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Lithological variation with depth and decoupling of maturity parameters in Apollo 16 regolith core 68001/2

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Abstract—Using ferromagnetic resonance (FMR) and instrumental neutron activation analysis (INAA), we have determined the maturity (surface exposure) parameter I_s/FeO and concentrations of twenty-five chemical elements on samples taken every half centimeter down the 61-cm length of the 68001/2 regolith core (double drive tube) collected at station 8 on the Apollo 16 mission to the Moon. Contrary to premission expectations, no ejecta or other influence from South Ray crater is evident in the core, although a small inflection in the I_s/FeO profile at 3 cm depth may be related the South Ray crater impact. Regolith maturity generally decreases with depth, as in several previously studied cores. We recognize five compositionally distinct units in the core, which we designate A through E, although all are similar in composition to each other and to other soils from the Cayley plains at the Apollo 16 site. Unit A (0–33 cm) is mature to submature throughout (I_s/FeO: 89–34 units) and is indistinguishable in composition from surface soils collected at station 8. Unit B (33–37 cm) is enriched slightly in a component of anorthositic norite composition. Unit D (42–53 cm) is compositionally equivalent to 80 wt% Unit-A soil plus 20 wt% Apollo-16-type dimict breccia consisting of subequal parts anorthosite and impact-melt breccia. Compared to Unit A, Unit E (53–61 cm) contains a small proportion (up to 4%) of some component compositionally similar to Apollo 14 sample 14321. Unit C (37–42 cm) is unusual. For lithophile and siderophile elements, it is similar to Units A and D. However, I_s/FeO is low throughout the unit (<30 units) and in a bluish-gray zone at 41 cm depth I_s/FeO drops to 1.6 units, the lowest value that we have observed in several hundred Apollo 16 soil samples. Samples from the bluish-gray zone also have low Zn concentrations, <10 μg/g, compared to 20–30 μg/g for the rest of the core. Although both values are consistent with fragmented rock material that has received virtually no surface exposure, the abundance of agglutinates in the bluish-gray soil of Unit C is moderately high, typical of a submature soil that would ordinarily have I_s/FeO $\approx$ 30. We believe that the anomalously low values of I_s/FeO and Zn concentration result because the soil was heated to ~800–1000 °C, probably during an impact. This temperature range is sufficient to volatize the surface-correlated Zn and agglomerate the nanophase metal giving rise to the FMR signal but is not great enough to sinter the soil. Alternatively, the unusual soil interval may represent a disaggregated or incipient regolith breccia, although there is no significant difference in the texture or clast-matrix relationships between Unit C and adjacent units. *Copyright © 1997 Elsevier Science Ltd*

1. INTRODUCTION

Drive tube sections 68001 and 68002 (hereafter, 68001/2) constitute a regolith core that was collected at station 8 on the Cayley plains during the Apollo 16 mission to the Moon in 1972. The core, which was 4 cm in diameter, penetrated to a depth of about 61 cm in an area that was nearly level but within a meter of the rim of an unnamed crater 10–15 m in diameter (Sutton, 1981). The objective of the station-8 core was to obtain fine-grained ejecta from South Ray crater, which is ~3.5 km away and 0.7 km in diameter and which appeared to be very young in premission reconnaissance. Post-mission studies of samples have shown this supposition to be correct, as the crater is only 2 Ma old (Drozd et al., 1974; Eugster et al., 1995). Station 8 was the closest sampling station to South Ray crater, and it was hoped that the contact between the old surface and its young ejecta would be sampled by the double-drive tube. In pre-mission planning, station 8 was to be located on a prominent high-albedo ray of the crater (e.g., Fig. 1 of Reed, 1981). However, no expression of rays was observed by the crew in the fine-grained regolith, although boulder trains and clusters believed to be associated with South Ray crater were observed. Station 8 was located in one of these boulder areas. The core, four samples of surface soil, and several rocks were collected at station 8. For comparison, a single drive tube, 69001 (~30 cm deep), and three samples of surface soil were collected 0.5 km away at station 9 with the intent of obtaining typical Cayley plains material undisturbed by South Ray crater. (This summary of sampling objectives is based on that of Muehlberger et al., 1980.) Drive tubes 68001 and 68002 were extruded and made available for study during 1993 and 1994 (Schwarz, 1993, 1994; Schwarz et al., 1994). As of 1997, drive tube 69001 is the only remaining unopened core of the six regolith cores taken on the Apollo 16 mission.

In this work we report on the variation with depth of

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several parameters in 68001/2, including maturity, chemical composition, and macroscopic features observed during core processing. We show that there is little evidence for any influence from South Ray crater in the regolith of the core. We show that the compositional variations with depth are consistent with minor changes in the proportions of lithologies of which the soil is composed. We also describe a peculiar layer of soil with characteristics that have not been previously observed in any lunar soil: the soil at 41 cm depth appears to have been heated to a temperature sufficiently hot to reset the maturity parameter I_s/FeO to nearly zero and volatize essentially all of the surface-correlated Zn but cause no obvious textural changes except perhaps a change in color.

2. SAMPLES AND METHODS

We have measured concentrations of twenty-five elements by INAA (instrumental neutron activation analysis) and determined the maturity parameter I_s/FeO by FMR (ferromagnetic resonance) on 123 samples of <1 mm fines taken approximately every half centimeter through the length of the core. The analyzed core samples derive from the first dissection pass of 68002 (Schwarz, 1993) and the third dissection pass of 68001 (Schwarz, 1994). Analytical procedures were similar to those described in Korotev and Morris (1993) with the following modifications. For each dissection interval (parent split number), two samples were allocated by NASA, one for FMR analysis and one for INAA. Sample masses for INAA were nominally 120 mg instead of 50 mg. FeO concentrations determined by INAA were used to calculate I_s/FeO. In addition to the core samples, we analyzed two or three subsamples each of all surface soils from stations 8 and 9 by INAA.

We have also examined six continuous thin sections prepared at the Johnson Space Center from epoxy-impregnated portions of the core (e.g., Fryxell and Heiken, 1974). Each thin section represented 2.5–3.0 cm of depth, and we divided each into 0.5 cm intervals for point counting. The goal of the point counting was to determine, for each 0.5 cm interval, the fraction of the soil particles between 20 μm and 1 mm in diameter that were agglutinates (most agglutinates in the sections are less than 200 μm in their maximum dimension). We examined approximately 1600 points per interval and counted several intervals twice, for a total of ~60,000 points. Point counts were made using a polarizing microscope equipped with reflected and transmitted optics. Optimal identification of agglutinates was made by working in a combined reflected- and transmitted-light mode, using mainly reflected light with a minor transmitted-light component. Agglutinatic glass takes a good polish and is readily distinguished from matrix in reflected light. Although agglutinatic glasses range from clear and colorless to dark brown in transmitted light, most are dark, so that a small component of transmitted light, with a maximum illumination from the substage condenser, enhances the identification of small agglutinates. Typical agglutinates are also easily identified on the basis of high vesicularity, schlieren, irregular shape, and smooth, curved edges (Fig. 1). Some large agglutinates have substantial areas (e.g., tens of micrometers) that are nonvesicular and very finely devitrified, thus small fragments of such agglutinates, when broken, may not display all of the typical characteristics and are not as easily identified as pieces of agglutinates. In our point counts, we counted agglutinates conservatively, including only those fragments that are obviously agglutinatic. Thus we consider the proportions of agglutinates determined in these counts to be minimum values.

