15016

Vesicular Olivine-normative Basalt

923.7 grams

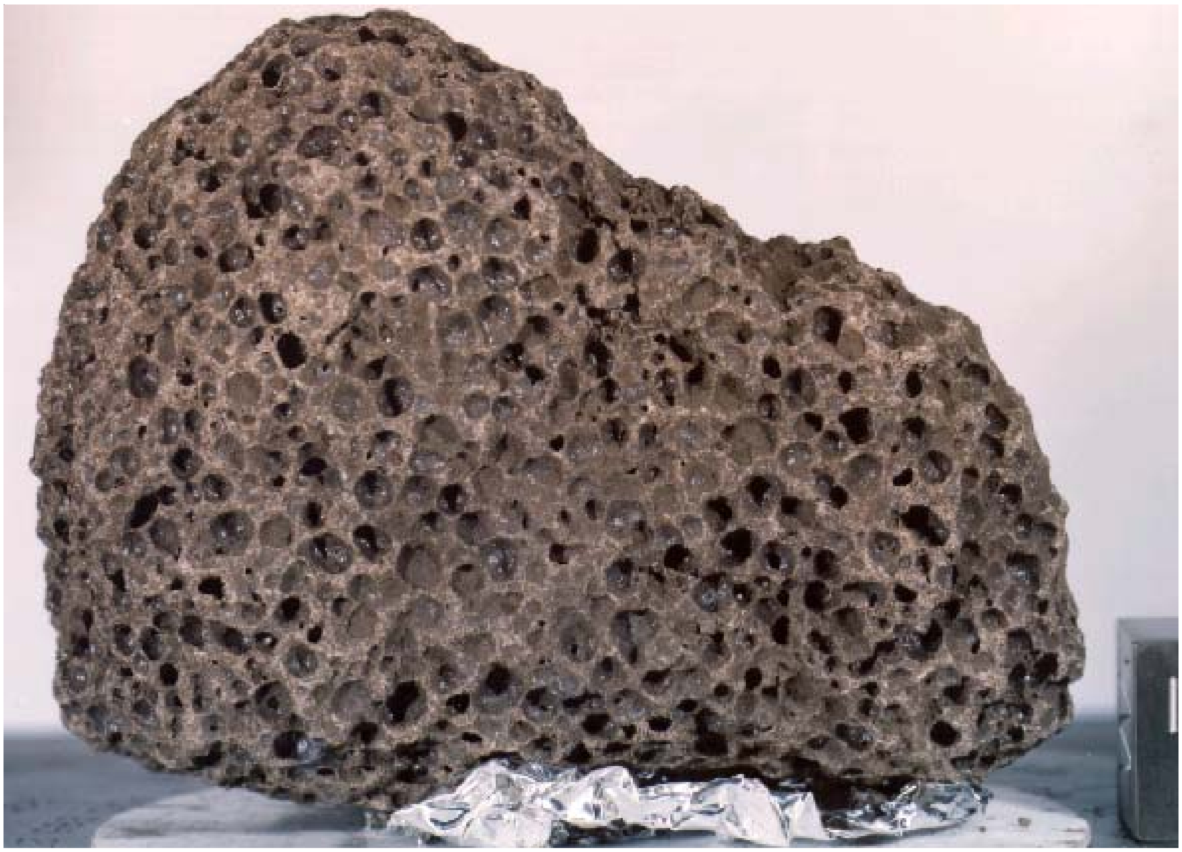


Figure 1: Photograph of vesicular basalt 15016. NASA# S71-46632. Cube is 1 inch.

