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Depth scales for Apollo 15, 16, and 17 drill cores

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Abstract—A scale of depth in cm from the surface and of overburden mass in g/cm^2 is presented for each drill core based on a review of original sample data, Apollo surface activity videotapes, and examination of flight hardware. The scales presented here are based on laboratory measurements of the soil. The relationship of these depth scales to *in situ* lunar conditions is somewhat speculative and includes larger uncertainties (±3 cm, Carrier, 1974) in measurements of depth of penetration (instead of length of soil column measured in tube) and insufficient understanding of what happens to lunar soil entering the drill stem (in terms of amount entering the drill, compaction, expansion). The scales for Apollo 15 and Apollo 17 drill cores are well constrained. The Apollo 16 drill core was returned to earth with a substantial void in the bottom of the upper half of the core. The scale presented proposes that significant amounts of soil fell out of the bottom of section 60005 in addition to poor recovery in the upper two sections. The lower half of the core (60001–60004) represents 100% soil recovery at a depth of 102–221 cm below the surface. A table of the weights and lengths for "end of tube" samples is provided for investigators who wish to correlate depths of thin sections continually along the drill string.

INTRODUCTION

Since lunar drill core samples first became available, investigators have used several sources and methods for calculating sample depths. This resulted in differences which ranged from 1–8% in sample depths calculated by two different investigators for the same Apollo 16 and 17 samples. For Apollo 16 there was the additional problem of how to account for the void space in the middle of the core. Comparison of calculated depths for the same samples are shown in Table 1. To facilitate interlaboratory comparison of analytical results, a well-constrained depth scale for the Apollo 15 and one for the Apollo 17 drill cores are presented. A less constrained scale for the Apollo 16 drill core is also given. The scales are presented in an abbreviated tabular form in this paper. Computer listings for depths and mass of overburden by sample number are available from the Lunar Sample Curator, and these listings are the most convenient form to use.* These depth scales are based on the length of the soil column measured in the laboratory since these are the depths most easily referenced in locating in-

* Lunar Sample Curator, SN2, Johnson Space Center, Houston, Texas 77058.

Table 1. Comparison of depth scales used previously for the same samples.

Sample	Depth in g/cm²	
	Stoenner *et al.*, 1974	Russ, 1973
60006,3	83	83.1
60004,3		164.8 (nothing included for missing soil)
	205 (includes 40 g/cm² for missing soil)	223.5 (includes 55 g/cm² for missing soil)
60003,3		234.4 (nothing included for missing soil)
	272 (includes 40 g/cm² for missing soil)	289.5 (includes 55 g/cm² for missing soil)
	Curtis and Wasserburg, 1975	Pepin *et al.*, 1975
70008,163	50	46
70006,3	180	179
70005,3	252	251
70004,3	326	324
70003,3	400	397
70002,3	473	470
70001,3	535	542

vestigators' samples. The relationship of these scales to actual *in situ* lunar conditions, critically important but slightly speculative, is discussed based on per cent of material recovered and soil mechanics information.

PREVIOUSLY AVAILABLE SOURCES OF SAMPLE DEPTH INFORMATION

The first weights and lengths of drill core soil columns were based on length measurements made on the lunar surface, gross weights of soil in the tube, and soil lengths observed in X-radiographs and published in the *Preliminary Science Reports* (Mitchell *et al.*, 1972a, 1972b, 1973b and LSPET 1972a, 1972b, 1973). After X-rays were taken, soil was dug out of the ends of most of the tubes for quick analyses of short-lived radionuclides and other studies. All material in the drill bits was dug out in this manner. Many early investigators received some of the samples and each calculated their own sample depths from the *Preliminary Science* data. After the cores were dissected and void spaces were more accurately determined, scales were published in the *Lunar Core Catalog* (Duke and Nagle, 1976) which are similar to those presented here.

METHODS OF CALCULATION, SOURCES OF DATA, EXPERIMENTAL ERROR

In the scales presented here, the soil column lengths were measured for individual sections after the tubes were milled open and the soil could be viewed directly. Appropriate soil column lengths were added to account for the early "end of tube" samples removed before the tubes were milled open. Known soil losses were taken into account. The lengths for the individual sections were summed for the total length of each of the drill cores.