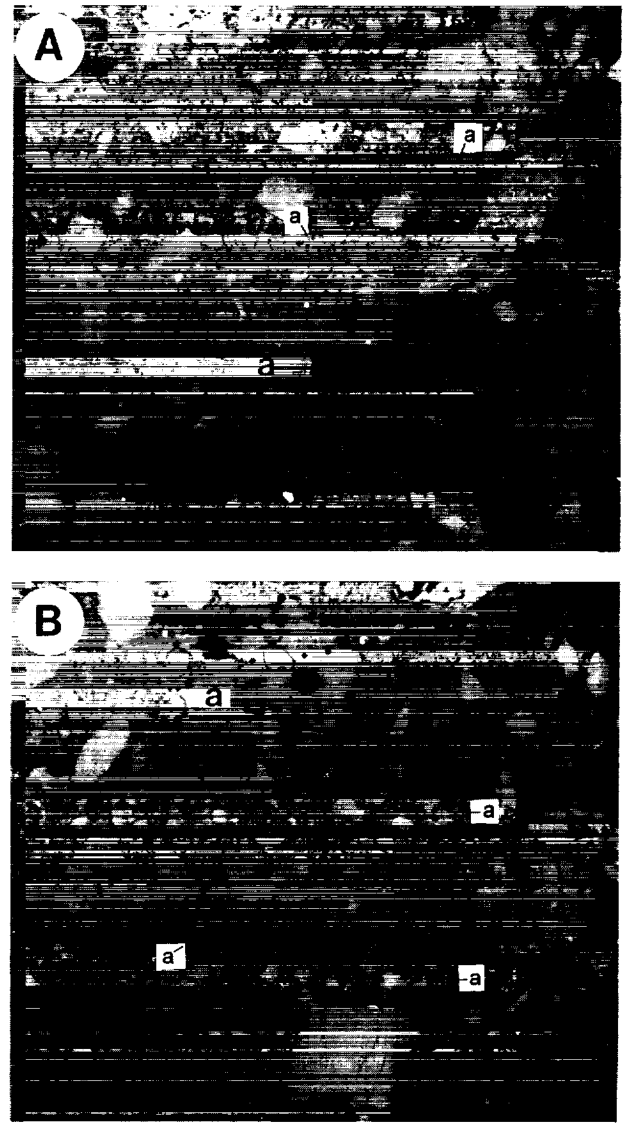

Fig. 1. Reflected light photomicrographs of agglutinates (a) in polished core thin sections. The field of view in both photos is ~1.2 mm. (A) Agglutinates in 68001,6030 at 41 cm depth. This depth corresponds to that with the lowest measured value of I_s/FeO (~2). The large agglutinate, ~350 μm in long dimension, has a smooth, well-polished surface (typical of glass). It has an irregular but smooth outline and is highly vesicular, typical of agglutinates. Light vesicles are filled with epoxy; dark ones are not. The three bright spots on the large agglutinate are Fe-Ni metal blebs. (B) Agglutinates in 68001,6033 at 43.5 cm depth, which has normal I_s/FeO (~35) for its proportion of agglutinates. The large agglutinate in the upper half is ~400 μm across.

3. RESULTS

3.1. Maturity

The regolith-maturity parameter I_s/FeO generally decreases with depth in the core, but not in a regular fashion, with the top 27 cm being mature and the bottom 19 cm straddling the boundary between submature and immature (Fig. 2). Irregular decrease in maturity with depth is characteristic of other Apollo cores (e.g., Morris and Gose, 1976; Bogard et al., 1982; Morris et al., 1989; Korotev and Morris, 1993) and indicates that on the scale of an Apollo double drive tube (~60 cm), regolith at the top has received more surface exposure than regolith at the bottom, i.e., mixing of the regolith by impacts is not so efficient that the upper 60 cm is homogeneous with respect to surface exposure.