Introduction

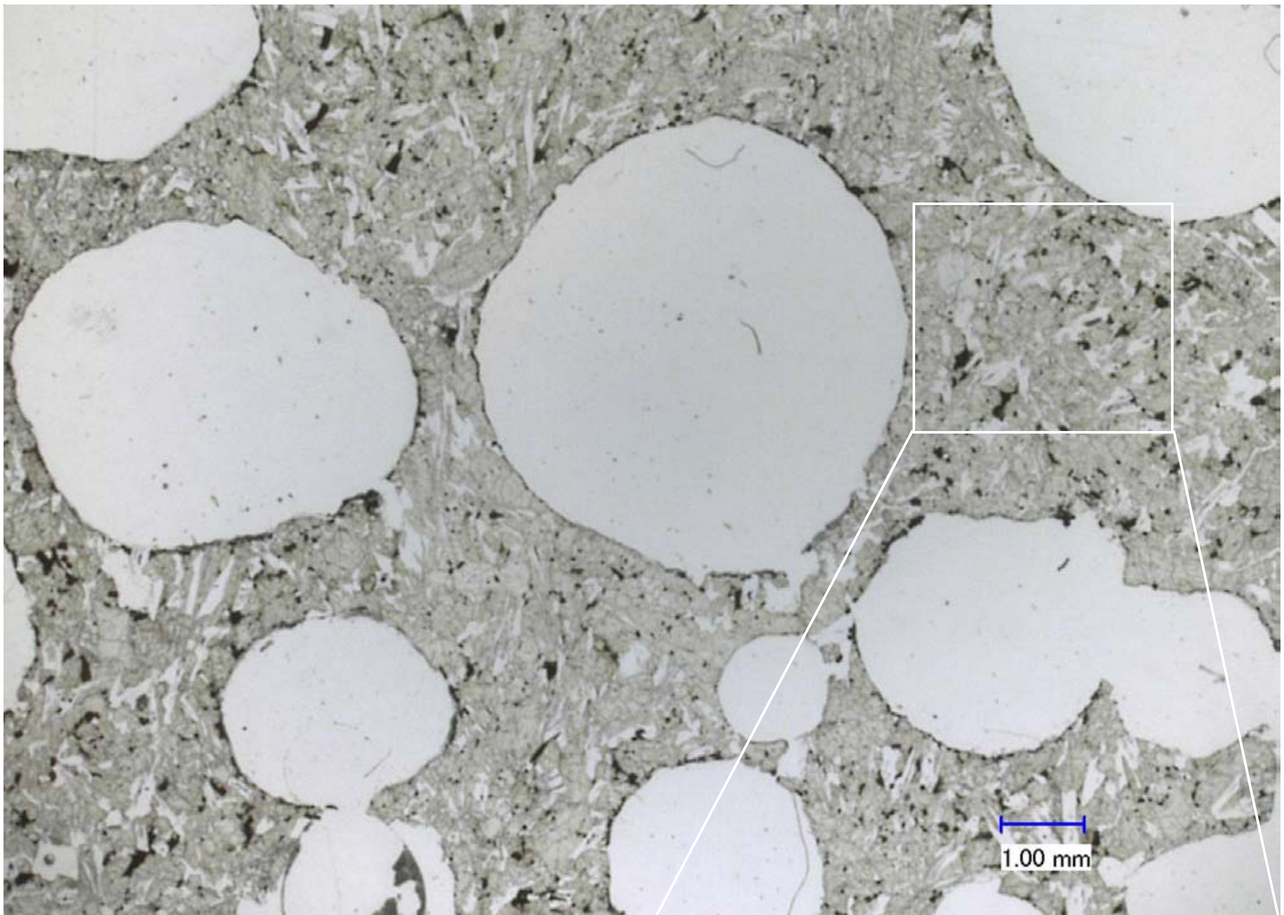
Lunar Sample 15016 is a highly-vesicular, olivine-normative, basalt with a major element composition similar to that of non-vesicular basalt 15555 (figure 1). These basalts are typical of many of the basalt samples returned from the Apollo 15, Hadley Rille site, and their composition has been studied experimentally to conclude that this volcanic magma came from a depth of greater than 250 km. 15529 and 15556 are also very vesicular basalts from other locations at Apollo 15 site..

15016 has been dated at 3.4 b.y. and has been exposed to cosmic rays for 300 m.y.

Petrography

Lunar sample 15016 is a medium-grained basalt with subhedral phenocrysts of zoned pyroxene (1-2 mm) and olivine (~1 mm) set in a matrix of subophitic intergrowths of pyroxene and plagioclase (figures 2 and 3). Vesicles (1 to 5 mm) make up about 50 % of the volume. Opaque minerals (ilmenite and ulvöspinel) frequently border the vesicles. Plagioclase platelets are sometimes hollow, with pyroxene cores. Subrounded grains of Cr-spinel are found in the pyroxene and olivine phenocrysts. Troilite and Fe-Ni metal are found in the mesostasis.

Experiments show that the paragenetic sequence is Cr-spinel (above 1300 C), olivine (1280 C), pyroxene (1170 C) and plagioclase (below 1150 C) matching the texture of the thin sections. Brown et al. (1972) found both low-K and high-K glass in the mesostasis, and speculate on Na loss during vesiculation. The interior walls of the vesicles have been studied by Goldberg et al. (1976).



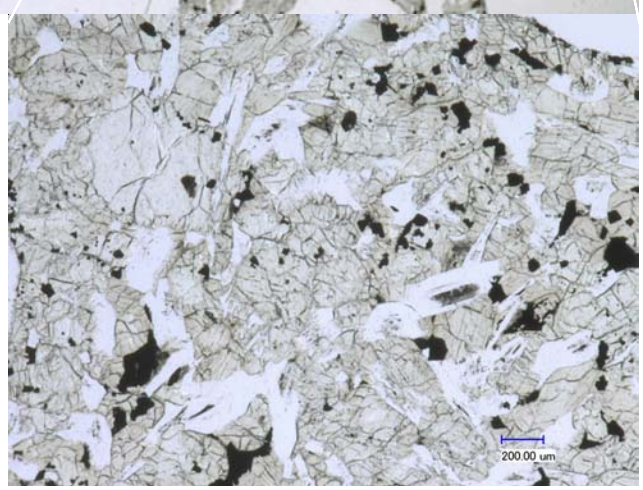


Figure 2: Photomicrographs of thin section 15016,146 by C Meyer @ 20x and 100x.

