Summary of Apollo Drive Tubes

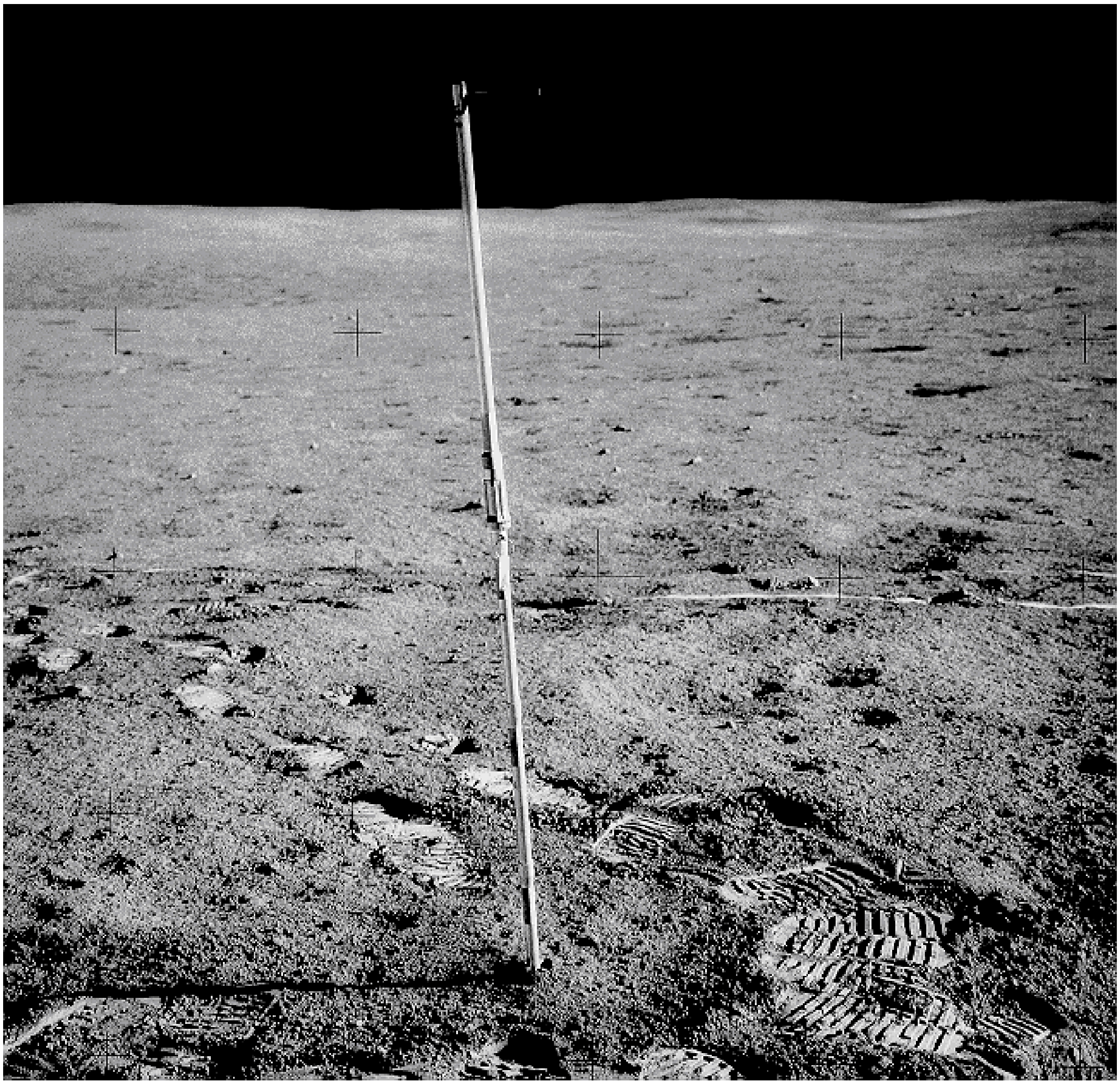

Figure 1: Photo of double drive tube at Apollo 14. NASA photo AS14-68-9454. Foot prints and cart tracks visible.

Introduction

In addition to 3 deep drill cores taken during Apollo missions, as many as 21 shallow drive tubes were used to core the lunar surface regolith down to ~50 cm. Although it had been expected that there would be significant stratigraphy preserved in these cores, little was found. When you think about it, you realize that the continuous and random cratering of the lunar surface results in a fine-grained mixture of rock and fused soil fragments in a manner likened to "gardening" (Shoemaker 1971; Arnold 1975). However, the drill cores and drive tubes did successfully record the profile of cosmogenic radionuclides produced by solar and galactic cosmic ray bombardment and the corresponding neutron flux that extends with depth (1

Table 1. Apollo Drive Tubes (only).

