular, whereas plagioclase is anhedral to subhedral (Kushiro and

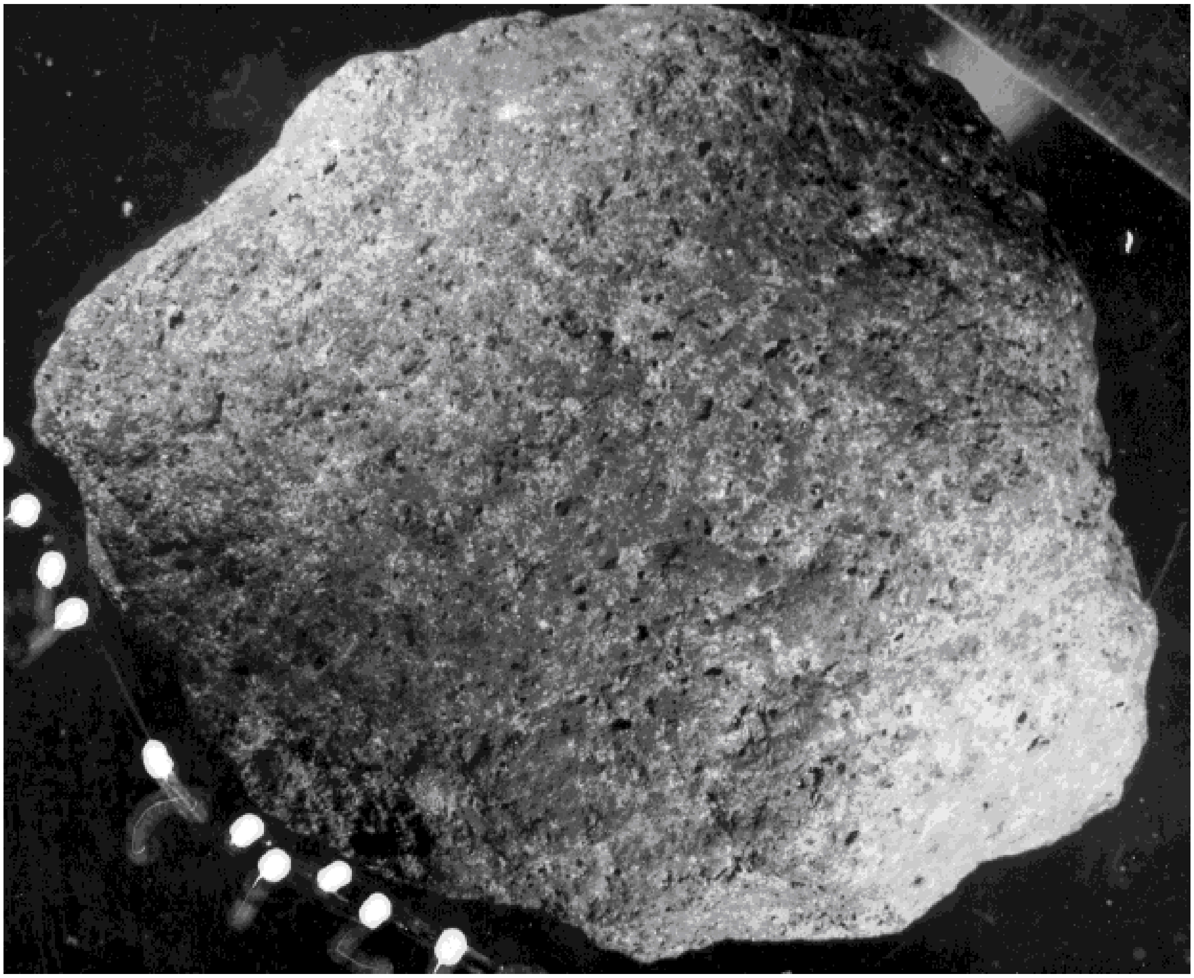


Figure 3: Original photo taken in F-201 of "flatter" side of 10017,0 showing numerous, well-developed micrometeorite craters. This side was eventually determined to be the most recent top surface, because it had abundant short-lived radionuclides (see text). NASA S69-47560. Sample is 16 cm long.

Nakamura 1970). The grain size is variable with pyroxene and ilmenite from 50 to 150 microns, but plagioclase is up to 2 - 3 mm in length (French et al. 1970). This high Ti, lunar basalt is unusual in that the ilmenite is equant rather than tabular.

Thin sections of 10017 exhibit regions with mineralogical segregations and differences in grain sizes. Plagioclase forms concentrations of large lath-shaped crystals, while adjacent areas are enriched in smaller grains of pyroxene and ilmenite (see figure 1 in French et al. 1970).

Mineralogy

Olivine: none

Pyroxene: The chemical compositions of fine-grained pyroxenes in 10017 were determined by French et al.

Mineralogical Mode for 10017

	Beaty and Albee 1978	French et al. 1970	Brown et al. 1970	Kushiro and Nakamura 70	James and Jackson 70
Olivine	absent				
Pyroxene	50.6 vol. %	49.7	59.4	51	47.6
Plagioclase	23.6	18	25.1	21.5	26.9
Ilmenite	15.1	23.9	14.5	20.2	15
mesostasis	8.5	8.3		6.1	8.5
silica	1.4		tr.	1.1	1.6
troilite	0.5		0.36		
phosphate	0.2				