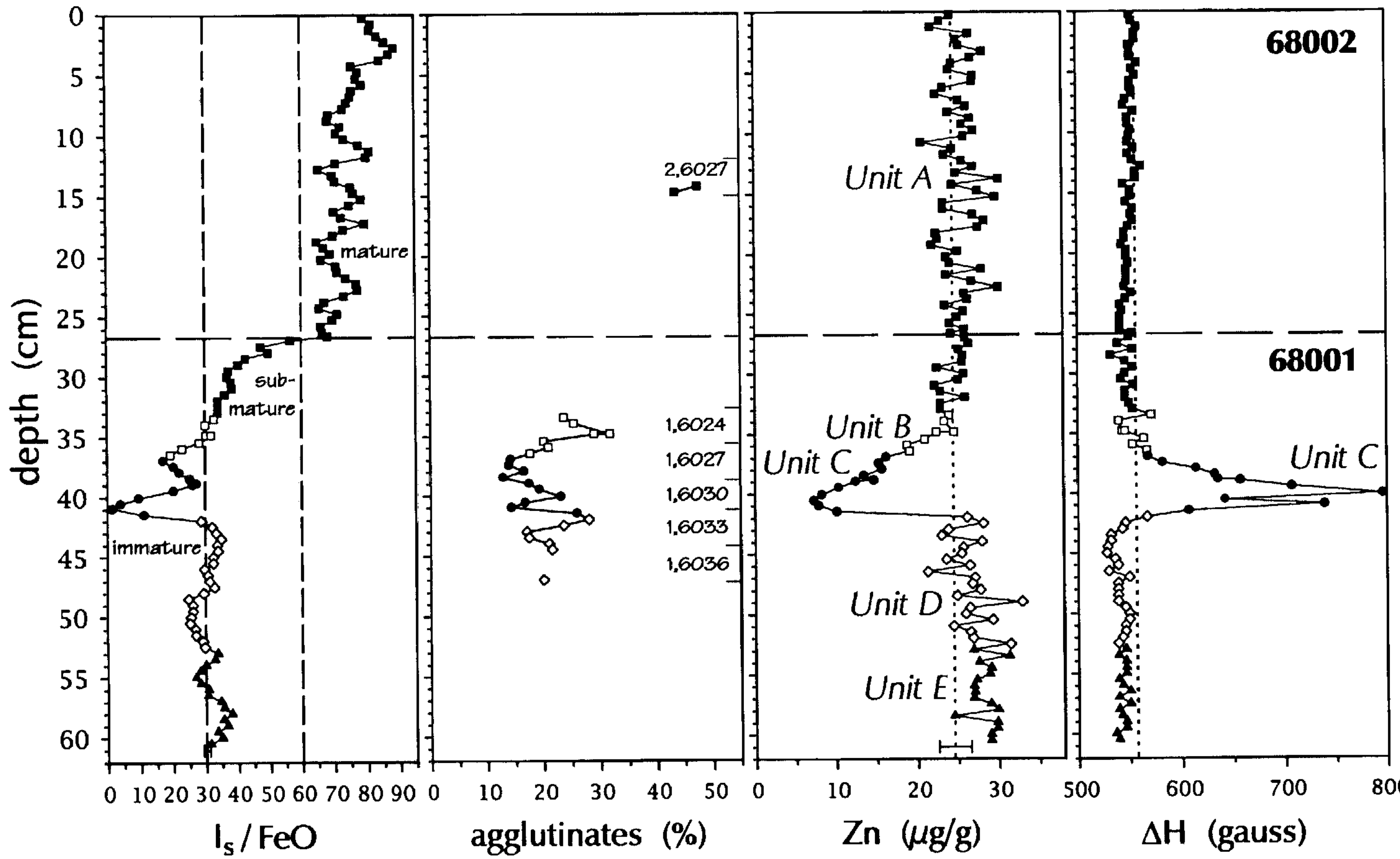

Fig. 2. Variation with depth in the core of I_s/FeO, agglutinate abundance, Zn concentration, and ΔH (FMR line width). The horizontal dashed lines mark the boundary between the 68002 and 68001 sections of the core. In the I_s/FeO profile, the vertical dashed lines represent the immature-submature-mature boundaries (Morris, 1976). In the Zn and ΔH plots (and profiles of Figs. 3–5), the vertical dashed line represents the mean concentration value (or ratio) for all samples of the core. The five compositional units (A–E) are each designated by a different symbol. The analytical uncertainties are indicated by the error bar at 61 cm depth (±1 standard deviation, Table 1). The agglutinate plot depicts the fraction of soil particles in the 20–1000 µm size range that are agglutinates, based on point counts of the continuous thin sections of the core. The section number is indicated on the right axis (e.g., 2,6027 refers to NASA thin section number 68002,6027). Each thin section represents 2.5 or 3 cm of depth, and point counts were done in intervals of 0.5 cm of depth on each section. There is some uncertainty, probably not greater than 1 cm (vertical), in correlating the samples with minimum I_s/FeO and the corresponding interval of the thin sections because the samples for chemical and magnetic analysis come from a different dissection pass than the thin sections.

The most unusual characteristic of the I_s/FeO profile is the minimum that occurs between 39 and 42 cm depth; over the same interval the FMR line width, ΔH (e.g., Morris, 1976), which is constant throughout the rest of the core, reaches a maximum (Fig. 2). At 41 cm, I_s/FeO is only 1.6 units, the lowest value that we have observed in any sample of Apollo 16 soil. It is comparable only to sample 67711 from North Ray crater (I_s/FeO = 2.8), which is an atypical soil consisting mostly of material scraped off the top of a buried, friable boulder (Sutton, 1981).

3.2. Composition

On average, the composition of the core material is typical of regolith from the Cayley plains at Apollo 16. For no element measured here does the mean concentration for the core differ by more than 6% (relative) from the mean concentration of all mature surface soils from Apollo 16. Concentrations of lithophile elements in individual core samples seldom differ from the mean value for the whole core by more than 10% (e.g., Figs. 3–4).

Despite the overall compositional uniformity, there are inflections and discontinuities in the composition profiles for some elements and element ratios. For purpose of discussion, we divide the core into five units, designated A through E, based on composition (Figs. 2–5). These five units do not each necessarily represent discrete depositional events; the divisions simply delimit regions of compositionally similar material. As we have observed in other cores (Korotev et al., 1984; Morris et al., 1989; Korotev, 1991), compositional discontinuities may occur at places where obvious changes in color, grain size, or lithologic character were observed during core dissection. Just as commonly, however, such changes are unaccompanied by compositional changes, and compositional discontinuities do not correlate with features observed during core dissection. Some compositional and textural features of the various units are described in the Appendix. As expected, the composition of the uppermost unit, Unit A, is very similar to the average composition of the four surface soils from station 8 (Table 1).

The most striking feature of the compositional profiles is that the Zn concentrations, which are essentially constant throughout other units of the core, reach a minimum of 30% of the mean value for the whole core in Unit C. This anomaly occurs at the same depth as the minimum in I_s/FeO.

3.3. Modal Abundance of Agglutinates

In the thin section representing the 12–15-cm depth range in Unit A (68002,6027), 43% and 47% of the 0.02–1.0 mm particles are agglutinates in the two half-centimeter intervals examined (Fig. 2). These values are relatively high, as we would expect for mature soils (McKay et al., 1974). Modal abundances of agglutinates are lower in Units B, C, and D, which are less mature. Significantly, however, the agglutinate abundance is only slightly lower in Unit C (mean: 17%; Fig. 2) than in Units B (24%) and D (21%). Although a local minimum in the agglutinate abundance (~10%) occurs at 41 cm depth, corresponding to the minimum in I_s/FeO, a minimum in agglutinate abundance of similar magnitude occurs at the top of Unit C where I_s/FeO is greater. We observed no other unusual petrographic features in the lower part of Unit C where the anomalies in I_s/FeO and Zn concentration occur, but macroscopically the anomalous soil has an unusual bluish gray color.

4. DISCUSSION

4.1. Station 8, South Ray Crater, and Dimict Breccia

As noted in the Introduction, a premission goal was to obtain fine-grained ejecta from South Ray crater at station 8. It is now believed that a principal, and the most easily recognized, component of that ejecta is the striking black-and-white rock known as dimict breccia (Norman and Nagle, 1981; James, 1981; Eugster et al., 1995). Dimict breccias consist of subequal parts of a cataclastic anorthosite (white) phase and a fine-grained impact-melt breccia (black) phase in a mutually intrusive relationship (James et al., 1984; McKinley et al., 1984). The composition of the melt-breccia phase of the Apollo 16 dimict breccias is distinct, and different samples of the melt breccia are all very similar in composition (McKinley et al., 1984; Korotev, 1994). Dimict breccias were found at several stations from the central (stations LM, 1, and 2) and southern (stations 4, 5, 6, 8, and 9) part of the site, but were most prevalent at station 4; one large sample was collected from station 8 (68515). Many dimict breccias are coated with glass and the consistent exposure age of 2 Ma for samples of that glass is taken as the age of South Ray crater (Drozd et al., 1974; Eugster et al., 1995).

The compositional differences between the surface soils of station 8 and 9 (Table 1), although small, can, in fact, be explained by a relative excess of dimict breccia at station 8. The mean composition of the surface soils from station 8 corresponds quantitatively to a mixture of 84% station-9 soil, and 7% anorthosite such as that occurring in the dimict breccias (mean from James et al., 1984), and 9% impact-melt breccia such as that found in the dimict breccias (Korotev, 1994); the same components in the proportions 92:4:4 account well for the average composition of Unit A of the station-8 core. Such mixtures come within 2% (relative) of accounting for the concentrations (C) of all precisely determined lithophile elements of Table 1 (i.e., those for which $\sigma/C < 0.05$). However despite this apparent excess of dimict breccia in the surface regolith of station 8, we believe that the station-8 regolith provides little evidence for any substantial influence from South Ray crater for various reasons detailed below.

