77017

Feldspathic Granulitic Impactite

1730 grams

Figure 1 : Photo of sawn surface of 77017,15 before slab was cut. Sample is 7 cm across. NASA S75-34250. See also figure 16 .

Introduction

Lunar sample 77017 contains a large, annealed feldpathic breccia set in a frothy black glass matrix. A photograph of a slab cut through this rock reveals how the anorthositic portion has been incorporated in the black glass matrix (figure 1).

This rock sample has experienced several thermal and shock events. The feldspathic portion is an annealed gabbroic rock. However, Warner et al. (1977) recognized that the feldspathic portion of 77017 was an impactite, because it contained a high concentration of meteoritic siderophile elements. Shock features indicate subsequent impact followed by the addition of black glass of mare composition.

Hudgins et al. (2008) recently described, analyzed and dated 77017. The major metamorphic event forming the feldspathic portion was at about 4 b.y., while the glass-forming event was about ~1.5 b.y. The sample has been exposed to cosmic ray irradation for about 100 m.y.

Figure 2: Photo of "anorthositic" side of 77017 showing numerous zap pits. Cube is 1 cm. S73-17770 (faded).

Figure 3: Photo of frothy side of 77017 showing chunks of feltdpathic material in frothy black glass coating. Cube is 1 cm. S73-17768.

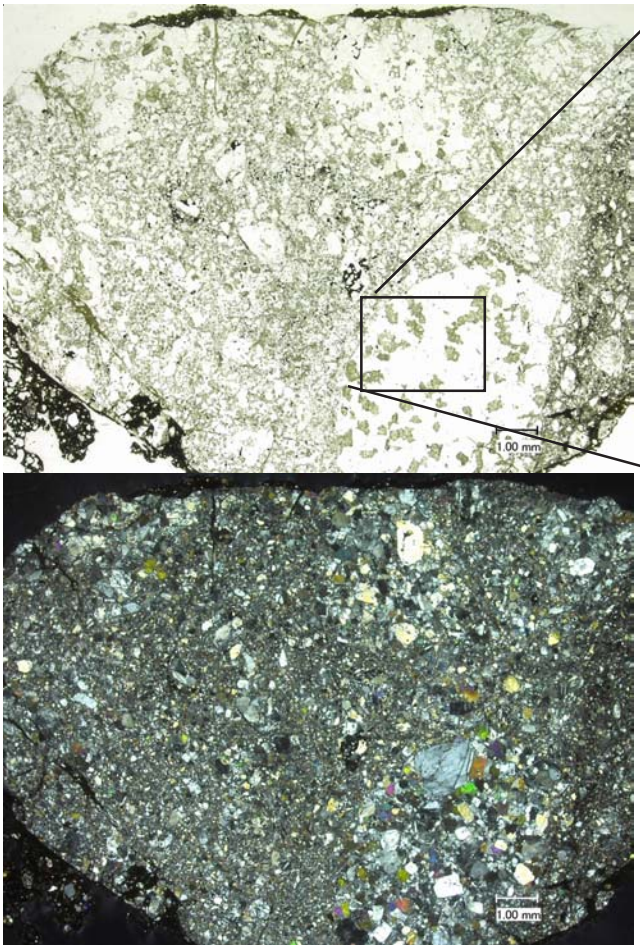

Figure 4a: Photomicrographs of thin section 77017,69 by C Meyer @ 20x.

