DIELECTRIC PROPERTIES OF THE FIRST 100 METERS OF THE MOON

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Reviewing 92 measurements of lunar sample dielectric constant versus density at frequencies above 100 kHz, gives the relation $K' = (1.93 \pm 0.17)^p$ by regression analysis, where K' is the dielectric constant of a soil or solid at a density of p g/cm. This formula is the geometric mean between the dielectric constant of vacuum (1) and the zero porosity dielectric constant of lunar material. Similarly, the loss tangent (D) can be described by $D = [(0.00053 \pm 0.00056) + (0.00025 \pm 0.00009)C]p$ where D is the loss tangent at density p g/cm^3 with C percent of total FeO + TiO$_2$ (approximately proportional to ilmenite content). Using the density versus depth relations derived from lunar surface core tubes, and from laboratory studies of lunar soil compression gives a model of the dielectric properties as a function of depth in the lunar regolith. The dielectric constant increases smoothly with depth, as a function of the soil compaction only. The loss tangent, however, is more sensitive to the ilmenite content than it is to density. Neither dielectric constant nor loss tangent varies significantly with the temperature observed in a lunar day.

1. Introduction

Until recently, the probing of planetary surfaces has been done entirely by remote sensing methods. One of the most useful of these approaches has been the use of infrared and microwave techniques over a range of wavelengths [35, 56]. The dielectric constant and loss tangent of the surface material may be found from the reflection and transmission coefficients, and these may then be used for mapping purposes to distinguish between soil and rock exposures, slope angles, and other features. The surfaces of the Moon, Mars, and Mercury have been found to be very similar, with dielectric constants between 1.5 and 3 and loss tangents on the order of 0.005 [35, 56, 17, 62, 72]. Precise values depend upon the detailed assumptions with regard to specular reflection and other model parameters.

It is the sense of this paper to review the dielectric properties of lunar samples, measured as a function of density under controlled laboratory conditions. Then, using a density versus depth profile determined from in-situ core tube measurements and laboratory compression studies on lunar samples, a model will be presented for dielectric properties versus depth in the lunar surface.

In the absence of moisture [61], the dominant parameter which effects the dielectric constant of soils above 10^5 Hz is the packing fraction or mean density. For this reason, a number of studies of the dielectric constant of soils as a function of density have been undertaken, with various empirical equations derived to describe the results. As examples, Campbell and Ulrichs [11], in an extensive study of terrestrial rock and mineral powders, found excellent agreement between their data and the Rayleigh mixing formula, whereas Saint-Amant and Strangway [68] found the Lichtenecker (geometrical mean) formula to fit their observations of powdered terrestrial samples. Other observers have at various times used these and other formulas to describe lunar and planetary electrical properties [71]. We will show below that the geometrical mean formula adequately describes the dielectric constant and loss tangent variation with density.

Lunar sample studies have been performed by a number of investigators. Gold et al. [30–33] and Bassett and Shackelford [5] have specifically investigated the variation of dielectric constant and loss

tangent with density at radar frequencies. At lower frequencies, Chung et al. [18–21], Alvarez [2, 3], Sill et al. [67] and Frisillo et al. [29] have measured dielectric properties as functions of density, temperature, moisture content, and pressure. The effect of overburden pressure [29] has been shown to be very small and will be neglected here. In general, these data permit us to derive a regression analysis model of the variation of electrical properties with depth to about 100 m into the lunar regolith. The main uncertainty in the model is the precise nature of the variation of density with depth.

2. Density versus depth

Several core tube samples have been returned from the moon by the Apollo program, sampling the lunar regolith to depths near 1 m. From a knowledge of the volume and mass of material in each tube, it has been possible to determine a mean density, which is assumed to be representative of the in-situ density. These results along with surface density estimates from bootprint and equipment tracks have been compiled largely in a series of papers by the soil mechanics investigators [12–14, 38, 55] representing the most positive information that we have about the lunar surface density. Fig. 1 graphically summarizes this data with the hatched box representative of the ranges of core tube and drill core determinations of density. It appears that the surface density varies considerably from one landing site to another.

This variation is considered by Mitchell et al. [55] to be a result of overpressure at some sites. Thus it will be difficult to determine a representative density versus depth profile for the whole lunar surface. Nevertheless, the soil mechanics investigators have fitted the core tube data to an empirical formula of the form:

$$p = p_0 + k \ln (z + 1)$$

where p is the density in g/cm^3 at the depth z in centimeters, p_0 is the surface density ($z = 0$), and k is an empirical constant. Typical values are $p_0 = 1.27$ g/cm^3 and $k = 0.121$. This formula shows that the density increases rapidly with depth but below depths of about 1 m the increase becomes unrealistic.
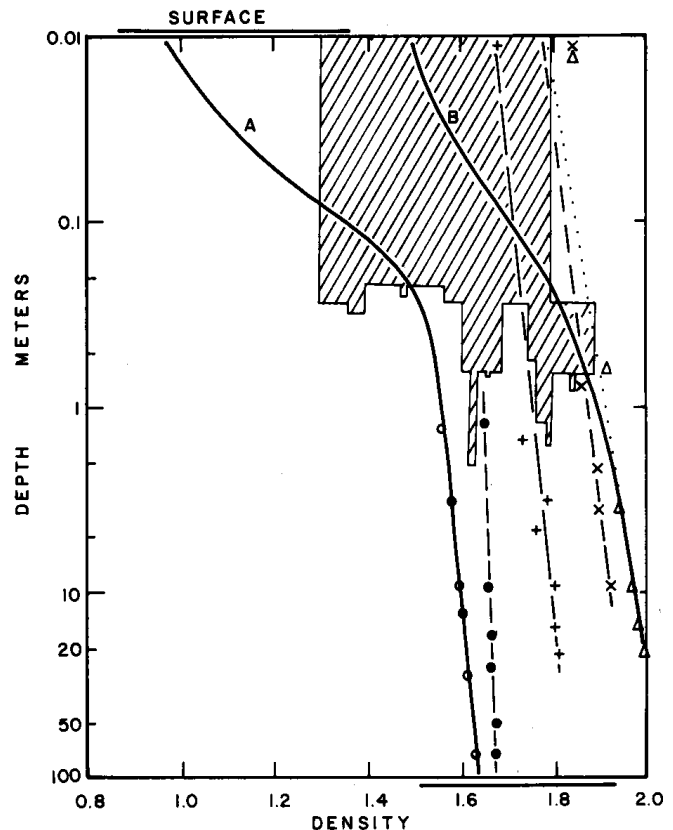

Fig. 1. Density versus depth in the moon; bars above and below the graph are the ranges of minimum and maximum lunar densities from laboratory sample measurements [14]; light hatched box shows limits of Apollo 15, 16, and 17 core tube and drill determinations of density; open and closed circles are laboratory compression results after Frisillo et al. [29]; pluses, crosses, and triangles are similar studies of Carrier et al. [13]; heavy solid lines, A and B, are present model profiles (see text).

