60015

Cataclastic Anorthosite

5574 grams

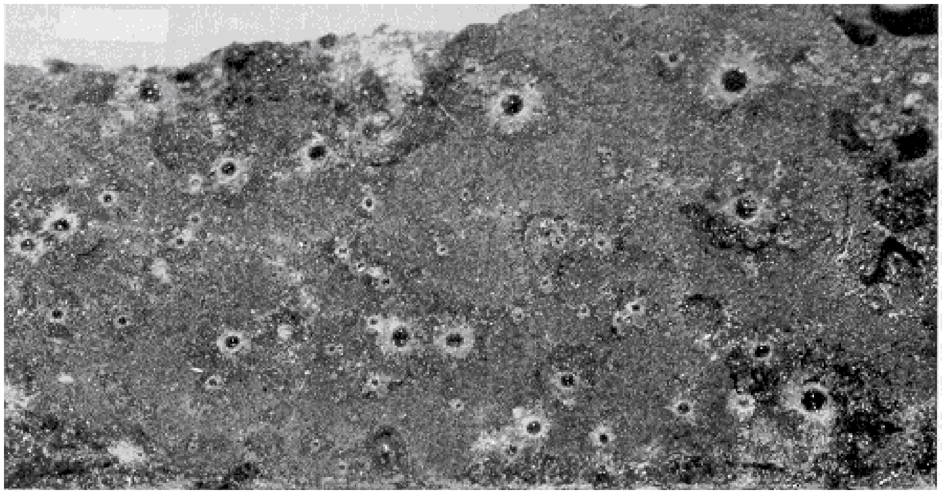


Figure 1: A portion of the glass surface of 60015 - about 0.6 cm across. Dark spots are glass-lined impact craters, which are surrounded by light "halo" spall zones. (from Hartung (1980) and/or Fechtig et al. (1974)

Figure 2: Sawn surfaces of 60015, showing glass rind and interior "anorthosite". NASA S75-21972. Note the prominant saw marks. Sample on left is about 3 inches across.

Introduction

60015 is a cataclastic anorthosite that is rather pure in bulk composition. It was collected near the Lunar Module but was not "oriented" by surface photography. It has a thick coat of glass splashed over all surfaces except B1 (bottom). 60015 has a cosmic-ray exposure age of about 2 m.y. (South Ray Crater?) and an Ar/Ar age of 3.5 b.y. (although it is probably older). The interior anorthosite is ferroan and chemically "pristine" (Ryder and Norman 1980). *The sample was once termed "Blue Genesis" (Sutton 1981).*

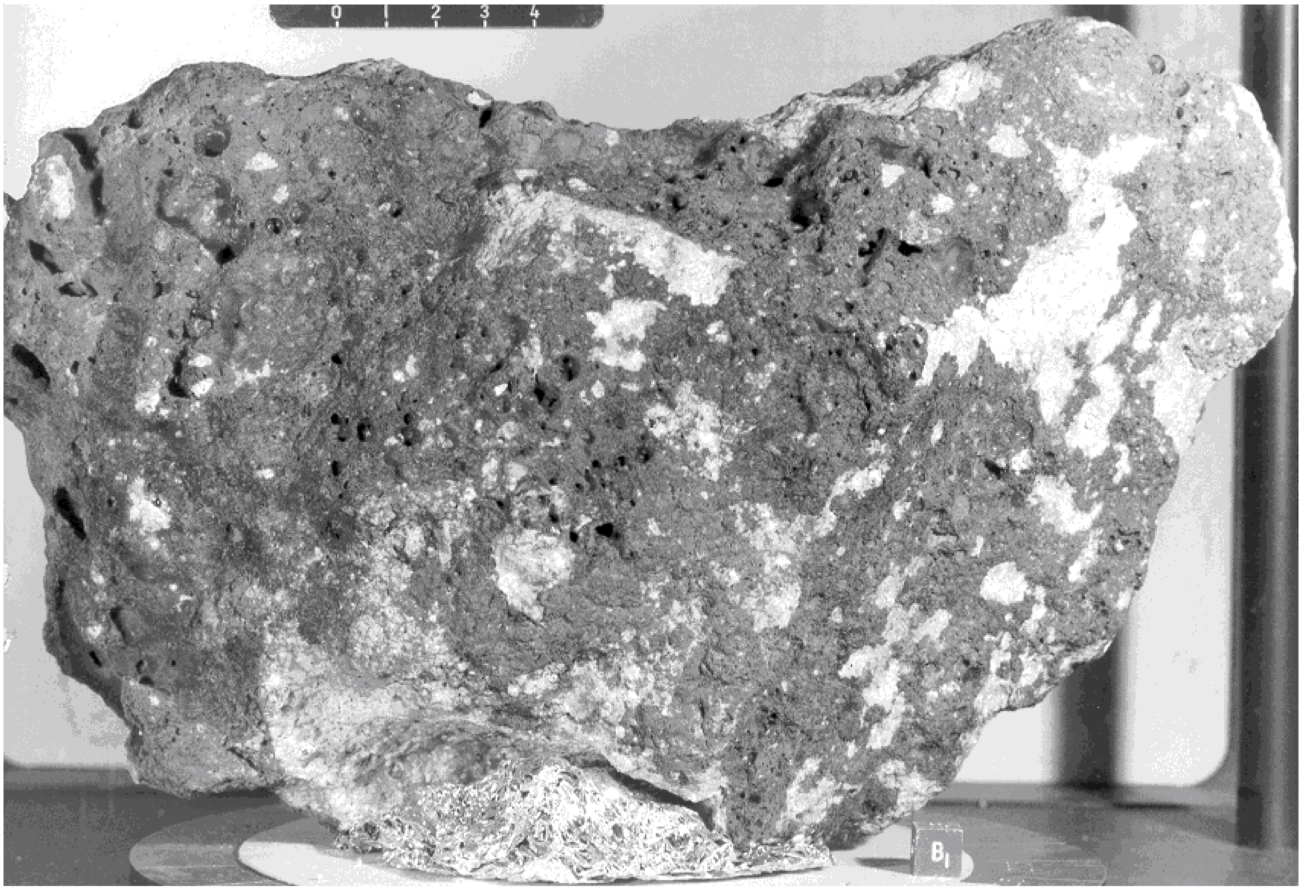


Figure 3: Seldom seen, bottom surface of 60015. NASA S72-42706. Scale at top is in cm.