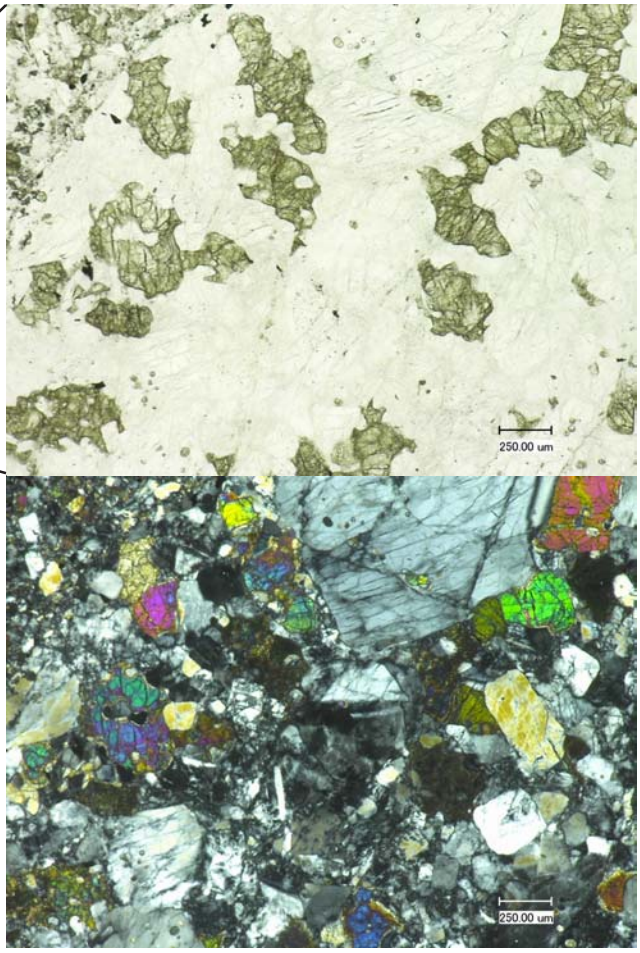

Figure 4a: Photomicrographs of norite clast in thin section 77017,69 by C Meyer @ 200x.

Petrography

77017 has been described by Helz and Appelman (1974), McCallum et al. (1974), Ashwal (1975), McGee et al. (1979), Meyer (1994), Cushing et al. (1999) and Hudgins et al. (2008). The feldspathic portion has been described as an olivine-bearing, anorthositic gabbro with a relatively coarse-grained poikilitic (or poikiloblastic) texture (figure 4). According to McCallum et al. (1974) there are areas with relict lithic clasts of annealed troctolitic anorthosite and anorthosite. Mineral clasts of plagioclase, olivine, pink spinel and ilmenite are enclosed within pigeonite and augite oikocrysts. All minerals show a restricted composition range and the various feldspathic areas all appear to be of similar type.

An early shock event has caused partial granulation, producing a fine-grained cataclastic matrix (figures 4 and 5). The proportions and compositions of minerals in the crushed areas are the same as in the uncrushed, indicating that the breccia is monomict. However, black glass has intruded the fragments of feldspathic breccia. The glass has a compsoition of mare basalt and is foreign. Finally, additional shock features such as undulatory extinction, mosaicism and partial vitrification of plagioclase indicate another, mild shock event.

Plagioclase in relict anorthosite and troctolitic anorthosite clasts has well-developed polygonal grain boundaries. This relict granulitic texture is indicative

Mineralogical Mode for 77017

	McCallum et al. 1974
Plagioclase	75%
Olivine	~5%
Pigeonite	10
Augite	10
Opaque	trace

Figure 5: Thin section photomicrograph, with crossed nicols, of poikiloblastic portion of 77017.

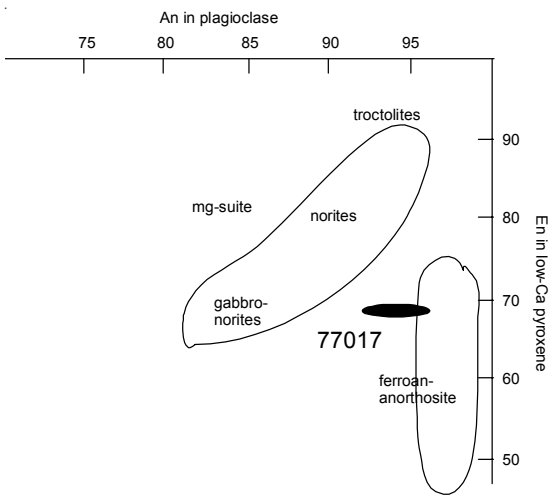

Figure 6: Plagioclase and pyroxene composition of lunar highlands samples showing 77017.

of extensive subsolidus annealing at high temperature. Temperatures of this metamorphism can be calculated from the composition of pyroxene pairs: 1050 to 1100 deg C (McCallum et al. 1974) or 1137 deg C (Cushing et al. 1999). Helz and Appelman (1974) and Lindstrom and Lindstrom (1986) interpret the feldspathic clasts in 77017 to represent a plutonic anorthositic norite lithology that was brecciated and metamorphosed to produce the poikilitic texture.

