AVAILABILITY OF HYDROGEN FOR LUNAR BASE ACTIVITIES

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Hydrogen will be needed on a lunar base to make water for consumables, to provide fuel, and to serve as a reducing agent in the extraction of oxygen from lunar minerals. This study was undertaken in order to learn more about the abundance and distribution of solar-wind-implanted hydrogen. Hydrogen was found in all samples studied, with concentrations varying widely depending on soil maturity, grain size, and mineral composition. Seven cores returned from the Moon were studied. Although hydrogen was implanted in the upper surface layer of the regolith, it was found throughout the cores due to micrometeorite reworking of the soil.

INTRODUCTION

Considering lunar materials from the perspective of utilizing them in space, hydrogen is one of the most valuable lunar resources. It will be needed in lunar base activities in making water, in reducing oxides, and in providing fuel for orbital transfer vehicles.

Solar wind has irradiated the lunar surface for extensive periods of time, implanting hydrogen in the lunar soil (*Becker,* 1980). In order to know if usable quantities of hydrogen are present within the lunar regolith, the abundances, distributions, and locations of hydrogen-containing lunar materials must be fully understood. In this study, bulk soils, size separates, mineral separates, and core samples have been examined.

EXPERIMENTAL TECHNIQUES

Hydrogen was extracted from lunar soil by vacuum pyrolysis (*Carr et al.,* 1987). Weighed lunar samples were placed directly into an alumina tube that was then attached to the sampling line and evacuated to a pressure of 1×10^{-2} atm. Hydrogen was extracted by heating at 900°C for 3 min using a resistance wire furnace. The liberated hydrogen was injected directly into a gas chromatograph (GC) equipped with a 12-ft Molecular Sieve 5A column and a helium ionization detector. The amount of hydrogen was determined from a calibration curve.

HYDROGEN ABUNDANCE

Bulk Surface Soils

Hydrogen abundances were determined for 31 bulk soils, with at least 1 soil from each of the 6 Apollo exploration sites. The results are given in Table 1. Hydrogen concentrations of these bulk surface soils ranged from 3.2 to 60.2 μg/g, with an average value of 36.3 μg/g. Using this "average" bulk surface soil value, 1 ton of lunar soil could provide 369 liters of hydrogen gas at STP.

Earlier studies have shown that concentrations of the noble gases, nitrogen, and carbon increase with increasing soil maturity as measured by the surface exposure index, I_s/FeO (*Charette and Adams,* 1975; *Morris,* 1986; *Morris et al.,* 1989). In general, our results showed that solar wind hydrogen also follows this same trend. Average hydrogen values for all immature, submature, and mature soils were 10.8, 35.3, and 44.6 μg/g, respectively.

Only three of the bulk soils examined had extremely low hydrogen content. The Apollo 16 soil 61221,11, a subsurface soil with abnormally coarse grain size from Plum Crater, had a hydrogen concentration of 3.2 μg/g. This soil contained only 6% agglutinates and had an I_s/FeO value of 9.2 (*Morris et al.,* 1983). The Apollo 12 soil 12033,467, with a hydrogen concentration of 3.2 μg/g, 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). The Apollo 17 soil 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 (*Morris et al.,* 1983).

Except for core samples, the bulk soils having the highest concentrations of hydrogen were 75121,6 and 15261,26 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 to date. Soil 15261,26 was also high in agglutinates with 50.5% (*Morris et al.,* 1983).

This relationship between soil maturity and hydrogen concentration could prove to have practical value as sites are chosen for "mining" hydrogen on the lunar surface.

Grain Size

Because the majority of the hydrogen in lunar soils has been implanted by solar wind, a marked surface correlation would be predicted. Compared to large grains, smaller-sized grains would be expected to show larger hydrogen abundances because of the

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], 45.9[2], 90.0[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* (1970); [3]*Friedman et al.* (1970); [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).

increase in the ratio of surface area to mass. *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 vs. 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 (*Bogard,* 1977; *Eberhardt et al.,* 1972; *Etique et al.,* 1978; *Morris,* 1977; *Schultz et al.,* 1977). The present study indicates a similar relationship between hydrogen abundance and grain size for the six lunar samples studied, as shown in Fig. 1. 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 that were originally exposed become buried inside the particles, gases that were implanted on surfaces become trapped inside, 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.

