DRAFT

15001 - 15006

Deep Drill Core

242 cm

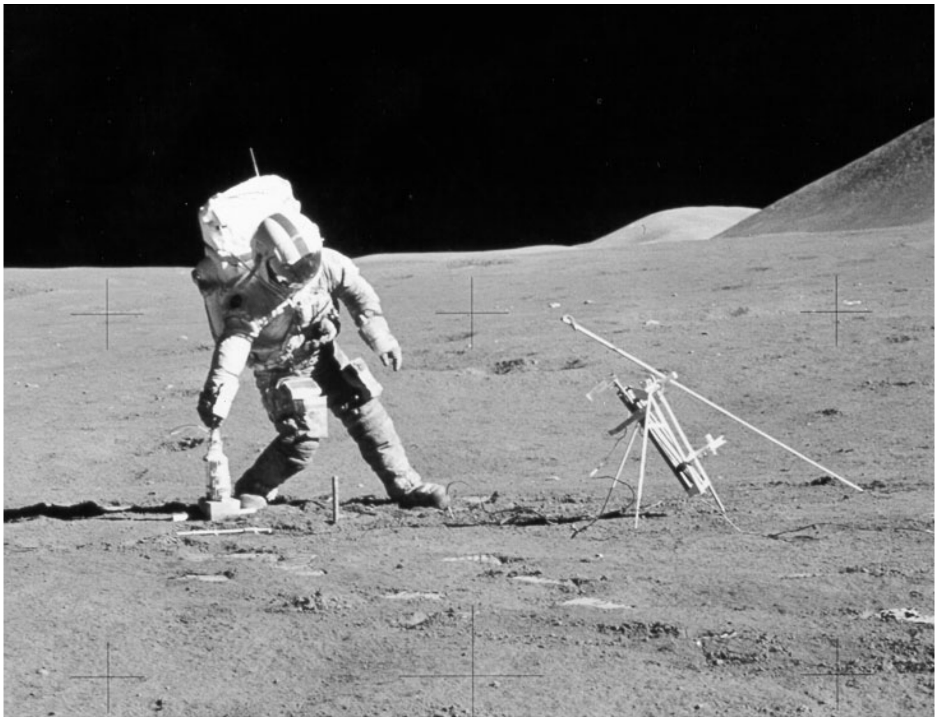


Figure 1: Photo of Apollo 15 CDR setting up the deep drill. NASA AS15-87-11847.

Introduction

The Apollo 15 deep drill (15001 – 15006) was taken at the ALSEP site – about 120 meters from the LM. There were no small craters in the vicinity (figure 1). The regolith is on top of a mare surface, but the highlands are only about 5 – 10 km away. The combined weight of the core was 1333 grams, and it was found to contain materials from both the mare and the highlands.

Trench soils 15030, 15040 and 15014 were collected about 10 meters away, and are better analyzed. 15030 and 15014 from the bottom of the trench (depth about 30 cm) might be comparable to material from 15005, which 15040 should be compared with 15006. Pre-mission, it was expected that the deep drill might obtain material from the apparent rays from Autolycus and/or Aristillus as well as detritus from the degradation of the Apennine Front.

This was the first use of the rotary-percussion drilling mechanism, but it obtained a core 2.42 meters long (2.04 cm diameter). However, it was very difficult to extract from its hole. Also segments 15001, 15002 and 15003 would not separate on the Moon, so they were brought back as one long segment and broken down in the LRL.

The main result of this core is that it has remained in place, slowing cooking in neutrons, for about half a billion years. The bottom of the core could not have been deposited more than 750 m.y. ago nor less than 420 m.y. ago (Curtis and Wasserburg 1977). That being said, it is also clear that the top of the core has become mature due to micrometeorite bombardment, because of the abundance of agglutinate particles. However, cosmic ray track studies, solar wind implanted rare gasses and other studies indicate that core material had previous exposure to solar wind and cosmic rays, and the record that can be read from this core still requires more work and interpretation.

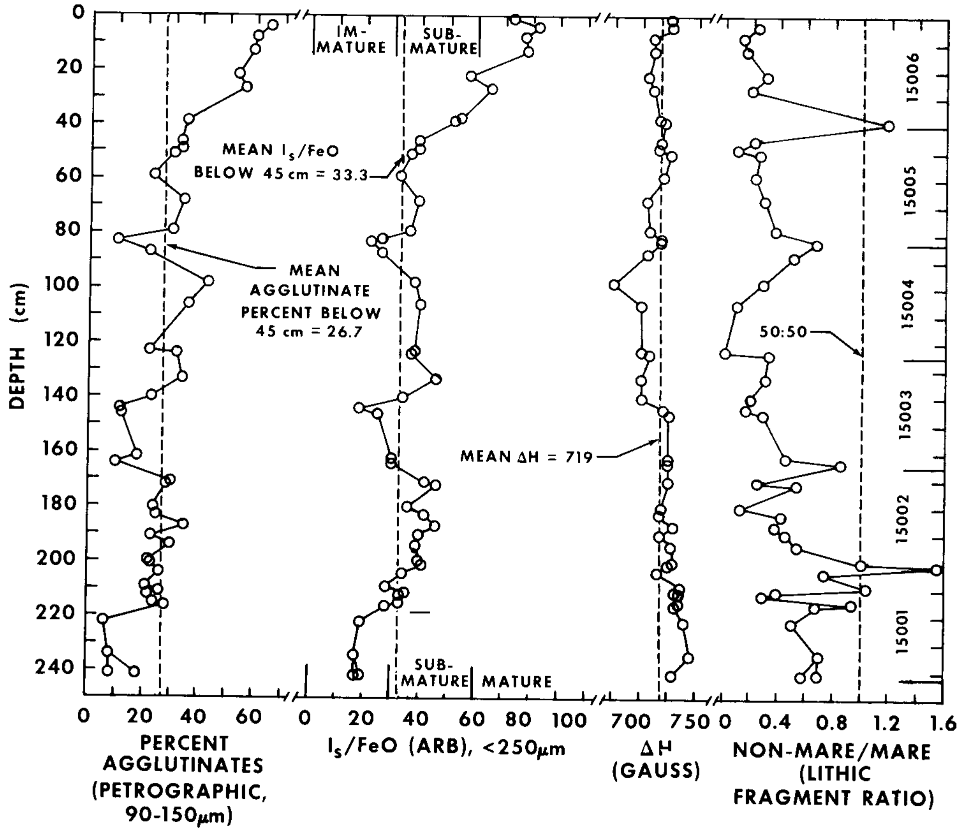


Figure 2: Maturity as function of depth in Apollo 15 deep drill core as determined by percentage agglutinate and Is/FeO (from Heiken et al. 1976). Maturity data is tabulated in Morris (1976). Note that the top of the core is very mature, while the bottom is very immature.