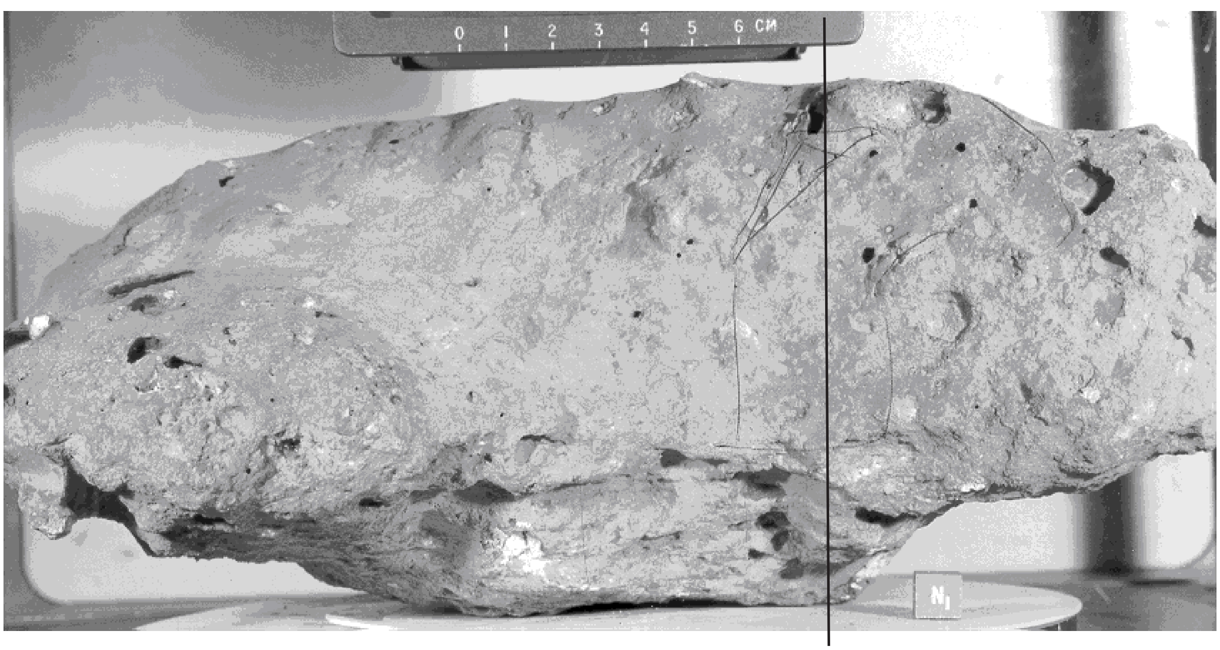


Figure 4: Never before seen, side view of 60015 before cutting showing glass coating on top and approximate position of infamous first saw cut. NASA S72-40119. Scale at top is 6 cm. This is the side where the zap pit studies were made.

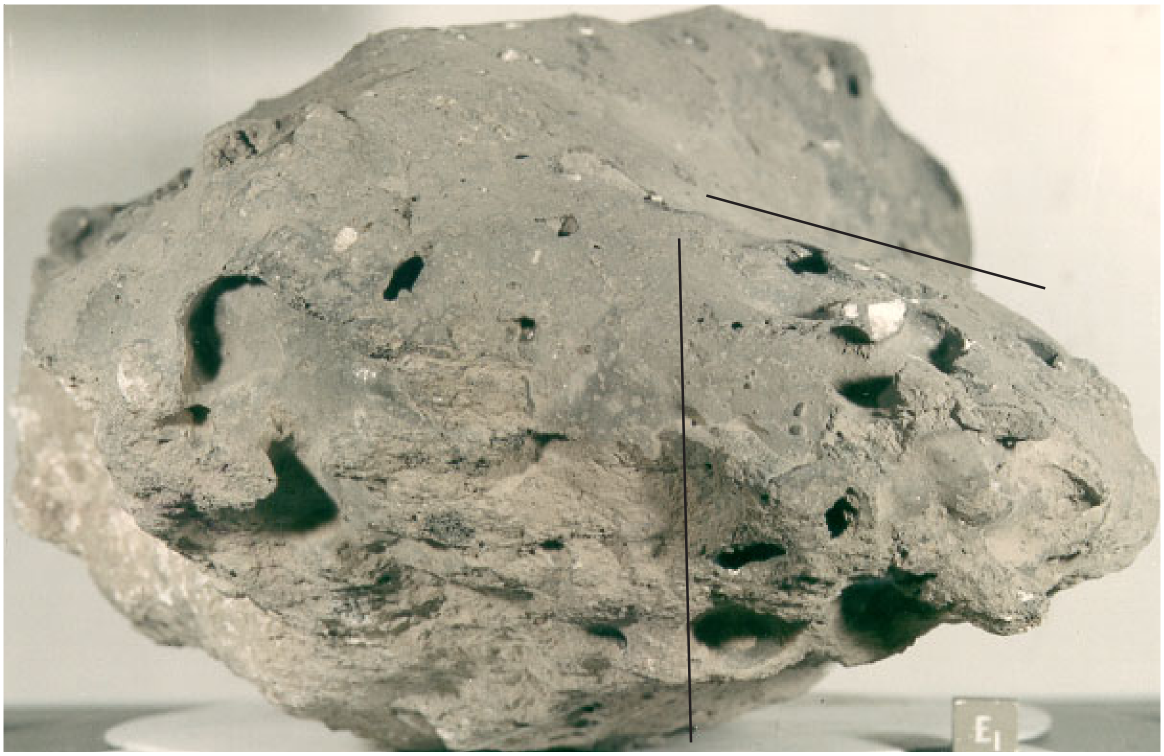


Figure 5: End view of 60015. Cube is 1 cm. NASA S72-40120. Approximate position of 1981 saw cut is indicated by lines (see figure 15).

Petrography

The top, sides and ends of 60015 are covered with a thick coat of black glass, as if the sample was a glass covered "bomb." The bottom surface, however, has less glass (figure 3), as if it had been "chipped" or eroded away. The micrometeorite exposure history of the glass covered surface is 10^5 years (Mandeville 1976), while the cosmic ray exposure age of the overall rock is ~2×10^6 years (Leich and Niemeyer 1975). Hence, it would appear that the bottom side of 60015 was originally facing up, and about 10^5 years ago the rock was turned over.

The interior of 60015 is a highly-shocked ferroan anorthosite (~98% plagioclase). Dixon and Papike (1975) pictured relict "triple junction" texture between large grains of plagioclase (1 – 3 mm) with small grains of pyroxene at the junction. The plagioclase has extensive evidence of shock (patchy and undulose extinction) and melted, but maskelynite is not reported. Pyroxene grains are rounded and also show evidence of shock. Some orthopyroxene occurs as thin "stringers" along feldspar. Pyroxene aggregates in the matrix have associated ilmenite, Cr spinel and troilite. No olivine was found.

According to Sclar et al. (1973), the snow-white interior of 60015 "consists of highly strained anhedral plagioclase with a seriate grain-size distribution plus a few percent of relatively large strained euhdral to subhedral plagioclase laths up to 3 mm long set in an intergranular and interstitial groundmass of very fine aggregates of feathery plagioclase." The highly-shocked plagioclase includes bubble-like melt inclusions with a very high index of refraction. Sclar and Bauer (1974) describe many complex shock, and quench, features in 60015.

