the thickness of the low-conductivity outer layer of the moon. To do this the value for the "global" conductivity determined in Eq. 1 is used. In that equation it was assumed that the outer layer had zero conductivity, that the core possessed uniform conductivity, and that the wavelength of the exciting radiation from the solar wind was long as compared to the size of the moon. The dominant amplification of the TE mode can then be written as

$$A \cong \Delta^3 B_1/(1 - \Delta^3 B_1) \qquad (2)$$

where $\Delta = R_c/R_m$, R_c is the core radius, and B_1 is an induction number for which values are tabulated (*6*). Examination of Eq. 2 suggests a confining layer approximately 100 km deep. Since the skin depth for the conductivity cited is of the order of 100 km, the value for the thickness of the crustal layer is only a rough approximation.

The principal conclusions to be derived from this preliminary report are that the moon exhibits an extraordinary level of induction from signals carried in the solar wind; the large amplification over that expected in a vacuum (when the induction is observed on the solar hemisphere of the moon) is indicative of a compression of a significant fraction of the induced field lines into a crustal layer of the moon where the bulk electrical conductivity is substantially less than that of deeper layers. Thus a model of the moon is suggested with a low-conductivity crustal layer overlying a core of higher conductivity. During the lunar night the response also shows about the same decay time but the amplification tends to unity, the response being more in keeping with the absence of plasma.

A conductivity gradient in the outer part of the moon is most likely associated with a thermal gradient since rocky matter, much like semiconducting material, exhibits an exponential dependence of conductivity on reciprocal temperature (*9*). Plausible lunar thermal models generally have thermal gradients in the range $1^\circ \lesssim T \lesssim 5^\circ$ per kilometer (*10*). Information presently available on lunar geochemistry is insufficient to permit us to judge the crustal thermal gradient. However, information on terrestrial olivines suggests that they may be effectively ruled out as a major constituent of the lunar crust unless the electrical conductivity of lunar olivines differs greatly from that of terrestrial olivines.

A complete Fourier analysis of the Explorer 35 and LSM magnetic field data (*11*) will include detailed tests for contributions from both the TE and the TM modes. These results will provide a complete electromagnetic transfer function for the moon. A formal inversion of these data into a conductivity profile is presently in preparation (*12*). In combination with appropriate geochemical information, the Apollo magnetometer experiment provides the unique potential for sounding the geophysical properties of the moon throughout most of its volume. The ability of electromagnetic radiation induced by the solar wind to penetrate to the center of the moon seems assured for the lowest frequencies under examination and appears to be unique.

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Surface-Related Mercury in Lunar Samples

Abstract. *Lunar samples contain mercury, which may be volatilized at lunar daytime temperatures. Such mercury may constitute part of the tenuous lunar atmosphere. If mercury can escape from the atmosphere by a nonthermal mechanism, an interior reservoir or exterior sources (such as meteorite infall or solar wind, or both) are required to replenish it. Core samples exhibit an increase in surface-related mercury with depth, which suggests that a cold trap exists below the surface. The orientation of rocks on the lunar surface may be inferred by differences in the amounts of surface-related mercury found on exterior and interior samples.*

Mercury is volatilized from lunar material at temperatures as low as that reached during lunar daytime, 130°C (*1*). The presence of this Hg and its distribution between the exterior and interior of rocks and in core samples from different depths could prove useful in understanding the behavior of volatiles on and in the moon. We report here the results of studies on the surface-related Hg in lunar samples. Surface-related concentrations of a number of other elements have been reported (*2*).

Two reservations must be kept in mind with regard to Hg on surfaces. One has to do with the possibility of contamination; the other with the effect of gases (N_2 and water vapor) on the properties of surfaces. The possibility of contamination can be assessed. The effect of gases requires evaluation of the consequences of exposure of the ultraclean vacuum-pumped and, in the case of exposed surfaces, vacuum-sputtered surfaces to gases that can be adsorbed. These compete for adsorption sites or may chemically alter the surface. The result of such exposure could reduce the amount and adhesiveness of the Hg on surfaces. Therefore, the concentrations measured may be lower limits, if losses have occurred, and the fraction released at lower temperatures may be upper limits because of increased lability.