This core was found to have significant Pb contamination (Silver 1972). There is also a concern that the ends of the core segments were exposed to moisture.

Petrography

Heiken et al. (1973, 1976) give a complete modal analysis of 34 samples along the length of the Apollo 15 deep drill. They found that the agglutinate content varied from 65% at the top to about 6 % at depth. This was found to be consistent with the maturity index Is/FeO (figure 2). If you ignore the agglutinates and re-average their mode you get the percentages of rock types in table B. Morris (1976) gives the magnetic maturity data and Morris (1978) discusses the evidence for gardening at the top of the deep drill core.

Walker and Papike (1981) and Papike et al. (1982) studied the thin sections prepared from 15003 and found that the deep drill was enriched in highlands materials relative to drive tube 15011 – 15010.

Basu and Bower (1976, 1977) studied fragments of KREEP basalt and determined the overall provenance of the materials in the Apollo 15 deep drill core. They concluded that the core has highland and mare materials in a ratio approximately 60:40, that the mare component generally increases from bottom to top in the core, quartz-normative basalts are nearly twice as abundant as olivine basalts, there were multiple sources of highland material, the highland component is similar to the highland regolith, KREEP basalt flow units were from depth, excavated and delivered as rays and that the green glass may be of impact origin.

Drake (1974) produced a catalog of the rock particles extracted from this core during dissection. Lindstrom et al. (1977) studied the mineralogy and chemistry of some of these particles.

Modal analysis was performed by Heiken et al. (1973 and 1975), and in detail for thin sections of 15003, by Walker and Papike (1981). These are summarized in

Table A: Petrologic mode of A15 drill core.

(90-150 microns) from Heiken et al. 1973

	15001	15001	15002	15002	15003	15003	15004	15004	15005	15005	15006	15006
depth cm	242	241	203	202	162	161	123	122	82	82	40	39
agglutinates	25	15	35	40	27	25	46	34	24	34	51	41
breccias												
vitric	4.2	8.6	3.1	7.5	5.6	9	0.5	3.6	7.9	9	4.5	5.2
meta.	7.8	5.2	4.1	3.5	4.2	3.5	2.5	2.1	2.1	4.9	5.7	1.7
Basalt	10	5.7	14	6	2.8	5.5	6	3.6	7.9	4.9	2.5	6.4
Anorthosite							0.5	0.7	0.5		0.6	0.6
plagioclase	6.6	12.6	8.2	11.5	5.6	9	5.5	7.1	9.9	8.2	5.7	4
orthopyx.	17	13	10	8	10	15	11	14	9.9	6.6	11	11
clinopyx.	17	22	11	13	18	20	19	24	28	20	13	14
ilmenite		0.6	1	0.5		0.5		2.1		0.8		1.2
Glass												
brown	1.8	6.3	5.2	3	7	3.5	1.5	4.3	2.1	3.3		3.5
colorless	5.4	9.2	4.1	4	16	9.5	4	4.3	7.3	5.6	1.9	10.4
green	2.4		3.1	2							2.5	

Table B: Average components of A15 drill core.

from Heiken et al. 1976

	Average (%)	Range (%)
Basalt		
coarse-grained	9.8	4 to 15
intergranular	3.9	0 to 6
fine-grained	1.7	0 to 4
vitrophyric	1.6	0 to 4
KREEP basalt		0 to 3
Breccia		
brown (vitric)	16.7	6 to 30
medium-grade	4.3	1 to 8
with shock melt	0.9	0 to 4
Anorthosite	0.9	0 to 2
plagioclase	10.4	7 to 14
orthopyroxene	0.3	0.3 to 1
clinopyroxene	37.4	30 to 47
olivine	0.3	0.3 to 2
ilmenite	0.4	0.3 to 2
green glass	1.5	0 to 6

Table C: Modal analysis of 15003 (0.02 to 0.2 mm).

from Walker and Papike 1981 (appendix)

	unit A			unit B			unit C								
Mare component	0.2		0.1	0.4	0.3	0.2	0.6	0.4	0.1	0.3	0.2	0.2	0.2	0.3	0.5
Highalnd component	0.3	0.40	0.2	0.2	0.5	0.4	0.3	0.4	0.4	0.3	1.9	0.1	1.1	0.3	0.2
Agglutinate	6.7	7.70	6.4	9.2	6.7	8	7.2	5	9.9	7.1	8.2	8.9	9.1	11	10
Minerals															
olivine		0.60	0.4	0.5	0.4	0.7	0.7		0.4	0.1	0.6	0.6	0.7	0.1	0.2
pyroxene	14.8	16.30	11	11.6	16.3	16.5	11.7	16.8	18.5	15.5	13.4	14.3	14.5	12.1	13.9
plagioclase	4.5	2.80	6.3	5.8	6.3	5.1	5.1	5	4.5	4.3	4.9	4.9	5.6	6.2	5.2
ilmenite	0.5	0.50	0.6	0.3	0.5	0.2	0.3	0.3	0.5	0.2	0.5	0.2	0.4	0.7	0.7
Glass															
green	0.9	1.20	1.8	1.2	0.3	0.6	0.9	1.3	0.8	0.7	1.4	1	1.5	0.5	0.7

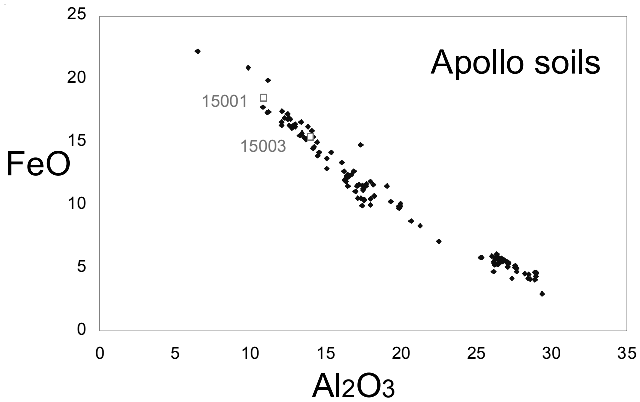


Figure 3: Chemical composition of A15 deep drill.

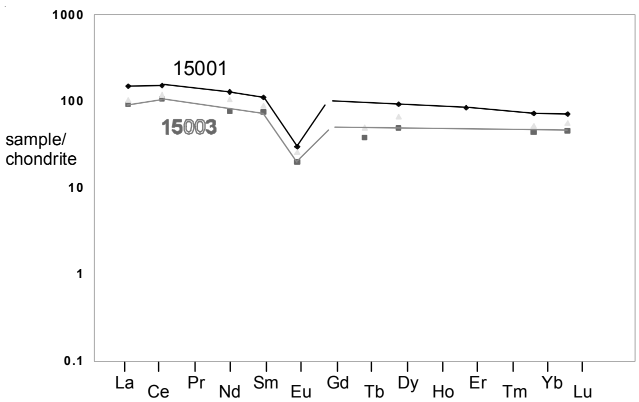


Figure 4: Normalized rare-earth-element diagram for three samples of A15 deep drill core (see Table 1).