Mineralogy

Plagioclase: Plagioclase (An_{92-97}) grains in 77017 are characteristically highly fractured and display offset twinning, undulatory extinction and mosaicism (figure 5).

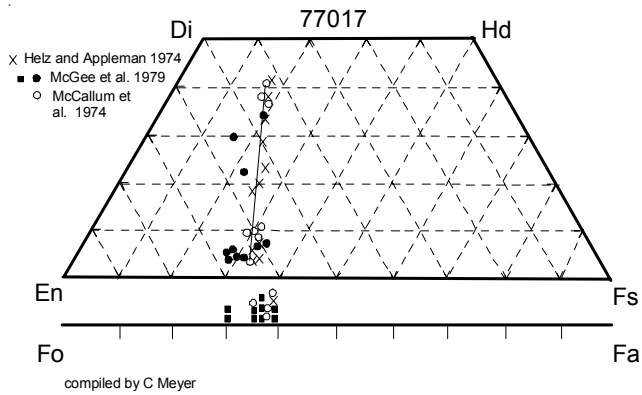

Figure 7: Pyroxene and olivine composition of feldspathic portion of 77017 (from Helz and Appleman 1974, McCallum et al 1974, McGee et al. 1979).

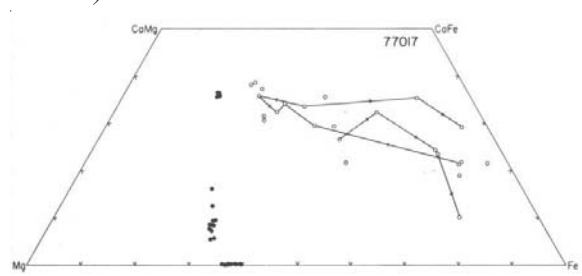

Figure 8: Pyroxene and olivine from 77017 (Hodges and Kushiro 1974). Open symbols are of a mare basalt clast and filled circles are of the feldspathic, granulitic portion.

Olivine: Olivine in 77017 is Fo_{58-62}. Much is made of olivine "necklaces" in large plagioclase.

Pyroxene: Helz and Appelman (1974), Hodges and Kushiro (1974), Cushing et al. (1999), McCallum et al. (1974) and Hudgins et al. (2008) reported pyroxene composition (figures 7 and 8). Pyroxene oikocrysts are typically homogeneous. According to Hudgins et al., high-Ca clinopyroxene is $Wo_{21-42}En_{43-57}Fs_{15-22}$, low-Ca clinopyroxene is $Wo_{5-17}En_{58-66}Fs_{25-34}$ and orthopyroxene is $Wo_{3-5}En_{61-71}Fs_{26-35}$. Augite oikocrysts have low-Ca exsolution. Other pyroxene grains found in the black glass are apparently from mare basalt (figure 8).

Spinel: Taylor and Williams (1974) reported pink spinel.

Ilmenite: Ilmenite grains have poikilitic texture, enclosing plagioclase and mafic minerals. Ilmenite in 77017 has 3.1 – 4.9 % MgO (Hudgins et al. 2008).

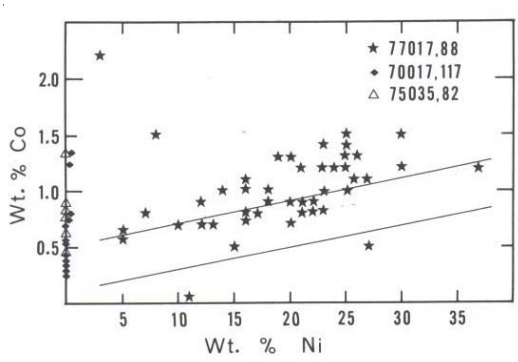

Figure 9: Ni and Co in metal grains in 77017 (from Taylor and Williams 1974).

