

Synopsis of Deep Lunar Drill Strings

Introduction

The literature on the collection and study of the Apollo deep drill cores is spread out (see most recent references attached). Perhaps the best review is found in Heiken et al. (1992). These cores were collected because it was hoped that they would represent material laid down slowly over time, allowing the collection of samples that were exposed to the solar wind in the distant past. It is still not certain whether this is the case or not. It would seem that the material in the cores is relatively homogeneous – no distinct ancient surfaces could be discerned. It also seems that the materials at the bottoms of the drill cores (2-3 meters deep), was last exposed on the lunar surface ~ 1 b.y. ago.

The deep drill strings obtained during the last three Apollo missions (one each) are probably among the most important samples collected, because they were studied quantitatively for isotopic changes induced by the interaction of cosmic rays with the lunar regolith (e.g. Nishiizumi et al. 1976; Curtis and Wasserburg 1975, 1977; Pepin et al. 1975). Knowledge of density and exact depth is required to interpret this data (Allton and Waltz 1980).

The Apollo drilling experience was successful – samples were collected and it was shown that drilling can be done, down to 3 meters. Drilling was also successful on the three Luna missions where a percussion-rotary drill was used to penetrate (on a 30 deg. angle) about 1.6 meters (Barsukov 1977).

The Apollo Drill

The Apollo drill used rotary-percussion action (280 rpm, 2270 blows/minute @ 40 in-pounds/blow). The hollow drill strings were made up of 6-8 segments (ea.

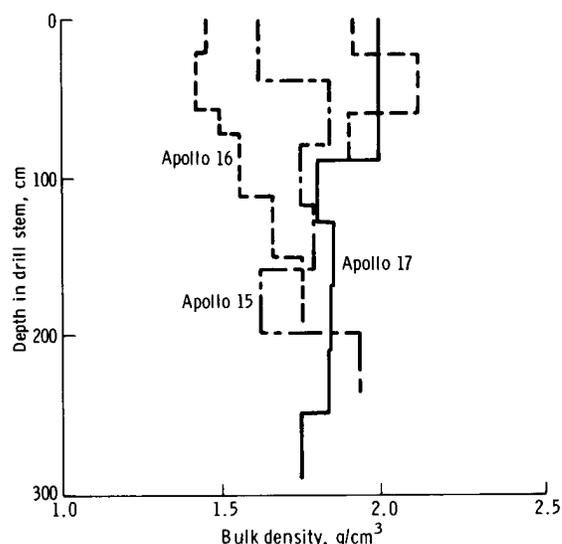


Figure 1: Density of drill core segments (Mitchell et al. 1974).

40 cm long, by 2 cm i.d.) with fluted wall on outside to act as auger. Drilling was a complicated dynamic exercise, as the astronauts “held back” on the drill as it augered in. Drill strings were hard to extract from holes. Drill strings could be broken down into 40 cm segments for return to earth (some segments were brought back connected). Core catchers and plugs did not stay in place (Sullivan 1994), but generally the sample remained in place, and stratigraphy was maintained (except for 60005).

The drill was also used to emplace heat flow probes (2 each site/~2 m deep). The second A15 probe broke, the CDR tripped over the cable at A16, but the A17 heat flow probes were successfully emplaced. A neutron probe was successfully inserted into the empty A17 drill hole, which was locatable by the plate used to extract core (Preliminary Science Reports).

	Apollo 15	Apollo 16	Apollo 17
Sample #	15001-6	60001-7	70001-9
depth (cm)	236	224	305
weight (g)	1345	1007	1772
density ave. (g/cc)	1.76	1.59	1.87
density range	1.62-1.93	1.43-1.75	1.62-2.11
segments	6	6	8

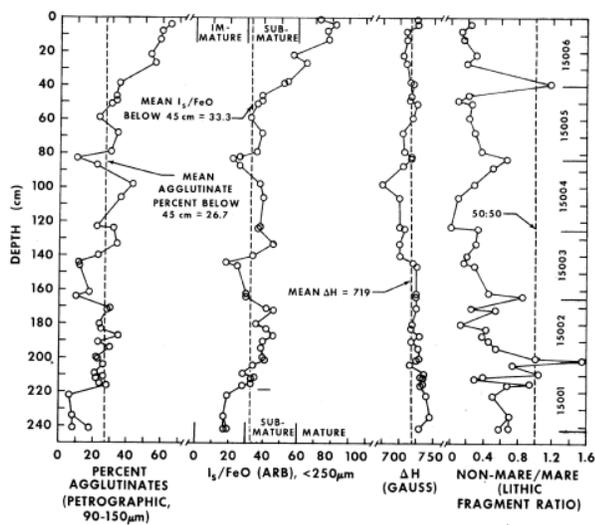


Figure 2: Maturity along Apollo 15 drill string (from Heiken et al. 1976).