The soil that showed the least amount of volume correlation for large grain sizes was sample 71501,138, the most immature of all those used in the grain size study. This result predicts that this soil has not seen much micrometeorite reworking and, thus, is not rich in agglutinates and other constructional particles that would have trapped hydrogen during formation. This is verified by a soil composition study (*Morris et al.,* 1983) that showed only 35% agglutinates in this soil.

Table 2 gives the hydrogen concentrations for each particle size for five lunar soils and a breccia. For each sample, the $<20\mu m$ grain size fraction was enriched by approximately a factor of 3 over the value obtained experimentally for the bulk soil. Also, 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 served as a check for the experimentally determined values. As shown in Table 2, there was good agreement between the calculated and the experimentally determined values of hydrogen concentration.

The technology required to separate the fine grains from bulk soil is simple, making it feasible to include such a separation prior to extracting the hydrogen. If this could be done, approximately 1100 liters of hydrogen at STP (based on the average bulk soil

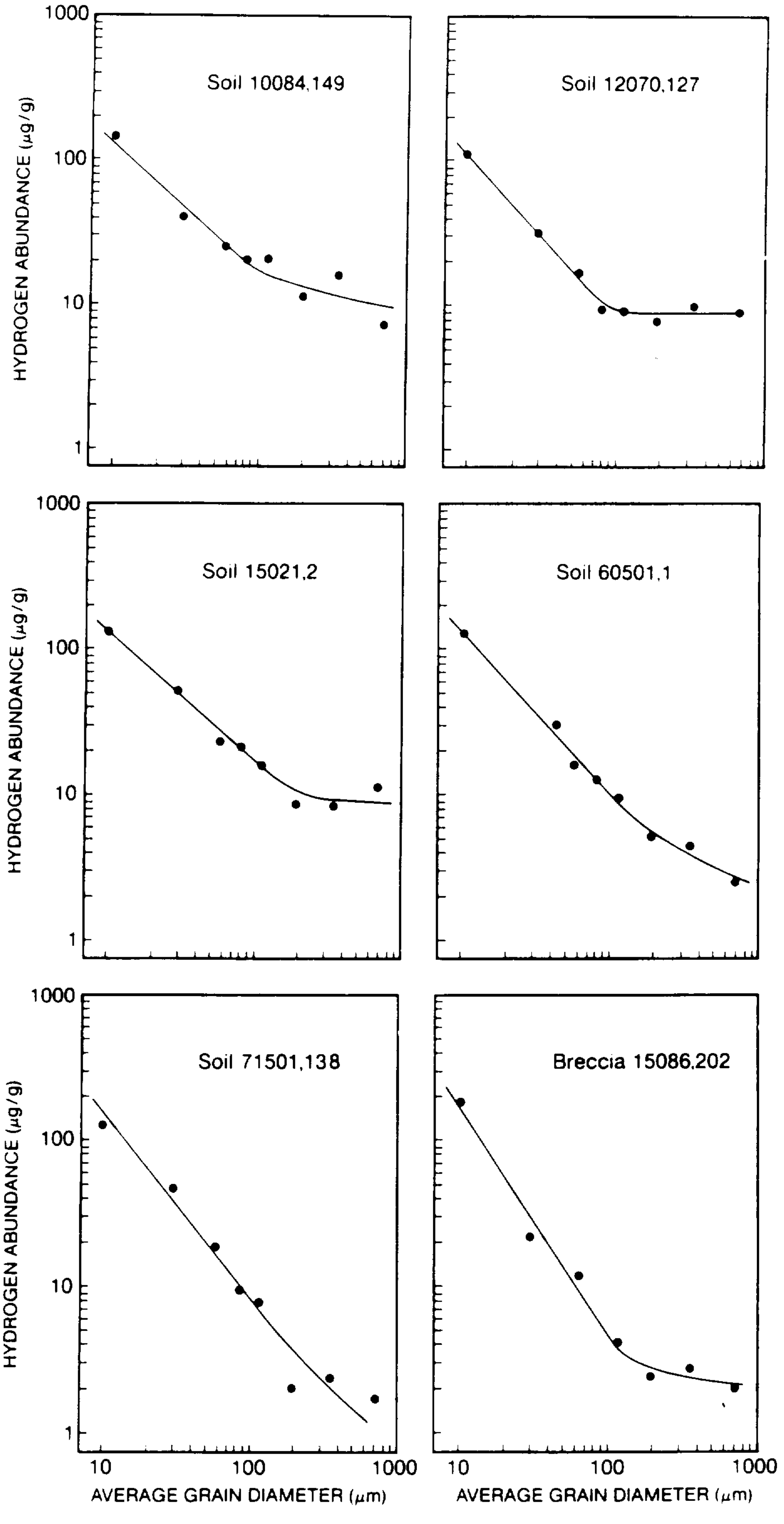


Fig. 1. Hydrogen abundances in grain size fractions of five bulk soil samples and one regolith breccia.

