APOLLO DRILL CORE DEPTH RELATIONSHIPS

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Abstract. Preliminary depth relationships are presented for the Apollo 15, 16 and 17 drill core samples. For a given depth in any of these drill stems, the *in situ* lunar surface depth can be estimated. Ranges of uncertainty are also established, based on percent core recovery and degree of sample disturbance. The most likely explanation for the sample disturbance observed in the top three sections of the Apollo 16 drill stem is sample migration after the stem was capped on the lunar surface; essentially no sample was lost. Similar disturbance occurred in the Apollo 17 drill core, although to a lesser degree. The average original bulk densities (i.e., before any disturbance occurred) of the Apollo 15, 16 and 17 drill cores are 1.76, 1.59, and 1.87 g cm^{-3}, respectively. The Apollo 15 and 17 values are probably close to the *in situ* values; but the Apollo 16 average *in situ* density could be as much as 13% less than the already low density in the drill core.

1. Introduction

The three deep drill cores recovered on the Apollo 15, 16 and 17 missions to the Moon are among the most valuable of all the returned lunar samples. Representative of the top 2 to 3 m of the lunar surface, and totalling more than 4 kg, these samples are extremely important to studies of regolith dynamics and stratigraphy, solar wind flux and composition, neutron flux, cosmic-ray track densities, thermolominescence, and other disciplines. The history of the lunar surface for the last 500 m.y. is recorded in these cores. Knowledge concerning the true depth in the lunar surface from which an element of core sample originated is a fundamental requirement to each of these studies.

Depth relationships have previously been developed for the Apollo 11, 12, 14 and 15 drive tubes (Carrier *et al.*, 1971, 1972), based on full-scale laboratory simulation tests involving stratified soil columns. Preliminary drill tests were also performed which demonstrated that preservation of *in situ* stratigraphy in the core is excellent, despite the agitation of the stem as it is advanced into the soil under a rotary-percussion action (280 rpm and 2270 blows/minute at 40 in-pounds/blow). Full-scale drill tests similar to the drive tube tests are necessary to determine quantitatively the depth relationships for the drill cores. As these tests will not be performed any time in the near future, the purpose of this paper is to provide an interim approximation of the Apollo drill stem depth relationships based on extrapolation of the previous simulation studies.

2. Apollo 15 Drill Core

The Apollo 15 drill stem consists of six sections. Each section, when full, contains 39.9 cm of sample, except for the bottom-most, or bit-end, stem which contains

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TABLE I

Apollo 15 drill core sample data

	NASA sample No.	Returned sample weight (g)	Returned sample length (cm)	Returned[a] bulk density (g cm^{-3})	Original sample length (cm)	Drill[c] stem depth (cm)	Percent[d] core recovery
Returned configuration	{ 15006	210.6	39.9	1.62	39.9		
	{ 15005	239.1	39.9	1.84	39.9		
	{ 15004	227.9	39.9	1.75	39.9		
	15003	223.0	39.9	1.79	39.9	236 ± 1	102 to 103%
	15002	210.1	39.9	1.62	39.9		
	15001	232.8	37.0[b]	1.93	42.5[b]		
	Total	1343.5			242.0		

[a] Based on a sample diameter of 2.04 cm.
[b] Approximately 5.5 cm fell out bottom of drill stem on lunar surface.
[c] Maximum depth of drill stem in lunar surface.
[d] Total original sample length: drill stem depth.

42.5 cm; the total assembled length is 242.0 cm. The sample was taken at Station 8 at the Hadley-Appenine landing site, as shown in Swann *et al.* (1972). The stems have been individually X-rayed and dissected and the stratigraphy of the core sample is described in great detail in Heiken *et al.* (1972, 1973). The sample weights and lengths for each of the sections is presented in Table I.

