DRAFT

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. 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).

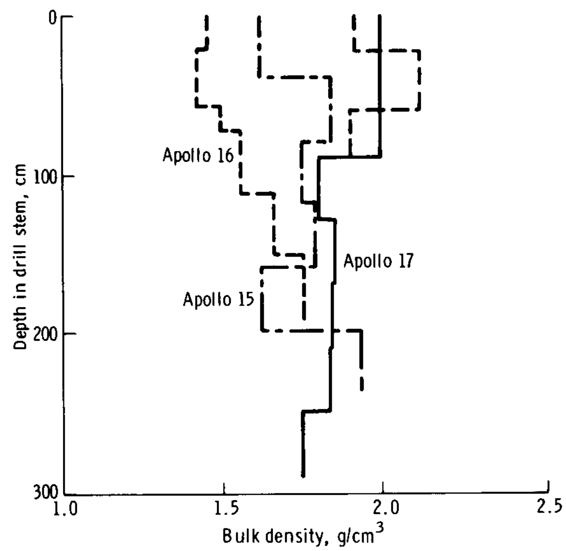

Figure 1: Density of drill core segments (Mitchell et al. 1974).

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

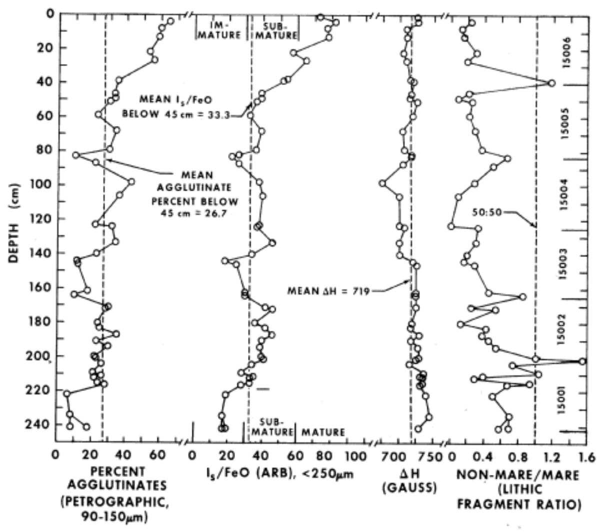

Figure 2: Maturity along Apollo 15 drill string (from Heiken et al. 1976).

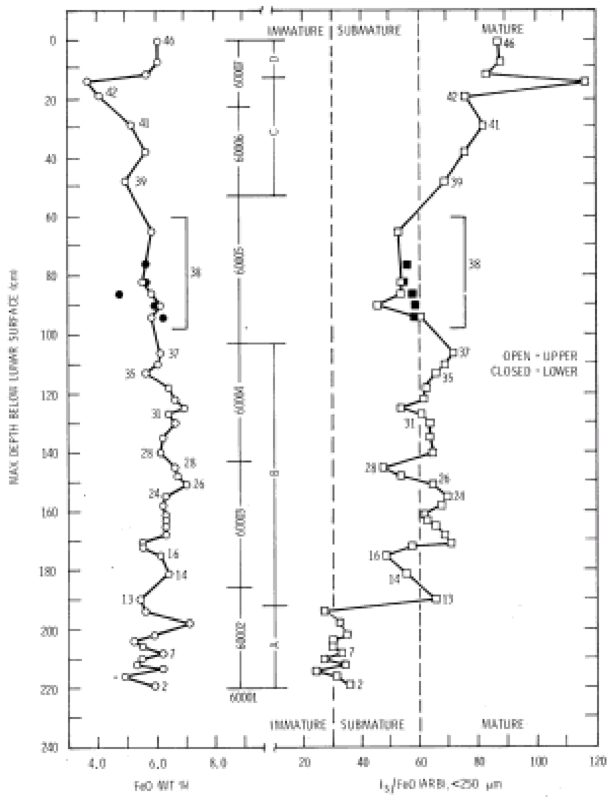

Figure 3: Maturity along Apollo 16 drill string (from Gose and Morris 1977).

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 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.