There are several lines of evidence against terrestrial Hg contamination. Samples were obtained from the Lunar Receiving Laboratory (LRL) as powders (soil and crushed rock) and as rock fragments. All sample handling, including the crushing of rock fragments, was done in an N_2 box in our laboratory. The amount of Hg volatilized at low temperatures showed no systematic variation. The core samples opened at LRL should have had equal opportunity to become contaminated by volatiles; however, the sample from the top of core 10004 released 0.24 parts per billion (ppb) of Hg at temperatures of < 130°C, whereas the sample from the bottom released 4 ppb. The top, middle, and bottom of the 40-cm core from Apollo 12 released 0.06, 0.3, and 16 ppb, respectively. We assume that the exterior and interior of rocks 12053 and 12052 had similar exposure, yet they contain very different surface-related Hg concentrations (Table 1).

The stepwise volatilization of Hg from rocks after neutron activation has been discussed elsewhere (*3*). The striking difference between lunar rocks on the one hand and terrestrial and meteoritic rocks on the other is the frequent large release of Hg (> 10 percent) at or below 130°C in the lunar samples. The total Hg and that released at or below 130°C are given in Table 1; details of the release patterns are not given here. Samples from Apollo 11 and Apollo 12, including cores 10004 and 12025, 12028 and exterior and interior samples from rocks 12053, 12052, and 12022, were measured.

Atomic absorption experiments were performed to attempt to test whether Hg volatilized at low temperature was surface adsorbed. Crushed samples of rocks 10072 and 10017 were placed in an arm on an absorption cell. The cell was evacuated to ~ 1 μm of pressure, sealed off, and placed in an oven. A thermocouple was placed adjacent to the sample arm. The temperature of the oven could be raised or lowered and the Hg present as vapor could be measured by using the 2537-Å line. Details of this type of measurement are reported by Goleb (*4*).

Sample 10072 was heated in steps of about 25°C up to 200°C, and the absorbance was measured during both the heating and cooling cycles. Thereafter, the sample was recycled twice between room temperature and 130°C. Sample 10017 was inadvertently heated to 350°C, at which temperature 11 ppb of Hg was measured. This is close to the total of 13 ppb found in this sample (Table 1). When the sample was cooled to room temperature, the absorption did not return to zero; all the released Hg was not resorbed even after 2 weeks. The sample was recycled twice from room temperature to 130°C.

The amount of Hg measured at a given temperature during the initial heating in these experiments lagged behind the amount observed in the activation analysis experiments. In the subsequent heating cycles this was not the case. The amounts of Hg sorbed and desorbed at 130°C in the recycles and the amounts released in the activation analysis experiments for rocks 10072 and 10017 were, respectively, 1.8 versus 2.0 and 3.2 versus 3.4 ppb.

Table 1. Total Hg concentrations and Hg released at low temperature in lunar samples.

Sample		Hg at ≤ 130°C (ppb)	Total Hg (ppb)
	*Cores**		
10004,27	(0.0 cm)	0.30	3.0
10004,27	(13.2 cm)	4.0	39
12025,74	(1.5–2.5 cm)	0.06	10
12028,215	(18–19 cm)	0.30	17
12028,216	(38–39 cm)	16	20
	Rocks†		
12052,18	(interior)	0.40	3.0
12052,49	(exterior)	1.6	9.0
12053,31	(interior)	0.60	1.6
12053,31	(interior)	0.72	3.8
12053,53	(exterior)	4.7	12
12022,109	(interior)	3.5	8.0
12022,69	(exterior)	1.8	7.6
10017,22	(interior)	3.4	13
10072,24	(interior)	2.0	5.5
10044,48	(interior)	0.26	0.60
12021,84	(interior)	0.33	2.0
	Soils‡		
10084,1		0.35	2.8
10084,1		0.11	1.0
10084,2		1.5	5.3
10084,2	(> 150 μm)	0.0003	0.016
10084,2	(44–74 μm)	0.25	2.5
12070,61	(> 150 μm)	0.15	0.9
12070,61	(< 74 μm)	0.13	3.3
12033,18		1.0	2.6
10061,22	(microbreccia)	0.43	1.2

* Depth in core is given in parentheses. † Location of samples is given in parentheses. ‡ Grain size is given in parentheses.

The lag during the initial heating could be due to slow temperature equilibration in the samples. Gas released during the initial heating may have enabled more rapid equalization of temperature in the subsequent cycles. An alternate and perhaps more attractive explanation is that the initial absorbance was due to atomic Hg being released. The absorbance on subsequent cycles is higher because Hg compounds, vaporized even at < 130°C, were thermally decomposed at 200° or 350°C and yielded atomic Hg. The fact that the concentration of Hg observed at 130°C in subsequent recycling was the same as the concentration found at this temperature in the neutron-activated samples suggests that such a compound (or compounds) could account for most of the Hg released at low temperatures. Still another possibility is that the period of approximately 10 minutes required to attain temperature stability was too short a time to permit Hg present in grain boundaries, fissures, and dislocations to escape.