Also shown in Fig. 1 are laboratory-determined self compression data from lunar soil samples after Carrier et al. [13] and Frisillo et al. [29]. The bars above and below the graph in Fig. 1 indicate the ranges of minimum and maximum soil compaction found for lunar samples in laboratory studies of self compression by Carrier et al. [13]. These laboratory studies may be fitted to a single formula encompassing the core tube data and formula given above if the formula is rewritten in the more general form:

$$z = 0.01 \left(-1 + \sum_{i=1} A_i e^{b_i p} \right)$$

where z is the depth in meters to the density, p, in g/cm^3 with the constants A_i and b_i to be determined.

TABLE 1

Curve A		Curve B	
A_1	0.0323	1.63×10^{-5}	
b_1	4.29	7.87	
A_2	1.9×10^{-39}	2.46×10^{-28}	
b_2	60.2	35.7	
p_0	0.80	1.40	$= -b_1^{-1} \ln A_1$
k	0.233	0.127	$= b_1^{-1}$

For only one term, A_1 and b_1 are representable in terms of Mitchell et al.'s formula above as $e^{-p_0/k}$ and k^{-1} respectively. Curves A and B in Fig. 1 are described by the constants in Table 1. The near-surface parts of the curves agree with the core tube density with depth relations in Mitchell et al. [55], and the deeper portions asymptotically approach the laboratory-derived soil self compression profiles of Frisillo et al. [29] and Carrier et al. [13]. This latter data is from measurements on surface fines and will not be representative of the compression of coarser rock mixtures or solid rock.

Hence, curves A and B represent estimates of the range of soil density with depth profiles in the lunar surface to 100 m, but they will deviate from reality when coarse rock chips or solid rock is encountered. Dunnebier et al. [27] and Kovach et al. [44] have found from the data of the Apollo 17 seismic profiling experiment evidence for a soil to rock transition near 8.5 m depth, and Strangway et al. [70] have found evidence from the Apollo 17 surface electrical properties experiment for a transition to rock near 7.0 m. Thus, the estimates of density versus depth in Fig. 1, while valid for soils to depths near 100 m, are probably not those actually encountered in the moon below 7–10 m depth.

3. Dielectric constant data

The dielectric constant of more than 100 samples of lunar soil and rock have been measured by the various investigating groups referenced above. Observations measured at 10^5 Hz or higher in frequency and for which there was a density and a chemical analysis

reported are used in this report (Table 2). Dielectric constants in dry materials below about 200°C are independent of frequency above a few kilohertz (see [58, 59]) so statistical comparison of data by different investigators using differing techniques and frequencies becomes feasible and useful. Fig. 2 illustrates the dielectric constant versus density for the samples of Table 2 as well as a formula to be discussed below. The relative measurement error within and between investigating groups is about ± 5% for soils and 10 to 15% for solids (due to poor sample geometries).

Specific studies on the relation between the dielectric constant and density in lunar samples have been previously reported by Gold et al. [30–33], Bassett and Shackelford [5], Alvarez [2], and Frisillo et al. [29]. The data from these investigations are also included in Table 2 and Fig. 2, and their conclusions are in general agreement with our observations below.

All of the data in Table 2 is used here in a standard regression analysis of the dielectric constant versus density, which yields the relation (with the requirement that $K' = 1.0$ at $p = 0.0$):

$$K' = (1.93 \pm 0.17)^p$$

where K' is the dielectric constant at the density p in g/cm^3. The standard deviation determined in the regression analysis is that expected due to errors in comparison between measurements of different investigators (it would be about half that shown, only if the measurements from a single laboratory were considered). This relation is shown in Fig. 2 and may be seen to be valid for both soil and rock samples. Thus, the relation may have general applicability to dry planetary surfaces. Moisture has a large effect [61] but most other adsorbed gases (e.g. from solar wind products) have a negligible contribution to the dielectric constant.

The striking exception to this relation is sample 60315 which Chung and Westphal [21] have measured, reporting a dielectric constant between 29. and 56. above 10^6 Hz. It has been described as a metal-rich rock. Thus it is possible that the space charge layer interfacial polarization mechanism is dominating the atomic (molecular) and electronic mechanisms of polarization which are the usual cause of the dielectric constant at these high frequencies. This mechanism, which is usually important only at much lower