Weights and lengths for each of the core sections and "end of tube" samples were taken from original records and photographs in the data packs for each sample maintained in the Lunar Curatorial Laboratory. It was estimated that errors in measurement of length were ± 0.5 mm, and 12–16 measurements were needed for each drill core. The balance tolerance for "original weight" of each core tube section was ±0.8 g. For each of the 14–16 "end of tube" samples from each drill string, the balance tolerance was ±0.05 g.

Measurements of the depths of penetration of the drill stems into the lunar surface, including error estimates, were done by Carrier (1974) based on observation of the length of each drill stem still protruding from the lunar surface when drilling was completed (photos, videotapes, astronaut comments). Review of the videotapes revealed that the position of the lunar surface in relation to the drill stem was somewhat obscured by soil movement from drilling and astronaut activities. However, Carrier (pers. comm.) believes the soil surface was not altered by more than 2 cm.

SOURCES OF SAMPLE DISTURBANCE

It is emphasized that the scales presented in Tables 2–4 are based on soil column lengths measured after milling open the tubes in the laboratory. Since the soil column length and density was altered during drilling, transport to laboratory, and opening of the tubes, an understanding of parameters affecting the soil during these operations is necessary.

Extensive experimentation to quantify the alteration of soil during drilling has not been done. Soil mechanics investigations indicate that drilling may not always recover all of the material in the path of the drill; some may be pushed aside, depending on the relative density of the soil. For very dense soils, the drill may recover more than what is in the path of the drill. Low relative density and fast drill rates will result in lower sample recovery; high relative density and a slow drill rate will result in higher sample recovery (Carrier *et al.,* 1972). Relative density is an expression of how tightly packed a particular soil is compared to the minimum density and the maximum density to which that soil can be packed (minimum density, loosely packed = 0% relative density; maximum density, tightly packed = 100% relative density) (Carrier *et al.,* 1973). Similar trends regarding per cent recovery, soil density, and drill rate occurred during testing for development of the Apollo Lunar Surface Drill by Martin Marietta Corporation (Crouch, 1971).

During transport, the soil was not completely confined if the tube were not full. The uppermost tube was full on Apollo 15, but this was not the case on the other two missions. Plugs used on the bottom ends (the female ends) of tubes, except those with a bit, were hollow and allowed the soil to expand about 1 cm.

In the laboratory, pressure was placed on the ends of the tubes during milling to stabilize them, and this compacted the soil lengths about 5 mm in the Apollo 15 and 16 drill cores (samples from the top ends of the Apollo 17 tubes alleviated the compaction).

PER CENT CORE RECOVERY

To relate the condition of the cores as observed in the laboratory to *in situ* conditions, the length of the soil column recovered in the drill can be compared

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Weights and lengths for each of the core sections and "end of tube" samples were taken from to the greatest depth of penetration into the lunar surface from which sample was recovered.

$$\% \text{ Recovery} = \frac{\text{length of soil column inside tubes}}{\text{depth of penetration in lunar surface}} \times 100.$$

When recovery is less than 100%, it indicates that not all of the soil in the path of the drill entered the drill or that the drilling process compacted the soil to occupy less length. For investigators using sample depths in g/cm^2 from a core with less than 100% recovery, it is important to realize that the drill may or may not have recovered all of the overburden that was actually there.

Carrier (1974) calculated recoveries from soil column lengths observed in X-rays counting a full 39.9 cm for filled tubes, whereas this paper uses the usually shorter lengths observed after the tubes were opened to be consistent with the lengths (depths) by which individual investigators' samples were taken. Carrier's figures probably more accurately reflect the true situation, but the difference in values is about 1% for Apollo 15 and 17 and 3% for Apollo 16.

The recovery for the 15 drill core was 103% which suggests that virtually all soil in the path of the drill was recovered.

In the Apollo 17 drill core the recovery was 96%. This indicates that the depth scale and soil densities presented here, with no correction for less than 100% recovery, are close to *in situ* conditions, but may be 4% too low in depths or 4% too high in densities. The correction factor was not applied since it cannot be determined if the difference was due to soil mass not entering the drill or soil compaction or if any effect is evenly distributed over the length of the core.

In the case of the Apollo 16 drill core, the recovery was significantly low at 84% (Carrier, 1974, gives 87%); therefore, an attempt was made to correct depth figures.