First, we would expect an ejecta deposit from South Ray crater (0.7 km in diameter) to be only about 2.5 cm thick at station 8 (~3.5 km away), on average, based on the model of Stöffler et al. (1981). Thus, it is not surprising that several early postmission studies showed that there was little ejecta from the crater at the surface of station 8, based on spectral reflectance and exposure age (Adams and McCord, 1973; Behrmann et al., 1973; Schaeffer and Husain, 1973). Second, the absence of a distinct zone of different composition or maturity at the top of the 68001/2 core argues that the fine-grained regolith at station 8 has been negligibly influenced by South Ray crater. Unit A is too thick (39 cm) and too mature to be composed entirely of South Ray crater ejecta. During the 2 Ma since the South Ray crater impact, material in the upper 3 cm of the regolith

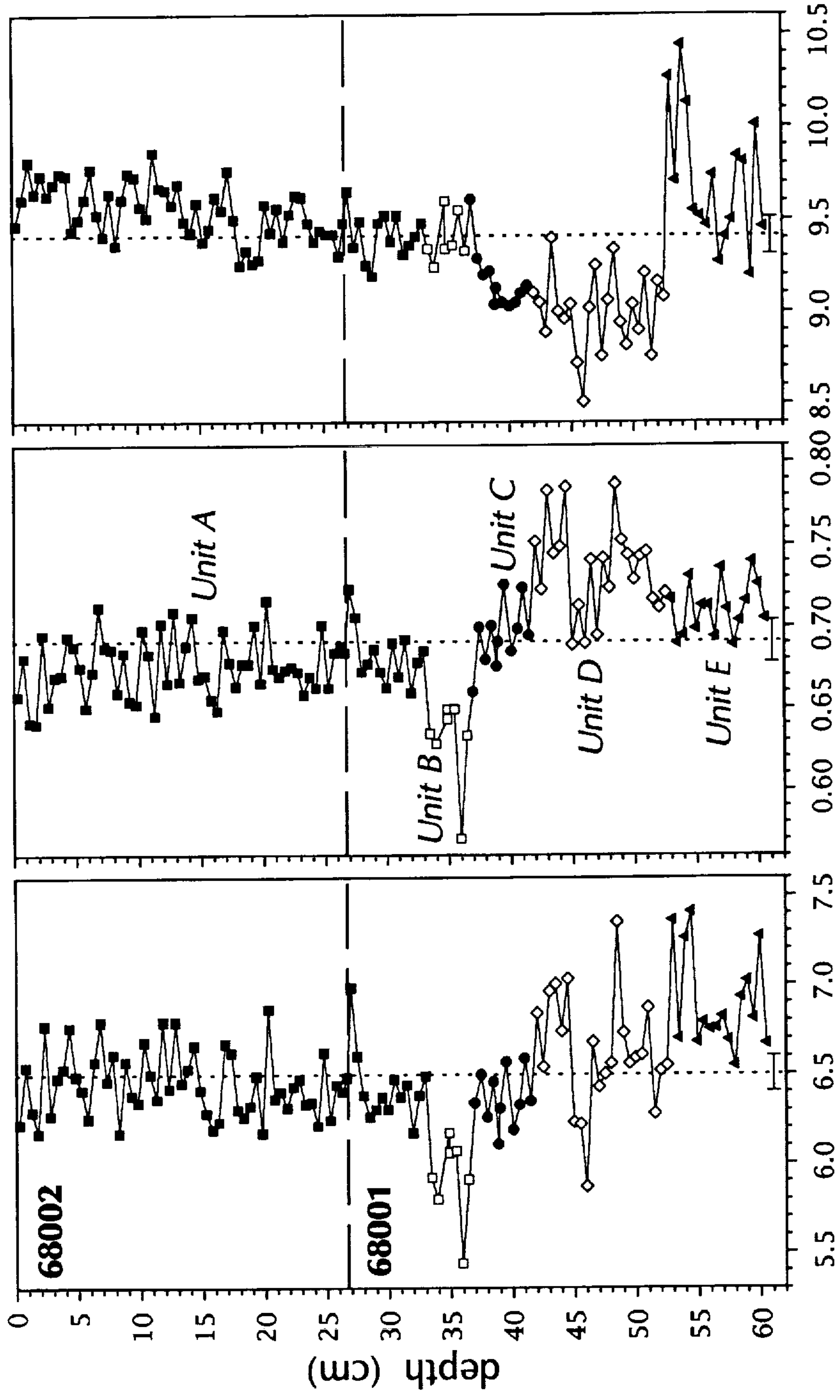

Fig. 3. Profiles for Sc and Sm concentrations and the Sm/Sc ratio; the Sm/Sc ratio increases with the relative abundance of mafic impact-melt breccia; see Fig. 2.

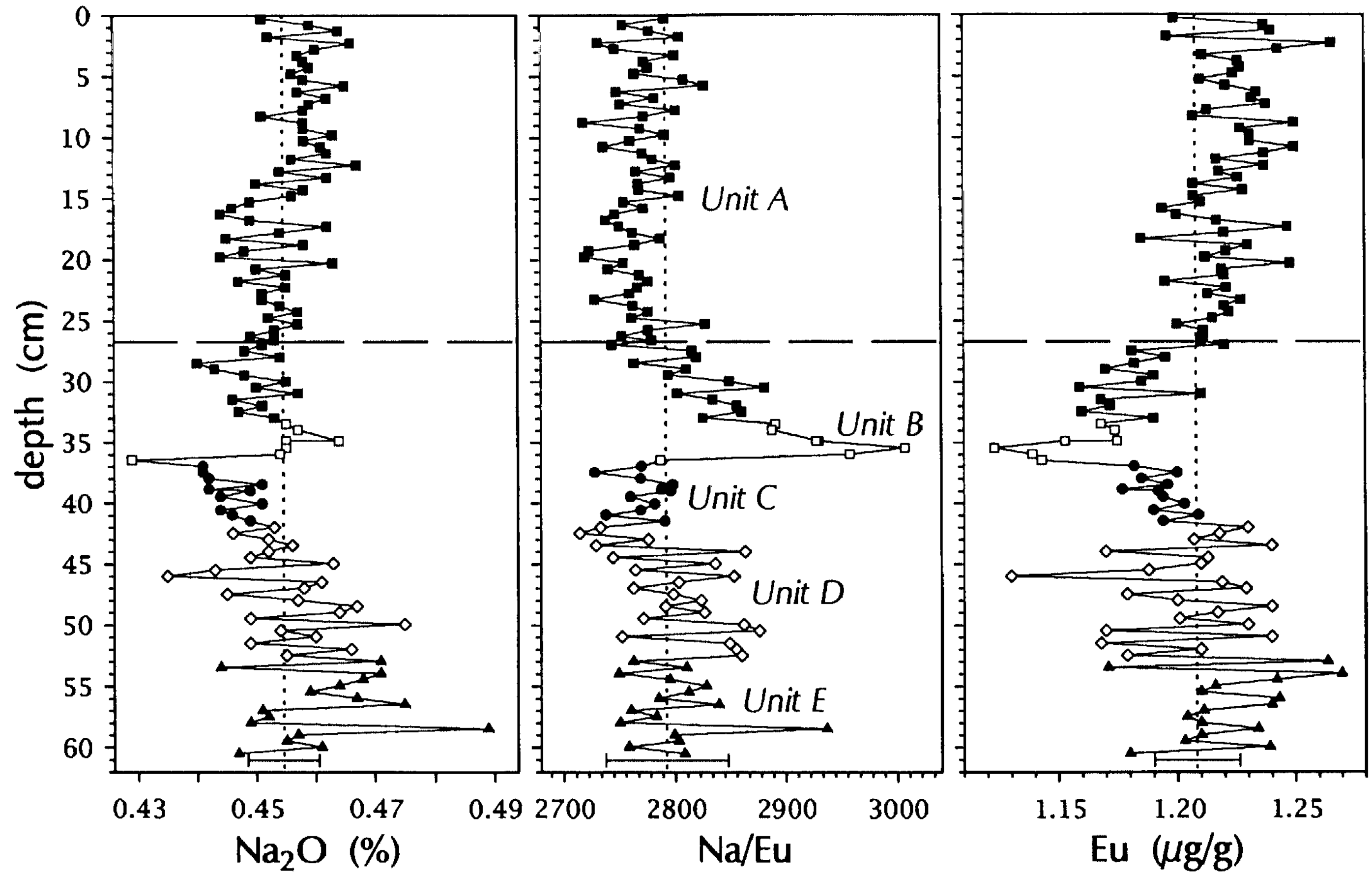

Fig. 4. Profiles for Na_2O and Eu concentrations and the Na/Eu ratio; see Fig. 2. Unit B contains an anorthositic norite component with a high Na/Eu ratio.