The penetration depth of the Apollo 15 drill stem, as with Apollo 16 and 17, is less than the full length of the stem: the astronauts always leave several centimeters remaining above the lunar surface to facilititate removal of the stem from the soil. At the completion of drilling, the top of the Apollo 15 core sample inside the stem was actually 6 ± 1 cm above the surrounding surface, unlike the other cores, which were below the surface. In fact, the Apollo 15 drill stem was filled to the top with sample. Consequently, the percent core recovery (= total original sample length: drill stem depth) is 102 to 103%. As discussed in Carrier *et al.* (1972), this very high recovery would only be expected if the soil were at a very high relative density (cf. Carrier *et al.*, 1973, for a discussion of relative density), which is consistent with the observed low rate of drill penetration. The fact that the recovery actually exceeds 100% (perfect sampling) suggests the possibility that the soil de-densified 2 to 3% from the *in situ* values, although this is not necessarily the only explanation. In any case, the results from the earlier drill tests indicated that a high percent core recovery has three very important inter-related implications: First, the depth relationship must be close to one-to-one. Second, the sample densities in the stem are probably within $\pm 2\%$ of the *in situ* densities. And third, virtually all of the mass of the soil that was initially in the path of the drill stem was recovered.

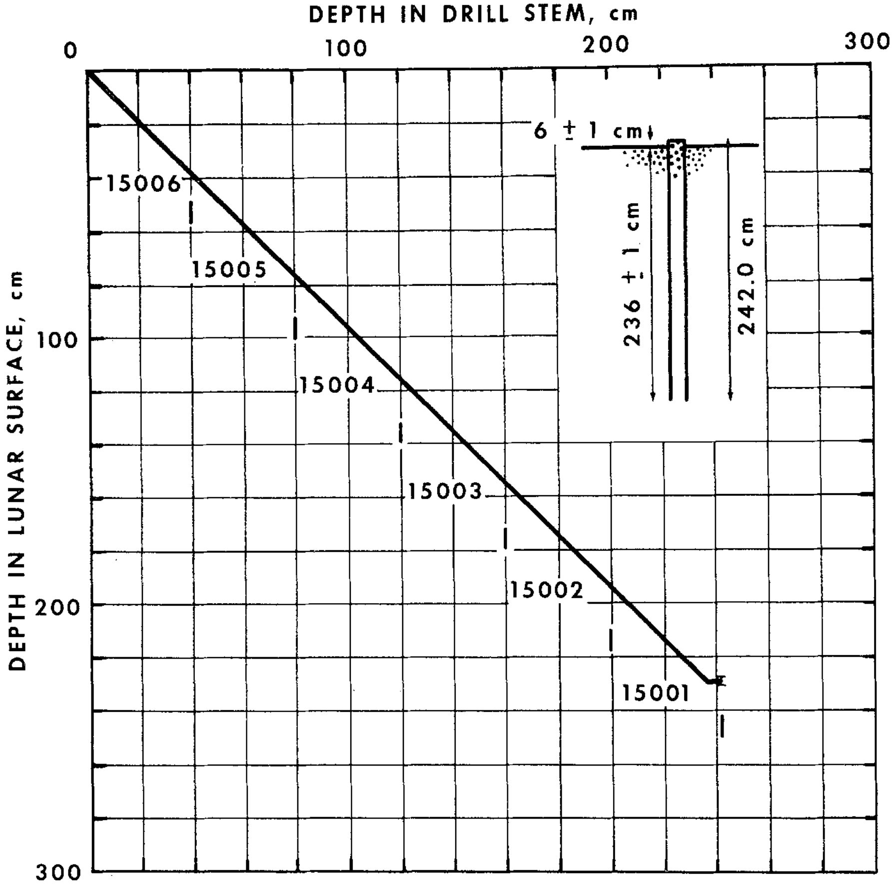

Fig. 1. Apollo 15 Drill Core Idealized Depth Relationship. Sample numbers for each of the drill stem sections are shown next to the depth relationship curve. The inset indicates the stem and core dimensions at the conclusion of drilling on the lunar surface. See text for discussion of range of uncertainty.

