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DETERMINATION OF HYDROGEN ABUNDANCE IN SELECTED LUNAR SOILS

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INTRODUCTION

With increasing interest in a lunar base, the need for utilizing the moon's resources is becoming more apparent. Future space activities will be enhanced if an extraterrestial source of hydrogen for propellants and consumables becomes available. Hydrogen has been implanted in lunar soil through solar wind activity (Becker, 1980). In order to determine the feasibility of utilizing this solar wind hydrogen, it is necessary to know not only hydrogen abundances in bulk soils from a variety of locations but also the distribution of hydrogen within a given soil. This study was undertaken to provide information about hydrogen distribution in bulk soils, grain size separates, mineral types, and core samples.

EXPERIMENTAL

Hydrogen was extracted from lunar soil by vacuum pyrolysis (Carr et al., 1987). Weighed lunar samples were placed directly into an alumina tube which was then attached to the sampling line and evacuated to a pressure of about $1x10^{-2}$ atm. Hydrogen was extracted by heating at 900°C for three minutes using a resistance wire furnace. The liberated hydrogen was injected directly into a gas chromatograph equipped with a 12 ft. Molecular Sieve 5A column and a helium ionization detector. In order to obtain a linear response for hydrogen, it was necessary to use a carrier gas containing an impurity. Helium containing 92 ppm nitrogen was used in this study.

The system was calibrated by injecting known amounts of hydrogen. This was accomplished by evacuating the sampling line and then filling this known volume with standard gas of hydrogen in helium to a given pressure, as measured by a capacitance manometer. The response was linear over the range 10 - 600 ng hydrogen.

RESULTS AND DISCUSSION

BULK SOILS

Hydrogen abundances were determined for 31 bulk soils, with at least one soil from each of the six Apollo exploration sites. The results are given in Table 1. Hydrogen concentrations of bulk soils ranged from 3.2 to 60.2 μg/g. A comparison of hydrogen abundances at different Apollo sites is given in Fig. 1.

McKay *et al.* (1972) measured soil maturity by the abundance of agglutinates and other reworked particles, the mean particle size, and other properties related to surface bombardment. Morris (1976) related maturity to a surface exposure index, I_s/FeO, based on the amount of Fe^{2+} in the soil which has been reduced to fine-grained iron particles by micrometeorite impact on the lunar surface. Based on these definitions of maturity, it would seem logical that concentrations of solar wind species would increase with increasing soil maturity. Studies have shown that this is indeed the case for certain solar wind gases (Charette et al., 1975 and Morris, 1976). Because the hydrogen in lunar soil is also derived from the solar wind, it would be expected to follow this same trend. In general, our results verified this. Fig. 2 shows the correlation between hydrogen abundance and soil maturity as measured by the I_s/FeO index for all Apollo 17 soils studied. Average hydrogen values for all immature, submature, and mature soils, as classified by Morris et al. (1983) were 10.8, 35.3, and 44.6 μg/g, respectively.

Only three of the soils studied had very low hydrogen content. Such low values would have been predicted because all three of these were very immature soils. Soil 61221,11, a subsurface soil from Plum Crater with abnormally coarse grain size, had a hydrogen concentration of only 3.2 μg/g. This soil contained only 6% agglutinates and had an I_s/FeO value of 9.2 (Morris et al., 1983). Sample 12033,467 also had a hydrogen concentration of 3.2 μg/g. It was collected from the bottom of a trench in Head Crater and had 17% agglutinates and an I_s/FeO value of 14.6 (Morris et al., 1983). Sample 74220, orange soil collected on the rim of Shorty Crater, had a hydrogen concentration of 3.3 μg/g. This is an extremely immature soil, with only 2% agglutinates and an I_s/FeO maturity index of 1. Some investigators consider this sample a friable clastic rock and not a soil (Morris et al., 1983).

The bulk soils having the highest concentrations of hydrogen were 75121,6 and 15261,16 with 60.2 and 58.2 μg/g, respectively. Both of these were mature soils with I_s/FeO values of 67 and 77, respectively. Soil 75121,6 had 63% agglutinates, the second highest value of any soil studied. Soil 15261,26 was also high in agglutinates with 50.5% (Morris et al., 1983).

Helium data were available for 20 of the bulk soils used in this study (Baur et al., 1972; Bogard and Nyquist, 1972; Bogard et al., 1974; Chang et al., 1974; Frick et al., 1973; Heymann and Yaniv, 1970; Heymann et al., 1972; Hintenberger and Weber, 1973; Hubner et al., 1975; Kirsten et al., 1972; Signer et al., 1977; Stoenner et al., 1974; Walton et al., 1973). The average $^{1}H/^{4}He$ atom ratio for these soils was 13. Stoenner et al. (1974) reported that spectroscopic measurements give a $^{1}H/^{4}He$ atom ratio of 12 to 20 for the sun. Solar wind ratios are often somewhat lower, usually from 7 to 10.

Signer et al. (1977) noted high noble gas concentrations in breccias and agglutinates. Through microscopic inspection of thin sections of several soil breccias, they confirmed that the constituents forming these composite materials were very fine-grained. Many of the breccias in our study had higher hydrogen concentrations than those of bulk lunar soils (FIG. 1 and Table 2).

DesMarais et al. (1974) studied the distribution of hydrogen with respect to soil particle types for six lunar soils. He found that agglutinates contained the most hydrogen of any particle type studied. In his two soils containing agglutinates, there was a considerable enrichment of hydrogen in the agglutinate fraction over that in the bulk soil. We found a similar enrichment in all but one of the ten hand-picked agglutinate size separates run in this study (Table 3). The amount of enrichment varied considerably from one soil to another. This enrichment is to be expected because agglutinates are constructional particles, built up by micrometeorite impact on the lunar surface. As the agglutinate particle gets larger, solar wind gas that had been implanted on the surface becomes imbedded within the particle, causing an overall enrichment of the solar wind species.

DesMarais _et al._ (1974) studied two very different lunar basalts, sample 15058,73, a porphyritic basalt with very few vugs or cavities, and sample 15556,56, a vesicular basalt. Both of these were very low in hydrogen. We studied 24 lunar basalt samples. As Table 4 shows, each of these samples had a very small hydrogen concentration.

GRAIN SIZE

Because most of the hydrogen in lunar soils has been implanted by solar wind, a marked surface correlation would be predicted. Smaller grain sizes would be expected to show larger hydrogen abundances because of the increase in the surface area to mass ratio, compared to large grains. Eberhardt _et al._ (1972) found such a correlation for the solar wind noble gases and showed that the grain size dependence of these gases can be described by the relationship $C \propto d^{-n}$ where C is the gas concentration in a grain size fraction with average diameter d, and -n is the slope in a log concentration versus log grain size plot. Several studies with noble gases have shown that not only is a surface correlated component present but that a volume correlated, grain size independent component is also evident (Eberhardt _et al._, 1972 and Schultz _et al._, 1977). The present study indicates a similar relationship between hydrogen abundance and grain size. Table 5 gives the hydrogen concentrations for each particle size for five lunar soils and a breccia. For each sample, the less than 20 μm grain size fraction was enriched by approximately a factor of three over the value obtained experimentally for the bulk soil. It can also be noted that a majority (from 59.4% to 87.4%) of the total hydrogen in each sample was found in the smallest grain size. Mass balance calculations showed good agreement between the calculated and the experimentally determined values of hydrogen concentration.

Fig. 3, showing the relationship between hydrogen concentration and grain size, clearly indicates both a grain size dependent, surface correlation and a grain size independent, volume correlated component for the six lunar samples studied. When log hydrogen abundance is plotted against log grain size, a linear relationship is seen for small grain sizes. Thus, solar wind implantation of hydrogen is definitely a surface phenomenon. However, as constructional particles such as agglutinates are built up from much smaller grains and surfaces which were originally exposed become buried inside the particles, gases which were implanted on surfaces become trapped inside the particles and a volume correlated component becomes evident for these large grains. This is shown graphically by a flattening of the curve for large grain sizes.