Soil Mechanics

The wall of the Apollo 17 drill hole did not collapse and the samples appeared cohesive when dissected. The walls of trenches also were maintained during trenching indicating cohesiveness of regolith. There was a whole PI ship dedicated to the understanding of “soil mechanics” with its own resulting literature (Preliminary Science Reports, Mitchell et al. 1974).

The density of core tubes may not exactly correspond to the regolith, because of the “ro-tap” action during drilling, shaking during extraction, weightlessness and various “G” forces during transit to earth (figure 1). However, rough stratigraphy of the sample was apparently maintained.

The density of the lunar regolith should be expected to increase with depth (due to pounding by meteorite bombardment), but this is not supported by the drill string data. The top of the A17 drill string was dense, because of abundant coarse mare basalt material. The A15 data are variable and the A16 data are generally low. However, generally, drive tube and trenches found more loose material near the top and more compacted material at depth.

Although preliminary tests were done, and the drill was carefully engineered, Carrier (1974) mentions that full-scale drill tests of stratified simulants were never performed to determine quantitatively the “depth relationship”. This is probably very dependent on the

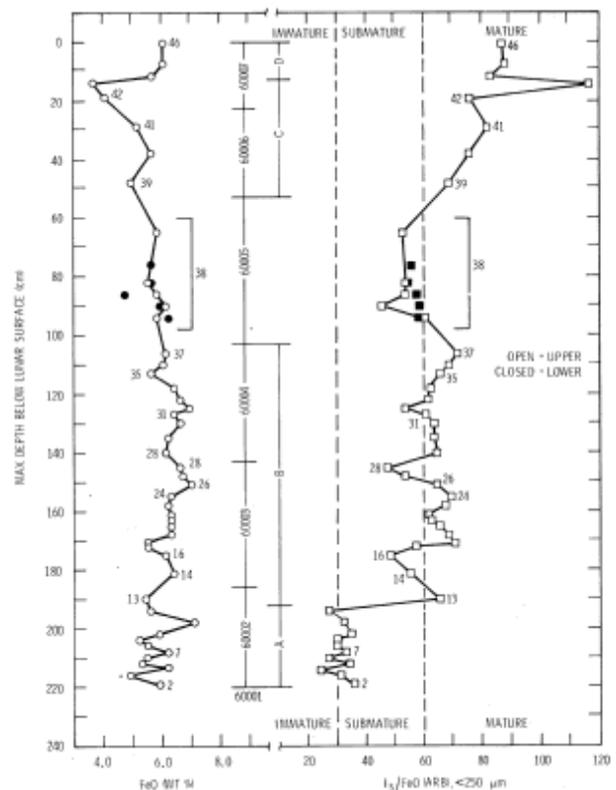


Figure 3: Maturity along Apollo 16 drill string (from Gose and Morris 1977).

dynamics of drilling and how much the astronaut/operator “holds back” on the drill.

Maturity

The maturity of the lunar regolith is measured by I_s/FeO , rare gas content, agglutinate % and/or grain size distribution (Heiken et al. 1992). Housley et al. (1975) and Morris (1976) showed that the relative ferromagnetic resonance (I_s/FeO), due to finely-divided Fe metal, is an excellent indication of soil reworking due to micrometeorite bombardment. Thin sections have been prepared and studied along the entire length of the drill cores (except segment 60005).

Apollo 15

Heiken et al. (1976) detail the maturity and petrography of the Apollo 15 drill string (figure 2). Maturity decreases with depth in this core. The upper 40-45 cm has been “reworked” and has a high maturity. It is thought that the remainder of the A15 core (200 cm) was deposited as a single unit about 420 m.y. ago (Pepin et al. 1974, Curtis and Wasserburg 1977), because the radiogenic nuclides follow a well defined profile. Goswami and Lal (1979) reviewed the track density data for the A15 deep drill.