TABLE 2

Sample	Sub-sample[1]	Ref.	Dens.	Freq. $(\times 10^6)$	Env.	K'	D	Ref.	%TiO$_2$	%FeO
10017	,30	41	3.10	1.0	N	8.8	0.075	48	11.74	19.82
10020	–	18	3.18	1.0	AN	10.0	0.13	48	10.72	19.35
1022	–	30	3.10	450.	A	4.2	0.06	63	12.20	18.90
1046	–	18	2.21	1.0	AN	9.0	0.05	48	10.35	19.22
10057	–	18	2.88	1.0	AN	11.0	–	28	11.44	19.35
10084	,83	41	1.94	1.0	N	3.8	0.0175	51	7.56	15.94
10084	–	30	1.00	450.	A	1.80	–			
			1.25	450.	A	2.06				
			1.56	450.	A	2.45				
12002	,58	19	3.30	1.0	AN	9.00	0.05	34	2.76	19.38
12002	,84	41	3.10	1.0	N	8.30	0.051			
12002	,85	41	3.04	1.0	N	7.80	0.056			
12002	,85	58	3.04	1.0	V	8.00	0.065			
12022	,60	19	3.32	1.0	AN	11.0	0.18	6	4.90	21.70
12063	,89	31	2.95	450.	A	7.0	0.069	76	5.00	21.26
12065	–	31	2.95	450.	A	7.30	–	49	3.80	22.00
12033	–	31	1.20	450.	A	1.80	–	22	2.48	14.20
			1.40	450.	A	2.20				
			1.70	450.	A	2.60				
12070	,107	42	1.74	1.0	N	3.0	0.025	51	2.81	16.40
12070	–	31	1.20	450.	A	1.80	–			
			1.40	450.	A	2.20	–			
			1.81	450.	A	3.20	–			
14301	,41	20	2.30	1.0	AN	4.80	0.05	50	1.70	9.80
14301	,37	20	2.17	1.0	AN	4.80	0.05			
14318	,30	20	2.30	1.0	AN	5.97	0.0082	64	1.46	9.50
14321	,163	20	2.40	1.0	AN	5.28	0.0123	50	2.40	13.00
14321	,228	20	2.35	1.0	AN	5.90	0.01			
14310	,72	20	2.86	1.0	AN	6.00	0.02	50	1.30	7.70
14310	,74	5	2.814	9000.	AN	6.46	0.0075			
14310	,75	20	3.30	1.0	AN	6.40	0.02			
14310	,87	20	3.30	1.0	AN	7.0	0.012			
14310	,161	32	2.75	450.	A	6.5	0.00454			
14003	–	32	1.16	450.	A	1.95	–	64	1.77	10.45
			1.55	450.	A	2.55	–			
14163	–	32	1.45	450.	A	2.55	–	64	1.77	10.41
			1.80	450.	A	3.25	–			
14163	,131	69	1.2	1.0	V	2.3	0.0006	51	1.79	10.35
14163	,164	5	1.71	9000.	AN	3.59	0.015			
			1.88	9000.	AN	3.59	0.015			
15415	,57	21	2.70	1.0	N	4.2	–	51	0.02	0.23
15459	,62	21	2.76	1.0	N	6.62	0.005	39	0.91	9.40
15498	,39	33	2.42	450.	A	5.45	0.008	46	1.60	17.30
15597	,30	33	2.85	450.	A	6.20	0.0022	57	1.87	20.17
15065	,27	21	2.86	1.0	N	6.70	0.01	54	1.48	19.18
15555	,88	21	3.10	1.0	N	6.15	0.0252	51	2.26	22.47
15021	,144	33	1.303	450.	A	2.20	0.00418	46	1.80	15.00
15041	,81	33	1.451	450.	A	2.50	0.00486	46	1.70	14.20
15211	,38	33	1.359	450.	A	2.45	0.00389	23	1.34	11.66
15221	,59	33	1.529	450.	A	2.55	0.00274	23	1.27	11.32
15301	,38	59	1.47	1.0	V	3.20	0.0008	51	1.17	14.05

TABLE 2 (continued)

Sample	Sub-sample[1]	Ref.	Dens.	Freq. (×10^6)	Env.	K'	D	Ref.	%TiO$_2$	%FeO
15301	,38	29	1.60	0.1	V	3.42	0.0122			
			1.62	0.1	V	3.49	0.0124			
			1.64	0.1	V	3.51	0.0125			
			1.68	0.1	V	3.58	0.0122			
			1.80	0.1	V	3.89	0.0125			
			1.83	0.1	V	3.98	0.0122			
15301	,43	33	1.576	450.	A	2.80	0.00438			
15601	,105	33	1.945	450.	A	3.30	0.00251	54	1.98	19.79
60015	,29	21	2.76	1.0	N	6.60	0.0002	46	0.06	0.35
61016	,34	21	2.79	1.0	N	7.82	0.016	65	0.69	4.97
60017	,45	33	2.85	450.	A	6.30	0.0024	65	0.30	2.97
65015	,7	67	2.70	1.0	V	7.00	0.008	25	1.26	8.59
65015	,6	58	2.70	1.0	V	7.70	0.008			
62235	,17	21	2.78	1.0	N	6.52	0.0066	52	1.21	9.45
61500	,7	33	1.143	450.	A	1.96	0.00277	52	0.56	5.31
			1.489			2.50	0.00347			
			1.906			3.55	0.00503			
62240	,5	33	1.383	450.	A	2.40	0.00364	65	0.56	5.49
			1.713			3.15	0.00416			
			1.906			3.30	0.00482			
62241	,21	67	1.34	1.0	V	2.40	0.001			
63501	,25	33	1.014	450.	A	1.70	0.00161	39	0.53	4.72
			1.420			2.40	0.00253			
			1.788			3.20	0.00341			
66041	,8	42	1.50	1.0	N	2.70	0.002	65	0.63	5.80
66014	,13	33	0.932	450.	A	1.60	0.00225			
			1.279			2.20	0.00300			
			1.531			2.70	0.00388			
66081	,20	67	1.490	1.0	V	2.80	0.001	52	0.67	5.85
67601	,22	33	1.151	450.	A	1.90	0.00216	52	0.42	4.09
			1.429			2.40	0.00259			
			1.675			2.95	0.00290			
72441	,12	29	1.56	0.1	V	3.05	0.005	66	1.53	8.68
			1.65	0.1	V	3.12	0.005			
			1.80	0.1	V	3.26	0.005			
74220	,24	60	1.37	1.0	V	2.60	0.019	53	8.81	22.04
74241	,2	2	1.38	0.1	V	2.20	0.010	53	8.61	15.84
			1.61	0.1	V	2.38	0.010			
75081	,3	*	1.90	1.0	N	3.50	0.010	53	9.52	17.41
75081	,27	60	2.08	1.0	V	2.40	0.018			

* T.J. Katsube, personal communication.

[1] Sub-sample number for electrical measurements, not generally the same as for the chemistry.

Dens. = density (g/cm^3).

Freq. = frequency of measurement in MHz.

Env. = environment: A = air, N = nitrogen, V = vacuum.

K' = dielectric constant (room temperature).

D = loss tangent.