As illustrated in Fig. 3, the soil which showed the least amount of volume correlation for large grain sizes was Soil 71501,138. This soil was the most immature of all those used in the grain size study with an I_s/FeO value of 35 (Morris et al., 1983). This would indicate that this soil has not seen much micrometeorite action, resulting in fewer agglutinates and other constructional particles which would have trapped hydrogen during formation. This is verified by a soil composition study (Morris et al., 1983) which shows only 35% agglutinates in this soil.

Bogard (1977) noted that values of n for the noble gases increase with decreasing ease of gas retention. Hydrogen is not retained as readily as the noble gases (DesMarais et al., 1974). Fig. 4 shows that the average value of n for hydrogen for the five soils in the grain size study is higher than n for the noble gases, continuing the trend observed with the noble gases. Values of n greater than 1.00 indicate enrichment. The high value of n (1.55) for hydrogen in the breccia sample shows a considerable enrichment, compared to hydrogen in soil samples. This is consistent with the results obtained from the bulk breccia samples in which many showed unusually high hydrogen abundances.

CORE SAMPLES

The core samples are among the most important samples returned from the moon. The depositional and irradiational histories of the cores have provided useful information about earlier processes which have occurred in the lunar regolith.

Hydrogen data on the core samples provide a different kind of valuable information. First, core data show more clearly than bulk soil data the excellent correlation between hydrogen abundance and soil maturity. From each of the six cores studied, it is clear that hydrogen abundance could be used to predict soil maturity. Also, from a practical standpoint, if hydrogen is to be mined from the lunar surface, it is essential to have some idea about depth distribution.

APOLLO 15 DEEP DRILL CORE 15001 - 15006

This 242 cm long core was collected from the regolith developed on Palus Putredinis 50 m from the ALSEP central station. This core is believed to be representative of the regolith developed on the mare surface (Duke and Nagle, 1976).

There is considerable variation in soil maturity throughout the length of the core. This is reflected in the hydrogen concentrations found in the 20 samples examined from this core (Fig. 5). There is a pronounced decrease in both maturity as measured by the Is/FeO index and hydrogen abundance going down from the surface to about 40 cm. The per cent agglutinates is also much higher for this section and increases from 33% at 45 cm to 64% agglutinates at the top of the core. Several alternative explanations are possible (Heiken et al., 1976). This section may represent extensive in situ reworking of an originally submature soil. Another possibility is continuous accretion of a submature soil at decreasing rates so that each new soil layer has more surface exposure time than the previous layer. It is also possible that mature soils from nearby have been deposited on this site, causing the upper layer to be more mature than the underlying soils. The true explanation could be a combination of any of these possibilities.

The least mature soils are in the lowest section of the core. Agglutinate content drops down to less than 10% near the bottom (Heiken et al., 1976). Similarly, hydrogen concentrations drop off steadily going from 185 cm to the bottom of the core.

APENNINE FRONT CORE 15007/8

This double drive tube was collected on the northeastern flank of St. George Crater within the continuous ejecta blanket of a small crater (Bogard et al., 1982). Fig. 6 shows the resemblance between the hydrogen abundance and I_s/FeO profiles. The increase in hydrogen from the surface to 10 cm can be explained by the nature of the soils in this section (Nagle, 1980). Going down from the lunar surface to 6.5 cm, the soils are moderately light colored and coarse-grained. From 6.5 to 8.0 cm, the soils are darker and finer-grained, and the unit from 8.0 to 10.0 cm consists of fine-grained, dark soils. The most striking feature in both profiles is the sharp drop at about 49 cm. A discontinuity at this point was noticed during core dissection (Bogard et al., 1982).

APOLLO 16 DEEP DRILL CORE 60002 - 60007

This core was collected from the Cayley Plains near the ALSEP at Station 10. It provided the hole for the heat flow experiment probes (Fruland, 1981). The surrounding area was covered by ejecta from South Ray Crater. Some of the core material may also be from nearby older craters such as Palmetto, Spook, and Gator (Meyer and McCallister, 1977).

The profile of hydrogen abundance matches the I_s/FeO profile fairly closely for approximately the lower two-thirds of the core (Fig. 7). Gose and Morris (1977) suggested that the uppermost 13 cm were emplaced much later than the rest of the core. The lowest unit below about 190 cm contained the most immature soils in this core. This unit consisted of coarse-grained material (Meyer and McCallister, 1977) and probably was not exposed to the lunar surface for any significant time period (Gose and Morris, 1977). As would be expected, hydrogen concentrations for this unit were also low.

APOLLO 17 DEEP DRILL CORE 70002 - 70009

The Apollo 17 Deep Drill Core was taken from the dark mare soils of the Taurus-Littrow Valley about 400 m SE of Camelot Crater. This was the deepest soil column (~295 cm) returned from the moon (Vaniman and Papike, 1977). The I_s/FeO profile for the entire core shows a wide range of soil maturities. The correlation between hydrogen abundance determined in this study and soil maturity as measured by the I_s/FeO index is striking (Fig. 8). One of the distinctive features of this core is the immature zone between ~20 and ~60 cm. As expected, we found very low hydrogen concentrations in this zone. Proceeding down the core, soils became more mature, and larger hydrogen concentrations were found. Both of these results would have been predicted by observing the grain size distribution down the core (Langevin and Nagle, 1980). The section of the core where hydrogen was depleted (the bottom of 70009 through 70008) consists of coarse-grained, basaltic material. As mentioned earlier, gas concentrations are generally low in large grains. Also, basalts are typically low in hydrogen. The section where the largest hydrogen concentrations were found (the middle of 70006 down to the middle of 70005) is characterized by very small grain sizes.

Stoenner _et al._ (1974) measured hydrogen and helium on nine samples from this core. The numbers they reported for hydrogen included water, and they stated that their samples were contaminated with terrestial water. This explains the unusually high $^{1}H/^{4}He$ ratio they obtained. Using our hydrogen values and their helium values, the average $^{1}H/^{4}He$ atom ratio for this core was 8.5. This is in the expected range of 7 to 10 for the solar wind $^{1}H/^{4}He$ atom ratio.

SHORTY CRATER CORE 74001/2

The soil in the 74001/2 double drive tube collected on the rim of Shorty Crater during Apollo 17 is unusual because it is relatively homogeneous and consists almost entirely of orange and black glassy droplets. It is unusually cohesive and dense. Of all lunar samples studied, the 74001/2 soil below 4.5 cm is believed to have seen the least amount of surface exposure (Morris et al., 1978). These soils are extremely immature with I_s/FeO values ranging from 0.1 to 0.3. Eugster et al. (1979) found extremely small amounts of trapped noble gases in these soils.

The values obtained for hydrogen concentrations throughout the length of the core were extremely low and showed very little variation (Fig. 9). These values were very close to the hydrogen concentration found in the local surface soil 74220,20. Our core sample nearest the lunar surface was from the interval 6.5 - 7.0 cm. This was below the surface zone where the soils were slightly more mature. Thus, we did not see an enrichment of hydrogen anywhere along the core.

APOLLO 17 DOUBLE DRIVE TUBE 79001/2

The most recently opened core is the Apollo 17 Double Drive Tube 79001/2. This tube was collected about 70 m S of Van Serg Crater in the Taurus Littrow Valley (Schwarz, 1986). The striking physical feature of this core was a distinct dark-light boundary inclined 25 to 30 degrees from approximately 8.5 to 11 cm below the surface. Morris (1986) showed that the upper dark portion was distinctly more mature than the underlying light material. Fig. 10 shows a definite change in both soil maturity and hydrogen abundance at approximately the interface between the dark and light layers. Schwarz (1986) observed that in the upper dark gray portion, soil breccias and soil clods were the dominant particle types. In the lower light gray end of the core, basalt and glass particles were noticeably more prevalent. This may provide a partial explanation for the depth profile observed for hydrogen abundance. As mentioned previously, breccias typically had high hydrogen contents, and basalts were very low in hydrogen. The correlation between hydrogen and soil maturity as measured by the I_s/FeO index is excellent.