		weight grams	length cm.	station	containers bag	ALSRC	other	date dissected	Newsletter #
10004	S	44.8	13.5	LM		yes	23 grams biology	1978	
10005	S	53.4	10	LM		yes	27 grams biology	1978	
12026	S	101.4	19.3	Surveyor Crater		yes	leaked, spilled, 47 g. bio.		
12027	S	80	17.4	Sharp Crater		yes	leaked	1979	26
12028	U	189.6	31.6	Halo Crater		yes	leaked, compounded, 10 g. bio.	1970	
12025	L	56.1	9.5	Halo Crater		yes	leaked		
14220	S	80.7	16.5	G, near LM	yes			1979	24
14230	S	76.7	12.5	North Triplet C.	yes			1971	
14211	U	39.5	7.5	Weird Crater	yes			1978	23
14210	L	169.7	32.5	Weird Crater	yes		7 grams biology	1978	23
15009	S	622	38.5	Spur Crater	yes			1988	50.51
15008	U	510.2	30.4	St. George C.	yes			1981	30
15007	L	768.2	35.6	St. George C.	yes			1981	30
15011	U	660.7	32	edge Rille	yes			1979	24
15010	L	740.4	35	edge Rille	yes			1978	18, 24
60010	U	635.3	combine	ALSEP site		yes		1975	1
60009	L	759.8	65.4	ALSEP site		yes		1975	1
60014	U	570.3	combine	ALSEP site				1991	53
60013	L	757.3	63.1	ALSEP site				1991	53
64002	U	584.1	combine	near South Ray		yes		1980	32
64001	L	752.3	65.6	near South Ray	yes			1980	34
68002	U	583.5	combine	near South Ray	yes			1980	55,56,58
68001	L	840.7	62.3	near South Ray	yes			1981	56,57
69001	S	558.4		near South Ray		cvsc	unopened, In		
70012	S	485	18.4	LM	yes		unopened		
76001	S	711.6	34.5	6, North Massif	yes		oriented	1978	23
73002	U	429.7	combine	Light mantle		yes	unopened, RSF		
73001	L	809	56	Light mantle		cvsc	unopened, In		
74002	U	909.6	combine	Shorty Crater		yes		1977	16
74001	L	1072	68.2	Shorty Crater		yes		1981	13
79002	U	409.4	combine	van Serg Crater	yes			1986	47
79001	L	743.4	51.3	van Serg Crater	yes			197	49

* weight from computer inventory

In = Indium contamination

S=singe, U=upper, L=lower

– 2 meters) into the lunar regolith (e.g. Nishizumi et al. 1977).

Throughout the six Apollo missions there was continuous improvement, with better engineered cores, better procedures and increasingly yield. However, it wasn't until about 1978 that the curator figured out how to extrude and properly examine the cores. In most cases the cores are now subdivided into carefully documented splits, sets of continuous thin sections, continuous "peels", and the remaining epoxy encapsulated reference core. As of 2007 several drive tubes are still unopened (Table 1).

The Drive Tubes

Table 1 gives a brief summary of the 21 drive tubes collected during the 6 Apollo missions. Apollo 11, 12 and 14 were collected in narrow tubes (with core liners), while Apollo 15, 16 and 17 were collected in wider tubes (figure 3). The depth of penetration was from 30 to about 70 cm. They were variously capped on the moon and some were returned in vacuum containers (ALSRC and CVSC). They weighed from about 50 grams (10004) up to 2 kilograms (74001/2).

The core tubes used for Apollo 11 and 12 were essentially the same design except for modification of the core bits (figure 3). The inner diameter was about 2 cm. They consisted of an outer anodized aluminum barrel attached to the bit and handle, and an aluminum inner barrel made of two halves held together with a Teflon sleeve (Allton 1989). To open, they slit the Teflon sleeve and removed one wall of the core liner (figure 4).

The core tubes for Apollo 15, 16 and 17 were thin-walled stainless steel with an inner diameter of about 4.1 cm. The length was ~ 34 cm, so as to be able to fit in the ALSRC (*but they were not all returned in ALSRC*). They were extruded.

Soil Mechanics

During Apollo there was a large engineering effort aimed at understanding the nature of the lunar regolith (called the Soil Mechanics Experiment). This PIship, led by Prof. J.K. Mitchell at UC Berkeley, found information obtained from the lunar drive tubes to be especially interesting. In general, drive tubes were easily pushed into the soil up to about 20 cm, but required hammer blows to obtain greater depth. The soil samples generally stuck in the cores as they were pulled out, capped and returned (Sullivan 1994).

Density of the lunar regolith was one of the important parameters that came out of soil mechanics investigations. Density was measured by dividing the weight by the volume. Initially, the sample weight was calculated as the difference between the total weight minus the preflight weight of the core tubes. Volume was calculated from the length of the core and its diameter, and the length was obtained by gently pushing plugs in the ends and x-raying the tube. As a general rule the bottom segment of each core was found to be more dense than the top (figures 2 a,b,c). Average density was about 1.5 g/cm^3, which is about half that of a rock (~3.3 g/cm^3).

