60025

Ferroan Anorthosite

1836 grams

Figure 1: 60025. NASA #S72-41586. Cube and scale are 1 cm. Note the thick black glass coating and numerous micrometeorite pits.

Introduction

Lunar sample 60025 is a large sample of coarse-grained cataclastic anorthosite (figure 1). Or, rather, it is a mixture of pieces from a related sequence of anorthosites, because the mafic minerals vary in composition (**Ryder 1982**, James et al. 1991). Warren and Wasson (1977) termed 60025 "pristine" because of its coarse grain size and low meteoritic siderophiles (Ni, Ir). The age of 60025 has been determined by Pb-Pb and Sm-Nd to be 4.36 b.y. and it has very low $^{87}Sr/^{86}Sr$ (0.699).

Ferroan anorthosites are one of the major lunar rock types (Dowty et al. 1974, James 1980) and are thought to be pieces of the original lunar crust formed by plagioclase floatation from a moon-wide magma ocean (e.g. Smith et al. 1970, Wood et al. 1970, Warren 1990).

Mineralogical Mode of 60025

	Dixon and Papike 1975	Warren and Wasson 1978	James et al. 1991	James et al. mafic region
Plagioclase	98 vol. %	70	74	5
Olivine		20	20	45
Orthopyroxene		10	5	45
Augite			1	5
Chromite			0.05	0.2
Ilmenite			0.02	

Figure 2: Group photo of pieces cut from first slab. Note the chalky white interior of 60025 and the patina on the exterior surface. Cubes are about 1 cm. NASA # S72-49109.

Alternatively, 60025 may be from a layered igneous pluton emplaced within the lunar crust (James 1980).

Ryder and Norman (1980) provided a compilation of what was known about 60025 up to that time. James et al. (1991) studied the mafic portions of 60025.

60025 was collected near the Lunar Module and its orientation was documented by photography.

Petrography

60025 has been described as a moderately shocked, cataclastic anorthosite (Hodges and Kushiro 1973, Walker et al. 1973, Dixon and Papike 1975, **Ryder 1982**, James et al. 1991) made up of mostly calcic plagioclase (see mode). The first slabs cut from 60025 were nearly pure plagioclase (figure 2), but other portions of 60025 were found to be more mafic (see Warren and Wasson 1977, Ryder 1982, James et al. 1991). Most pyroxene grains are distinct augite or orthopyroxene, but some grains are exsolved into end member components (figure 3). There are trace amounts of silica, ilmenite and chromite.

A variety of textures are reported (figure 3). In some areas, large fractured plagioclase grains (2-4 mm) sit in a sea of crushed plagioclase and pyroxene (Walker et al. 1973).

Pyroxene compositions are variable in different portions of the rock (En_{50} to En_{70}) indicating a differentiation sequence (Ryder 1982). However, the origin of some pyroxene by sub-solidus exsolution should be considered (see Smith and Steele 1974). The wide composition gap between augite and hypersthene (Wo_{45} to Wo_2) indicates thermal equilibrium well below magmatic temperatures (Walker et al 1973, Dixon and Papike 1975), presumably as a slowly-cooled plutonic rock.

Mineralogy

Plagioclase: A number of people have analyzed the plagioclase in 60025 and found it to be uniform and very calcic (An_{96-98}) (see table for some of the analyses).

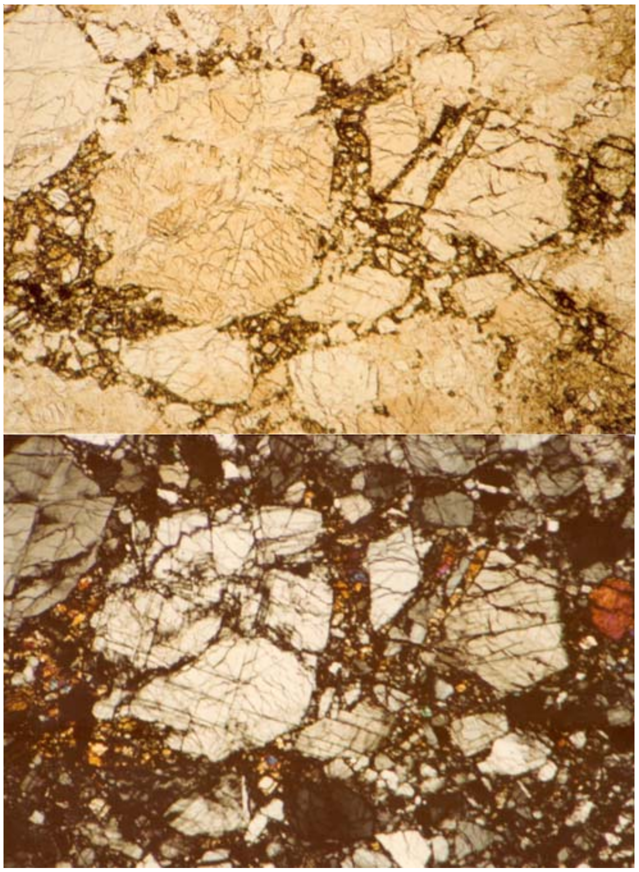


Figure 3: Plane-polarized and cross-polarized photos of thin section 60025,21. Field of view is 2.5 mm. S79-27300 and 301.

Olivine: Warren and Wasson (1977), Ryder (1982) and James et al. (1991) find that olivine in various portions of 60025 has a range of compositions (Fo_{42-66}).

Pyroxene: Pyroxene is present as subhedral to anhedral grains included in plagioclase, as anhedral grains at grain boundaries and in mafic clumps with olivine. 60025 contains both high-Ca and low-Ca pyroxene with a wide miscibility gap (figure 4). Hodges and Kushiro (1973) noted that three pyroxenes (augite, hypersthene and pigeonite) were probably present at time of crystallization. Pigeonite is now exsolved to endmember compositions. Fine exsolution is also found in sub-calcic augite (Hodges and Kushiro 1973). Dixon and Papike (1975) find that the composition of coexisting augite and orthopyroxene indicates an equilibrium temperature of less than 800 deg. C (see also Lindsley et al. 1974). Floss et al. (1998) determined the REE for pyroxenes in 60025 (figure 6).