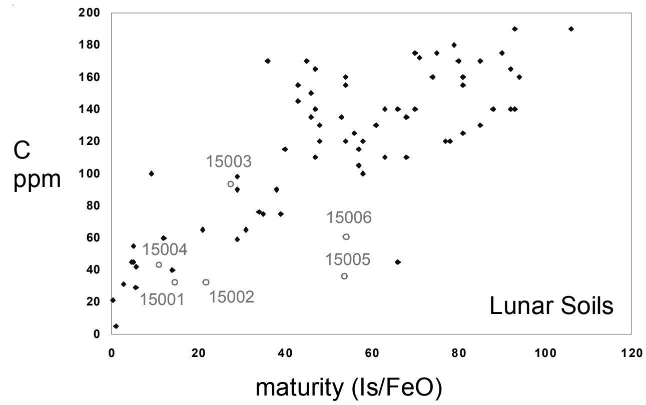


Figure 5: Carbon content determined by Wszolek et al.(1973), maturity from Morris (1976).

tables A, B and C. Walker and Papike subdivide 15003 into three units based on different percentages of agglutinates, mare component and highland component (table C).

Chemistry

While there is a lot of other data on this core, the chemical composition as function of depth is sparce, and one needs to look at the composition of the nearby trench samples, 15030 and 15040. Helmke et al. (1973) and Gold et al. (1977) appear to be the only ones who reported complete analyses of the deep drill. Wiesmann and Hubbard (1975) tabulated a few elements from the bottom of each segment and have reported a somewhat complete analysis of the bottom of the drill (table 1). Chou and Pearce (1979) determined the composition of different grain sizes. Reed and Jovanovic (1972) determined Ru, Os, Hg and U.

Gold et al. (1977) noted that there was a distinct difference in chemical composition between 15003 and 15001 (figure 3 and 4). Evensen et al. (1974) tried to characterize the exotic component by analyzing size fractions (see table 2). Wszolek et al. (1973) and Wszolek and Burlingame (1973) determined the carbon chemistry of the deep drill core (figure 5).

Ma et al. (1976) and Lindstrom et al. (1977) analyzed some of the particles extracted from the core (some in table 4, figure 7).

Radiogenic age dating

Pepin et al. (1974) reported the K-Ar age of soils from the core (3 b.y) - but that's not the age of the core!

Cosmogenic isotopes and exposure ages

Russ et al. (1972) and Pepin et al. (1974) showed that cosmic ray produced spallation nuclides are all smooth functions of depth. This indicates that the depositional history of the drill core is coherent and relatively simple.

Hubner et al. (1973), Bogard et al. (1973) and Bogard and Hirsch (1975) found that solar wind components were present throughout the length of the core. Bogard showed that ^{4}He and $^{4}He/^{3}He$ were relatively constant.

Russ et al. (1972) and Curtis and Wasserburg (1977) determined the isotopic composition of soils and fresh particles along the length of the core and found substantial variation (figure 8, 9 and 10). They were able to model the neutron fluence that produced these variations and concluded that the bottom of the core "could not have been deposited more then 750 m.y. ago, nor less than 420 my. ago".

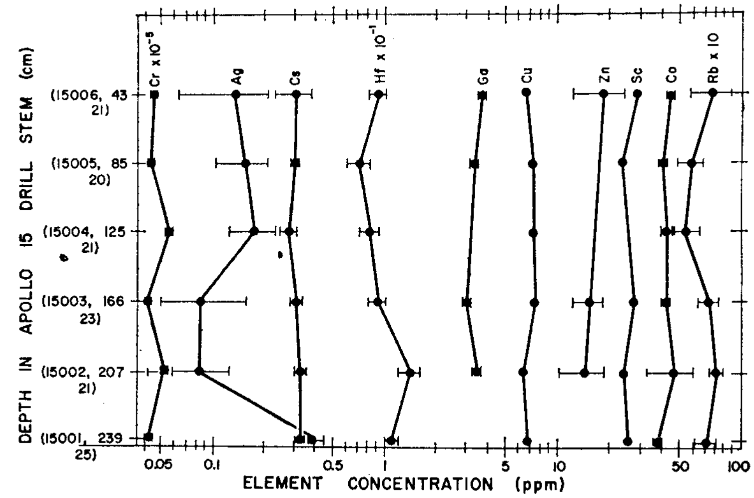


Figure 6: Chemical composition as function of depth for Apollo 15 drill core (from Helmke et al. 1972).

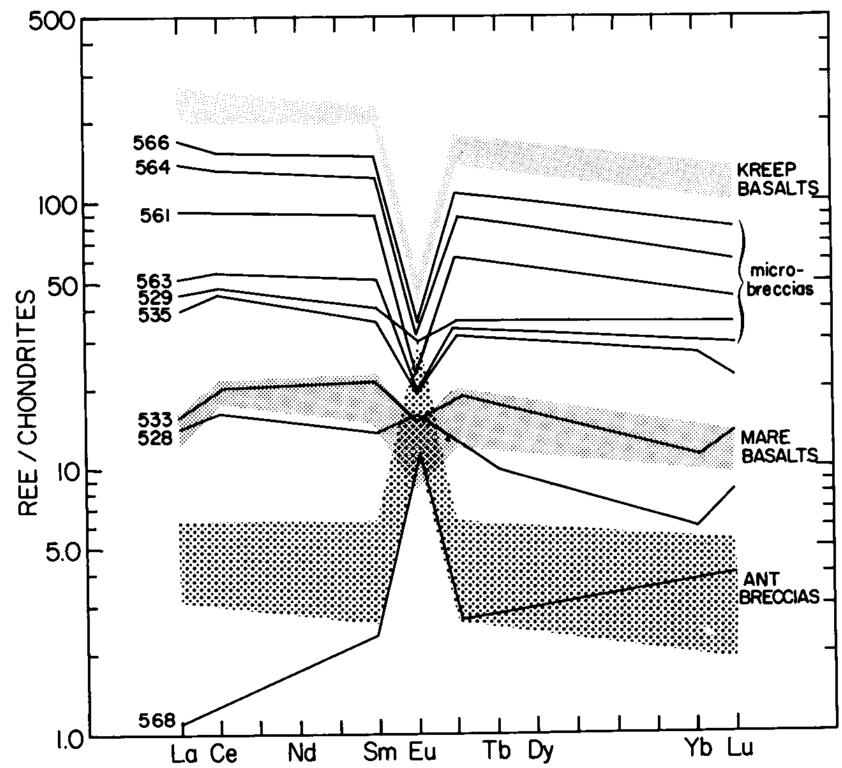


Figure 7: Normalized rare-earth-element composition of small rocks found in A15 deep drill (Lindstrom et al. 1977).