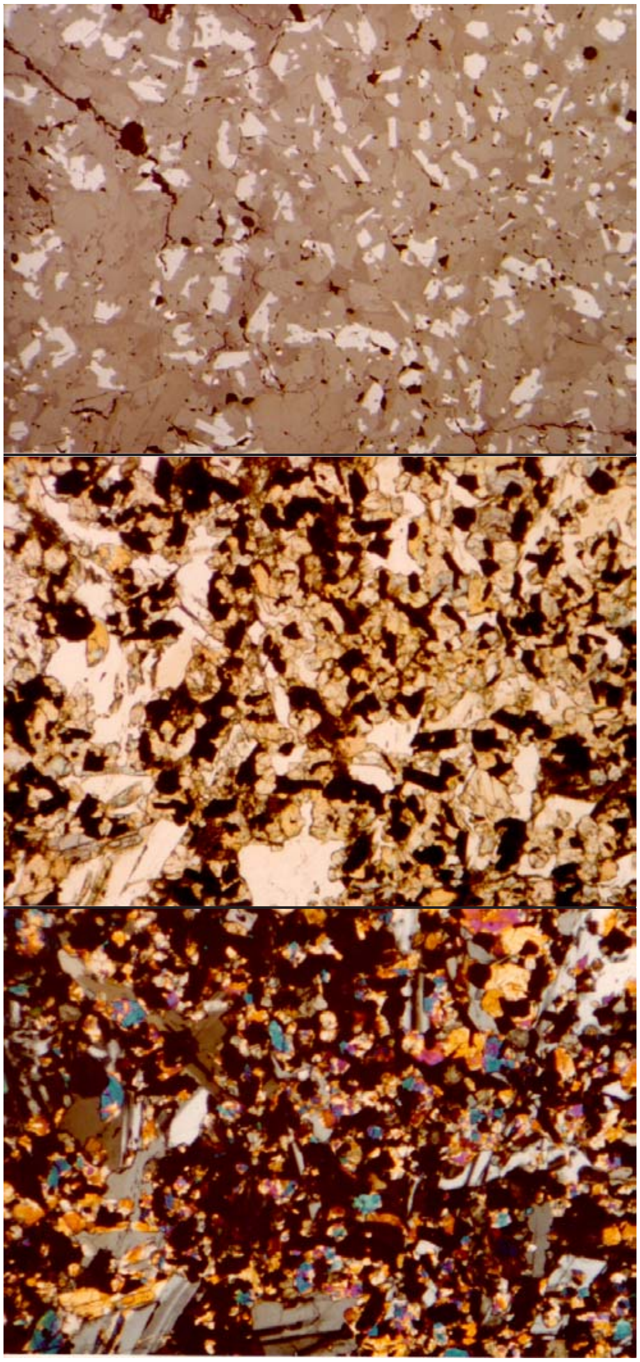


Figure 4: Thin section photomicrographs of 10017,20 (reflected, transmitted and crossed-Nicols of same area). Scale is 2.5 mm across. NASA S79-27113 - 27115.

(1970), Brown et al. (1970), Dence et al. (1970) and Beaty and Albee (1978) (figure 5).

Plagioclase: The composition of plagioclase in 10017 is $An_{78}Ab_{20}Or_2$.

Ilmenite: Ilmenite in 10017 occurs as equant grains (French et al. 1970).

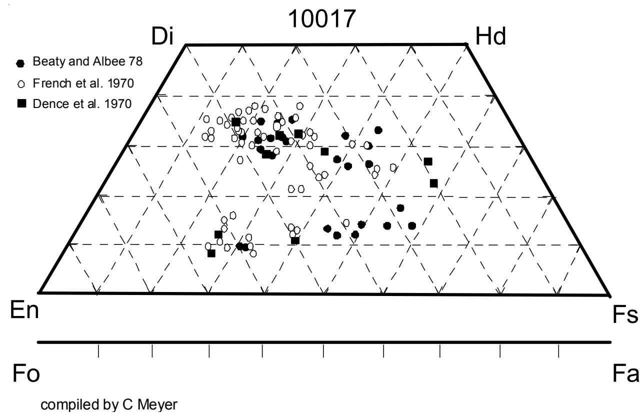


Figure 5: Pyroxene composition of 10017 (note lack of extreme iron enrichment).

Apatite: French et al. give an analysis of fluoroapatite (F = 3.1%).

Silica: Kushiro and Nakamura (1970) report relatively large cristobalite crystals in 10017.

Mesostasis: French et al. (1970) and Dence et al. (1970) report K-rich mesostasis.

Chemistry

Compston et al. (1970), Gast et al. (1970) and others observed that Apollo 11 basalts could be divided in two groups based on the higher K and Rb contents of Group 1 as compared with that of Group 2 (low-K). 10017 belongs to the high-K group and also has higher REE content (figure 6). Anders et al. (1971) found that the meteoritic siderophiles (Ir and Au) were low in this igneous rock. Neal (2001) showed the Ni was low (table 1c). Gibson and Johnson (1970) determined the gas released from 10017 (figure 11).

Radiogenic age dating

Papanastassiou et al. (1970), deLaeter et al. (1973) and Gopalan et al. (1970) determined the Rb/Sr isochron age for 10017 (figures 8, 9). Turner (1970) determined the Ar/Ar age. Eberhardt et al. (1974) determined 2.35 b.y. by whole rock K/Ar.

Cosmogenic isotopes and exposure ages

Perkins et al. (1970) determined the cosmic ray induced activity of ^{22}Na (45 dpm/kg), ^{26}Al (80 dpm/kg), ^{46}Sc (13 dpm/kg) and ^{54}Mn (46 dpm/kg). O'Kelley et al. (1970) determined of ^{22}Na (39 dpm/kg), ^{26}Al (73 dpm/kg), ^{46}Sc (13 dpm/kg) and ^{54}Mn (33 dpm/kg) and ^{56}Co (26 dpm/kg). Wrigley and Quaide (1970) also determined ^{22}Na (47 dpm/kg) and ^{26}Al (83 dpm/kg) in

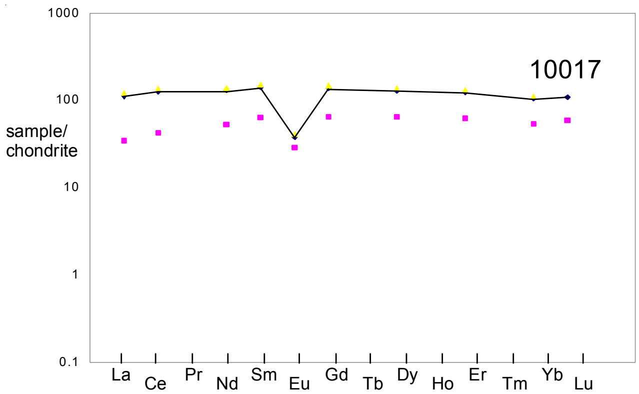


Figure 6: Normalized rare-earth-element composition for high-K basalt 10017 (the line) compared with that of low-K basalt 10020 and high-K basalt 10049 (the dots) (data from Wiesmann et al. 1975).