The variation of FeO/MgO in pyroxene, from one portion of 60025 to another, is the evidence used by Ryder (1982) to argue that 60025 may actually be a mix of anorthosites from a differentiated sequence.

Opaques: Hodges and Kushiro (1973) and James et al. (1991) determined the composition of chromite and ilmenite.

Glass: The black glass found attached to the surface of 60025 has been studied by See et al. (1986) and Morris et al. (1986).

Chemistry

Plagioclase dominates the composition of 60025 (figures 6 and 9). Haskin et al. (1973, 1981) and Krahenbuhl et al. (1973) showed that 60025 was free of meteoritic siderophile elements (Ni, Ir). James et al. (1991) determined the composition of mafic portions of 60025 (table 1).

Radiogenic age dating

Tera and Wasserburg (1972), Papanastassiou and Wasserburg (1972), Nunes et al. (1974), Schaeffer and Husain (1974), Hanan and Tilton (1987) and Carlson and Lugmair (1988) have attempted to date 60025. The $^{87}Sr/^{86}Sr$ ratio is extremely (0.699) low indicating that 60025 is very old and formed from a low Rb source (Nyquist et al. 1974). The mafic minerals allowed a precise Sm/Nd isochron (figure 7), which is only about 110 m.y. younger than the age of the moon. However, the interpretation that 60025 is in fact a mix of related anorthosites, this is perhaps equivalent to a "whole rock" isochron.

The exact age of 60025 has been recently (2011) reinvestigated by Pb/Pb and Nd/Sm and found to be significantly younger (4.36 b.y.) than previously thought (Borg et al. 2011).

Cosmogenic isotopes and exposure ages

Kurt Marti determined the exposure age of 60025 as 1.9 m.y. (see Drozd et al. 1977 and Arvidson et al. 1975). Fruchter et al. (1977) and Kohl et al. (1977) determined ^{53}Mn in 60025 as 105 ± 13 and 76 ± 6 dpm/kg respectively.

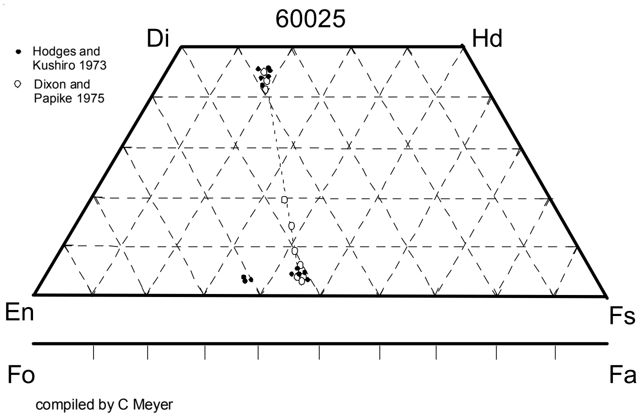
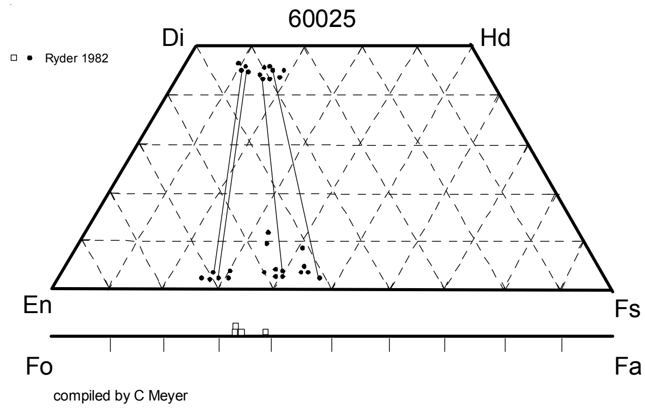
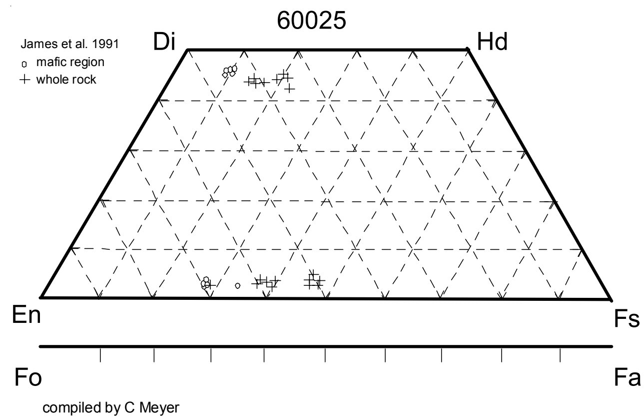


Figure 4: Pyroxene data from various investigators studing various different regions of 60025.





Other Studies

Sato (1986) determined the intrinsic oxygen fugacity of 60025. Flory et al. (1973) studied the hydrocarbons that were emitted during heating of 60025 (apparently produced by hydrolysis of solar wind implanted carbon). Schaeffer and Husain (1974), Lightner and Marti (1974) and Leich and Niemeyer (1975) analyzed the rare gases in 60025. Katsube and Collett (1973), Gold et al. (1976) and Cisowski et al. (1976) determined electrical and magnetic properties. Hapke et al. (1978) collected ultraviolet reflectance spectra. Simmons et al. (1975) studied the microcracks and Jeanloz and Ahrens (1978) studied the compressibility (equation of state). Sondergeld et al. (1979) determined seismic wave velocities to compare with seismic data collected at Apollo 16.

Processing

Two thick slabs have been cut from 60025 (figures 2 and 10) and several pieces are used in public displays (see flow diagram). Mafic-rich pieces were taken from the side opposite the slabs (W1).

