12021

Pigeonite Basalt

1876.6 grams

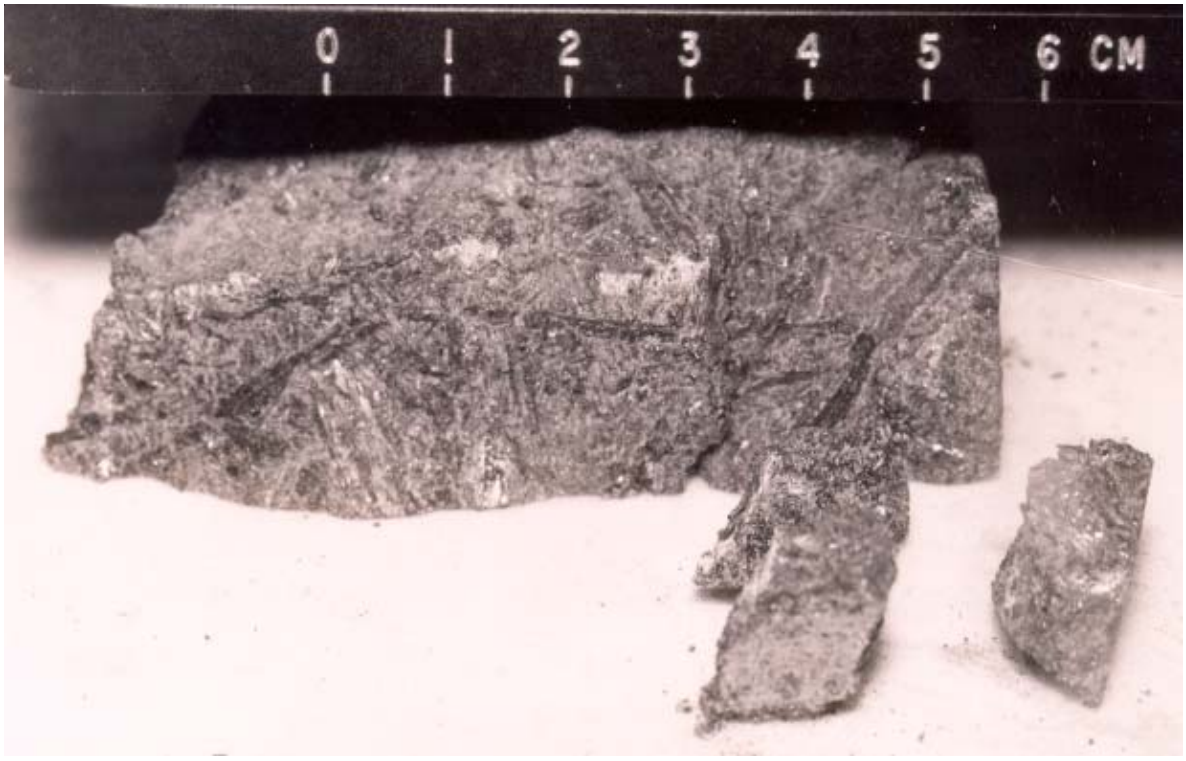


Figure 1: Photo of 12021,36 showing elongate pyroxene in broken surface.

Introduction

12021 is a porphyritic pigeonite basalt (figure 1) that has been dated at 3.3 b.y. old.

Hörz and Hartung (1972) found that 12021 must have changed orientation at least once because "old" zap pits were found beneath the soil line. In any case, the orientation found by Hörz and Hartung (based on cratered – uncratered surfaces) differs from that found by Sutton and Schaber (1971) (based on surface photography).

Petrography

Weill et al. (1971) describe 12021 as a porphyritic basalt with elongate pyroxene phenocrysts up to 2 cm in length set in a variolitic groundmass of pyroxene, plagioclase and ilmenite (figure 2). Mesostasis includes silica phases, metallic iron, and glass. French et al. (1972) describe 12021 as "generally coarse grained. A striking feature is the presence of large anhedral pyroxene phenocrysts up to 10 mm long. No olivine was observed".

Mineralogical Mode of 12021

	McGee et al. 1977	Neal et al. 1994	Boyd and Smith 1971	Klein et al. 1971	Papike et al. 1976	Brown et al. 1971
Olivine	- -	1				
Pyroxene	50-71	71.3	64	70.5	62.6	66
Plagioclase	22-34	25.5	27	22.7	30.7	22.4
Opaques	5-12	1.7	5	5.5	5.6	11.6
"silica"	5	0.2	2	1.3	0.3	
mesostasis	0.8				0.8	

