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Surface exposure indices of lunar soils: A comparative FMR study

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Abstract—It has been previously suggested (Housley *et al.*, 1973, 1974, 1975) that the intensity of the characteristic FMR resonance of a lunar soil normalized to its total iron content (I_s/FeO) can be used as its index of relative surface exposure age. The characteristic resonance is due to fine-grained metal that is the result of micrometeorite impact at the lunar surface. In this study, I_s/FeO was measured for the <250 μm size fraction of 152 soils and for the 90–150 μm size fraction of 88 soils. With this large suite of samples it was possible to correlate I_s/FeO with a variety of other indices of relative surface exposure age (N, C, $^4He_{tr}$, $^{36}Ar_{tr}$, petrographic and magnetic agglutinates, and mean grain size) and thus not only affirm that I_s/FeO is an index of relative surface exposure age but also consider the relative merits of the various surface exposure indices.

INTRODUCTION

THE FERROMAGNETIC RESONANCE (FMR) spectra of all lunar soils are dominated by a resonance (usually called the characteristic resonance) due to fine-grained particles that are ferromagnetically ordered. These particles are constrained by the FMR resonance condition in powders to have negligible shape anisotropy (i.e., they are spherical or nearly spherical in shape) and to have a size sufficiently small so that they are not multidomain in the mean resonance field of ~ 3 kG used in the FMR experiment (Tsay *et al.*, 1971). FMR Curie point measurements have shown that the fine-grained particles are essentially pure metallic iron in composition (Morris *et al.*, 1975) and thus they must also be less than ~ 300 Å in diameter so that they will not be multidomain (e.g., Nagata, 1961).

Housley *et al.* (1974) have shown for soil particles in the size range 420–1000 μm that the characteristic resonance is predominantly associated with agglutinates and regolith breccias. They associated the presence of a much less intense characteristic resonance on other soil particles with the presence of agglutinatic glass splashed on the surfaces of those particles. Thus, Housley *et al.* (1973; 1974; 1975) proposed that the fine-grained metal particles are formed from reduction of Fe^{2+} in response to micrometeorite impact on the lunar surface. Furthermore, they suggested that the specific FMR intensity normalized to the total iron content (I_s/FeO) could be used to measure the relative surface exposure ages of lunar soils. This suggestion is supported by the study of Pillinger *et al.* (1974) who showed for a few soils that I_s/FeO correlates with $^{36}Ar_{tr}$.

In this study, I_s/FeO was measured for the <250 μm size fraction of 152 soils and for the 90–150 μm size fraction of 88 soils. With this large suite of samples, it was possible to correlate I_s/FeO with a variety of other indices of surface exposure (N, C, $^4He_{tr}$, $^{36}Ar_{tr}$, petrographic and magnetic agglutinates, and mean

grain size) and thus not only affirm that I_s/FeO (as measured for the <250 μm size fraction) is an index of relative surface exposure age (i.e., an index of soil maturity) but also consider the relative merits of the various surface exposure (i.e., maturation) indices.

It is worthwhile to point out that this study affirms that the parameter I_s/FeO is an index of maturity or relative surface exposure age. As such, no particular mechanism for the production of the fine-grained metal is implied, except that the fine-grained metal must be produced by reduction of Fe^{2+} during exposure on the lunar surface.

EXPERIMENTAL

The FMR spectra were recorded at room temperature on a Varian E-12 EPR spectrometer operating at a nominal frequency of 9.5 GHz. The intensity of the characteristic resonance (I_s) was calculated from $(\Delta H)^2 A/m$ where ΔH and A are the peak-to-peak linewidth and amplitude of the characteristic resonance and m is the mass of the sample. The measurements were obtained from ~2.0 mg of sample in 2.0 mm O.D. − 0.5 mm I.D. quartz sample tubes. Since the values of A are measured in chart recorder (arbitrary) units, the values of I_s are calculated relative to the standard sample. Replicate measurements on the same sample shows that the precision of the measurement of I_s is about ±5%.

The FMR measurements were performed on both sieved and unsieved (<1 mm) samples of soil. The size fractions of the sieved soils included the 90–150 μm size fraction so that a direct comparison can be made with petrographic agglutinates which are also measured in the 90–150 μm size fraction. For the sieved soils, the values of A and ΔH and thus I_s for the <250 μm size fraction were calculated from the weighted sum of all the size fractions less than 250 μm. The vials containing the <1 mm fines were sampled by inserting the open end of the sample tube directly into the vial. For a few soils for which both grain size separates and <1 mm fines were available, comparison of the values of I_s and ΔH for the <1 mm fines to the corresponding values for the <250 μm size fraction gives nearly the same (within ±5%) value. Thus, the sampling procedure effectively samples only the <250 μm size fraction of the <1 mm fines. Presumably, this is the result of the small diameter of the sample tube (500 μm) and the fact that the <250 μm size fraction constitutes 70–90 wt.% of the <1 mm size fraction (McKay, unpublished results). Therefore, all results for the <1 mm fines are reported as the <250 μm size fraction.

RESULTS AND DISCUSSION

The values of ΔH, I_s, FeO and I_s/FeO for the <250 μm size fraction of the 152 soils are reported in Table 1. For the soils that were sieved, the value of I_s/FeO for the 90–150 μm size fraction is also reported. The values of FeO were obtained from a curatorial data base (compiled by J. Warner) and are the average of literature values for total FeO. Also reported in Table 1 are literature values for the concentrations of N, C, $^4He_{tr}$ and $^{36}Ar_{tr}$, the percentages of petrographic agglutinates, the percentage magnetic fraction (magnetic agglutinates), the <1 cm and <1 mm mean grain sizes, and the values of Fe°/FeO (Fe° determined magnetically); references for this data are given at the bottom of Table 1. From the list of references, it can be seen that this compilation is somewhat selective in order to minimize experimental bias between laboratories.

To place the observed variation of I_s/FeO (<250 μm) for the six Apollo

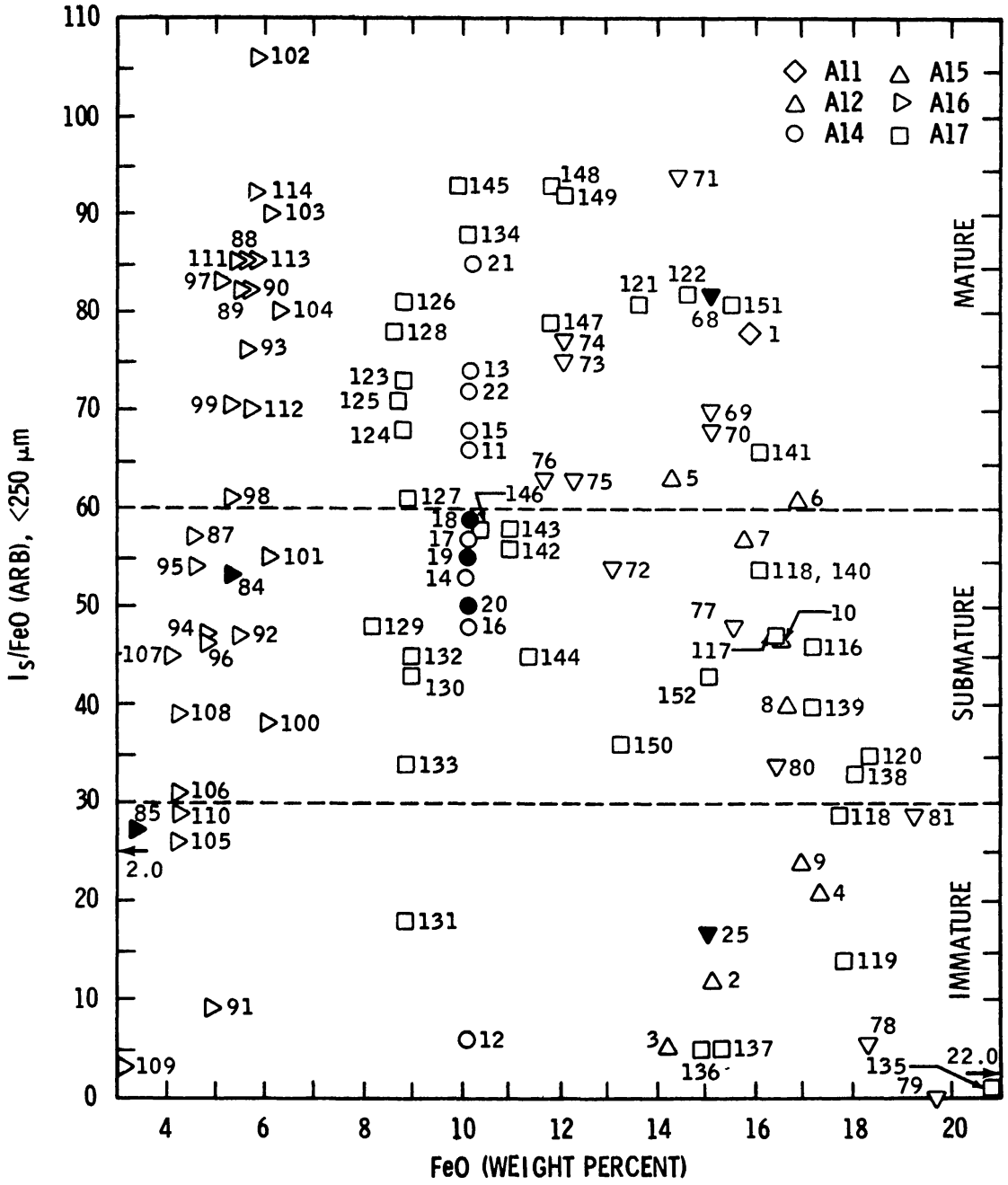

Fig. 1. Variation of I_s/FeO with FeO for soils from all Apollo landing sites. The values of FeO for the soils are a convenient parameter to separate data into highland (low FeO) and mare (high FeO) types of soil. The open symbols denote surface and trench soils, the closed soils denote drive tube and core soils. The numbers on the graph correspond to the samples given in Table 1.