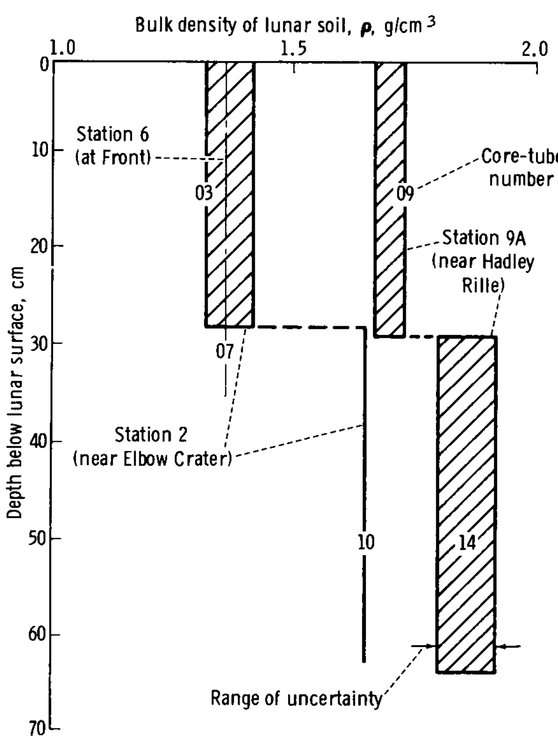

Figure 2a: Density of drive tubes from Apollo 15 (Preliminary Science Rept.).

Maturity

The maturity of the lunar regolith is measured by I_s/FeO, rare gas content, agglutinate % and/or grain size

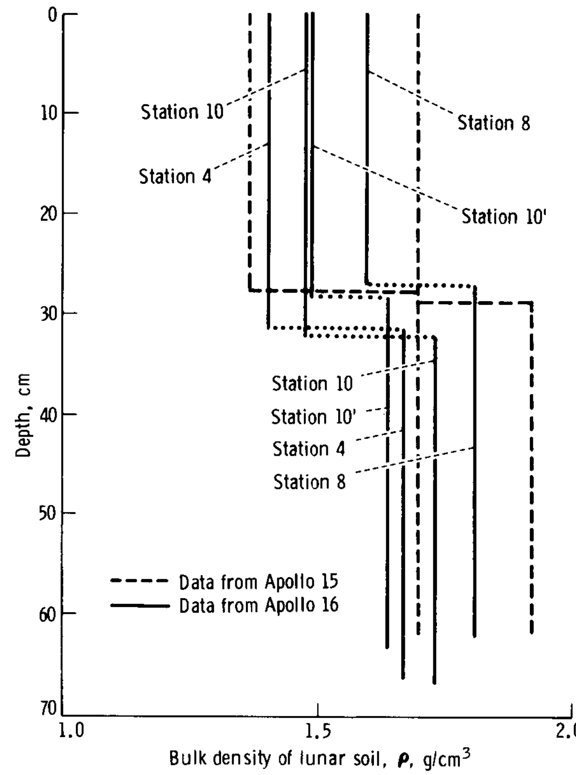

Figure 2b: Density of drive tubes from Apollo 16 (Preliminary Science Rept.).

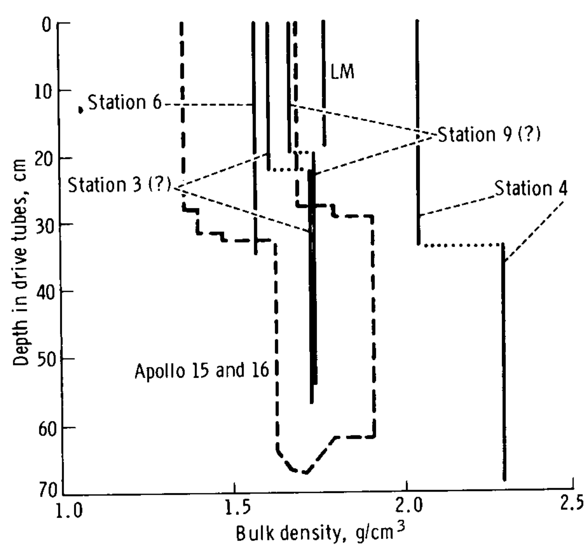

Figure 2c: Density of drive tubes from Apollo 17 (Preliminary Science Rept.).