APOLLO 15 DRILL CORE

The Apollo 15 drill string penetrated 236 ± 1 cm into the lunar surface (Carrier, 1974). A small amount of soil fell out of the bottom of the drill on the lunar surface. This void, when observed in the laboratory, was 5.5 cm long. Thus, the greatest depth of penetration from which soil was recovered was 230.5 ± 1 cm. The total soil column length measured after the tubes were opened was 237.2 ± 1.2 cm. This corresponds to 103% recovery, and indicates that the soil density decreased somewhat after entering the drill tube. The uppermost tube was completely full even though the astronauts left some of the tube protruding above the surface to facilitate extraction of the drill stem. The situation is depicted graphically in Fig. 1.

As can be seen in Table 2, cores 15004, 15005, and 15006 expanded slightly from the nominal 39.9 cm tube capacity, and cores 15001, 15002, and 15003, which were returned to earth as one piece, were compacted slightly. Use of hollowed out plugs in the bottom ends of 15004, 15005, and 15006 allowed this to the greatest depth of penetration into the lunar surface from which sample was recovered.

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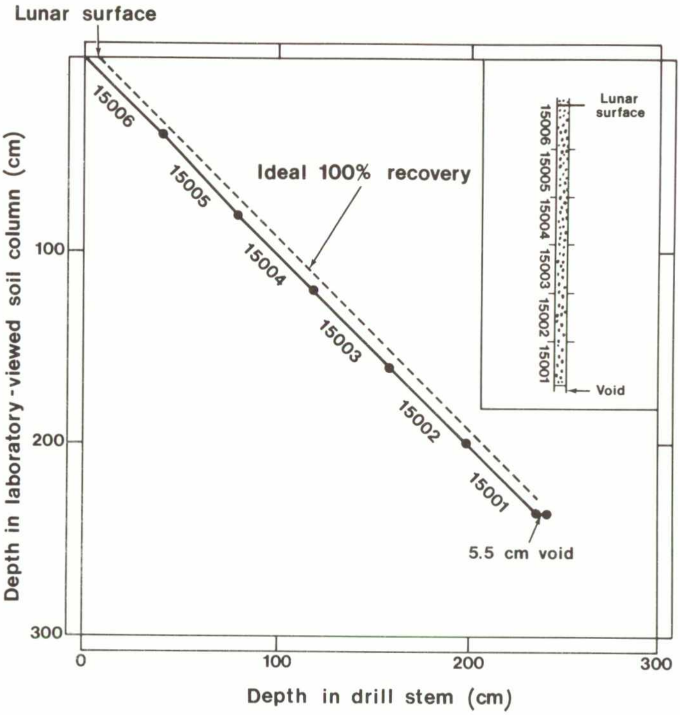

Fig. 1. Apollo 15 drill core depth relationship. Data points determined at top of each core section (e.g., 15006, 15005). Slope of line is not constant throughout length of core; therefore, Table 2 describes each core section separately. Dashed line indicates ideal 100% recovery. Insert shows distribution of soil observed in the laboratory and the position of the drill stem with respect to the lunar surface as observed on the moon. After style of Carrier, 1974.

expansion to occur. The compaction of 15001, 15002, and 15003 occurred after separation of these tubes in the laboratory, probably during the milling procedure, because pressure was put on the ends of the tube to hold it in place during cutting.

The good recovery indicates that the sample depths and densities reported in Table 2 closely resemble *in situ* conditions. Table 5 gives the lengths calculated for "end of tube" samples, which are not included in thin sections or peels, for investigators correlating sample depths of peels. Thin sections were not made along the length of the Apollo 15 drill core.

APOLLO 16 DRILL CORE

Unlike the Apollo 15 drill core, the Apollo 16 drill core does not have a straightforward relationship between soil column length measured in the laboratory and *in situ* conditions. The poor recovery of 84% is significant and requires correction factors.

Table 2. Depth scale for Apollo 15 drill core.

This scale is an accounting of the length of the soil column as viewed in the laboratory. This length is 103% of the depth penetrated into the lunar surface.

Listings of sample depth and mass of overburden *by sample number* are available from the Lunar Sample Curator, SN2, Johnson Space Center, Houston, Texas 77058.