The depth relationship for the Apollo 15 core sample is shown in Figure 1. The top of the lunar surface occurs at the top of the drill stem; consequently, the relationship begins at the origin. At the bit-end of the stem, 242.0 cm from the top, the drill is assumed to have recovered sample from the maximum penetration depth of the drill stem in the lunar surface: 236 ± 1 cm. A straight line connects these two points, with a small jog to account for the $\sim$5.5 cm of material which evidently fell out of the bit when the stem was being recovered and dis-assembled on the lunar surface. The sample numbers for each of the sections are also shown. The range of uncertainty for this depth relationship curve is estimated to be $+2$ to -5%. The range of uncertainty is biased in the negative direction, as it has been observed that the maximum depth in the lunar surface from which sample is recovered generally tends to be slightly less than the maximum depth of penetration of the drill stem, and this difference increases with increasing depth of penetration. There is an additional uncertainty of ±0.5% to account for the ±1 cm uncertainty associated with the drill stem depth. For example, if a sample comes from a depth of 200 cm in the stem, the corresponding lunar surface depth of 195 cm is accurate within +4.9 to −10.7 cm.

3. Apollo 16 Drill Core

The Apollo 16 drill stem also consists of six sections, again with a total assembled length of 242.0 cm. The sample was taken at the ALSEP area at the Descartes landing site, as shown in Muehlberger *et al.* (1972). The stems have been individually X-rayed and dissected and a preliminary stratigraphy is described in Hörz *et al.* (1972). The sample weights and lengths for each of the sections is presented in Table II.

The X-radiography of the upper three stems (which were returned as a unit) immediately indicated that the sample had undergone some disturbance: the top section is half full; the second section is nearly full, with a 5-cm long void at the bottom; and the third section is nearly empty, with what sample it does contain strewn along its length. Three possible scenarios were initially advanced to account for the condition of the sample in the drill stem.

The first scenario proposes that the top of the core sample has not moved from its present position since drilling was completed on the lunar surface. The initial over-all sample length would then be 224.3 cm, implying an initial core recovery of 100%. Then, when the drill stem was separated into two three-section lengths by Astronaut Duke for return to Earth, some sample fell out of the bottom of the upper three sections and was lost. The amount of material presumably lost can be computed by assuming the original density of the soil in the third section was 1.5 g cm^{-3} and then calculating how much volume the remaining 76 g would have occupied in the third section and the bottom of the second section. The gap in the core recovery thus computed is approximately 29 cm. This scenario was prompted by a remark made by Astronaut Young on the lunar surface when he cautioned Astronaut Duke about losing some sample during separation of the sections. After the mission, when the crew was debriefed, they explained that the amount of material lost from the drill stem was in fact only a few particles and they considered it to be negligible. What is more, Astronaut Duke did not move the top three sections from the horizontal position on the back of the Lunar Roving Vehicle until after he had capped both ends, so that there was no opportunity for significant spillage to occur unnoticed. Finally, the drill rate observed at this site was considerably higher than at the Apollo 15 site, implying a lower relative density (Mitchell *et al.*, 1972). The drill simulation tests previously discussed indicated that a core recovery of 100% only occurs at a very high *in situ* relative density. Consequently, this scenario is considered to be unlikely.

The second scenario also proposed that the initial core recovery was 100%, but that the sample fell out when the drill was powered on briefly to help extract it from the lunar surface. This implies that the missing 29 cm of soil occurs at the bottom of the drill stem rather than near the middle. This scenario was proposed because similar

TABLE II

Apollo 16 drill core sample data

NASA sample No.	Returned sample weight (g)	Returned sample length (cm)	Returned bulk density (g cm^{-3})	Original[b] sample length (cm)	Original[b] bulk density (g cm^{-3})	Drill stem depth (cm)	Percent core recovery
Returned configuration							
60007	105.7	22.2 ± 0.5	1.46 ± 0.03	empty			
60006	165.6	35.5 ± 0.5[a]	1.43 ± 0.02	33.1 ± 5	1.47 ± 0.10		
60005	76.1	disturbed		39.9			
60004	202.7	39.9	1.56	39.9	1.56	224 ± 3	84 to 90%
60003	215.5	39.9	1.66	39.9	1.66		
60002	211.9	42.5	1.75	42.5	1.75		
60001 (bit)	30.1						
Total	1007.6			195.3 ± 5			

[a] Approximately 4.5 cm void at bottom.
[b] Corrected according to third scenario in text.

behaviour had been experienced in some early simulation tests. However, as with the first scenario, 100% core recovery is inconsistent with the higher penetration rate. Furthermore, Astronaut Duke dropped a long thin rod down into the open core hole in the lunar surface after the drill stem had been extracted. The rod came to rest within 6 cm of the bottom of the hole, indicating that 29 cm could not have fallen out of the bottom of the drill stem. Finally, the fact that no voids are observed in any of the bottom three sections of the drill stem argues against such a mechanism having occurred. Consequently, this scenario is also considered to be unlikely.