    References 4, 7, 15, 16, 26, 40, 47, 74, 75 and 77 are alternative sources for chemical information on samples in the table.
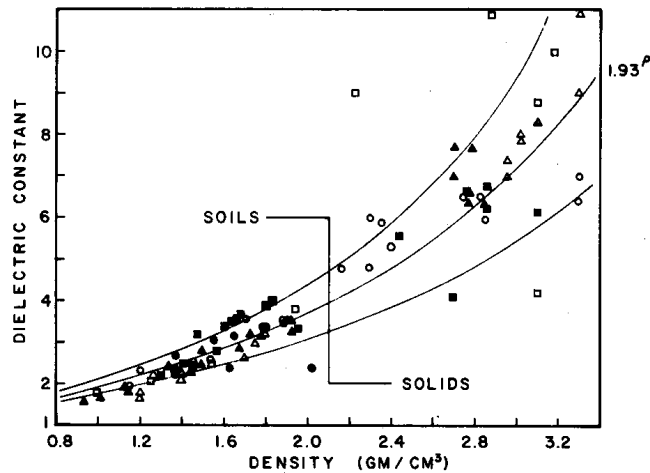
Fig. 2. Dielectric constant versus density with fitted equation from regression analysis (also shown are curves for plus or minus one standard deviation). Open squares, triangles, and circles are data from Apollo 11, 12, and 14 samples, respectively, and closed squares, triangles and circles are from Apollo 15, 16, and 17 samples, respectively.

frequencies, coupled with the high conductivity expected in the metallized sample probably explain the anomalous result of 60315.

The formula derived for the dielectric constant density relation is identical to the Lichtenecker formula which is a geometric mean (see Von Hippel [73]) between the dielectric constants of the various fractions making up the sample. This formula is a logarithmic addition formula given as:

$$\log K = \sum_i V_i \log K_i$$

where K_i and V_i are the dielectric constant and volume fraction of the ith component in a mixture of bulk dielectric constant K. Where one component of a two-component mixture is free space, the formula reduces to:

$$K = K_1^{p/G}$$

where K_1 is the dielectric constant at density G, and K is the dielectric constant at density p. This corresponds to the formula derived for the lunar samples by the regression analysis.

$$K_1^{1/G} = 1.93 \pm 0.17$$

From this we can determine the zero porosity dielectric constant, K_1, by inserting the specific gravity
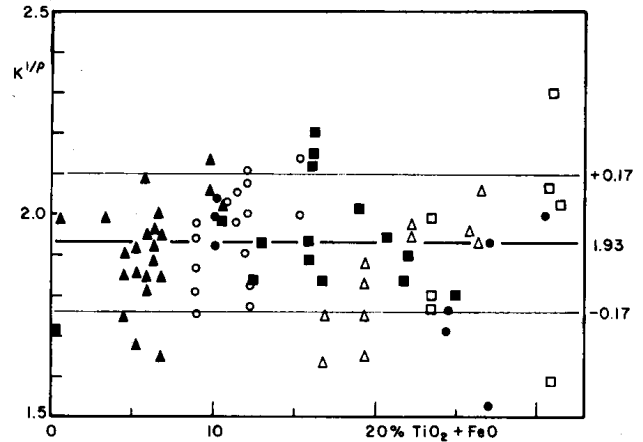

Fig. 3. Density normalized dielectric constant versus percent titanium and total iron oxides (key as for Fig. 2).

[9, 10, 14, 24]. For specific gravities in the range of 2.9 and 3.3 we find that the solid sample dielectric constant between 5.1 and 11.6 with a mean of 7.7 for a density of 3.1 g/cm^3. These values are in agreement with the solid sample measured values illustrated in Fig. 2.

It is particularly noteworthy that most of the samples, whether in soil or solid form, have the same density dependence. As is illustrated in Fig. 3, this implies a lack of variation of dielectric constant with chemistry. Although there is very little literature available on the variation of dielectric constant with chemistry, the lunar samples measured cover a wide range of compositions from almost pure anorthositic to pyroxene- and olivine-rich basalts. In addition there are wide ranges of iron and ilmenite contents in the lunar samples. Hansen et al. [36] have noted a correspondence between the dielectric constant and iron and titanium compounds (particularly ilmenite), but their measurements were not normalized to constant density. After normalization, the variation of dielectric constant with iron and titanium compound content is below the experimental error and not statistically significant. It should be noted that the lack of correlation in Fig. 3 does not mean that there is no relation between dielectric constant and ilmenite content (related to the FeO + TiO$_2$ content) as increasing ilmenite content does increase the density and thus indirectly the dielectric constant.

As a word of caution, these observations on lunar soils are mostly based on measurements performed on samples which contain fines less than 1 mm in size.

The true lunar soil is composed of this material, plus
a large number of small rock fragments. Typically,
however, this material represents only a very small
fraction of the bulk of lunar soils [37, 8] and further,
the lunar solid samples fit the same general relation-
ship as the soils, so the effect of rock chips on the
dielectric constant cannot be large. Also, sorting the
samples by type (basalt, soil, etc.) or mission or
frequency and then doing a regression analysis
produces essentially the same formula.

4. Loss tangents (D)

The loss tangent of lunar materials is much harder
to measure in a representative manner, as a very small
amount of atmospheric moisture may have a profound
effect [61, 69]. Nevertheless, a large number of mea-
surements are available (Table 2) to be used in a
regression analysis. Normalizing the loss tangent to
density with a formula of geometric mean, there ap-
pear to be two groups of data. Again, there is no clear
distinction between soil and solid samples, but those
measurements on samples from Apollo 11, 12, and
14 are consistently higher than the results found for
Apollo 15, 16, and 17 samples. This observation is
indicative of the profound effects of contamination
since the sample environment was not carefully con-
trolled during the early part of the lunar sample
program.

Fig. 4 displays the loss tangent data normalized
against density and plotted against FeO + TiO$_2$
content. (The data available are more limited than
those used in the dielectric constant analysis due to
the difficulties in extrapolating data from the figures
given in the literature.) A clear correlation between
the loss tangent and both the density and ilmenite
content may be seen. For the uncontaminated sample
measurements of Apollo 14, 15, 16, and 17 the data
fit a formula:

$$D = [(0.00053 \pm 0.00056) + (0.00025 \pm 0.00009)C]p$$

where D is the loss tangent at density p, and C is the
percent of FeO + TiO$_2$. This formula reduces to
Lichtenecker's formula of geometric mean for $C = 0\%$.