landing sites into perspective, I_s/FeO is plotted against the weight percentage of FeO in Fig. 1 for surface, trench, and selected core and drive tube soils. Note that although there is no inherent upper limit for the values of I_s/FeO, the largest values observed correspond to I_s/FeO ~ 100 units. The range of the parameter I_s/FeO for immature, submature, and mature levels of soil maturity are also

Table 1. Compilation of FMR data and maturity indices. References are given at the bottom of the table.

No.	Sample*	ΔH <250 μm (G)	FeO (wt.%)	I_s/FeO (Arb.) <250 μm	I_s/FeO (Arb.) 90–150 μm	N (μg/g)	C (μg/g)	$^4He_{tr}$ (10^{-2} cc/g)	$^{36}Ar_{tr}$ (10^{-4} cc/g)	Pet. agglut-inates (%)	Mag. fraction (%)	Mean grain size (μm) <1 cm	Mean grain size (μm) <1 mm	Fe°/FeO	No.
1.	10084,853	790	15.8	78.0	48.0	92	—	21.9	4.36	—	84	—	52	0.025	1.
2.	12032,24	760	15.1	12.0	—	—	60	—	—	—	—	—	—	—	2.
3.	12033,40	764	14.2	4.6	—	—	45	—	—	—	—	—	—	—	3.
4.	12037,18	742	17.3	21.0	—	—	65	—	—	—	—	—	—	—	4.
5.	12041,10	742	14.2	63.0	—	—	—	—	—	—	—	—	—	—	5.
6.	12042,27	747	16.8	61.0	—	—	130	9.76	3.01	—	—	—	—	—	6.
7.	12044,11	750	15.7	57.0	—	—	—	8.42	3.06	—	—	—	—	—	7.
8.	12057,43	739	16.6	40.0	—	—	—	—	—	—	—	—	—	—	8.
9.	12060,6	742	16.9	24.0	—	—	—	—	—	—	—	—	—	—	9.
10.	12070,29	725	16.5	47.0	—	79	—	8.60	2.94	—	—	—	—	0.042	10.
11.	14003,71	600	10.4	66.0	—	92	140	6.26	3.54	60	76	129	99	—	11.
12.	14141,30	560	10.2	5.7	3.4	—	42	—	—	5	23	616	123	—	12.
13.	14148,23	600	10.4	74.0	52.0	—	160	5.50	2.67	50	74	77	60	—	13.
14.	14149,39	600	10.0	53.0	43.0	—	135	5.10	2.39	26	63	230	92	—	14.
15.	14156,23	600	10.4	68.0	56.0	—	110	5.20	3.21	48	68	70	64	—	15.
16.	14161,46	599	10.2†	48.0	—	—	—	—	—	—	—	—	—	—	16.
17.	14163,178	595	10.4	57.0	—	—	115	6.05	3.09	—	71	76	56	0.052	17.
18.	14230,113	580	10.2†	59.0	59.0	—	—	—	—	53	—	109	85	—	18.
19.	14230,121	580	10.4†	55.0	47.0	—	—	—	—	57	—	74	70	—	19.
20.	14230,130	580	10.2†	50.0	41.0	—	—	—	—	52	—	118	103	—	20.
21.	14259,52	600	10.5	81.0	87.0	—	160	—	4.39	52	83	69	63	0.066	21.
21.	14259,111	595	10.5	89.0	—	—	—	—	—	—	—	—	—	—	21.
22.	14260,4	590	10.0	72.0	69.0	—	—	—	—	—	83	117	86	—	22.
23.	15001,21	730	15.0†	19.0	7.3	—	—	—	—	25	—	81	62	—	23.
24.	15001,28	730	15.0†	17.0	7.8	—	—	—	—	20	—	73	65	—	24.
25.	15001,265	745	15.0†	17.0	3.8	—	—	—	—	8	—	—	73	—	25.
26.	15001,266	740	15.0†	19.0	8.9	—	—	—	—	6	—	—	52	—	26.
27.	15001,267	732	15.0†	28.0	16.0	—	—	—	—	28	—	—	—	—	27.
28.	15001,268	735	15.0†	33.0	21.0	—	—	—	—	24	—	—	—	—	28.
29.	15001,269	735	15.0†	33.0	16.0	—	—	—	—	22	—	—	—	—	29.
30.	15001,270	732	15.0†	35.0	20.0	—	—	—	—	26	—	—	55	—	30.
31.	15001,271	737	15.0†	28.0	17.0	—	—	—	—	21	—	—	—	—	31.
32.	15002,24	715	15.0†	34.0	22.0	—	—	—	—	41	—	73	66	—	32.
33.	15002,326	725	15.0†	41.0	20.0	—	—	—	—	23	—	—	—	—	33.
34.	15002,327	730	15.0†	40.0	17.0	—	—	—	—	22	—	—	74	—	34.
35.	15002,328	728	15.0†	39.0	23.0	—	—	—	—	30	—	—	—	—	35.
36.	15002,329	718	15.0†	40.0	20.0	—	—	—	—	23	—	—	78	—	36.
37.	15002,330	730	15.0†	46.0	29.0	—	—	—	—	35	—	—	—	—	37.
38.	15002,331	717	15.0†	42.0	28.0	—	—	—	—	25	—	—	238	—	38.
39.	15002,332	718	15.0†	36.0	18.0	—	—	—	—	24	—	—	—	—	39.
40.	15002,333	723	15.0†	46.0	22.0	—	—	—	—	28	—	—	50	—	40.