Mineralogy

Olivine: Olivine ranges in composition Fo_{70-10} (Bence and Papike 1972).

Pyroxene: Pyroxene analyses are given in Bence and Papike (1972), Papike et al. (1976), and Kushiro (1973) (figure 4). Large pyroxene grains are highly zoned first towards Ca-rich, then Fe-rich, indicating rapid crystallization.

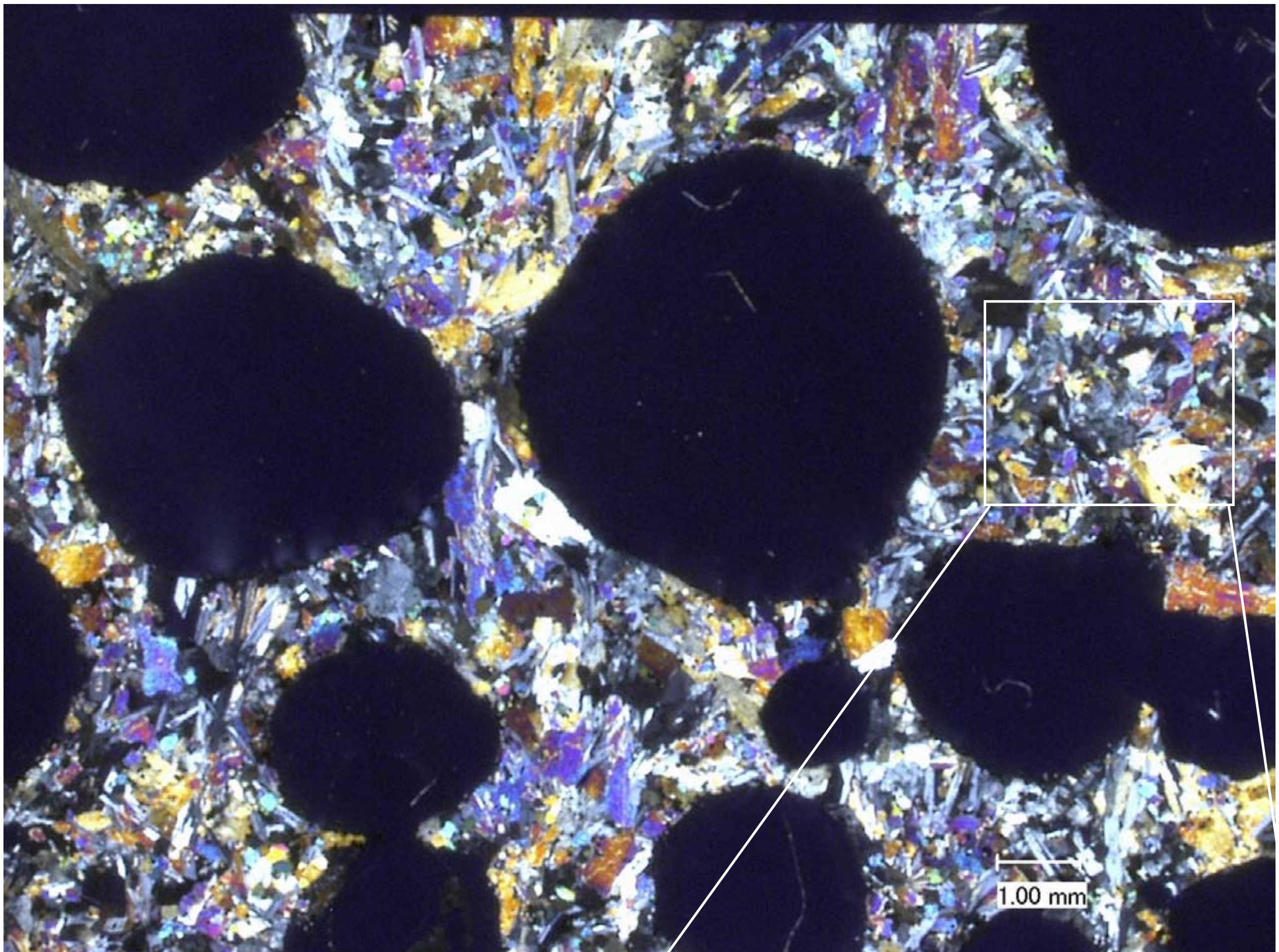
Plagioclase: Plagioclase ranges An_{94-80} (Bence and Papike 1972). Brown et al. (1972) found reverse zoning indicating volatile loss.

Ilmenite: Ilmenite was studied by Engelhardt (1979).

Silica: Brown et al. (1972) found that silica in 15016 was cristobalite.