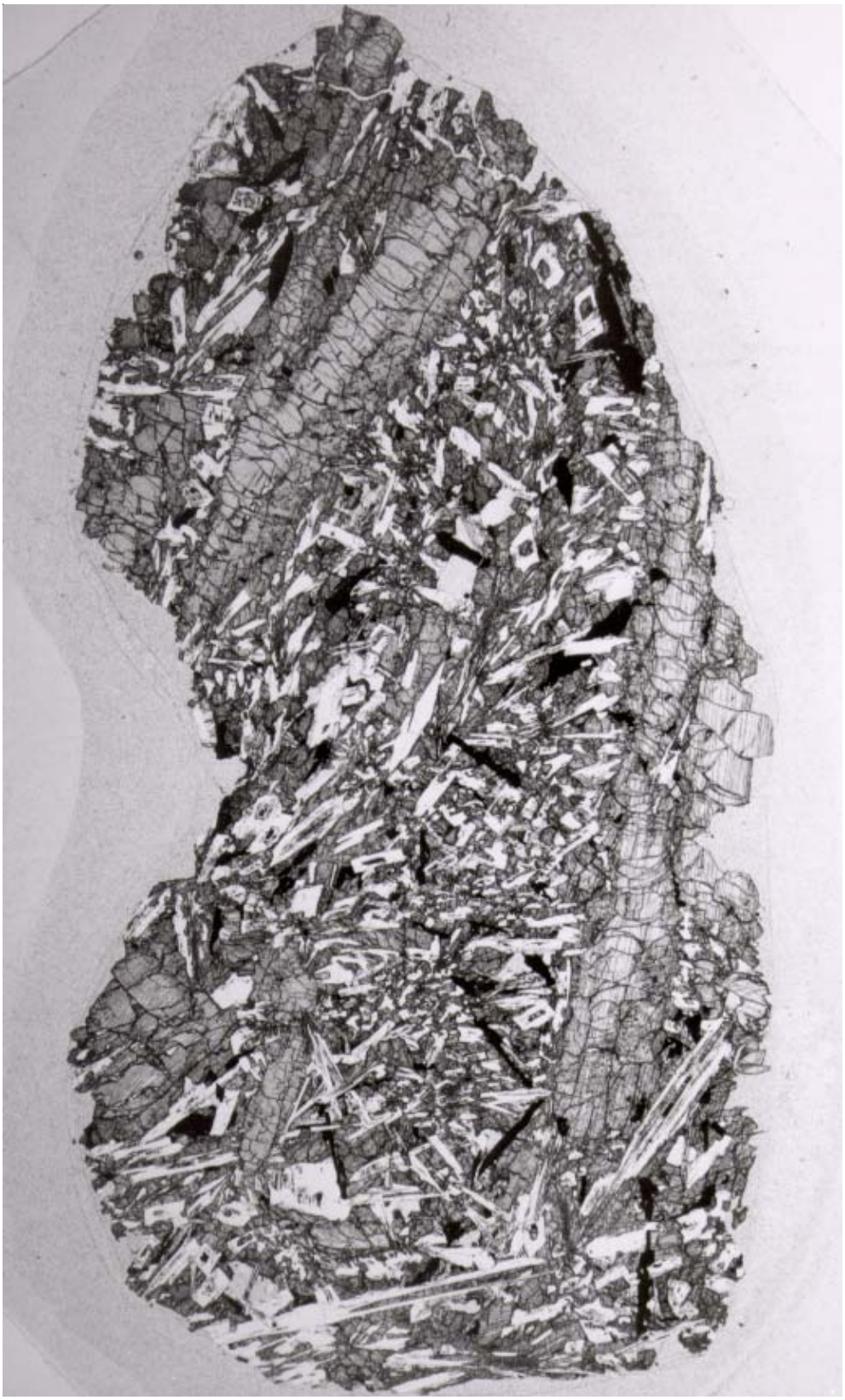
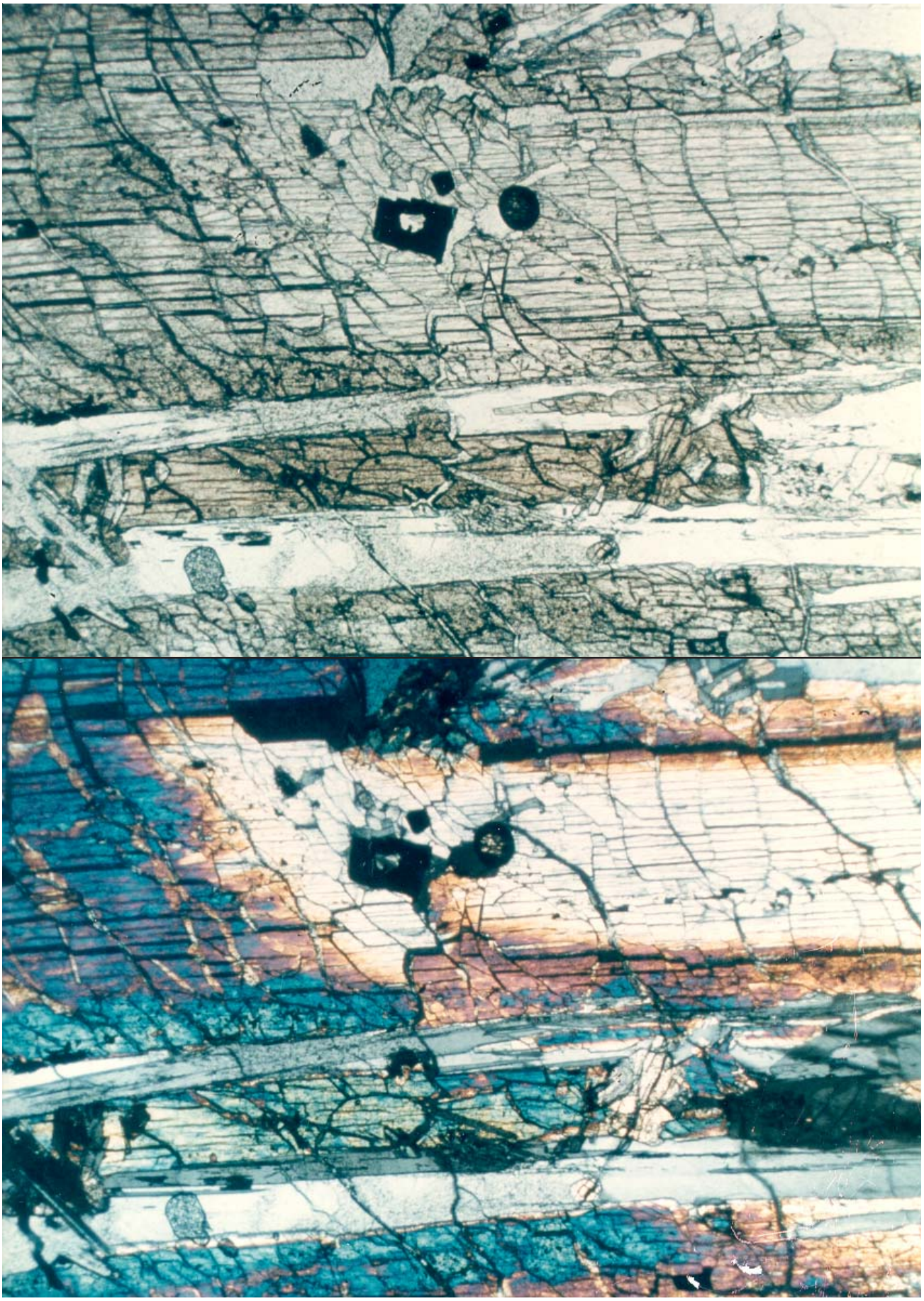


Figure 2: Photomicrograph of thin section of 12021,3 showing elongate and sector-zoned pyroxene. Field of view is 3 cm. NASA # S70-25401.