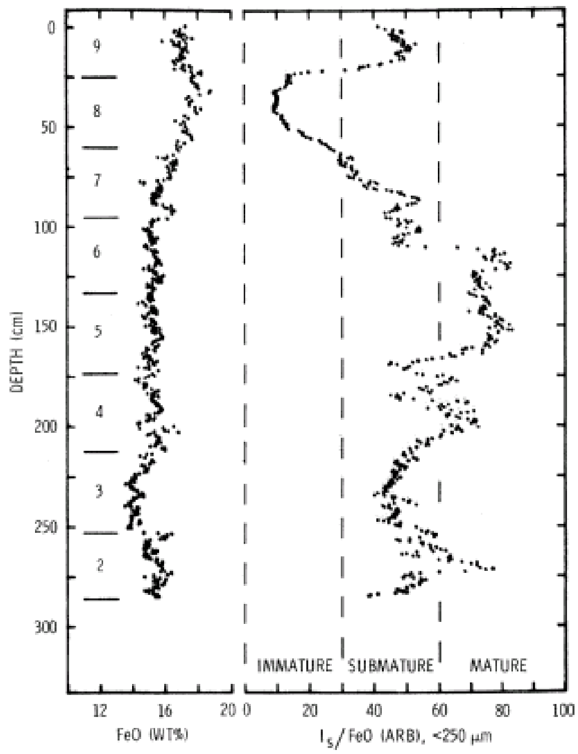

Figure 4: Maturity along Apollo 17 drill string (from Morris et al. 1979).

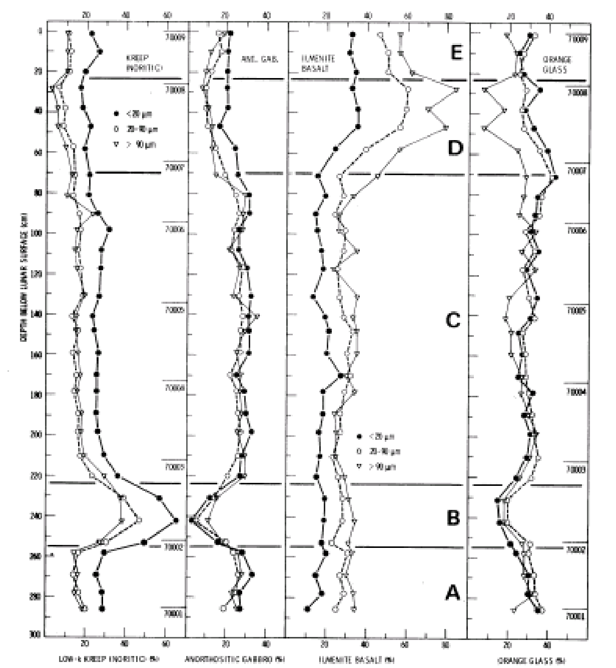

Figure 6: Composition of Apollo 17 drill string as determined by Laul and Papike (1981).

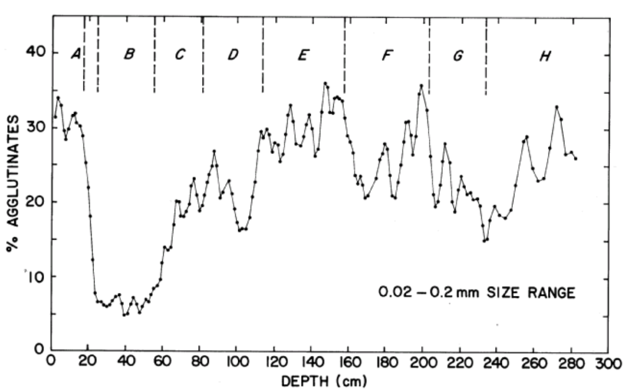

Figure 5: Agglutinate content along Apollo 17 drill string (from Taylor et al. 1979).

Apollo 16

Gose and Morris (1977) give the Is/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 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.)