41.	15002,334	723	15.0†	42.0	22.0	—	—	—	—	30	—	—	—	—	41.
42.	15003,19	725	15.0†	30.0	21.0	—	—	—	—	27	—	60	55	—	42.
43.	15003,26	725	15.0†	30.0	14.0	—	—	—	—	25	—	51	44	—	43.
44.	15003,321	725	15.0†	25.0	5.7	—	—	—	—	12	—	—	57	—	44.
45.	15003,322	720	15.0†	18.0	6.0	—	—	—	—	11	—	—	105	—	45.
46.	15003,323	700	15.0†	34.0	17.0	—	—	—	—	23	—	—	—	—	46.
47.	15003,324	703	15.0†	46.0	28.0	—	—	—	—	34	—	—	48	—	47.
48.	15004,17	708	15.0†	37.0	32.0	—	—	—	—	47	—	63	59	—	48.
49.	15004,24	700	15.0†	38.0	30.0	—	—	—	—	34	—	—	70	—	49.
50.	15004,131	700	15.0†	40.0	30.0	—	—	—	—	36	—	—	53	—	50.
51.	15004,132	675	15.0†	38.0	25.0	—	—	—	—	43	—	—	54	—	51.
52.	15004,133	705	15.0†	26.0	13.0	—	—	—	—	22	—	—	52	—	52.
53.	15005,16	715	15.0†	22.0	15.0	—	—	—	—	24	—	97	86	—	53.
54.	15005,23	715	15.0†	26.0	19.0	—	—	—	—	33	—	73	65	—	54.
55.	15005,390	707	15.0†	36.0	19.0	—	—	—	—	30	—	—	—	—	55.
56.	15005,391	705	15.0†	39.0	24.0	—	—	—	—	34	—	—	46	—	56.
57.	15005,392	720	15.0†	32.0	14.0	—	—	—	—	23	—	—	—	—	57.
58.	15005,393	725	15.0†	36.0	17.0	—	—	—	—	30	—	—	49	—	58.
59.	15005,394	715	15.0†	39.0	15.0	—	—	—	—	34	—	—	—	—	59.
60.	15005,395	717	15.0†	39.0	19.0	—	—	—	—	33	—	—	46	—	60.
61.	15006,17	720	15.0†	52.0	54.0	—	—	—	—	51	—	63	58	—	61.
62.	15006,24	715	15.0†	54.0	46.0	—	—	—	—	41	—	—	65	—	62.
63.	15006,176	725	15.0†	73.0	47.0	—	—	—	—	—	—	—	—	—	63.
64.	15006,200	710	15.0†	65.0	50.0	—	—	—	—	57	—	—	50	—	64.
65.	15006,201	705	15.0†	57.0	52.0	—	—	—	—	58	—	—	51	—	65.
66.	15006,202	710	15.0†	78.0	59.0	—	—	—	—	58	—	—	47	—	66.
67.	15006,203	710	15.0†	77.0	68.0	—	—	—	—	60	—	—	61	—	67.
68.	15006,204	727	15.0†	82.0	55.0	—	—	—	—	65	—	—	50	—	68.
69.	15021,21	730	15.0	70.0	—	—	175	—	2.29	—	81	—	—	0.051	69.
70.	15031,70	717	15.0	68.0	—	—	135	—	2.37	—	—	—	—	—	70.
71.	15041,51	731	14.3	94.0	—	—	160	—	3.57	—	—	—	—	—	71.
72.	15210,2	685	13.0†	54.0	—	—	155	—	—	—	—	—	—	—	72.
73.	15251,49	676	12.0	75.0	—	—	175	6.78	2.98	—	66	—	—	—	73.
74.	15261,26	678	12.1	77.0	—	106	120	—	—	—	—	—	—	—	74.
75.	15271,64	664	12.2	63.0	—	91	140	7.07	3.15	—	68	—	—	0.044	75.
76.	15291,34	666	11.6	63.0	—	—	110	5.94	3.08	—	—	—	—	—	76.
77.	15301,88	701	15.5	48.0	—	—	130	—	2.33	—	63	—	—	0.031	77.
78.	15401,61	655	18.3	5.6	3.8	—	29	—	—	—	—	133	61	—	78.
79.	15426,97	560	19.7	0.3	—	—	21	—	—	0	—	—	—	0.001	79.
80.	15471,50	715	16.4	34.0	—	—	76	2.55	1.70	—	58	—	—	0.0140	80.
81.	15601,101	746	19.2	29.0	—	60	98	—	0.95	—	67	—	—	0.025	81.
82.	60009,454	556	5.3	37.0	28.0	—	—	—	—	15	—	77	67	—	82.
83.	60009,455	557	3.6	32.0	15.0	—	—	—	—	13	—	101	80	—	83.
84.	60009.456	565	5.2	53.0	29.0	—	—	—	—	22	—	102	53	—	84.
85.	60009,457	548	2.0	27.0	13.0	—	—	—	—	3	—	139	74	—	85.
86.	60009,458	567	5.2	52.0	44.0	—	—	—	—	29	—	86	51	—	86.
87.	60051,15	557	4.5	57.0	—	52	105	2.71	1.81	—	—	—	—	—	87.
88.	60601,9	560	5.5	85.0	—	—	—	4.50	4.64	—	65	—	—	0.091	88.
89.	61161,2	575	5.4	82.0	76.0	72	—	—	—	36	—	90	66	—	89.

Table 1. (*Continued*).

No.	Sample*	ΔH <250 μm (G)	FeO (wt.%)	I_s/FeO (Arb.) <250 μm	I_s/FeO (Arb.) 90–150 μm	N (μg/g)	C (μg/g)	$^4He_{TR}$ (10^{-2} cc/g)	$^{36}Ar_{tr}$ (10^{-4} cc/g)	Pet. agglut-inates (%)	Mag. fraction (%)	Mean grain size (μm) <1 cm	Mean grain size (μm) <1 mm	Fe°/FeO	No.
90.	61181,2	575	5.5	82.0	53.0	—	—	3.78	4.08	38	—	94	64	—	90.
91.	61221,12	568	4.9	9.2	—	15	100	0.63	1.20	6	12	216	68	—	91.
92.	61241,14	560	5.4	47.0	—	—	110	5.09	5.29	27	57	120	72	0.076	92.
93.	62281,9	590	5.5	76.0	49.0	—	—	4.04	4.87	40	—	134	70	—	93.
94.	63321,14	545	4.7	47.0	34.0	60	140	3.03	2.80	33	36	153	87	—	94.
95.	63341,9	550	4.5	54.0	37.0	59	160	2.80	2.75	40	34	144	80	—	95.
96.	63501,51	555	4.7	46.0	—	70	135	2.96	2.60	10	40	110	71	—	96.
97.	64421,16	551	5.0	83.0	—	118	—	4.58	4.90	54	56	—	—	—	97.
98.	64501,11	555	5.2	61.0	—	82	—	3.07	3.51	52	42	104	65	—	98.
99.	64801,35	530	5.2	71.0	—	86	172	4.32	4.68	—	63	—	—	0.094	99.
100.	65501,4	570	6.0	38.0	—	60	90	2.96	2.71	—	—	—	—	—	100.
101.	65511,1	572	6.0†	55.0	—	—	—	3.37	3.41	—	—	—	—	—	101.
102.	65701,8	565	5.7	106.0	—	118	190	4.90	5.90	—	61	—	—	0.137	102.
103.	66041,12	562	6.0	90.0	—	105	175	4.21	4.31	39	—	—	—	0.092	103.
104.	66081,28	560	6.2	80.0	—	110	170	3.36	4.02	53	76	—	—	—	104.
105.	67010,4	555	4.2†	26.0	—	—	—	—	—	—	—	—	—	—	105.
106.	67481,23	545	4.2	31.0	19.0	30	65	1.72	1.66	23	15	178	110	—	106.
107.	67601,15	552	4.0	45.0	—	39	—	2.29	2.14	36	29	116	82	0.068	107.
108.	67701,17	550	4.2	39.0	23.0	47	75	2.06	1.86	16	19	140	92	—	108.
109.	67711,16	550	3.0	2.8	0.7	4	31	—	—	2	2	166	71	—	109.
110.	67941,13	540	4.2†	29.0	14.0	27	59	—	—	12	—	202	97	—	110.
111.	68501,36	558	5.3	85.0	66.0	83	130	3.43	3.53	39	—	106	68	—	111.
112.	68841,29	570	5.6	70.0	—	97	140	3.78	3.78	—	68	—	—	—	112.
113.	69941,25	562	5.7	85.0	—	118	170	4.24	4.64	—	64	—	—	—	113.
114.	69961,33	572	5.7	92.0	—	125	140	—	—	—	—	—	—	—	114.
115.	70011,19	795	16.0	54.0	—	77	120	22.0	3.36	—	—	—	—	—	115.
116.	70161,1	792	17.1	46.0	27.0	—	150	—	—	34	—	68	59	—	116.
117.	70181,10	790	16.4	47.0	—	—	165	—	—	56	78	67	58	—	117.
118.	71041,	772	17.7	29.0	14.0	—	90	—	—	27	—	114	56	—	118.
119.	71061,1	775	17.8	14.0	3.9	—	40	—	—	9	—	170	58	—	119.
120.	71501,18	797	18.3	35.0	—	60	75	23.2	2.86	35	73	83	65	0.030	120.
121.	72141,15	750	13.5	81.0	76.0	—	155	14.8	4.01	51	—	57	50	—	121.
122.	72150,2	765	14.5	82.0	70.0	—	—	—	—	53	—	—	—	—	122.
123.	72321,7	665	8.7	73.0	60.0	—	—	—	3.28	45	—	53	47	0.072	123.
124.	72441,7	656	8.7	68.0	46.0	—	135	6.79	3.60	42	—	65	53	0.054	124.
125.	72461,5	655	8.6	71.0	50.0	—	—	7.40	3.27	43	—	80	61	—	125.
126.	72501,1	660	8.7	81.0	62.0	70	125	8.60	3.40	48	—	67	57	0.062	126.

