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The surface exposure (maturity) of lunar soils: Some concepts and I_s/FeO compilation

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Abstract—Surface exposure (or, equivalently, maturity) indices of lunar soils are a measure of residence time of soil in the upper one millimeter of the regolith. Several concepts concerning the use of and terminology associated with maturity indices are discussed. For reasons which include its generally-applicable nature and large data base, the FMR surface exposure (maturity) index I_s/FeO is particularly suitable and useful. A compilation of values of I_s/FeO for 164 Apollo surface and trench soils and six Luna 24 core soils is given.

INTRODUCTION

Since the moon is a planetary body without an atmosphere, its surface is exposed to unattenuated bombardment by micrometeorites, the solar wind, and galactic cosmic rays. The micrometeorites and solar wind interact with the upper one millimeter or so of the lunar regolith (i.e., virtually only the surface), in part producing fine-grained metal (from reduction of Fe^{2+} in the silicate and oxide phases of soil), agglutinate particles, and solarflare particle tracks and implanting solar wind gases (including N, C, and the trapped rare gases). In contrast, the galactic cosmic rays interact with the upper few meters of regolith, in part producing the cosmogenic rare gases and galactic particle tracks. It has been the practice of this and some other laboratories to use the term maturity when discussing the degree of surface exposure of lunar soils, the surface being defined as the upper one millimeter of regolith. Still other laboratories, however, use the same term when discussing the degree of exposure of lunar soils in the upper few meters. Obviously, conceptual difficulties have developed when discussing the exposure history of lunar soils. The problem is removed if, as is already the general practice, the term maturity is associated only with the surface exposure of lunar soils. The term age can be associated with exposure in the upper few meters of the regolith. Thus, a soil located at 20 cm depth is aging but not maturing.

The remainder of this paper is divided into two parts. In the first part, some concepts regarding surface exposure (maturity) indices are discussed. It is argued that the FMR surface exposure index, I_s/FeO, is particularly suitable as a general, quantitative index of surface exposure (maturity). The surface exposure index I_s/FeO is the ratio of the value of the intensity ($I_s = (\Delta H)^2 A$, where ΔH = linewidth and A = amplitude) in arbitrary units of the FMR resonance at $g \sim 2.1$ to the value of the FeO concentration (Morris, 1976). The FMR resonance at $g \sim 2.1$ in lunar soils is due to non-interacting fine-grained metal particles in, according to Housley *et al.* (1976), the diameter range from about 40 to 330 Å. It is necessary to normalize I_s to the FeO content of the soil in order to obtain a surface exposure index because I_s (i.e., the amount of fine-grained metal) is proportional to both the length of surface exposure and the amount of FeO available for reduction (e.g., Morris, 1976). The second part of the paper is a compilation of values of I_s/FeO for 164 Apollo surface and trench soils and six Luna 24 core soils.

CONCEPTS

Generally-applicable indices of surface exposure

In lunar soil studies, it sometimes becomes appropriate to correlate the values of experimentally or theoretically-derived parameters with the values of a surface exposure index representative of the bulk soil, i.e., to construct maturity correlations. Obviously, a generally-applicable index of surface exposure is the most suitable for this purpose. Generally-applicable means that there is no available evidence that the numerical values of a particular surface exposure index saturate or unduly reflect variations other than in the length of surface exposure. In an earlier paper (Morris, 1976), the FMR maturity index I_s/FeO was shown to be a generally-applicable index of surface exposure, and two other often-used indices, agglutinates and mean grain size, were shown not to be generally-applicable indices. The number percentage of petrographic agglutinates both saturates and is somewhat dependent on bulk soil composition. Mean grain size based on size data less than 1 mm is an especially insensitive surface exposure index (also see Morris, 1977). Mean grain size based on size data less than 1 cm is much more sensitive, but systematic offsets are present between different landing sites. Solar-flare track densities were not considered by Morris (1976), but they are not generally-applicable because the density of tracks saturates (e.g., Blanford *et al.*, 1977).