Core section	Depth below surface of top of core section (cm)	Core section length (cm)[a]	Core section weight (g)	Density (g/cm^3)[b]	Wt. of overburden at top of section (g/cm^2)
15006	0.0	40.7[c]	210.6	1.58	0.0
15005	40.7	41.0[c]	239.1	1.78	64.43
15004	81.7	40.1[c]	227.9	1.74	137.59
15003	121.8	39.3	223.0	1.74	207.31
15002	161.1	39.2	210.1	1.64	275.54
15001	200.3	36.9	232.8	1.93	339.82
Totals		237.2 ± 1.2	1343.5 ± 4.8	1.73 (average)	411.04 ± 1.5

[a]Linear capacity of tubes 15002–15006 was 39.9 cm each. Capacity of 15001 was 42.5 cm.
[b]Core tube diameter was 2.04 cm.
[c]Soil length expanded into joint because hollowed out plug was used.

Because of these difficulties, the drilling procedure as seen in the videotape is summarized. The first 80 cm was taken at a very fast drilling rate of 150 cm/min (drilling rates calculated by L. G. Bromwell, pers. comm. from W. D. Carrier, III). Afterwards the astronaut held back on the drill and the rate slowed to 70 cm/min. The bottom 60 cm was drilled a little more slowly than the middle section. When the drilling was completed, the drill stem penetrated 224 ± 3 cm into the regolith, and there was about 18 cm of drill stem still protruding up on the lunar surface (Carrier, 1974). The top end was capped before the core was jacked out. A loss of <1 cm occurred from the bottom of the drill before it was capped. This was deduced from the void in the bottom of the bit observed in the laboratory. The hole from which the drill was extracted was measured to be 218 cm deep. This was done by dropping the heat flow probe into the hole. Then the core was placed horizontally on the back of the Lunar Roving Vehicle where only the lower half of the drill remained within the view of the television camera. A wrench was used to separate 60001-4 from 60005-7 with a slight but definite jerk. A cap was placed on the top of 60004. Loss of soil was noted by Astronaut Duke at this point. He later clarified that the amount he noticed spilled was only a few milligrams. In a review of the TV recordings John Young did not appear to be observing this part of the procedure as indicated in the crew debriefings reported by Carrier (1974). Duke then capped the bottom of 60005. Both halves of the core were reported to have remained horizontal until capped (Carrier, 1974).

The lower half of the core, 60001–60004, was returned as one piece completely full of soil. The upper half, 60005–60007, was also returned as one piece, but with substantial voids. The 77.3 g in 60005 was distributed along the length of the core tube. Soil in 60006 extended from the top down to 32 cm in the section. The 60007 soil extended from the bottom upward to 22 cm. Figure 2 shows the soil distribution.

Carrier (1974) describes 3 scenarios to account for the voids. Briefly these are:

1. The top of the core sample did not move from its initial position—implying 100% recovery. (There was 18 cm of drill stem exposed when the drilling was completed, and the top of the soil column was found to be 18 cm below the top of the drill stem.) Then when the two halves of the drill stem were separated, soil fell out of the bottom of 60005.
2. This scenario also proposed 100% recovery, but surmises that the soil fell out of the bottom of 60001 (the bit) when the drill was powered in place briefly to clear the flutes of soil and to allow for easier extraction of the core.