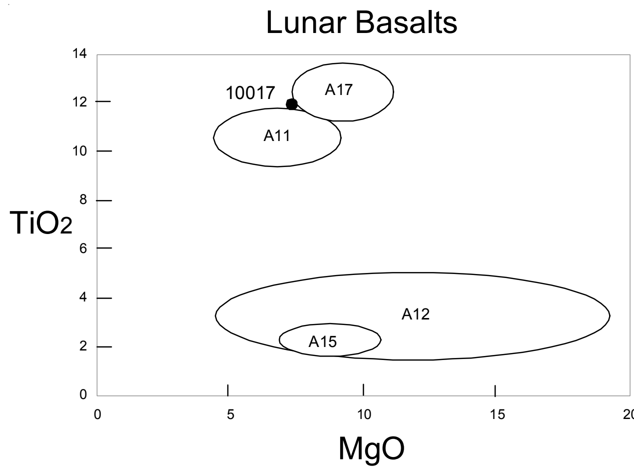


Figure 7: Composition of 10017 compared with that of other lunar basalts.

general agreement if one considers the counting errors (see references).

Eberhardt et al. (1970) observed that high-K basalts had distinctly different exposure ages from low-K Apollo 11 basalts. Eberhardt et al. (1974) determined the cosmic ray exposure age as 480 ± 25 m.y. by the reliable ^{83}Kr method and 371 m.y. by ^{126}Xe (as calculated by Srinivasan 1974) while Marti et al. (1970) determined 509 ± 29 m.y. by ^{83}Kr and 308 m.y. by ^{126}Xe (calculated). Turner (1970) and Hintenberger et al. (1971) reported exposure ages of 440 and 510 m.y. respectively by ^{38}Ar.

Shedlovsky et al. (1970) and O'Kelley et al. (1970) reported significant ^{56}Co (77 days) on the "top" surface of 10017 (125 and 44 dpm/kg respectively), thus establishing its most recent lunar surface orientation.

Other Studies

A detailed cosmic ray depth profile was attempted by Shredlldaff (1970), but only ^{22}Na showed significant variation with depth (table 3). The problem is that this sample was irradiated on both sides, and it was not thick enough to stop high-energy cosmic rays. Additionally, the analytical techniques in 1969 required large subsamples. 10017 was the first of these studies, later carried out with more success on 14310, 68815 and 74275.

Fleischer et al. (1970), Lal et al. (1970) and Crozaz et al. (1970) studied solar flare and cosmic ray tracks as a function of depth in 10017 (figures 15 and 16). The near surface regions were dominated by solar flare tracks and the erosion rate from micrometeorite bombardment could be determined.

Oxygen isotopes were reported for mineral separates of 10017 by Onuma et al. (1970) and Taylor and Epstein (1970).

O'Hara et al. (1970) and Ringwood and Essene (1970) experimentally determined the phase diagram for 10017 (figures 12 and 13). These experiments showed that Apollo 11 basalts probably formed at depths of 200 to 400 km by a small degree of partial melting from pyroxenitic source material.

Eugster et al. (1970) reported a significant isotopic anomaly in ^{158}Gd proving that 10017 had received a high dosage of low energy neutrons over a long period of time (burial?).

Bogard et al. (1971) and Eberhardt et al. (1974) reported the abundance and isotopic ratios of noble gases in 10017.

The elastic properties for a lunar basalt (compressibility, sound velocity) were determined on 10017 by Anderson et al. (1970). The magnetic properties of 10017 were determined by Runcorn et al. (1970) and the remanent magnetization was found to be weak.

Processing

10017 was returned in ALSRC #1004 and originally processed in the "Vac Lab". It was one of the rocks in the F-201 at the time of the glove rupture (with

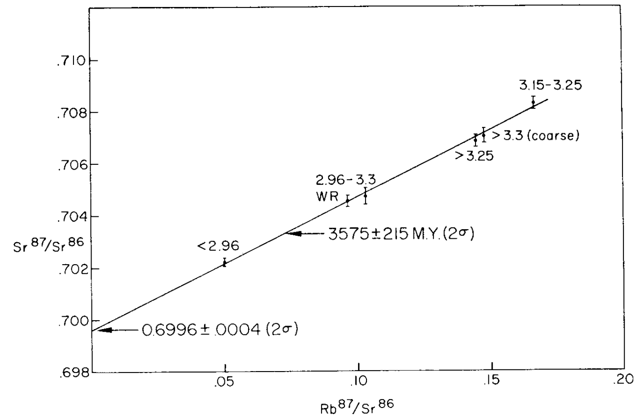


Figure 8: Rb/Sr isochron for 10017 (from Gopalan et al. 1970).