TABLE 2. Hydrogen abundances of grain size fractions and mass balance calculations.

Sample Number	Grain Size (μm)	Weight Percent	Hydrogen Content (μg/g)	Contribution to Bulk (μg/g)	Hydrogen Calculated (μg/g)	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

value) could be obtained for each ton of soil going through the extraction facility. If this size separation were carried out on the most mature soil studied, this value would be increased to approximately 1840 liters at STP.

Soil Components

Signer et al. (1977) looked at the retentivity of solar wind noble gases by several particle types. They found that agglutinates consistently contained the highest noble gas concentrations among soil constituents. This is not surprising because agglutinates are constructional particles, built up by micrometeorite impact on the lunar surface. *DesMarais et al.* (1974) studied the distribution of hydrogen with respect to soil particle types. As expected, they found a considerable enrichment of hydrogen in the agglutinate fraction over that in the bulk soil; in fact, agglutinates contained the most hydrogen of any particle type studied. We found a similar enrichment in all but 1 of the 10 hand-picked agglutinate size separates run in this study (Table 3).

Signer et al. (1977) noted high noble gas concentrations in breccia samples. They attributed this to the trapped gases in the particles that make up the breccia. Our results (Table 4) showed a similar hydrogen enrichment in breccias over that found in bulk surface soils.

TABLE 3. Hydrogen abundances of agglutinates compared to original samples.

Sample Number	Grain Size (μm)	Original Sample (μg/g)	Agglutinate Fraction (μg/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 breccias.

Sample Number	Brief Description*	Hydrogen Abundance (μg/g)
10018,54	Dark gray, fine-grained 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-grained 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	96.6
10065,136	Medium dark gray, microbreccia, a grab sample in the Documented Sample Container	95.6
12073,253	Coherent, medium gray breccia, part of the contingency sample, from NW of the LM	21.6
15086,97	Medium gray, friable breccia, 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 drill core	11.4
70295,23	Medium gray regolith breccia collected at the LM station	77.2
79035,76	Moderately friable breccia locally cemented by glass, from a few meters E of rim crest of Van Serg	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 meters SE of Van Serg Crater	92.8
79195,7	Friable, dark gray breccia	19.2

*References: *Butler* (1973); *Fruland* (1983); *Kramer et al.* (1977).

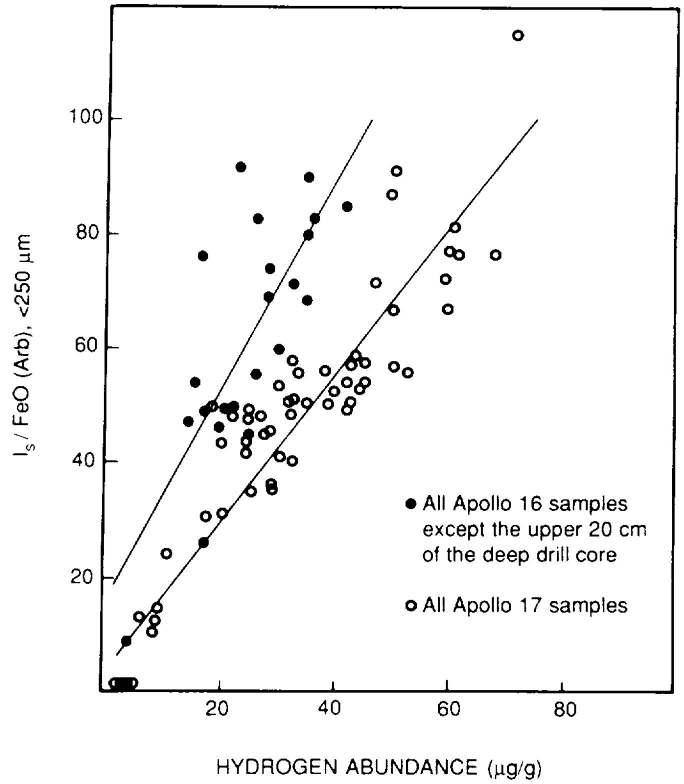


Fig. 2. Comparison of hydrogen retentivity of Apollo 16 and Apollo 17 soils. The slope of the Apollo 16 line is 1.82, compared to 1.28 for the Apollo 17 line. Maturity data as measured by the I_s/FeO index are from *Gose and Morris* (1977); *Morris* (1986), *Morris et al.* (1978, 1979, 1983).