Mineralogical Mode for 15016

	Brown et al. 1972	Papike et al. 1976	McGee et al. 1977
Olivine	6-10 vol. %	7.5	7-8
Pyroxene	59-63	63.9	64-67
Plagioclase	21-27	22.2	20-22
Opaques	4-7	5.9	
Ilmenite			6
Chromite			0.1
Ulvöspinel			0.4
Mesostasis			0.3
Silica	1-2	0.2	



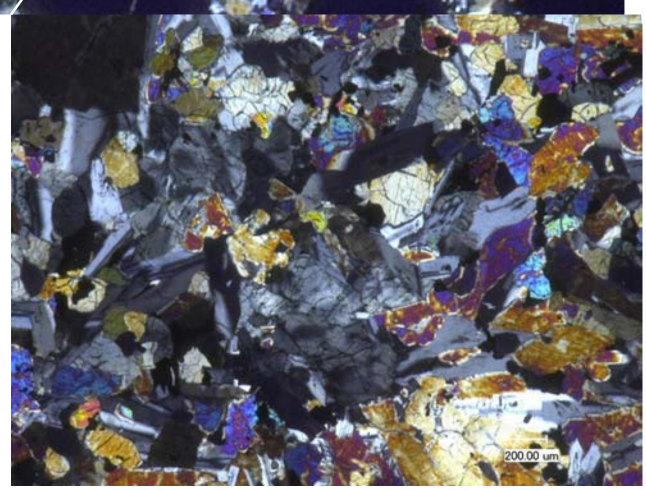


Figure 3: Photomicrographs of thin section 15016,146 (crossed nicols) by C Meyer @ 20x and 100x.

Chemistry

Although the major element composition of 15016 is very similar to that of 15555, the trace element composition is higher (figure 6). Cr may also be higher in 15016 than 15555.

Barker (1974) and Gibson et al. (1975) studied the gas (CO, CO_2 etc.) released by heating or mechanically crushing the sample. Goldberg et al. (1976) studied fluorine in the vesicle walls.

Radiogenic age dating

Murthy et al. (1973) and Evensen et al. (1973) determined the age of 15016 as 3.29 ± 0.05 b.y. by the Rb-Sr method (figure 7). Both the age and the initial Sr isotopic ratio ($^{87}Sr/^{86}Sr$ = 0.69914 ± 0.00005) are similar to that of 15555 measured in the same lab. Kirsten et al. (1973) determined a plateau age of 3.38 ± 0.08 b.y. Snyder et al. (1998) determined mineral isochrons by Rb/Sr and Sm/Nd giving ages 3.34 ± 0.03 b.y. and 3.22 ± 0.07 b.y. (respectively)(figure 8).

Cosmogenic isotopes and exposure ages

O'Kelley et al. (1972) and Eldridge et al. (1972) determined the ^{26}Al, ^{22}Na, ^{46}Sc, ^{48}V, ^{54}Mn and ^{56}Co activity by whole rock radiation counting. Aluminum 26 is saturated!

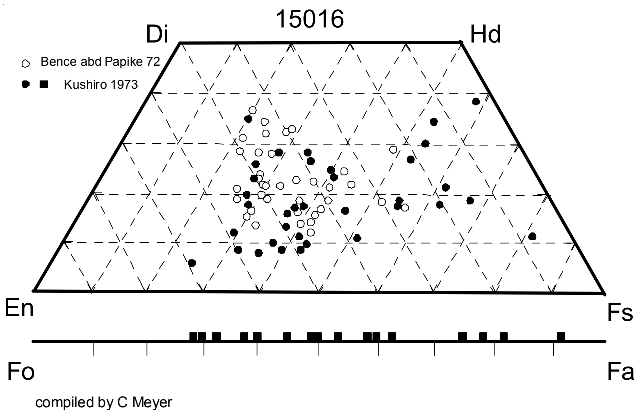


Figure 4: Pyroxene and olivine composition of 15016, showing extreme Fe-enrichment (data from Bence and Papike 1972 and Kushiro 1973).

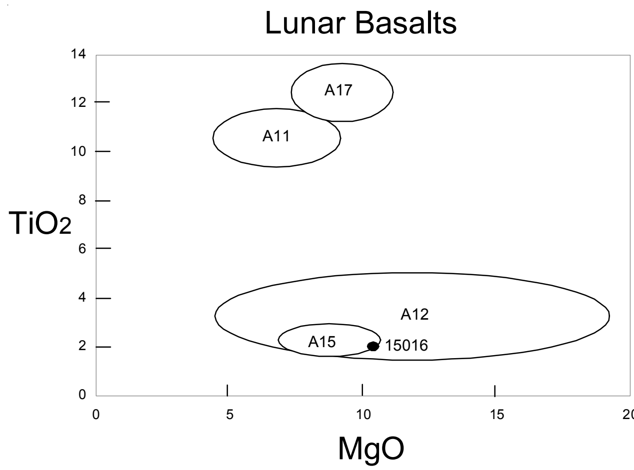


Figure 5: Composition diagram for lunar basalts with 15016.