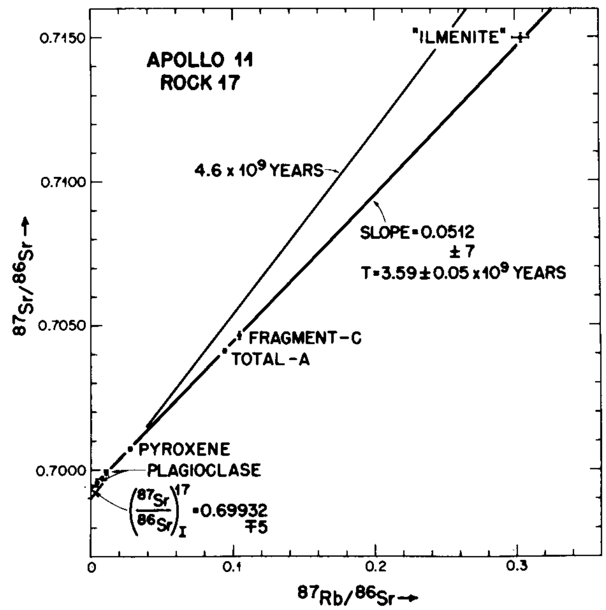


Figure 9: Rb/Sr isochron for 10017 (from Papanastassiou and Wasserburg 1970).

exposure to Houston air). Apollo 11 samples were originally described and cataloged in 1969 and "recataloged" by Kramer et al. (1977).

10017 originally broke in two large pieces (,5 and ,6) along a penetrating fracture (figure 19). Surface pieces ,74 and ,42 from opposite ends of this fractured surface were allocated to Arnold.

Shredlldaff (1970) illustrated the cutting plan as it pertained to their depth profile studies (figure 14). A cube (,180) and a column (,64) were cut from the sample by sawing (figure 18). *All the King's men couldn't put 10017 together again !*

There are 24 thin sections for 10017.

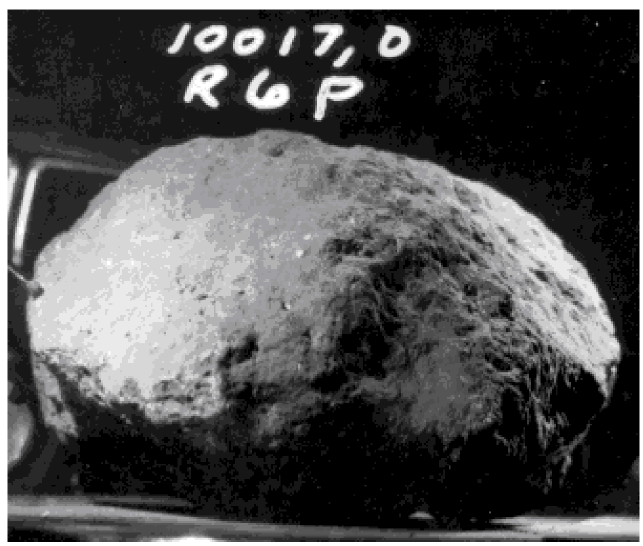


Figure 10: Original PET photo of side of 10017,0 in F-201. The sample is sitting on its top surface (flatter side). NASA S69-45375.

Summary of Age Data for 10017

	Rb/Sr	Nd/Sm	Ar/Ar	K/Ar
Papanastassiou et al. 1970	3.59 ± 0.05 b.y.			
deLaeter et al. 1973	3.71 ± 0.11			
Gopalan et al. 1970	3.575 ± 0.215			
Turner 1970			3.23 ± 0.06	
Eberhardt et al. 1974				2.35 ± 0.06 whole rock

Caution: These ages have not been corrected for new decay constants.

Table 1a. Chemical composition of 10017.

reference	LSPET69		Maxwell70			Maxwell70		Gast70		Wiesmann75		Perkins70		Wrigley70		O'Kelley70	
weight			GSC	GSF		Abbey				187 mg		115 g		115 g		971 g	
SiO2 %	40	(a)	40.78	40.77	(b)	40.14	(c)										
TiO2	11	(a)	11.71	11.82	(b)	11.16	(c)										
Al2O3	10	(a)	8.12	7.92	(b)	8.17	(c)										
FeO	19	(a)	19.82	19.79	(b)	19.38	(c)										
MnO	0.35	(a)	0.22	0.22	(b)	0.25	(c)										
MgO	8.5	(a)	7.65	7.74	(b)	7.72	(c)										
CaO	10	(a)	10.55	10.58	(b)	10.99	(c)										
Na2O	0.65	(a)	0.51	0.51	(b)	0.51	(c)	0.51	(e)	0.51	(e)						
K2O	0.22	(a)	0.3	0.29	(b)	0.3	(c)	0.31	(d)	0.31	(d)	0.31	(h)			0.29	(h)
P2O5			0.13	0.18	(b)	0.15	(c)										
S %			0.22		(b)												
sum																	
Sc ppm	55	(a)	52	77	(b)												
V	30	(a)	49	70	(b)												
Cr	4600	(a)	2200	2260	(b)	2463	(c)										
Co	10	(a)	20	30	(b)												
Ni																	
Cu				20	(b)												
Zn			49	47	(b)												
Ga																	
Ge ppb																	
As																	
Se																	
Rb	6	(a)						5.63	(d)	5.63	(d)						
Sr	55	(a)						175	(d)	175	(d)						
Y	310	(a)	160	160	(b)												
Zr	1250	(a)	410	430	(b)												
Nb																	
Mo																	
Ru																	
Rh																	
Pd ppb																	
Ag ppb																	
Cd ppb																	
In ppb																	
Sn ppb																	
Sb ppb																	
Te ppb																	
Cs ppm								0.16	(d)	0.155	(d)						
Ba	120	(a)						309	(d)	309	(d)						
La								26.6	(d)	26.6	(d)						
Ce								77.3	(d)	77.3	(d)						
Pr																	
Nd								59.5	(d)	59.5	(d)						
Sm				25	(b)			20.9	(d)	20.9	(d)						
Eu				2.1	(b)			2.14	(d)	2.14	(d)						
Gd								27.4	(d)	27.4	(d)						
Tb				4	(b)												
Dy								31.7	(d)	31.7	(d)						
Ho																	
Er								20	(d)	20	(d)						
Tm																	
Yb				19	(b)			19.2	(d)	17.1	(d)						
Lu				5	(b)			2.66	(d)	2.66	(d)						
Hf				12	(b)												
Ta				5	(b)												
W ppb																	
Re ppb																	
Os ppb																	
Ir ppb																	
Pt ppb																	
Au ppb																	
Th ppm				4.6	(b)							3.2	(h)	2.9	(h)	3.25	(h)
U ppm												0.86	(h)	0.9	(h)	0.83	(h)

technique: (a) OES, (b) mixed, (c) atomic absorption spec., colorimetry, (d) idms, (e) AA, (f) wet, (g) XRF, (h) radiation counting