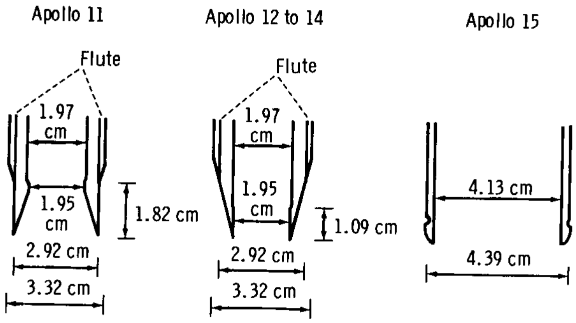

Figure 3: Design of core "bits" for drive tubes for different Apollo missions. Note that the Apollo 15 cores were much wider, such that material was much less disturbed.

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 cores. They were made from epoxy encapsulated material that remained in the core tube after several dissection passes.

Apollo 11

"Two core tubes were driven, and each collected a satisfactory sample. Each tube had an internally tapered bit that compressed the sample 2.2:1 inside the tube. One core tube contained 10 cm of sample, and the other contained 13 cm of sample. The tubes were difficult to drive deeper that approximately 20 cm. This difficulty may have been partially caused by increasing density of the fine-grained material with depth or by other mechanical characteristics of the lunar regolith. The difficulty of penetration was also a function of the tapered bit, which caused greater resistance with increased penetration. One tube was difficult to attach to the extension handle. When this tube was detached from the extension handle, the butt end of the tube unscrewed and was lost on the lunar surface. The tubes were opened after the flight, and the split liners inside both tubes were found to be offset at the bit end. The Teflon core follower in one tube was originally inserted upside down, and the follower in the other tube was inserted without the expansion spring which holds the follower snugly against the inside of the split tube."(Mission Evaluation Team 1971)

During the quarantine and preliminary examination (PET) a large part of each Apollo 11 core was used (sacrificed) for biologic studies. In 1978, the remainder was examined and sieved to extract additional rock fragments for Gerry and Dimitri (Allton 1978).

Apollo 12

Drive tube 12026 was collected near the Lunar Module. 12027 was collected from the bottom of the trench (20 cm deep) at Sharp Crater where 12023 and 12024 were collected. It penetrated another 17 cm or so. 12025 – 12028 was a double drive tube collected from near Halo crater. The lower segment, 12028, had a very distinct

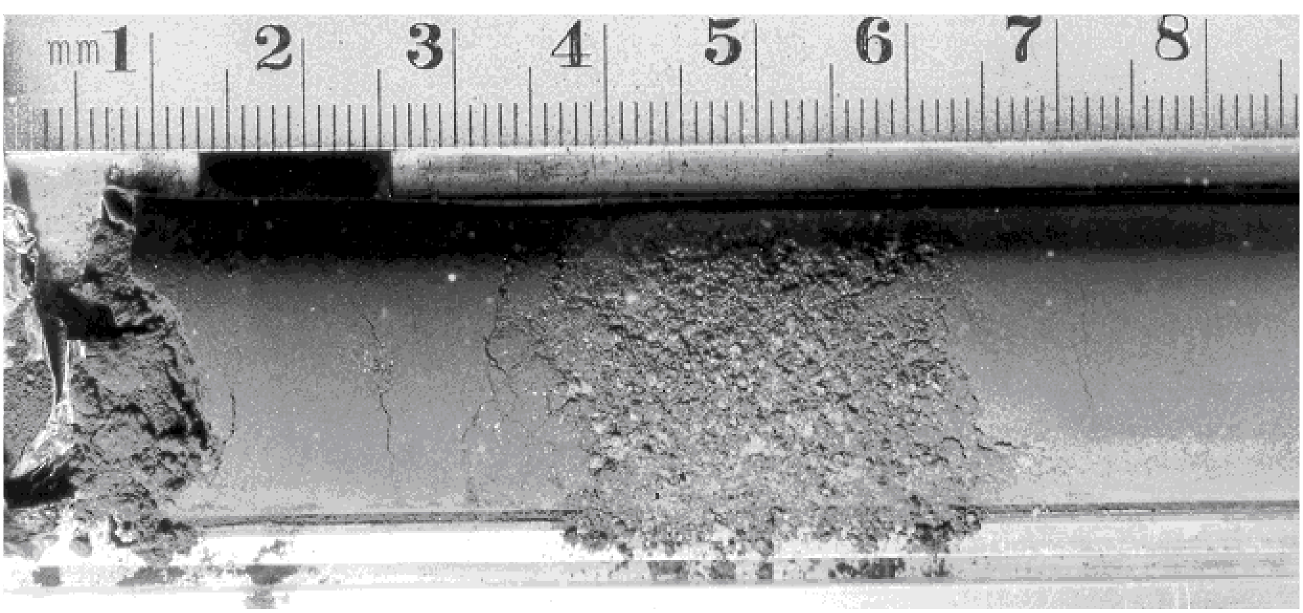

Figure 4: Drive tube 12028 with 2 cm thick coarse layer. NASA S69-23404. Scale in cm.