Figure 3: Photomicrographs of large pyroxene in 12021,145. NASA #S70-49467-468. Scale is 2.2 mm.



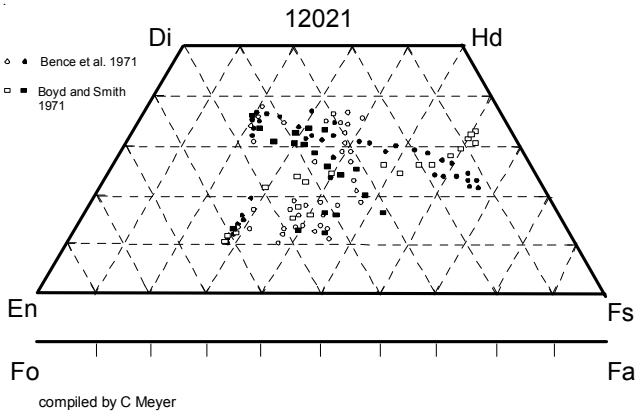


Figure 4: Only some of the many analyses of pyroxene in 12021 by numerous investigators (there was no olivine reported).

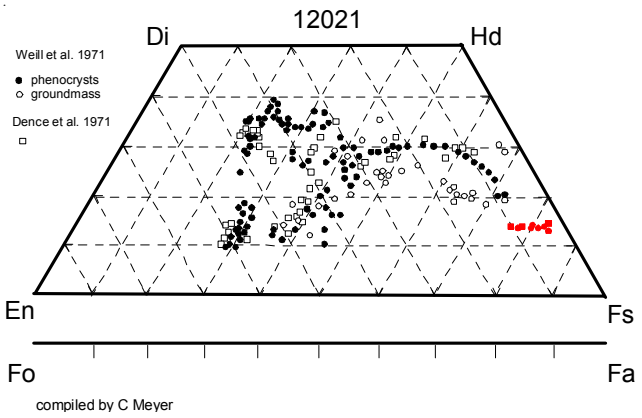


Figure 5: Additional pyroxene analyses including pyroxferroite (red).

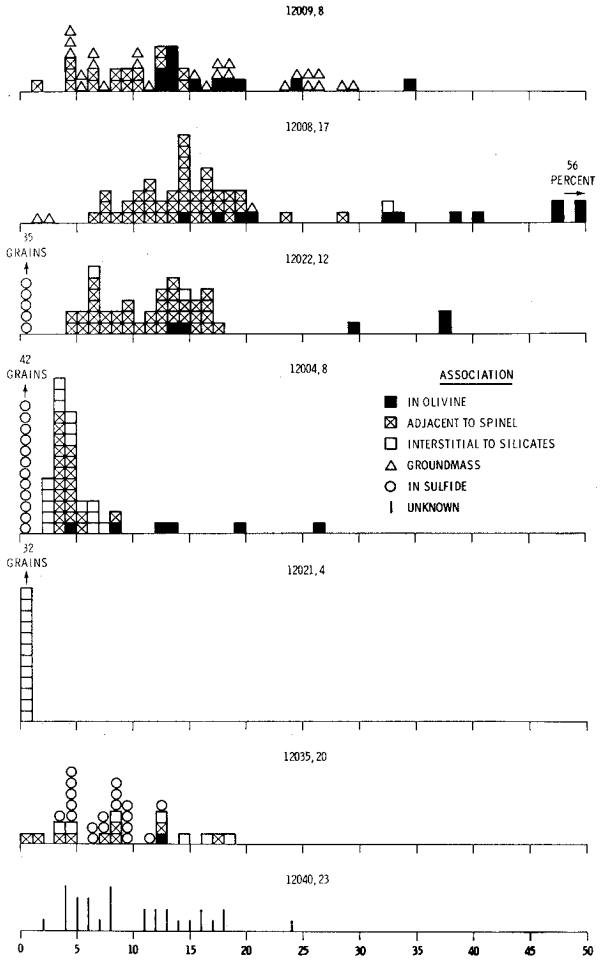


Figure 6: Histogram of Ni conentrations of metal grains in 7 lunar samples (lifted from Brett et al. 1971).

Drever et al. (1972) discuss the texture of 12021 and introduce a new term *intrafasciculate* to describe the hollow cores of elongate plagioclase and pyroxene needles in this rock. They explain that "this intravasciculate texture is closely related to the "plumose" texture commonly referred to as variolitic" in descriptions of Apollo 12 basalts.

Mineralogy

Olivine: none in 12021

Pyroxene: Weill et al. (1971), Klein et al. (1971), Boyd and Smith (1971), Dence et al. (1971), Walter et al. (1971) and Bence et al. (1970, 1971) studied the complex zoning patterns in the large pyroxenes in 12021 (figures 4 and 5). Pigeonite cores have sharp boundaries with augite rims and groundmass pyroxene is increasingly Fe-rich. Many of the large pyroxene crystals are sector zoned. Papike et al. (1971) and Ross et al. (1973) reported crystallographic data and discussed epitaxy, exsolution and phase relations of pyroxene from 12021.

Pyroxferroite: Boyd and Smith (1971) and Weill et al. (1971) found large (~500 micron) grains of "pyroxferroite" in the groundmass of 12021. When in contact with Fe-augite, the boundary is sharp.

Plagioclase: Plagioclase is An_{91-96}. Long (1.5 cm) crystals of plagioclase often have a non-plagioclase cores (*as in straws*) (figure 7 , Walter et al. 1971). Wenk et al. (1972) determined crystal structure for anorthite in 12021. This was termed intrafasciulate by Drever et al. (1972).