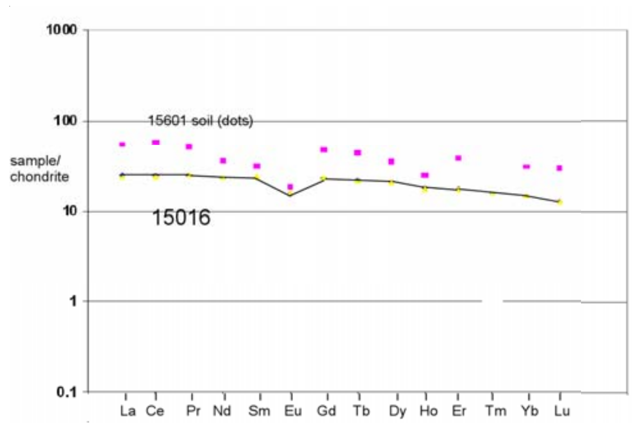


Figure 6: Normalized rare-earth-element diagram for 15016 (Neal 2001), with 15601 soil (Wanke et al. 1973) for comparison.

Kirsten et al. (1973) determined a ^{38}Ar exposure age of 285 m.y. Husain (1974) determined 315 m.y.

Other Studies

15016 and 15555 are among the more magnesian of the Apollo 15 basalts (figure 5). Phase diagrams have been prepared from the experimental studies of Humphries et al. (1972), Kushiro (1972) (figure 9) and Kesson (1975, 1977)(figure 10). These liquids are multi-saturated at ~12 kbar and 1350 deg C, indicating that the basaltic liquid may have come from an olivine-pyroxenite at greater than 250 km depth in the moon.

Gose et al. (1972) and Pearce et al. (1973) studied the magnetic properties of chips of 15016. Cisowski et al. (1975) gives a low field strength estimate for magnetization.

Charette and Adams (1975) determined the reflectance spectra of 15016 was similar to that of 15555.

Clayton et al. (1972) reported the isotopic composition of oxygen.

Summary of Age Data for 15016

	Ar/Ar	Rb/Sr	Pb/Pb	Sm/Nd
Evensen et al. 1973		3.29 ± 0.05 b.y.		
Kirsten et al. 1973	3.38 ± 0.08			
Husain 1974	no plateau			
Anderson and Hinthorne 1973			3.75 ± 0.27 (ion probe, phosphate)	
Snyder et al. 1998		3.34 ± 0.03		3.22 ± 0.07

Caution: Original radioactive decay “constants” are used.

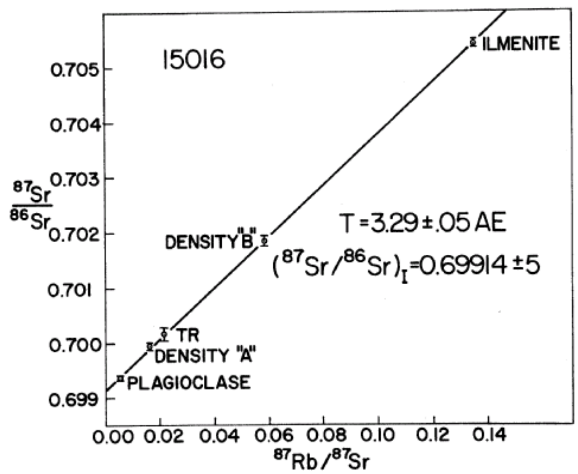


Figure 7: Rb/Sr isochron diagram for 15016 (from Evensen et al. 1973).

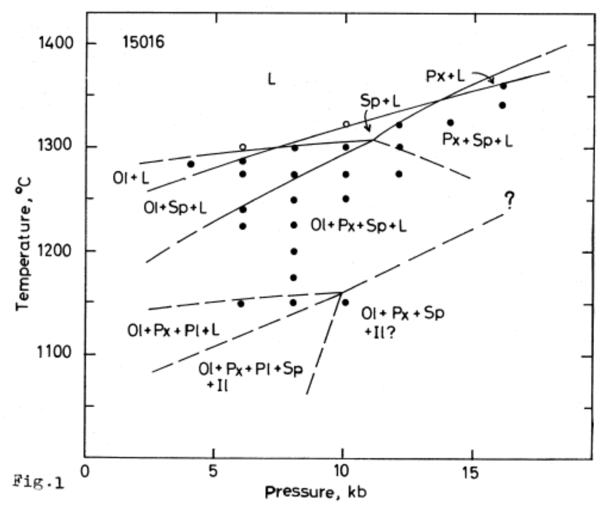


Figure 9: High-pressure phase diagram for 15016 (from Kushiro 1972).

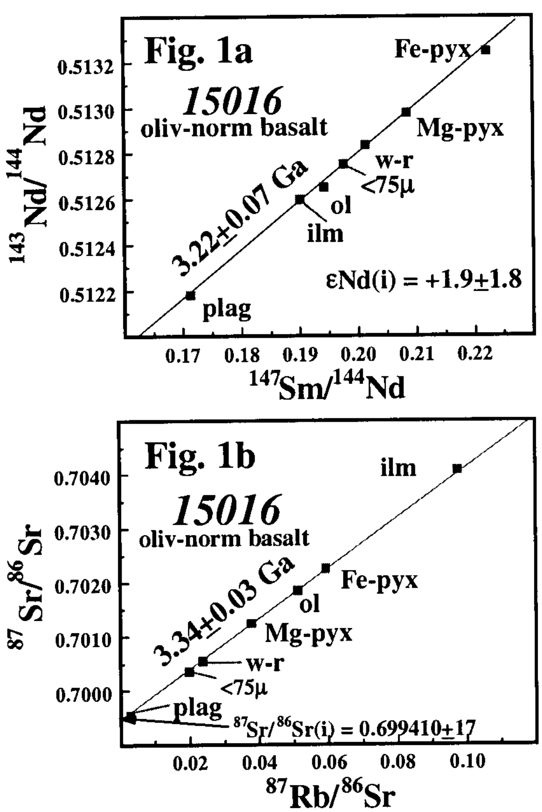


Figure 8: Sm/Nd and Rb/Sr isochrons for 15016 (from Snyder et al. 1997).