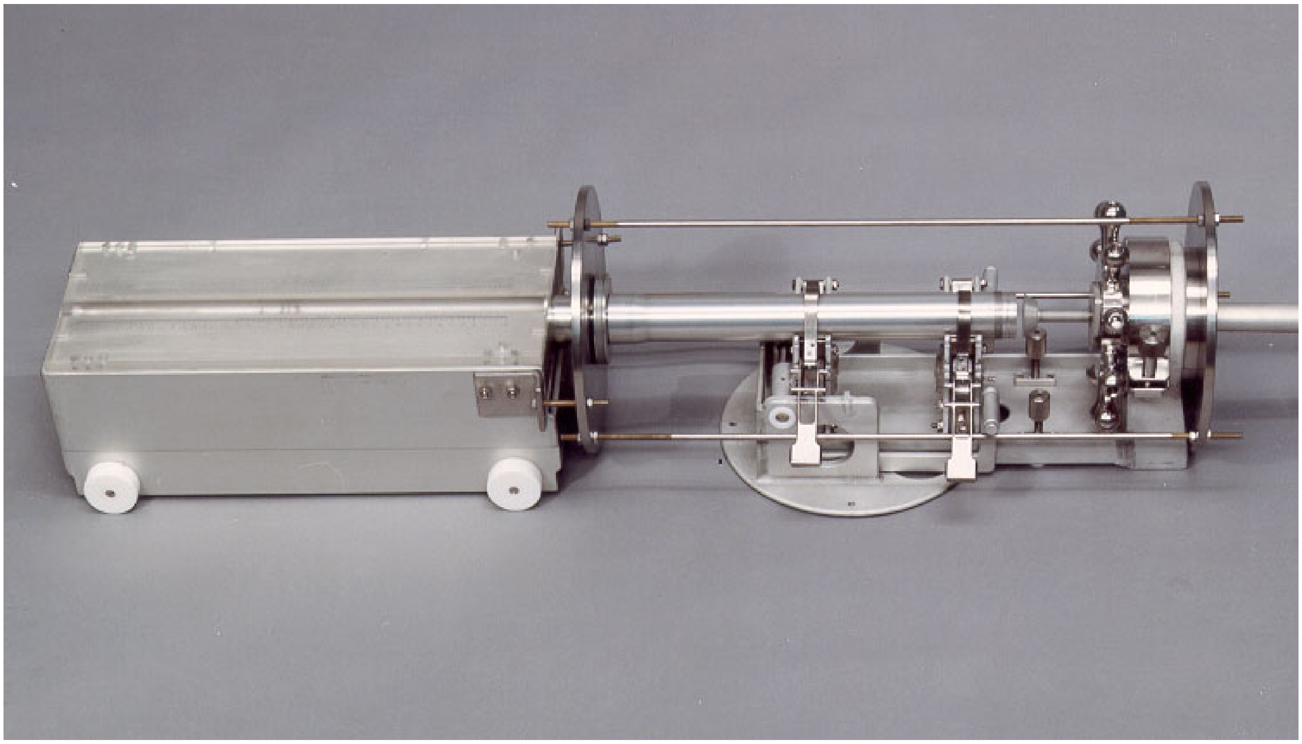

Figure 5: Device used to extrude drive tubes (A15-17) into dissection tray (on cart). S80-43518. Tube is about 4 cm diameter.

coarse layer (figure 4). However, on Apollo 12, ALSRC#2 containing the core tubes leaked to about one half atmosphere.

Apollo 14

The Apollo 14 crew experienced difficulty getting full core tubes at Apollo 14. They had planned to get a triple drive tube, but struck a rock, denting the end. At Cone Crater the material in the tube fell out. They ended up leaving 2 empty core tubes on the moon, but were able to obtain a double drive tube (14211-14210) and two singles (14210 and 14220). However, these were not returned in vacuum containers.

Apollo 15

One drive tube was collected on each of the three EVA. Double drive tube (15008-15007) was taken at station 2 on the rim of a 10-m crater between Elbow and St. George Crater at the Apennine Front. The crew pushed the first tube in full length, but it took 35 hammer blows to sink the upper tube. On the second EVA, a single core (15009) was taken at station 6 on the Apennine Front near Spur Crater. The crew just pushed it in. A third core (15011 – 15010) was taken, as a double core, from near the edge of Hadley Rille, station 9A. The bottom 2/3 went in easy, but it took 50 hammer blows to complete the core.

Apollo 16

Sutton (in Ulrich et al. 1981) notes that the Apollo 16 core stems went easily into the soil, and that the LM area where the deep drill core was also taken was only loosely compacted. Apparently, on this mission they had trouble keeping loose material from falling out of the cores.

Double drive tube 60009/10 has often been studied instead of the deep drill (Korotev 1991). It was collected, along with the deep drill and drive tube 60014/13, from the ALSEP site on the Cayley Plains at Apollo 16. It was easily pushed in to 18 cm, but then had to be hammered hard. It apparently broke through a rock fragment at depth. The core was placed in ALSRC#2, which was returned under good vacuum. Details of the dissection of 60009/10 and a review of the science is summarized in the catalog by Fruland et al. (1982).