Cosmic ray inducted profiles of ^{22}Na and ^{26}Al activity (figure 11) were determined by Rancitelli et al. (1975) and Fruchter et al. (1976), ^{53}Mn by Nishiizumi et al. (figure 12) and ^{14}C by Jull et al. (1998).

Other Studies

Lindsay (1973), Heiken et al. (1973, 1976) and Graf (1993) reported detailed grain size data along the length of the A15 deep drill core. Morris (1976) tabulates the maturity index and Morris (1977) studied the variation with grain size (figure 13).

Smith et al. (1973) and Becker and Clayton (1977) found that nitrogen from the solar wind was considerably lighter in the past using the Apollo 15 deep drill samples.

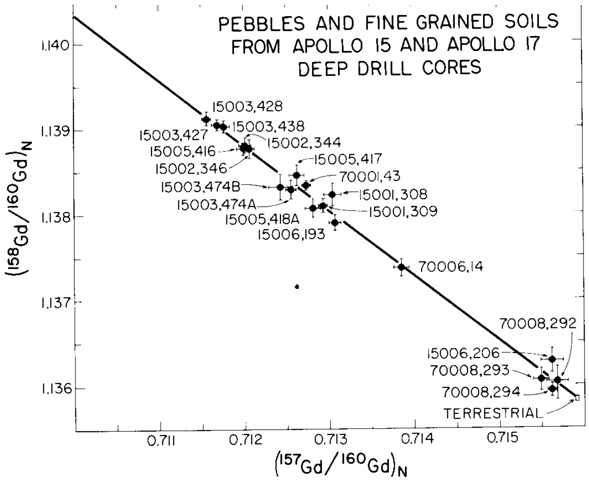


Figure 8: Variation in the isotopic composition of Gd due to adsorbtion of neutrons produced by cosmic rays (from Curtis and Wasserburg 1977).

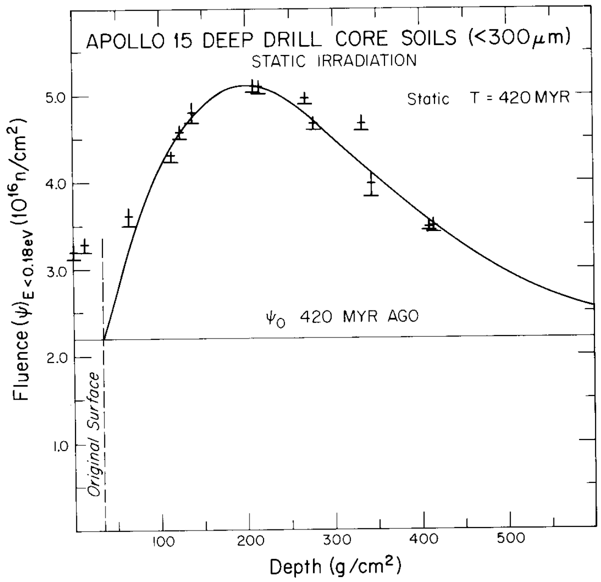


Figure 9: Neutron flux as function of depth of soil sample in Apollo 15 deep drill (Curtis and Wasserburg 1977).

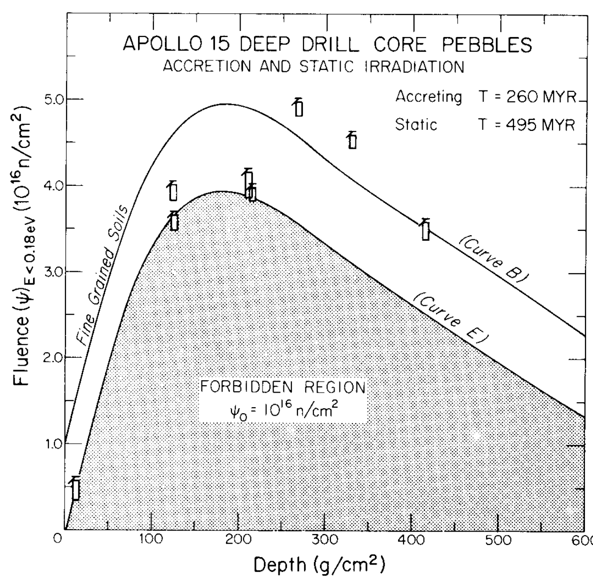


Figure 10: Neutron flux for soil and pebbles in A15 deep drill core (Curtis and Wasserburg 1977).

Phakey et al. (1972), Crozaz et al. (1972), Bhandari et al. (1972, 1973), Fleischer et al. (1973, 1974) and Goswami and Lal (1977) determined the density of cosmic ray induced nuclear tracks in mineral grains as a function of depth in the A15 drill core (figure 14). Goswami and Lal (1977) claimed that the data indicated cyclic variation with an apparent periodicity of ~ 200-300 m.y.

Lindsay and Srnka (1975) reported evidence for periodic fluctuation in the micrometeorite bombardment of the moon based on detailed petrography of samples from 120 to 240 cm depth in the A15 drill core. They even proposed that this was because the earth-moon system passed thru dense interstellar clouds at the time of deposition of this core!

These imaginative studies need verification.

Processing

The three deepest segments of the deep drill (15001, 15002 and 15003) would not separate on the Moon and had to be brought back in a bag linked together (Duke and Nagle 1974). *"The ends were plugged on the lunar surface and tapped in the LM. The exteriors of the linked core sections were exposed to atmospheres of the LM and CM cabins and had water spots on them (probably caused by sea water splashing into the cabin through an open door after splashdown). The remaining sections were protected by the nylon bag, but the exteriors were exposed to the air in the cabin."*

Early allocations were made from the junctions of the core segments (3.75 g each) and portions of this soil was used for biomedical experiments. Other portions were used for initial allocations. The segments were then mounted in a cradle and split lengthwise with a milling machine (Heiken et al. 1972). Then the segments were transferred to another cabinet, the split core top removed, and the sample dissected into 5 mm intervals along the length down to approximately two-thirds tube diameter. For thermoluminescence studies,