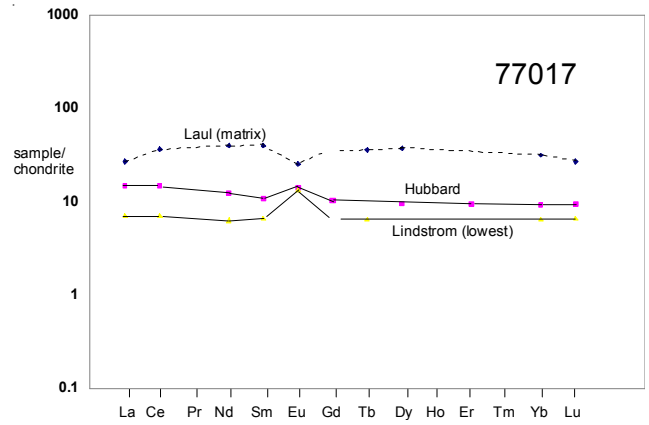

Figure 10: Normalized rare-earth-element diagram for 77017 (see tables).

Metal: Taylor and Williams (1974) and Hewins and Goldstein (1975) found the metal grain in 77017 were high in Ni and Co, but generally within the range of meteoritic metal (figure 9).

Chemistry

LSPET (1973), Hubbard et al. (1974), Laul et al. (1974), Morgan et al. (1974), Lindstrom and Lindstrom (1986) and Hudgins et al. (2008) determined the chemical composition of 77017 including trace elements and siderophiles (tables and figure 10). The apparent lack of trace elements that normally are abundant in KREEP has been discussed by Warner et al. (1977). The high content of meteoritic siderophiles (Ir, Au etc) in the feldspathic portion strongly indicates that this rock was formed or influenced by impact.

Gibson and Moore (1974) determined S = 955 ppm. Moore et al. (1974) and Petrowski et al. (1974) determined C = 80 ppm and 25 ppm respectively. Moore and Lewis (1976) and Muller et al. (1976) determined nitrogen 45 = ppm and 5 ppm, respectively.

Radiogenic age dating

Kirsten and Horn (1974), Phinney et al. (1975) and Hudgins et al. (2008) determined the "age" of 77017 by the Ar/Ar plateau technique (figures 11-13) – but it is not clear what these ages mean. The high temperature plateau at about 4 b.y. may be the time of (granulitic) metamorphism.

Nunes et al. (1975) reported U/Th/Pb analyses and Nyquist et al. (1974) reported Rb/Sr studies, but these studies did not yield radiometric ages.

Summary of Age Data for 77017

	Ar/Ar
Kirsten and Horn 1974	3.98 ± 0.1 b.y.
	and 1.5 ± 0.3 b.y.
Phinney et al. 1975	3.82 ± 0.02 b.y.
Hudgins et al. 2008	4.016 ± 0.039 b.y.
	and ~ 2.3 b.y.

Ages have been corrected using decay constants recommended by Steiger and Jager 1977.

Cosmogenic isotopes and exposure ages

Kirsten and Horn (1974), Phinney et al. (1975) and Hudgins et al. (2008) determined cosmic ray expsoure ages of 80 m.y., 224 ± 20 m.y., 133 ± 9.5 m.y., respectively, by the ^{38}Ar method.

Other Studies

Mayeda et al. (1975) determined the oxygen isotopic composition of mineral separates from 77017, discussing the temperature of equilibration. *But these mineral separates could not be pure!*

Charette and Adams (1977) compared spectra of 77017 with other samples.

Huffman et al. (1974), Nagata et al. (1974, 1975), Pearce et al. (1974), Schwerer and Nagata (1976) and Cisowski et al. (1983) determined magnetic properties. Mizutani and Osako (1974) determined the elastic wave velocity of 77017 and also measured thermal diffusivity.

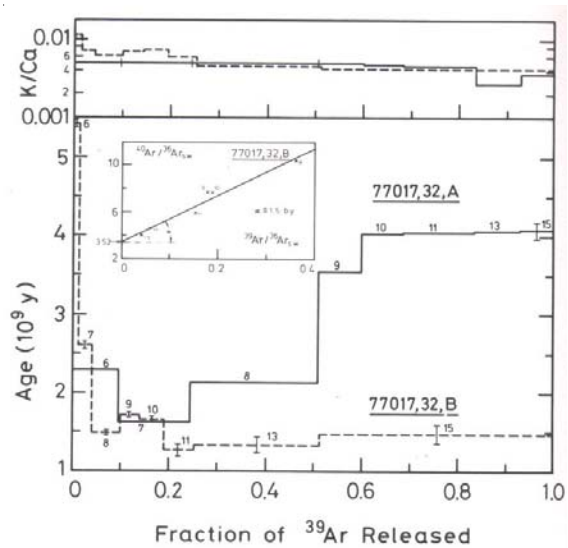

Figure 11: Ar/Ar plateau diagrams for 77017 (Kirsten and Horn 1974).