The preceding discussion should not be taken to imply that I_s/FeO can be used to the exclusion of other surface exposure indices. Agglutinate contents, solar-flare track densities, etc. have properties that are not inherent to I_s/FeO. Two examples illustrate this. The percentage of petrographically-determined agglutinates in a particular size range can be used to normalize the modal analysis of that size range to an "agglutinate free" basis (e.g., McKay *et al.*, 1977); this procedure allows modal analyses to be compared without the effect of maturation. Solar-flare track densities, because they are measured on individual mineral grains, can sometimes distinguish whether a soil has components having different maturities (e.g., Blanford *et al.*, 1977; Crozaz and Dust, 1977). It should also be pointed out that if an index is found with respect to which I_s/FeO saturates, then that index would be the appropriate index for maturity correlations.

In addition to its generally-applicable property, there are three additional factors that make I_s/FeO a particularly useful and suitable surface exposure (maturity) index for maturity-correlation plots. (1) The data base is large. The compilation at the end of this paper contains values of I_s/FeO for 164 surface and trench soils collected during the Apollo missions and 6 soils collected during the Luna 24 mission. The compilation thus contains greater than 96% of all surface and trench soils in the Apollo sample collection. Depth profiles of I_s/FeO are also available for five Apollo cores (Apollo 15 deep drill core, Heiken *et al.*, 1976; Apollo 16 deep drill core, Gose and Morris, 1977; 60009/10 core, Morris and Gose, 1976; Apollo 17 deep drill core, Morris *et al.*, 1978a; 74001/2 core, Morris and Gose, 1977, and Morris *et al.*, 1978b). (2) The values of I_s/FeO are based on measurements of a substantial size fraction of soil (<250 μm). (3) The values of I_s/FeO were all determined in one laboratory so that inter-laboratory biases are not possible.

Immature, submature, and mature

It is a semantic convenience when discussing the relative length of surface exposure of lunar soils to have them classified into immature, submature, and mature groups. This terminology was apparently first applied to lunar soils by McKay *et al.* (1974), and the classification is accomplished in the following manner. The observed range of values of a generally-applicable index of surface exposure is arbitrarily, but sensibly, divided into three parts. The part having the lowest values of the index, and thus reflecting relatively the shortest duration of surface exposure, is designated the immature range for the index. The part having the intermediate values, and thus reflecting relatively an intermediate duration of surface exposure, is designated the submature range. And similarly, the part having the highest values, and thus reflecting relatively the longest duration of surface exposure, is designated the mature range. For I_s/FeO, the immature range is from 0.0 through 29.0 units, the submature range is from 30.0 through 59.0 units, and the mature range is greater than or equal to 60.0 units.

Unfortunately, the classification immature, submature, and mature loses some of its usefulness because consistent ranges have not been maintained among the indices. This condition appears to have arisen largely because some of the classifications were based on surface exposure indices which subsequent studies have shown to be not generally-applicable. In any event, the correlations of various surface exposure indices given by Morris (1976) and/or the compilation given later in this paper can be used to define, in as much as is possible, consistent immature, submature, and mature ranges. As an example, the above ranges for I_s/FeO define the following equivalent ranges for petrographically-determined agglutinates: soils having about 0 to 28% agglutinates are immature; soils having about 28 to 45% agglutinates and <10.0 wt.% FeO or about 28 to 55% agglutinates and ≥10.0 wt.% FeO are submature; and soils having ~45% agglutinates and <10.0 wt.% FeO or ~55% agglutinates and ≥10.0 wt.% FeO can also be mature. The complex definition for the classification and lack of resolution at high agglutinate contents is due to the aforementioned compositional and saturation effects associated with agglutinates.