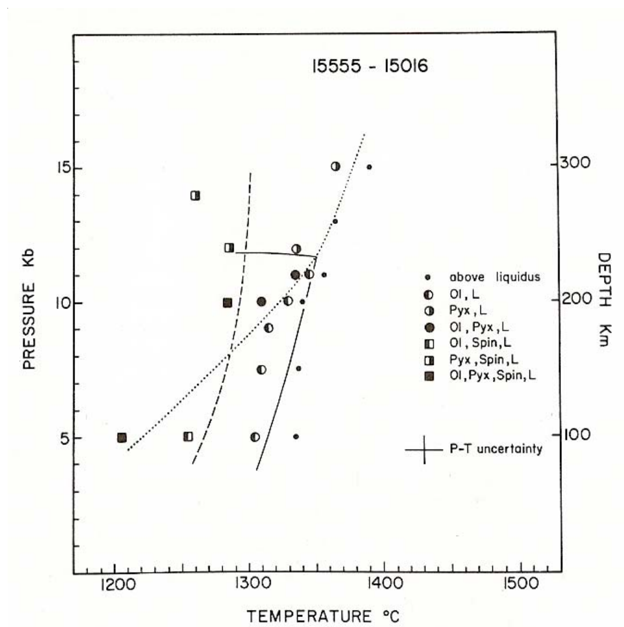


Figure 10: Phase diagram for mare basalts 15016 - 15555 (Kesson 1975, 1977).

Table 2	U ppm	Th ppm	K ppm	Rb ppm	Sr ppm	Nd ppm	Sm ppm	technique
Evensen et al. 1973				0.67	90.7			IDMS
Compston et al. 1972				0.73	89.7			IDMS
				0.81	91.4			IDMS
				0.65	93.3			IDMS
O'Kelley et al. 1972	0.15	0.52	373					counting
Snyder et al. 1998				0.656	79.9	9.09	3.03	IDMS

Table 1a. Chemical composition of 15016.

reference	A15PET		Kushiro 72		Cuttitta 73		Laul 73		Muller 75	Taylor 73		Janghorbani 73	Baedecker 73	
weight	Rhodes 73				Christian 72		365 mg						replica	
SiO2 %	43.97	(a)	43.78	(b)	44.3	(b)						43.86		
TiO2	2.31	(a)	2.28	(b)	2.27		2.1	(c)		1.77	(d)	3		
Al2O3	8.43	(a)	8.17	(b)	8.39		8.8	(c)				8.31		
FeO	22.58	(a)	22.5	(b)	22.95		21.8	(c)		16.53	(d)	21.84		
MnO	0.33	(a)	0.33	(b)	0.29		0.26	(c)				0.27		
MgO	11.14	(a)	11.58	(b)	11.65		11	(c)	11.12			11.44		
CaO	9.4	(a)	9.06	(b)	9.2		9	(c)	10.73	10.93	(d)			
Na2O	0.21	(a)	0.24	(b)	0.32		0.251	(c)	0.25	0.32	(d)			
K2O	0.03	(a)	0.04	(b)	0.05		0.041	(c)	0.041					
P2O5	0.07	(a)	0.25	(b)	0.06									
S %	0.07	(a)	0.19	(b)										
sum														
Sc ppm					32		36	(c)		25	(d)			
V					200		250	(c)		140	(d)			
Cr			7526	(b)	4516		5866	(c)		4100	(d)			
Co					65		53	(c)		56	(d)			
Ni					86					74	(d)		85	(e)
Cu					0.11					10	(d)			
Zn													1.8	(e)
Ga					4.6								3.6	(e)
Ge ppb													28	(e)
As														
Se														
Rb									1	0.83	(d)			
Sr	83	(a)			80				90					
Y					21					26	(d)			
Zr	95	(a)			69		150	(c)		94	(d)			
Nb					<10					6.2	(d)			
Mo														
Ru														
Rh														
Pd ppb														
Ag ppb														
Cd ppb													2	(e)
In ppb													0.36	(e)
Sn ppb										190	(d)			
Sb ppb														
Te ppb														
Cs ppm									0.04					
Ba					30		70	(c)	53	61	(d)			
La					<10		5.5	(c)	5.2	5.3	(d)			
Ce										14.4	(d)			
Pr										2	(d)			
Nd										9.6	(d)			
Sm							3.6	(c)		3.42	(d)			
Eu							0.8	(c)		0.87	(d)			
Gd										4.5	(d)			
Tb							0.59	(c)		0.73	(d)			
Dy										4.55	(d)			
Ho										1.1	(d)			
Er										2.86	(d)			
Tm										0.4	(d)			
Yb					4.2		2.2	(c)		2.42	(d)			
Lu							0.35	(c)		0.38	(d)			
Hf							2.5	(c)		2.04	(d)			
Ta							0.4	(c)						
W ppb														
Re ppb														
Os ppb														
Ir ppb													0.12	(e)
Pt ppb														
Au ppb													0.27	(e)
Th ppm										0.5	(d)			
U ppm									0.15	0.12	(d)			