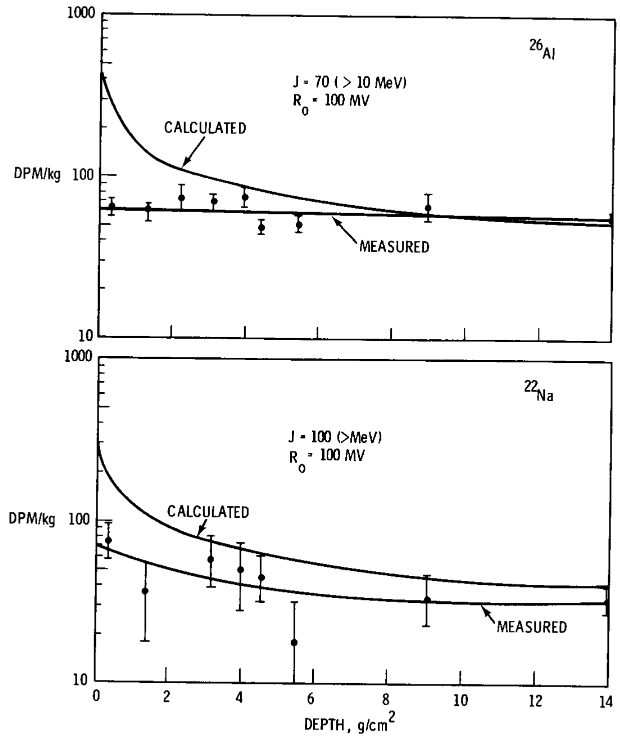


Figure 11: 22Na and 26Al profiles in 15006 showing disturbance at top of Apollo 15 drill (Fruchter et al. 1977).

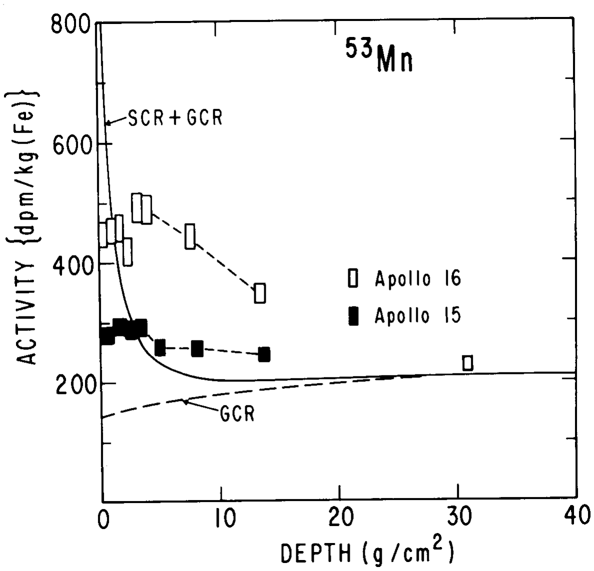


Figure 12: 53Mn as function of depth at top of Apollo 15 deep drill (Nishiizumi et al. 1976).

representative samples for each stratigraphic unit were collected under "red dark-room light". After dissection, the remaining third of the core was removed to a laminar flow bench where it was impregnated with n-butly methacrylate to make "peels". The peels were intended to maintain grain orientation and permanent stratigraphic record.

15003 is the only segment that was encapsulated in epoxy and for which a continuous set of thin sections were prepared.

According to Allton and Waltz (1977) *"the Apollo 15 drill core was completely filled and its scale is straightforward and accurately represents in situ lunar conditions."*

Silver (1972) found extensive Pb contamination from the joints in the deep drill.

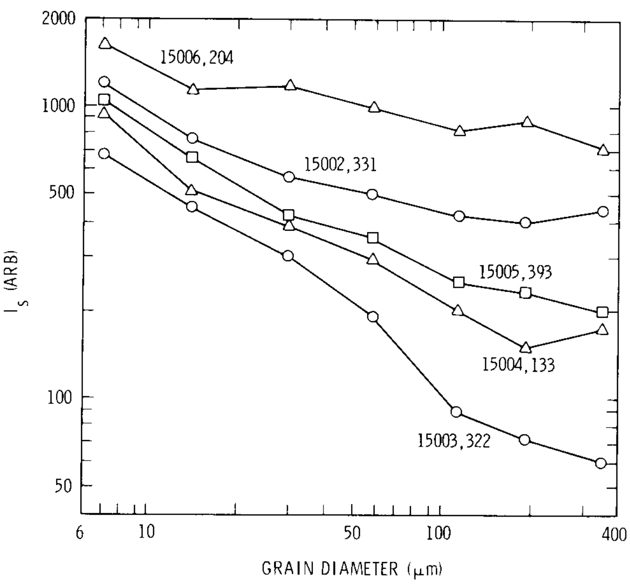


Figure 13: Grain size dependence for A15 deep drill samples (Morris 1977).

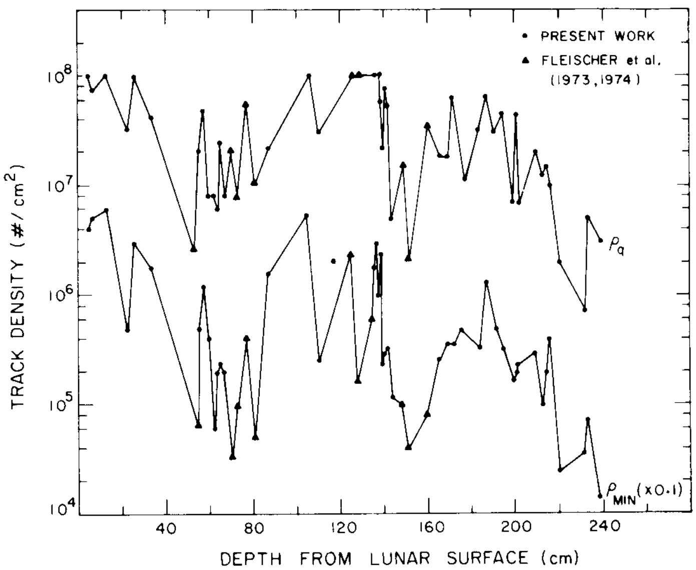


Figure 14: Apparent cyclic variation in nuclear track density along length of A15 deep drill (Goswami and Lal 1977).

Table 1. Chemical composition of A15 drill-core.