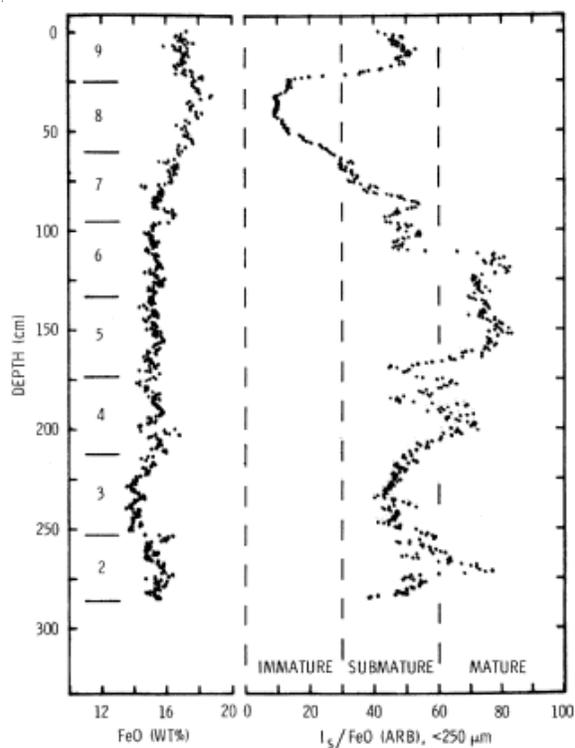


Figure 4: Maturity along Apollo 17 drill string (from Morris et al. 1979).

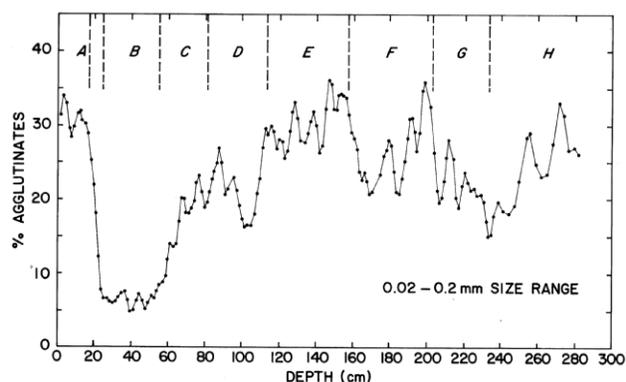


Figure 5: Agglutinate content along Apollo 17 drill string (from Taylor et al. 1979).

Apollo 16

Gose and Morris (1977) give the I_5/FeO for the Apollo 16 drill string (figure 3). Vaniman et al. (1976) identify 4 distinct stratigraphic units (A-D) in the A16 drill string. The upper unit (6 cm) had fewer mafic mineral fragments than the rest of the core. The basal unit (35 cm) has been recognized as an ancient regolith (Bogard and Hirsch 1976). Meyer and McCallister (1977) carefully reviewed the data for the A16 core and concluded that accumulation of material has taken place

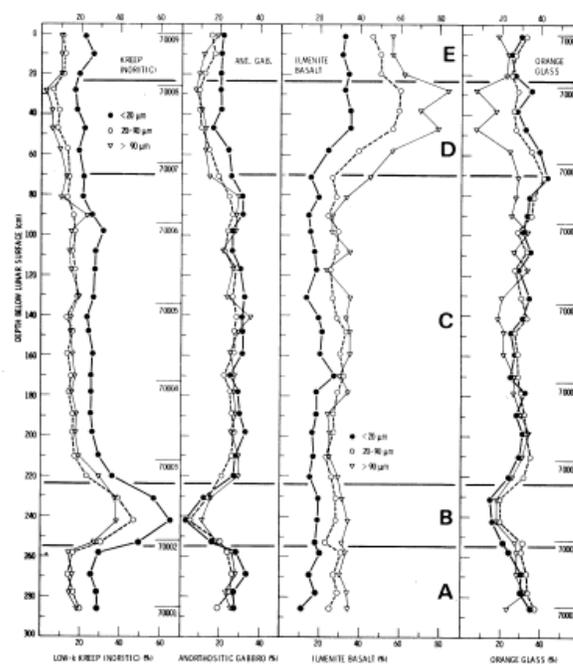


Figure 6: Composition of Apollo 17 drill string as determined by Laul and Papike (1981).

over 1 b.y. and that the material is predominantly locally derived highlands origin. Segment 5 (middle) of the A16 drill was largely empty (Duke and Nagle 1974), possibly due to spillage on the way back. The double drive tube 60009/10 has often been studied instead of the deep drill (Korotev 1991).