Double drive tubes 64002/1 and 68002/1 should contain fresh material ejected from South Ray Crater, but it could not be identified.

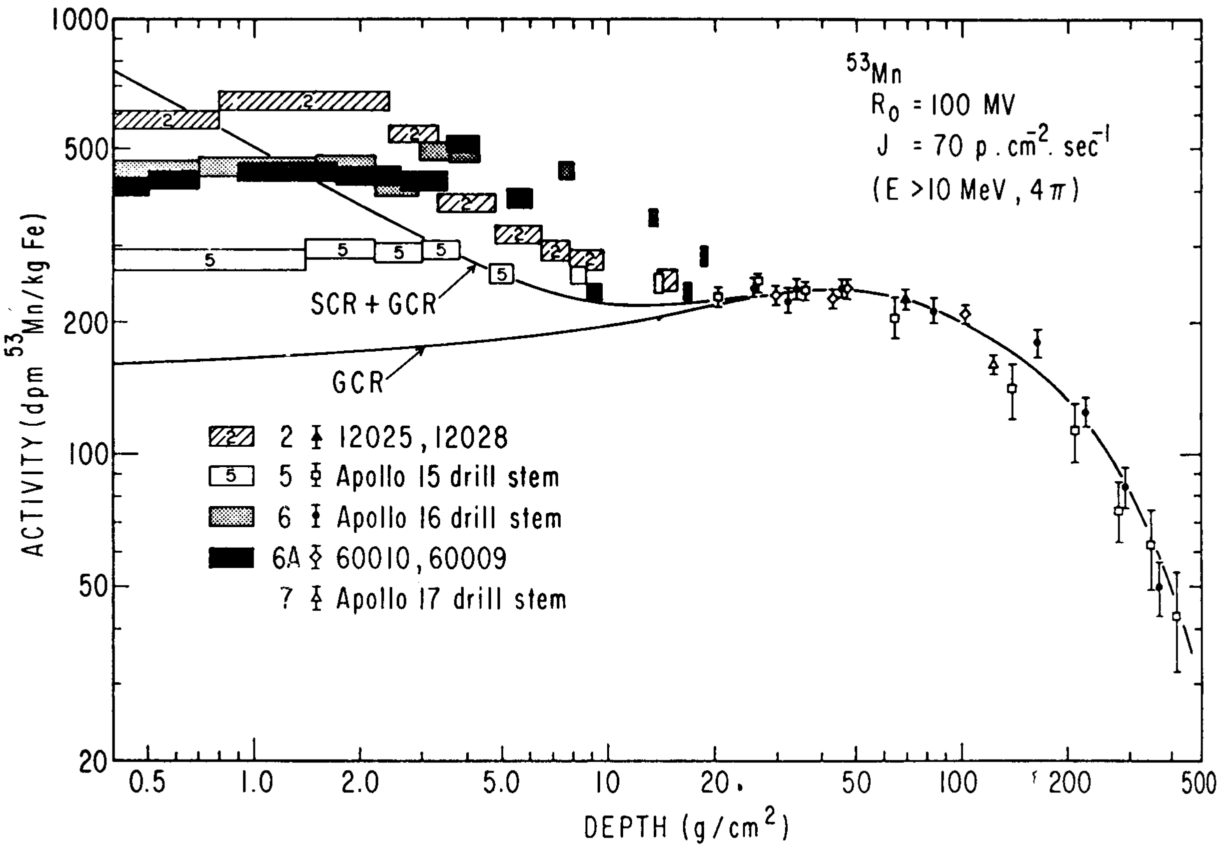

Figure 6: Profile of 53Mn activity with depth for various drill cores and drive tubes (Nishiizumi et al 1979). The curves marked SCR and GCR are predicted by the Reedy-Arnold model.

69001 was immediately placed in a core sample vacuum container (CVSC), which, as of today, has not been opened.

No core was taken at North Ray Crater.

Apollo 17

As with previous missions the bulk density of the lower tube is always higher than the upper, indicating that the regolith is more dense below 10-20 cm (Mitchell et al. 1973).

70012 is a single drive tube that was hand driven to a hard layer at 28 cm depth into the regolith next to the footpad of the LM. The top few cm may have been blown away by the exhaust of the LM descent propulsion engine. It was returned in the BSLSS bag. When the BSLSS bag was opened in the LRL, the bottom cap of the core had come off with material spilling out (47 grams of core material was removed to create a fresh vertical face, which was then plugged for X-radiography). Additional spilled material was in the BSLSS (PET report). As of 2007, this core has not been dissected.