List of Photo #s

S72-41586-41591	color mug shots
S72-42582-42597	B&W exterior
S72-49096-49109	first slab
S72-49095	slab assembled
S72-49094	end piece, subdivided
S74-28116	second slab

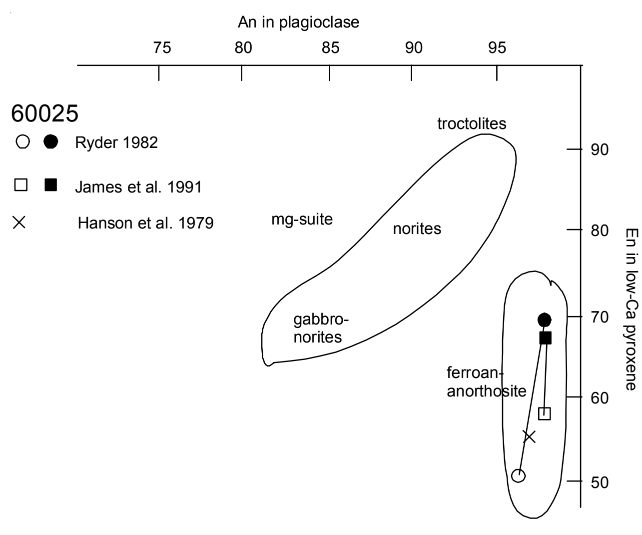


Figure 5: Plagioclase-low-Ca pyroxene diagram for various portions of ferroan anorthosite 60025.

Plagioclase in 60025

electron probe (wt.%)

	Papike 97	Hanson 79	McGee 93	Dixon and Papike 1975					James et al. 1991	
SiO2	43.9			43.4	44.7	44.8	44.4	44.8	44.15	44.08
Al2O3	35.3			35.2	35.2	35.2	35.4	34.4	36.03	36.01
FeO	0.18	0.145	0.145	0.19	0.15	0.19	0.17	0.23		
MgO	0.051	0.064	0.077	0.04	0.02	0.06	0.07	0.02	0.058	0.048
CaO	19			19.5	19.6	19.3	19.5	19.6	19.13	19.08
Na2O	0.426			0.42	0.39	0.48	0.46	0.36	0.34	0.359
K2O	0.009	0.031		0	0	0	0	0	0.01	0.06
Ab	3.9	3.9								
An	96		96.9	96.3	96.5	95.7	95.9	96.8	96.82	96.65
Or	0.057									

ion probe (ppm)

	Meyer 79	Steele 80	Papike 97	Floss 98	
Li	1.4	1.9			mafic area
Mg	474	410			
Ti	85	80			
Sr	197	240	168		
Y			0.22		
Ba	15	15	10.42		
La			0.29	0.24	0.33
Ce			0.483	0.67	0.82
Nd			0.26	0.39	0.43
Sm			0.086	0.094	0.06
Eu			1.16	1.03	1.05
Gd			0.066	0.093	0.071
Dy			0.047	0.055	0.039
Er			0.018	0.025	0.018
Yb			0.016	0.031	0.022

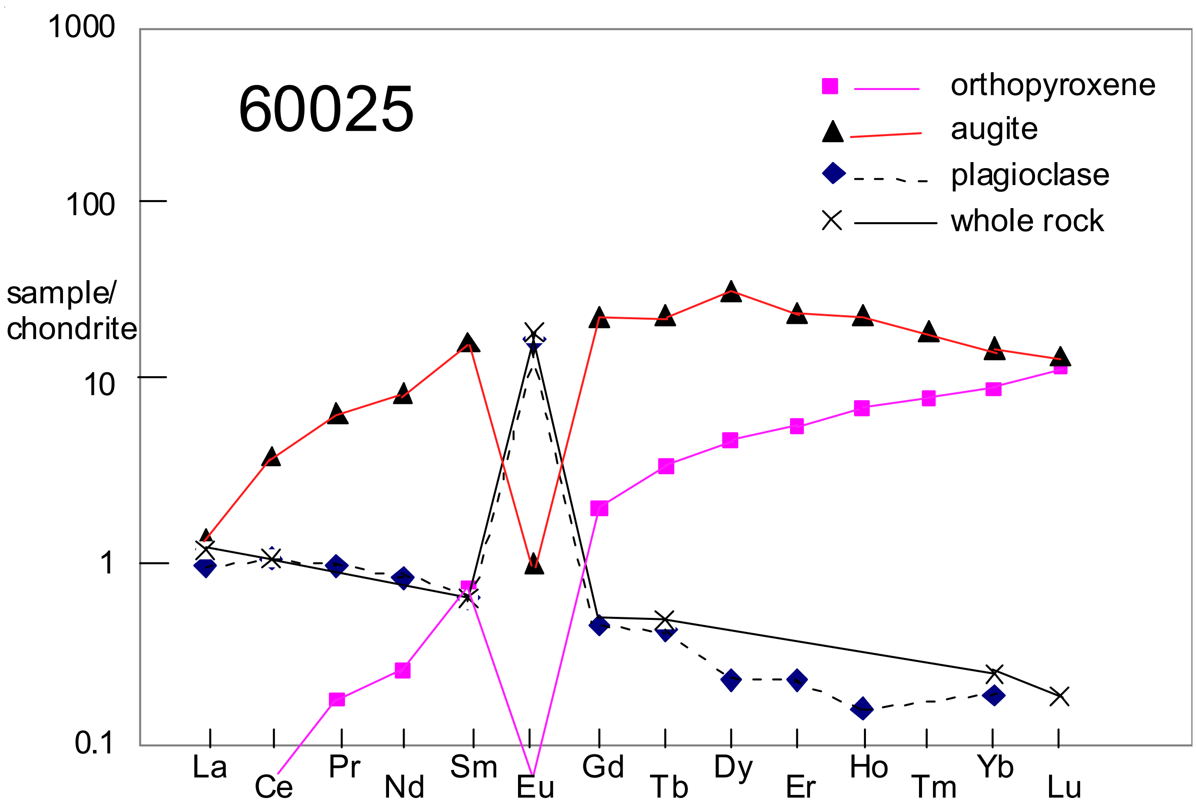


Figure 6: Noramlized rare-earth-element diagram for 60025 and its minerals. Data for whole rock from Haskin et al. 1981, data for minerals from Floss et al. 1998. Note that plagioclase dominates.