127.	72701,24	657	8.8	61.0	—	81	130	7.60	3.65	43	63	62	54	—	127.
128.	73121,10	670	8.5	78.0	60.0	—	120	7.34	3.67	42	62	64	58	—	128.
129.	73141,8	665	8.1	48.0	—	—	120	5.94	2.53	32	—	—	—	—	129.
130.	73221,1	675	8.9	43.0	35.0	44	155	—	—	26	38	95	64	—	130.
131.	73241,9	680	8.8	18.0	10.0	22	—	—	—	8	—	127	51	—	131.
132.	73261,1	680	8.9	45.0	32.0	51	170	—	—	34	—	87	56	—	132.
133.	73281,1	680	8.8	34.0	27.0	40	—	—	—	25	—	90	49	—	133.
134.	74121,12	700	10.0	88.0	81.0	—	140	—	—	52	—	54	49	—	134.
135.	74220,6	730	22.0	1.0	0.9	7	5	1.43	0.17	2	—	—	41	0.003	135.
136.	74241,61	685	14.9	5.1	3.1	19	55	15.9	1.58	8	—	130	56	0.132	136.
137.	74261,9	660	15.3	5.0	2.6	13	45	14.2	1.71	8	—	127	56	—	137.
138.	75061,2	790	18.0	33.0	16.0	44	—	13.0	2.00	24	—	128	81	—	138.
139.	75081,36	782	17.1	40.0	19.0	—	115	16.0	3.10	35	—	87	67	0.033	139.
140.	75111,5	785	16.0†	58.0	—	—	—	—	—	52	—	—	—	—	140.
140.	75111,6	778	16.0†	50.0	—	—	—	—	—	—	—	—	—	—	140.
141.	75121,6	790	16.0	66.0	—	—	45	14.4	4.39	63	87	—	—	—	141.
141.	75121,7	785	16.0	68.0	—	—	—	—	—	—	—	—	—	—	141.
142.	76240,9	735	10.9	56.0	—	—	125	—	—	48	—	100	53	—	142.
143.	76261,26	720	10.9	58.0	37.0	—	100	8.99	3.07	45	—	87	58	—	143.
144.	76281,6	720	11.3	45.0	29.0	—	—	9.87	2.86	45	—	86	53	—	144.
145.	76321,10	720	9.8	93.0	83.0	—	140	12.5	3.51	39	—	69	53	—	145.
146.	76501,19	718	10.3	58.0	—	68	120	11.6	3.60	47	—	67	51	0.050	146.
147.	77531,1	735	11.7	79.0	56.0	—	180	—	—	54	—	63	49	—	147.
148.	78221,7	736	11.7	93.0	—	—	190	—	—	57	—	50	45	—	148.
149.	78421,1	740	12.0†	92.0	67.0	101	165	—	—	63	—	46	41	0.057	149.
150.	78501,55	727	13.2	36.0	—	73	170	9.69	2.77	35	—	42	34	0.035	150.
151.	79221,1	795	15.4	81.0	55.0	—	160	29.2	6.10	44	—	90	53	—	151.
152.	79261,1	785	15.0†	43.0	21.0	—	145	12.3	2.72	22	—	125	70	—	152.

*Daughter number applies only to the ΔH and I_s/FeO data.

†Estimated.

References:

FeO: Warner, unpublished curatorial data base.

N: Becker and Clayton, 1975; Chang *et al.*, 1974; Kerridge *et al.*, 1975a,b; Müller, 1973, 1974; Petrowski *et al.*, 1974, 1976.

C: Moore, 1974.

$^4He_{tr}$, $^{36}Ar_{tr}$: Bogard and Nyquist, 1972, 1973; Bogard *et al.*, 1974; Frick *et al.*, 1973; Heymann *et al.*, 1972; Hintenberger *et al.*, 1971, 1973, 1974, 1975; Hubner *et al.*, 1975; Jordan and Heymann, 1975; Kirsten *et al.*, 1971, 1972, Walton *et al.*, 1973, 1974; Yaniv and Heymann, 1972.

Petrographic agglutinates; Heiken *et al.*, 1973a,b, 1976, McKay *et al.*, 1972, 1974, 1976; McKay and Heiken, 1973; McKay, unpublished results.

Magnetic fraction: Charette and Adams, 1975; Rhodes *et al.*, 1975.

Mean grain size: Heiken *et al.*, 1973a,b, 1976; McKay *et al.*, 1972, 1974, 1976; McKay, unpublished results.

Fe°: Brecher *et al.*, 1974; Cisowski *et al.*, 1974; Nagata *et al.*, 1974; Pearce *et al.*, 1973, 1974.

indicated in Fig. 1. As is discussed in more detail later, this classification in terms of I_s/FeO is roughly equivalent to the same classification in terms of petrographic agglutinates for Apollo 17 soils by McKay *et al.* (1974). This classification scheme does not distinguish between mixing and evolutionary routes of maturation. For example, a submature soil may result from only exposure at the lunar surface or may result from a mechanical mixture of appropriate amounts of immature and submature soils. However, the routes of maturation are second order questions relative to the overall maturity of lunar soils. That is, the immature, submature, and mature levels of soil maturity constitute a first order characterization of the soils in terms of their evolution at the lunar surface. It is readily apparent from Fig. 1 that each landing site is characterized by immature, submature, and mature soils.

It has previously been pointed out that the values of ΔH vary with the chemistry of the lunar soils (Griscom and Marquardt, 1972; Weeks, 1973; Tsay *et al.*, 1973). This variation is shown in Fig. 2 for many of the soils in this study as a plot of ΔH vs. wt.% FeO. No causal relationship between ΔH and FeO is necessarily implied by Fig. 2, and other parameters which covary or contravary with FeO will also correlate with ΔH. Since a comparison of Figs. 1 and 2 shows that ΔH is not correlated with I_s/FeO and thus maturity, ΔH will not be considered further in this study.

In most of the rest of this section, I_s/FeO is correlated with various other properties of lunar soils that are, or are presumed to be, indices of relative surface exposure age (or, equivalently, indices of soil maturity). These correlations demonstrate the relative merits of the various indices.

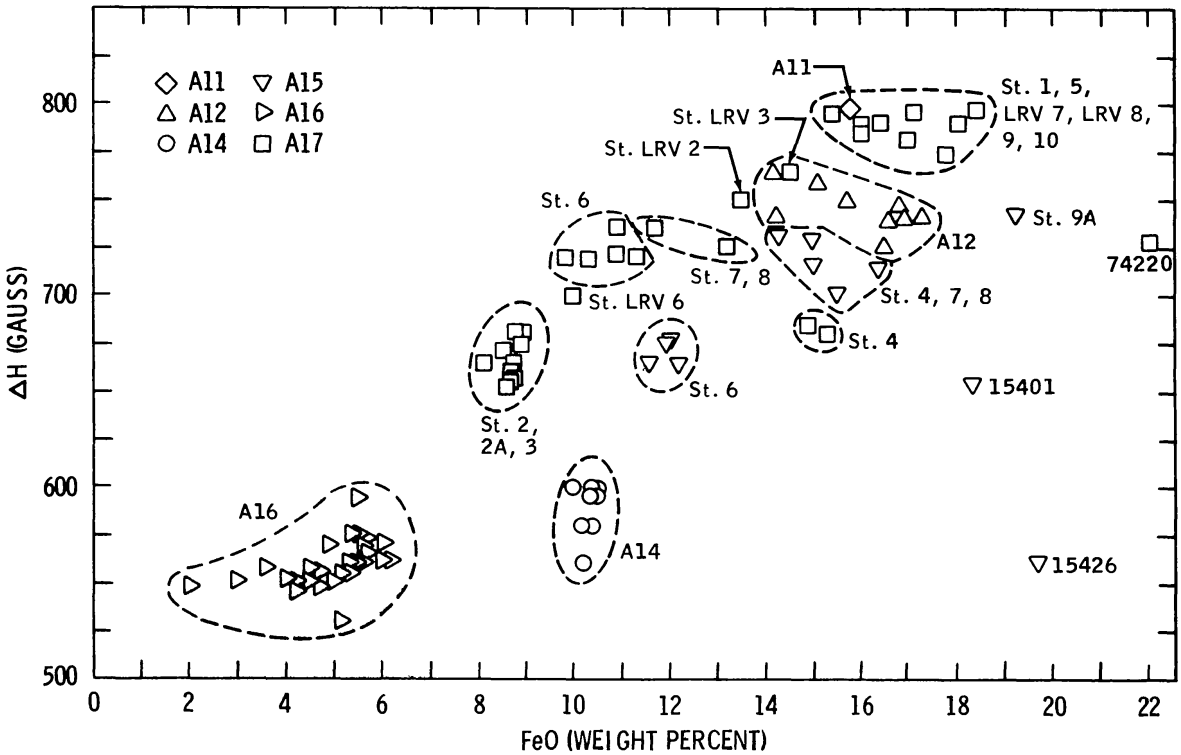

Fig. 2. Variation of ΔH with FeO for soils from all Apollo landing sites.

Correlation of I_s/FeO with solar wind gases

Chang *et al.* (1973), Müller (1974), Kerridge (1975), and others have shown that the N found in the regolith is primarily solar-wind implanted. In addition, these studies indicate that the N is quantitatively retained; that is, appreciable N is not lost from the soil during the agglutination process. Similar considerations hold for C except that there is a significant component of C that is indigenous to the soil.

The correlations of I_s/FeO with the concentrations of N and C are shown in Figs. 3a and b. The data are well correlated with linear coefficients of correlation equal to 0.92 and 0.83, respectively. Note that in the plot of I_s/FeO vs. C, the data extrapolates at $I_s/\mathrm{FeO} = 0$ to the values of C that are found in the igneous rocks, which presumably corresponds to the indigenous carbon content in the soils. There are also no apparent effects of either the variable composition of the lunar soils or saturation (i.e., either I_s/FeO, C, or N approach a limiting value) in the plots of I_s/FeO vs. N and C. The absence of saturation effects implies the fine-grained metal is as quantitatively retained in the maturation process as are C and N. In terms of the fine-grained metal, quantitatively retained means that the fine-grained metal has not grown sufficiently in size (i.e., grown to larger than ~ 300 Å) during maturation so that it no longer contributes to I_s.