The third scenario proposed that the gap occurred after the top three-section stem was capped on the lunar surface. Subsequent vibrations and accelerations are presumed to have caused the top of the sample to migrate 29±5 cm up the stem to its present position. The original over-all sample length would then be 195.3±5 cm. This

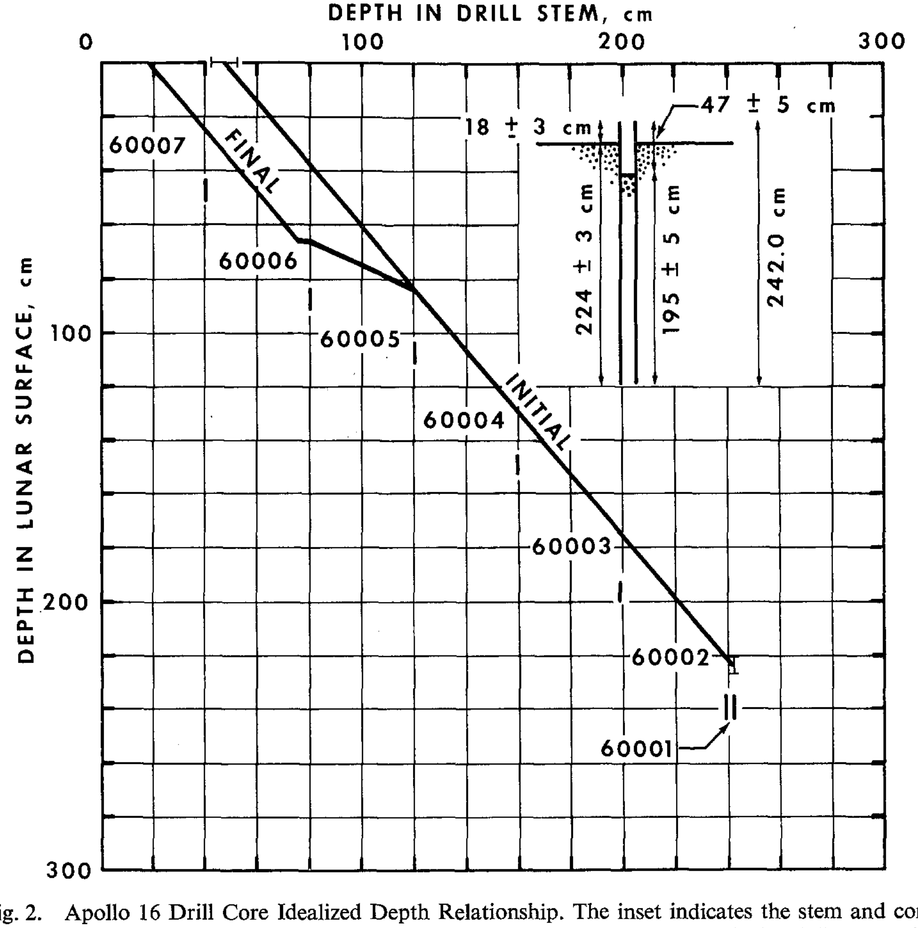

Fig. 2. Apollo 16 Drill Core Idealized Depth Relationship. The inset indicates the stem and core dimensions at the conclusion of drilling on the lunar surface, corresponding to the 'Initial' curve. The 'Final' curve is the depth relationship for the drill core sample as returned to the Lunar Receiving Laboratory, based on the third scenario described in the text. See text also for discussion of range of uncertainty.

scenario results in an initial core recovery of approximately 87%, which is consistent with the lower relative density. Furthermore, the phenomenon of sample migration unambiguously occurred with the Apollo 17 drill core sample, as will be described in the following section. Consequently, this scenario is considered to be the most likely.