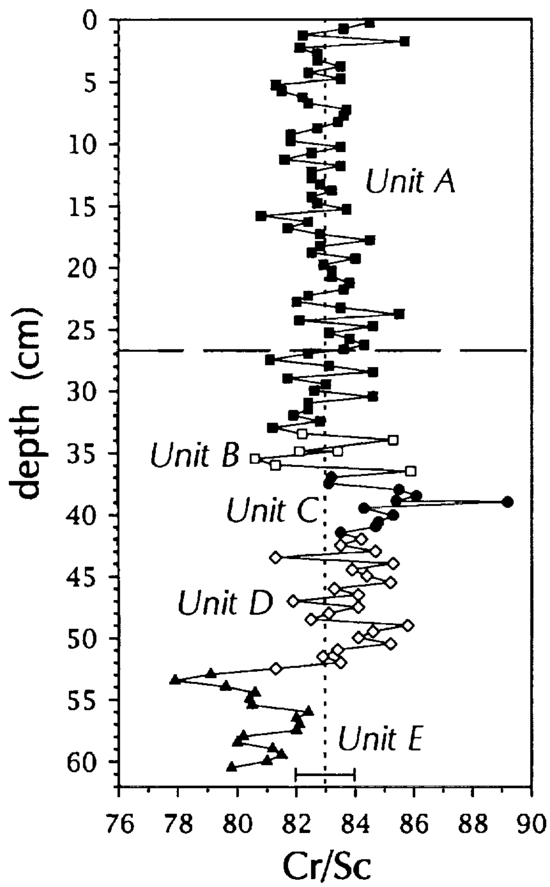

Fig. 5. Cr/Sc ratios correlates positively with Mg/Fe ratios in nonmare polymict materials (Korotev, 1994, 1996b), so it is likely that Unit E has a lower Mg/Fe ratio than the rest of the core.

would have been reworked by micrometeorite impacts; material below 3 cm would have remained undisturbed (Morris, 1978a). A small inflection in the I_s/FeO profile occurs at 3 cm depth in the core (Fig. 2). If the upper 3 cm is interpreted as a reworking zone, the shape of the profile above the inflection, at one extreme, is consistent with addition of at most a centimeter of submature ejecta compositionally similar to the station-8 soil. At the other and more likely extreme, it might reflect a thin layer (~1 mm) of immature ejecta of indeterminate composition. Ejecta from South Ray crater at station 8 probably does not occur primarily as fine-grained material but as the numerous blocks and boulders found in the vicinity, some of which are dimict breccias, and it is these blocks and boulders that constitute the rays observed in premission photos.

Finally, dimict breccias are not restricted to South Ray crater; the ferroan anorthosite and the mafic impact-melt breccia of which they are composed are principal lithologic components of the regolith throughout the Cayley plains at the Apollo 16 site. Ferroan anorthosite such as that found in dimict breccias is ubiquitous; estimates based on mass-balance models range from 30 wt% to 56 wt% (Kempa et al., 1980; Morris et al., 1986; Korotev, 1996a) for mature soils from the Cayley plains, such as those of Unit A of 68001/2. Estimates for the abundance of mafic impact-melt breccias (VHA basalt and LKFM basalt, i.e., compositional groups 1 and 2 of McKinley et al., 1984 and Korotev, 1994) range from 30 wt% to 37 wt%. A recent study of several hundred 2–4 mm particles from the regolith of the central and southern stations (Korotev et al., 1997) shows that of the several compositionally distinct types of impact-melt breccias occurring in the regolith, the most common type, ~40% of the mafic impact-melt breccias studied, is that associated with the dimict breccias (compositional group 2DB). Particles of this composition occur in regolith cores at least to a depth of 2 m at the LM (lunar module) area (Korotev, 1991). Thus it is likely that about 12–15% of regolith (i.e., 0.4 × 30–37%) is melt breccia such as that found in the dimict breccias. If the dimict-breccia component of the regolith is assumed to consist of equal parts anorthosite and melt breccia, then perhaps 24–30% of the regolith of the Cayley plains is the disaggregated remains of dimict breccias. Thus, although dimict breccias may be common in the ejecta of South Ray crater, the two main lithologies of which they are composed are prevalent locally throughout the Cayley plains. If the compositional differences between the surface soils of stations 8 and 9 actually result from a greater relative abundance of dimict breccia in the soils of station 8, as suggested by the compositional differences, then this excess reflects lateral variation that almost certainly predates the formation of South Ray crater.

4.2. Composition Variation with Depth in 68001/2

Because, to first order, the soils of the different units identified in the core are so similar in composition, they are probably all composed of the same lithologic components, but in somewhat different proportions, and it is the variation in the relative proportions of those components that leads to the observed compositional variation with depth. The first-order compositional similarity with depth attests to the efficiency of the impact-mixing process in the upper 0.6 m of regolith; the second-order dissimilarities show that mixing efficiency is not 100%. Below, we discuss three examples of how differences in the average composition between units might be explained by variation in the abundance of a single lithologic component. For these examples, we use Unit A as the reference because it is the most fine-grained and mature soil and, therefore, the best mixed.

Compared to Unit A, Unit B has similar concentrations of elements associated with mafic phases (Sc, Cr), but differs in being poorer in incompatible elements, siderophile elements, and Eu (Table 1; Figs. 3–5). These characteristics are consistent with an excess, compared to Unit A, of some lithology of anorthositic norite composition that is poor in incompatible elements. Numerous such materials occur in the regolith of the Cayley plains (e.g., Korotev et al., 1997), usually as granulitic breccias, feldspathic fragmental breccias, or feldspathic impact-melt breccias.

Unit D differs from Unit A in having slightly greater concentrations of incompatible elements, implying a greater relative abundance of mafic impact-melt breccias in Unit D because such breccias are the major carriers of incompatible elements in the Apollo 16 regolith. Unit D also has slightly lower concentrations of elements associated with mafic min-

Table 1. Results of FMR and INAA: Mean I_S/FeO, element concentrations, and some element ratios for units in 68001/2, and comparison to surface soils from stations 8 and 9.