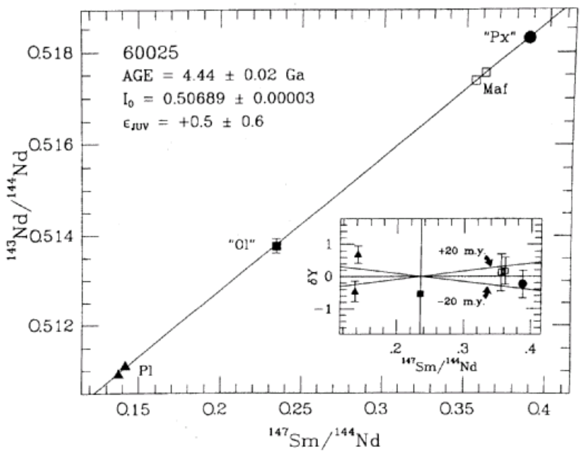


Figure 7: Sm-Nd mineral isochron for 60025 by Carlson and Lugmair (1988).

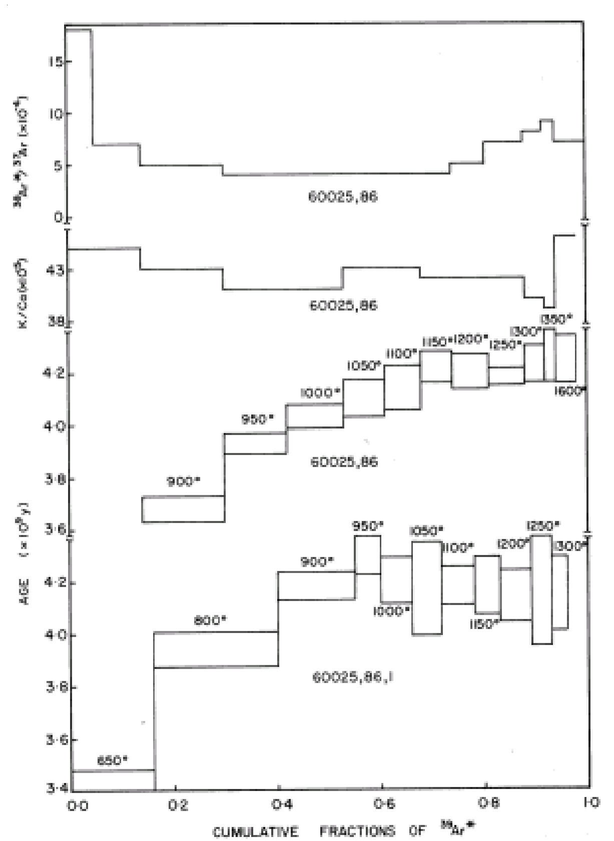


Figure 8a: Argon release pattern for 60025 by Schaeffer and Husain (1975).

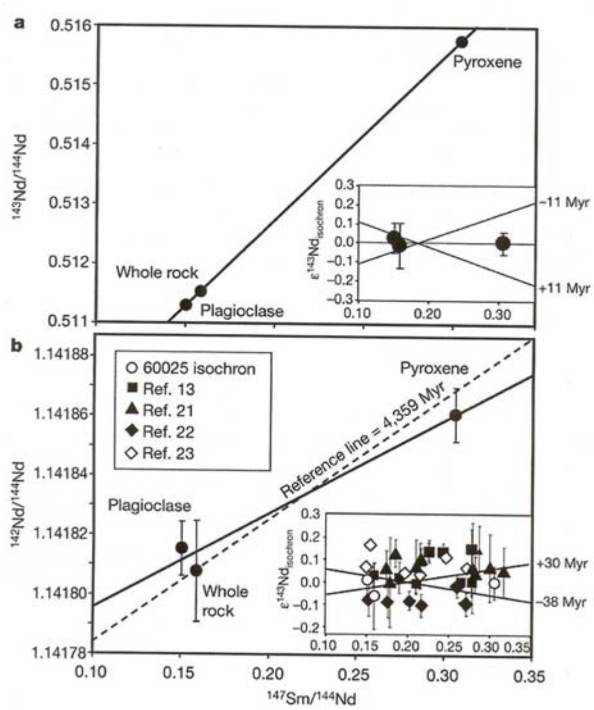


Figure 8b: Sm-Nd mineral isochrons for portion of 60025 (Borg et al. 2011).

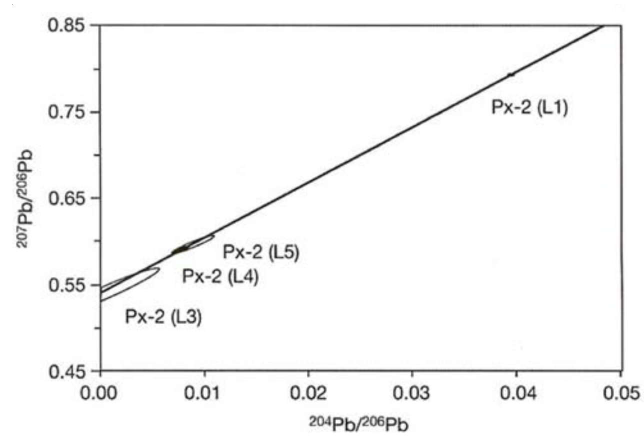


Figure 8c: Pb-Pb isochron for 60025 (Borg et al. 2011).