The formula given above for the variation of loss
tangent with density and ilmenite content covers
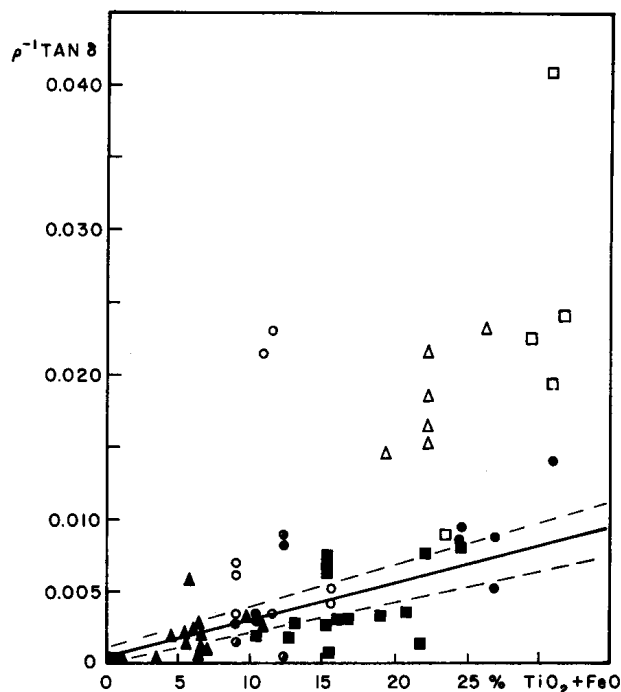three orders of magnitude in loss tangent for the

Fig. 4. Density normalized loss tangent versus titanium and
total iron oxides content (key as for Fig. 2, except half
closed circles are more reliable Apollo 14 data).

range of densities and ilmenite contents found on the
lunar surface, and it predicts the loss tangent at a
given density and ilmenite content to within ± 0.0035,
which is order of magnitude accuracy at the lower
densities and ilmenite contents and about 10% accu-
racy at the higher.

The above discussion and formula must be tem-
pered with some reservation. Unlike the dielectric
constant, the loss tangent is not necessarily indepen-
dent of frequency above 10^5 Hz. As has been discussed
elsewhere [58, 59], the frequency dependence of the
loss tangent is dependent upon the breadth of the distri-
bution of relaxation mechanisms, the loss tangent be-
coming more frequency independent with increasing
breadth of the distribution. Lunar samples have distri-
butions tending to be 2 to 4 or more times broader
than most terrestrial samples, with the result that lunar
sample loss tangents measured at frequencies four
orders of magnitude apart may be more readily com-
pared than terrestrial sample loss tangents an order of
magnitude apart in frequency.

The effect of the distribution on the frequency
response of the above formula for loss tangent at a
given density and ilmenite content would be to decrease
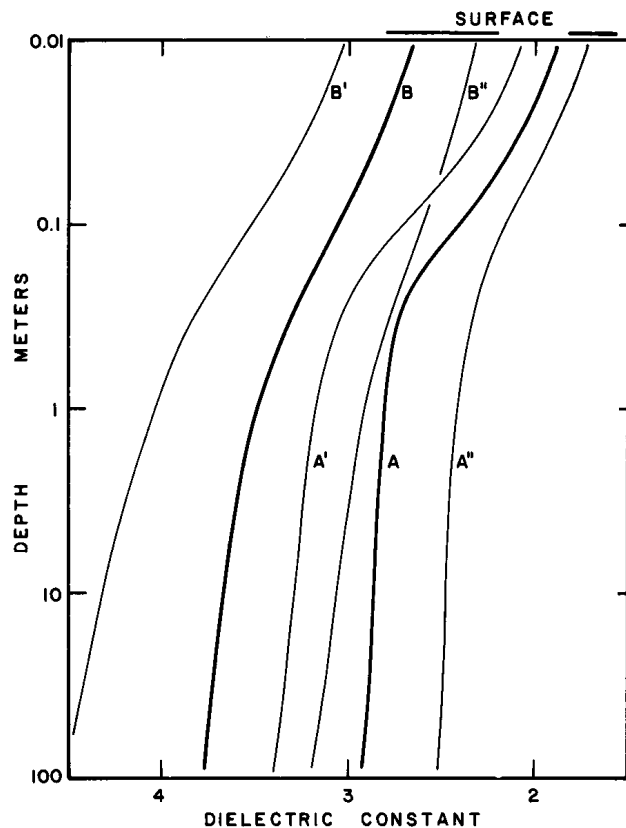the ilmenite dependence at frequencies higher than

Fig. 5. Dielectric constant versus depth in the moon. Curves A and B are models fitted to density profiles A and B from Fig. 1 (prime and double prime curves are plus and minus one standard deviation from dielectric constant versus depth formula).

10^6 Hz. Specific variations, however, would require the exact knowledge of the loss tangent frequency response for a particular sample. Some measure of this effect may be seen by sorting the data and doing a regression analysis of the 450-MHz data from Apollo 16 (15 points) to find

$$D = [(0.0015 \pm 0.0012) + (0.00009 \pm 0.00022)C]p$$

with a 68% probability that the coefficient for C is zero. This formula overlaps the previous loss tangent formula, but with much larger standard deviations and allowing the possibility of a decreased ilmenite dependence. This will be further investigated as more data becomes available.

5. Temperature dependence

As seen in a number of papers [18–21, 58, 59, 69,

1–3) the effect of temperature on the dielectric properties is very small over the range of temperatures found during a typical lunar day. Langseth et al. [45] and Keihm and Langseth [43] have shown that the lunar temperature becomes constant, independent of time of lunar day, below depths of a few centimeters of lunar soil. At the very surface, the dielectric constant may change by as much as 5% over a lunar day, and the loss tangent by 20–30%, but no changes will occur at depth. Thus the effects of temperature may be neglected in the top 100 m of the lunar surface as the interior temperature gradient is also negligible.