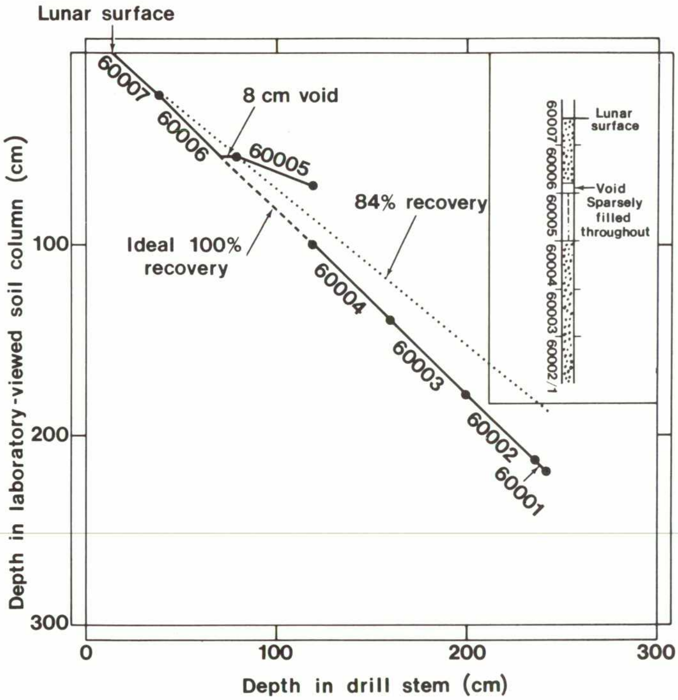

Fig. 2. Apollo 16 drill core depth relationship. Solid line data points determined at top of each core tube section (e.g., 60007, 60006). Data for 60004–60001 are accurate. The discontinuity between 60005 and 60004 may be due to a combination of poor recovery and loss of sample from the bottom of 60005. An 8 cm void was found in the bottom of 60006, and 60005 was only partially filled throughout its length. Dashed line represents 100% recovery with no sample loss. Dotted line represents alternate view that 84% recovery was operational throughout length of core. Insert shows distribution of soil and voids as observed in the laboratory and the position of the drill stem with respect to the lunar surface as observed on the moon. After style of Carrier, 1974.

3. A poor recovery resulted in a total soil column length of only 195 cm according to Carrier's third scenario. After the top half of the core was capped, soil migrated upward in the stem to its final position.

Carrier finds 100% recovery inconsistent with the high penetration rate of the drill. He also gives supporting and detracting evidence for each scenario, some of which is repeated in this paper.

Before these three scenarios are re-analyzed, some unpublished information obtained from dissection and some recent observations of the drilling hardware will be mentioned.

Some features were observed in the soil in 60006 and 60007 that are concerned with soil movement. A region in the lower part of 60007 and a region in the upper part of 60006 show laminar stratigraphic structures indicating that the soil was not greatly disturbed. Migration of soil in these two regions, if it occurred, must have happened as a plug of soil. Movement of this type was evident in the Apollo 17 drill core.

Knowing exactly how far the soil column was pushed up into the hardware by drilling action would yield a per cent recovery excluding spillage losses. Uel S. Clanton and the authors examined the interior surface of the now empty drill stems under a binocular microscope. Due to the great hardness and the surface roughness of the milled bore in the titanium alloy, no scratches or polishing resulting from the rotary-percussion action on the soil in the tubes was observed.

Scenario 2 is discarded because the hole was maintained to the 218 cm depth and because soil in 60003 was packed tightly enough to adhere to the "lid" half of the core tube removed after milling.

It seems unlikely that the full 168 g spilled unnoticed from the bottom of 60005 as in scenario 1, but the possibility exists for significant loss of soil. Likewise, because of the cohesive nature of the lower half of the drill core and soil densities resembling those in Apollo 15 and 17 drill cores, it seems unlikely that a poor recovery of 84% would be operational in the bottom half of the core.

The favored hypothesis is that soil in sections 60001–60004 represents 100% recovery in place at the bottom of the drill string. The "missing" 168 g of soil was most likely lost by a combination of spillage from the bottom of 60005 and a very poor recovery (about 50%) in the upper two sections where the drilling rate was extremely fast. Conditions for a poor recovery may be seen in porosity calculations and self-recording penetrometer data (Mitchell *et al.*, 1973a). (Relative density, not porosity, controls the mechanical behavior of soil as reported in Carrier *et al.*, 1973, but relative density calculations were not done for Apollo 16. Since composition, size, morphology, and environment of soil grains are similar for all lunar landing sites, high porosity probably indicates low relative density.) The porosity of the upper 5–10 cm of soil at Apollo 16 intercrater areas is higher than other missions based on footprint analyses (Mitchell *et al.*, 1973a). The self-recording penetrometer data taken within 22 m of the drill core indicate a soft surface layer about 10 cm thick and a second soft layer 15–20 cm thick within 50 cm of the surface. The force required to penetrate the deeper soft layer was only three-fourths of that required for the firmer layer above it (Mitchell *et* *al*., 1973a). These hard and soft layers may reflect changes in relative density of the soil (they may also reflect other characteristics such abundance of larger rock fragments). Similar hard/soft layers probably occur at the Apollo 16 drill core site. Two lines of evidence suggest that the same layers indicated in the penetrometer tests may extend to the drill core site. First, the penetrometer-defined layers can be correlated in a 3 point traverse toward the drill core site (Mitchell *et al*., 1973a), and second, petrographic composition in 60006–60007 correlates with layers observed in the upper part of nearby (30 m distant) drive tubes 60009–60010 which extend to 60 cm depth (J. S. Nagle, pers. comm.).