Summary of Age Data for 60025

	Pb/Pb	Sm/Nd	Ar/Ar
Schaeffer and Husain 1974			4.21 ± 0.06 b.y.
			4.17 ± 0.06
Hanan and Tilton 1987			
Plagioclase	4.51 ± 0.01 b.y.		
Mafic	4.42		
Carlson and Lugmair 1988		4.44 ± 0.02	
Borg et al. 2011	4.359 ± 0.002	4.367 ± 0.011	

Table 1a. Chemical composition of 60025.

													Ehmann 75	
reference	Wiesmann 75		Rose 73		Haskin 73		Laul 73		Krahenbuhl 73		Nakamura 73		Garg 76	Janghorbani 73
weight									*Wolf 79*					
SiO2 %			43.03	(b)	45.3	(c)					44.75			42.79
TiO2	0.02	(a)	0.02	(b)	<0.02	(c)	<0.06	(c)			0.2			
Al2O3			35.21	(b)	34.2	(c)	35.5	(c)			35.28			36.84
FeO			0.67	(b)	0.495	(c)	0.35	(c)			0.31			*1.3*
MnO			0.03	(b)	0.008	(c)	0.009	(c)			0.013			0.012
MgO	0.14	(a)	0.27	(b)	0.206	(c)					0.17			*0.16*
CaO			18.92	(b)	19.8	(c)	18.2	(c)			19.38			17.2
Na2O			0.49	(b)	0.45	(c)	0.414	(c)			0.44			0.44
K2O	0.008	(a)	0.03	(b)	0.113	(c)	<0.01	(c)			0.028			
P2O5			0								0.003			
S %														
sum														
Sc ppm					0.7	(c)	0.55	(c)					0.4	
V			<5	(b)			<7	(c)						
Cr			0	(b)	24	(c)	102	(c)			205			
Co			3.6	(b)	0.73	(c)	0.7	(c)					0.7	
Ni			30	(b)	1.1	(c)			<3	(d)				
Cu			8.4	(b)										
Zn			15	(b)	<2	(c)			0.17	(d)				
Ga					4	(c)								
Ge ppb									2.3	(d)				
As														
Se									0.022	(d)				
Rb	0.03	(a)	0.8	(b)	<0.1	(c)			0.017	(d)				
Sr	231	(a)	205	(b)										
Y														
Zr	9	(a)	<10	(b)									0.5	
Nb			<10	(b)										
Mo														
Ru														
Rh														
Pd ppb														
Ag ppb									0.22	(d)				
Cd ppb									7.25	(d)				
In ppb														
Sn ppb														
Sb ppb									0.035	(d)				
Te ppb									65	(d)				
Cs ppm					<0.003	(c)			0.002	(d)				
Ba	13.2	(a)	27	(b)			10	(c)			15.87	(a)		
La	0.294	(a)			0.28	(c)	0.3	(c)			0.301	(a)		
Ce	0.607	(a)			0.65	(c)	0.8	(c)			0.645	(a)		
Pr														
Nd	0.368	(a)			0.42	(c)	0.5	(c)			0.361	(a)		
Sm	0.091	(a)			0.092	(c)	0.12	(c)			0.0881	(a)		
Eu	1.13	(a)			1.04	(c)	1.04	(c)			1.044	(a)	1.1	
Gd	0.103	(a)									0.0895	(a)		
Tb					0.2	(c)	<0.02	(c)						
Dy	0.083	(a)			0.19	(c)	0.11	(c)			0.0783	(a)		
Ho														
Er	0.042	(a)			0.05	(c)					0.042	(a)		
Tm														
Yb	0.042	(a)			0.048	(c)	0.051	(c)			0.0429	(a)		
Lu	0.0046	(a)			0.006	(c)	0.005	(c)			0.00465	(a)		
Hf					0.02	(c)	0.013	(c)					0.0165	
Ta							<0.01	(c)						
W ppb														
Re ppb														
Os ppb														
Ir ppb														
Pt ppb														
Au ppb														
Th ppm														
U ppm									0.00092	(d)				

technique (a) IDMS, (b) combined XRF, microchem., emiss. spec., c) INAA, (d) RNAA

Table 1b. Chemical composition of 60025.

	glass										mafic patches	
reference	Morris 86		Haskin 81					Haskin 82		James 91		
weight								av. 12		,702WR	,691WR	,697WR
SiO2 %	44.54	(b)										
TiO2	0.36	(b)										
Al2O3	27.65	(b)										
FeO	5.14	(b)	0.32	0.362	0.36	1.31	0.315	0.63	(a)	0.665	13.1	11.8
MnO												
MgO	6.35	(b)										
CaO	15.46	(b)	18.5	18.2	18.1	17.8	18.4	18.6	(a)	18.5	8.3	10.4
Na2O	0.34	(b)	0.45	0.42	0.43	0.4	0.44	0.42	(a)	0.423	0.169	0.219
K2O	0.08	(b)										
P2O5												
S %												
sum												
Sc ppm	6.15	(a)	0.47	0.47	0.55	2.47	0.54	1.02	(a)	1.05	9.66	9.18
V												
Cr	754	(a)	0.55	0.69	0.59	1.99	0.54	73	(a)	42.7	812	781
Co	49	(a)	14.7	13.4	14.7	8	12.9	1.05	(a)	1.07	23.8	21.2
Ni	711	(a)										
Cu												
Zn												
Ga												
Ge ppb												
As												
Se												
Rb												
Sr			226	208	207	193	198			199	71	39
Y												
Zr												
Nb												
Mo												
Ru												
Rh												
Pd ppb												
Ag ppb												
Cd ppb												
In ppb												
Sn ppb												
Sb ppb												
Te ppb												
Cs ppm												
Ba	233	(a)	10.4	12	11.5	10	65			16		
La	10.49		0.289	0.252	0.234	0.23	0.275	0.27		0.235	0.14	0.173
Ce	31.3		0.67	0.69	0.54		0.7	0.65		0.62	0.71	
Pr												
Nd												
Sm	4.79		0.097	0.088	0.085	0.089	0.093	0.098		0.086	0.089	0.086
Eu	1.13		1.11	1.05	1.07	1	1.01	1.025		0.97	0.46	0.586
Gd												
Tb	0.97		0.0183	0.0152	0.0178	0.0252	0.015			0.018	0.029	0.015
Dy												
Ho												
Er												
Tm												
Yb			0.04	0.045	0.049	0.085	0.04	0.051		0.032	0.211	0.178
Lu	0.45		0.0046	0.0052	0.005	0.0111		0.0081		0.009	0.037	0.031
Hf	3.53		0.0078	0.0064	0.0086	0.021	0.018				0.076	0.08
Ta	0.43										0.018	0.036
W ppb												
Re ppb												
Os ppb												
Ir ppb												
Pt ppb												
Au ppb												
Th ppm	2.71											
U ppm	0.22											