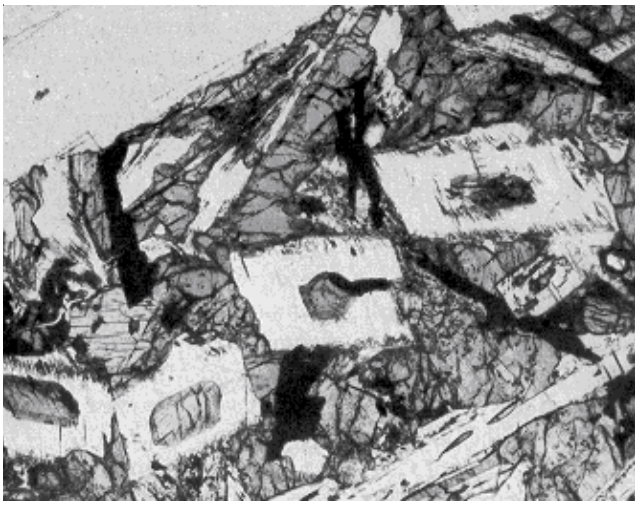


Figure 7: Hollow plagioclase crystsal in 12021 (from Walter et al. 1971). Field of view about 500 microns.

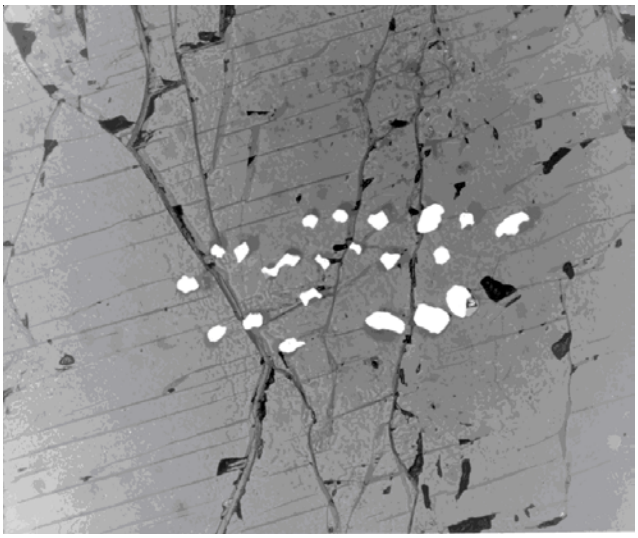


Figure 8: Unusual group of iron grains in 12021,4. NASA #S70-20751. Field of view about 1 mm. See also figure in Walter et al. 1971.

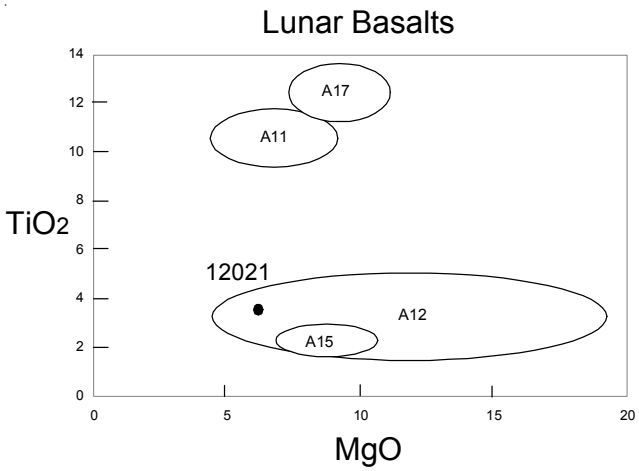


Figure 9: Composition of lunar basalts with that of 12021 indicated.

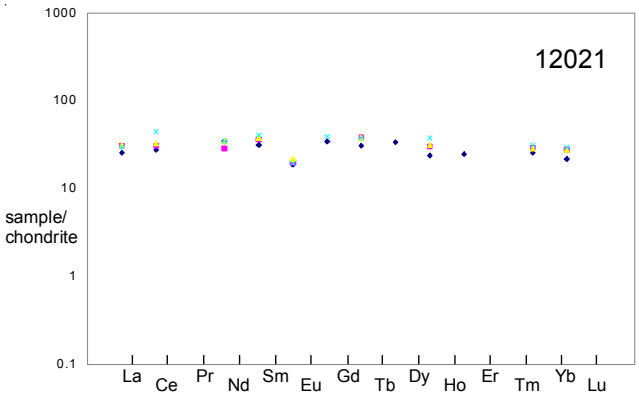


Figure 10: Normalized rare-earth-element composition diagram for 12021 (data from table 1).

Opaques: Ilmenite, chromite, troilite and tranquillityite (see metal).

Silica: In 12021, cristobalite occurs as clear, subhedral grains up to 75 microns across, and displays characteristic mosaic twinning and curved features (Weill et al. 1971). Tridymite forms long needles. Appleman et al. (1971) and Dollase et al. (1971) reported the crystal structure of tridymite in 12021.

Metal: Brett et al. (1971) determined that there was essentially no Ni content in the metallic iron grains in 12021 (figure 6) while Walter et al. (1971) reported 0.5 wt. % Ni in iron needles in pyroxene (figure 8). This is unusual when compared with other lunar basalts.

Chemistry

The chemical composition of 12021 was determined by numerous investigators, using a variety of techniques (table 1). This sample is found to be relatively low in Mg (figure 9). It has a relatively flat REE pattern (figure 10).

Radiogenic age dating

Cliff et al. (1971) determined a mineral isochron in the Rb/Sr system for 12021 with an age of 3.3 ± 0.1 b.y (figure 11). Papanastassiou and Wasserburg (1971a) reported 3.33 ± 0.06 b.y. (figure 12).

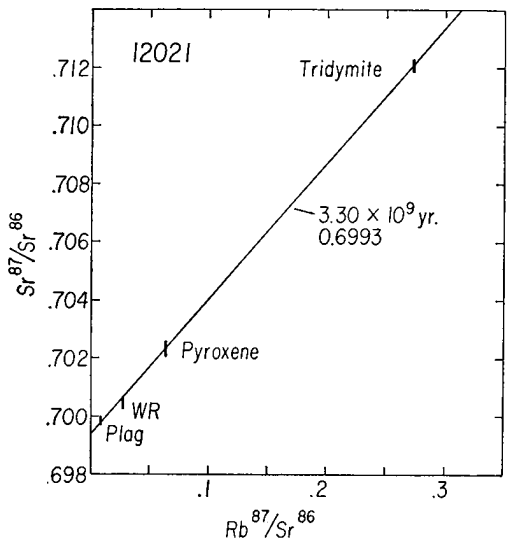


Figure 11: Rb/Sr isochron for 12021 (from Cliff et al. 1971).