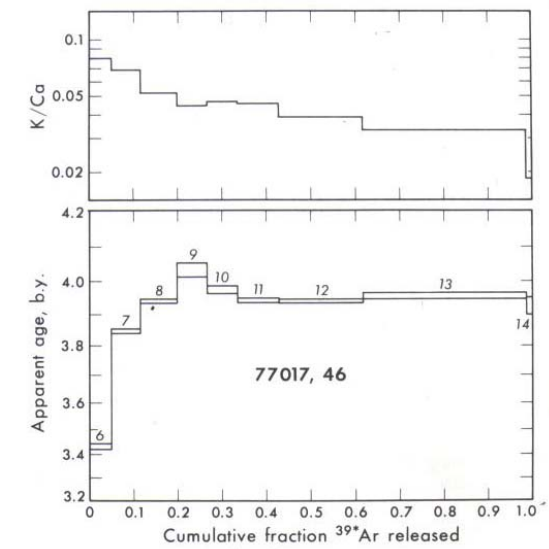

Figure 12: Ar/Ar plateau diagram for 77017 (Phinney et al. 1975).

Processing

A slab was cut through the middle of 77017 (figure 16). A large piece (,14 = 1053 g) remains unstudied. One suspects, but one does not know, that all the feldspathic material is the same. However, to make real progress, it would seem best that a consortium chief, with a petrologic background, should carefully organize future study so that chemistry, petrography and isotope studies can be matched to their respective lithology.

There are 32 thin sections of 77017 (see diagram).

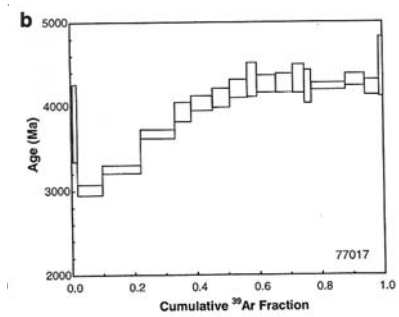

Figure 13: Ar/Ar plateau diagram for 77017 (Hudgins et al. 2008).

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Table 1a. Chemical composition of 77017.

reference	LSPET 73		Laul 74				Morgan 74		Hubbard74		Nunes74		
weight	Hubbard74		,57	"matrix"	gray				Wiesmann75				
SiO2 %	44.09	(a)											
TiO2	0.41	(a)	0.75	5.3	0.35	(b)							
Al2O3	26.59	(a)	26	18.9	27.1	(b)							
FeO	6.19	(a)	6.2	12.1	5.7	(b)							
MnO	0.08	(a)	0.085	0.155	0.077	(b)							
MgO	6.06	(a)	6	8	6	(b)							
CaO	15.43	(a)	14.5	11.7	15.7	(b)							
Na2O	0.3	(a)	0.31	0.39	0.36	(b)			0.43				
K2O	0.06	(a)	0.05	0.1	0.076	(b)			0.051	(c)			
P2O5	0.03	(a)											
S %	0.15	(a)											
sum													
Sc ppm			12	36	9.8	(b)							
V			40	70	40	(b)							
Cr	889	(a)	959	1984	862	(b)			881	(c)			
Co			24	27	23	(b)							
Ni	95	(a)	290	290	300	(b)	443	(d)					
Cu													
Zn	4	(a)					2.5	(d)					
Ga													
Ge ppb							110	(d)					
As													
Se							68	(d)					
Rb	1.2	(a)					1.34	(d)	1.3	(c)			
Sr	141	(a)							141	(c)			
Y	14	(a)											
Zr	50	(a)		200		(b)			59.1	(c)			
Nb	4.1	(a)											
Mo													
Ru													
Rh													
Pd ppb													
Ag ppb							0.87	(d)					
Cd ppb							9	(d)					
In ppb													
Sn ppb													
Sb ppb							0.72	(d)					
Te ppb							1.9	(d)					
Cs ppm							0.061	(d)					
Ba			30	70	40	(b)			49	(c)			
La			3.3	6.4	3.6	(b)			3.48	(c)			
Ce			9	22	10	(b)			8.9	(c)			
Pr													
Nd			5	18	5	(b)			5.56	(c)			
Sm			1.5	5.9	1.7	(b)			1.6	(c)			
Eu			0.78	1.42	0.81	(b)			0.794	(c)			
Gd									2.01	(c)			
Tb			0.3	1.3	0.3	(b)							
Dy			2.4	9	2.4	(b)			2.34	(c)			
Ho													
Er									1.5	(c)			
Tm													
Yb			1.6	5.1	1.4	(b)			1.5	(c)			
Lu			0.21	0.66	0.18	(b)			0.23	(c)			
Hf			1.5	4.9	1	(b)			1.6	(c)			
Ta			0.22	0.85	0.14	(b)							
W ppb													
Re ppb							1.73	(d)					
Os ppb													
Ir ppb			10	9	10	(b)	17	(d)					
Pt ppb													
Au ppb			3	3	3	(b)	5.65	(d)					
Th ppm			0.4	0.6		(b)					1.025	1.49	(d)
U ppm							0.137	(d)	0.22	(c)	0.27	0.415	(d)