technique (a) INAA, (b) microprobe

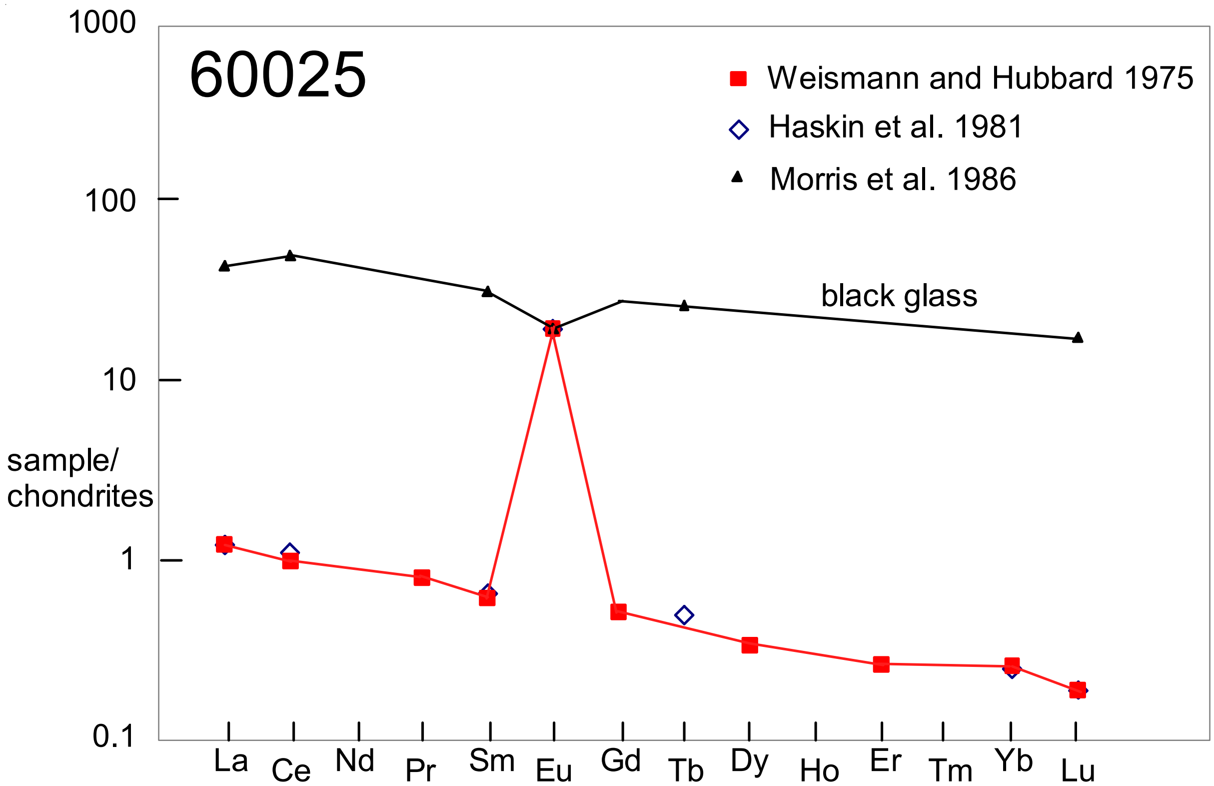


Figure 9: Chemical composition of black glass coating on 60025, compared with composition of interior anorthosite.