ENERGY CONSIDERATIONS

From an engineering perspective with a view toward utilizing lunar resources, it is important to consider the ease of recovering lunar hydrogen. Gibson and Johnson (1971) and Gibson and Moore (1972) found that solar wind hydrogen was released between 300°C and 700°C from several lunar samples. In this study we found that soil 10084,149 began to release hydrogen about 400°C but did not reach a maximum until about 900°C. One fact which should aid in recovering hydrogen from the soil is that hydrogen was evolved quickly rather than slowly permeating out of the sample. For example, all the hydrogen appeared to be released from a 10 mg soil sample in three minutes at 900°C. Breccias required a longer heating interval; however, all the hydrogen appeared to be released from a 10 mg sample in nine minutes at 900°C.

When lunar processing becomes a reality, facilities will be available for heating lunar soils to 900°C (Gibson and Knudsen, 1985). It might even be feasible to use a mobile microwave generator to produce _in situ_ heating of the upper layer of the lunar regolith (Tucker _et al._, 1985). However, collecting the hydrogen might be a potential problem with this technique.

CONCLUSION

Hydrogen was found in all samples studied. The amount varied considerably, depending on soil maturity, mineral types present, grain size distribution, and depth.

Hydrogen implantation is definitely a surface phenomenon. However, as constructional particles are formed, previously exposed surfaces become embedded within particles, causing an enrichment of hydrogen in these species.

In all the cores studied except one (which was from an area of very immature soil), hydrogen was distributed throughout the core in varying amounts. In view of possibly extracting the hydrogen for use on the lunar surface, it is encouraging to know that hydrogen is present to a considerable depth and not only in the upper few millimeters of soil.

Based on these preliminary studies, extraction of solar wind hydrogen from lunar soil appears feasible, particularly if some kind of grain size separation is possible. Even if concentrations are determined to be too low to extract enough hydrogen to use for propulsion, water obtained from the hydrogen could be used for crew activities and industrial processes.

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Table 1. Hydrogen Abundances in Bulk Lunar Soils

Sample Number	Brief Description*[1]	Hydrogen Abundance (μg/g) This Study	Hydrogen Abundance (μg/g) Literature Values*
10084,149	Mature, from fines in Bulk Sample Container	54.2	44.7[2,3],45.9[2,3]
12033,467	Immature, from a trench in Head Crater	3.2	1.9[4]
12070,127	Submature, from rim of Surveyor Crater	39.2	37.8[4]
14003,71	Mature, collected near the LM	50.8	26.8[5],29.8[5]
14163,178	Submature, surface sample near the LM	45.6	
15021,2	Mature, surface sample 25 m W of the LM	49.6	62.1[6]
15210,2	Mature, fillet sample from St. George Crater	54.7	
15261,26	Mature, from bottom of a small trench	58.2	
15271,25	Mature, surface soil	47.2	
15301,25	Submature, from Spur Crater	44.6	52.2[7], 50.0[8]
15471,12	Submature, from Dune Crater	35.9	
15601,31	Immature, collected near Hadley Rille	33.6	27.8[9],36.8[9]
60051,15	Submature, probably ejecta from a small crater	16.0	
60501,1	Mature, surface soil	35.8	
61221,11	Immature, from trench bottom on Plum Crater rim	3.2	7.8[6],35.0[8]
64421,61	Mature, from trench bottom in subdued crater	36.2	45.6[6]
64801,30	Mature, from crater rim on Stone Mountain	33.0	
66041,12	Mature, from crater rim at Stone Mountain base	35.2	
69941,36	Mature, collected in shadow of small boulder	41.7	34.3[10],65.0[11]
69961,33	Mature, collected under a small boulder	22.7	49.0[11]
70011,19	Submature, collected under the LM	45.8	47.2[12],55.1[13]
71501,138	Submature, part of rake sample	34.7	49.6[12]
73141,8	Submature, from 15 cm below the surface	27.0	
74220,20	Immature, orange soil from rim of Shorty Crater	3.3	0.2[6],0.6[14]
75111,5	Submature, from inner slope of Victory Crater	42.2	
75121,6	Mature, between Victory and Horatio Craters	60.2	
76240,9	Submature, shadowed from overhang of a boulder	38.4	
76260,3	Submature, "skim" sample	32.9	
76280,6	Submature, "scoop" sample below sample 76260	28.0	
76501,18	Submature, surface sample	43.8	43.0[12]
78501,20	Submature, surface sample near rim of crater	29.0	32.8[9]

*References

[1]Morris *et al.* (1983)
[2]Epstein and Taylor (1970a)
[3]Epstein and Taylor (1970b)
[4]Epstein and Taylor (1971)
[5]Merlivat *et al.* (1972)
[6]Epstein and Taylor (1973)
[7]Epstein and Taylor (1972)
[8]Des Marais *et al.* (1974)
[9]Merlivat *et al.* (1974)
[10]Becker (1980)
[11]Stoenner *et al.* (1974)
[12]Petrowski *et al.* (1974)
[13]Epstein and Taylor (1975)
[14]Chang *et al.* (1974)

Table 2. Hydrogen Abundances in Lunar Breccias

Sample Number	Brief Description*	Hydrogen Abundance (μg/g)
10018,54	Dark gray, fine breccia, returned in the Documented Sample Container	116.6
10021,73	Medium light gray breccia, returned in the Contingency Sample Bag	105.2
10048,25	Medium light gray, fine breccia, returned in the Bulk Sample Container	93.3
10056,69	Medium dark gray, microbreccia, returned in the Bulk Sample Container	17.8
10059,38	Medium dark gray, microbreccia, returned in the Bulk Sample Container	96.5
10065,136	Medium dark gray, microbreccia, a grab sample in the Documented Sample Container	95.6
12073,253	Coherent, medium gray, part of the contingency sample, from NW of the LM	21.6
15086,97	Medium gray, friable, collected about 65 m E of the Elbow Crater rim crest	60.4
70175,16	Moderately coherent, highly fractured brown-black breccia, collected near Apollo 17 deep	11.4
70295,23	Medium gray regolith breccia collected at the LM station	77.2
79035,76	Moderately friable, locally cemented by glass, from a few m E of rim crest of Van Serg Crater	44.8
79115,22	Friable, medium gray soil breccia, foliated appearance due to intense fracturing	102.4
79135,33	Polymict matrix fine breccia, collected a few m from the rim of a large subdued crater about 80 m SE of Van Serg Crater	92.8
79195,7	Friable, dark gray breccia	19.2

*References

Butler (1973)
Fruland (1983)
Kramer _et al._ (1977)

Table 3. Hydrogen Abundances of Agglutinates Compared to Original Samples

Sample Number	Grain Size (μm)	Original Sample ($\mu g/g$)	Agglutinate Fraction ($\mu g/g$)
10084,149	150-250	11.3	16.6
	250-500	15.7	16.8
	500-1000	7.2	11.5
12070,127	250-500	9.4	7.4
15021,2	250-500	8.2	11.2
60501,1	250-500	4.4	11.4
71501,138	90-150	7.7	22.2
	150-250	2.0	20.0
	250-500	2.3	10.2
	500-1000	1.7	4.7

Table 4. Hydrogen Abundances in Lunar Basalts

Sample Number	Brief Description*	Hydrogen Abundance (μg/g)
15016,41	Medium-grained,vesicular olivine-normative, collected 30 m from the ALSEP central station	2.2
15058,72	Coarse-grained, vuggy quartz normative collected on E flank of Elbow Crater	1.8
15065,39	Coarse-grained, quartz normative with pigeonite phenocrysts, collected on E flank of Elbow Crater	1.2
15076,8	Tough, coarse-grained with some pigeonite phenocrysts, collected on E flank of Elbow Crater	1.4
15085,97	Coarse-grained quartz-normative mare basalt, collected on E flank of Elbow Crater	1.8
15499,20	Vitrophyric pigeonite basalt, collected on the S rim of Dune Crater	2.0
15555,136	From "Great Scott," a medium-grained olivine basalt, collected 12 m N of rim of Hadley Rille	1.7
15556,159	Medium-grained, extremely vesicular olivine-normative, collected 60 m NE of rim of Hadley Rille	1.8
70035,1	Moderate brown basalt	2.2
70215,54	Fine-grained, medium dark gray with brownish tint	2.4
74275,56	Medium dark gray porphyritic basalt	3.8
75035,37	Medium to brownish gray	1.8
75055,6	White and medium brownish gray	3.5
78505,26	Coarse, vuggy, medium dark brownish gray	2.4