Sclar and Bauer (1974) also describe a zone of melted and recrystallized anorthosite which would require very high temperature (>1500 deg C) at some point in the history of the sample.

Micrometeorite craters

The smooth glass surface on the top of 60015 provided a nice target for micrometeorites (figure 1). Neukum et al. (1973), Fechtig et al. (1974), Mandeville (1976) and Hartung et al. (1977) reported studies of the number and size distribution of zap pits on this surface (figure 10). They found that the size distribution of zap pits was different from that of other lunar samples and concluded the surface is "undersatuated" with respect

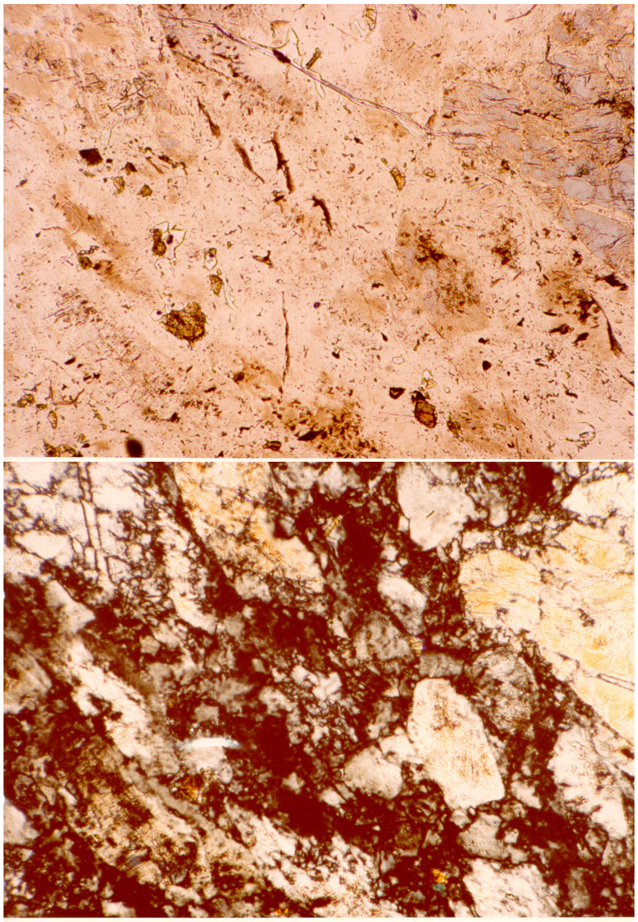


Figure 6: Thin section photomicrographs of 60015,129 (same area). Scale is 1.3 mm across. NASA S79-27804 and 888. Top is plane polarized, bottom is cross-polarized.

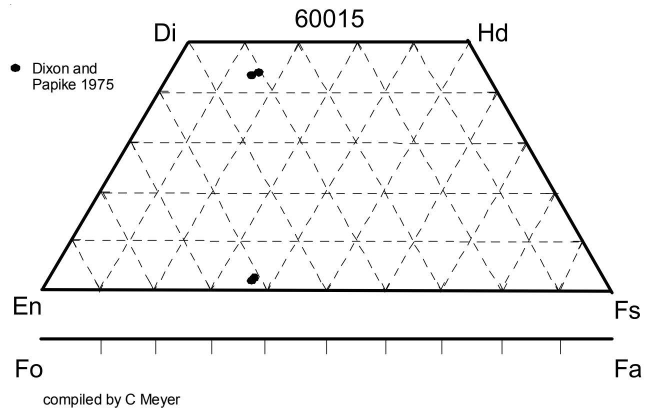


Figure 7: Composition of pyroxene in 60015.

to micrometeorites and only about 10^5 years old. Flavill et al. (1978) show evidence that some of the microcraters may be secondary in origin.

Mineralogy

Olivine: none

Pyroxene: Dixon and Papike (1975) give the only detailed analyses of mafic minerals in 60015 (figure 7). Ishii et al. (1976) calculate the equilibration temperature of the pyroxene (987 C).

Plagioclase: Sclar et al. (1973) give the plagioclase composition as An_{90-95}, Sclar and Bauer (1974) report An_{95-98} and Dixon and Papike (1973) find $An_{96.5-97.1}$. Sad to say, the plagioclase in 60015 has been severely shocked. Some plagioclase needles are quench products of plagioclase glass. Maskelynite is not reported (?)

Ilmenite: Trace ilmenite is found within pyroxene aggregates.

Metallic iron: Hewins and Goldstein (1975) found the metallic iron was low in Ni and Co in the anorthosite, but high in the metal in the glass. Mao and Bell (1976) show that the metal composition is the result of reaction.

High Pressure Phases: *HPP may be present and should be looked for!*

Chemistry

A lot of chemical and isotopic analyses have been published for 60015 (Tables 1 and 2). Dixon and Papike (1973), Sclar and Bauer (1974) and See et al. (1986) have also provided microprobe analyses of the glass splash. Sclar and Bauer note that the glass has the same composition as Apollo 16 soil.

Laul and Schmitt (1973), Taylor et al. (1973) and others found anorthosite 60015 was lacking in trace elements (figure 9). Ebihara et al. (1992) determined the meteoritic siderophiles, showing that anorthosite 60015 had little meteoritic contamination.

Radiogenic age dating

Schaeffer and Husain (1974) determined a relatively nice Ar/Ar plateau at ~ 3.5 b.y. (figure 11), which was

Mineralogical Mode 60015

	Sclar et al. 1973	**Dixon and Papike 1975**
Orthopyroxene	3 vol. %	1.5 %
Augite		tr.
Plagioclase	97	98.5%
Ilmenite		0.1

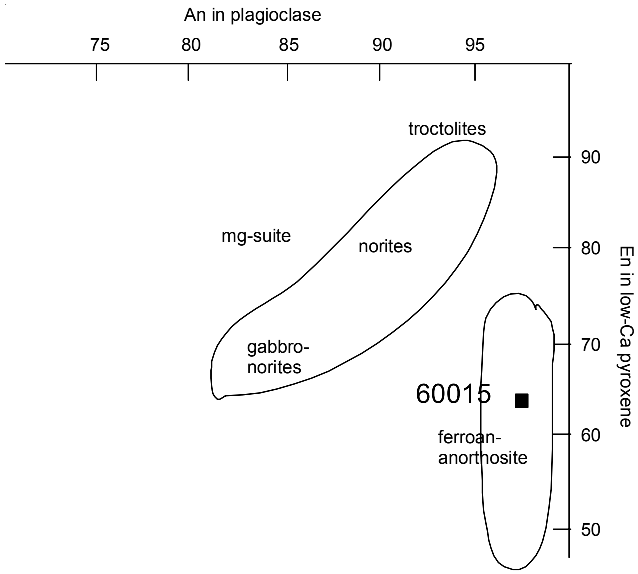


Figure 8: Composition of pyroxene and plagioclase in 60015.