The trapped rare gases $^4He_{tr}$, $^{20}Ne_{tr}$, $^{36}Ar_{tr}$, $^{34}Kr_{tr}$, and $^{132}Xe_{tr}$ are those rare gases which originate directly from the solar wind and not from *in situ* nuclear reactions (Eberhardt *et al.*, 1972). The retentivity of the light rare gases, especially He, in lunar soils are known to be strongly dependent on the ilmenite or TiO_2 content of the soil. That is, He is more strongly retained by ilmenite than other minerals in the soil (Hintenberger and Weber, 1973). On the other hand, the retentivity of the heavier rare gases (Ar, Kr, and Xe) is not strongly influenced by composition (Hintenberger and Weber, 1973). It is thus expected and shown in Fig. 3c that I_s/FeO correlates with $^4He_{tr}$ only for those soils for which the bulk chemistry is relatively constant (e.g., the Apollo 16 soils). Likewise, compositional effects are not observed in the correlation of I_s/FeO with $^{36}Ar_{tr}$ as shown in Fig. 3d. Neither do I_s/FeO and $^{36}Ar_{tr}$ approach a limiting value with respect to each other. The coefficient of correlation is 0.78.

In summary, the correlations of I_s/FeO with N, C, and $^{36}Ar_{tr}$ firmly establish I_s/FeO as a generally applicable index of relative surface exposure age or soil maturity. By "generally applicable index" it is meant that changes in the numerical value of the index reflect *only* changes in relative surface exposure age. Of course, I_s/FeO and thus N, C, and $^{36}Ar_{tr}$ can be shown not to be generally applicable indices of relative surface exposure age if an index can be found with respect to which I_s/FeO, N, C, and $^{36}Ar_{tr}$ saturate.

Correlation of I_s/FeO with petrographic agglutinates

Agglutinates are aggregates of crystalline grains and lithic fragments bonded together by glass (Duke *et al.*, 1970) that is produced by micrometeorite impact in the upper 0.5–1.0 mm of the lunar surface (Gault *et al.*, 1972, 1974). The number percentage of agglutinates determined petrographically in the 90–150 μm size

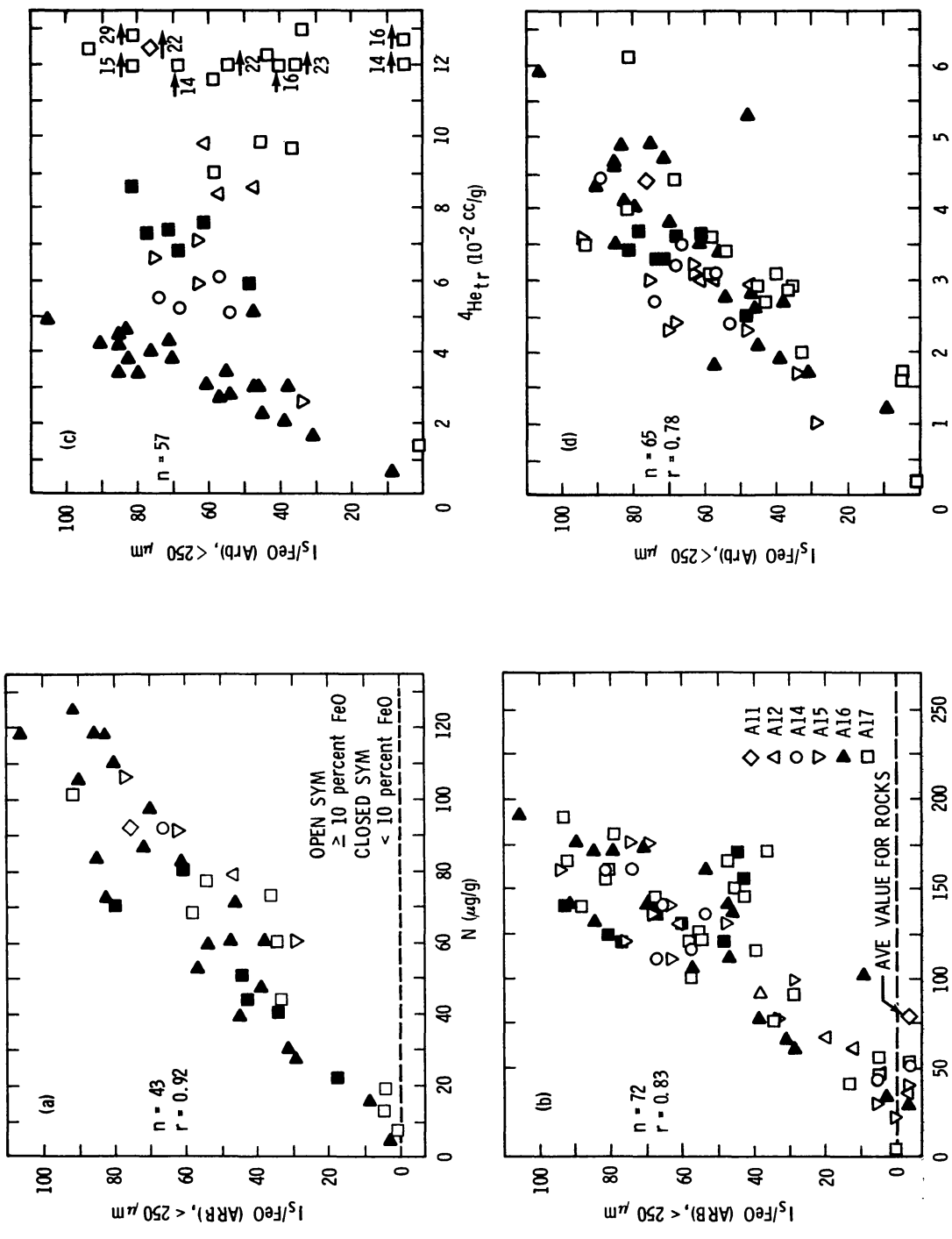

Fig. 3. Correlation of I_s/FeO with solar wind gases: (a) N; (b) C; (c) $^4He_{tr}$; (d) $^{36}Ar_{tr}$. The parameter r is the correlation coefficient. The symbols below the dashed line in (b) are the average values for igneous rocks. The closed symbols denote soils which have <10.0 wt.% FeO; the open symbols denote soils which have ≥ 10.0 wt.% FeO.

fraction has been widely used as an index of soil maturity (e.g., McKay *et al.*, 1974).

In Fig. 4a, I_s/FeO for the 90–150 μm size fraction is correlated with the percentage of petrographic agglutinates. The use of data from only the 90–150 μm size fraction eliminates any potential bias due to comparing data from different size fractions. One trend noted in Fig. 4a is an apparent effect of bulk composition. At a constant value of I_s/FeO, soils that have < 10 wt.% FeO (predominantly Apollo 16 and highland Apollo 17 soils) have fewer petrographic agglutinates than do soils with greater than or equal to 10 wt.% FeO. This effect has also been reported by Rhodes *et al.* (1975) in connection with studies on magnetic agglutinates.

A second trend shown in Fig. 4a is that the percentage of petrographic agglutinates approaches a limiting value, or saturates, with respect to I_s/FeO. This effect, which is observed for both the soils that follow the < 10 wt.% FeO trend and those that follow the ≥ 10 wt.% FeO trend, is predicted by steady-state models for production of agglutinates (e.g., Lindsay, 1975; Mendell and McKay, 1975). According to those models, a steady-state condition can exist in which the pulverization of coarse particles and agglutinates is balanced by the constructional process of agglutination. That is, as a soil becomes mature, the number percentage of agglutinates approaches a constant or steady-state value. Since the data in Fig. 3 show that the values of I_s/FeO for the < 250 μm size fraction, and presumably also the 90–150 μm size fraction, continue to increase as lunar soils mature, the observed saturation effect directly follows from the steady-state models of agglutinate production.

Although the data of McKay *et al.* (1972) show for a few soils that the percentage of petrographic agglutinates in several size fractions between 45 and 1000 μm is relatively constant, it has been suggested (e.g., Housley *et al.*, 1975; Gose *et al.*, 1975; Charette and Adams, 1975) that agglutinates may not be representative of the bulk soil since they are measured for the 90–150 μm size fraction. However, Fig. 4b shows that the percentage of petrographic agglutinates is nearly as representative of I_s/FeO for the < 250 μm size fraction as it is for the 90–150 μm size fraction. That is, both the effects of composition and saturation are preserved in Fig. 4b. It is also concluded on the basis of the data in Fig. 4b that I_s/FeO is a more appropriate maturity index than petrographic agglutinates because the latter are subject to effects of composition and saturation.

The complex relationship between I_s/FeO and petrographic agglutinates shown in Fig. 4 may, in part, be the reason why Griscom *et al.* (1975) were not able to discern that relationship from their FMR measurements on only 16 samples of soil. The use of data for agglutinates determined magnetically and petrographically and the use of petrographic agglutinate data from different laboratories also contributed to obscuring the relationship between FMR intensity and agglutinates in the work of Griscom *et al.* (1975).