*References

Butler (1973)
Ryder (1985)

Table 5. Hydrogen Abundances of Grain Size Fractions and Mass Balance Calculations

Sample Number	Grain Size (μm)	Weight %	Hydrogen Content (μg/g)	Contribution To Bulk (μg/g)	Hydrogen Calculated (μg/g)	Hydrogen Found (μg/g)
10084,149	<20	25.78	146.7	37.8		
	20-45	18.33	39.7	7.3		
	45-75	15.01	24.4	3.7		
	75-90	5.01	20.1	1.0		
	90-150	12.24	20.2	2.5		
	150-250	9.06	11.3	1.0		
	250-500	8.73	15.7	1.4		
	500-1000	5.82	7.2	0.4		
					55.1	54.2
12070,127	<20	22.35	107.4	24.0		
	20-45	17.34	30.1	5.2		
	45-75	14.82	16.2	2.4		
	75-90	5.09	9.0	0.5		
	90-150	13.37	8.7	1.2		
	150-250	10.60	7.5	0.8		
	250-500	8.80	9.4	0.8		
	500-1000	7.63	8.5	0.6		
					35.5	39.2
15021,2	<20	23.02	128.5	29.6		
	20-45	22.96	51.1	11.7		
	45-75	15.61	22.4	3.5		
	75-90	4.37	20.8	1.1		
	90-150	13.26	15.5	2.1		
	150-250	9.25	8.4	0.8		
	250-500	7.23	8.2	0.6		
	500-1000	3.31	11.0	0.4		
					49.8	49.6
60501,1	<20	24.12	124.1	29.9		
	20-45	17.76	43.0	7.6		
	45-75	13.48	16.1	2.2		
	75-90	4.40	12.8	0.6		
	90-150	11.54	9.6	1.1		
	150-250	9.72	5.2	0.5		
	250-500	10.75	4.4	0.5		
	500-1000	8.22	2.6	0.2		
					42.6	35.8
71501,138	<20	17.62	126.4	22.3		
	20-45	17.67	47.2	8.3		
	45-75	15.60	18.5	2.9		
	75-90	4.42	9.4	0.5		
	90-150	14.75	7.7	1.1		
	150-250	11.51	2.0	0.2		
	250-500	10.69	2.4	0.3		
	500-1000	6.64	1.7	0.1		
					35.7	34.7
Breccia 15086,202	<20	28.62	176.3	50.5		
	20-45	19.05	21.9	4.2		
	45-90	18.30	11.7	2.1		
	90-150	12.55	4.0	0.5		
	150-250	9.12	2.3	0.2		
	250-500	7.51	2.7	0.2		
	500-1000	4.85	1.9	0.1		
					57.8	60.4

FIGURE CAPTIONS

FIG. 1. Comparison of hydrogen abundances in bulk soils, breccias, and basalts from different Apollo sites.

FIG. 2. Relationship between soil maturity as measured by the I_s/FeO index (Morris, 1986 and Morris et al., 1978, 1979, 1983) and hydrogen abundance for all Apollo 17 soils studied.

FIG. 3. Hydrogen abundances in grain size fractions of five bulk soil samples and one regolith breccia.

FIG. 4. Relation between n ($C \propto d^{-n}$) and solar wind gases. Hydrogen data are for Breccia 15086 and the average of five lunar soils. Noble gas data are averages for seven lunar soils (Bogard, 1977).

FIG. 5. Depth profiles of I_s/FeO (Heiken et al., 1976) and hydrogen abundance for the Apollo 15 Deep Drill Core 15001 - 15006.

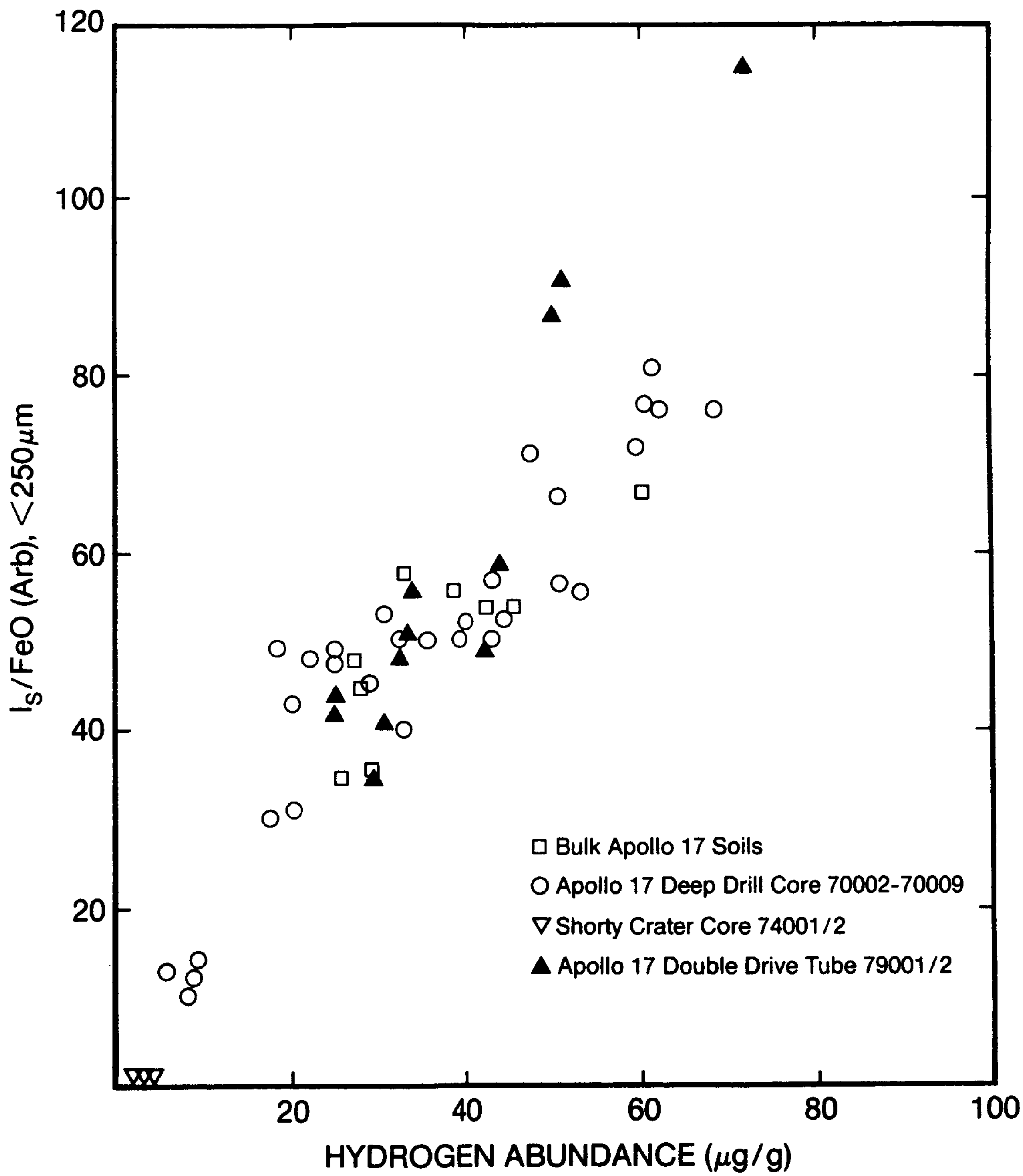
FIG. 6. Depth profiles of I_s/FeO (Bogard et al., 1982) and hydrogen abundance for the Apennine Front Core 15007/8.