Table 1b. Chemical composition of 10017.

reference	Tera70		Wanke70		Dickinson89			Wiik70		Philpotts69 Philpotts70		Haramura in Kushiro 70		Compston70		Wakita70		
weight										125 mg						637 mg	343 mg	
SiO2 %			41.9					40.77	(b)			40.03	(f)	40.69	(g)	42.8	44.5	(a)
TiO2			11.7					11.82	(b)			11.61	(f)	11.92	(g)		13	(a)
Al2O3			8.3					7.92	(b)			8.04	(f)	7.78	(g)	7.94	7.6	(a)
FeO			18.8					19.79	(b)			20.46	(f)	19.59	(g)	21.9	23.3	(a)
MnO			0.19					0.22	(b)			0.24	(f)	0.28	(g)	0.24	0.25	(a)
MgO			7.96					7.74	(b)			8.17	(f)	7.51	(g)	7.96	7.63	(a)
CaO	10.3	(d)	11.5		8.8	13.4		10.58	(b)			10.26	(f)	10.76	(g)		10.6	(a)
Na2O	0.47		0.42		0.4	0.43		0.51	(b)			0.49	(f)	0.51		0.49	0.5	(a)
K2O	0.29	(d)	0.25					0.29	(b)	0.29	(d)	0.3	(f)	0.3	(g)	0.19	0.26	(a)
P2O5								0.18	(b)			0.17	(f)	0.18	(g)			
S %														0.23	(g)			
sum																		
Sc ppm			86	(a)	73	80	(a)	77	(b)							87	93	(a)
V						820	(a)	70	(b)							49	43	(a)
Cr			2310	(a)	1500	2600	(a)	2258	(b)			2326	(f)			2450	2710	(a)
Co			24.5	(a)	24	26	(a)	30	(b)							35	37	(a)
Ni								<5	(b)									
Cu			7.7	(a)				20	(b)									
Zn								47	(b)									
Ga			4.2	(a)		56	(a)											
Ge ppb					5.5	6	(a)											
As																		
Se																		
Rb	5.57	(d)	4.2	(a)						5.7	(d)			5.72	(g)	6		(a)
Sr	156	(d)	151	(a)	151					165	(d)			164	(g)			
Y								160	(b)					159	(g)	184		(a)
Zr					418			430	(b)					476	(g)	1200	1570	(a)
Nb																		
Mo																		
Ru																		
Rh																		
Pd ppb			1	(a)														
Ag ppb																		
Cd ppb																44		(a)
In ppb			138	(a)												1		(a)
Sn ppb																		
Sb ppb																		
Te ppb																		
Cs ppm	0.159	(d)	0.12	(a)												0.26		(a)
Ba	280	(d)	256	(a)	254	258	(a)			287	(d)					350	410	(a)
La			21	(a)	22.1	23.8	(a)									24	28	(a)
Ce			64	(a)	62	62	(a)			75.5	(d)					84		(a)
Pr			7.3	(a)												12.9		(a)
Nd			58	(a)	56	54	(a)			66.1	(d)					74		(a)
Sm			18	(a)	15	19	(a)	25	(b)	23.4	(d)					23	27	(a)
Eu			1.89	(a)	1.9	2.1	(a)	2.1	(b)	2.26	(d)					2.3	2.9	(a)
Gd			19	(a)						28.4	(d)					30		(a)
Tb			4.6	(a)	4.7	5	(a)	4	(b)							5.5		(a)
Dy			19	(a)						32.8	(d)					36		(a)
Ho			3.8	(a)												8.3		(a)
Er			13	(a)		11.5	(a)			19.1	(d)					21		(a)
Tm						2	(a)									3		(a)
Yb			15.6	(a)	15.8	16.4	(a)	19	(b)	18.1	(d)					17.8	23	(a)
Lu			2.12	(a)	2.4	2.7	(a)	5	(b)	2.63	(d)					2.5	3	(a)
Hf			16.5	(a)	13.2	14.9	(a)	12	(b)							23	26	(a)
Ta			2.2	(a)	1.9	2.1	(a)	5	(b)									
W ppb			0.4	(a)														
Re ppb																		
Os ppb																		
Ir ppb																		
Pt ppb																		
Au ppb			8.1	(a)														
Th ppm			3.94	(a)	2.9	3.1	(a)	4.6	(b)					3.7	(g)	4.3	6.4	(a)
U ppm			0.69	(a)														

technique: (a) INAA & RNAA, (b) mixed, (c) atomic absorption spec., colorimetry, (d) idms, (e) AA, (f) wet, (g) XRF

Table 1c. Chemical composition of 10017.