Sutton (in Ulrich et al. 1981) notes that the A16 core stems went easily into the soil, and that the LM area where the core was taken was only loosely compacted.

Apollo 17

The uppermost 18 cm of the 3 meter deep Apollo 17 drill string is fine-grained sediment composed of fragments of glass, regolith breccia, and agglutinate (Vaniman and Papike 1977). It overlies a fresh, dense, coarse basalt-rich unit 65 cm deep. The lower portion contains a mixture of local basalt and highlands components (Wolfe et al. 1981). Pepin et al. (1975) found that cosmic-ray-induced spallation of rare gases is not compatible with lengthy in-place radiation. Curtis and Wasserburg (1975) proposed that the deep core was deposited within the last 100 m.y. Goswami and Lal (1979) determined a 600 m.y. history for the A17 deep drill, and found episodic increases in track density. Langevin and Nagle (1981) review the evidence for a more lengthy history (~1 b.y.).

Morris et al. (1979) present the maturity index as a function of depth in the Apollo 17 deep drill (figure 4) while Taylor et al. (1979) give the agglutinate count (figure 5). Laul and Papike (1981) find that the Apollo 17 drill samples are heterogeneous with depth and define 5 stratigraphic units (A-E; figure 6).

Processing

The Apollo drill strings were milled open along their length and dissected (figure 7). Observations made during dissection were recorded in the core catalog, and numerous PI letters, by Duke and Nagle (1976). After dissection, a special “peel” was made, after which the stratigraphy was best seen (Fryxell and Heiken 1974). Material remaining in the bottom of the core after the dissection and peel, was impregnated with epoxy and made into thin sections (see attached tables). A long segment with a sawn surface remains encapsulated in epoxy - see collages under individual sample numbers which perhaps provide the best illustration of the “nature of the regolith.”

Inventory weights (grams) Deep drill stems

	Apollo 15	Apollo 16	Apollo 17
1	232.8	30.1	29.78
2	210.1	211.9	207.8
3	223	215.5	237.8
4	210.6	202.7	238.8
5	239.1	76.1	240.7
6	227.9	165.6	234.2
7		105.7	179.4
8			261
9			143.3

Selected 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.)

Allton J.H. and Waltz S.R. (1980) Depth scales for Apollo 15, 16 and 17 drill cores. Proc. 11th Lunar Planet. Sci. Conf., 1463.

Arnold J.R. (1975) A Monte-Carlo model for the gardening of the lunar regolith. The Moon 13, 159-172.

Barsukov V.L. (1977) Preliminary data for the regolith core brought to earth by the automatic lunar station Luna 24. Proc. 8th Lunar Planet. Sci. Conf. 3303-3318.

Bogard D.D., Nyquist L.E., Hirsch W.C. and Moore D.R. (1973b) Trapped solar and cosmogenic noble gas abundances in Apollo 15 and 16 deep drill samples. Earth Planet. Sci. Lett. 21, 52-69.

Bogard D.D. and Hirsch W.C. (1975) Noble gas evidence for the depositional and irradiational history of the 60010-60009 core soils. Proc. 8th Lunar Sci. Conf. 2983-2999.

Carrier David (1974) Apollo drill core depth relationships. The Moon 10, 183.

Curtis D.B. and Wasserburg G.J. (1975) Apollo 17 neutron stratigraphy – sedimentation and mixing in the lunar regolith. The Moon 13, 185-227.

Curtis D.B. and Wasserburg G.J. (1977) Stratigraphic processes in the lunar regolith. Proc. 8th Lunar Sci. Conf. 3575-3593.

Duke M.B. and Nagle J.S. (1976) Lunar Core Catalog (*and many supplements*). JSC 09252. 242 pages.

Fryxell R. and Heiken G. (1974) Preservation of lunar core samples: Preparation and interpretation of three-dimensional stratigraphic sections. Proc. 5th Lunar Sci. Conf. 935-966.

Gose W.A. and Morris R.V. (1977) Deposition history of the Apollo 16 deep drill core. Proc. 8th Lunar Sci. Conf. 2909-2928.