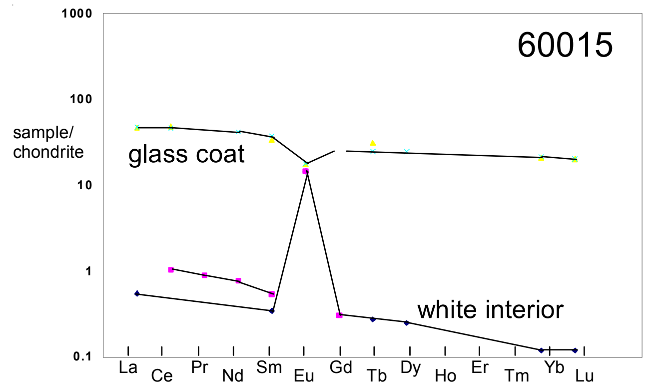


Figure 9: Normalized rare-earth-element diagram for anorthosite interior and for glass rind on 60015. Data from Laul and Schmitt 1973, Taylor et al. 1973 and Morris et al. 1986.

duplicated nicely by the work of Phinney et al. (1975) >3.49 b.y. (figure 12). However, this rock should be older than that !

Nunes et al. (1973, 1974) were not able to date 60015 by U, Th, Pb analysis due to severe Pb contamination (and very low U).

Nyquist et al. (1975) and Papanastassiou and Wasserburg (1976) reported the Sr isotopic composition of 60015.

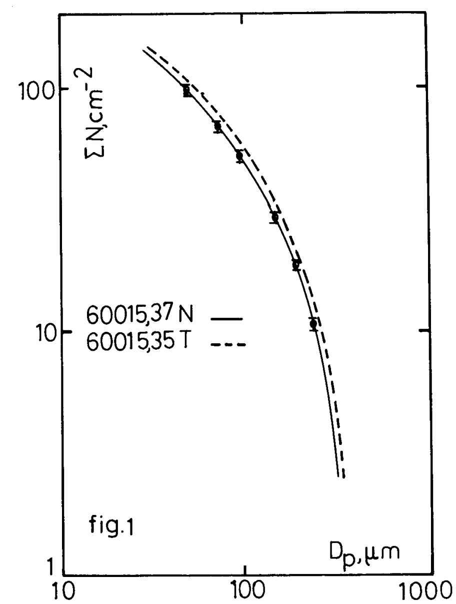


Figure 10: Size distribution of micrometeorite craters on top surface of 60015 (by Mandeville 1976 and Neukum et al. 1973).

Cosmogenic isotopes and exposure ages

Schaeffer and Husain (1974) and Phinney et al. (1975) reported ^{38}Ar exposure ages of 5.4 ± 0.7 m.y. and 3 ± 1 m.y. respectively. Leich and Niemeyer (1975) determined an accurate ^{81}Kr exposure age of 1.9 ± 0.1 m.y. (~ the age of South Ray Crater). Niemeyer and Leich (1976) found they could release additionally rare gases by crushing the sample. Horz et al. (1975) reported an Ar exposure age of 1.8 m.y. and a "subdecimeter"age from track studies of 10 m.y.

Other Studies

Clayton et al. (1973)	oxygen isotopes
Jovanovic and Reed (1973)	halogens
Ehmann and Chyi (1974)	Hf, Zr
Moore et al. (1973)	C
Moore and Lewis (1976)	N
Cripe and Moore (1974)	S
Carey and McDonnell (1976)	surface analysis
Storzer et al. (1973)	solar flare tracks
Collinson et al. (1973)	magnetics
Stephensen et al. (1974, 5)	magnetics
Weeks (1973)	EPR
Chung and Westpfal (1973)	sound
Chung (1978)	sound
Herminghaus and Berckhemer (1974)	
Mandeville and Dollfus (1977)	polarization

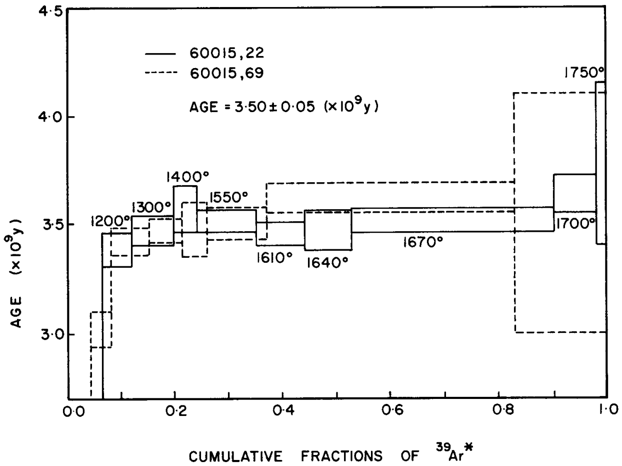


Figure 11: Ar/Ar plateau diagram for 60015 (Schaeffer and Husain 1974).

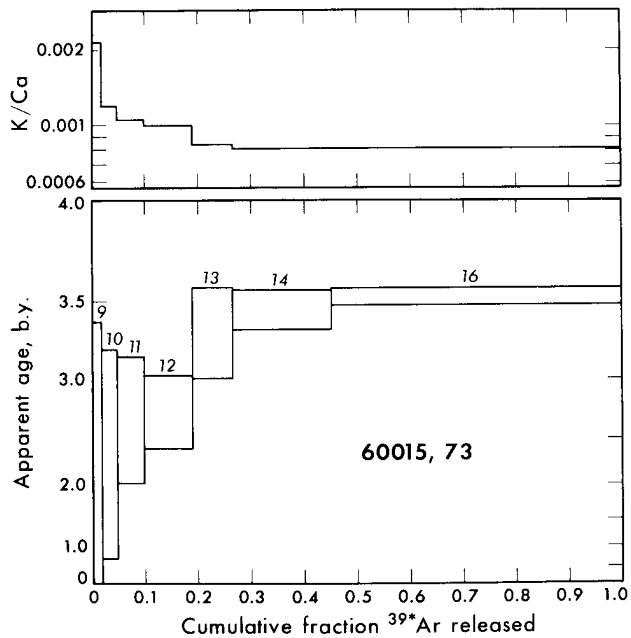


Figure 12: Ar/Ar plateau diagram for 60015 (Phinney et al. 1975).