FIG. 7. Depth profiles of I_s/FeO (Gose and Morris, 1977) and hydrogen abundance for the Apollo 16 Deep Drill Core 60002 - 60007.

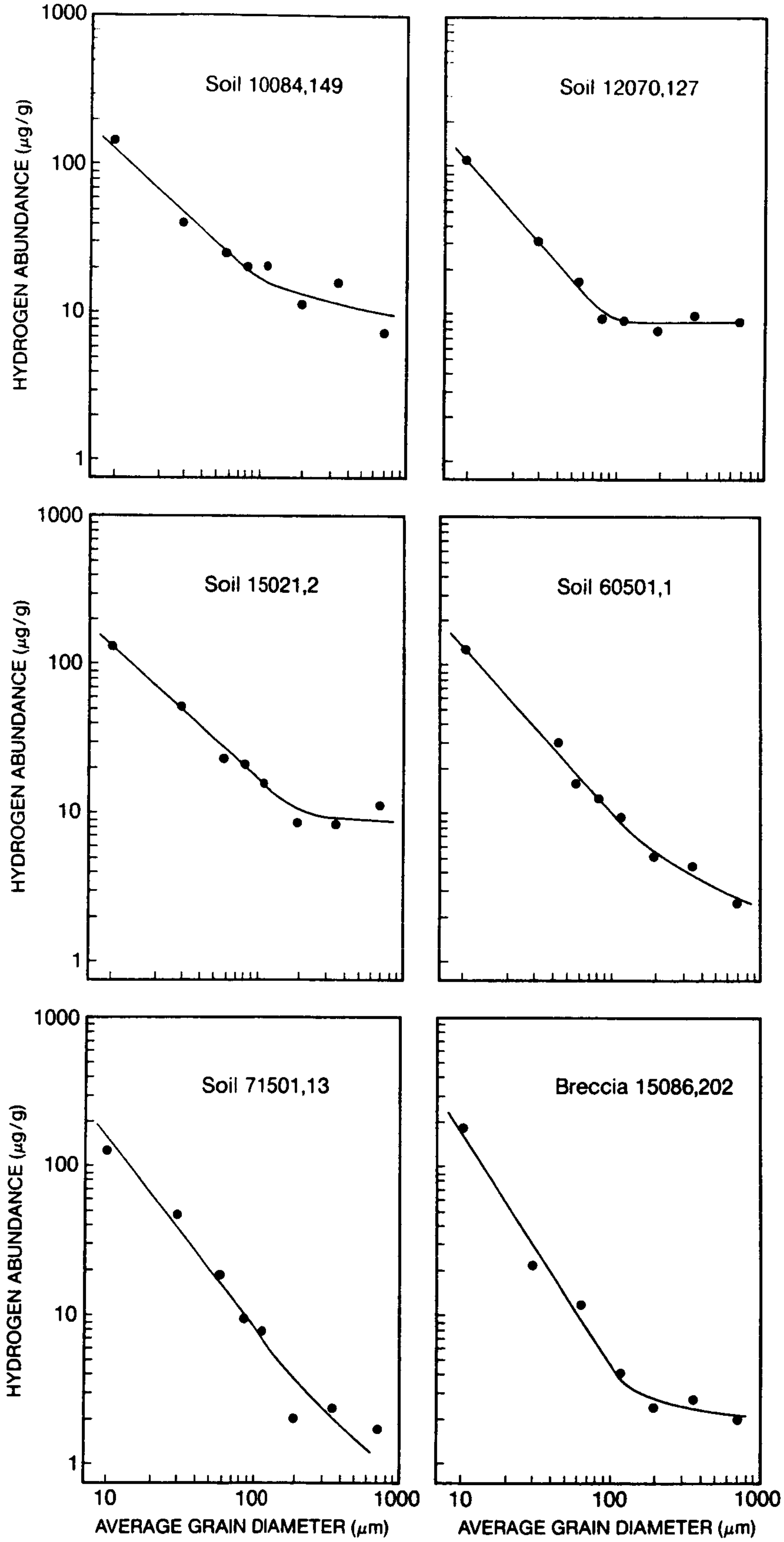
FIG. 8. Depth profiles of I_s/FeO (Morris et al., 1979) and hydrogen abundance for the Apollo 17 Deep Drill Core 70002 - 70009.

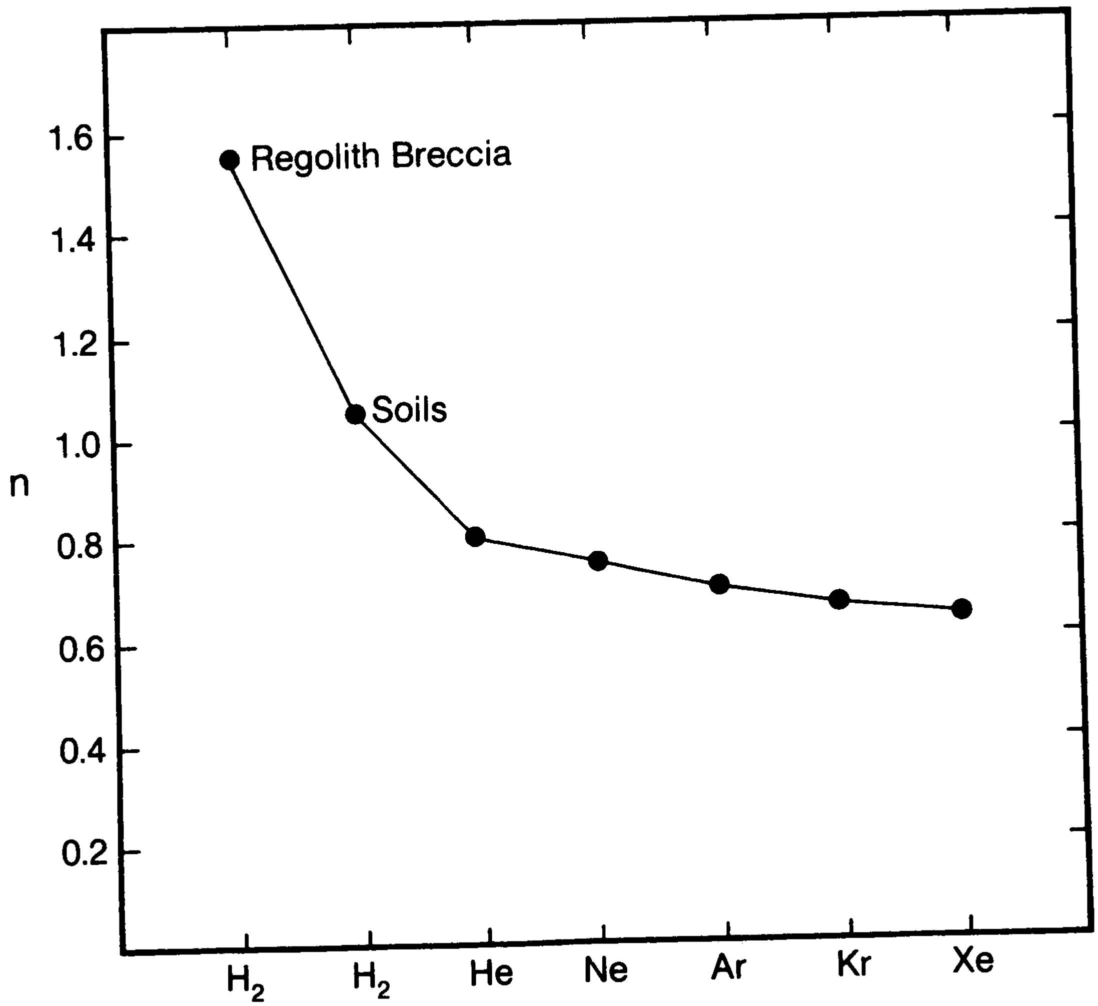
FIG 9. Depth profiles of I_s/FeO (Morris et al., 1978) and hydrogen abundance for the Shorty Crater Core 74001/2.