Some results of the activation analysis experiments are:

1) The surface-related Hg concentrations cluster into two groups: 0.1 to 0.5 ppb, predominantly soils; and 1 to 5 ppb, predominantly crystalline rocks (see Fig. 1).

2) The two core samples gave results that are consistent with each other. Both indicate a gradient with depth in total and surface-related Hg. Soil sample 12033 is from 15 cm below the surface. It falls in the group containing the higher concentrations of surface-related Hg. The other soil samples are from nearer the surface and with one exception fall in the low group. Rocks 12053 and 12052 would be consistent with this behavior if the exterior samples we received are bottom surfaces, or if these samples are similar to the fragments of rocks 10072 and 10017 discussed below.

3) There is no consistent correlation of surface-related Hg concentrations with grain size (Table 1). The < 74-μm fraction of sample 12070 has the same amount of surface Hg as the > 150-μm fraction, although the total Hg concentration is larger in the former (3.3 versus 0.9 ppb). In sample 10084,2 the finer-grained fraction does have more surface and total Hg than the coarser-grained fraction. The Preliminary Examination Team (*5*) reported that grain size in core 12025, 12028 increases with depth but so does the concentration of surface-related Hg (Table 1).

4) The gross correlation between Hg released below 130°C and total Hg is consistent with the expectation that Hg will attempt to equilibrate among all possible sites.

The surface of the moon may be divided into a substrate or bulk phase, an interface (perhaps a few centimeters thick), and an atmosphere that extends into voids in the interface. The distribution of volatiles between the atmosphere and the interface should be determined primarily by the sorbtive capacity and tenacity of the surfaces, by the temperature, and the volatility of the volatile component. The distribution of Hg between the substrate and the interface will be determined by diffusion through voids, along surfaces associated with grain boundaries, cracks, fissures, and dislocations, and by volume diffusion through crystal lattices.

The trend in Hg distribution in the bulk phase may be represented by the profiles observed in the core samples. In both cores the total and surface-related Hg concentration increases with

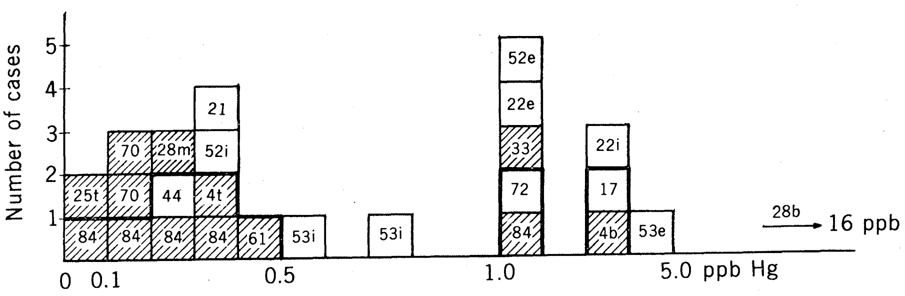

Fig. 1. Histogram of surface-related Hg in Apollo 11 and Apollo 12 samples. Apollo 11 samples are enclosed in heavy lines. Soil samples are shaded. Notation: *t*, top of core; *m*, middle of core; *b*, bottom of core; *i*, interior of rock; and *e*, exterior of rock.

depth. If our exterior samples of rocks 12053 and 12052 were buried surfaces, the pattern in these rocks is consistent with the core samples.

This trend is in agreement with the expectation that a cold trap may exist near the surface of the moon during lunar day. The temperature decreases from inside the moon toward a nighttime low of 140°K. In the daytime a temperature gradient descends from the surface, and a minimum temperature is probably attained at a few centimeters below the surface. Volatiles from the interior of the moon, or from the surface, may be condensed or adsorbed at this depth; from here they may diffuse to the surface, where they may volatilize or be released into the atmosphere by erosion processes.

If Hg is released from the lunar surface, it may either return to the surface, since the lifetime for gravitational escape is $> 10^{22}$ years, or it may be lost from the moon by nonthermal processes such as that proposed by Manka and Michel (*6*). If Hg is lost, it has to be replenished; otherwise, the amount of Hg in the moon has been decreasing with time.