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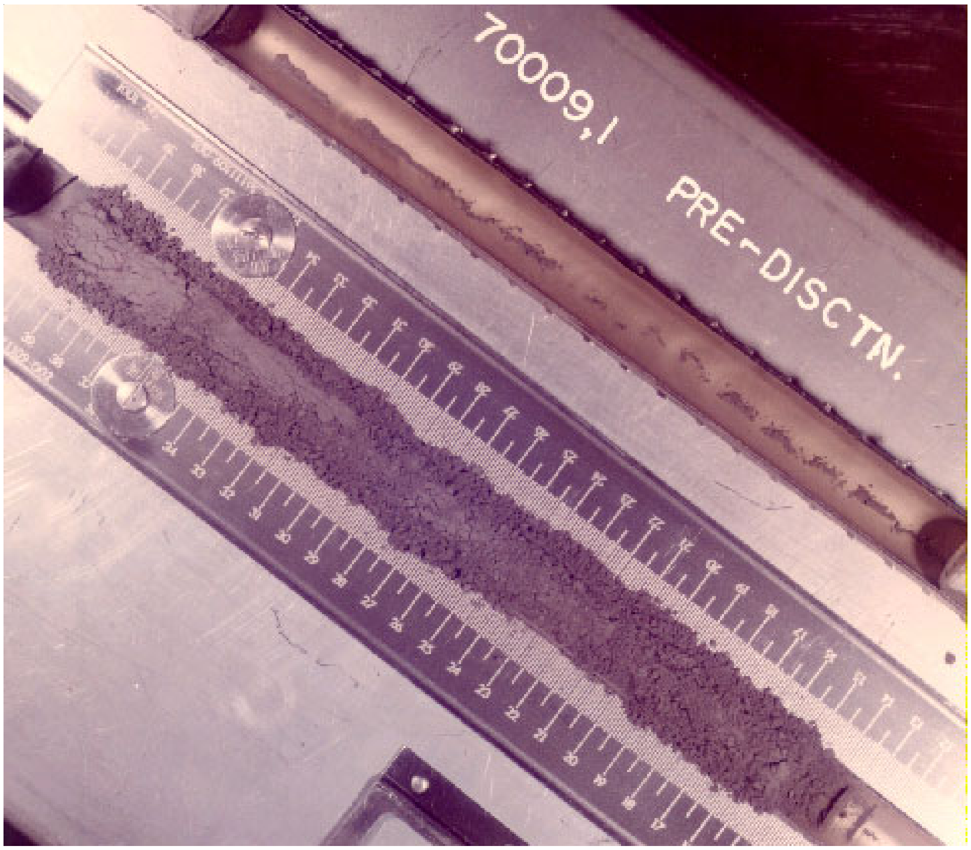

Figure 7: Photograph of top section of A17 drill string prior to dissection. NASA# S75-24316. Scale is cm.