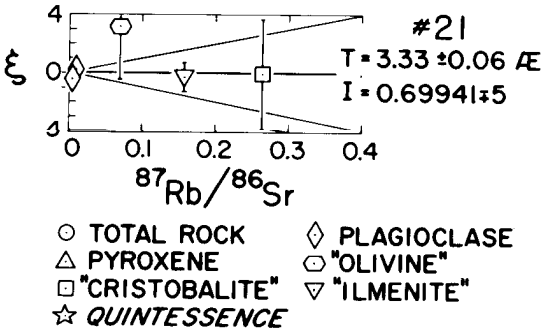


Figure 12: Rb-Sr ages and initial Sr/Sr intercept for Apollo 12 basalt 12021 (from Papanastassiou and Wasserburg 1971a).

Cosmogenic isotopes and exposure ages

Marti and Lugmair (1971) determined a Kr^{81} –K^{83} exposure age of 303 ± 18 m.y.

Other Studies

Fleischer et al. (1971) determined the nuclear track densities in pyroxene and estimated the surface residence time. Price et al. (1971) reported track lengths > 1mm in pyroxene apparently due to high-energy, heavy (Z ~ 80) cosmic rays.

Processing

Originally some small pieces (,1 to ,15) were broken off one end. Then a large piece (B, 33) was split off and subdivided by sawing with a wire saw (figures 14 and 15). 12021,8 was apparently used for public display (see picture).

There are 39 thin sections

List of Photo #s for 12021

S69-61985	
S69-64084	
S69-64109	
S70-16782 – 16783	TS
S70-16792 – 16793	TS
S70-20751	iron
S70-20960	TS
S70-49145 – 49150	TS
S70-49467 – 49468	TS
S74-27037	, 8 display
S74-23060	
S76-21649	
S76-21646	slices
S79-27123 – 27124	TS

Summary of Age Data for 12021

	Ar/Ar	Rb/Sr
Cliff et al. 1971		3.3 ± 0.1 b.y.
Papanastassiou and Wasserburg 1971a		3.33 ± 0.06

Table 1a. Chemical composition of 12021.

reference	Kushiro71		Goles71			O'Kelly71		Morrison71		Cuttitta71			Haskin71		Engel71		Kharkar71	
weight						1877 g												
SiO2 %	46.46	(a)	46	47	(b)					46.5	46.7	(d)			47.05	(a)		
TiO2	3.44	(a)	3.5	3.5	(b)			3.84	(b)	3.51	3.45	(d)			3.74	(a)	4.17	(b)
Al2O3	10.55	(a)	10	10.5	(b)			11.15	(b)	10.5	11.1	(d)			10.97	(a)		
FeO	19.68	(a)	19.2	19.2	(b)			20.07	(b)	19.4	19.1	(d)			19.04	(a)	18.91	(b)
MnO	0.26	(a)	0.25	0.25	(b)			0.28	(b)	0.27	0.27	(d)			0.25	(a)	0.26	(b)
MgO	7.6	(a)						7.29	(b)	7.48	7.38	(d)			7.08	(a)		
CaO	11.37	(a)	9.9	10.5	(b)			12.7	(b)	11.3	11.5	(d)			11.34	(a)	11.2	(b)
Na2O	0.35	(a)	0.26	0.27	(b)			0.28	(b)	0.3	0.3	(d)			0.29	(a)	0.27	(b)
K2O	0.07	(a)				0.06	(c)	0.07	(b)	0.06	0.05	(d)			0.08	(a)		
P2O5	0.01	(a)								0.09	0.09	(d)			0.09	(a)		
S %																		
sum																		
Sc ppm			51	48.3	(b)			45	(b)	51	48	(d)			64		55	(b)
V				130	(b)			190	(b)	130	147	(d)			160			
Cr	2737	(a)	2060	1870	(b)			2500	(b)	2850	3180	(d)			2400		2390	(b)
Co			29.6	27.7	(b)			37	(b)	38	36	(d)			22		32	(b)
Ni								87	(b)	16	13	(d)			3			
Cu								9.7	(b)	13	14	(d)			11			
Zn								4.2	(b)	4.3	4	(d)						
Ga								3.4	(b)	4.7	5.4	(d)						
Ge ppb																		
As																		
Se																		
Rb										1.2	1.4	(d)						
Sr										84	73	(d)			130			
Y										53	48	(d)			58			
Zr				100	(b)			140	(b)	133	112	(d)			180			
Nb																		
Mo																		
Ru																		
Rh																		
Pd ppb																		
Ag ppb																		
Cd ppb																		
In ppb																		
Sn ppb																		
Sb ppb								32	(b)									
Te ppb																		
Cs ppm																		
Ba			120	130	(b)			72	(b)	71	88	(d)			86			
La			7.29	7.46	(b)			7.2	(b)				6.16	(b)			6.3	(b)
Ce			19	20	(b)			27	(b)				17.1	(b)			49	(b)
Pr																		
Nd			13	16	(b)			16	(b)				16	(b)				
Sm			5.43	5.68	(b)			6	(b)				4.75	(b)			3.7	(b)
Eu			1.12	1.24	(b)			1.1	(b)				1.055	(b)			1.2	(b)
Gd								8	(b)				6.9	(b)				
Tb			1.41	1.38	(b)			1.4	(b)				1.14	(b)			1.79	(b)
Dy													8.3	(b)			14.3	(b)
Ho			1.7	1.8	(b)			2.1	(b)				1.36	(b)				
Er													4	(b)				
Tm								0.53	(b)									
Yb			4.81	4.77	(b)			5.3	(b)	5.4	5.7	(d)	4.2	(b)	10		4.4	(b)
Lu			0.68	0.69	(b)			0.72	(b)				0.523	(b)			0.83	(b)
Hf			4.03	4.09	(b)			4.6	(b)								4.2	(b)
Ta			0.4	0.41	(b)			0.7	(b)								0.79	(b)
W ppb								150	(b)									
Re ppb																		
Os ppb																		
Ir ppb																		
Pt ppb																		
Au ppb																	0.08	(b)
Th ppm			1.7	1.5	(b)	0.98	(c)	1.1	(b)									
U ppm						0.26	(c)										0.29	(b)

technique: (a) conventional wet, (b) INAA, (c) radiation counting, (d) mixed microchem. XRF, emis. Spec.