FIG. 10. Depth profiles of Is/FeO (Morris, 1986, 1987) and hydrogen abundance for the Apollo 17 Double Drive Tube 79001/2.



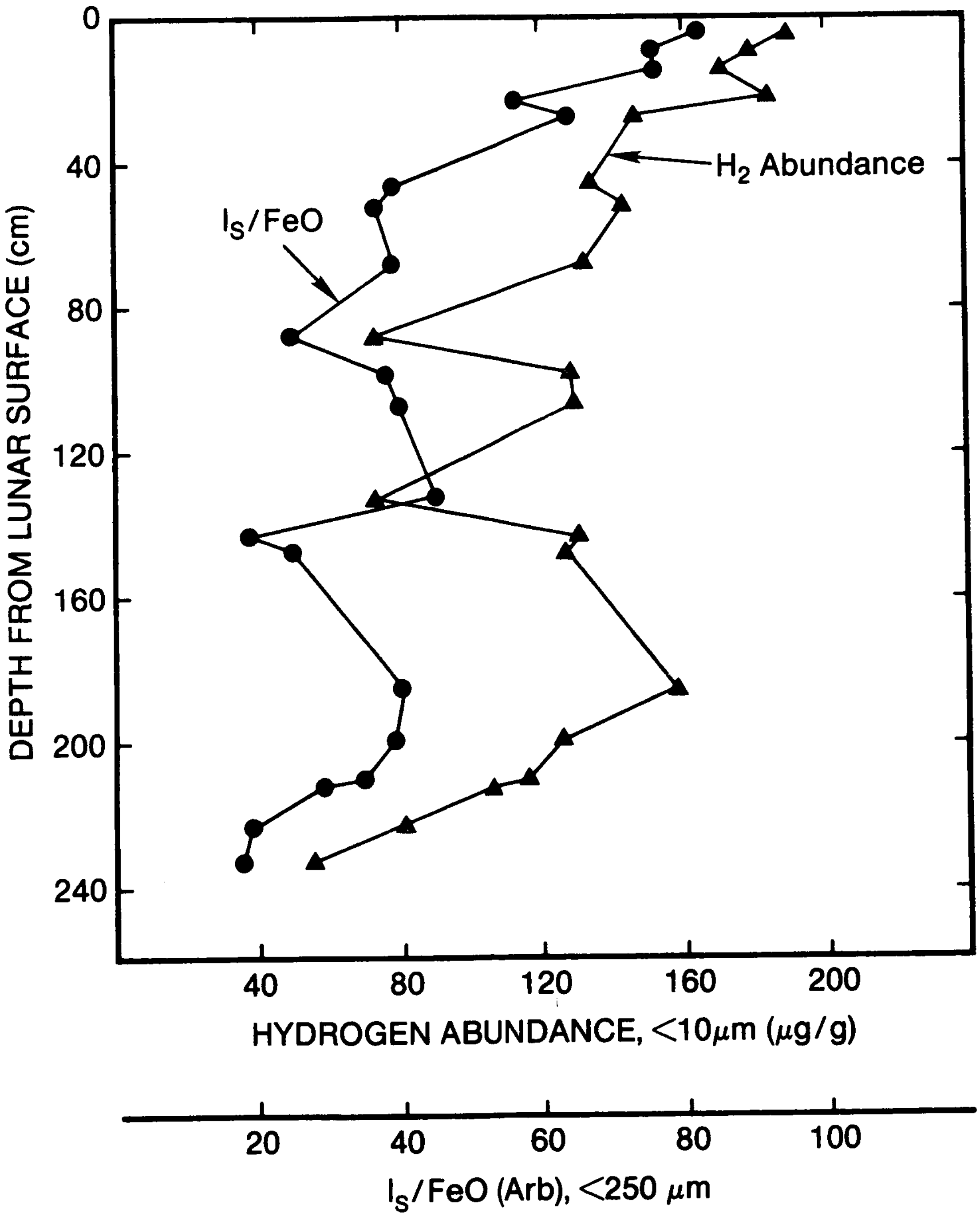
120
100
80
60
40
20
20
40
60
80
100
I_S/FeO (Arb), <250μm
HYDROGEN ABUNDANCE (μg/g)
□ Bulk Apollo 17 Soils
○ Apollo 17 Deep Drill Core 70002-70009
▽ Shorty Crater Core 74001/2
▲ Apollo 17 Double Drive Tube 79001/2

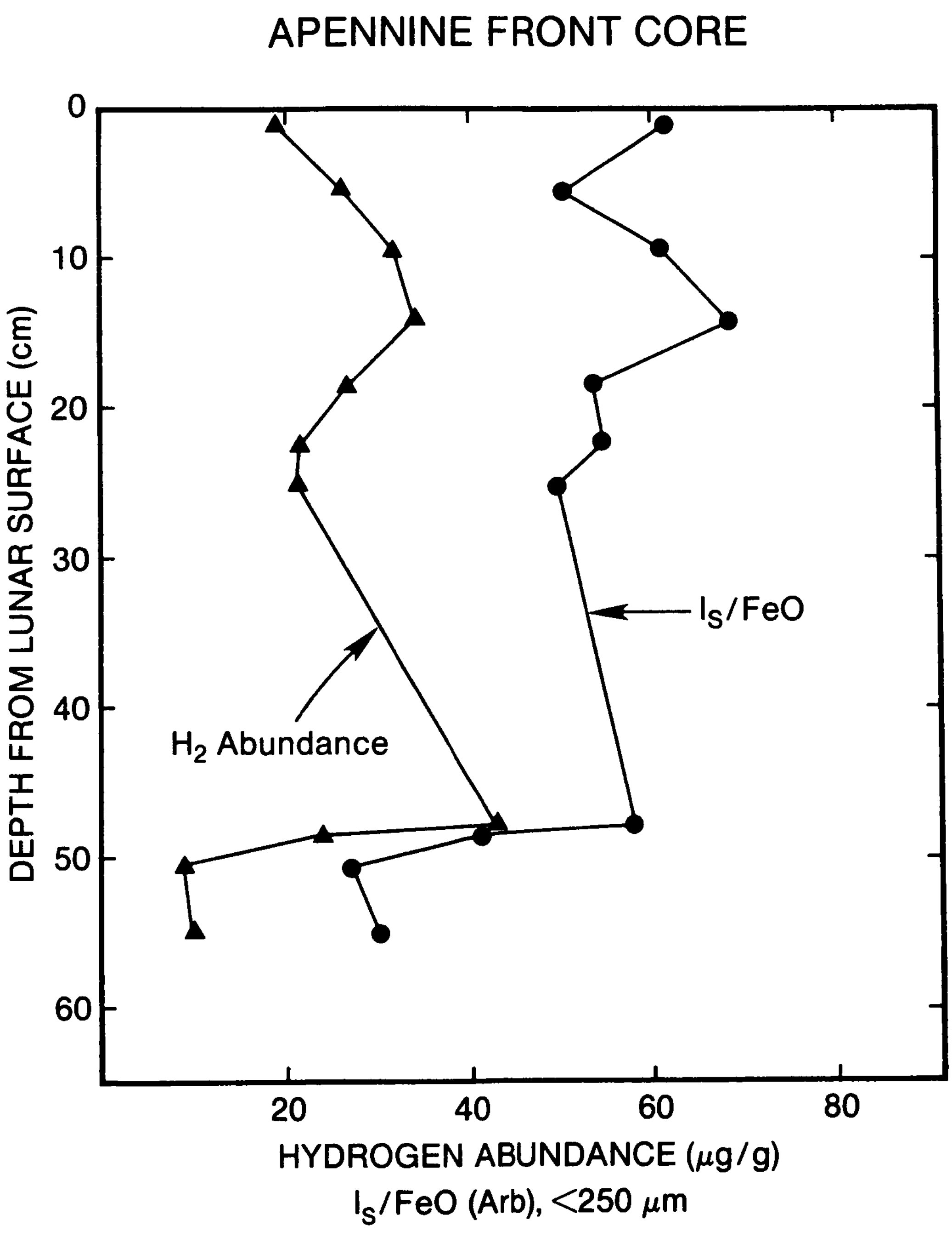

Soil 10084,149
Soil 12070,127
Soil 15021,2
Soil 60501,1
Soil 71501,13
Breccia 15086,202
HYDROGEN ABUNDANCE (μg/g)
1000
100
10
1
10
100
1000
AVERAGE GRAIN DIAMETER (μm)