reference	Anders71		Neal2001	
weight				
SiO2 %				
TiO2				
Al2O3				
FeO				
MnO				
MgO				
CaO				
Na2O				
K2O				
P2O5				
S %				
sum				
Sc ppm			75.4	(b)
V			47.6	(b)
Cr			2019	(b)
Co	31	(a)	27.9	(b)
Ni			6.37	(b)
Cu			32.8	(b)
Zn	18	(a)	73.6	(b)
Ga	5.1	(a)	4.9	(b)
Ge ppb				
As				
Se	0.215	(a)		
Rb	6.6	(a)	5.22	(b)
Sr			143	(b)
Y			147	(b)
Zr			334	(b)
Nb			25	(b)
Mo			0.99	(b)
Ru				
Rh				
Pd ppb				
Ag ppb	16	(a)		
Cd ppb	68	(a)		
In ppb	70	(a)		
Sn ppb				
Sb ppb			20	(b)
Te ppb				
Cs ppm	0.186	(a)	0.37	(b)
Ba			243	(b)
La			23.2	(b)
Ce			81.8	(b)
Pr			11.2	(b)
Nd			61.6	(b)
Sm			21.2	(b)
Eu			2.03	(b)
Gd			27.7	(b)
Tb			4.8	(b)
Dy			29.8	(b)
Ho			6.31	(b)
Er			17.7	(b)
Tm			2.39	(b)
Yb			17.3	(b)
Lu			2.12	(b)
Hf			14	(b)
Ta			1.69	(b)
W ppb			0.51	(b)
Re ppb				
Os ppb				
Ir ppb	0.02	(a)		
Pt ppb				
Au ppb	0.72	(a)		
Th ppm			2.66	(b)
U ppm			0.77	(b)

technique: (a) RNAA, (b) ICP-MS

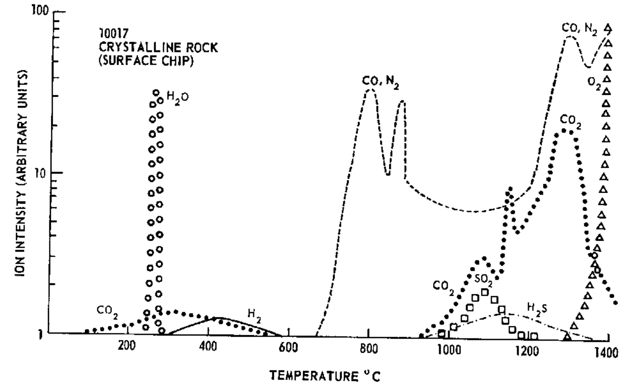


Figure 11: Gas released as function of increasing temperature for 10017 (Gibson et al. 1971).

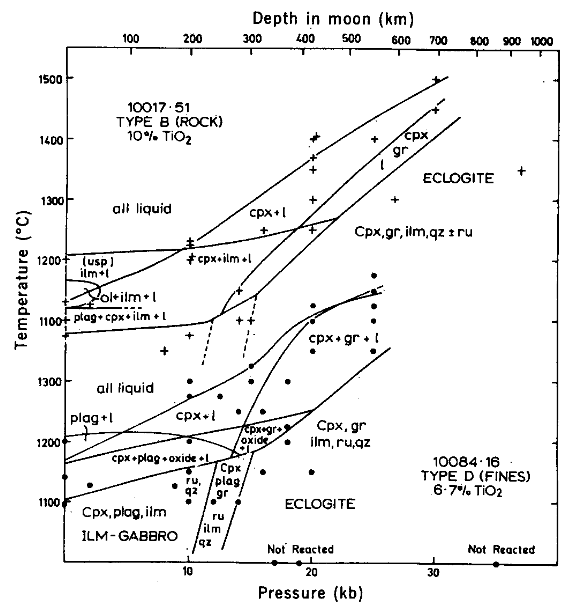


Figure 12: Phase diagram determined for 10017 (and 10084?) by O'Hara et al. 1970.

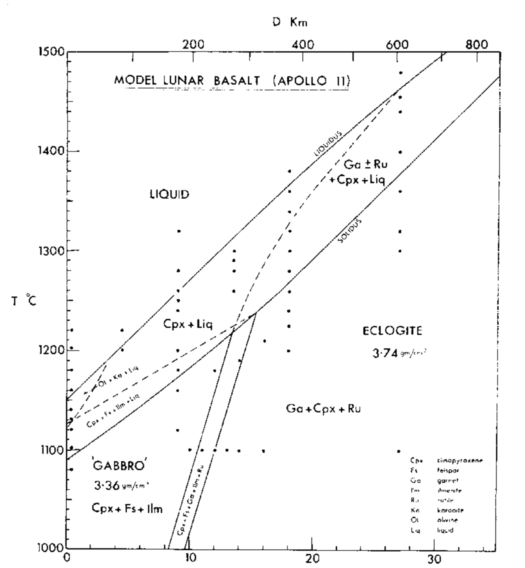


Figure 13: Phase diagram for Apollo 11 basalt from Ringwood and Essene 1970.

Table 2

	U ppm	Th ppm	K ppm	Rb ppm	Sr ppm	Nd ppm	Sm ppm	technique
Perkins et al. 1970	0.86	3.2	2600					rad. Cout.
O'Kelley et al. 1970	0.83	3.25	2430					rad. Cout.
Tatsumoto 70	0.854	3.363						idms
Silver 1970	0.73	2.72						idms
Gopalan et al. 1970			2500	5.8	174.2			
Murthy			2207	5.33	169			idms
Gast and Hubbard 1970			2610	5.63	174.8	59.7	21	idms
Philpotts 1970			2390	5.7	165	66.1	23.4	idms
Wanke et al. 1970	0.69	3.05	2060	4.2		58	11.9	inaa
Compston et al. 1970		3.7		5.72	163.7			

Table 3: Cosmic-ray induced activity in dpm/kg

depth	0 - 4 mm	4 - 12 mm	12 - 30 mm	60 mm
nuclide				
Be10	14		16	
Na22	81	43	37	31
Al26	133	74	66	65
Cl36	<33	16	17	
Mn53	94	43	50	48
Mn54	36	39	10	36
Fe55	445	96	94	98
Co56	125	<16	<8	
Co57	5.8	<1.5	<2.3	

(see SHRELLDALFF 1970 for associated counting errors)

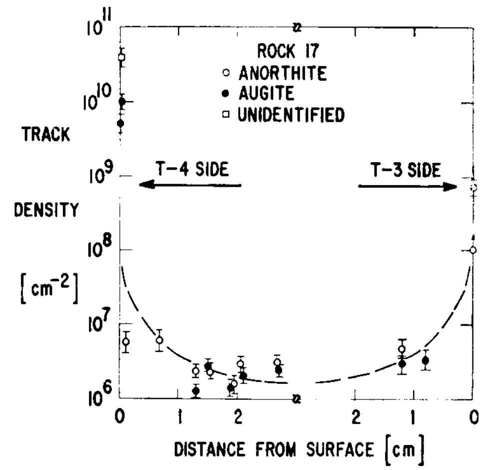


Figure 15: Track denisty for 10017 (from Fleischer et al. 1970).