Regolith depth and maximum I_s/FeO

Earlier in this paper it was pointed out that saturation (i.e., after a certain time of surface exposure a surface exposure index reaches a maximum value and becomes insensitive to additional periods of surface exposure) limits the usefulness of a surface exposure index. Examination of the I_s/FeO compilation shows that the numerical values for I_s/FeO range from near 0.0 to over 100.0 units. Does the maximum value of I_s/FeO reflect a saturation effect or does it reflect a maximum surface exposure that is an inherent property of lunar soils? Available evidence indicates the latter is the case. The data of Morris (1978, unpublished material) shows that on the average only about 2% of the total FeO available for reduction has been reduced to fine-grained metal through surface exposure. Thus, for any soil examined to date, neither does I_s/FeO approach its absolute upper limit (the complete reduction of FeO to fine-grained metal) nor does the concentration of FeO available for reduction change appreciably with maturity. Nevertheless, I_s/FeO could still saturate before it reaches its upper limit, say by a process which coalesces fine-grained metal so that it is no longer observed in the FMR experiment. However, I_s/FeO and nitrogen do not saturate with respect to each other (Morris, 1976), indicating both saturate at the same rate with respect to a third and as yet unidentified index or, more likely, neither saturates. The conclusion that neither saturates seems reasonable on phenomonological grounds, but cannot be rigorously justified, because the processes associated with the derivations of fine-grained metal and nitrogen are so different, the former being reduction of FeO and the latter being direct implantation by the solar wind. In summary, there does not seem to be any available evidence that the maximum value of I_s/FeO for lunar soils is due to saturation of the index. What, then, limits the observed values of I_s/FeO? An argument adapted from one given by McKay *et al.* (1974) provides an answer.

According to the calculations of Quaide and Oberbeck (1975), the ratio of the volume of bedrock to the volume of regolith excavated per unit time by impacts decreases as the thickness of the regolith increases. Since crushed bedrock necessarily has no surface exposure, the maximum values of I_s/FeO should thus be determined ultimately by regolith thickness, and thin regoliths should have relatively lower maximum values of I_s/FeO than thicker ones. This appears to be the case, although there are the associated problems with applying the statistical treatment of Quaide and Oberbeck (1975) to relatively few data points. The Apollo 12 and 16 landing sites have, respectively, among the thinnest and thickest regoliths sampled during the Apollo missions (e.g., Quaide and Oberbeck, 1975). From the compilation, the maximum values of I_s/FeO for the Apollo 12 and 16 landing sites are, respectively, about 60 and 100 units.

The above argument does not endorse the general use of maximum values of I_s/FeO over a particular area on the moon to estimate regolith depths. A recent large impact excavating bedrock will leave a low maturity imprint on the surrounding area independent of the regolith thickness. Thus, the limited Luna 24 I_s/FeO data (maximum I_s/FeO = 39.0 units) should not be used to infer that the regolith at the Luna 24 site is thin, although it could be.

In summary, there is no available evidence that the maximum values of I_s/FeO observed in the lunar regolith are due to the saturation of the index. It seems most likely that maximum observed values of I_s/FeO reflect the input of unexposed material, which is related to the thickness of the regolith.

I_s/FeO Compilation

Table 1 is a compilation of values of I_s/FeO (<250 μm) for 164 Apollo surface

Table 1. Compilation of values of the FMR maturity index I_s/FeO for Apollo (excepting cores) and Luna 24 soils. Also given for each soil is its concentration of FeO and value of the FMR linewidth (ΔH). Soils having values of I_s/FeO (<250 μm) from 0.0 through 29.0 units are immature; from 30.0 through 59.0 units, submature; and greater than or equal to 60.0 units, mature.