As in Fig. 1, the range of the values of I_s/FeO (< 250 μm) for immature, submature, and mature soils is indicated on Fig. 4b. This classification in terms of I_s/FeO was chosen to roughly correspond to the same classification in terms of

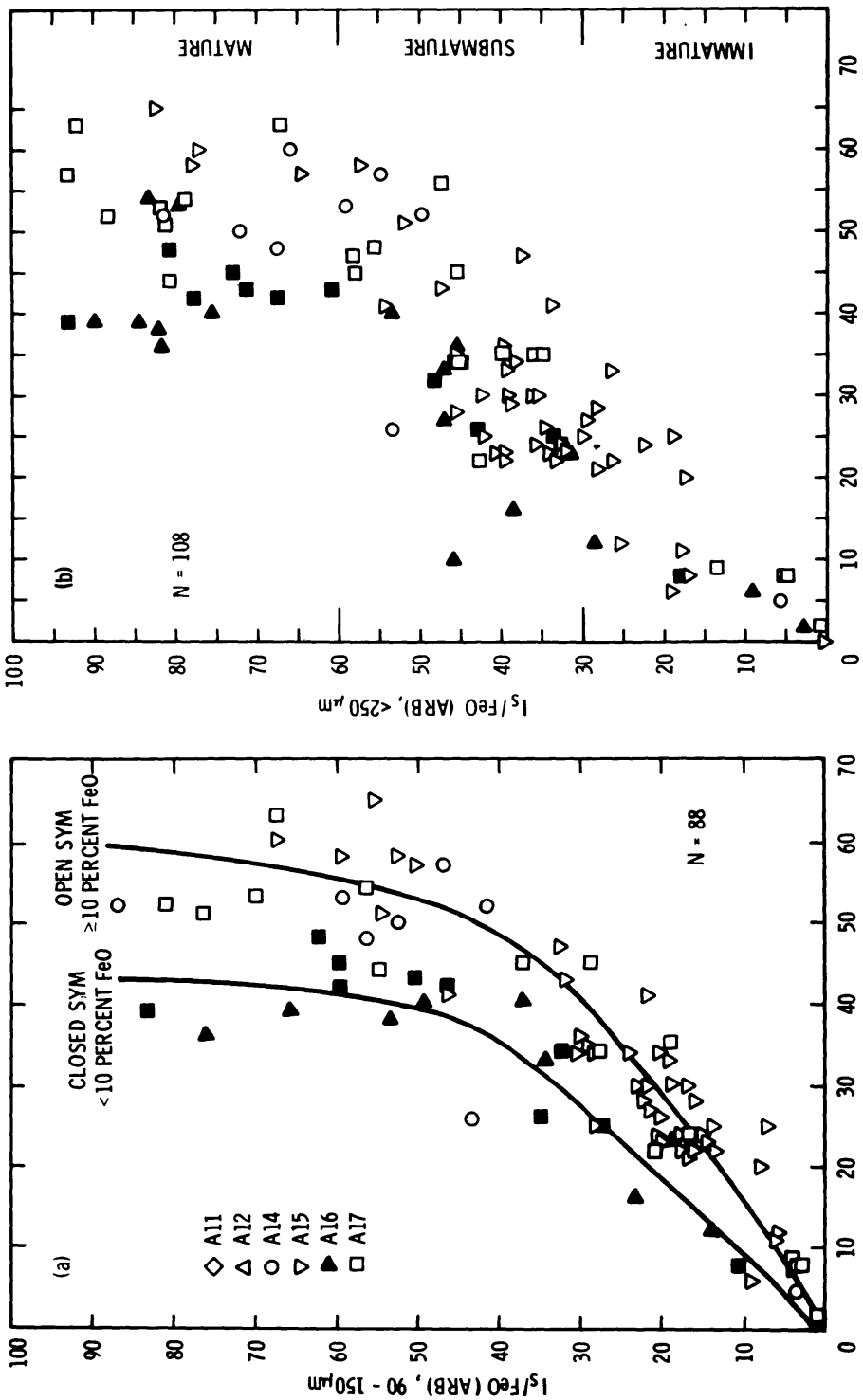

Fig. 4. Correlation of I_s/FeO with petrographic agglutinates: (a) 90–150 μm size fraction for I_s/FeO; (b) <250 μm size fraction for I_s/FeO. The closed symbols denote soils which have <10.0 wt.% FeO; the open symbols denote soils which have ≥ 10.0 wt.% FeO.

petrographic agglutinates for Apollo 17 soils by McKay *et al.* (1974). That is, soils that are classified as mature in terms of I_s/FeO are also usually classified as mature in terms of petrographic agglutinates. In this way, a common meaning is established for both parameters.

Correlation of I_s/FeO with mean grain size

Grain size parameters have been widely used in developing models for the maturation of the regolith with accumulation of exposure time at the lunar surface (e.g., Mendell and McKay, 1975; Lindsay, 1975). A general result of these models is that as a soil accumulates exposure time at the lunar surface, it both becomes finer grained in response to destructive forces (meteorite pulverization) and contains a higher proportion of agglutinates; the minimum grain size of a soil is ultimately limited by the constructional process of agglutination. However, McKay *et al.* (1974) have pointed out that for the returned lunar soils the minimum mean grain size appears to be limited by the depth of the regolith to bedrock. That is, the regolith is nowhere (at least for the returned soils) sufficiently thick so that the minimum mean grain size is not limited by the input of fresh and coarse material from bedrock.

In Figs. 5a and b, I_s/FeO is correlated with mean grain size data for Apollo 17 soils (McKay *et al.*, 1974) for that data calculated from both <1 mm and <1 cm grain size data. It is readily apparent that I_s/FeO is independent of $<$ 1 mm mean grain size but correlates with $<$ 1 cm mean grain size. Thus, for the Apollo 17 soils, only the $<$ 1 cm data can be used as an index of soil maturity. The same conclusion was also reached by McKay *et al.* (1974) who showed that the expected negative correlation between sorting and mean grain size held for the <1 cm data but not the <1 mm data. The Apollo 17 soils represent an extreme case of the difference obtained between the correlations of I_s/FeO with <1 mm and <1 cm mean grain size. However, correlation of I_s/FeO with the mean grain size data in Table 1 for the Apollo 14 and 16 soils shows that the <1 cm data is always a more sensitive index of maturity than the <1 mm data.

In Figs. 5c and d, I_s/FeO is correlated with the <1 cm mean grain size of Apollo 16 and 17 soils. An inspection of those correlations shows that the mature (I_s/FeO >60) Apollo 16 soils are coarser grained than the mature Apollo 17 soils. The data in Table 1 shows that similar differences are also observed for Apollo 14 and 15 soils. This is probably the result of the complex dependence of mean grain size on the depth of the regolith and pulverization rates (i.e., coherency) of rock at each particular landing site. In any event, the data in Fig. 5 and Table 1 show that it is not appropriate to use mean grain size data as an index of soil maturity when comparing soils from different landing sites.

In addition, Fig. 5 suggests that there may be some inconsistencies in models of regolith evolution that are based solely on grain size parameters. One such model is the steady-state model described by Lindsay (1975). One of the tenets of that model is the occurrence of a cycling (or steady-state) stage for lunar soils.