6. Discussion of model and conclusions

We have now presented and discussed the available data for the density, dielectric constant, and loss tangent of the surface of the moon. As the loss tangent is dependent upon ilmenite content, we will consider a model with 5%, 15%, and 30% FeO + TiO_2 which covers the most important ranges of lunar compositions. The formulas for density and dielectric constant derived can be combined to give an estimate of the dielectric constant versus depth as in Fig. 5. Profiles A and B represent the lower and upper density profiles of Fig. 1 in the formula found for dielectric constant versus density from sample analysis. Profiles with prime and double-prime superscripts show the standard deviation in the dielectric constant versus density. Again, it should be noted that these estimates are based upon measurements of surface samples and sieved fines, such that this model actually represents the range of lower limits of the dielectric constant with depth profiles. Also at some depth, the soil should give way to rock, where the dielectric constant will abruptly increase to about 7.7 as discussed above.

Fig. 6 shows the corresponding loss tangent profile with depth. Note that the ilmenite content is far more important than the density in determining the loss tangent at a given depth, and that variations in ilmenite content could very easily mask the effects of density. These curves are subject to the cautions noted above with regard to frequency response (they are primarily for the 10^5 to 10^8-Hz range). Where the soil changes to bedrock, the loss tangent will increase sharply (as will the dielectric constant) to values of about 0.0055, 0.013, 0.025 for 5%, 15%, and 30% ilmenite respectively at a density of 3.1 g/cm^3. The highest loss
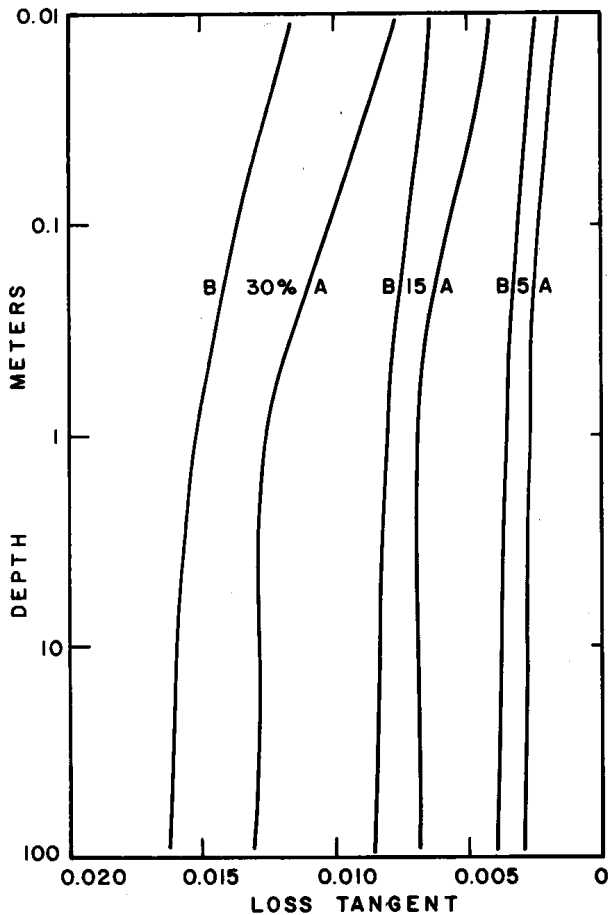
Fig. 6. Loss tangent versus depth in the moon. Curves A and B are for density profiles A and B of Fig. 1 with 5%, 15%, and 30% TiO_2 + FeO. Note that the chemistry is more important than the density.

The dielectric constant varies with density, independent of temperature, frequency, and ilmenite content. The loss tangent varies primarily with the metallic ilmenite content, with secondary effects due to density and frequency and is independent of temperature below a few centimeters depth. As further data becomes available in the literature, we will refine our observations.

References

1 R. Alvarez, Lunar powder simulator under lunarlike conditions: dielectric properties, J. Geophys. Res. 78 (1973) 6833–6844.
2 R. Alvarez, Lunar fines 74241, 2: low frequency dielectric variations with density and temperature, Trans. AGU 54 (1973) 1129.
3 R. Alvarez, Electrical properties of sample 70215 in the lunar temperature range of 100° to 373°K, in: Lunar Science V (Lunar Science Institute, 1974) 15–17.
4 B.M. Bansal, P.W. Gast, N.J. Hubbard, L.E. Nyquist, J.M. Rhodes, C.Y. Shih and H. Wiesmann, Lunar rock types, in: Lunar Science IV (LSI, 1973) 48–50.
5 H.L. Bassett and R.G. Shackelford, Dielectric properties of Apollo 14 lunar samples at microwave and millimeter wavelengths, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 3157–3160.
6 R. Brett, P. Butler, Jr., C. Meyer, Jr., A.M. Reid, H. Takeda and R. Williams, Apollo 12 igneous rocks 12004, 12008, 12009, 12022: a mineralogical and petrological study, Geochim. Cosmochim. Acta, Suppl. 2 (1971) 301–317.
7 A.O. Brunfelt, K.S. Heier, B. Nilssen, E. Steinnes and B. Sundvoll, Elemental composition of Apollo 17 fines, in: Lunar Science V (LSI, 1974) 92–94.
8 J.C. Butler, G.M. Greene and E.A. King, Grain size, frequency distribution and modal analysis of Apollo 16 fines, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 267–278.
9 D.A. Cadenhead, N.J. Wagner, B.R. Jones and J.R. Stetter, Some surface characteristics and gas interactions of Apollo 14 fines and rock fragments, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 2247–2257.
10 D.A. Cadenhead, B.R. Jones, W.G. Buergel and J.R. Stetter, Solar wind and terrestrial atmosphere effects on lunar sample surface composition, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 2391–2401.
11 M.J. Campbell and J. Ulrichs, Electrical properties of rocks and their significance for lunar radar observations, JGR 74 (1969) 5867–5881.
12 W.D. Carrier, S.W. Johnson, L.H. Carrasco and R. Schmidt, Core sample depth relationships: Apollo 14 and 15, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 3213–3221.

tangent above 10^5 Hz in the absence of metalized rocks like 60315 would likely be about 0.037 based on samples measured to date.