				68001/2							
		Surface			Unit						
		station 9	station 8	all	A	B	C	D	E	s_A	σ
I_S/FeO	—	89	75	49	68	27	17	30	33	15	1
Na_2O	%	0.453	0.452	0.454	0.455	0.453	0.446	0.455	0.461	0.006	0.006
CaO	%	15.1	15.1	15.2	15.2	15.6	15.6	15.2	15.1	0.3	0.4
Sc	μg/g	9.83	9.34	9.41	9.52	9.39	9.17	9.00	9.71	0.15	0.10
Cr	μg/g	795	789	781	789	779	779	754	783	14	10
FeO_t	%	5.60	5.80	5.53	5.61	5.36	5.40	5.31	5.65	0.28	0.06
Co	μg/g	31.2	41.1	31.7	33.1	27.0	31.0	29.8	31.1	9.0	0.4
Ni	μg/g	469	639	459	479	375	443	440	451	137	20
Zn	μg/g	n.a.	n.a.	24	25	22	12	26	28	2	2
Sr	μg/g	172	186	179	181	169	181	176	179	11	20
Zr	μg/g	196	195	197	198	172	192	199	205	14	20
Cs	μg/g	0.15	0.14	0.14	0.13	0.13	0.12	0.15	0.15	0.02	0.03
Ba	μg/g	153	152	149	149	133	144	150	157	6	8
La	μg/g	13.8	14.0	14.1	13.9	12.8	13.8	14.3	15.0	0.4	0.2
Ce	μg/g	35.8	36.6	36.8	36.1	33.1	35.8	37.2	38.8	1.2	0.7
Sm	μg/g	6.38	6.48	6.50	6.44	5.91	6.36	6.62	6.90	0.19	0.10
Eu	μg/g	1.22	1.21	1.21	1.21	1.15	1.19	1.20	1.22	0.02	0.02
Tb	μg/g	1.32	1.33	1.33	1.32	1.18	1.27	1.36	1.41	0.04	0.03
Yb	μg/g	4.54	4.54	4.54	4.52	4.13	4.43	4.60	4.82	0.14	0.06
Lu	μg/g	0.626	0.631	0.633	0.627	0.577	0.619	0.643	0.677	0.018	0.009
Hf	μg/g	4.85	4.94	4.85	4.84	4.35	4.67	4.93	5.16	0.26	0.07
Ta	μg/g	0.58	0.59	0.58	0.58	0.52	0.56	0.58	0.61	0.02	0.02
Ir	ng/g	15.4	19.6	14.0	15.2	10.8	14.1	12.4	12.6	4.8	1.1
Au	ng/g	10.2	13.9	9.0	9.5	6.9	8.6	8.3	8.8	3.4	1.0
Th	μg/g	2.28	2.29	2.31	2.30	2.10	2.24	2.32	2.46	0.09	0.05
U	μg/g	0.60	0.60	0.61	0.61	0.55	0.58	0.60	0.64	0.05	0.06
Cr/Sc	g/g	80.8	84.5	83.0	82.9	83.0	85.0	83.7	80.6	1.0	0.6
±95%	g/g	1.7	3.5	0.3	0.2	1.8	1.1	0.5	0.7	—	—
Sm/Sc	g/g	0.649	0.695	0.691	0.677	0.629	0.694	0.735	0.711	0.019	0.005
±95%	g/g	0.014	0.021	0.006	0.005	0.025	0.013	0.012	0.008	—	—
La/Sm	g/g	2.158	2.160	2.165	2.165	2.167	2.162	2.164	2.173	0.020	0.015
±95%	g/g	0.015	0.010	0.004	0.005	0.020	0.011	0.010	0.010	—	—
Na/Eu	g/g	2754	2781	2972	2778	2913	2772	2802	2799	35	21
±95%	g/g	23	24	9	8	61	15	23	24	—	—
N	—	8	7	123	67	7	11	22	16	67	—

Surface = means of 2 subsamples each of surface soils 68121, 68501, 68821, and 68841 from station 8 and 2 or 3 subsamples each of 69921, 69941, and 69961 from station 9; I_S/FeO values from Morris (1978b). To show the compositional uniformity of mature surface soil in the core, the sample standard deviation (s_A) for samples for Unit A is tabulated. σ = estimated analytical uncertainty of a single analysis based primarily on counting statistics (one standard deviation). FeO_t = total Fe as FeO. n.a. = not analyzed. ±95% = 95% confidence limit on mean ratio value above. N = number of sample analyses averaged. Concentrations of siderophile elements are high in the mean for station-8 surface soils because one of the eight subsamples analyzed (from 68821) has anomalously high concentrations (e.g., 1450 μg/g Ni).

erals (Sc, Cr, Fe), implying that it also has a greater relative abundance of plagioclase. Together, these observations suggest, but do not require, that Unit D is enriched in a component of dimict breccia compared to Unit A. Quantitatively, the average concentrations in Unit D of all elements determined here can be matched by a mixture of 80 wt% Unit-A soil, 9 wt% anorthosite such as that occurring in the Apollo 16 dimict breccias, and 11 wt% impact-melt breccia such as that occurring in the Apollo 16 dimict breccias. Such a mixture comes within 2% (relative) of accounting for the concentrations of all the precisely determined lithophile elements in Unit D (Table 1) and within 5% for some less precisely determined elements (Sr, Cs, U). In other words, if we assume from the discussion of the previous section that Unit A is composed of 26 wt% dimict breccia, the compositional differences between Units A and D, on average, can be quantitatively explained by a greater abundance, 41 wt% (0.8 × 26% + 0.2 × 100%), of dimict breccia (or, the disaggregated remains) in Unit D compared to Unit A. Other scenarios may provide an equivalently good accounting of the composition of Unit D, but some excess of a combination of mafic melt breccia and anorthosite seems to be required.

Consideration of Unit E is more speculative. Unit E has the greatest concentrations of incompatible elements of any unit of the core (by a small margin), suggesting that it has the greatest relative abundance of mafic impact-melt breccias. However, admixture of any type of Apollo 16 mafic melt breccia (Cr/Sc = 82–120; Sm/Sc = 0.9–1.7) would lead to an increase in Cr/Sc and Sm/Sc, which is not observed. Unit E, in fact, has a lower Cr/Sc ratio than any other unit of the core (Fig. 5). Absolute concentrations of Sc are distinctly greater in Unit E, and the four most Sc-rich samples have the lowest Cr/Sc ratios, so the carrier of the excess Sc must have a low Cr/Sc ratio. The combination of enrichment in Sc but lower Cr/Sc is reminiscent of thin layers of soil with an excess of mare-derived material that occur in the station-4 core (Korotev et al., 1984), which was collected about a kilometer away from station 8. However, at station 4, the Sc enrichments are accompanied by anomalously low La/Sm ratios (<2.0 in the most Sc-rich samples) because mare basalts and glass tend to have low La/Sm ratios (typically 0.8–1.6); in Unit E of 68001/2, La/Sm ratios are slightly greater that other units of the core (Table 1). Thus, neither admixture of Apollo 16 mafic melt breccias or typical mare basalt to any of the other units of the core can account for the composition of Unit E.

We are aware of no common or uncommon Apollo 16 lithologies that have the required characteristics. In order to account for the composition of the most Sc-rich samples from Unit E, we have calculated compositions of mixtures of soil from Unit A with various types of plausible and less plausible components represented by lithologies from other sites, including mare basalts, KREEP basalts, and impact-melt breccias. The only successful mixture that we have found involves an intriguing set of components, a combination of Apollo 14 aluminous mare basalt (groups 1 and 2 of Dickinson et al., 1985, which have low Cr/Sc ratios and the highest La/Sm ratios among mare basalts) and Apollo 14 impact-melt breccia (low Cr/Sc, very high Sm/Sc). These two lithologies are reasonable cocomponents because both occur together in Apollo 14 breccia 14321.

Our mass-balance calculations indicate that addition of 1% of Apollo 14 aluminous basalt and 2.5% Apollo 14 impact-melt breccia to the mean composition of Unit A soil accounts well for the mean composition of the most Sc-rich samples of Unit E. Again, this is not a unique solution, but it is the only good solution that we have found. The implication is that Unit E may contain a small fraction of an unusual lithology previously recognized only from Apollo 14. Whatever the identity of the inferred component(s), it may also account for surface soils 65501 and 65511, both submature, from station 5 (Korotev, 1981) and the soil of stratigraphic unit 2 of drive-tube section 60010 (18–21 cm depth; Korotev, 1991), which are all compositionally similar to the soils of Unit E from 68001/2, including Cr/Sc and Sm/Sc. Thus the inferred component, while minor, may be widespread at the site.