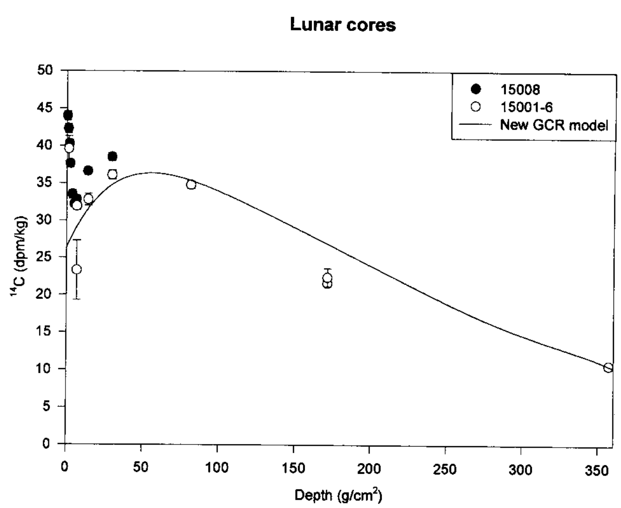

Figure 7: Activity of 14C in lunar cores and Apollo 15 deep drill (from Jull et al. 1998).

73002 and 73001 is a double drive tube that was taken at station 3 in an effort to sample the light mantle (landslide). The lower segment, 73001, was vacuum sealed in a core vacuum sample container. The total

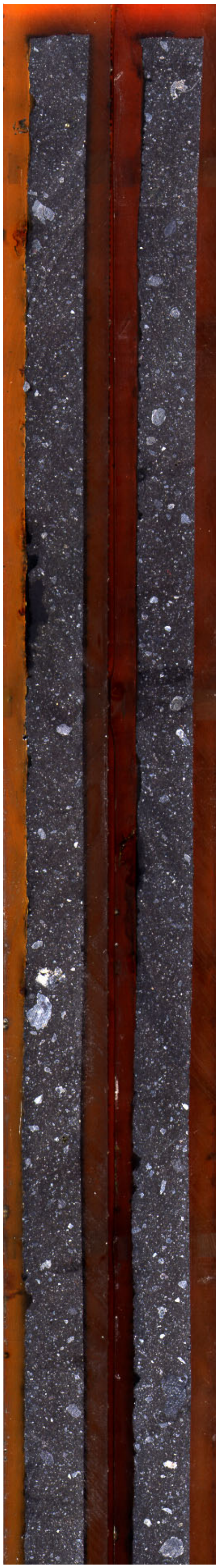

Figure 8: Image of epoxy encapsulated core 76001 - sawn lengthwise, twice - scanned at low resolution (100dpi) - and compressed. Total length is ~30 cm. See section on 76001 for high resolution.

depth penetrated was 70.6 cm (9 hammer blows). The upper segment, 73002, was about 22 cm long. It was taken in the area of several small fresh craters and the lunar surface fairly rough, with about 20% coverage of 1-2 cm fragments. Trench 73220-73280, from near the rim of one of the small craters, showed a marbled layering. Neither 73002 nor 73001 have been opened (as of 2007). However, material from the trench has been studied.

76001 is a single drive tube collected from the soil at the bottom of the North Massif about 250 meters from the mare boundary. It was simply pushed in, up to about 16 cm, and then hammered (5-6 blows) to 37.1 cm (34.5 cm were recovered). It was found to rather homogeneous along it length (figure 8).

Double drive tube 74002/1 (68.2 cm long) was taken next to the trench in the orange soil at Shorty Crater. It is one of the most densely packed cores, with each segment weighing about 1 kg. The top few cm have been gardened, but the remainder has been in place for a very long time (Eugster et al. 1980).

Drive tube 79002/1 (51.3 cm long) was taken at van Serg Crater, out on the mare plain. The top 8 cm of this core is slightly more mature than the rest of the core (Morris et al. 1989).

Chemical Composition

Although cores were dissected into splits every 0.5 cm, chemical analyses of all these splits somehow can't be found in the literature. Table 2 gives a sample of what can be found.

Cosmogenic Radionuclides

Figure 6 is a summary of the cosmic ray induced activity of ^{53}Mn as a function of depth in the lunar surface as determined from drill cores and drive tubes (Nishiizumi et al. 1979). Figure 7 shows the activity of ^{14}C (Jull et al. 1998). As techniques continue to improve, and new questions are asked, lunar samples are found to be a "gift that keeps on giving"(Drake).

Processing

Early processing (~1972) of drive tubes included X-ray radiography, and sampling the ends of each segment. Starting about 1978, the large diameter drive tubes (A15, 16 and 17) were then extruded into a layered core receptacle to allow careful dissection (figure 5). Some early drive tubes (A11, 12 and 14) were processed differently (see core catalog for details). Dissection consisted of carefully spooning material in a sequential manner, cm by cm in multiple (3) passes.

Table 2. Chemical composition of drive tubes.