No.	Soil	FeO (wt. %)	ΔH (Gauss)	I_s/FeO (<250 μm, Arb.)	Comment	No.
			Apollo 11			
1.	10010	15.1*	790	75.0	Mature	1.
2.	10011	14.6*	794	69.0	Mature	2.
3.	10084	15.8	790	78.0	Mature	3.
			Apollo 12			
4.	12001	16.8	752	56.0	Submature	4.
5.	12003	15.4	737	57.0	Submature	5.
6.	12023	16.0	737	60.0	Mature	6.
7.	12024	14.6*	705	30.0	Submature	7.
8.	12030	14.3	768	14.0	Immature	8.
9.	12032	15.1	760	12.0	Immature	9.
10.	12033	14.2	764	4.6	Immature	10.
11.	12037	17.3	742	21.0	Immature	11.
12.	12041	14.2	742	63.0	Mature	12.
13.	12042	16.8	747	61.0	Mature	13.
14.	12044	15.7	750	57.0	Submature	14.
15.	12057	16.6	739	40.0	Submature	15.
16.	12060	16.9	745	24.0	Immature	16.
17.	12070	16.5	725	47.0	Submature	17.
			Apollo 14			
18.	14003	10.4	600	66.0	Mature	18.
19.	14141	10.2	560	5.7	Immature	19.
20.	14148	10.4	600	74.0	Mature	20.
21.	14149	10.0	600	53.0	Submature	21.
22.	14156	10.4	600	68.0	Mature	22.
23.	14161	10.2	599	48.0	Submature	23.
24.	14163	10.4	595	57.0	Submature	24.
25.	14240†	10.4	582	46.0	Submature	25.
26.	14259	10.5	597	85.0	Mature	26.
27.	14260	10.0	590	72.0	Mature	27.

Table 1. *(cont'd.)*

No.	Soil	FeO (wt. %)	ΔH (Gauss)	I_s/Fe0 (<250 μm, Arb.)	Comment	No.
			Apollo 15			
28.	15012	12.4	660	66.0	Mature	28.
29.	15013	15.0	717	77.0	Mature	29.
30.	15021	15.0	730	70.0	Mature	30.
31.	15031	15.0	717	68.0	Mature	31.
32.	15041	14.3	731	94.0	Mature	32.
33.	15071†	16.4	715	52.0	Submature	33.
34.	15081	15.4	715	68.0	Mature	34.
35.	15091†	11.6	670	74.0	Mature	35.
36.	15101†	11.6	670	70.0	Mature	36.
37.	15201	11.9*	663	68.0	Mature	37.
38.	15211	11.7	685	60.0	Mature	38.
39.	15221†	11.5	665	63.0	Mature	39.
40.	15231†	11.6	663	71.0	Mature	40.
41.	15241†	12.3	658	45.0	Submature	41.
42.	15251	12.0	676	75.0	Mature	42.
43.	15261	12.1	678	77.0	Mature	43.
44.	15271	12.2	664	63.0	Mature	44.
45.	15291	11.6	666	63.0	Mature	45.
46.	15301	15.5	701	48.0	Submature	46.
47.	15401	18.3	665	5.6	Immature	47.
48.	15411†	13.2	680	43.0	Submature	48.
49.	15426	19.7	560	0.3	Immature	49.
50.	15431†	11.9	762	39.0	Submature	50.
51.	15471†	16.4	715	34.0	Submature	51.
52.	15501†	16.6	738	51.0	Submature	52.
53.	15531†	19.2	755	27.0	Immature	53.
54.	15601	19.2	746	29.0	Immature	54.
			Apollo 16			
55.	60051	4.5	557	57.0	Submature	55.
56.	60501†	5.5	554	80.0	Mature	56.
57.	60601	5.5	560	85.0	Mature	57.
58.	61141	5.3	570	56.0	Submature	58.
59.	61161	5.4	575	82.0	Mature	59.
60.	61181	5.5	575	82.0	Mature	60.