The depth relationship based on the third scenario is shown in Figure 2. The 'Initial' curve is the depth relationship before any disturbance occurred. The top of the lunar surface originally occurred at a depth of 47 ± 5 cm from the top of the drill stem; at the bit-end of the stem, the drill is assumed to have recovered sample from the maximum depth of the drill stem: 224 ± 3 cm. Again, a straight line connects these two points. The 'Final' curve is the depth relationship for the drill core sample as returned to the Lunar Receiving Laboratory. It is produced by shifting the curve for the upper two sections to the left 29 cm, parallel to the Initial curve, including a jog of 5 cm to account for the void at the bottom of the second section, and adding a straight line representing the third section joining the Final and Initial curves together at the top of the fourth section.

The range of uncertainty for the Apollo 16 drill core depth relationship is considerably more complicated than that of the Apollo 15 drill core. Even if there had been no disturbance, the Initial curve would be subject to a larger uncertainty due to the lower relative density. As noted above, the implied initial core recovery is 87%. One possibility is that the soil in the core was uniformly compressed 13% all along the stem, so that the *in situ* densities are significantly less than those shown in Table II. Another possibility is that the density remained unchanged but that 13% of the mass of the soil in the path of the drill stem was just not recovered. (For those investigators who require the total mass originally overlying a given element of sample, rather than its true depth of burial, it is important to realize that not all of the mass was necessarily recovered in the Apollo 16 drill stem.) Yet another possibility is that the recovery was 100% to a depth of 195 cm, but that below that depth no additional sample entered the drill stem, resulting in an overall recovery of 87%. Each of these are extreme possibilities; what actually happened is probably a combination of the three phenomena. Without additional knowledge, it is necessary to assign an uncertainty of 0 to -10% for the Initial curve, in addition to $\pm 1.5\%$ to account for the ± 3 cm for the drill stem depth. That is, a sample from a depth of 200 cm in the drill stem corresponds to a depth in the lunar surface of 176 cm within $+2.6$ to -20.2 cm.

The uncertainty for the Final curve for the top two drill sections is $+10$ to -20% to account for the additional sample disturbance. A sample from a depth of 60 cm in the drill stem corresponds to a depth in the lunar surface of 49 cm within $+4.9$ to -9.8 cm. The soil in the third section may be totally homogenized and therefore a sample from anywhere in this section could be representative of the lunar surface from a depth of 67 cm ($+6.7$ to -13.4 cm) to 85 cm ($+1.3$ to -9.8 cm); i.e., from 43.6 to 86.3 cm.

4. Apollo 17 Drill Core

The Apollo 17 drill stem was longer than the two earlier stems, consisting of eight

TABLE III

Apollo 17 drill core sample data

Returned configuration	NASA sample No.	Returned sample weight (g)	Returned[a] sample length (cm)	Returned bulk density (g cm^{-3})	Original[e] sample length (cm)	Original[e] bulk density (g cm^{-3})	Drill stem depth (cm)	Percent core recovery
	70009	143.3	25 ± 2	1.76 ± 0.14	10 ± 2			
	70008	260.9	38[b]	2.11	39.9	1.99 ± 0.05		
	70007	179.4	34 ± 2[c]	1.62 ± 0.10	39.9			
	70006	234.2	39.9	1.80	39.9	1.80		
	70005	240.6	39.9	1.85	39.9	1.85	305 ± 1	95 to 97%
	70004	238.8	39.9	1.84	39.9	1.84		
	70003	237.8	39.9	1.83	39.9	1.83		
	70002	207.7	42.0[d]	1.74	42.5[d]	1.74		
	70001 (bit)	29.8						
	Total	1772.5			292 ± 2			

[a] Measured from X-radiographs; subject to change when the sections are opened later.
[b] Approximately 2-cm void at top.
[c] Approximately 6-cm void at top.
[d] Approximately 0.5 cm fell out bottom of drill stem on lunar surface.
[e] Corrected as described in text.

sections with a total assembled length of 321.8 cm. The sample was taken at the ALSEP area at the Taurus-Littrow landing site, as shown in Muehlberger *et al.* (1973a, b). The stems have been individually X-rayed and dissection of the core samples is taking place now. A detailed stratigraphy will be available later. The sample weights and lengths for each of the sections is presented in Table III.