- Goswami J.N. and Lal D. (1979) Depositional history of the Apollo 17 deep drill based on particle track record. Proc. 10th Lunar Planet. Sci. Conf., 1253-1267.
- Heiken G.H., Morris R.V., McKay D.S. and Fruland R.M. (1976) Petrographic and ferromagnetic resonance studies of the Apollo 15 deep drill. Proc. 7th Lunar Sci. Conf., 93-111.
- Heiken G.H., Vaniman D.T. and French B.M. (1992) The Lunar Sourcebook. Cambridge Press – see pages 337-342
- Housley R.M., Cirlin E.H., Goldberg I.B., Crowe H., Weeks R.A. and Perhac R. (1975) Ferromagnetic resonance as a method of studying the micrometeorite bombardment history of the lunar surface. Proc. 6th Lunar Sci. Conf. 3173-3186.
- Korotev (1991) Geochemical stratigraphy of two regolith cores from the central highlands of the moon. Proc. 21st Lunar Planet. Sci. Conf. 229.
- Langevin Y. and Nagle J.S. (1980) The deposition history of the Apollo 17 deep drill core: A reappraisal. Proc. 11th Lunar Sci. Conf. 1415-1434.
- Laul J.C. and Papike J.J. (1980) The Apollo 17 drill core: Chemistry of size fractions and the nature of the fused soil component. Proc. 11th Lunar Sci. Conf. 1395-1413.
- Nagle J.S. and Duke M.D. (1974) Stabilization of lunar core samples. Proc. 5th Lunar Sci. Conf. 967-973.
- Meyer H.O.A. and McCallister R.H. (1977) The Apollo 16 deep drill core. Proc. 8th Lunar Sci. Conf. 2889-2907.
- Mitchell et al. (1974) Apollo Soil Mechanics Experiment S-200. Space Science Laboratory Series 15, Issue 7, UC Berkeley
- Morris R.V. (1976) Surface exposure indices of lunar soils: A comparative FMR study. Proc. 7th Lunar Sci. Conf. 315-335.
- Morris R.V., Lauer H.V. and Gose W.A. (1979) Characterization and depositional and evolutionary history of the Apollo 17 deep drill core. Proc. 10th Lunar Planet. Sci. Conf. 1141-1157.
- Nishiizumi K., Imamura M., Honda M., Russ G.P., Kohl C.P. and Arnold J.R. (1976) ⁵³Mn in the Apollo 15 and 16 drill stems: Evidence for surface mixing. Proc. 7th Lunar Sci. Conf. 41-54.
- Pepin R.O., Dragon J.C., Johnson N.L., Bates A., Coscio M.R. and Murthy V.R. (1975) Rare gases and Ca, Sr, and Ba in Apollo 17 drill-core fines. Proc. 6th Lunar Sci. Conf. 2027-2055.
- Preliminary Science Reports, A15, A16, A17, NASA-SP 289, 315, 330.
- Sullivan Tom (1994) Catalog of Apollo Experiment Operations. NASA Ref. 1317
- Taylor G.J. (1979) Stratigraphy and depositional history of the Apollo 17 drill core. Proc. 10th Lunar Sci. Conf. 1159-1184.
- Ulrich et al. (1981) Geology Apollo 16. USGS Prof. Paper 1048.
- Vaniman D.T., Lellis S.F., Papike J.J. and Cameron K.L. (1976) The Apollo 16 drill core: Modal petrology and characterization of the mineral and lithic component. Proc. 7th Lunar Sci. Conf. 199-239.
- Vaniman D.T. and Papike J.J. (1977) The Apollo 17 drill core: Characterization of the mineral and lithic component (sections 70007, 70008, 70009). Proc. 8th Lunar Sci. Conf. 3123-3159.
- Wolfe et al. (1981) The Geological Investigation of Taurus-Littrow. USGS Prof. Paper 1080.