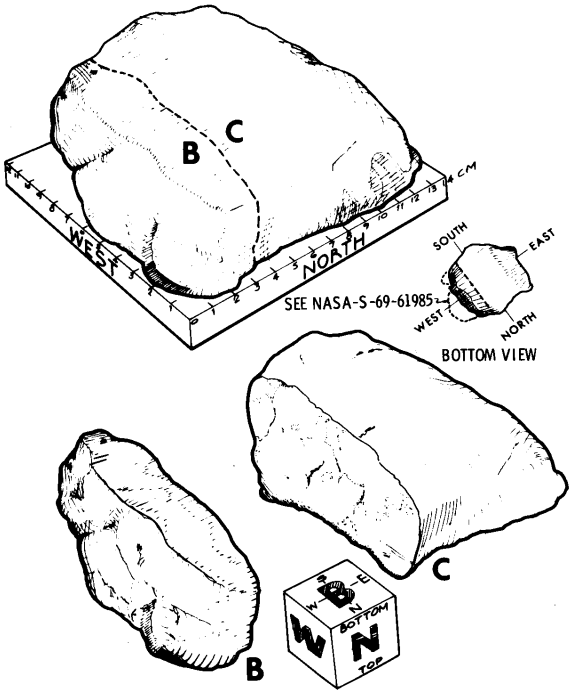
Table 1b. Chemical composition of 12021.

reference	Brunfelt71			Klein71		Tatsumoto71	
weight				Neal2001			
SiO2 %				46.2	(a)		
TiO2	3.22	3.22	(e)	3.9	(a)		
Al2O3	11.28	10.45	(e)	12.5	(a)		
FeO				19.4	(a)		
MnO	0.27	0.27	(e)	0.24	(a)		
MgO	19.17	19.68	(e)	5.7	(a)		
CaO				11.33	(a)		
Na2O	0.25	0.24	(e)	0.29	(a)		
K2O	0.058	0.059	(e)	0.04	(a)		
P2O5				0.08	(a)		
S %							
sum							
Sc ppm	54.6	52.5	(e)	54	(g)		
V	192	217	(e)	117	(g)		
Cr	2570	2650	(e)	2295	(g)		
Co	31.7	31.2	(e)	34	(g)		
Ni				6.7	(g)		
Cu	8.1	8.3	(e)	15.4	(g)		
Zn	1.2	1.2	(e)	26	(g)		
Ga	3.7	3.5	(e)	3.7	(g)		
Ge ppb							
As	0.09	0.18	(e)				
Se	0.226	0.221	(e)				
Rb	1.19	1.3	(e)	0.96	(g)		
Sr	137		(e)	112	(g)		
Y				39	(g)		
Zr				109	(g)		
Nb				8.75	(g)		
Mo				0.12	(g)		
Ru							
Rh							
Pd ppb							
Ag ppb	100	130	(e)				
Cd ppb							
In ppb	640	470	(e)				
Sn ppb							
Sb ppb	40	40	(e)	40	(g)		
Te ppb							
Cs ppm	0.062	0.073	(e)	0.06	(g)		
Ba	46	42	(e)	67	(g)		
La	5.9	6.7	(e)	6.48	(g)		
Ce	24	17	(e)	20.2	(g)		
Pr				2.82	(g)		
Nd				15.6	(g)		
Sm	5.32	5.55	(e)	5.81	(g)		
Eu	1.05	1.04	(e)	1.13	(g)		
Gd				7.7	(g)		
Tb	1.28	1.21	(e)	1.36	(g)		
Dy	9.1	9.5	(e)	8.52	(g)		
Ho	2.32	2.22	(e)	1.63	(g)		
Er	7.9	8	(e)	4.87	(g)		
Tm				0.66	(g)		
Yb	10.2	9.4	(e)	4.47	(g)		
Lu	1.65	1.48	(e)	0.59	(g)		
Hf	3.8	3.3	(e)	3.62	(g)		
Ta	0.43	0.41	(e)	0.53	(g)		
W ppb	0.26	0.21	(e)	130	(g)		
Re ppb							
Os ppb							
Ir ppb	0.1		(e)				
Pt ppb							
Au ppb	2.1	2.2	(e)				
Th ppm	*5.2*	*3.8*	(e)	0.87	(g)	0.932	(f)
U ppm	*3.3*	*3.4*	(e)	0.29	(g)	0.261	(f)

technique: (e) various NAA, (f) IDMS, (g) ICP-MS

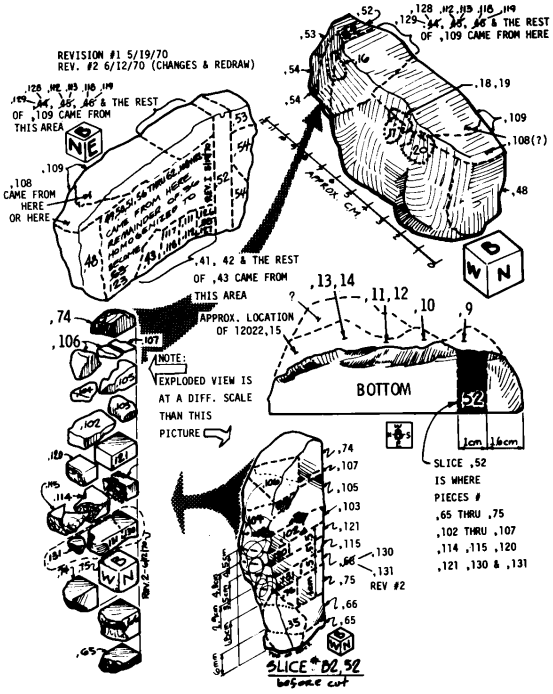
Figure 13: Photomicrograph of thin section 12021,135 illustrating elongate pyroxene crystals growing from a common nucleation point. Section is about 2 cm long. NASA S70-43351.