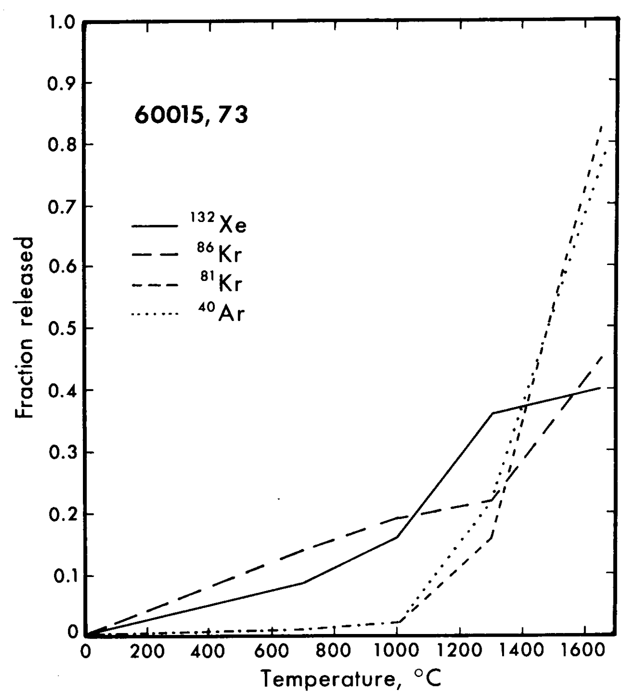


Figure 13: Temperature release of rare gasses from 60015. (Leich and Niemeyer 1975)

Processing

This is a popular public display sample because of the black glass and white interior (figure 20). The sample was cut three different times. In 1972 the E1 end was sawn off (figure 4) and two slabs were made and thin column was cut from slab B (figures 17, 18). In 1975 the end piece was divided to create pieces for public displays. Again, in 1981, additional displays were cut from a piece sawn off of the west end (figures 15 and 16).

Saw marks are prominent in the photos (figure 2, 17, 18 and 19) indicating that the blade was dull (1972). Nunes et al. (1973) noted that sawing caused substantial Pb "contamination". Compare with the 1981 cut (figure 16).

Most of the thin sections are from the same portion of the sample.

Summary of Age Data for 60015

	Ar/Ar
Schaeffer and Husain 1974	3.5 ± 0.05 b.y.
	3.51 ± 0.06
Phinney et al. 1975	>3.49

Table 1. Chemical composition of 60015.

reference	Laul and Schmitt 1973			Taylor73		Juan 74	Janghorbani73			Garg 76		Morris86		See86	Ebihara91	
weight	,63	glass		,64								glass		interior		
SiO2 %						43.97	43.86	43.64	(c)			44.69		43.41		
TiO2	0.06	0.36	(a)			0.02						0.38		0.05		
Al2O3	35.5	27	(a)	35.7	(b)	35.83	34.4	33.44	(c)			27.32		35.78		
FeO	0.35	4.8	(a)	0.26	(b)	0.36				0.35	(c)	5.28		0.22		
MnO	0.009	0.064	(a)				0.01	0.01	(c)					0.01		
MgO		7	(a)	0.35	(b)	0.25	0.99		(c)			7.17		0.18		
CaO	20	14.8	(a)	19.3	(b)	18.95	17.35	19.17	(c)			15.18		19.4		
Na2O	0.41	0.546	(a)	0.36	(b)	0.34	0.43	0.42	(c)			0.42		0.44		
K2O	0.01	0.094	(a)	0.13	(b)	0.01						0.13		0.05		
P2O5																
S %																
sum																
Sc ppm	0.6	5.8	(a)							0.6	(c)	6.1	(c)			
V	7	20	(a)	4.7	(b)											
Cr	48	650	(a)	40	(b)	<15						671	(c)			
Co	0.7	42	(a)			44				0.9	(c)	66	(c)			
Ni		900	(a)			30						1250	(c)		<2	(d)
Cu				0.5	(b)	2										
Zn															0.75	(d)
Ga																
Ge ppb															25.4	(d)
As																
Se															3.13	(d)
Rb				0.1	(b)										0.111	(d)
Sr						156										
Y				0.4	(b)											
Zr		70	(a)	1.1	(b)					0.135	(c)					
Nb																
Mo																
Ru																
Rh																
Pd ppb															<104	(d)
Ag ppb															1.42	(d)
Cd ppb															40	(d)
In ppb															221	(d)
Sn ppb																
Sb ppb															0.711	(d)
Te ppb															3.02	(d)
Cs ppm															0.014	(d)
Ba	8	100	(a)	10	(b)							151	(c)			
La	0.13	11.1	(a)									11.06	(c)			
Ce		28	(a)	0.63	(b)							29.1	(c)			
Pr				0.08	(b)											
Nd		19	(a)	0.35	(b)											
Sm	0.051	5.5	(a)	0.08	(b)							4.93	(c)			
Eu	0.81	1.01	(a)	0.81	(b)					0.73	(c)	0.98	(c)			
Gd				0.06	(b)											
Tb	0.01	0.9	(a)									1.14	(c)			
Dy	0.06	6	(a)													
Ho																
Er																
Tm																
Yb	0.02	3.5	(a)									3.34	(c)			
Lu	0.003	0.49	(a)									0.49	(c)			
Hf	0.013	3.2	(a)							0.009	(c)	3.49	(c)			
Ta		0.42	(a)									0.36	(c)			
W ppb																
Re ppb															0.001	(d)
Os ppb															<0.13	(d)
Ir ppb		23	(a)												0.013	(d)
Pt ppb																
Au ppb		8	(a)												0.005	(d)
Th ppm		1.7	(a)									2.95	(c)			
U ppm		0.41	(a)									0.61	(c)		0.001	(d)