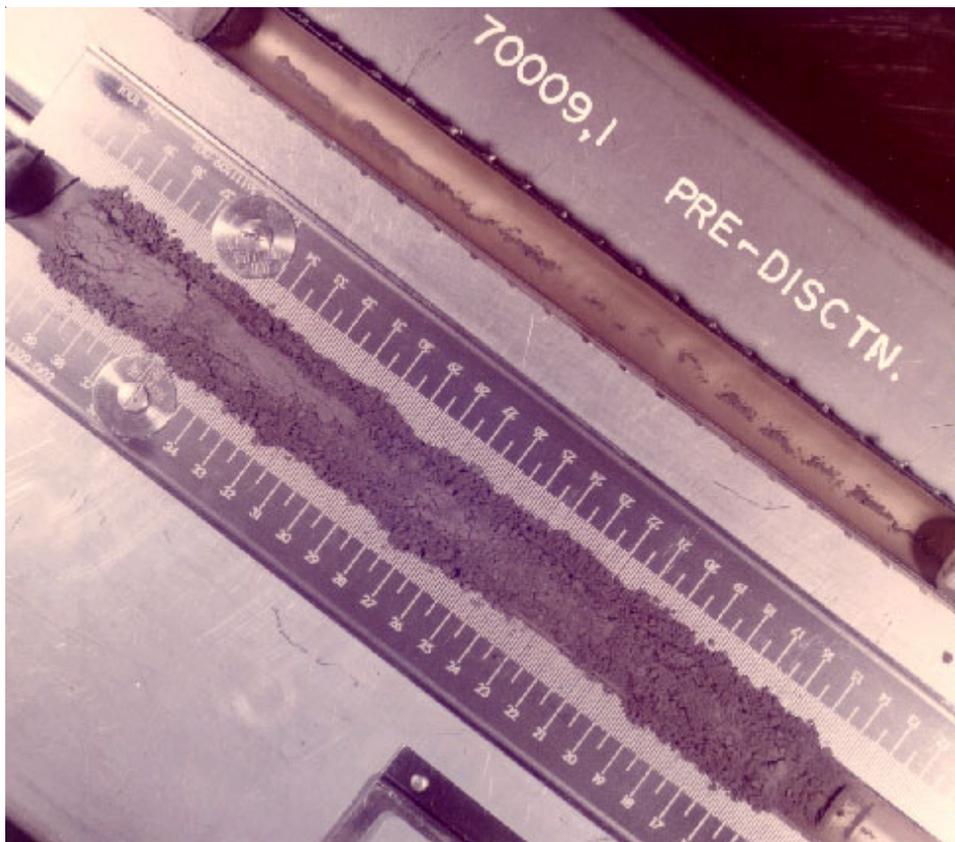


Figure 7: Photograph of top section of A17 drill string prior to dissection. NASA# S75-24316. Scale is cm.

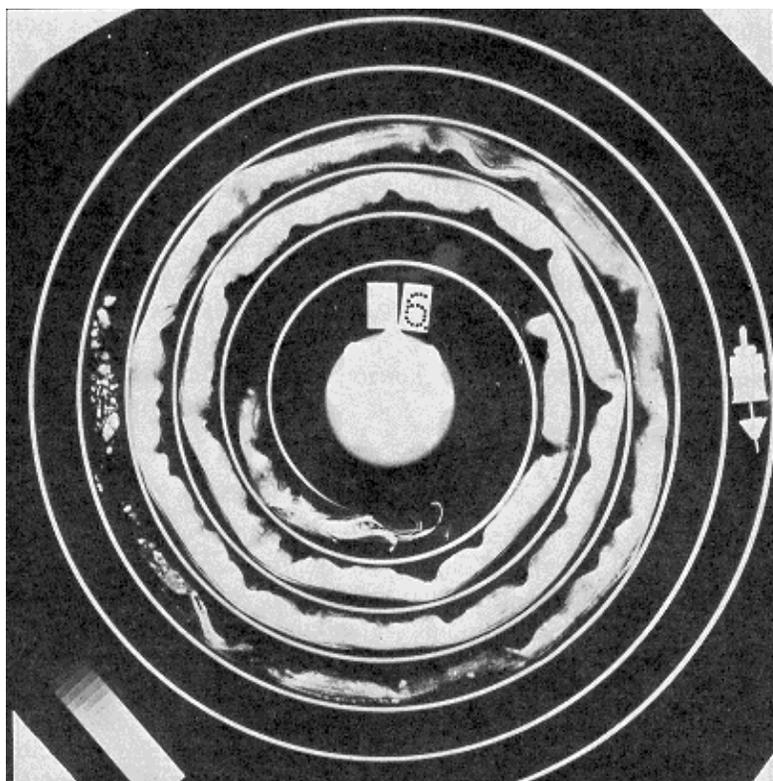


Figure 8: X-ray of Luna 24 drill core (from Barsukov 1977).