***technique** (a) XRF, (b) conventional, (c) INAA, (d) SSMS, (e) RNAA*

Table 1b. Chemical composition of 15016.

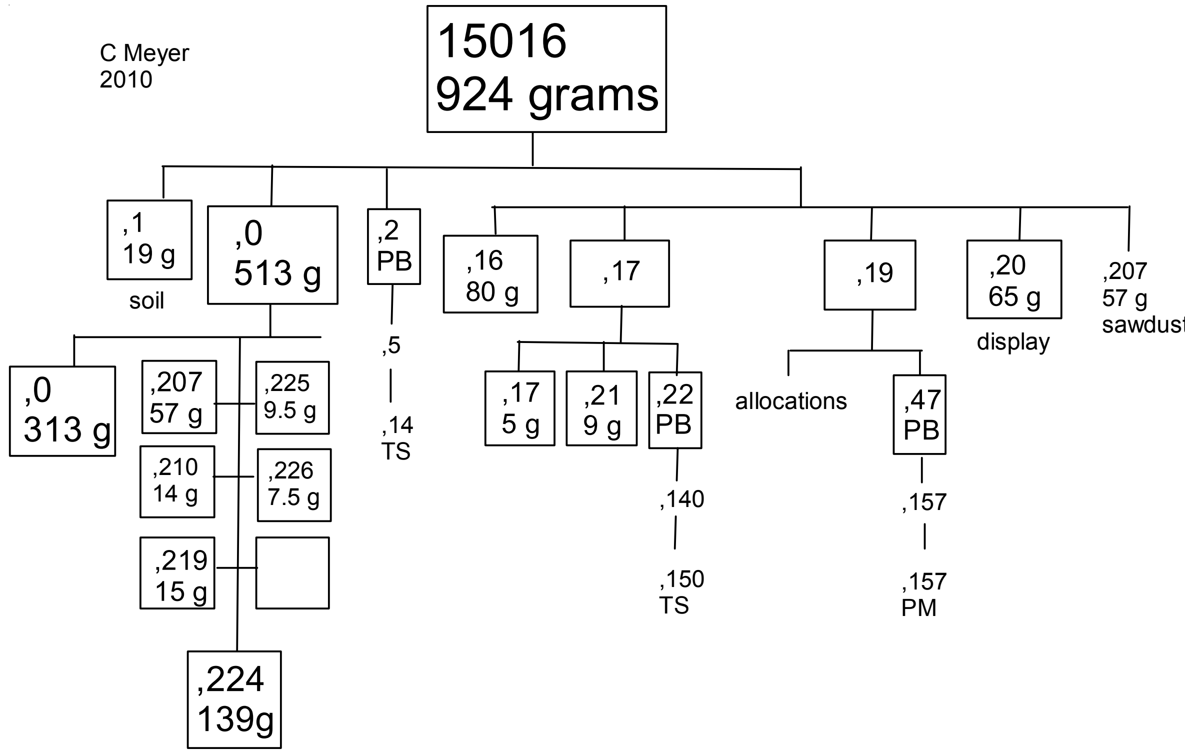
reference	Chappell 73		Helmke 73		Wolf 79		Garg 76		O'Kelly 72		Evensen 73		Compston 72				Gibson 75
weight			*1.04 g*						923 grams								
SiO2 %	44.26	(f)															
TiO2	2.29	(f)															
Al2O3	8.52	(f)															
FeO	22.93	(f)															
MnO	0.31	(f)															
MgO	10.84	(f)															
CaO	9.43	(f)															
Na2O	0.32	(f)															
K2O	0.05	(f)							0.045	(l)	0.0405	(j)					
P2O5	0.08	(f)															
S %	0.04																0.086
sum																	
Sc ppm			39.1	(g)													
V																	
Cr	5500	(f)	6400	(g)													
Co			54	(g)													
Ni					68	(h)											
Cu																	
Zn			<4		1.05	(h)											
Ga	2.7	(f)	3.2	(g)													
Ge ppb					4.38	(h)											
As																	
Se					0.114	(h)											
Rb	0.65	(f)			0.879	(h)					0.67	(j)	0.73	0.81	0.65	(j)	
Sr	93.3	(f)									90.7	(j)	89.7	91.4	93.3	(j)	
Y	23	(f)															
Zr	86	(f)					94.7	(h)									
Nb	7	(f)															
Mo																	
Ru																	
Rh																	
Pd ppb																	
Ag ppb					0.84	(h)											
Cd ppb					2.05	(h)											
In ppb					0.34	(h)											
Sn ppb					<60	(h)											
Sb ppb					3.8	(h)											
Te ppb					2.4	(h)											
Cs ppm			0.029	(g)	0.0335	(h)											
Ba																	
La			5.77	(g)													
Ce			15.6	(g)													
Pr																	
Nd			11.4	(g)													
Sm			4.05	(g)													
Eu			0.97	(g)													
Gd			5.4	(g)													
Tb			0.9	(g)													
Dy			5.74	(g)													
Ho			1.1	(g)													
Er			3.1	(g)													
Tm																	
Yb			2.62	(g)													
Lu			0.321	(g)													
Hf			2.6	(g)			2.53	(h)									
Ta																	
W ppb																	
Re ppb					0.033	(h)											
Os ppb					<0.01	(h)											
Ir ppb					0.018	(h)											
Pt ppb																	
Au ppb					0.025	(h)											
Th ppm									0.52	(l)							
U ppm					0.16	(h)			0.15	(l)							