Table 1. *(cont'd.)*

No.	Soil	FeO (wt. %)	ΔH (Gauss)	I_s/FeO (<250 μm, Arb)	Comment	No.
61.	61221	4.9	568	9.2	Immature	61.
62.	61241	5.4	560	47.0	Submature	62.
63.	61281†	5.4	556	69.0	Mature	63.
64.	61501	5.6	563	53.0	Submature	64.
65.	62231	5.1*	594	91.0	Mature	65.
66.	62241†	5.2	583	100.0	Mature	66.
67.	62281	5.5	590	76.0	Mature	57.
68.	63321	4.7	545	47.0	Submature	68.
69.	63341	4.5	550	54.0	Submature	69.
70.	63501	4.7	555	46.0	Submature	70.
71.	64421	5.0	551	83.0	Mature	71.
72.	64501	5.2	555	61.0	Mature	72.
73.	64801	5.2	530	71.0	Mature	73.
74.	64811	5.6	555	54.0	Submature	74.
75.	65501	6.0	570	38.0	Submature	75.
76.	65511	6.0*	572	55.0	Submature	76.
77.	65701	5.7	565	106.0	Mature	77.
78.	65901	5.8	570	99.0	Mature	78.
79.	66031	5.5	573	102.0	Mature	79.
80.	66041	6.0	562	90.0	Mature	80.
81.	66081	6.2	560	80.0	Mature	81.
82.	67010	4.2*	555	26.0	Immature	82.
83.	67461	4.3	550	25.0	Immature	83.
84.	67481	4.2	545	31.0	Submature	84.
85.	67511	4.2*	555	8.8	Immature	85.
86.	67601	4.0	552	45.0	Submature	86.
87.	67701	4.2	550	39.0	Submature	87.
88.	67711	3.0	550	2.8	Immature	88.
89.	67941	4.2*	540	29.0	Immature	89.
90.	67960	4.6*	545	20.0	Immature	90.
91.	68121†	5.4	544	61.0	Mature	91.
92.	68501	5.3	558	85.0	Mature	92.
93.	68821†	5.2	555	84.0	Mature	93.
94.	68841	5.6	570	70.0	Mature	94.

Table 1. *(cont'd.)*

No.	Soil	FeO (wt. %)	ΔH (Gauss)	I_s/FeO (<250 μm, Arb.)	Comment	No.
95.	69921	5.6	555	90.0	Mature	95.
96.	69941	5.7	562	85.0	Mature	96.
97.	69961	5.7	572	92.0	Mature	97.
			Apollo 17			
98.	70011	16.0	795	54.0	Submature	98.
99.	70161	17.1	792	46.0	Submature	99.
100.	70181	16.4	790	47.0	Submature	100.
101.	70251	16.6*	790	43.0	Submature	101.
102.	70271	16.2*	790	56.0	Submature	102.
103.	70311	17.5*	795	39.0	Submature	103.
104.	70321	16.5*	785	42.0	Submature	104.
105.	71041	17.7	772	29.0	Immature	105.
106.	71061	17.8	775	14.0	Immature	106.
107.	71131	18.2*	783	33.0	Submature	107.
108.	71151	18.0*	795	34.0	Submature	108.
109.	71501	18.3	797	35.0	Submature	109.
110.	72131	17.2*	790	60.0	Mature	110.
111.	72141	13.5	750	81.0	Mature	111.
112.	72150	14.5	765	82.0	Mature	112.
113.	72161	14.9	765	87.0	Mature	113.
114.	72221	9.6*	652	58.0	Submature	114.
115.	72241	9.1*	660	64.0	Mature	115.
116.	72261	9.6*	657	59.0	Submature	116.
117.	72321	8.7	665	73.0	Mature	117.
118.	72431	9.8*	658	63.0	Mature	118.
119.	72441	8.7	656	68.0	Mature	119.
120.	72461	8.6	655	71.0	Mature	120.
121.	72501	8.7	660	81.0	Mature	121.
122.	72701	8.8	657	61.0	Mature	122.
123.	73121	8.5	670	78.0	Mature	123.
124.	73131	6.8*	635	16.0	Immature	124.
125.	73141	8.1	665	48.0	Submature	125.
126.	73151	9.3*	655	68.0	Mature	126.
127.	73211	9.4*	673	39.0	Submature	127.