technique: (a) XRF, (b) INAA, (c) IDMS, (d) RNAA

Table 1b. Chemical composition of 77017.

reference	Lindstrom and Lindstrom 86										
weight	151G	151	152	153	154	155	2	57	57D	57G	
SiO2 %											
TiO2	1.17	0.7		0.41			0.41	0.75	5.3	0.35	(a)
Al2O3	24.9	24.7		24.9			26.59	26	18.9	27.1	(a)
FeO	6.34	5.99	6.18	6.21	6.02	6.02	6.19	6.2	12.1	5.7	(a)
MnO							0.08	0.085	0.155	0.077	(a)
MgO	6.2	6.5		6.1			6.06	6	8	6	(a)
CaO	15.5	14.9	15.3	15.4	14.9	15	15.43	14.5	11.7	15.7	(a)
Na2O	0.36	0.33	0.34	0.34	0.34	0.33	0.3	0.31	0.39	0.36	(a)
K2O							0.05	0.05	0.1	0.076	(a)
P2O5											
S %											
sum											
Sc ppm	15.1	13.4	12	13.1	11.8	11.5		12	36	9.8	(a)
V											
Cr	1018	1092	853	932	986	839	881	960	1986	863	(a)
Co	28.5	24.8	27	25.2	24.9	24.6		24	27	23	(a)
Ni	360	300	312	297	296	290		290	290	300	(a)
Cu											
Zn											
Ga											
Ge ppb											
As											
Se											
Rb							1.31				(a)
Sr	165	155	170	147	151	150	142				(a)
Y											
Zr	40	30	38	50	32	48	59		200		(a)
Nb											
Mo											
Ru											
Rh											
Pd ppb											
Ag ppb											
Cd ppb											
In ppb											
Sn ppb											
Sb ppb											
Te ppb											
Cs ppm	0.1	0.07	0.09	0.11	0.06	0.05					(a)
Ba	45	34	45	46	47	50	49	30	70	40	(a)
La	2.76	1.68	3.17	3.46	2.69	2.4	3.48	3.3	6.4	3.6	(a)
Ce	7.1	4.3	8.3	9.2	6.6	5.7	8.9	9	22	10	(a)
Pr											
Nd	4.5	2.9	5	5.7	4	3.4	5.56	5	18	5	(a)
Sm	1.61	0.984	1.621	1.824	1.258	1.164	1.6	1.5	5.9	1.7	(a)
Eu	0.835	0.75	0.765	0.762	0.74	0.745	0.794	0.78	1.42	0.8	(a)
Gd											
Tb	0.41	0.235	0.403	0.44	0.29	0.295		0.3	1.3	0.3	(a)
Dy											
Ho											
Er											
Tm											
Yb	1.57	1.06	1.6	1.61	1.26	1.28	1.5	1.6	5.1	1.4	(a)
Lu	0.237	0.163	0.24	0.248	0.193	0.203		0.21	0.66	0.18	(a)
Hf	1.57	0.8	1.1	1.27	0.89	1.16	1.6	1.5	4.9	1	(a)
Ta	0.28	0.103	0.112	0.152	0.128	0.148		0.22	0.85	0.14	(a)
W ppb											
Re ppb											
Os ppb											
Ir ppb	15	14	13	13	13	13		10	9	10	(a)
Pt ppb											
Au ppb	6.2	4.1	4.8	3.5	7.9	3.5		3	3	3	(a)
Th ppm	0.47	0.52	0.52	0.72	0.84	0.71		0.4	0.6		(a)
U ppm	0.11	0.05	0.18	0.17	0.13	0.06	0.22				(a)