THE CUTTING OF LUNAR ROCK NO. 12021



DRWG COMPLETED APRIL 26, 1970

THE CUTTING AND CHIPPING OF SLICE 'B' NO. 12021,33



DRWG COMPLETED MAY 4, 1970

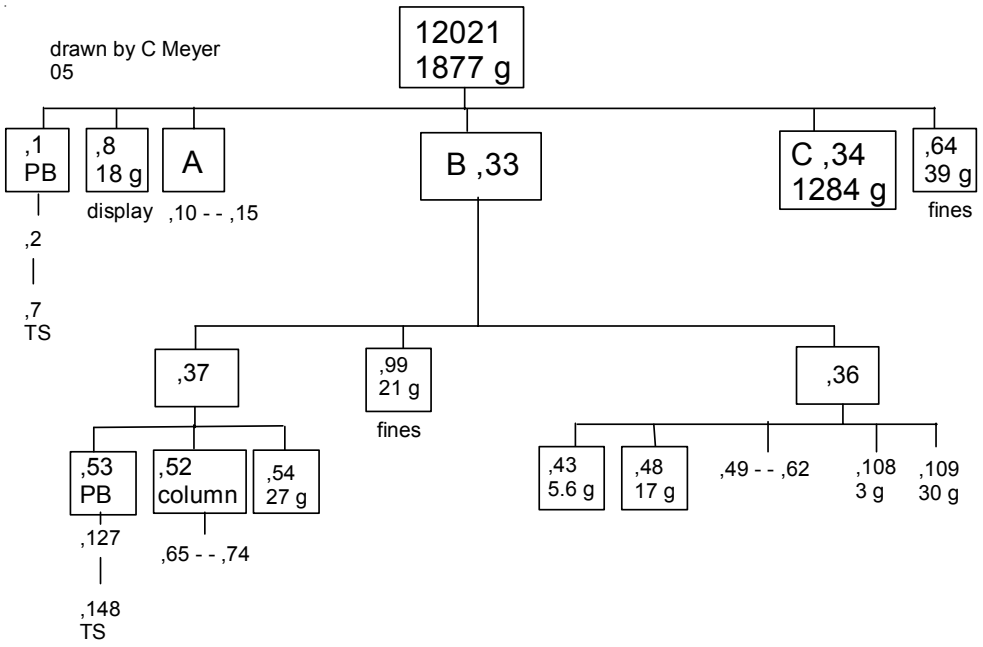


Figure 14: Slices known as 12021,37.

Figure 15: Pieces cut from 12021,52.

References for 12021

Appleman D.E., Nissen H.-U., Stewart D.B., Clark J.R., Dowty E. and Huebner J.S. (1971) Studies of lunar plagioclases, tridymite and cristobalite. *Proc. Second Lunar Sci. Conf.* 117-133.

Bence A.E., Papike J.J. and Prewitt C.T. (1970) Apollo 12 clinopyroxene chemical trends. *Earth Planet. Sci. Lett.* **8**, 393-399.

Bence A.E., Papike J.J. and Lindsley D.H. (1971a) Crystallization histories of clinopyroxenes in two porphyritic rocks from Oceanus Procellarum. *Proc. 2nd Lunar Sci. Conf.* 559-574.

Boyd F.R. and Smith D. (1971) Compositional zoning in pyroxenes from lunar rock 12021, Oceanus Procellarum. *J. Petrol.* **12**, 439-464.

Brett R., Butler P., Meyer C., Reid A.M., Takeda H. and Williams R. (1971) Apollo 12 igneous rocks 12004, 12008, 12009 and 12022: A mineralogical and petrological study. *Proc. 2nd Lunar Sci. Conf.* 301-317.

Brunfelt A.O., Heier K.S. and Steiennes E. (1971a) Determination of 40 elements in Apollo 12 materials be neutron activation analysis. *Proc. 2nd Lunar Sci. Conf.* 1281-1290.

Brown G.M., Emeleus C.H., Holland J.G., Peckett A. and Phillips R. (1971) Picrite basalts, ferrobasalts, feldspathic norites, and rhyolites in a strongly fractionated lunar crust. *Proc. 2nd Lunar Sci. Conf.* 583-600.

Cliff R.A., Lee-Hu C. and Wetherill G.W. (1971) Rb-Sr and U, Th-Pb measurements on Apollo 12 material. *Proc. 2nd Lunar Sci. Conf.* 1493-1502.

Cuttitta F., Rose H.J., Annell C.S., Carron M.K., Christian R.P., Dwornik E.J., Greenland L.P., Helz A.P. and Ligon D.T. (1971) Elemental composition of some Apollo 12 lunar rocks and soils. *Proc. 2nd Lunar Sci. Conf.* 1217-1229.

Dence M.R., Douglas J.A.V., Plant A.G. and Traill R.J. (1971) Mineralogy and peterology of some Apollo 12 samples. *Proc. Second Lunar Sci. Conf.* 285-299.

Dollase W.A., Cliff R.A. and Wetherill G.W. (1971) Note on trymite in rock 12021. *Proc. Second Lunar Sci. Conf.* 141-142.

Drever H.I., Johnston R., Butler P. and Gibb F.G.F. (1972) Some textures in Apollo 12 lunar igneous rocks and in terrestrial analogs. *Proc. 3rd Lunar Sci. Conf.* 171-184.

Drever H.I., Johnston R. and Brebner G. (1973) Radiate texture in lunar igneous rocks and terrestrial analogs (abs). *Lunar Sci.* **IV**, 187-189.

Engel A.E.J., Engel C.G., Sutton A.L. and Myers A.T. (1971) Composition of five Apollo 11 and Apollo 12 rocks and one Apollo 11 soil and some petrogenetic considerations. *Proc. 2nd Lunar Sci. Conf.* 439-448.