												comparison	
reference	Wiesmann and Hubbard 1975							Gold et al. 1977				Korotev87	
weight	15001	15002	15003	15004	15005	15006		15001	15001	15003		15030	15040
SiO2 %								46.4	44.7	47.3	(b)	30 cm	surface
TiO2	1.82	1.82	1.75	1.72	1.72	1.73	(a)	1.83	1.77	1.87	(b)	1.7	1.7
Al2O3								10.8	10.8	14.5	(b)	14.1	14.2
FeO								18.7	18.1	14.9	(b)	15.9	14.5
MnO								0.23	0.23	0.21	(b)	0.19	0.19
MgO	10.3	10.1	10.1	10.4	10.3	10.1	(a)	11.5	11.9	9.8	(b)	12	11.5
CaO	9.93	10.1	10.5	10.3	10.5	9.93	(a)	8.5	8.3	10.5	(b)	9.6	11.6
Na2O	0.48	0.55	0.51	0.57	0.53	0.48	(a)	0.4	0.34	0.45	(b)	0.41	0.44
K2O	0.3	0.26	0.22	0.21	0.23	0.22	(a)	0.3	0.2	0.25	(b)		
P2O5													
S %													
sum													
Sc ppm								31.5		28.9	(b)	31.6	28.5
V								151	147	129	(b)	120	110
Cr								3750	3640	2670	(b)	2840	2710
Co								54.8		41.2	(b)	46.4	46.3
Ni								382		124	(b)	203	252
Cu													
Zn													
Ga													
Ge ppb													
As													
Se													
Rb	8.13	7.17	6.11	5.89	6.39	5.94	(a)						
Sr	136	137	134	132	136	127	(a)					115	150
Y													
Zr	600						(a)					430	370
Nb													
Mo													
Ru													
Rh													
Pd ppb													
Ag ppb													
Cd ppb													
In ppb													
Sn ppb													
Sb ppb													
Te ppb													
Cs ppm												0.27	0.27
Ba	370	334	285	279	297	283	(a)	252		285	(b)	271	259
La	35						(a)	21.6	18.9	24.4	(b)	26.4	26.1
Ce	92.2						(a)	64.5		71.7	(b)	70	68
Pr													
Nd	57.8						(a)	35		48	(b)	41	36
Sm	16.4						(a)	11.2	10.1	13.2	(b)	12.6	12.4
Eu	1.7						(a)	1.13		1.45	(b)	1.36	1.4
Gd													
Tb								1.38		1.8	(b)	2.49	2.5
Dy	22.5						(a)	12		16	(b)		
Ho													
Er	13.5						(a)						
Tm													
Yb	11.8						(a)	7.2		8.4	(b)	8.8	8.3
Lu	1.73						(a)	1.13		1.36	(b)	1.32	1.25
Hf	17.8						(a)	8.2		9.81	(b)	11.8	9.8
Ta								0.97		1.26	(b)	1.24	1.18
W ppb													
Re ppb													
Os ppb													
Ir ppb												4.9	9.3
Pt ppb													
Au ppb												<4	3.9
Th ppm								1.72		3.4	(b)	4.8	4.3
U ppm	1.69	1.52	1.29	1.25	1.33	1.35	(a)					1.1	1.18

technique: (a) IDMS, (b) INAA

Table 2a. Chemical composition of A15 drill-core.

reference	Evensen74												
weight	15001		15002		15003		15004		15005		15006		
depth	241 cm		202		161		121		82		39		
size frac	>74	<16	>74	<16	>74	<16	>74	<16	>74	<16	>74	<16	(a)
Al2O3													
FeO													
MnO													
MgO													
CaO													
Na2O													
K2O	0.29	0.47	0.29	0.27	0.22	0.25	0.22	0.22	0.26	0.26	0.23	0.21	(a)
P2O5													
Se													
Rb	6.63	8.19	7.38	7.23	5.62	6.72		5.88	5.3	8.56	5.86	5.77	(a)
Sr	139	154	120	155	114	153	130	138	119	149	129	135	(a)
Y													
Zr													
Cs ppm													
Ba	377	383	337	355	249	297		268	340	316	273	302	(a)
La													
technique:	*(a) IDMS*												

Table 2b. Chemical composition of A15 drill.

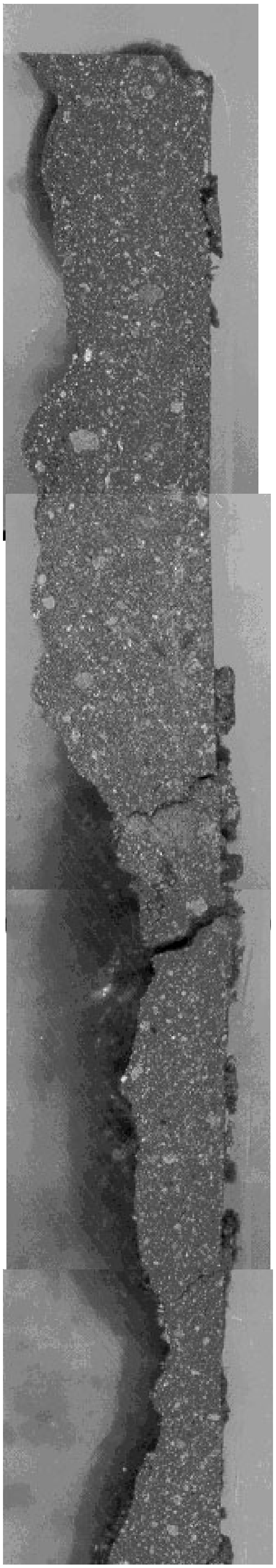
reference	Nyquist 1973						
weight	15001	15002	15003	15004	15005	15006	
Se							
Rb	8.01	7.17	6.11	5.89	6.39	5.94	(a)
Sr	136	137	134	132	136	127	(a)
Y							
technique:	*(a) INAA*						

Table 3: Composition of A15 Deep Core.

	depth (cm)	K20 %	U ppm	Th ppm	author
15006	5.50	0.254	0.9	4.65	Fruchter 75
15006	9.00	0.24	1.06	4.58	Fruchter 75
15006	14.50	0.195	1.16	4.59	Fruchter 75
15006	21.50	0.22	1.13	4.33	Fruchter 75
15006	33.00	0.24	1.41	5.6	Fruchter 75
15006	39.00		1.27	4.84	Silver 73
15005	51.00	0.2	1.52	6.13	Fruchter 75
15005	54.00		1.38	5.21	Silver 73
15005	79.00	0.093	0.99	4.42	Fruchter 75
15005	79.00		1.37	5.16	Silver 73
15004	95.00	0.144	1.22	5.39	Silver 73
15004	119.00		1.33	5	Silver 73
15003	138.00	0.194	1.18	4.69	Fruchter 75
15003	159.00		1.26	4.85	Silver 73
15002	176.00		1.32	4.96	Silver 73
15002	184.00		1.34	5.24	Silver 73
15002	199.00		1.54	5.8	Silver 73
15001	216.00	0.37	1.89	7.35	Fruchter 75
15001	239.00		1.75	6.58	Silver 73

Table 4. Chemical composition of basaltic rocklets from 15003.