The scale height for Hg is 10 km. Its cycloid radius calculated after Manka and Michel is $\sim 10^5$ km. Mercury has a lower ionization potential than the rare gases and will have a shorter ionization mean life than the 0.6 year for Ar. Because of its lower scale height, more than 40 percent of the ions (the estimate for Ar) will be accelerated into the surface.

The maximum surface-related Hg concentration averages $\sim 3.4 \times 10^{-9}$ g/g $= 3.4 \times 10^{-9}$ g per 0.6 cm^3 of soil. If the thickness of the surface layer from which Hg can be desorbed is ~ 2 mm there are ($\sim 3.4 \times 10^{-9}$ g per 3 cm^2) $\sim 1.1 \times 10^{-9}$ g/cm^2 of surface. If most of this is in the atmosphere, there will be $\sim 10^{-9}$ g (1.8×10^{11} atoms) in a 10-km column of 1-cm^2 cross section. This is compared with a total of $\sim 10^{14}$ atoms, based on an estimated atmospheric pressure of $\sim 10^{-8}$ torr (*7*).

Approximately one-half the Hg atoms in the atmosphere will be accelerated away from the moon an a time scale of less than 0.6 year. If the surface persists for 10^6 years, then 10^{12} atom/cm^2 ($\sim 10^{-9}$ g) will be lost. This is probably an overestimate; all the Hg on surfaces at the surface may not be desorbed. Our experiments indicate that 10 to 50 percent of the Hg measured at 130°C is released at 75°C. On the moon a temperature of 130°C is reached only at the subsolar point, and even at this point the mean temperature in a 2-mm layer will be lower. Furthermore, as already mentioned, the surface of the moon may be much more adhesive.

If we assume a loss rate from the surface of 10^{-10} g/cm^2 per 10^6 years, then in 1 million years all the surface-related Hg will be lost from a 1-mm layer of soil with an average Hg concentration of $\sim 2 \times 10^{-9}$ g/g and a density of ~ 2 g/cm^3. If the surface layers are gardened to 10 cm, in 10^8 years 100 times this amount ($\sim 10^{-8}$ g) of Hg will be lost. We see no decrease in Hg concentration with depth; in fact, the Hg concentration increases. Thus it appears that the present Hg concentrations represent steady-state amounts and that the Hg lost is being replenished. This can occur by replenishing depleted soil with new soil (*8*) or by supplying the Hg itself.

Rocks such as sample 10017 have large concentrations of surface-related Hg; yet they are quite porous, have higher thermal conductivities than does soil, and have spent from 50 to 500 million years at or very near the surface (*9, 10*). Since these rocks have not been reconstituted in 2.3 to 3 billion years, their surface-related Hg had to be replenished if it was ever lost.

To maintain the Hg concentration at the surface, there must be a reservoir inside the moon or there must be outside sources, such as meteorites or solar wind.

Interior reservoir. The Hg from an interior source may diffuse to the surface or it may be vented. The outermost layers of the moon may be honeycombed with fissures and cracks resulting from major impact events or tectonic activity. Gases may vent along these channels and be continuously available to the surface.

The possibility of a reservoir of volatiles inside the moon cannot be discounted. Unfortunately, the only other relatively volatile gravitationally bound elements are the heavier rare gases, but no surface-related Kr or Xe have been reported. Compounds such as the hydrides and oxides of C and N_2 may be candidates, and the interior of the moon may be an alternate source to those proposed—for instance, by Moore *et al.* (*11*).

Exterior sources. Of the two outside sources, meteorite influx has been the choice of Keays *et al.* (*12*) and of Moore *et al.* (*11*) to account for the increase in the soil versus rocks of the so-called depleted elements—such as Bi, Tl, Cd, Zn—and of C. They have estimated a 2 to 3 percent contribution from carbonaceous chondritic material. Öpik (*13*) has also postulated that 3 percent of meteorite material could be mixed in the soil if such material is to account for erosion.

The nanogram amounts of Hg found to be surface related can be provided by a few tenths percent of meteoritic material with an Hg abundance of 2.3 atoms per 10^6 Si atoms. If Hg can be lost, then the influx of such material must be at this level now.