5. DECOUPLING OF MATURITY PARAMETERS IN UNIT C

Compositionally, Unit C is unexceptional. Concentrations of all lithophile elements are similar to those of Units A and D. Only Zn is unusual, approaching a minimum of 7 $\mu g/g$ in the bluish-gray soil at 41 cm depth, compared with 20–30 $\mu g/g$ in other units of the core (Fig. 2). The minimum in Zn concentration also corresponds to the minimum in I_s/FeO and maximum in ΔH. Most of the Zn in Apollo 16 soil derives from micrometeorites and is surface correlated (Boynton et al., 1976). Because the abundance of micrometeorite material in the regolith increases with surface exposure, we previously observed a correlation between Zn concentration and I_s/FeO in samples from core 60013/14, with an intercept of 5 $\mu g/g$ Zn at $I_s/FeO = 0$ (Korotev and Morris, 1993); the intercept value represents the nonsurface-correlated component and is consistent in magnitude with Zn concentrations in rocks of which the soil is composed (typically, <10 $\mu g/g$; Krähenbühl et al., 1973). Thus in terms of Zn and I_s/FeO and our experience with other Apollo 16 soils, the anomalous bluish-gray soil in 68001/2 would appear to be comminuted rock debris that has received virtually no surface exposure, and the gradual increase in Zn concentration and I_s/FeO toward the surface would appear to be a mixing effect between this disaggregated but unexposed rock material and a mature or submature soil of otherwise similar composition. However, other evidence we discuss next indicates that the bluish-gray soil at the bottom of Unit C has, in fact, received a degree of surface exposure equivalent to soil below and above it and that some effect we have not previously observed has caused loss of Zn and resetting of I_s/FeO to values typical of unexposed rock.

5.1. How Much Surface Exposure?

The most compelling evidence that the soil of Unit C is not simply disaggregated rock that has received minimal surface exposure is the presence of agglutinates. Agglutinate abundances generally increase with maturity (McKay et al., 1974) and correlate positively with I_s/FeO in Apollo 16 soils (Fig. 6b). The relative abundance of agglutinates in the lower portion of Unit C, although only half that of Unit A, is not as low as we would expect for a soil that had received as little surface exposure as that implied by the low I_s/FeO values (Fig. 6a). Throughout Unit C, the abundance of agglutinates is only slightly less than the abundance in the upper part of underlying Unit D, which has I_s/FeO ranging from 30 to 35, implying that Unit C has received the surface exposure typical of a submature soil.

Although perhaps not as compelling as the presence of agglutinates, three other parameters also argue that Unit C has received a degree of surface exposure equivalent to the soils of adjacent units. First, other highly immature soils from Apollo 16 (e.g., 61221 and those from North Ray crater) have greater mean grain sizes than mature or submature soils (Heiken et al., 1973; McKay et al., 1974) because they have not had long exposures to comminution by micrometeorites. Unit C, however, is not anomalously coarse grained compared to other units of the core. Second, the composition of Unit C is more consistent with well-mixed soil than with the disaggregated remains of one or a few rocks. All other immature soils from Apollo 16 are compositionally distinct from mature surface soils because each contains a significant proportion of some component, comminuted rock, or perhaps previously buried regolith, with little or no surface exposure (Korotev, 1981). The soils of North Ray crater are highly variable in composition from sample to sample because they are poorly mixed and each is dominated by different rock types (Korotev, 1996b). Except for breccias composed of regolith, there is no Apollo 16 rock type that has a composition like the soil of Unit C. Thus admixture of fragments of any common Apollo 16 lithology to the station-8 soil should alter the composition (as for Unit B), and the concentration of at least some lithophile element in the soil should correlate with I_s/FeO in Unit C, which is not observed. Unit C is nearly identical in composition to

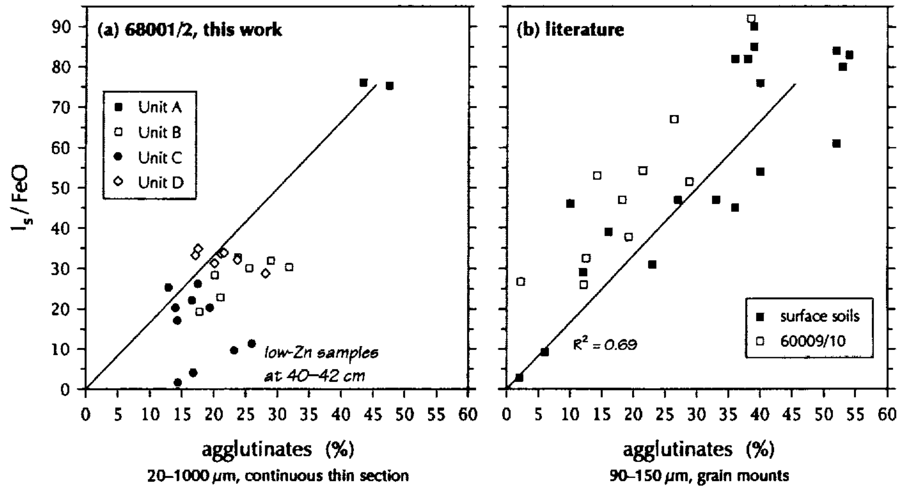

Fig. 6. Correlation of the maturity parameters I_s/FeO and agglutinate abundance in Apollo 16 regolith (after Morris, 1976): (a) data for 68001/2 (from Fig. 2) and (b) comparison to literature data for Apollo 16 soils. In (b), the filled symbols represent surface and trench soils; the unfilled symbols are for samples from double drive tube 60009/10 (data from Heiken et al., 1973; McKay et al., 1976, 1977; Morris, 1976). In (a), the diagonal line is defined by the origin and the mean values for the two most mature samples (from Unit A). For reference, the same line is shown in (b); however the two plots are not strictly comparable. In (a), I_s/FeO was determined on <1 mm fines, and the abscissa value represents the percent of soil particles in the 20–1000 μm size range that are agglutinates, based on point counts of thin sections prepared from epoxy-impregnated core material. In (b), I_s/FeO was determined on <0.25 mm fines and the abscissa value represents the percent of all particles in the 90–150 μm grain-size fraction that are agglutinates, based on thin sections of grain mounts. Despite these differences, the line of (a) provides a reasonable fit to the data of (b). Compared to Apollo 16 regolith of similar agglutinate abundance, the low-Zn samples from the bottom of Unit C at 40–42 cm depth in 68001/2 have anomalously low values of I_s/FeO, ranging from 7% to 26% of the expected values.

some samples from Unit A, implying that it is equivalently well mixed.

Finally, siderophile-element abundances are inconsistent with highly immature soil. Mature soils have higher concentrations of siderophile elements than immature soils because surface exposure leads to admixture of micrometeorite material (Wasson et al., 1975). For example, the only immature surface soil collected from the Cayley plains, sample 61221 (I_s/FeO = 9), contains 220 μg/g Ni (R. L. Korotev, unpubl. data; mean of three analyses) compared to 479 μg/g Ni in Unit A (mean I_s/FeO = 68). In contrast, Unit C is not depleted in siderophile elements (mean Ni = 443 μg/g) and the mean Ni abundance of the four samples in the zone of minimum I_s/FeO (520 μg/g) is actually greater than that of Unit A, implying that Unit C has received surface exposure equivalent to that of other units of the core.