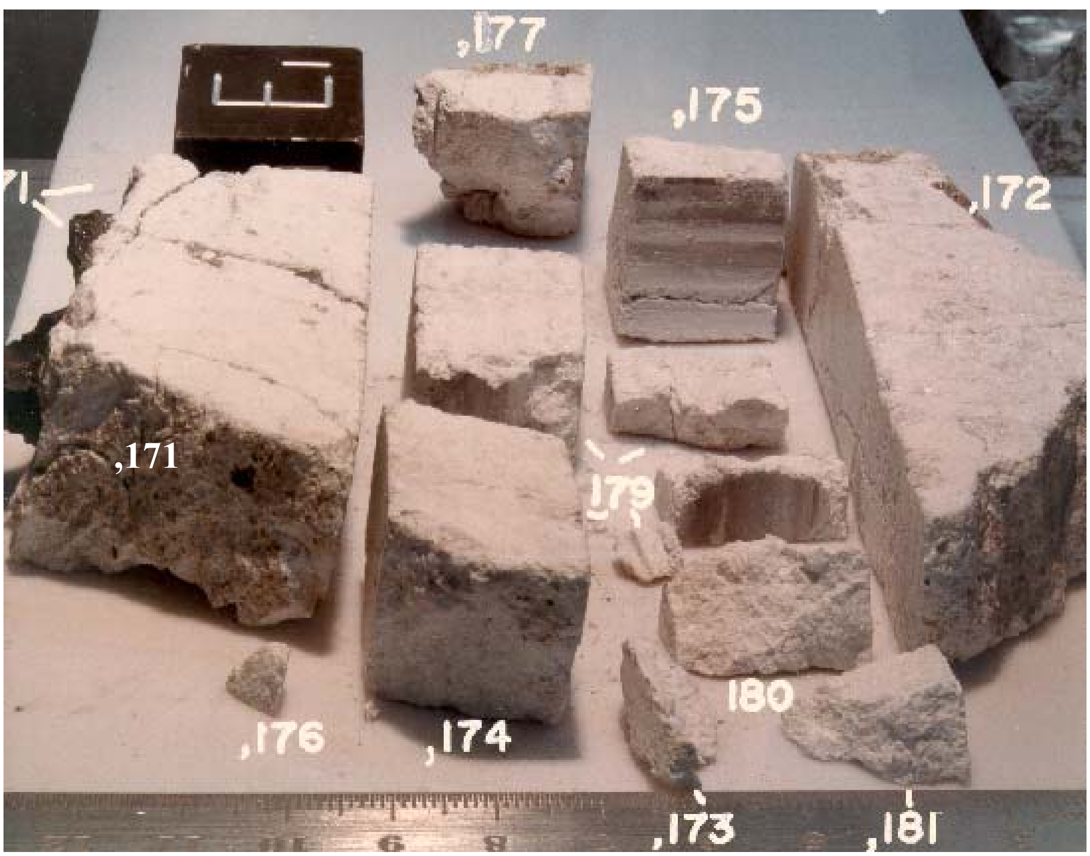


Figure 10: Second slab cut from 60025in 1974. Scale is in cm and cube is 1 inch. Slab was about 1 inch thick. NASA photo # S74-28116

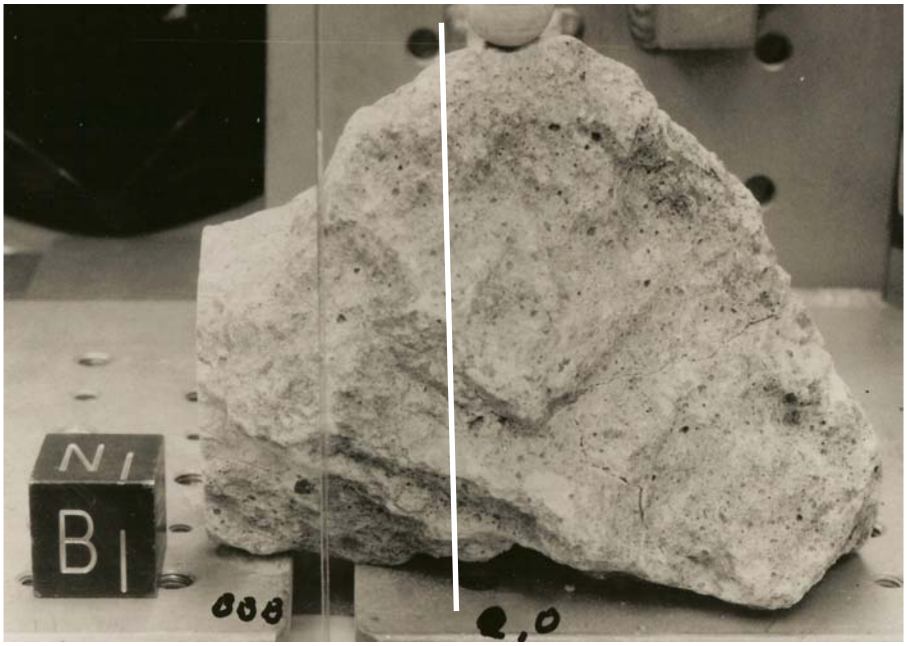
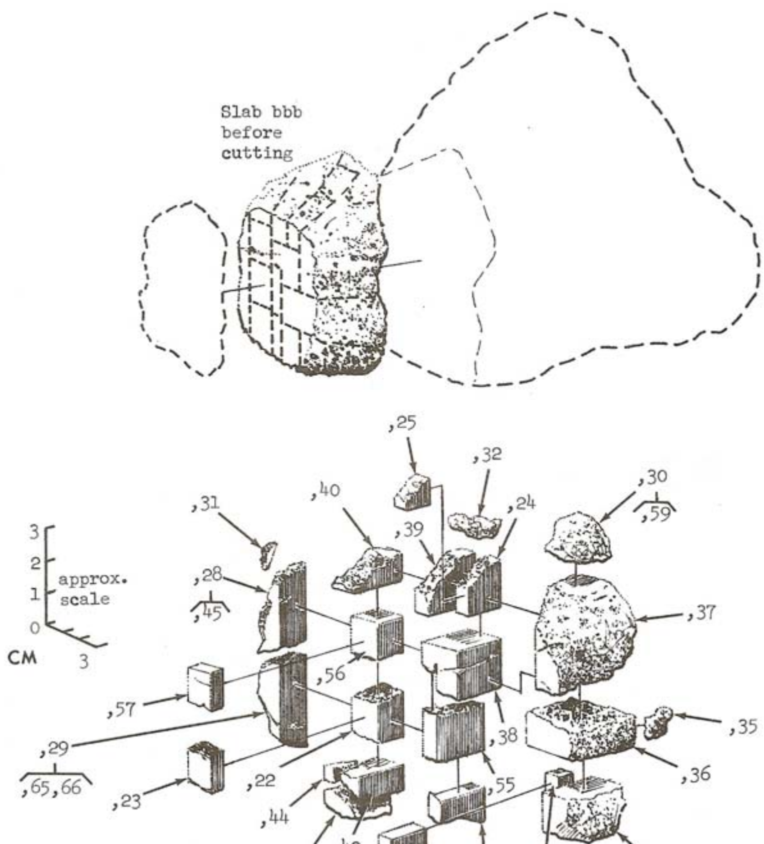


Figure 11: Position of saw blade prior to cutting first slab. White line shows approximate position of second slab. Cube is 1 inch. S76-21590 (copy of processing photo).