technique: (a) INAA

Table 1c. Chemical composition of 77017.

reference	Hudgins et al. 2008				
weight					
SiO2 %					
TiO2					
Al2O3					
FeO					
MnO					
MgO					
CaO					
Na2O					
K2O					
P2O5					
S %					
sum					
Sc ppm	11.02	11.4	11.76	11.91	(a)
V					
Cr					
Co	30.8	27.3	26.5	27	(a)
Ni	372	312	298	300	(a)
Cu					
Zn					
Ga					
Ge ppb					
As					
Se					
Rb					
Sr	144	140	150	150	(a)
Y					
Zr	47	45	50	51	(a)
Nb					
Mo					
Ru					
Rh					
Pd ppb					
Ag ppb					
Cd ppb					
In ppb					
Sn ppb					
Sb ppb					
Te ppb					
Cs ppm					
Ba	49	45	51	47	(a)
La	3.81	3.26	3.61	4.14	(a)
Ce	9.6	8.3	9.1	10.6	(a)
Pr					
Nd	5.4	4.7	6.4	7	(a)
Sm	1.74	1.55	1.78	2.06	(a)
Eu	0.8	0.8	0.8	0.82	(a)
Gd					
Tb	0.37	0.33	0.39	0.44	(a)
Dy					
Ho					
Er					
Tm					
Yb	1.5	1.41	1.62	1.81	(a)
Lu	0.212	0.197	0.224	0.248	(a)
Hf	1.5	1.48	1.25	1.45	(a)
Ta	0.37	0.25	0.18	0.2	(a)
W ppb					
Re ppb					
Os ppb					
Ir ppb	15.8	14.7	13.7	13.5	(a)
Pt ppb					
Au ppb	5.2	4.8	4.3	4.1	(a)
Th ppm	0.91	0.7	0.68	0.88	(a)
U ppm	0.27	0.21	0.2	0.25	(a)
technique:	*(a) INAA*				

of the early lunar crust (abs). Lunar Planet. Sci. XXIV, 369-370. Lunar Planet. Institute, Houston

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Figure 14: 77017,15 after saw cut. S73-28611. Ruler is marked in cm.

Figure 15: Photo of 77017,14 after saw cut. S73-28611. Ruler is in cm.