Fleischer R.L., Hart H.R., Comstock G.M. and Evwarate A.O. (1971) The particle track record of the Ocean of Storms. *Proc. 2nd Lunar Sci. Conf.* 2559-2568.

French B.M., Walter L.S., Heinrich K.F.J., Loman P.D., Doan A.S. and Adler I. (1972) Composition of major and minor minerals in five Apollo 12 crystalline rocks. NASA SP-306

Goles G.G., Duncan A.R., Lindstrom D.J.,Martin M.R., Beyer R.L., Osawa M., Randle K., Meek L.T., Steinborn T.L. and McKay S.M. (1971) Analyses of Apollo 12 specimens: Compositional variations, differentiation processes, and lunar soil mixing models. *Proc. 2nd Lunar Sci. Conf.* 1063-1081.

Haskin L.A., Helmke P.A., Allen R.O., Anderson M.R., Korotev R.L. and Zweifel K.A. (1971) Rare-earth elements in Apollo 12 lunar materials. *Proc. 2nd Lunar Sci. Conf.* 1307-1317.

Hörz F. and Hartung J.B. (1971c) The lunar-surface orientation of some Apollo 12 rocks. *Proc. 2nd Lunar Planet. Sci. 2629*-2638.

James O.B. and Wright T.L. (1972) Apollo 11 and 12 mare basalts and gabbros: Classification, compositional variations and possible petrogenetic relations. *Geol. Soc. Am. Bull.* **83**, 2357-2382.

Klein C., Drake J.C. and Frondel C. (1971) Mineralogical, petrological, and chemical features of four Apollo 12 lunar microgabbros. *Proc. 2nd Lunar Sci. Conf.* 265-284.

Kushiro I. and Haramura H. (1971) Major element variation and possible source materials of Apollo 12 crystalline rocks. *Science* **171**, 1235-1237.

LSPET (1970) Preliminary examination of lunar samples from Apollo 12. *Science* **167**, 1325-1339.

Marti K. and Lugmair G.W. (1971) Kr^{81}-Kr and Kr-Ar^{40} ages, cosmic-ray spallation products and neutron effects in lunar samples from Oceanus Procellarum. *Proc. 2nd Lunar Sci. Conf.* 1591-1605.

McGee P.E., Warner J.L. and Simonds C.H. (1977) Introduction to the Apollo Collections. Part I: Lunar Igneous Rocks. Curators Office, JSC.

Morrison G.H., Gerard J.T., Potter N.M., Gangadharam E.V., Rothenberg A.M. and Burdo R.A. (1971) Elemental abundances of lunar soil and rocks from Apollo 12. *Proc. 2nd Lunar Sci. Conf.* 1169-1185.

Neal C.R. (2001) Interior of the moon: The presence of garnet in the primitive deep lunar mantle. *J. Geophys. Res.* **106**, 27865-27885.

Neal C.R., Hacker M.D., Snyder G.A., Taylor L.A., Liu Y.-G. and Schmitt R.A. (1994a) Basalt generation at the Apollo 12 site, Part 1: New data, classification and re-evaluation. *Meteoritics* **29**, 334-348.

Neal C.R., Hacker M.D., Snyder G.A., Taylor L.A., Liu Y.-G. and Schmitt R.A. (1994b) Basalt generation at the Apollo 12 site, Part 2: Source heterogeneity, multiple melts and crustal contamination. *Meteoritics* **29,** 349-361.

O'Kelley G.D., Eldridge J.S., Schonfeld E. and Bell P.R. (1971a) Abundances of the primordial radionuclides K, Th, and U in Apollo 12 luanr samples by nondestructive gamma-ray spectroscopy: implications for the origin of lunar soils. *Proc. Second Lunar Sci. Conf.* 1159-1168.

O'Kelley G.D., Eldridge J.S., Schonfeld E. and Bell P.R. (1971b) Cosmogenic radionuclide concentrations and exposure ages of lunar samples from Apollo 12. *Proc. Second Lunar Sci. Conf.* 1747-1755.

Papanastassiou D.A. and Wasserburg G.J. (1971a) Lunar chronology and evolution from Rb-Sr studies of Apollo 11 and 12 samples. *Earth Planet. Sci. Lett.* **11**, 37-62.

Papike J.J., Bence A.E., Brown G.E., Prewitt C.T. and Wu C.H. (1971) Apollo 12 clinopyroxenes: Exsolution and epitaxy. *Earth Planet. Sci. Lett.* **10**, 307-315.

Papike J.J., Hodges F.N., Bence A.E., Cameron M. and Rhodes J.M. (1976) Mare basalts: Crystal chemistry, mineralogy and petrology. *Rev. Geophys. Space Phys.* **14**, 475-540.

Ross M., Huebner J.S. and Dowty E. (1973) Delineation of the one atmosphere augite-pigeonite miscibility gap for pyroxenes from lunar basalt 12021. *Am. Mineral*. **58**, 619-635.

Sutton R.L. and Schaber G.G. (1971) Lunar locations and orientations of rock samples from Apollo missions 11 and 12. *Proc. 2nd Lunar Sci. Conf.* 17-26.

Tatsumoto M., Knight R.J. and Doe B.R. (1971) U-Th-Pb systematic of Apollo lunar samples. *Proc. 2nd Lunar Sci. Conf.* 1521-1546.

Walter L.S., French B.M., Heinrich K.F.J., Lowman P.D., Doan A.S. and Adler I. (1971) Mineralogical studies of Apollo 12 samples. *Proc. Second Lunar Sci. Conf.* 343-358.

Weill D.F., Grieve R.A., McCallum I.S. and Bottinga Y. (1971) Mineralogy-petrology of lunar samples. Microprobe studies of samples 12021 and 12022; viscosity of melts of selected lunar compositions. *Proc. Second Lunar Sci. Conf.* 413-430.

Wenk H.R. and Wilde W.R. (1973) Chemical anomalies of lunar plagioclase, described by substitution vectors and their relation to optical and structural properties. *Contrib. Mineral. Petrol.* **41**, 89-104.