After the experiences with the Apollo 16 drill core, teflon plugs were added to the Apollo 17 mission, which were to be inserted into the top and bottom of the drill stem after the drilling was completed. The purpose of these plugs was to prevent the sample from moving and therby to preserve its integrity. The plug for the bottom of the stem was not necessary, as the stem was full to within 0.5 cm of the end. The plug for the top of the core fell into the stem so easily that it was obvious that insufficient friction existed between the plug and the inside of the drill stem. Astronaut Cernan attempted to set the plug against the soil column by pushing it down with one of the handtools, but when the drill stem was returned to the Lunar Receiving Laboratory, the plug was found to have migrated back to the top of the stem and the sample had clearly moved up inside the upper three-section stem. The resistance of the plug to movement in the drill stem has subsequently been tested by the designers and adequate friction was measured, comparable to the friction measured before the mission. Previous experience with teflon plugs had led the designers to expect that, if anything, the plug would expand on the lunar surface and thereby exert even greater resistance. Unaccountably, the opposite occurred.

Nonetheless, it was possible to measure the insertion depth of the handtool into the drill stem, and therby to determine the initial depth of the sample in the core: 30 ± 2 cm. This implies an initial core recovery of about 96%, which is consistent with the lower drill rate, similar to the Apollo 15 site (Mitchell *et al.*, 1973).

The depth to the sample in the core as returned to the Lunar Receiving Laboratory is 15 ± 2 cm (error due to parallax in the X-radiographs), indicating that the top of the sample moved 15 ± 4 cm after the teflon plug was inserted on the lunar surface. Gaps of 2 and 6 ± 2 cm have been observed in the X-radiographs at the tops of the second and third sections, respectively, for a combined void of 8 ± 2 cm. Therefore, these gaps could possibly account for nearly all of the observed movement, implying that the sample in the top three sections may have been only slightly disturbed.

The depth relationship for the Apollo 17 drill core sample is shown in Figure 3. The top of the lunar surface on the Initial curve occurs at a depth of 30 ± 2 cm from the top of the drill stem; at the bit-end of the sample, 321.8 cm from the top, the sample is assumed to have originated from a depth in the lunar surface of 305 ± 1 cm. The Final curve is produced by shifting the top section to the left to a depth of 15 ± 2 cm and including the gaps at the tops of the second and third sections. The Final curve joins the Initial curve at the top of the fourth section.

Since the core recovery is nearly 100%, the original bulk densities in the drill stem are probably very close to the *in situ* values, and the range of uncertainty in the Initial depth relationship curve is small: 0 to -5%, in addition to $\pm 0.5\%$ for the ± 1 cm for the drill stem depth. That is, a sample from a depth of 200 cm in the drill stem corre-