Figs. 1, 5, and 6 are our best estimates of the depth variation of the density, dielectric constant, and loss tangent based on currently available measurements of lunar samples. The density with depth determination is based upon core tube and other in-situ data for depth less than 2 m and on laboratory studies of lunar sample compression for depths corresponding to 75 m (extrapolated to 100 m). These profiles are thought to be good estimates of physical properties to depths of a few meters. Below this the transition from soil to broken rock or solid rock will give a sharp increase in the dielectric constant and loss tangent.

13 W.D. Carrier, L.G. Bromwell and R.T. Martin, Strength and compressibility of returned lunar soil, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 3223–3234.

14 W.D. Carrier, J.K. Mitchell and A. Mahmood, The relative density of lunar soil, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 2403–2411.

15 E.C.T. Chao, J.A. Minkin and J.B. Best, Apollo 14 breccias: general characteristics and classification, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 645–659.

16 E.C.T. Chao, J.B. Best and J.A. Minkin, Apollo 14 glasses of impact origin and their parent rock types, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 907–925.

17 S.C. Chase, E.D. Miner, D. Morrison, G. Munch, G. Neugebauer and M. Schroeder, Preliminary infrared radiometry of the night side of Mercury from Mariner 10, Science 185 (1974) 142–145.

18 D.H. Chung, W.B. Westphal and G. Simmons, Dielectric properties of Apollo 11 lunar samples and their comparison with earth materials, JGR 75 (1970) 6524–6531.

19 D.H. Chung, W.B. Westphal and G. Simmons, Dielectric behavior of lunar samples: electromagnetic probing of the lunar interior, Geochim. Cosmochim. Acta, Suppl. 2 (1971) 2381–2390.

20 D.H. Chung, W.B. Westphal and G.R. Olhoeft, Dielectric properties of Apollo 14 lunar samples, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 3161–3172.

21 D.H. Chung and W.B. Westphal, Dielectric spectra of Apollo 15 and 16 lunar solid samples, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 3077–3091.

22 F. Cuttitta, H.J. Rose, Jr., C.S. Annell, M.K. Carron, R.P. Christian, E.J. Dwornik, L.P. Greenland, A.W. Helz and D.T. Ligon, Jr., Elemental composition of some Apollo 12 lunar rocks and soils, Geochim. Cosmochim. Acta, Suppl. 2 (1971) 1217–1229.

23 F. Cuttitta, H.J. Rose, Jr., C.S. Annell, M.K. Carron, R.P. Christian, D.T. Ligon, Jr., E.J. Dwornik, T.L. Wright and L.P. Greenland, Chemistry of twenty-one igneous rocks and soils returned by the Apollo 15 mission, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 1081–1096.

24 M.B. Duke, C.C. Woo, M.L. Bird, G.A. Sellers and R.B. Finkelman, Lunar soil: size distribution and mineralogical constituents, Science 167 (1970) 648–650.

25 A.R. Duncan, A.J. Erlank, J.P. Willis and L.H. Ahrens, Composition and interrelationships of some Apollo 16 samples, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 1097–1113.

26 A.R. Duncan, A.J. Erlank, J.P. Willis and M.K. Sher, Compositional characteristics of the Apollo 17 Regolith, in: Lunar Science V (LSI, 1974) 184–186.

27 F.K. Dunnebier, J. Watkins and R. Kovach, Results from the lunar surface profiling experiment, in: Lunar Science V (LSI, 1974) 183.

28 A.E.J. Engel and C.C. Engel, Lunar rock compositions and some interpretations, Science 167 (1970) 527–528.

29 A.L. Frisillo, G.R. Olhoeft and D.W. Strangway, Effects of pressure, temperature and density on the electrical properties of lunar samples 72441 and 15301, and a terrestrial basalt, Earth Planet. Sci. Lett., 24 (1975) 345–356.

30 T. Gold, M.J. Campbell and B.T. O'Leary, Optical and high frequency electrical properties of lunar samples, Geochim. Cosmochim. Acta, Suppl. 1 (1970) 2149–2154.

31 T. Gold, B.T. O'Leary and M. Campbell, Some physical properties of Apollo 12 lunar samples, Geochim. Cosmochim. Acta, Suppl. 2 (1971) 2173–2181.

32 T. Gold, E. Bilson and M. Yerbury, Grain size analysis, optical reflectivity measurements and determination of high frequency electrical properties for Apollo 14 lunar samples, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 3187–3193.

33 T. Gold, E. Bilson and M. Yerbury, Grain size analysis and high frequency electrical properties of Apollo 15 and 16 samples, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 3093–3100.

34 T.L. Grove, D. Walker, J. Longhi, E. Stolper and J.F. Hays, Petrology of rock 12002 and origin of picritic basalts at Oceanus Procellarum, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 995–1011.

35 T. Hagfors, Remote probing of the moon by infrared and microwave emissions and by radar, Radio Sci., 5 (1970) 189–227.

36 W. Hansen, W.R. Sill and S.H. Ward, The dielectric properties of selected basalts, Geophysics, 38 (1973) 135–139.

37 G.H. Heiken, D.S. McKay and R.M. Fruland, Apollo 16 soils: grain size analysis and petrography, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 251–265.

38 W.N. Houston, J.K. Mitchell and W.D. Carrier, Lunar soil density and porosity, in: Lunar Science V (LSI, 1974) 363–365.

39 N.J. Hubbard, J.M. Rhodes, P.W. Gast, B.M. Bansal, C.Y. Shih, H. Weismann and L.E. Nyquist, Lunar rock types: the role of plagioclase in non-mare and highland rock types, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 1297–1312.

40 V.C. Juan, J.C. Chen, C.K. Huang, P.Y. Chen and C.M. WangLee, Petrology and chemistry of some Apollo 14 lunar samples, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 687–705.

41 T.J. Katsube and L.S. Collett, Electrical properties of Apollo 11 and 12 rock samples, Geochim. Cosmochim. Acta, Suppl. 2 (1971) 2367–2379.

42 T.J. Katsube and L.S. Collett, Electrical characteristics of Apollo 16 lunar samples, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 3101–3111.

43 S.J. Keihm and M.G. Langseth, Surface brightness temperature at the Apollo 17 heat flow site: thermal conductivity of the upper 15 cm of regolith, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 2503–2513.