	12027		14210	14220	15007	60009		60010	74001/2		76001	79001/2	
reference	Smith84		Laul82	Laul82	Korotev87	Ali 76		Ali 77	Blanchard78		Korotev	Morris 89	
weight	*16 cm*		*36 cm*	*16 cm*	*top of*	*unit 1*	*unit 4*		0 - 2 cm	*2 - 68 cm*	unpub.	ave	
SiO2 %						46.4	44.3	48.1			ave		
TiO2	2.6	(a)	1.7	1.6	1.31	0.63	0.4	0.81	8.8	8.9			
Al2O3	13.6	(a)	17.1	17.6	20	27.8	32.7	29.3	6.7	5.8			
FeO	16.1	(a)	10.7	10.5	10.1	4.64	2.12	4.41	22.5	23.7	10.58	15.61	(a)
MnO	0.19	(a)	0.14	0.13	0.14	0.1	0.039	0.075	0.26	0.27			
MgO	10	(a)	9.1	9.5	10.6	7.11	3.95	5.47	14	15			
CaO	10.8	(a)	11.2	11.6	11.7	16.2	18.2	17.1	8.6	7.6	12.3		(a)
Na2O	0.59	(a)	0.68	0.76	0.46	0.4	0.39	0.4	0.45	0.42	0.39	0.4	(a)
K2O	0.36	(a)	0.51	0.52		0.114	0.146	0.094					
P2O5													
S %													
sum													
Sc ppm	38	(a)	22.2	21.7	18.6	7.24	3.04	7.94	49	48	28.2	50.3	(a)
V	110	(a)	45	40	64	23.8	12	35.5					
Cr	2258	(a)	1334	1266	1940	770	260	700	5063	5200	1887	2924	(a)
Co	40	(a)	35.7	35	30.5	23.4	8.74	28.7	60	66	*37.6*	36.1	(a)
Ni	*290*	(a)	400	420	165			370			244	186	(a)
Cu													
Zn													
Ga													
Ge ppb													
As													
Se													
Rb													
Sr			200	170	150						154		
Y													
Zr	550		770	770	350						165		
Nb													
Mo													
Ru													
Rh													
Pd ppb													
Ag ppb													
Cd ppb													
In ppb													
Sn ppb													
Sb ppb													
Te ppb													
Cs ppm					0.24								
Ba	540		730	830	235	133	60	160			118	102	(a)
La	49		62	65	22	12.2	4.8	11.3	6.4	5.9	9.55	8.56	(a)
Ce	120		170	180	57	30.3	11.3	22	24	21	26.9	25.3	(a)
Pr													
Nd	80		100	100	33	22.7	6.8	14			17		(a)
Sm	22		27.8	28.5	10.4	4.5	1.7	5	7.4	6.9	5.9	7.32	(a)
Eu	2.1		2.4	2.35	1.34	1.12	0.97	1.11	1.85	1.88	1.29	1.51	(a)
Gd													
Tb	3.6		5.55	5.5	1.96	0.84	0.32	0.71	1.7	1.6	1.35	1.68	(a)
Dy	27		41	38				2.6					
Ho			8.4	8.3									
Er													
Tm	2.3		3	3.2									
Yb	15.7		21.1	21.5	7.3	3.75	1.59	2.61	4.5	4.2	4.81	6.09	(a)
Lu	2.25		2.94	2.9	1	0.42	0.16	0.56	0.66	0.59	0.673	0.86	(a)
Hf	15		21.7	24.9	8.4	2.65	0.96	3.5	5.9	6.3	4.83	6.39	(a)
Ta	2.2		3	3	0.97	0.61	0.17	0.37	1.3	1.2	0.75	1.07	(a)
W ppb													
Re ppb													
Os ppb													
Ir ppb					4.3						8.8	6	(a)
Pt ppb													
Au ppb					2.1						4.1		(a)
Th ppm	7.7		11.9	13.5	3.8	1.72	0.6	1	0.5	0.4	1.55	1.06	(a)
U ppm	2.2		3.2	3.5	1.18						0.42		(a)
technique:	*(a) INAA*												

After the final pass, a thin coating of plastic was used to create a "peel" in order to have a continuous section of material (*but this material was disturbed by the final dissection*). These "peels" are stored in a restricted access collection (RAC).

Material laying in the bottom of the core after the dissection and "peel", was impregnated with epoxy and made into thin sections (see attached tables). In this process, epoxy encapsulated core material, maintaining stratigraphy, was created for the full length of each core. These were sawn in half, lengthwise, twice. One third was subdivided into potted butts for thin sections and the other thirds were preserved as a reference (figure 8). Included in this section of the Lunar Sample Compendium are enlarged photos (and collages) of the sawn surfaces of these encapsulated cores (*shown here for the very first time*). The various core catalogs and supplements have additional collages of the thin sections, loose dirt during dissection passes and of the peels, but they are no very revealing.

Selected References

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

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