technique: (a) INAA, (b) ssms, (c) neutron activation, (d) RNAA

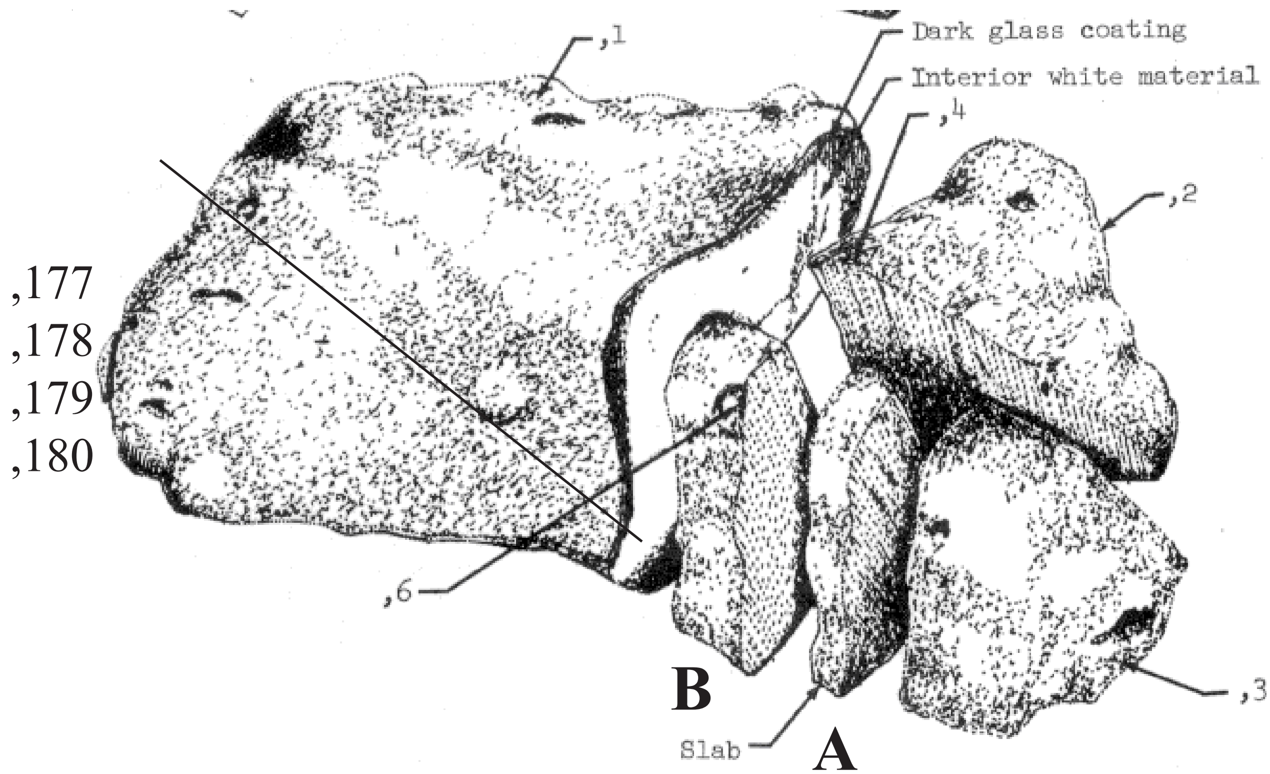
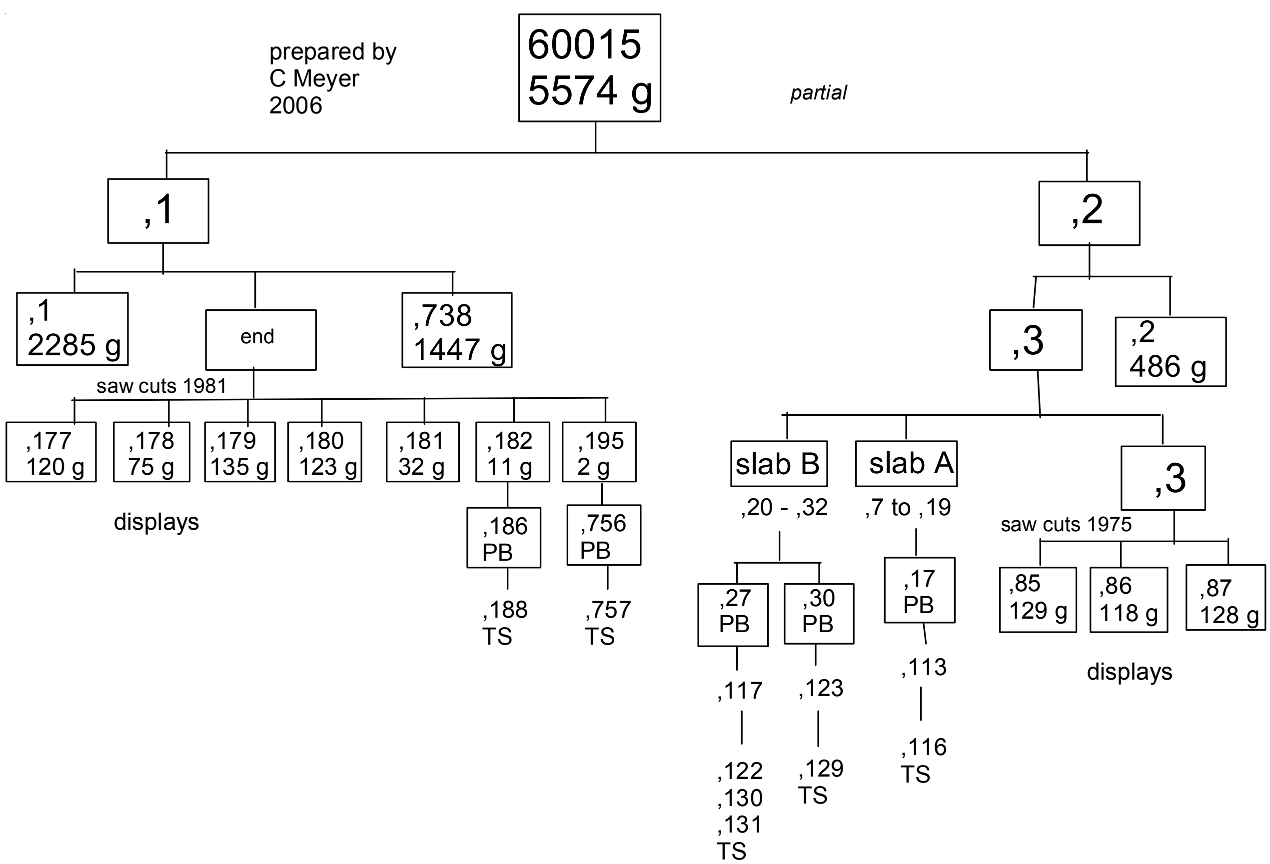


Figure 14: Rock model and flow diagram showing major subdivision of 60015.