The idea of loss by both spillage and poor recovery results in an unknown loss of soil from the bottom of 60005, and the location of losses from poor recovery in the core above this point is also unknown (recovery varies with relative density). Therefore, the linear depth of the top of 60004 was arbitrarily set as 102.2 cm below the lunar surface (calculated by a soil length in 60007 of 22.4 cm and 39.9 cm each for 60005 and 60006). Depths below this point were calculated from soil weights and lengths observed in the laboratory. This relationship is illustrated in Fig. 2 and Table 3.

Table 3. Depth scale for Apollo 16 drill core.

The soil column length as viewed in the laboratory was only 84% of the depth penetrated into the lunar surface. This deficit in recovery was compensated for between 60004 and 60005.

Listings of sample depth and mass of overburden *by sample number* are available from the Lunar Sample Curator, SN2, Johnson Space Center, Houston, Texas 77058.

Core section	Depth below surface of top of core section (cm)	Core section length (cm)[a]	Core section weight (g)	Density (g/cm^3)[b]	Wt. of overburden at top of section (g/cm^2)
60007	0.0	22.4	105.7	1.44	0.0
60006	22.4	32.0	165.6	1.58	32.34
60005	54.4	14.6[c]	77.3[d]	1.62	83.00
missing soil	69.0	33.2[e]	168.2	1.55[f]	106.65
60004	102.2	38.3	202.7	1.62	158.09
60003	140.5	39.5	215.9[g]	1.67	220.13
60002	180.0	35.8	211.8	1.81	286.15
60001	215.8	5.5	30.1	1.67	350.95
Totals		221.3 ± 1.4	1177.3 ± 6.4	1.63 (average)	360.16 ± 2.0

[a]Linear capacity of tubes 60007–60003 was 39.9 cm each. Capacity of 60001 + 60002 was 42.5 cm.

[b]Core tube diameter was 2.04 cm.

[c]Since the smaller amount of soil in 60005 was distributed along the whole length of the tube, the density of 60004 was assumed, and the sample length was calculated.

[d]Wt. revised after dissection when flight hardware was reweighed, previous wt. was 76.1 g.

[e]Length calculated to equal void space observed in 60005–60006.

[f]Density is average for top three sections.

[g]Wt. revised in Lunar Curatorial Laboratory after reweighing gross wt. Lunar Receiving Laboratory reported wt. was 215.5 g.

A complex scheme to apportion the "missing" weight along the top 3 sections was not attempted since guesswork is involved. The missing weight was simply compensated for between 60005 and 60004. This should give good depths for 60004 and below, and the user should be aware of the problems connected with depths given for 60005–60007.

In looking forward to better resolution of the problems with the Apollo 16 scale, it is interesting to note how some radionuclide data plot on another scale. Imamura *et al.* (1974) plotted ^{53}Mn data on a depth scale by Russ (1973) which is very similar to the one proposed here and compensates for missing soil between 60005 and 60004. These data do not fit the theoretical production curve for cosmic ray produced nuclides of Reedy and Arnold (1972) as well as when these data are plotted on a scale based on 84% recovery linearly distributed throughout the core as shown in Fig. 3. Carrier proposed this depth relationship in 1973. Experimental work needs to be done to show support for or disprove this relationship.

APOLLO 17 DRILL CORE

Mitchell *et al.* (1973b) estimated that the drill stem penetrated 305 ± 1 cm. The estimate agrees well with crew comments in the geologic transcript that the core

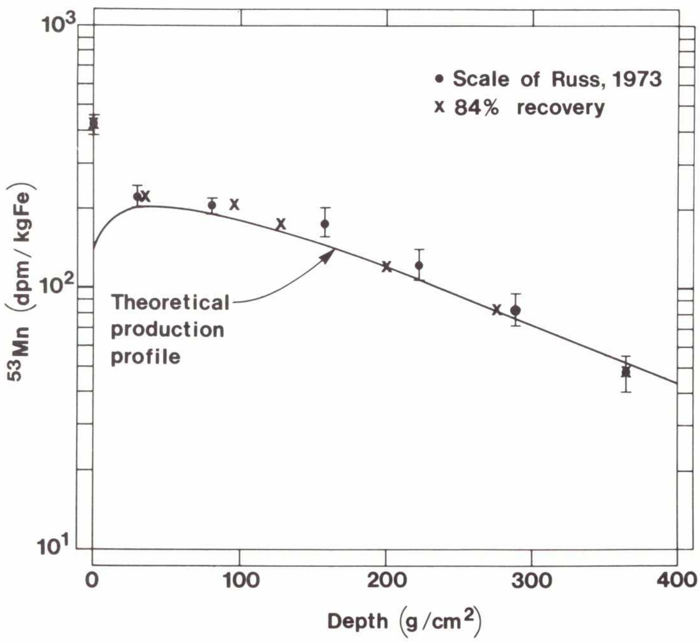

Fig. 3. ^{53}Mn data on Apollo 16 drill core depth scale of 84% recovery. ^{53}Mn data and theoretical production profile are plotted on a scale by Russ (1973) as published by Imamura *et al.* (1974). The Russ scale presumes that 180 g fell out of the bottom of 60005. The same data are also shown on a scale which assumes 84% recovery of soil throughout core length.