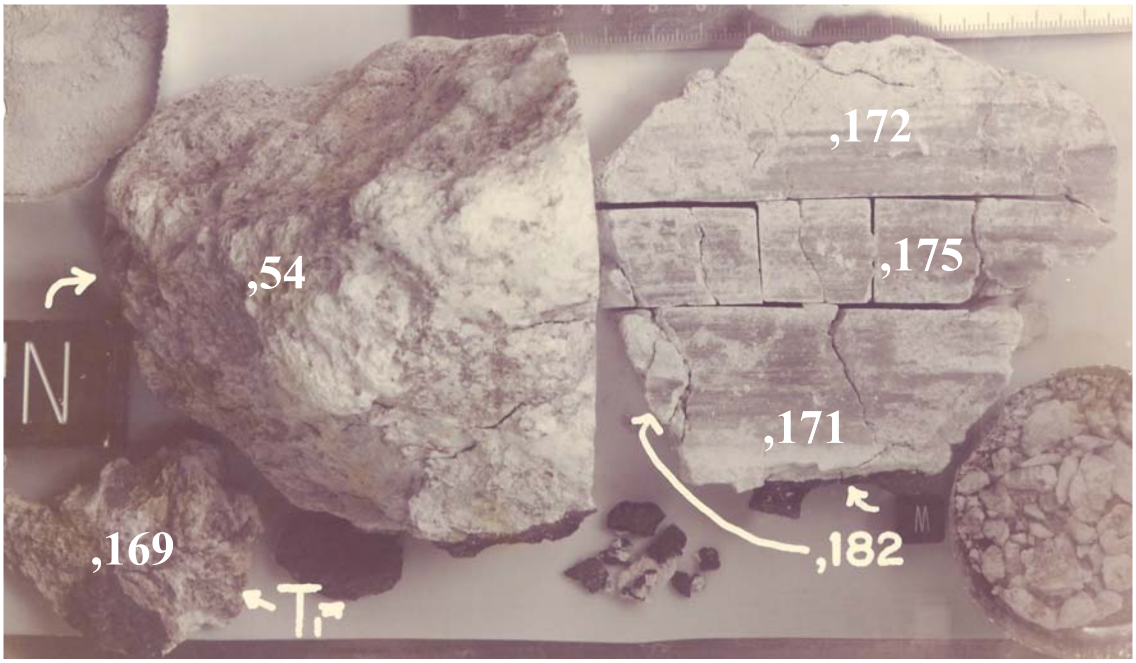
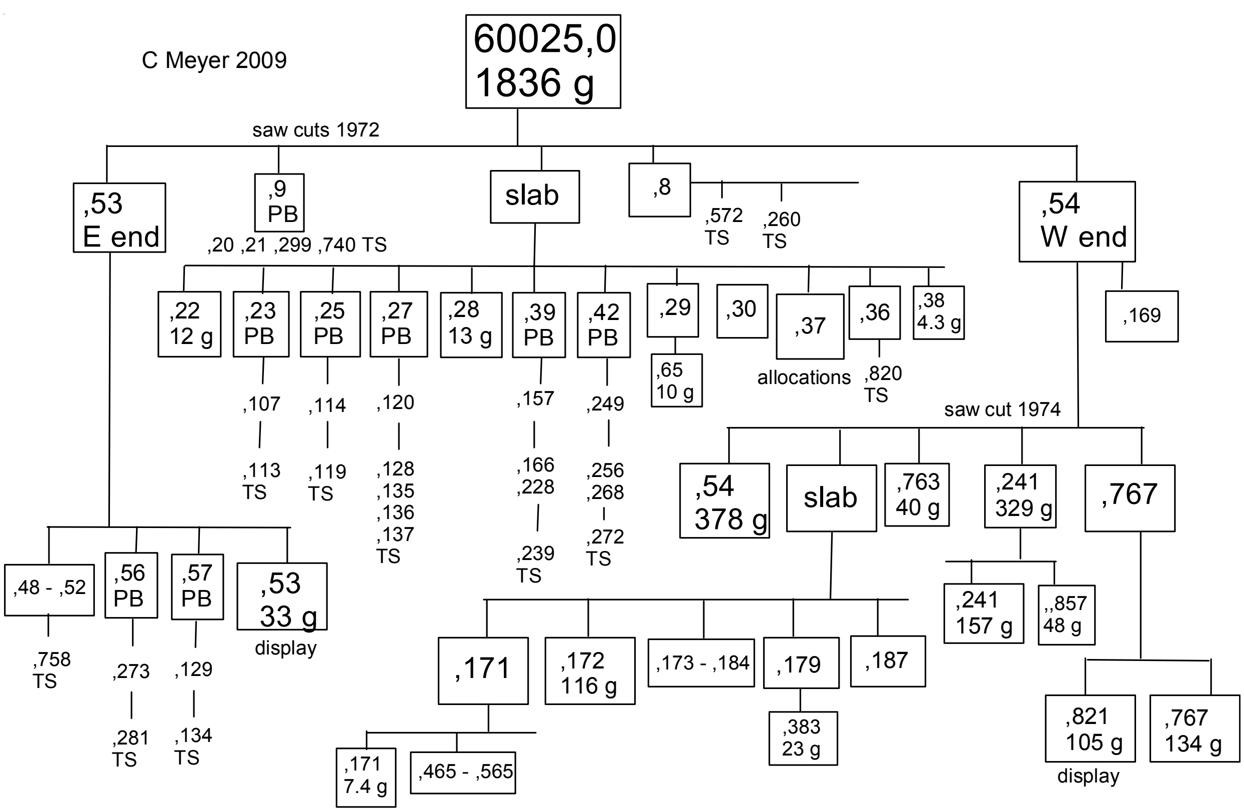


Figure 12: Processing photo of second slab. Big cube is 1 inch. S74-28115. Note the saw marks.



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