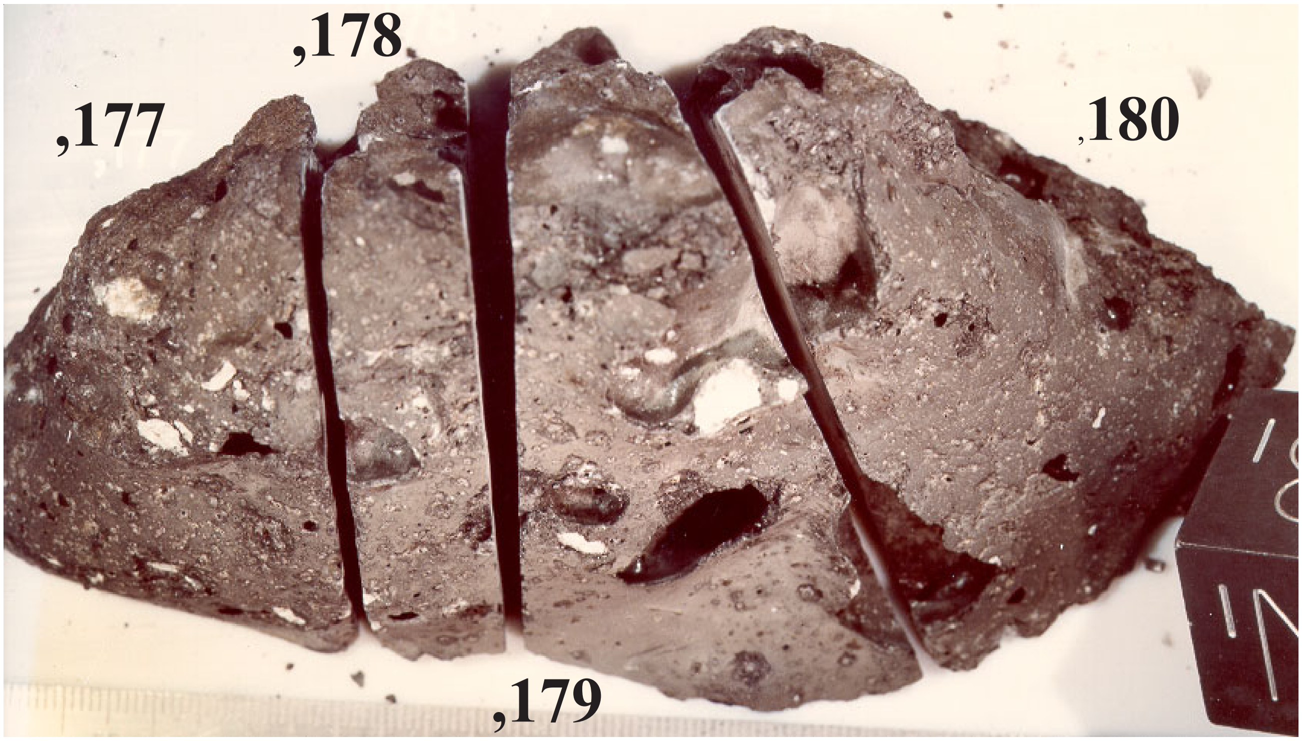


Figure 15: End cut in 1981 to produce display samples of 60015. NASA S81-27668. Cube is 1 inch, scale marked in cm/mm.

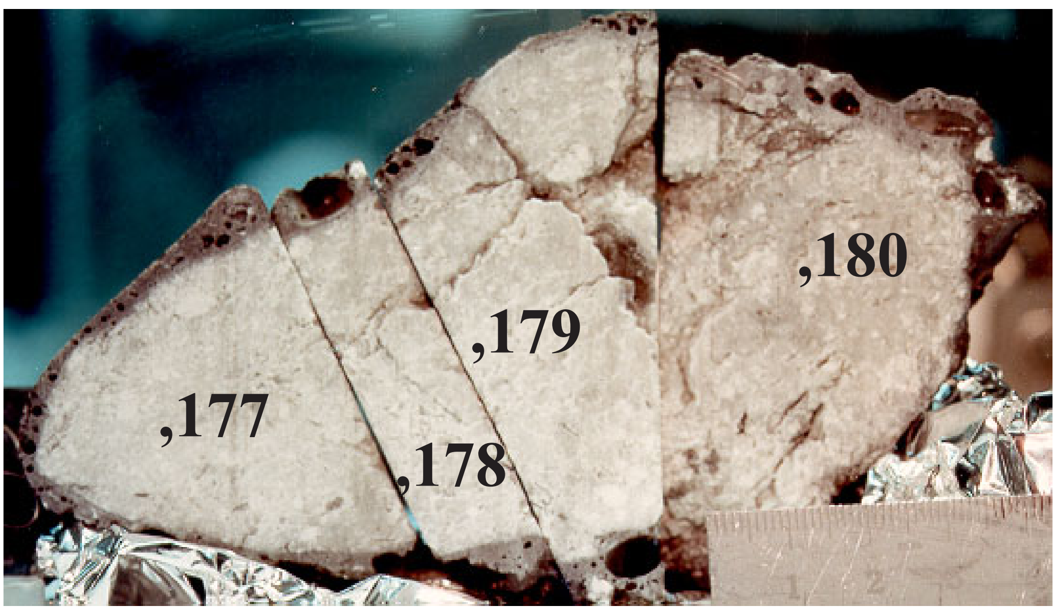


Figure 16: Samples for public displays of 60015. NASA S81-27666. Scale in cm/mm.

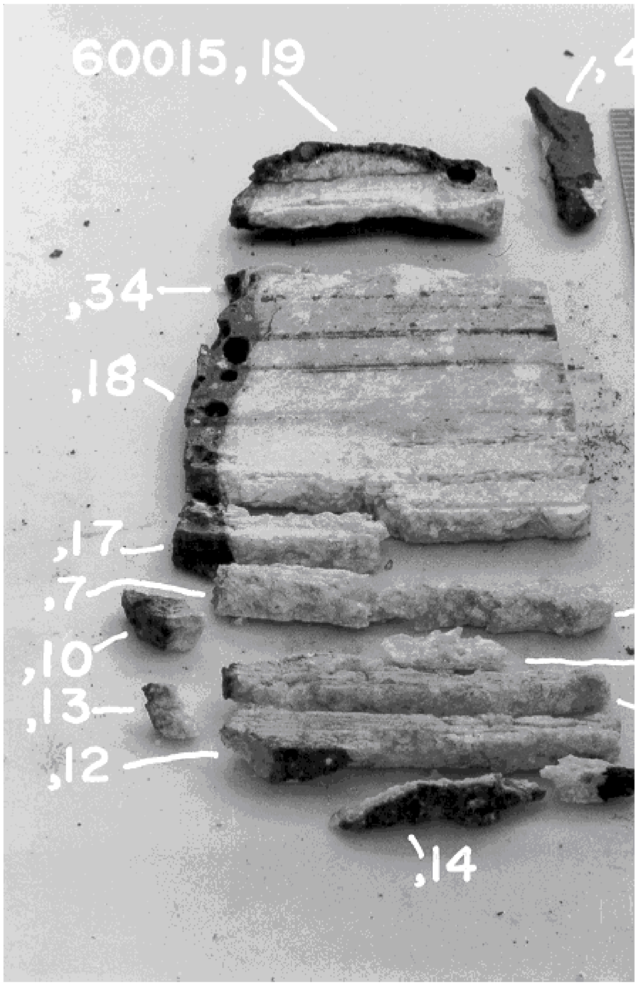


Figure 17: Slab A cut from 60015,3. NASA S72-55507.