Evidence in the form of tracks for the presence of 200 atomic mass unit nuclei in surface particles has been obtained by Fleischer *et al.* (*10*). They estimate an abundance relative to solar wind protons (10^8 cm^{-2} sec^{-1}) of 1.5×10^{-11}, in good agreement with the photospheric Pb/H ratio of 2×10^{-11}. In meteoritic matter Hg is about as abundant as Pb (*8*), and this is probably true throughout the solar system. Hence, perhaps almost half of the tracks could be due to Hg. The sun, through the solar wind and solar flares, could then be a significant source of Hg to the surface of the moon. The track density represents a lower limit to the contribution from this source, since lower-energy particles will not register a track and since erosion will have erased some tracks. The Hg arriving at the surface with a low velocity may not be retained, since it may be ejected before it has had time to diffuse into the surface. The situation is complex; nevertheless, simple consideration of the Hg cosmic abundance (2.3 atoms per 10^6 Si atoms) and a solar wind flux of 10^8 protons cm^{-2} sec^{-1} will provide the 10^{11} atoms or 10^{-10} g cm^{-2} of Hg lost from the surface over 10^6 years.

Exterior and interior samples from rocks 12052, 12053, and 12022 were measured. Of these, orientation and burial depth of only rock 12022 are known with some confidence. Most of this rock was buried, and our samples appeared to come from just at or below the surface of the soil. Rocks 12052 and 12053 were moved before being photographed; hence their orientation is not known. The lower part of rock 12052 appears to have been partially buried (*14*). Neither rock 12052 nor rock 12053 appears to have been buried as deeply as rock 12022.

If the core results are used as a guide, the rock results can be explained as follows. Our exterior samples of rocks 12052 and 12053 were buried and contain more surface-related Hg than do the interior samples. A possible explanation is that the interior of a crystalline rock exposed to the sun will be warmer than the buried surface in contact with the soil. The Hg that has migrated to the surface might be trapped at the cool interface of the rock and the soil. Rock 12022 was so deeply buried that the whole of the submerged part may have been at about the same low temperature; hence, the amount of Hg adsorbed on surfaces in the interior is about the same as that at the soil-rock interface. If this can be verified, the surface-related Hg might also be helpful in establishing the orientation of a rock.

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Selenium and Sulfur in a Greenland Ice Sheet: Relation to Fossil Fuel Combustion

Abstract. *In the combustion of fossil fuels, selenium is mobilized in the atmosphere to a much lesser extent than is sulfur. This difference is ascribed to the chemical behavior of their respective tetravalent oxides. The ratio of selenium to sulfur in glacial ice is characteristic of terrestrial matter, and these elements may find their way to ice sheets by the formation of volatile compounds in biochemical processes.*

The combustion of fossil fuels (coal, lignite, oil, and natural gas) mobilizes a variety of chemical species from the continents to the atmosphere, where they are subject to translocation. Recent investigations of glacial material have indicated that the amount of sulfur that enters the atmosphere from fossil fuel combustion is of the same order of magnitude as that which has resulted over historic time from the oxidation of organic matter and from volcanic activity (*1*). To determine whether the same is true of selenium was the purpose of this investigation. Selenium is a member of the group VI A elements in the periodic table, to which sulfur also belongs. Such an investigation might, therefore, also contribute to an understanding of the atmospheric chemistry of selenium as compared with sulfur. The value of measuring the concentration of closely related elements in geochemical studies is well recognized and, in relation to the current study, could extend our insight on the origin of sulfur in permanent snowfields.

Glacial samples are productive for studies of man's input of matter to the atmosphere. Various strata, which can be dated by a variety of techniques such as firn stratigraphy, isotopic analyses of oxygen, and ^{210}Pb geochronologies, contain in essentially unchanged condition both the waters and the accumulated solids that precipitated from the atmosphere.

The availability of dated glacial samples from Greenland (and a single sample from Antarctica) with known sulfate contents provided the materials for this investigation. The selenium content of these samples was determined by measurement of neutron induced ^{81}Se.

The samples were from the Camp Century area of the Greenland ice sheet (77°10′N and 61°07′W) and from a virgin area 80 km east southeast of this location. They were collected by C. C. Patterson of the California Institute of Technology for his investigations on Pb (*2*). The older samples of the Greenland ice sheets were recovered from the walls of an inclined shaft at Camp Century; the younger samples (1952–65) were taken from the walls of open trenches at the virgin site.

The single sample from Antarctica was recovered from an inclined shaft at the New Byrd Station.

These samples were collected and handled with extreme care to reduce the possibility of contamination. They were melted and stored in sealed polyethylene containers in 1966. The procedures and precautions involved in sample collection have been described in detail (*2*).

Fourteen samples were analyzed: eleven in duplicate, two in triplicate, and one was analyzed once. The sample volume ranged from 1 to 4 liters. The precise sample size was measured gravimetrically.

Each sample was transferred from its original polyethylene container to a round-bottom quartz flask, which had been previously leached with hot con-