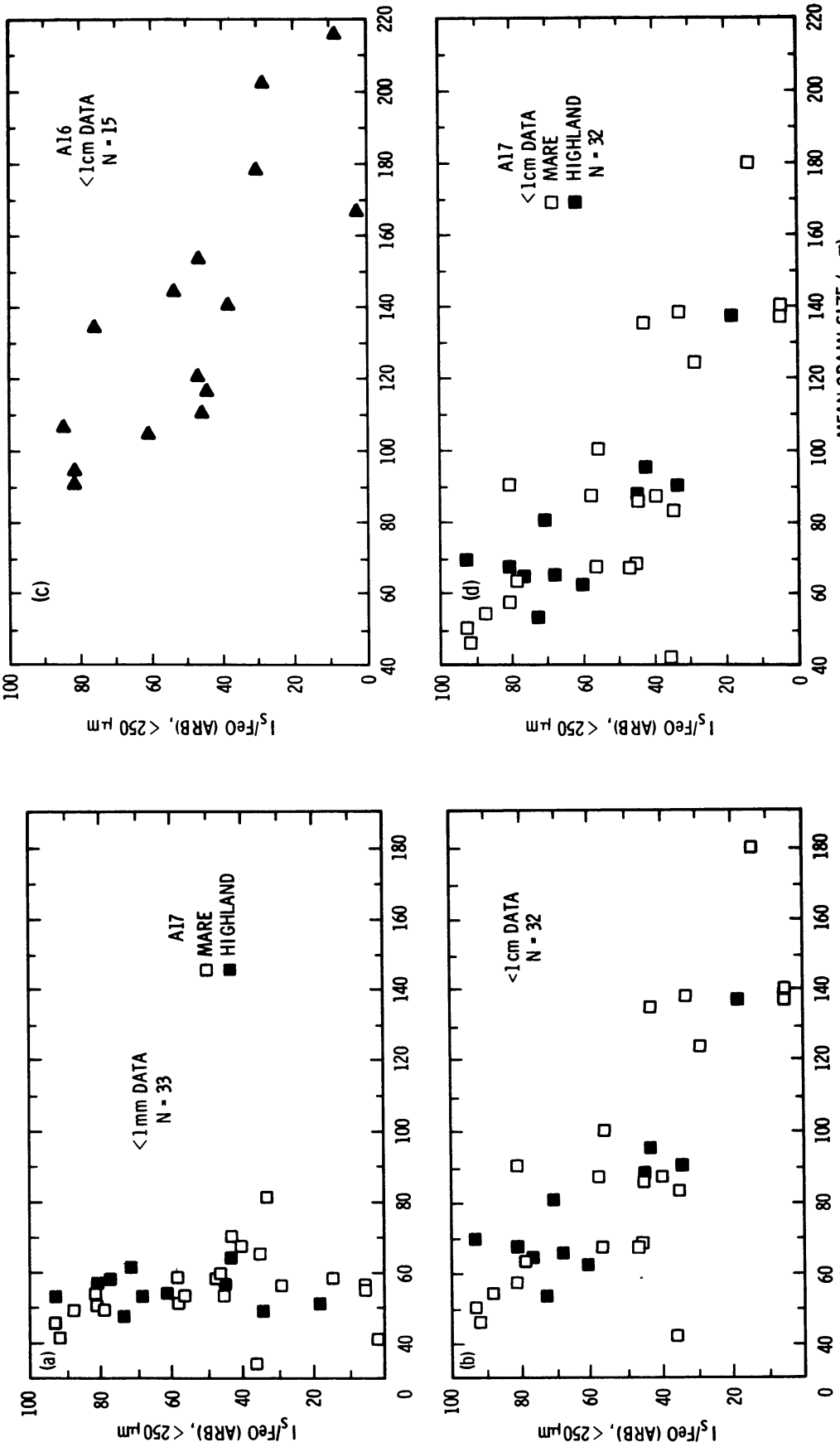

Fig. 5. Correlation of I_s/FeO with mean grain size: (a) mean grain size calculated from <1 mm data for Apollo 17 soils; (b) mean grain size calculated from <1 cm data for Apollo 17 soils; (c) mean grain size calculated from <1 cm data for Apollo 16 soils; (d) mean grain size calculated from <1 cm data for Apollo 17 soils. The closed symbols denote soils which have <10.0 wt.% FeO, the open symbols denote soils which have ≥10.0 wt.% FeO.

One cycle consists of the crushing of agglutinates by a layer-forming event that redistributes the soil on the lunar surface and the subsequent exposure of the soil to the micrometeorite flux that produces more agglutinates. It is readily apparent that soils in the cycling stage are the most mature and should contain the highest concentrations of fine-grained metal. According to Lindsay (1975), soils that have a mean grain size (<1 mm) less than 58 μm (4.1 ϕ) have evolved to the cycling stage. A few examples of soils in Table 1 that have a mean grain size (<1 mm) less than 58 μm are 15003,324 (48 μm), 15002,333 (50 μm), and 15001,266 (52 μm). However, the values of I_s/FeO for these three soils are, respectively, 46.0, 46.0, and 19.0, which indicates that they are immature to submature (cf. Fig. 1), not mature, soils. This difference is not merely a matter of differences in nomenclature between this study and that of Lindsay (1975). This is apparent because the data in Fig. 4 show that the values of I_s/FeO for the three soils do not lie in the saturation (i.e., steady-state or cycling) portion of the correlation of I_s/FeO with the percentage of petrographic agglutinates. Therefore, the Apollo 15 soils mentioned above, and there are others in Table 1, do not actually support the model of Lindsay (1975). Note that this study does not dispute the existence of a steady-state or cycling stage. In fact, the data in Fig. 4 is very supportative of the presence of such a stage. This study does dispute the use of grain size data as a criterion for determining which soils are in the cycling stage of their evolution.

Correlation of I_s/FeO with magnetic agglutinates

By definition, magnetic agglutinates are the weight percentage of the magnetic fraction of the 10–250 μm size fraction of the bulk soil (Charette and Adams, 1975). The magnetic separation technique uses the high magnetic susceptibility of agglutinatic glass to concentrate it in the magnetic fraction. According to Charette and Adams (1975), magnetic agglutinates should be a more representative maturity index of the bulk soil than petrographic agglutinates because magnetic agglutinates are determined from the 10–250 μm size fraction while petrographic agglutinates are determined on the much smaller 90–150 μm size fraction. However, an important conclusion of an earlier subsection was that petrographic agglutinates are nearly as representative of the fine-grained metal in the < 250 μm size fraction as they are of the fine-grained metal in the 90–150 μm size fraction.

The correlation of I_s/FeO with magnetic agglutinates is shown in Fig. 6. The Apollo 16 and highland Apollo 17 soils correlate with I_s/FeO with a correlation coefficient of 0.88. Although the data is very limited, linear relationships also appear to exist for the Apollo 14 and the Apollo 15 and mare Apollo 17 soils. However, the latter relationships do not extrapolate through the origin of coordinates. That is, at zero exposure in terms of I_s/FeO, a linear extrapolation of the data gives ~20% magnetic agglutinates for the Apollo 14 soils and ~50% magnetic agglutinates for the Apollo 15 and mare Apollo 17 soils. One possibility for this effect is that a significant mass of material not related to exposure resides in the magnetic fraction of those soils. However, more magnetic agglutinate data

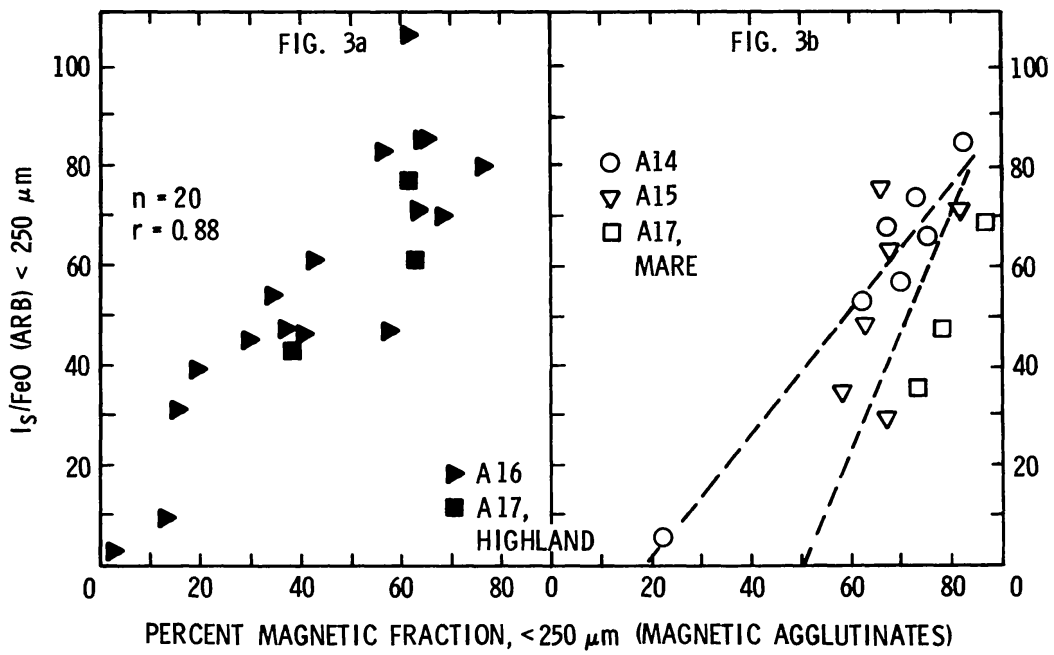

Fig. 6. Correlation of I_s/FeO with magnetic agglutinates: (a) Apollo 16 and highland Apollo 17 soils; (b) Apollo 14, Apollo 15, and mare Apollo 17 soils. The parameter r is the correlation coefficient. The closed symbols denote soils which have <10.0 wt.% FeO; the open symbols denote soils which have ≥10.0 wt.% FeO.

on immature soils is needed to delineate the extent of the validity of the linear extrapolation. Although the Apollo 16 data do not suggest such a trend, additional samples may show that a strong saturation effect is involved. In any event, there is a strong trend apparently due to compositional differences in which magnetic agglutinates increase with increasing concentration of FeO in the soil, the value of I_s/FeO in the soil being held constant. The compositional trend is more severe than that observed for petrographic agglutinates. Therefore, it is concluded that magnetic agglutinates should not be used as a generally applicable index of soil maturity.