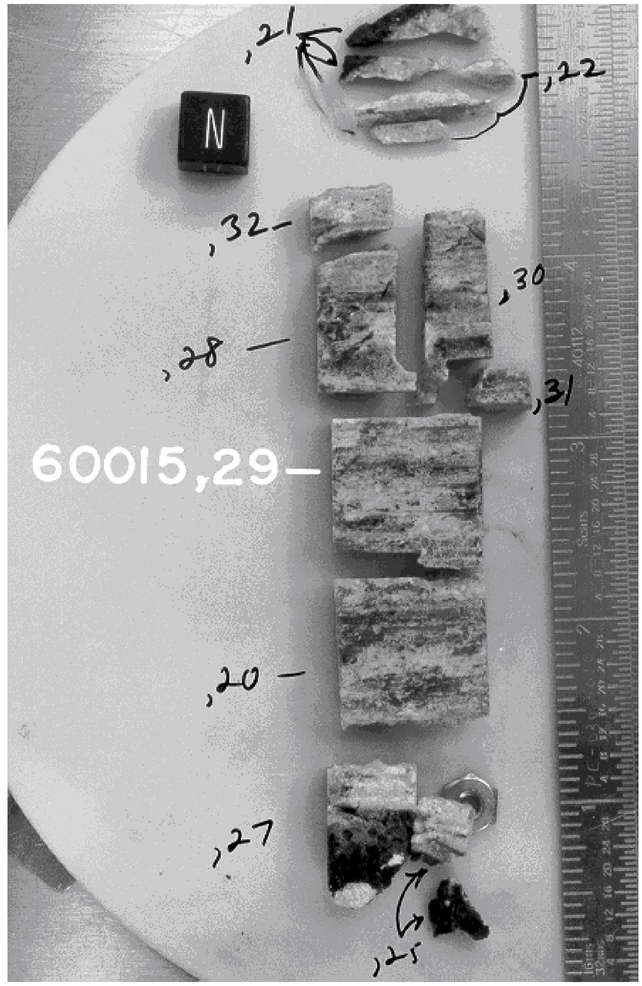


Figure 18: Column cut from slab B 60015. NASA S72-54199. Cube is 1 cm. (see figure 19). Note the horrific saw marks.

Table 2: Composition of 60015.

	U ppm	Th ppm	K2O %	Rb ppm	Sr ppm	Nd ppm	Sm ppm	technique
Nunes et al. 1973	0.0012	0.0051						idms
	0.0009	0.0026						idms
	0.0005	0.0014						idms
	0.0015	0.0038						idms
Nunes et al. 1974	0.409	1.539	0.0836	1.91	156.8		glass	idms
			0.0065	0.1221	166.2		plag.	
Nyquist et al. 1975				0.299	181			idms
				0.078	178			idms
Papanastassiou and			0.0047	*moles/g*	*moles/g*			idms
Wasserburg 1976			0.0064					idms

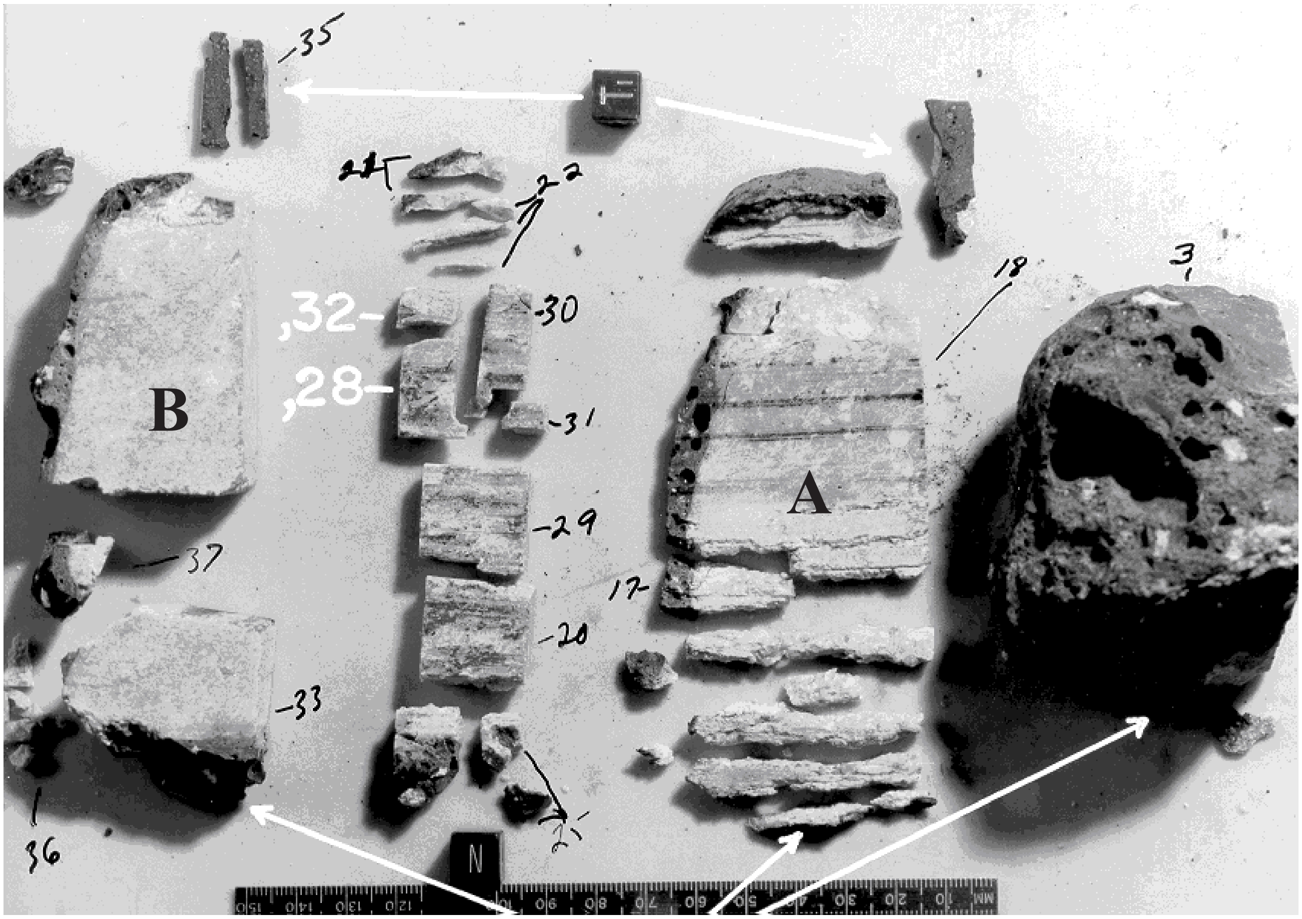


Figure 19: Group photo of slabs (A and B) and column cut from 60015,3. NASA S72-54200. Cubes are 1 cm for scale and orientation. Majority of thin sections were made from ,17 ,27 and ,30. End piece ,3 was cut into three display pieces (see figure 16).

Figure 20: Public display sample 60015,3. NASA S88-52988. British Museum of Natural History.

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