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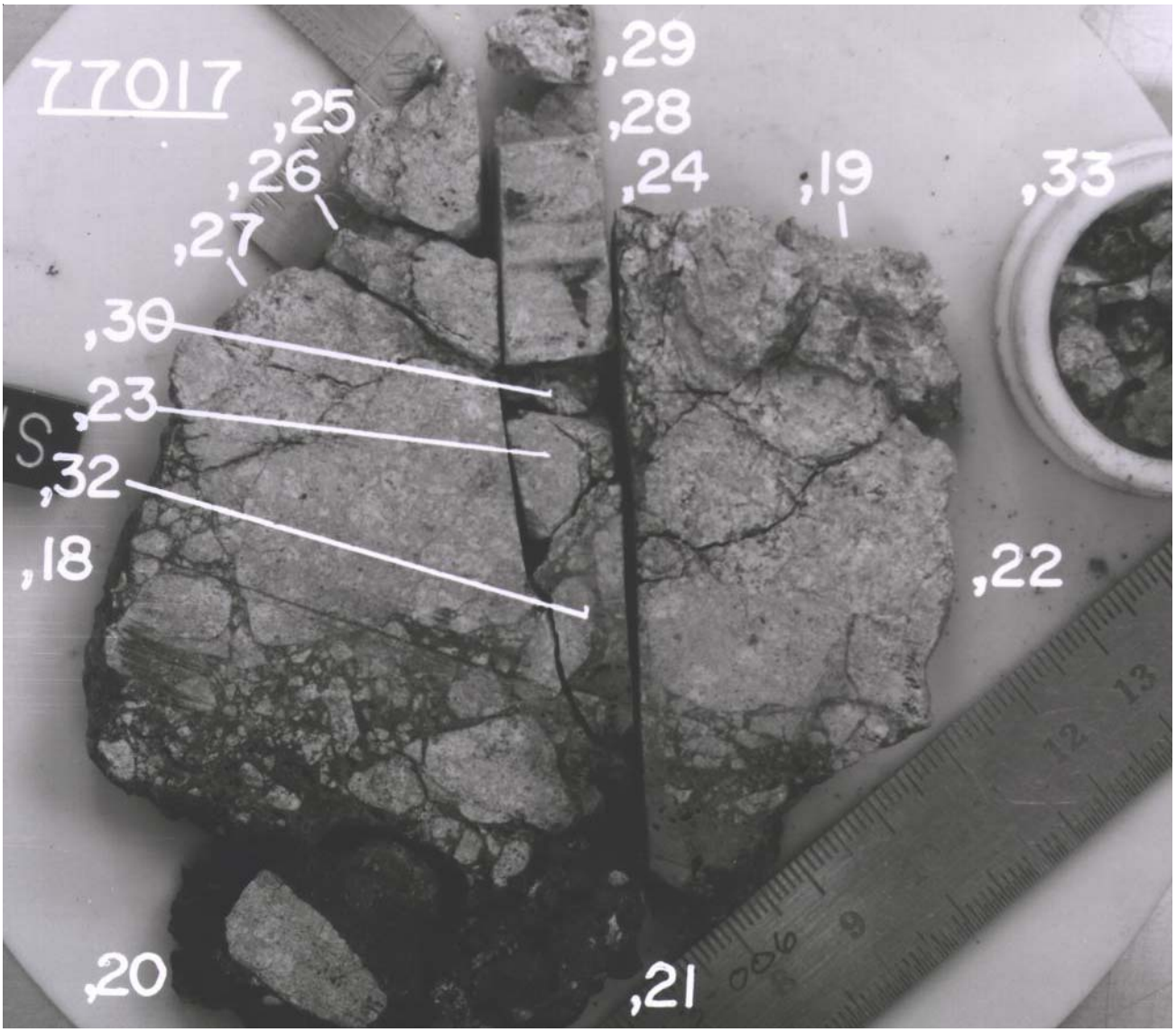
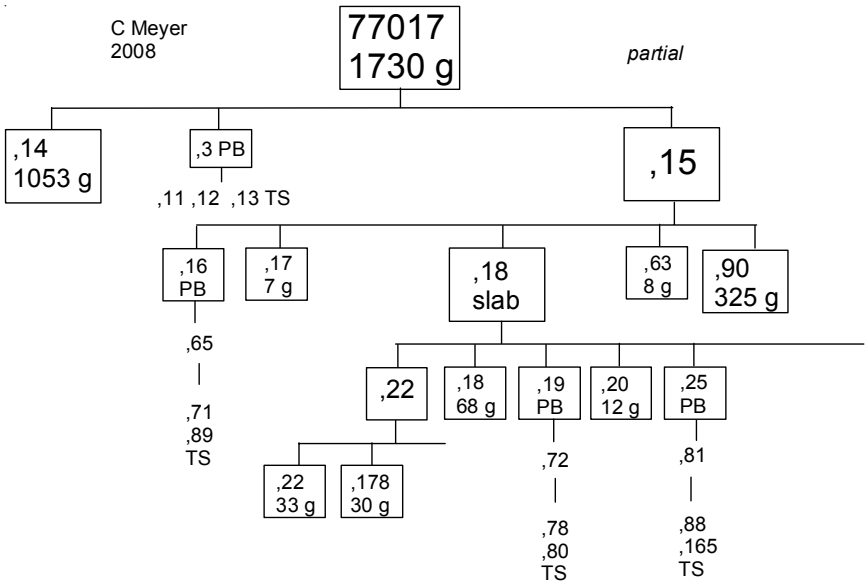


Figure 16: Processing photo showing subdivision of slab of 77017,18. S73-28613. Ruler is marked in cm.



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