Correlation of I_s/FeO with Fe°/FeO.

Although Fe°/FeO has been suggested, but not rigorously established, as an index of soil maturity (Pearce *et al.*, 1973), the main purpose of this section is to detail the relationship between the fine-grained metal, as measured by I_s/FeO, and the coarse-grained metal, as measured by Fe°/FeO. It is first necessary to describe in more detail what is meant by fine- and coarse-grained metal. As was discussed in the introduction, only metallic iron particles that are spherical or nearly spherical in shape and have diameters less than ~300 Å contribute to I_s at room temperature. This is a consequence of the fact that multidomain iron does not contribute to I_s; spherical metallic iron particles that have a diameter greater than ~300 Å are multidomain (e.g., Nagata, 1961) in the 3.0 kG mean resonance field used in the FMR experiment. On the other hand, Fe° as measured using static

magnetic techniques at room temperature does not contain a significant contribution from particles less than ~100–150 Å in diameter because those particles are superparamagnetic. Thus there is some overlap in the distribution of particle sizes that are observed by each technique.

It is important to recognize and maintain the distinction between fine- and coarse-grained metal because available evidence indicates that the coarse- and fine-grained particles are not genetically related. FMR thermomagnetic data (Morris *et al.*, 1975) show that the fine-grained metal is nearly pure metallic iron which is consistent with its formation from reduction of FeO. Impurities are present in the fine-grained iron because the nature of the fine-grained metal is constrained not only by the observed Curie points, which are that of pure metallic iron (Morris *et al.*, 1975), but also by the values of ΔH, which are ~550 to 800 G (see Fig. 2) and not the ~900–1000 G predicted for pure metallic iron (Friebele *et al.*, 1974). The impurity that determines the values of ΔH is probably not Ni since the Curie point measurements require <5 wt.% Ni and the 550 G value of ΔH requires ~12% Ni (Bozorth, 1951; Griscom *et al.*, 1973). Microprobe (Hewins *et al.*, 1976; Goldstein and Axon, 1975) and static thermomagnetic (e.g., Pearce *et al.*, 1973) studies, on the other hand, have shown that many of coarse-grained metallic particles contain sufficient Ni to be meteoritic in origin. (Microprobe studies are performed on metallic particles whose diameters are greater than ~1 μm so that those particles contribute to Fe° but not to I_s.) The fact that I_s/FeO correlates with such surface exposure indices as N and C also show that the fine-grained metal that contributes to I_s is formed by exposure-induced reduction of FeO and is not meteoritic in origin. If the source of the fine-grained metal were meteoritic, the amount of that metal would be independent of the concentration of FeO in the soils, and the correlation of I_s with N and C would be more statistically significant than the correlation of I_s/FeO with N and C. This is not the case since the correlation coefficients for the correlation of I_s/FeO with N and C are 0.92 and 0.83 and the corresponding coefficients for the correlation of I_s with N and C are 0.70 and 0.67.

The correlation of I_s/FeO with Fe°/FeO is shown in Fig. 7. It is readily apparent that Fe°/FeO does not correlate with I_s/FeO, and Fe°/FeO should not be used as an index of soil maturity. The dashed line indicates the locus of points followed by a number of surface and trench soils from the Apollo 12, 14, 15, and 17 landing sites. The dashed line is intended primarily for reference. It does not imply that for those soils all the metallic particles contribute to both I_s and Fe°; it does imply that the metallic particles that contribute to I_s and Fe° constitute roughly the same percentage of the total population of metallic particles in those soils. Any soil to the left of the dashed line has relatively more fine-grained metal than the soils that lie along the dashed line. Likewise, any soil to the right of the dashed line has relatively more coarse-grained metal than the soils that lie along the dashed line. Thus, the data plotted in Fig. 7 shows that the Apollo 16 soils, in general, have relatively more coarse-grain metal than soils from any other landing site. The same conclusion was independently obtained by Pearce *et al.* (1973) from measurements of the values of J_{rs}/J_s for the lunar soils.

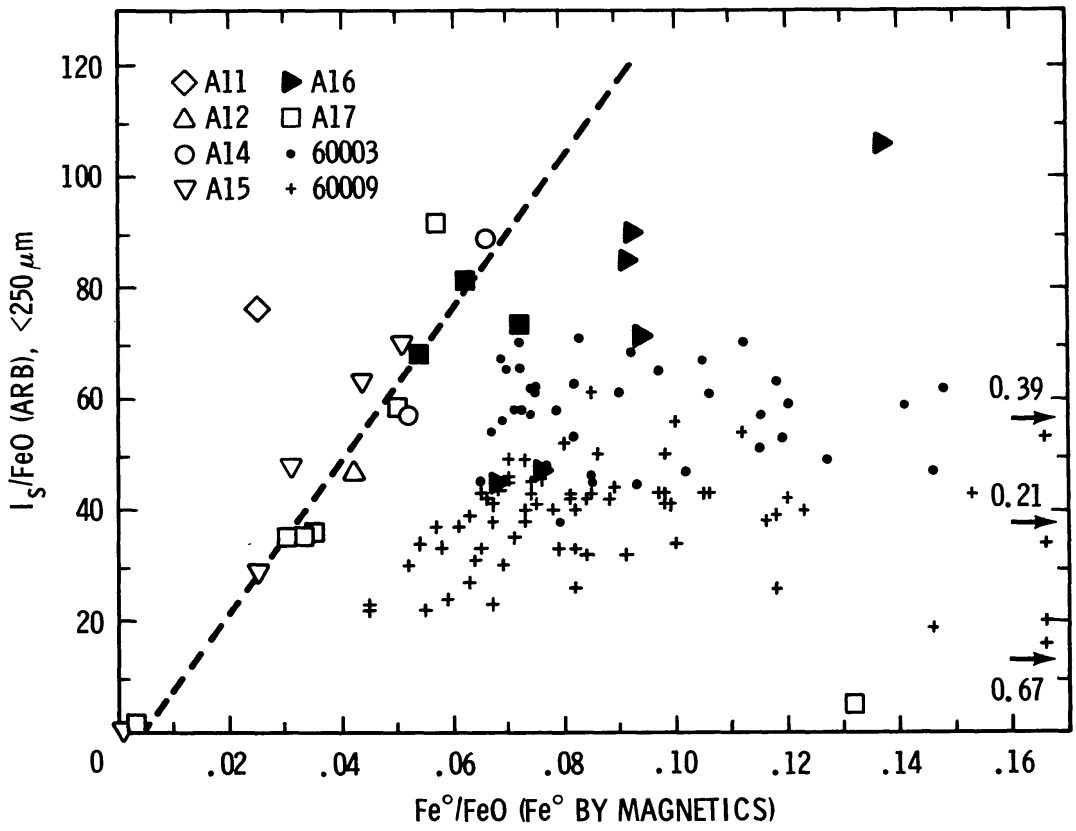

Fig. 7. Correlation of I_s/FeO with Fe°/FeO. The values of Fe° were determined magnetically. The dashed line is only for reference. Soils which lie to the right of the dashed line have relatively more coarse-grained metal than the soils which lie along the dashed line, conversely, soils which lie to the left of the dashed line have relatively more fine-grained metal than the soils which lie along the dashed line. The closed symbols denote soils which have <10.0 wt.% FeO, the open symbols denote soils which have ≥10.0 wt.% FeO. The data for 60003 and 60009 were obtained from Morris and Gose (1976).

CONCLUSIONS

1. Within the scatter of the data, I_s/FeO, C, N, and $^{36}Ar_{tr}$ neither saturate nor show effects of bulk composition with respect to each other. This affirms that I_s/FeO is a generally applicable index of relative surface exposure age. By "generally applicable index" it is meant that changes in the numerical value of the index reflect *only* changes in relative surface exposure age.

2. The fact that I_s/FeO and not I_s is an index of relative surface exposure age confirms that the fine-grained metal is predominantly formed as the result of exposure-induced reduction of Fe^{2+} and not the result of addition of meteoritic metal.

3. Relative to I_s/FeO, the percentage of petrographic agglutinates both saturate and show a variation that is apparently due to bulk composition. Thus, at high agglutinate contents, the percentage of petrographic agglutinates becomes less sensitive to changes in relative surface exposure ages. The saturation effect may be the first direct evidence for the steady-state production of agglutinates

that is predicted by the models of Mendell and McKay (1975) and Lindsay (1975). The effects of saturation and bulk composition also show that the percentage of petrographic agglutinates is not a generally applicable index of relative surface exposure age.

4. Mean grain size data calculated from <1 cm data are a more sensitive index of relative surface exposure age than are mean grain size data calculated from <1 mm data. Relative to I_s/FeO, the mean grain size data show a strong variation with landing site and are thus not a generally applicable index of relative surface exposure age.

5. Relative to I_s/FeO, magnetic agglutinates show a strong variation that is apparently due to bulk composition. Thus magnetic agglutinates are not a generally applicable index of relative surface exposure age.

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