technique (f) XRF (g) INAA, (h) RNAA, (l) radiation counting, (j) IDMS

Table 1c. Chemical composition of 15016.

reference	Ryder 2001				Neal 2001	
weight	5 g					
SiO2 %	44.6	(a)				
TiO2	2.24	(a)				
Al2O3	8.54	(a)				
FeO	21.74	(a)	21.8	(b)		
MnO	0.28	(a)				
MgO	11.22	(a)				
CaO	9.37	(a)				
Na2O	0.222	(a)	0.244	(b)		
K2O	0.043	(a)				
P2O5	0.068	(a)				
S %						
sum						
Sc ppm			40.7	(b)	42	(h)
V					304	(h)
Cr	6000	(a)	5840	(b)	5867	(h)
Co			54.6	(b)	58	(h)
Ni	72	(a)	66	(b)	75	(h)
Cu	9	(a)			14	(h)
Zn					18	(h)
Ga					3.65	(h)
Ge ppb						
As						
Se						
Rb	2	(a)			0.94	(h)
Sr	90	(a)	100	(b)	97.2	(h)
Y	26	(a)			31	(h)
Zr	85	(a)			109	(h)
Nb	9	(a)			7.5	(h)
Mo					0.08	(h)
Ru						
Rh						
Pd ppb						
Ag ppb						
Cd ppb						
In ppb						
Sn ppb						
Sb ppb						
Te ppb						
Cs ppm					0.02	(h)
Ba			57	(b)	56	(h)
La			5.22	(b)	5.9	(h)
Ce			15.2	(b)	15	(h)
Pr					2.24	(h)
Nd			8	(b)	10.5	(h)
Sm			3.67	(b)	3.42	(h)
Eu			0.82	(b)	0.87	(h)
Gd					4.53	(h)
Tb			0.82	(b)	0.8	(h)
Dy					5.1	(h)
Ho					1	(h)
Er					2.77	(h)
Tm					0.38	(h)
Yb			2.18	(b)	2.38	(h)
Lu			0.31	(b)	0.31	(h)
Hf			2.49	(b)	2.58	(h)
Ta			0.37	(b)	0.46	(h)
W ppb					0.05	(h)
Re ppb						
Os ppb						
Ir ppb						
Pt ppb						
Au ppb						
Th ppm			0.41	(b)	0.26	(h)
U ppm					0.08	(h)

technique (f) XRF (g) INAA, (h) ICP-MS



Processing

15016 was sawn, several times, and pieces of 15016 are used for public display. There are 21 thin sections.

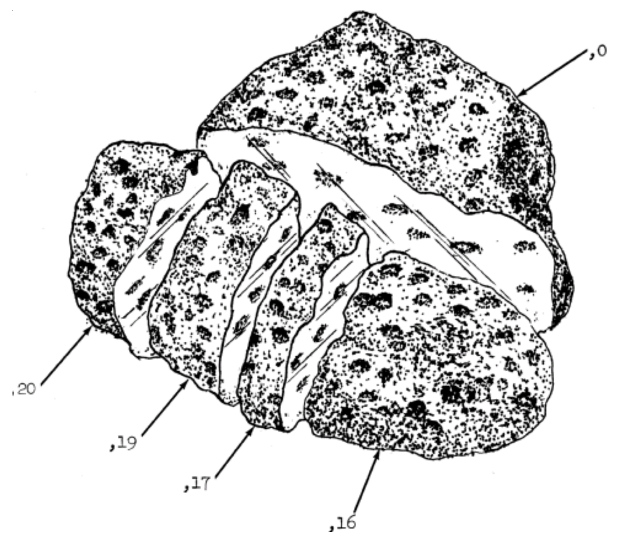


Photo #s of 15016

S71-45477-45481	color
S71-46630-46635	color
S71-46962-46993	B&W
S71-52221	TS
S71-58683	group

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