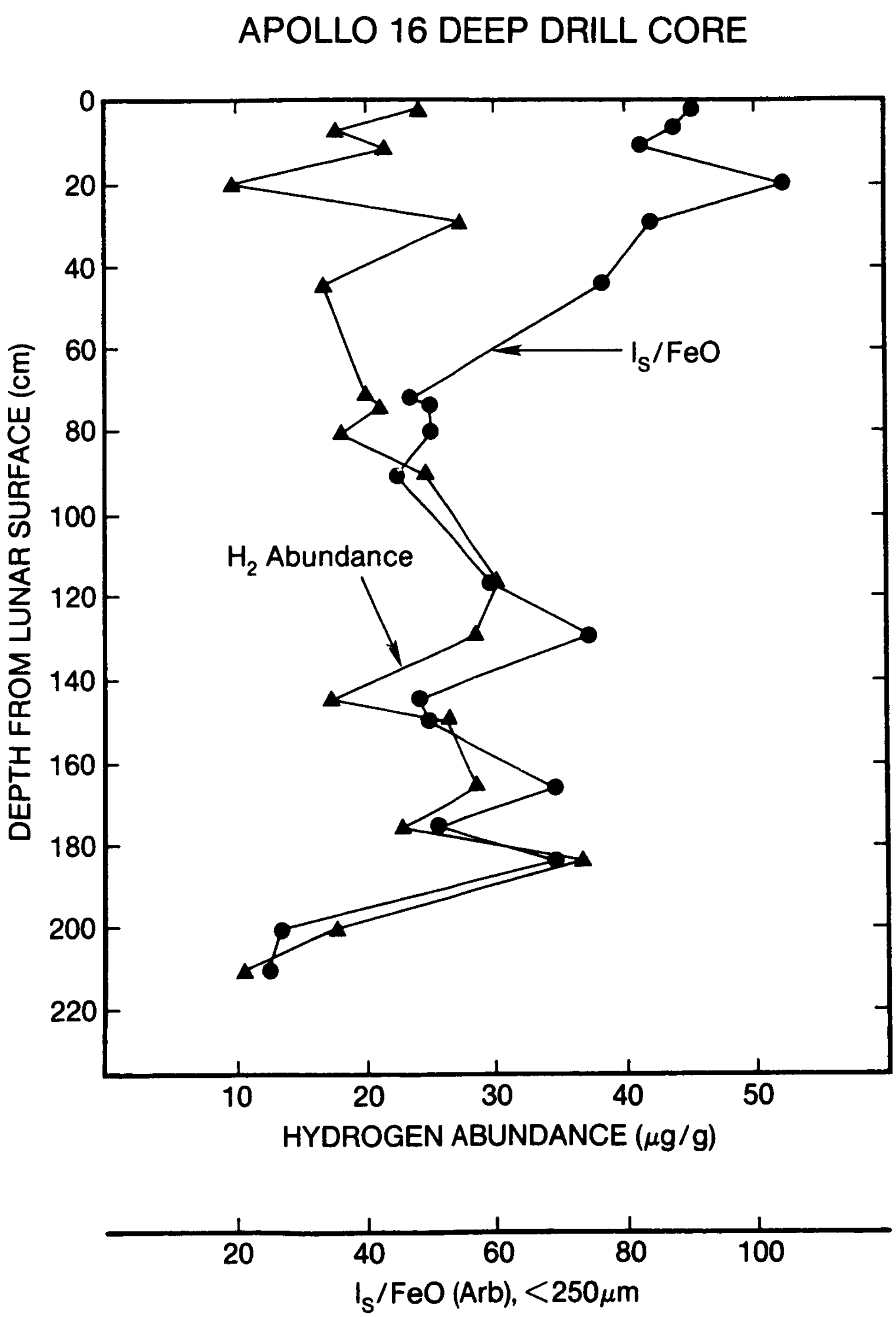
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
n
Regolith Breccia
Soils
H_2
H_2
He
Ne
Ar
Kr
Xe