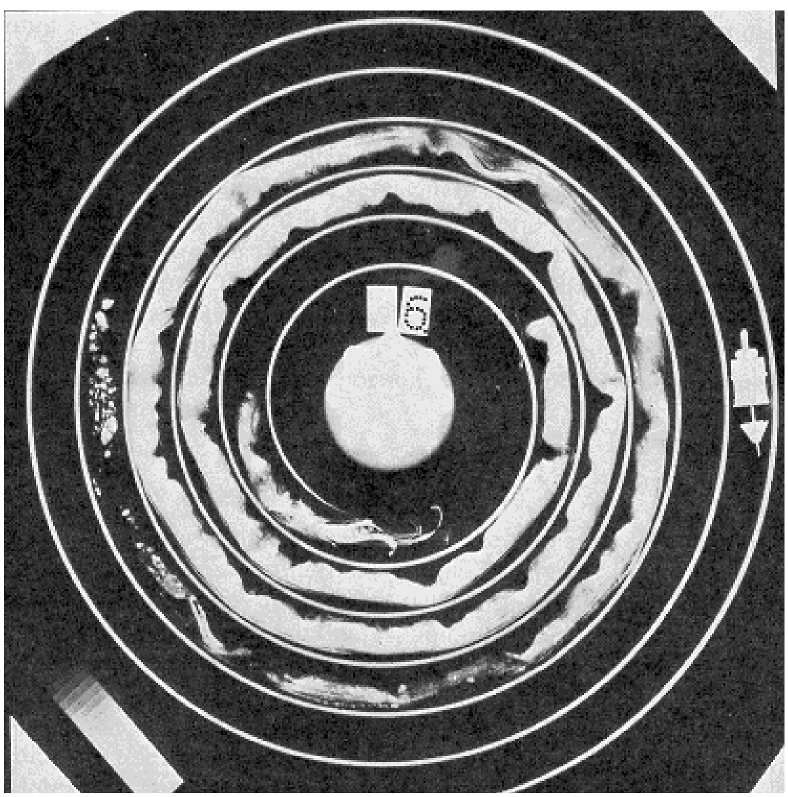

Figure 8: X-ray of Luna 24 drill core (from Barsukov 1977).

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

Apollo 15 Deep Drill String

potted butts	depth (mm)	TS	TS	TS	mm
15002,508		522			11
509		523			27
510		524			29
511		525			25
512		526			29
513		527			29
514		528			29
515		529			34
516		530			24
517		531			34
518		532			19
519		533			28
520		534			21
521		535			22
15003,6000		6015	6030	6045	27
6001		6016	6031	6046	22
6002		6017	6032	6047	22
6003		6018	6033	6048	32
6004		6019	6034	6049	30
6005		6020	6035	6050	26
6006		6021	6036	6051	20
6007		6022	6037	6052	27
6008		6023	6038	6053	23
6009		6024	6039	6054	25
6010		6025	6040	6055	26
6011		6026	6041	6056	26
6,012		6027	6042	6057	23
6013		6028	6043	6058	29
6014		6029	6044	6059	30

Apollo 16 Deep Drill String

potted butts	depth (mm)	TS	TS	TS	mm
60002,400		389	440		11
401		390			14
402		391	437		16
403		392			18
404		380	438		17
405		381	439		13
406		382			16
407		383			14
408		384	414		12
409		385			13
410		386	415		13
411		387	416		16
412		388			16
60003,208		228			11
209		229	256	257	14
210		230	231		16
211		232	269		18
212		234	270		17
213		236	237		13
214		238	239		16
215		240			14
216		242	243		12
217		244	245		13
218		246	247		13
219		248	249		16
220		250	251		16
221		252	253		25
222		254	255		25
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
185	48-79	368	380		30
186	79-109	369	381		30
187	109-142	370	382		30
188	142-172	371	383		30
189	172-202	372	384		31
190	202-227	373	385		24
191	227-257	374	386	396	30
192	257-282	375	387	397	25
193	282-307	376	388	398	23
194	307-332	377	389		27
195	332-361	378	390		28
70003,307		321	335		
308		322	336		
309		323	337		
310		324	338		
311		325	339		
312		326	340		
313		327	341		
314		328	342	472	
315		329	343	473	
316		330	344		
317		331	345		
318		332	346		
319		333	347		
320		334	348		
70004,451		465	466		25
452		467	468		23
453		469	470	525	29
454		471	472		26
455		473	474		28
456		475	476		29
457		477	478		23
458		479	480		24
459		481	482		28
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
70007,301		312	313		29
302		314	315		27
303		316	317		23
304		318	319		28
305		320	321		27
306		322	323		27
307		324	325		27
308		326	327		27
309		328	329		28
310		330	331		27
311		332	333		31
70008,339		354	355		29
340		356	357		29
341		358	359		17
342		360	361		27
343		362	363		21
344		364	365		25
345		366	367		19
346		368	369		30
347		370	371		21
348		372	373		29
349		374	375		28
350		376	377		26
351		378	379		22
352		380	381		19
353		382	383		18
70009,278	149-163	287	288		12
279	163-190	289	290		25
280	190-219	291	292		28
281	219-250	293	294		25
282	250-278	295	296		27
283	278-311	297	298		32
284	311-342	299	300	446	31
285	342-365	301	302	447	23
286	367-400	303	304		32