Table 1. *(cont'd.)*

No.	Soil	FeO (wt. %)	ΔH (Gauss)	I_s/Fe0 (<250 μm, Arb.)	Comment	No.
128.	73221	8.9	675	43.0	Submature	128.
129.	73241	8.8	680	18.0	Immature	129.
130.	73261	8.9	680	45.0	Submature	130.
131.	73281	8.9	680	34.0	Submature	131.
132.	74111	10.2*	705	31.0	Submature	132.
133.	74121	10.0	700	88.0	Mature	133.
134.	74220	22.0	730	1.0	Immature	134.
135.	74241	14.9	685	5.1	Immature	135.
136.	74261	15.3	660	5.0	Immature	136.
137.	75061	18.0	790	33.0	Submature	137.
138.	75081	17.1	782	40.0	Submature	138.
139.	75111	16.0*	781	54.0	Submature	139.
140.	75121	16.0	787	67.0	Mature	140.
141.	76031	11.7*	720	64.0	Mature	141.
142.	76121	15.2*	770	71.0	Mature	142.
143.	76131	12.3*	737	70.0	Mature	143.
144.	76221	10.9*	720	66.0	Mature	144.
145.	76240	10.9	735	56.0	Submature	145.
146.	76261	10.9	720	58.0	Submature	146.
147.	76281	11.3	720	45.0	Submature	147.
148.	76321	9.8	720	93.0	Mature	148.
149.	76501	10.3	718	58.0	Submature	149.
150.	77511	12.3*	728	80.0	Mature	150.
151.	77531	11.7	735	79.0	Mature	151.
152.	78121	14.2*	740	68.0	Mature	152.
153.	78221	11.7	736	93.0	Mature	153.
154.	78231	13.1*	735	81.0	Mature	154.
155.	78421	12.0*	740	92.0	Mature	155.
156.	78441	12.4	740	77.0	Mature	156.
157.	78461†	12.2	732	83.0	Mature	157.
158.	78481	13.1	740	82.0	Mature	158.
159.	78501	13.2	727	36.0	Submature	159.
160.	79121	16.5	780	57.0	Submature	160.
161.	79221	15.4	795	81.0	Mature	161.

Table 1. *(cont'd.)*

No.	Soil	FeO (wt. %)	ΔH (Gauss)	I_s/FeO (<250 μm, Arb)	Comment	No.
162.	79241	15.6	788	51.0	Submature	162.
163.	79261	15.0*	785	43.0	Submature	163.
164.	79511	15.3	785	61.0	Mature	164.
			Luna 24			
165.	24077	19.9	787	39.0	Submature	165.
166.	24109	20.6	783	31.0	Submature	166.
167.	24149	20.3	798	21.0	Immature	167.
168.	24174	20.9	790	27.0	Immature	168.
169.	24182	20.2	793	19.0	Immature	169.
170.	24210	21.1	790	19.0	Immature	170.

*Determined magnetically. The other FeO values were determined chemically and obtained from the Curatorial Data Base (J. Warner, compiler).

†These samples were reissued by the RSPL. The pedigree of these samples is thus not as secure as it is for the other samples.

and trench soils and six Luna 24 core soils. The compilation includes the data of Morris (1976) and new data. The experimental technique for the measurement of I_s (relative concentration of fine-grained, i.e., ~40 to 330 Å, metal) is given in the above paper. Except as noted in the compilation, the values of FeO determined by chemical analysis were used to compute I_s/FeO. The other FeO values were determined magnetically as chemically-determined values were apparently not available. Since the accuracy of the magnetic method is not quite as good as that of chemical methods, some of the values of I_s/FeO in the compilation may require updating as chemical data becomes available.

SUMMARY

(1) Surface exposure, or maturity, indices of lunar soils are a measure of residence time of soil in the upper one millimeter of the regolith. Confusion in terminology will be avoided if the term maturity is associated only with the surface exposure of lunar soils, the surface being defined as the upper one millimeter of soil. The terms immature, submature, and mature represent a semiquantitative maturity grouping denoting, respectively, successively longer periods of surface exposure.

(2) For reasons which include a generally-applicable nature and a large data base, the FMR surface exposure (maturity) index I_s/FeO is particularly suitable and useful. A compilation of values of I_s/FeO for 164 Apollo surface and trench soils and six Luna 24 core soils is given.

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