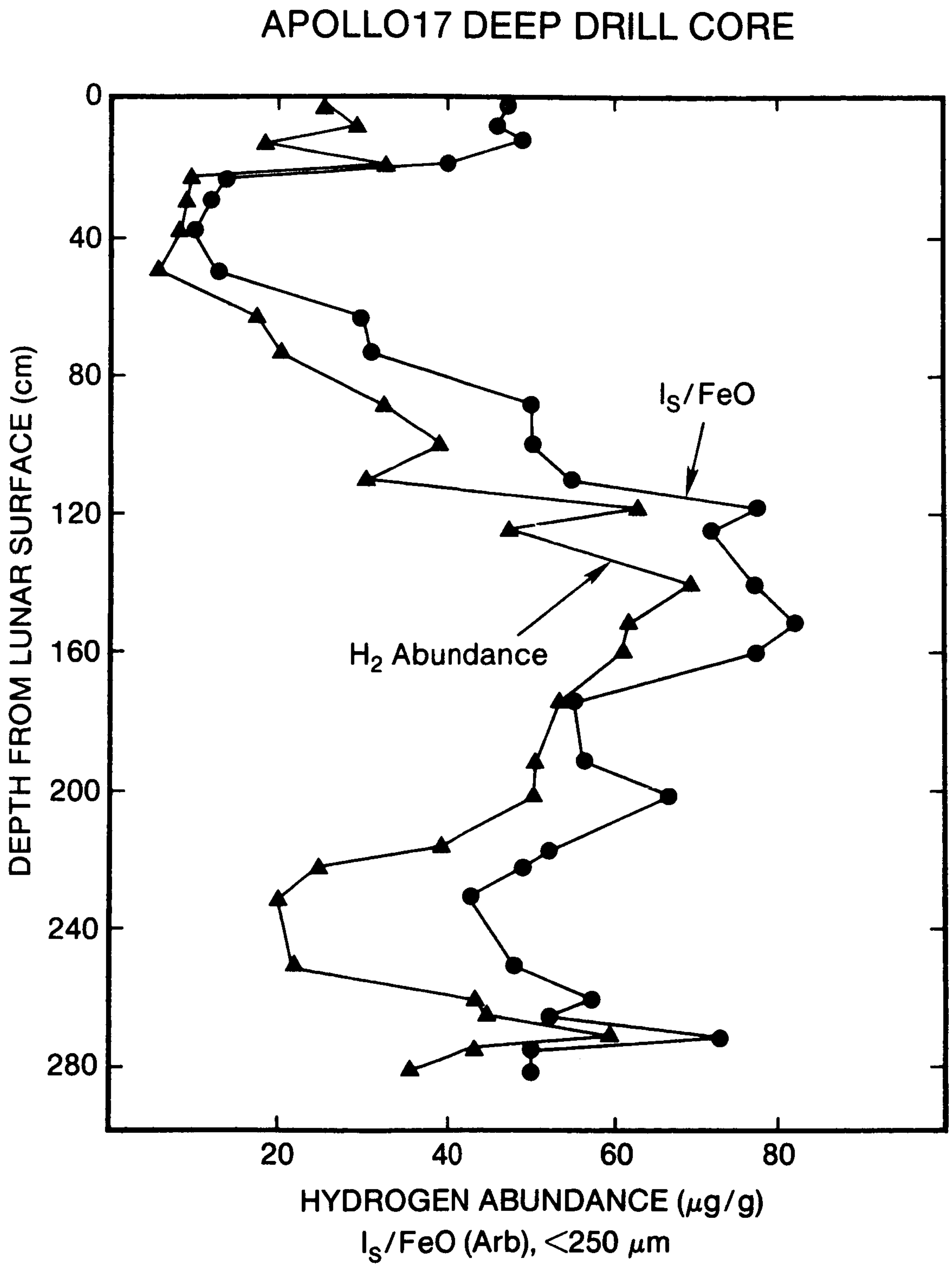
APOLLO15 DEEP DRILL CORE



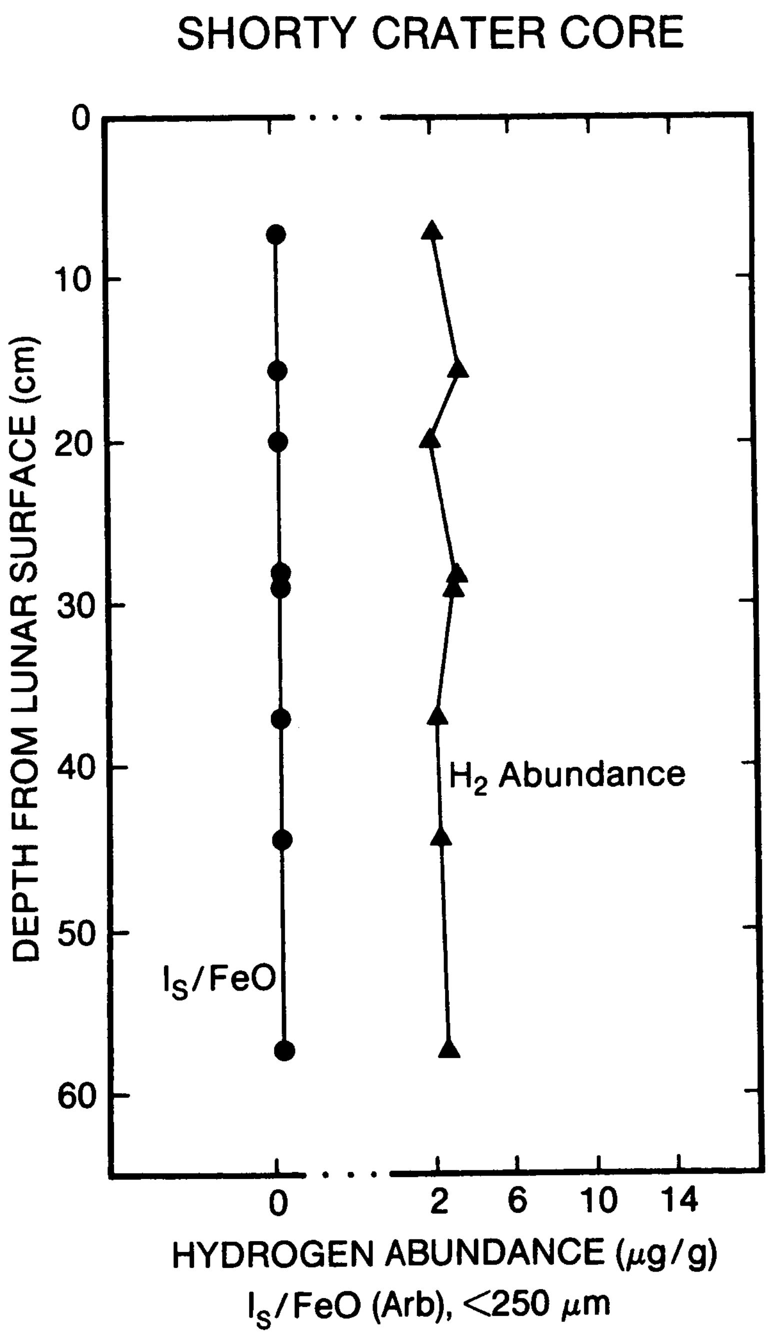


APENNINE FRONT CORE
DEPTH FROM LUNAR SURFACE (cm)
0
10
20
30
40
50
60
20
40
60
80
HYDROGEN ABUNDANCE (μg/g)
I_S/FeO (Arb), <250 μm
I_S/FeO
H_2 Abundance


APOLLO 16 DEEP DRILL CORE
DEPTH FROM LUNAR SURFACE (cm)
0
20
40
60
80
100
120
140
160
180
200
220
I_s/FeO
H_2 Abundance
10
20
30
40
50
HYDROGEN ABUNDANCE (μg/g)
20
40
60
80
100
I_s/FeO (Arb), <250μm

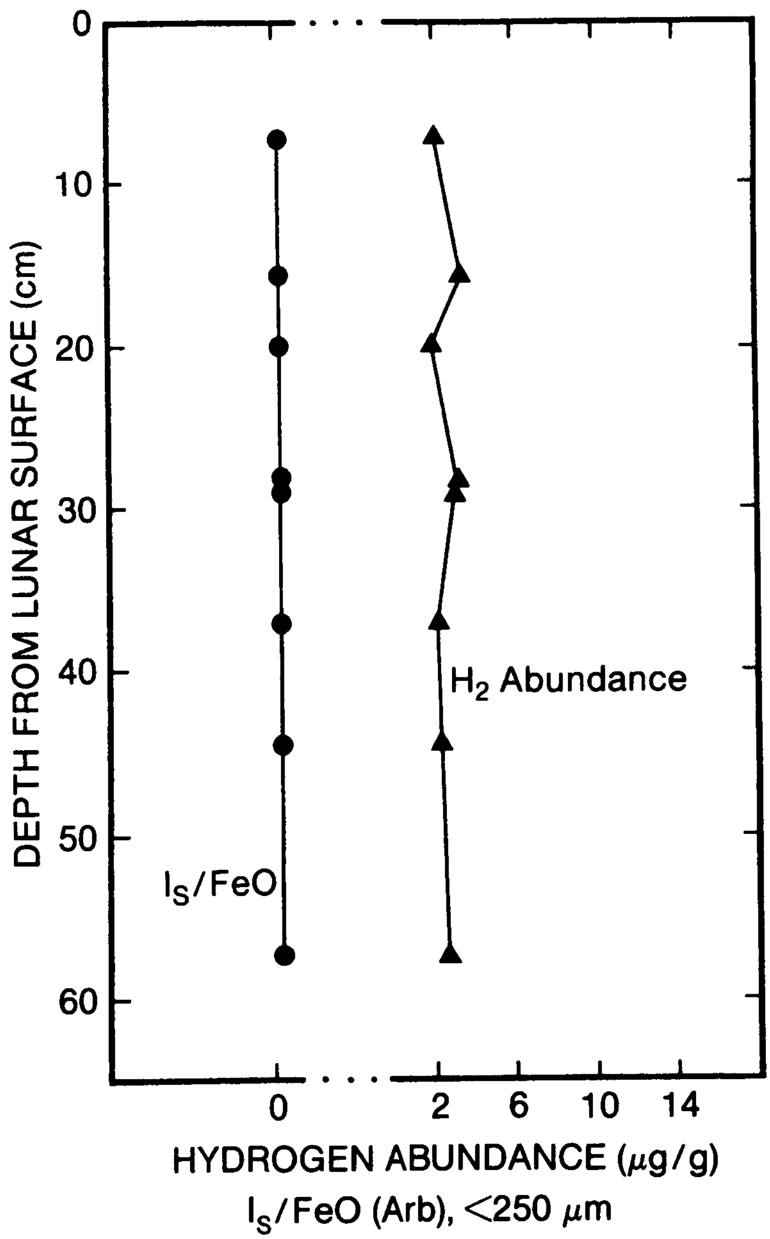


APOLLO17 DEEP DRILL CORE
0
40
80
120
160
200
240
280
DEPTH FROM LUNAR SURFACE (cm)
I_S/FeO
H_2 Abundance
20
40
60
80
HYDROGEN ABUNDANCE (μg/g)
I_S/FeO (Arb), <250 μm



SHORTY CRATER CORE
0
10
20
30
40
50
60
DEPTH FROM LUNAR SURFACE (cm)
H_2 Abundance
I_S/FeO
0
2
6
10
14
HYDROGEN ABUNDANCE (μg/g)
I_S/FeO (Arb), <250 μm

SHORTY CRATER CORE



APOLLO 17 DOUBLE DRIVE TUBE 79001/2