INVENTORY Listing
(potted butts and thin sections, top/bottom
not specified)

						Apollo 16	Deep Drill	String			
Apollo 15	Deep Drill	String				potted butts	depth (mm)	TS	TS	TS	mm
15002,508						60002,400		389	440		11
509						401		390			14
510						402		391	437		16
511						403		392			18
512						404		380	438		17
513						405		381	439		13
514						406		382			16
515						407		383			14
516						408		384	414		12
517						409		385			13
518						410		386	415		13
519						411		387	416		16
520						412		388			16
521						60003,208		228			11
15003,6000						209		229	256	257	14
6001						210		230	231		16
6002						211		232	269		18
6003						212		234	270		17
6004						213		236	237		13
6005						214		238	239		16
6006						215		240			14
6007						216		242	243		12
6008						217		244	245		13
6009						218		246	247		13
6010						219		248	249		16
6011						220		250	251		16
6,012						221		252	253		25
6013						222		254	255		25
6014						60004,455		470			13
						456		471			15
						457		472			19
						458		473			9
						459		474			18
						460		475			12
						461		476			15
						462		477			16
						463		478			14
						464		479	486		8
						465		480	487		16
						466		481	488		14
						467		482			14
						468		483			10
						469		484			13
						60005	spilled				
							no sections				
						60006,236		246			13
						237		247			15
						238		248			13
						239		249			15
						240		250			16
						241		251			12
						242		252			12
						243		253			13
						244		254			11
						60007,326		333			13
						327		334			11
						328		335			9
						329		336			5
						330		337			14
						331		338			12
						332		339			13

Apollo 17

Deep Drill

String

potted butts	depth (mm)	TS	TS	TS	mm						
70002,184	29-48	367	379		18	70007,301		312	313	29	
185	48-79	368	380		30	302		314	315	27	
186	79-109	369	381		30	303		316	317	23	
187	109-142	370	382		30	304		318	319	28	
188	142-172	371	383		30	305		320	321	27	
189	172-202	372	384		31	306		322	323	27	
190	202-227	373	385		24	307		324	325	27	
191	227-257	374	386	396	30	308		326	327	27	
192	257-282	375	387	397	25	309		328	329	28	
193	282-307	376	388	398	23	310		330	331	27	
194	307-332	377	389		27	311		332	333	31	
195	332-361	378	390		28	70008,339		354	355	29	
70003,307		321	335			340		356	357	29	
308		322	336			341		358	359	17	
309		323	337			342		360	361	27	
310		324	338			343		362	363	21	
311		325	339			344		364	365	25	
312		326	340			345		366	367	19	
313		327	341			346		368	369	30	
314		328	342	472		347		370	371	21	
315		329	343	473		348		372	373	29	
316		330	344			349		374	375	28	
317		331	345			350		376	377	26	
318		332	346			351		378	379	22	
319		333	347			352		380	381	19	
320		334	348			353		382	383	18	
70004,451		465	466		25	70009,278	149-163	287	288	12	
452		467	468		23	279	163-190	289	290	25	
453		469	470	525	29	280	190-219	291	292	28	
454		471	472		26	281	219-250	293	294	25	
455		473	474		28	282	250-278	295	296	27	
456		475	476		29	283	278-311	297	298	32	
457		477	478		23	284	311-342	299	300	446	31
458		479	480		24	285	342-365	301	302	447	23
459		481	482		28	286	367-400	303	304		32
460		483	484		29						
461		485	486		23						
462		487	488		23						
463		489	490		24						
464		491	492		22						
70005,378		391	404		27						
379		392	405		29						
380		393	406		35						
381		394	407	423	35						
382		395	408		30						
383		396	409		24						
384		397	410		20						
385		398	411	461	30						
386		399	412	462	30						
387		400	413	463	30						
388		401	414	464	25						
389		402	415	465	28						
390		403	416	466	23						
70006,309		322	335		28						
310		323	336		30						
311		324	337		24						
312		325	338		29						
313		326	339		26						
314		327	340		30						
315		328	341		29						
316		329	342		27						
317		330	343		25						
318		331	344		30						
319		332	345		25						
320		333	346		22						
321		334	347		25						