44 R.L. Kovach, J.S. Watkins and P. Talwani, Lunar seismic profiling experiment, 10-1, Apollo 17 Prelim. Sci. Rept. NASA SP-330 (1973).

45 M.G. Langseth, S.J. Keihm and J.L. Chute, Heat flow experiment, 9-1, Apollo 17 Prelim. Sci. Rept., NASA SP-330 (1973).

46 J.C. Laul and R.A. Schmidt, Chemical composition of Apollo 15, 16, and 17 samples, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 1349–1367.

47 J. Longhi, D. Walker and J.F. Hays, Petrography and crystallization history of basalts 14310 and 14072, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 131–139.

48 LSPET (Lunar Sample Preliminary Examination Team), Preliminary examination of lunar samples from Apollo 11, Science 165 (1969) 1211–1227.

49 LSPET, Preliminary examination of lunar samples from Apollo 12, Science 167 (1970) 1325–1339.

50 LSPET, Preliminary examination of lunar samples from Apollo 14, Science 173 (1971) 681–693.

51 LSPET, The Apollo 15 lunar samples: a preliminary description, Science 175 (1972) 363–375.

52 LSPET, The Apollo 16 lunar samples: petrographic and chemical description, Science 179 (1973) 23–34.

53 LSPET, Apollo 17 lunar samples: chemical and petrographic description, Science 182 (1973) 659–672.

54 LSPET, Lunar sample information catalog: Apollo 15, NASA MSC-03209 (1971).

55 J.K. Mitchell, W.N. Houston, R.F. Scott, W.D. Carrier and L.G. Bromwell, Mechanical properties of lunar soil: density, porosity, cohesion and angle of internal friction, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 3235–3253.

56 D. Morrison, Thermophysics of the planet Mercury, Space Sci. Rev., 11 (1970) 271–307.

57 D.F. Nava, Chemistry of some rock types and soils from the Apollo 15, 16, and 17 lunar sites, in: Lunar Science V (LSI, 1974) 547–549.

58 G.R. Olhoeft, D.W. Strangway and A.L. Frisillo, Lunar sample electrical properties, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 3133–3149.

59 G.R. Olhoeft, A.L. Frisillo and D.W. Strangway, Electrical properties of lunar soil sample 15301, 38, JGR 79 (1974) 1599–1604.

60 G.R. Olhoeft, D.W. Strangway, G.W. Pearce, A.L. Frisillo and W.A. Gose, Electrical and magnetic properties of Apollo 17 soils, Trans. AGU 54 (1973) 601.

61 G.R. Olhoeft and D.W. Strangway, Electrical properties of the surface layers of Mars, Geophys. Res. Lett. 1 (1974) 141–143.

62 G.H. Pettingill, I.I. Shapiro and A.E.E. Rogers, Topography and radar scattering properties of Mars, Icarus, 18 (1973) 22–28.

63 H.J. Rose, Jr., F. Cuttitta, E.J. Dwornik, M.K. Carron, R.P. Christian, J.R. Lindsay, D.T. Ligon, Jr. and R.R. Larson, Semimicro X-ray fluorescence analysis of lunar samples, Geochim. Cosmochim. Acta, Suppl. 1 (1970) 1493–1497.

64 H.J. Rose, Jr., F. Cuttitta, C.S. Annell, M.K. Carron, R.P. Christian, E.J. Dwornik, L. Greenland and D.T. Ligon, Jr., Compositional data from Fra-Mauro lunar materials, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 1215–1229.

65 H.J. Rose, Jr., F. Cuttitta, S. Berman, M.K. Carron, R.P. Christian, E.J. Dwornik, L.P. Greenland and D.T. Ligon, Jr., Compositional data for twenty-two Apollo 16 lunar samples, Geochim. Cosmochim. Acta, Suppl. 4 (1973) 1149–1158.

66 H.J. Rose, Jr., F.W. Brown, M.K. Carron, R.P. Christian, F. Cuttitta, E.J. Dwornik and D.T. Ligon, Jr., Composition of some Apollo 17 samples, in: Lunar Science V (LSI, 1974) 645–646.

67 W.R. Sill, W. Hansen, S.H. Ward, T.J. Katsube and L.S. Collett, The Dielectric properties of Apollo 14 and 16 rock and soil samples, presented to the Geophysical and Geochemical Exploration of the Moon and Planets Conference, Lunar Science Institute, Houston, January (1973)

68 M. Saint-Amant and D.W. Strangway, Dielectric properties of dry, geologic materials, Geophysics, 35 (1970) 624–645.

69 D.W. Strangway, G.R. Olhoeft, W.B. Chapman and J. Carnes, Electrical properties of lunar soils: dependence upon frequency, temperature and moisture, Earth Planet. Sci. Lett., 16 (1972) 275–281.

70 D.W. Strangway, G.W. Pearce and G.R. Olhoeft, Magnetic and dielectric properties of lunar samples, submitted to Proceedings of the USA-USSR conference on Cosmochemistry of the Moon and Planets.

71 V.S. Troitsky and S.A. Shmulevich, Dependence of dielectric properties of rocks on their volume weight, JGR 78 (1973) 6933–6935.

72 G.T. Tyler and H.T. Howard, Dual frequency bistatic radar investigations of the moon with Apollo 14 and 15, JGR 78 (1973) 4552–4874.

73 A.R. Von Hippel, Dielectric materials and applications (MIT Press, Cambridge, Mass., 1954).

74 J.L. Warner, Apollo 12 lunar sample information, NASA TR-R-353 (1970).

75 J.L. Warner, Metamorphism of Apollo 14 breccias, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 623–643.

76 J.P. Willis, L.H. Ahrens, R.V. Danchin, A.J. Erlank, J.J. Gurney, P.K. Hofmeyr, T.S. McCarthy and M.J. Orren, Some inter-element relationships between lunar rocks and fines and stony meteorites, Geochim. Cosmochim. Acta, Suppl. 2 (1971) 1123–1138.

77 J.P. Willis, A.J. Erlank, J.J. Gurney, R.H. Theil and L.H. Ahrens, Major, minor and trace element data for some Apollo 11, 12, 14 and 15 samples, Geochim. Cosmochim. Acta, Suppl. 3 (1972) 1269–1273.