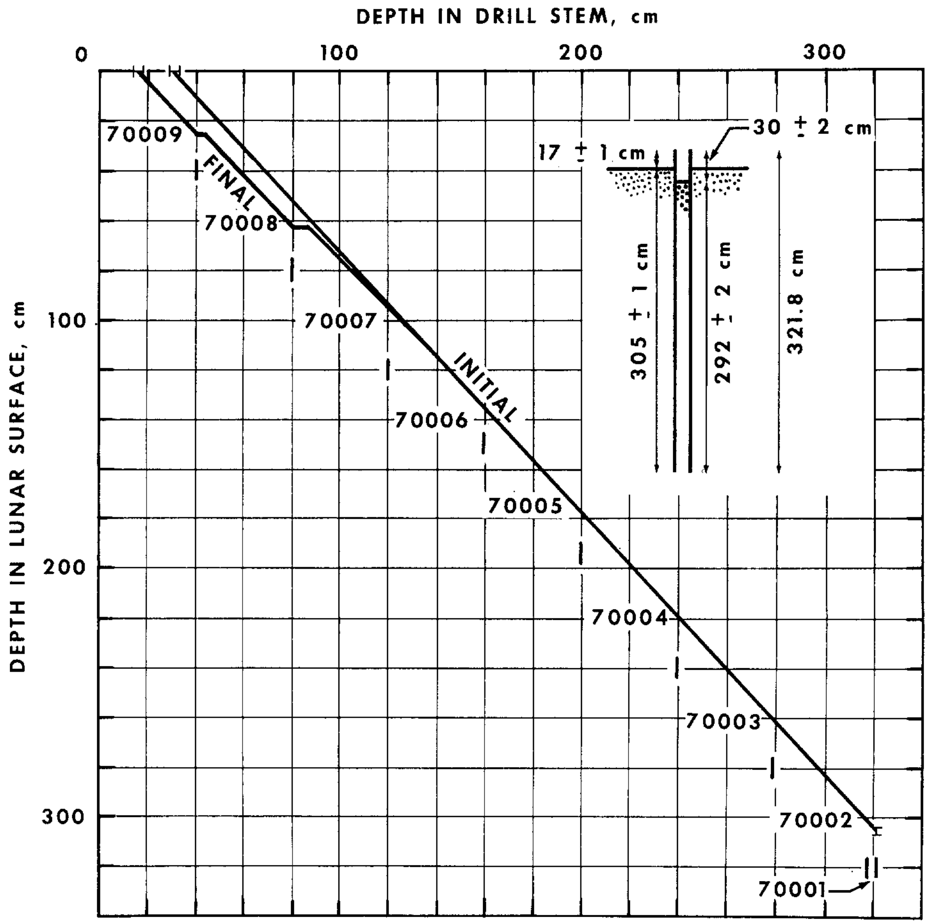

Fig. 3. Apollo 17 Drill Core Idealized Depth Relationship. Disturbance in the upper three sections of the Apollo 17 drill stem again occurred during return to Earth, but was less than in the case of Apollo 16. See text for discussion of range of uncertainty.

sponds to a depth in the lunar surface of 177 cm within +0.9 to −9.7 cm. The uncertainty in the Final curve for the top three sections is greater to account for the disturbance: +5 to −10%. A sample from a depth of 60 cm in the drill stem corresponds to a depth in the lunar surface of 43 cm within +1.7 to −4.3 cm.

5. Conclusions

Preliminary depth relationships have been developed for the Apollo 15, 16 and 17 drill stem samples. Samples from a depth of 200 cm in the respective drill stems correspond to *in situ* lunar surface depths of 184 to 200 cm, 156 to 179 cm, and 167 to 178 cm. The range of uncertainty for the Apollo 15 and 17 drill samples is small, due to the high percent core recoveries: 102% and 96%, respectively. The lower percent core recovery of Apollo 16 (87%) results in a slightly greater uncertainty.

The sample disturbance observed in the top three sections of the Apollo 16 stem has been attributed to sample migration inside the three-section length after it was capped on the lunar surface; virtually no sample fell out and was lost on the lunar surface. Nonetheless, the range of uncertainty is considerable: a sample from a depth of 60 cm in the drill stem corresponds to an *in situ* depth of 39 to 54 cm.

Sample migration also occurred in the top three sections of the Apollo 17 stem, although to a lesser degree. Consequently, the uncertainty is less than for the top three sections of the Apollo 16 stem: a sample from a depth of 60 cm in the Apollo 17 stem corresponds to an *in situ* depth of 39 to 45 cm.

The similar, high percent core recoveries at the Apollo 15 and 17 sites imply a similar, high *in situ* relative density, and consequently the original absolute bulk densities in these drill stems are probably very close to the *in situ* values. The Apollo 15 drill stem densities range from 1.62 to 1.93 g cm^{-3}, with an average of 1.76 g cm^{-3}; the original densities in the Apollo 17 stem range from 1.74 to 1.99 g cm^{-3}, with an average of 1.87 g cm^{-3}.

The original bulk densities in the Apollo 16 stem range from 1.47 to 1.75 g cm^{-3}, with an average of 1.59 g cm^{-3}. These densities are significantly less than either the Apollo 15 or 17 cores. Furthermore, the lower percent core recovery at the Apollo 16 site implies a lower *in situ* relative density, which may have resulted in sample compression during the coring process. Consequently, the *in situ* bulk densities may be as much as 13% less than the already low densities in the drill core.

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