reference	Ma 76						Lindstrom 77						
weight	mare basalts						mare basalts				KREEP basalts		
SiO2													
TiO2	2	1.6	3.3	1.9	1.6	2.6	1.8	1.6	2	1.9	2.6	2.2	(a)
Al2O3	10.7	8	9.9	10.7		9.2	9.2	8	10.7	10.7	15.7	15.5	(a)
FeO	18.4	22.1	21.1	20.5	17.8	22.9	23.3	22.1	18.4	20.4	10.2	10.5	(a)
MnO	0.268	0.26	0.274	0.262	0.246	0.278	0.27	0.26	0.27	0.26	0.14	0.14	(a)
MgO	8.9	10	9.4	11.1		11.9	18.9	10	8.9	11.1	9.7	6.4	(a)
CaO	10.2	8.6	10.5	9.8	10.7	9.7	8	8.6	10.2	9.8	10.2	9.3	(a)
Na2O	0.25	0.249	0.413	0.298	0.22	0.384	0.241	0.209	0.249	0.295	0.82	0.91	(a)
K2O	0.047	0.037	0.035	0.039		0.011	0.033	0.037	0.047	0.039	0.55	0.69	(a)
P2O5													
S %													
sum	*note: there are many more analyses in these pubs than can be reentered here.*												
Sc ppm	43	38	43	42	35	41	28.5	38.1	42.6	41.9	21.8	23.4	(a)
V	240	220	200	250		230	210	220	240	250	58	49	(a)
Cr	4215	5029	3181	4413	4100	4262	5650	5035	4420	4415	1970	1860	(a)
Co	42	66	45	56	55	54	66.5	66.1	42.1	55.8	19	17.8	(a)
Ni													
Cu													
Zn													
Ga													
Ge ppb													
As													
Se													
Rb													
Sr													
Y													
Zr											800	1020	(a)
Nb													
Mo													
Ru													
Rh													
Pd ppb													
Ag ppb													
Cd ppb													
In ppb													
Sn ppb													
Sb ppb													
Te ppb													
Cs ppm													
Ba											690	950	(a)
La	5.4	4.6	4.9	3.7	2.6		4.02	4.64	5.39	3.67	70.7	84	(a)
Ce	17.5	15.6	15.7	13.6	6.7		15	15.6	17.5	13.6	173	242	(a)
Pr													
Nd											113	161	(a)
Sm	3.6	3.1	3.6	2.9	2		2.82	3.13	3.59	2.9	34	40.7	(a)
Eu	0.86	0.69	1	0.94	0.67		0.96	0.69	0.86	0.94	2.74	3.08	(a)
Gd													
Tb	0.98	0.84	0.92	0.74	0.41		0.86	0.84	0.98	0.74	7.33	8.7	(a)
Dy	5.3	3.9	6.4	3.5	2.5		5	4	5	4	43	47	(a)
Ho													
Er													
Tm													
Yb	2.8	2	2.5	1.8			1.7	2	2.8	1.8	23	27	(a)
Lu	0.44	0.33	0.36	0.32	0.26		0.3	0.33	0.44	0.32	3.5	4.2	(a)
Hf	2.4	2.1	2.4	1.9			1.95	2.06	2.43	1.85	27.5	33.9	(a)
Ta													
W ppb													
Re ppb													
Os ppb													
Ir ppb													
Pt ppb													
Au ppb													
Th ppm									0.49	0.24	12	15.6	(a)
U ppm													
technique:	*(a) INAA*												

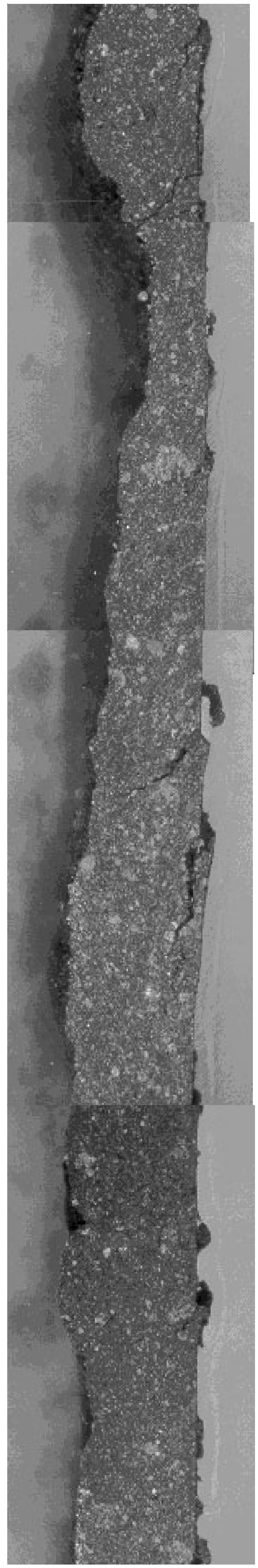


15003,655

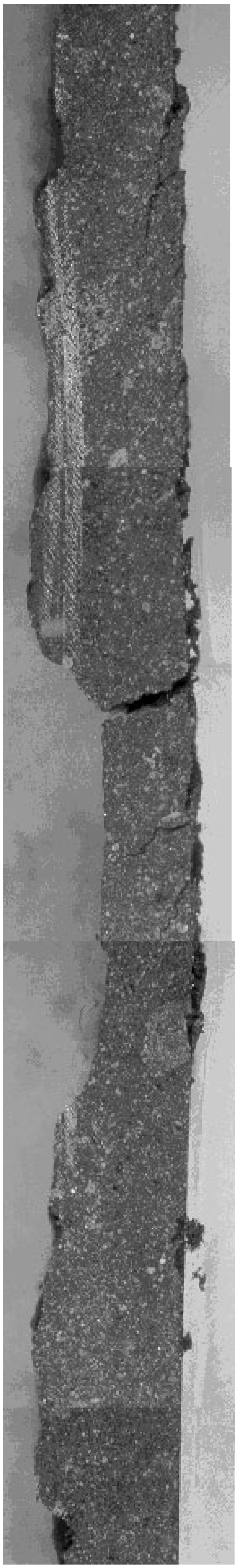
or ,317 ?