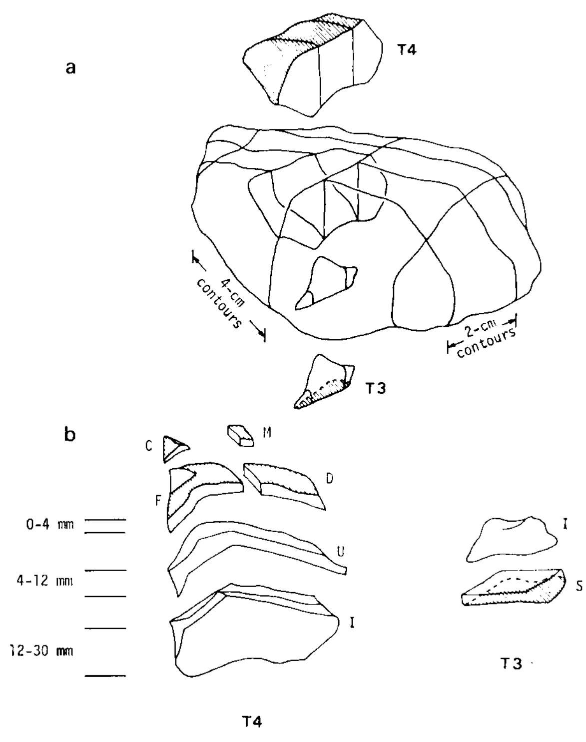


Figure 14: Cutting diagram for 10017 (as depicted in paper by Shedlovsky et al. 1970).

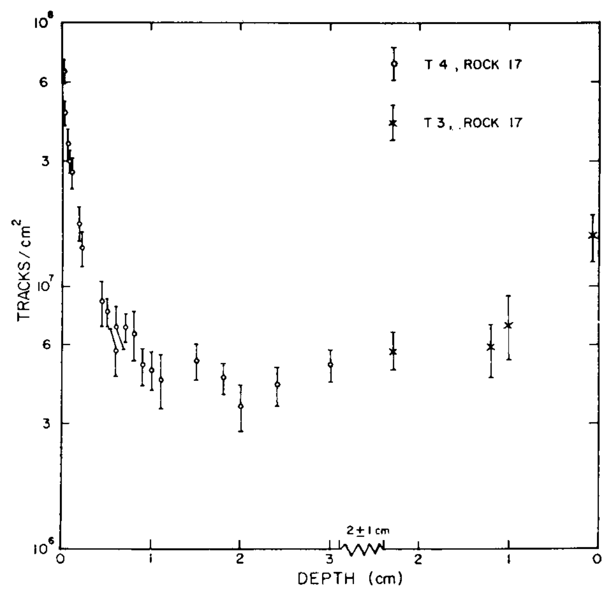


Figure 16: Track density of top and bottom of 10017 (as determined by Lal et al. 1970).