TABLE 5. 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).

It is well known that ilmenite grains retain helium readily. ***Eberhardt et al.*** (1972) noted that the ilmenite grain size fractions from soil 12001 were considerably enriched in helium (up to 12 times) over the corresponding bulk grain size fractions. ***Hintenberger et al.*** (1971) found that the ilmenite grains in some lunar soils were enriched in helium by a factor of 3 to 6 over the bulk material in the same grain size range. Because hydrogen is also a solar wind species, it is felt that the retention mechanism would be similar for hydrogen and helium and that ilmenite would also be high in hydrogen. No ilmenite grains were available for this study; however, some interesting observations may be made. Apollo 16 soils are highland soils and are known to be lower in

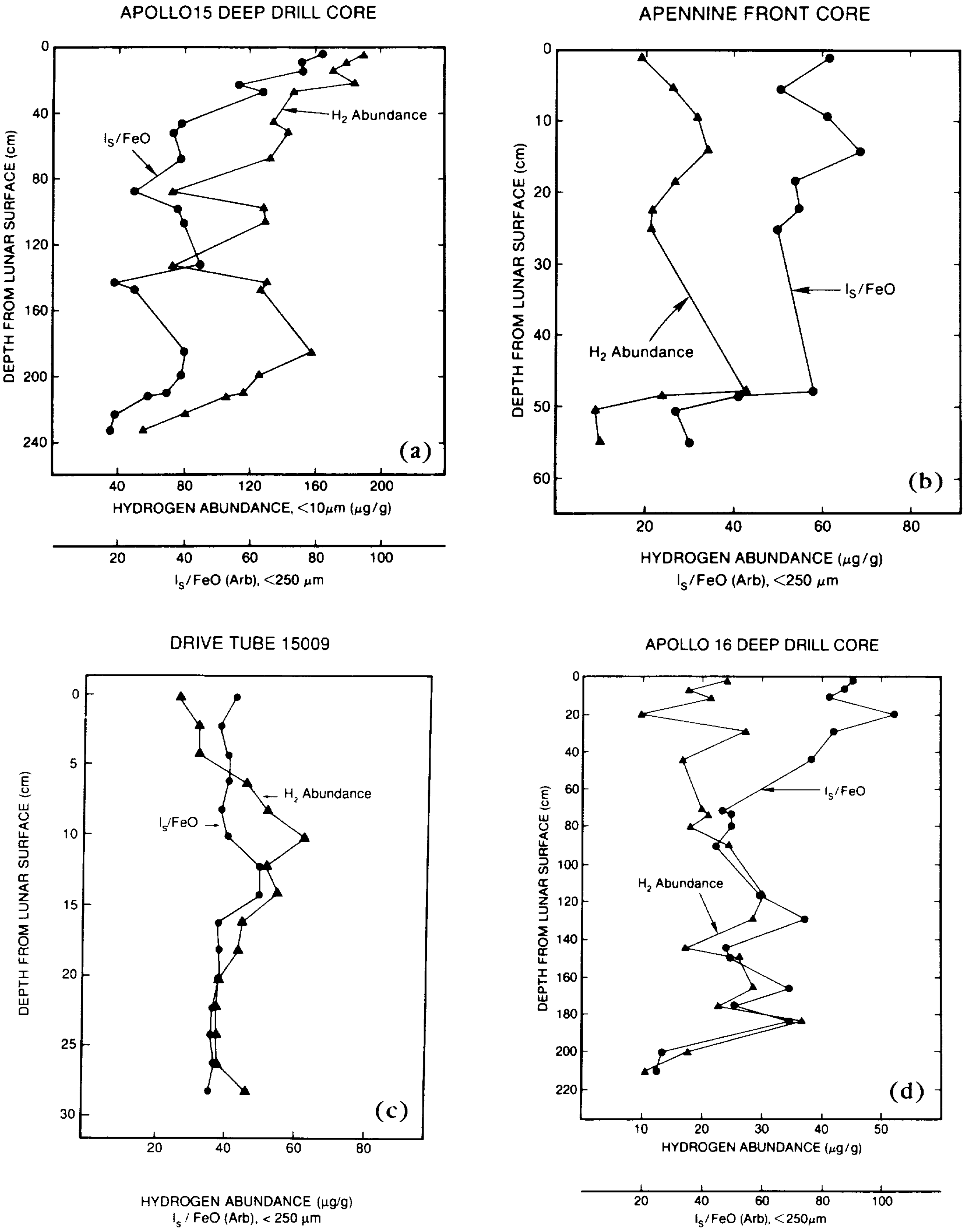
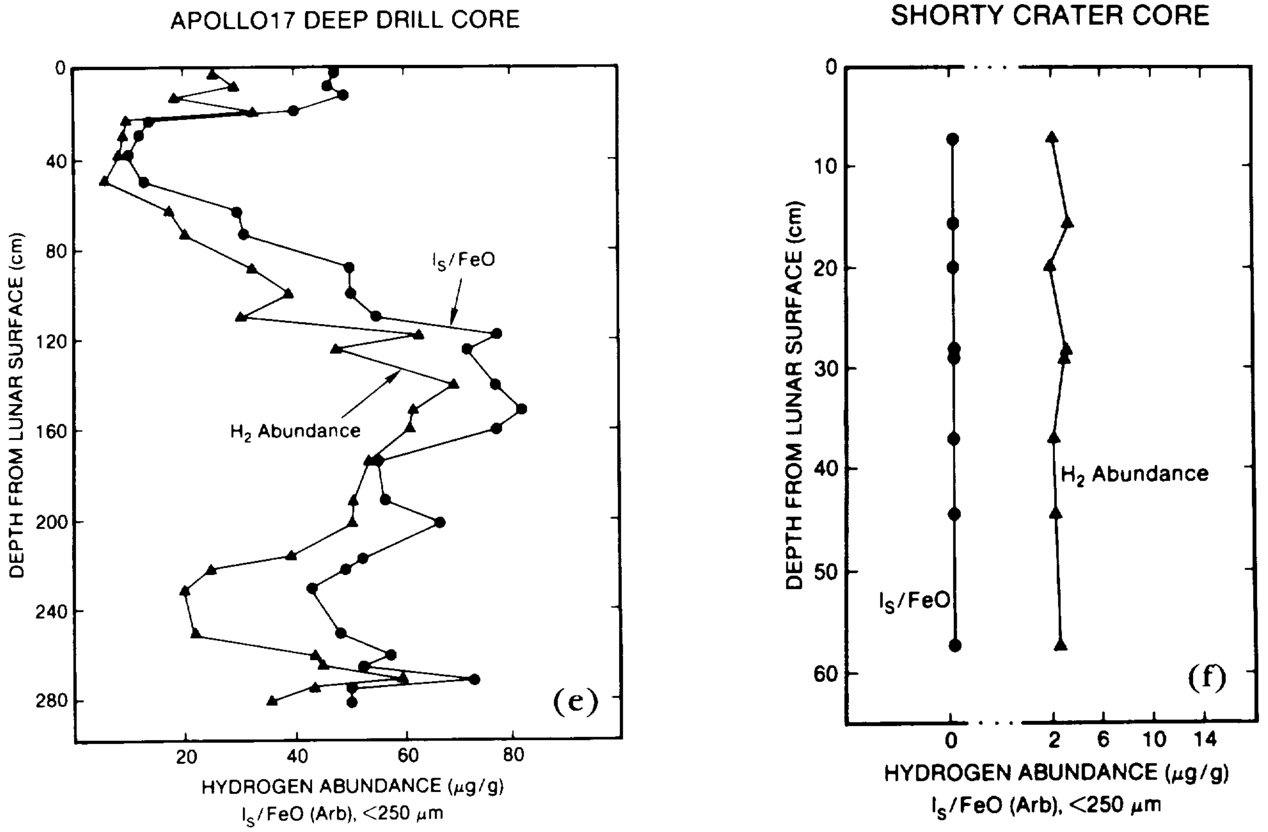
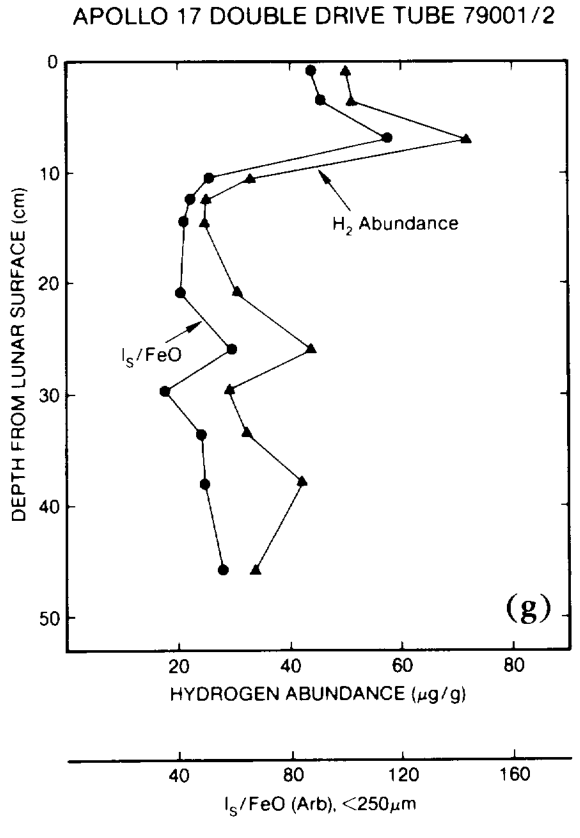