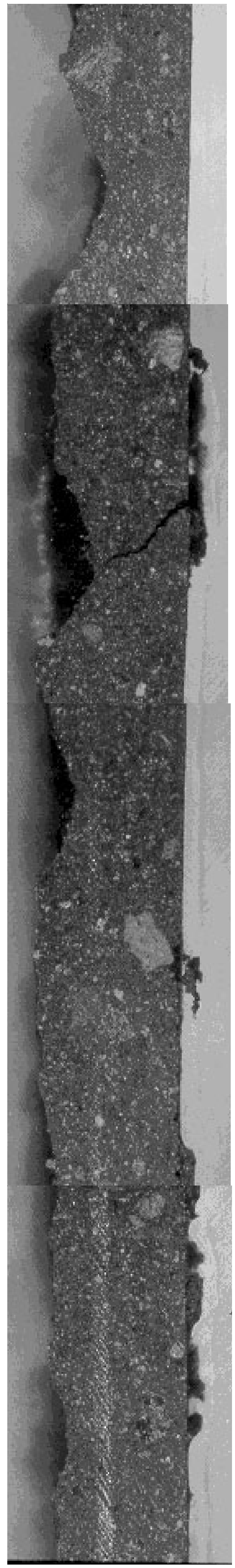
W1

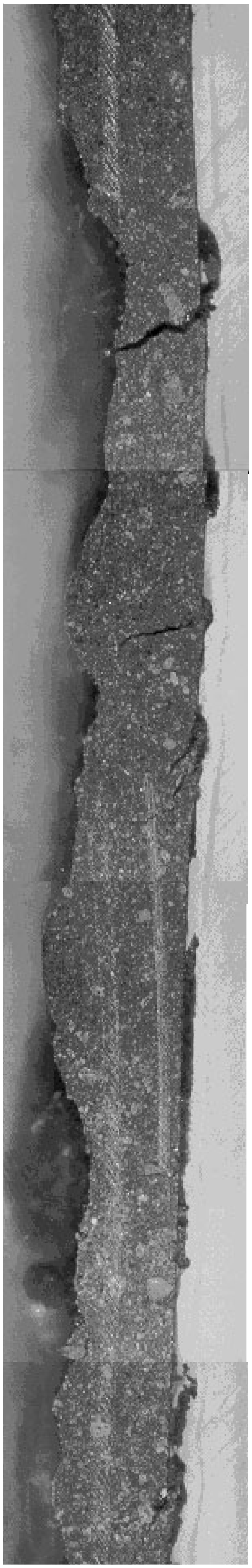
Note:
The top of 15003 was 121.8 cm below the lunar surface (a la Allton and Waltz1977).

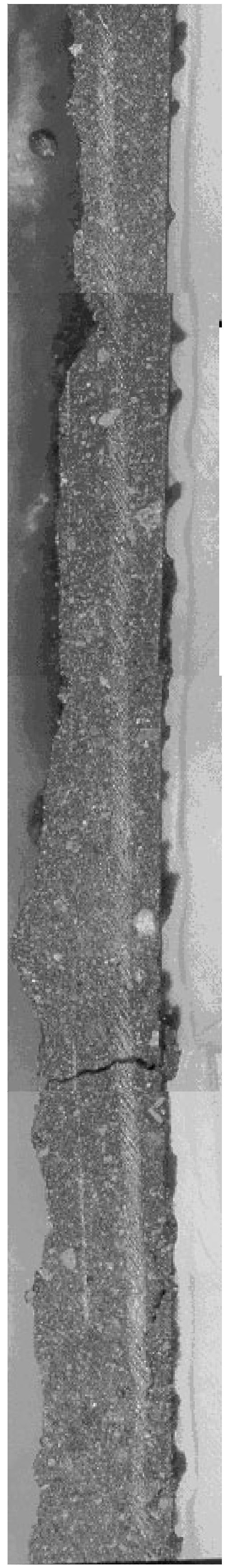


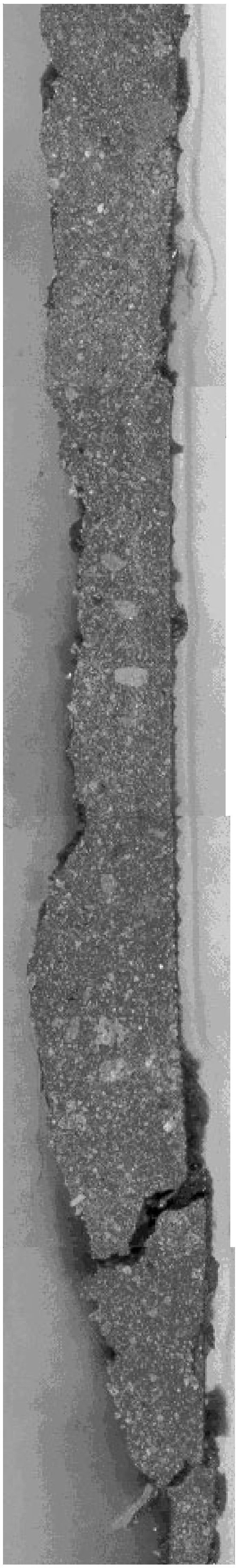
epoxy
encapsulated
core

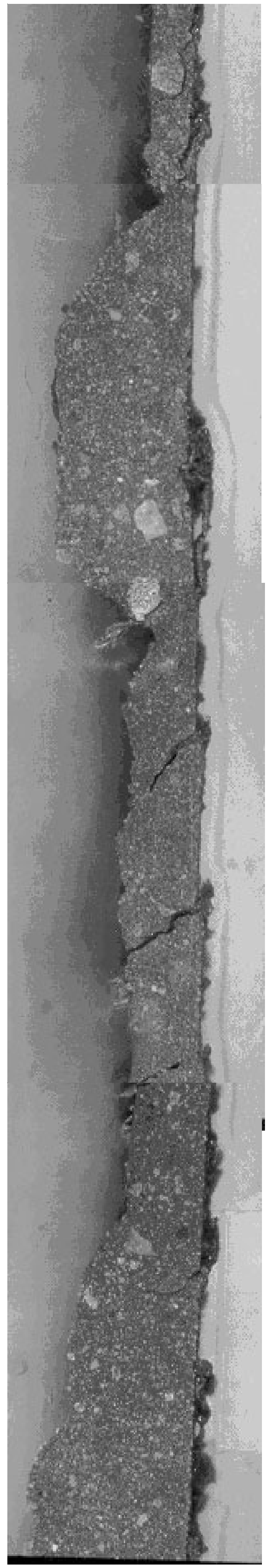


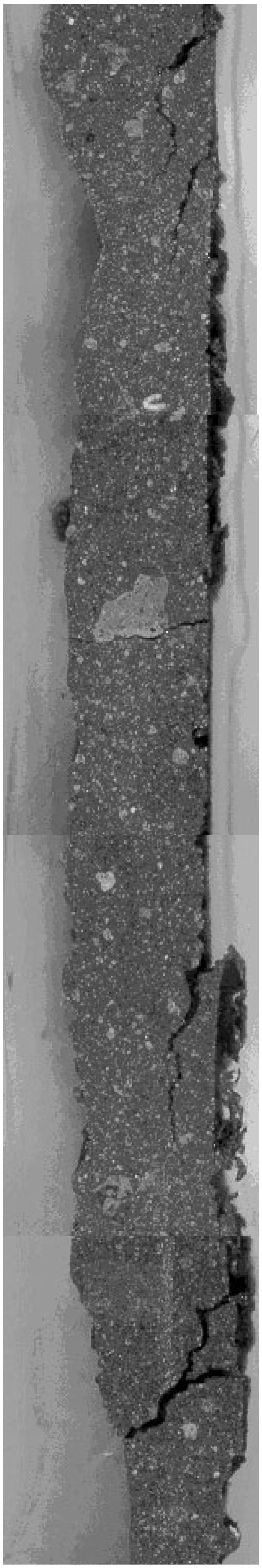












15001-6 References

(note: There is a vast literature on the lunar drill cores, which can not all be listed at once. Please excuse the complier for his brevity.)

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