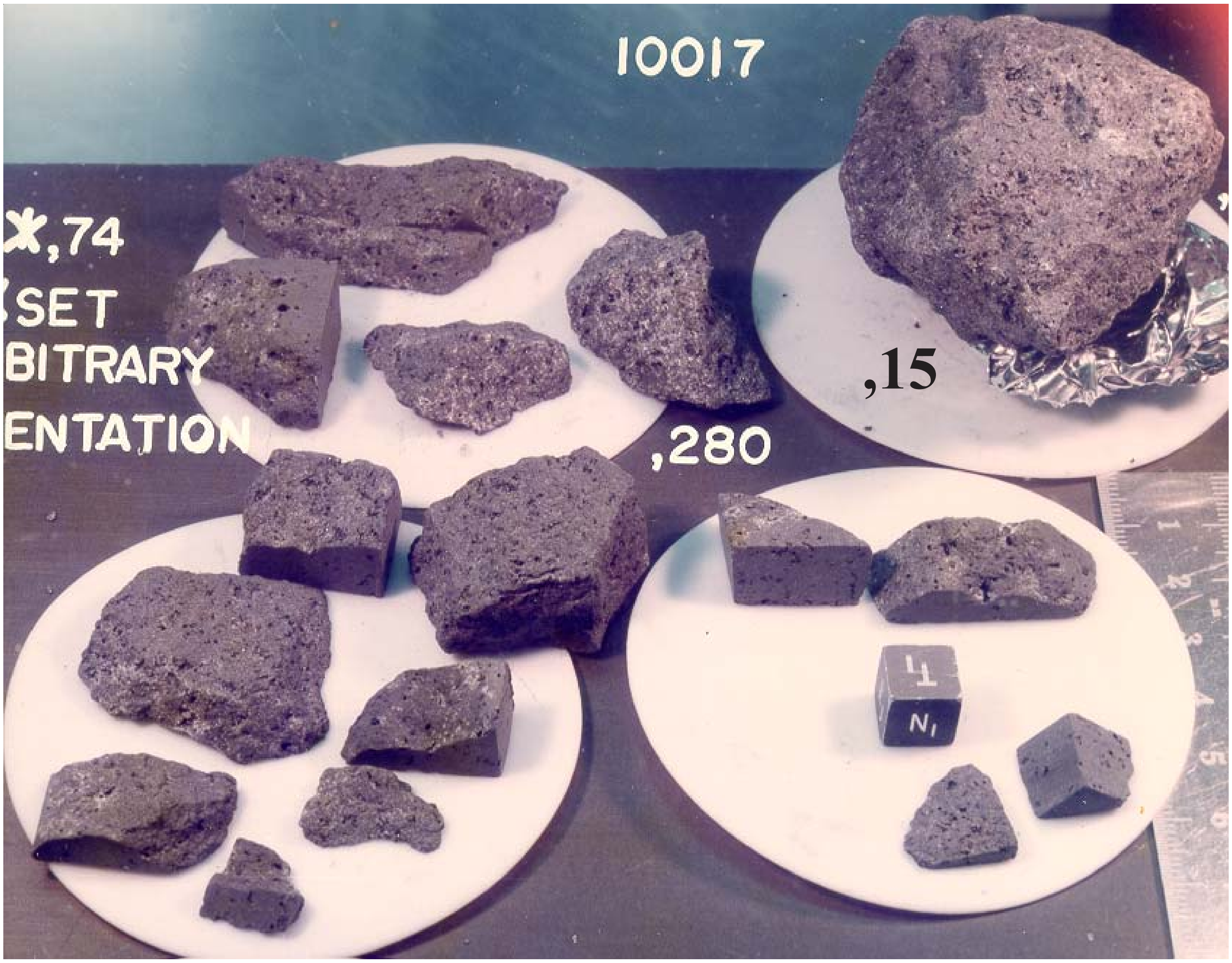


Figure 17 : Group photo of 10017. NASA S75-30215. Cube is 1 cm.

Figure 18: Group photo of 10017. NASA S76-21150. Cube is 1 cm.

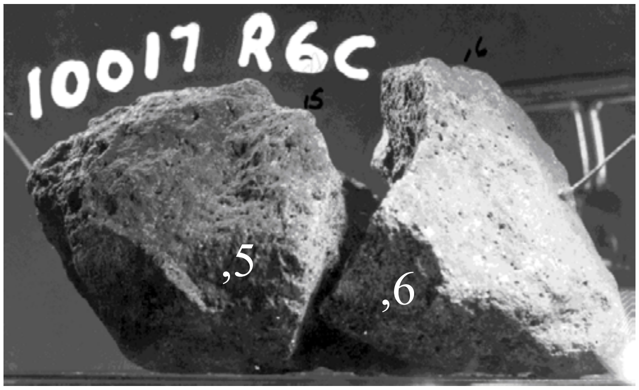


Figure 19: Photo showing original break of 10017. S69-49220.

The band saw used to cut lunar samples, created a lot of heat, perhaps even melting the rock – see cube ,180 in figure 18.

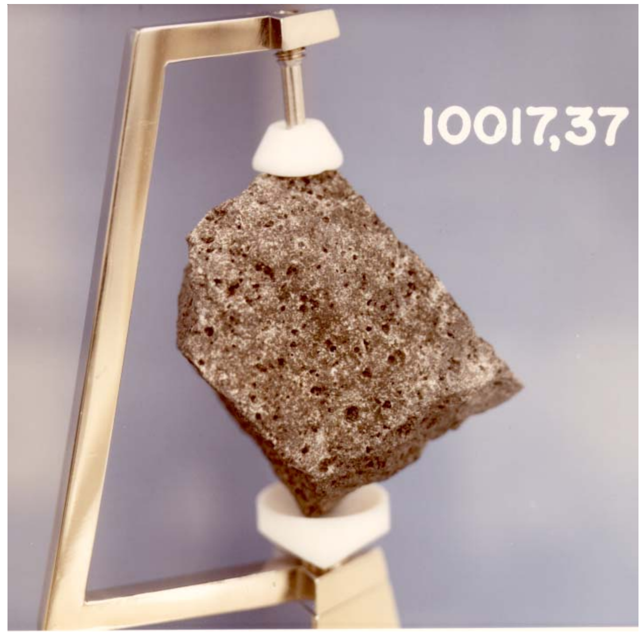
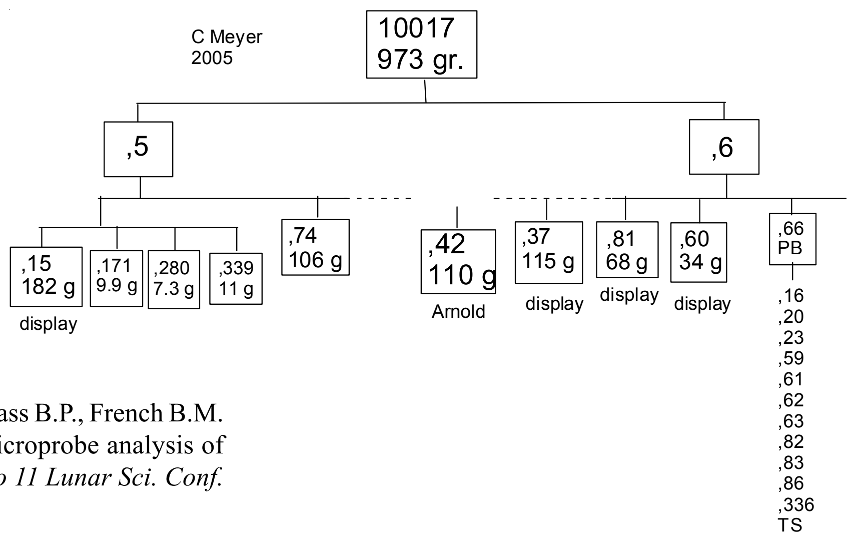


Figure 20: Photo of display sample 10017,37 showing micrometorite craters and vesicles. NASA photo #S84-40064.



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