Fig. 3. Depth profiles of I_s/FeO and hydrogen abundance for seven core tubes. Maturity data as measured by the I_s/FeO index are from *Bogard et al.* (1982); *Gose and Morris* (1977); *Heiken et al.* (1976); *Morris et al.* (1978, 1979); *Morris* (1986); *Schwarz* (1988); R. V. Morris, personal communication (1987).





ilmenite that mare soils (*Taylor*, 1975). Hydrogen concentrations in highland soils were noticeably lower than would have been predicted from maturity data. The average hydrogen concentration in the eight Apollo 16 bulk surface soils studied was only 28.0 μg/g, compared to 39.2 μg/g for the other 23 bulk surface soils. Although six of the Apollo 16 bulk surface soils were classified as mature according to their I_s/FeO values, their average was only 34.1 μg/g, considerably lower than the average of 53.6 μg/g for all other mature surface soils. In a plot of I_s/FeO vs. hydrogen concentration (Fig. 2), the difference in hydrogen retentivity of the Apollo 16 highland soils and the Apollo 17 mare soils is quite apparent.

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 low in hydrogen. We studied 14 lunar basalt samples. As Table 5 shows, all these samples had extremely low hydrogen concentrations, ranging only from 1.2 to 3.8 μg/g.

Core Samples

The depositional and irradiational histories of the lunar regolith are reflected in the soil samples from lunar cores. They provide useful information about earlier processes that have occurred on the lunar surface. Hydrogen data on the core samples provide a different kind of valuable information. First, the correlation between hydrogen abundance and soil maturity can often be seen more clearly from core data than from bulk soil data. As shown in Fig. 3, this correlation is quite striking for several of the cores. 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.

Two of the cores were particularly unusual. The Shorty Crater core is relatively homogeneous and consists almost entirely of orange and black glassy droplets. 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). The values obtained for hydrogen concentrations throughout the length of the core were extremely low and showed very little variation. These values were very close to the hydrogen concentration found in the local surface soil 74220,20. On the other extreme was the Apollo 17 double drive tube 79001/2. The striking physical feature of this core was a distinct dark-light boundary inclined 25° to 30° from approximately 8.5 to 11 cm below the surface (*Schwarz,* 1986). There is a definite change in both soil maturity and hydrogen abundance at approximately the interface between the dark and light layers. The upper dark section of this core includes the most mature lunar soils ever observed (*Korotev et al.,* 1987). Soils from this section also have the highest hydrogen concentrations of any soils studied. The highest hydrogen value obtained in this study for a bulk soil was 72.0 μg/g, obtained for the 6.5- to 7.0-cm section of this core; this sample also had the highest I_s/FeO value recorded for a bulk soil (*Korotev et al.,* 1987). Grain size separates were run on selected samples from this core. The highest hydrogen values obtained for any samples in the entire study were obtained for the <20-μm grain sizes for the soils in the upper 10 cm of the core. These values were all greater than 269 μg/g, with a high of 306.4 μg/g.

The deepest soil column (~295 cm) returned from the Moon was the Apollo 17 deep drill core. Although we don't know how deep hydrogen extends in the lunar regolith, it is encouraging to see that it is present completely to the bottom of this deep drill core. This makes mining for hydrogen much more feasible than if it were only present in a thin surface layer.

CONCLUSION

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. When plans for an extraction facility are being made, consideration should be given to the fact that hydrogen concentrations vary significantly from one site to another. A site should be chosen where the soil is mature.

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