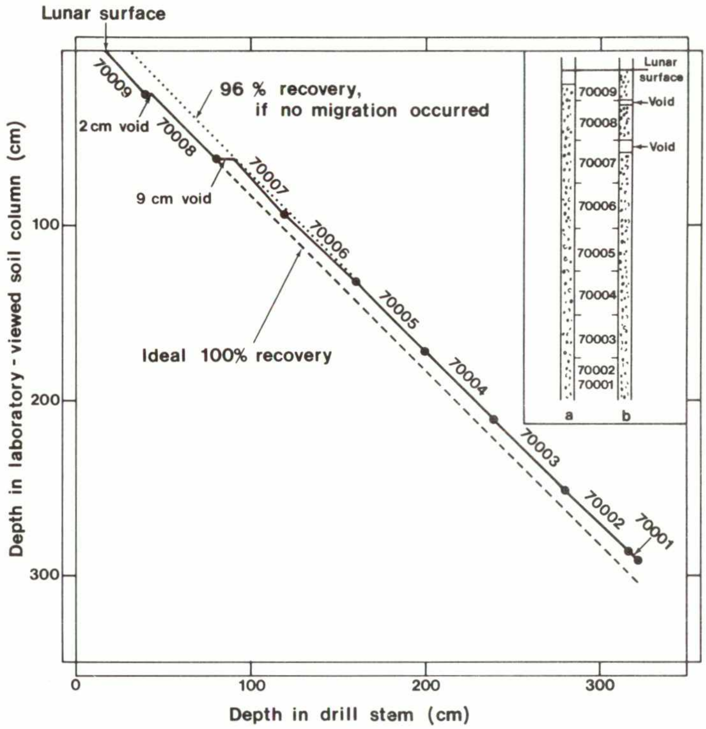

Fig. 4. Apollo 17 drill core depth relationship. Data points determined at top of each core tube section (e.g., 70009, 70008). Dotted line near top of core indicates the expected soil relationship for 96% recovery if no migration had occurred. Offset curve near top of core depicts voids left by migration of soil toward top of core during transport to laboratory. Dashed line represents ideal 100% recovery. Insert shows position of drill stem with respect to lunar surface as observed on moon. Insert (a) shows deduced *in situ* soil position in tube, and (b) shows position of soil as viewed in the laboratory.

penetrated to within an inch of the white stripes painted on the 70009 core tube and based on measurement of flight hardware. A soil column length of 292 ± 2 cm was determined from how far the plug was pushed into the top of the drill core (Mitchell *et al.*, 1973b). The rammer-jammer pushing the plug was inserted two-thirds of its length before the surface of the soil was encountered (Bailey and Ulrich, 1975). The apparent recovery (96%) does not include uncertainties about where the actual surface was during drilling or to the effects of drilling on the compaction or expansion of soil in the tube. The crew noted that about 3–5 mm had fallen out of the bottom of the core (Bailey and Ulrich, 1975).

In the laboratory, measurement of the soil column length was not a straightforward procedure because of soil movement during transfer from the moon. The astronaut measured a 30 cm void space in the top of the drill stem after drilling was completed and pushed a teflon plug in the tube to hold the soil in place. The drill stem was broken down into 3 pieces on the moon for transport to earth, and tubes 70007, 70008, and 70009 were returned as one unit. The position of the soil part of the core is missing, but evidence indicates that only the upper half of the core has been disturbed. Therefore, the scale for the bottom half of the core probably represents *in situ* lunar conditions.

3. There were voids in the upper part of the Apollo 17 drill core. The lengths of the voids within the stem equals the length of the core tube protruding above the surface when the drilling was completed. Thus, the voids are explained by sample migration in the tube, and the scale for the core closely represents *in situ* lunar conditions.

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