5.2. A Heating Event?

The data reviewed above show that the bluish-gray soil of Unit C is characterized by a conflicting set of observations regarding surface exposure. Excluding the unlikely event that a swarm of micrometeorites formed a large number of agglutinate particles in a short time, agglutinate abundances argue that the soil is submature, i.e., it has received moderate surface exposure. Yet I_s/FeO and Zn indicate that it is highly immature. We conclude that the soil has received a degree of surface exposure at least equivalent to that implied by the agglutinate abundance (Fig. 6) and that the low values of I_s/FeO and low Zn concentrations result from a resetting of these two parameters (but not agglutinate abundance) to values typical of unexposed soil. Specifically, we suspect that the soil of Unit C was heated to a temperature sufficiently high and for a duration sufficiently short (1) to volatize the surface-correlated Zn, but not the volume-correlated volatile elements like Na, Cs, and Au, and (2) to reduce the ferromagnetic resonance index (I_s/FeO) to near zero by coalescing the nanophase metallic iron to larger particle diameters. Depending on the temperatures and times involved, such heating would not necessarily affect agglutinate and siderophile-element abundances but it would explain the anomaly in ΔH, as we discuss next.

The FMR line width, ΔH, is relatively constant at ~550 G (gauss) for all of the core except Unit C, where values approach 800 G in the region of minimum I_s/FeO (Fig. 2). The theoretical value of ΔH for an assemblage of rigidly-embedded, randomly-oriented, noninteracting, single-domain metallic iron particles is 830–1030 G at 298 K depending on the value used for the anisotropy constant (e.g., Tsay et al., 1973; Griscom et al., 1979). Experimental values obtained on reduced, Fe-bearing glasses are ~1000 G (e.g., Weeks and Prestel, 1974; Griscom et al., 1979). As noted and discussed previously (e.g., Morris, 1976), values of ΔH for lunar soils are less than the theoretical value for metallic iron and ΔH generally increases with FeO concentration in lunar soils (Fig. 7). The deviation and correlation have not been adequately explained, but possible explanations include systematic variations in alloying elements (e.g., Ni and Si) and/or particle diameters (e.g., Griscom et al., 1979; Griscom, 1981). In any event, the most anomalous samples from Unit C have values of ΔH that are typical of Fe-rich soils from the maria, and Unit-C soils deviate substantially from

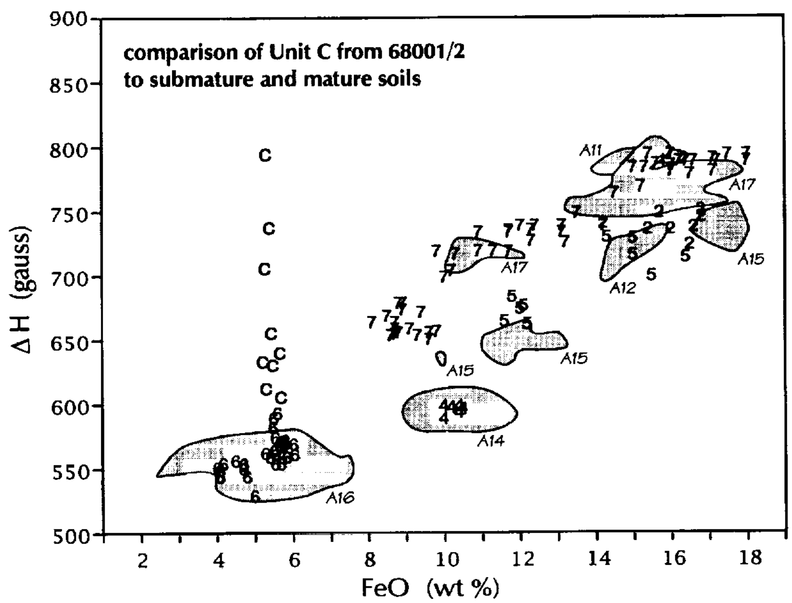

Fig. 7. Comparison of ΔH and FeO concentrations in soil from Unit C of 68001/2 (symbol C) to submature and mature soils collected during the Apollo lunar missions. The filled fields enclose ~1700 data points for soils from core tubes (R. V. Morris, unpubl. data). The numbers, which denote the Apollo mission number (e.g., 7 for Apollo 17), correspond to data points for surface and trench samples (Morris, 1978b). The high-ΔH samples from Unit C are anomalous compared to any previously studied Apollo 16 sample.

the ΔH-FeO correlation observed in other lunar soils (Fig. 7).

In principle, if Unit C were to consist of Apollo 16 material with no surface exposure (i.e., 5–6% FeO and I_s/FeO ≈ 0) to which a small amount (<1%) of mature mare soil was added (FeO > 15% and ΔH=700–800 G), the resulting soil would plot in the region of the Unit-C samples on Fig. 7 because the mare component would not appreciably affect the FeO concentration, but the entire FMR signal would derive from it. However, this explanation is implausible because (1) there is no compositional evidence for an excess component of mare-derived material (Appendix), (2) the range of values of ΔH observed for Unit C require that mare materials with different values of ΔH were involved, and (3) the presence of agglutinates in substantial abundances means that the nonmare components of the soil received exposure at the surface and, thus, should contribute substantially to the line width.

Several lines of evidence suggest instead that all of the anomalies in Unit C were caused by heating. First, Zn is the most volatile element determined here and occurs mostly on the surface of the soil grains; thus moderate heating would easily evaporate the surface-correlated Zn. Second, ΔH, which is typically in the range of 530–580 G for Apollo 16 soils (Fig. 7), increases and I_s/FeO decreases with heating. For example, Tsay and Live (1974) heated an Apollo 17 soil (75081) in vacuum at temperatures between 600 and 1025 °C. The linewidth at room temperature increased after annealing and the amount of nanophase metal (i.e., I_s/FeO) decreased). Morris et al. (1975) report FMR thermomagnetic data for four Apollo soils. The value of ΔH for soil 10084 increased from 790 to 950 G after heating to ~900°C, and the concentration of nanophase metal decreased by a factor of ~5. Although the post-heating value is not reported, ΔH increased from 540 to 690 G in a similar experiment on soil 67010 (R. V. Morris, unpubl. results). Griscom et al. (1973) report ΔH values of ~710 G for two Apollo 16 soils heated in vacuum at 650°C for 3190 h. Finally, several immature Apollo 16 regolith breccias (60275, 61295, 63588, and 63595; I_s/FeO < 6 units) studied by McKay et al. (1986) have high values of ΔH (630–740 G) compared to Apollo 16 soils (R. V. Morris, unpubl. results). For these samples, the heating presumably occurred during formation of the breccias by impact (shock lithification). Thus both laboratory experiments and data for lunar breccias indicate that the heating of submature or mature lunar soils to moderate temperatures can produce high values of ΔH, such as those observed in Unit C. The laboratory experiments also show that heating can reduce I_s/FeO to values typical of immature soils.

Unfortunately, there is insufficient data to place strict temperature and time constraints on the heating event that affected Unit C. Results of vacuum heating studies indicate that temperatures higher than 600–650°C are sufficient to cause increases in ΔH over laboratory timescales (Griscom et al., 1973; Tsay and Live, 1974; Morris et al., 1975). Cirlin and Housley (1979) showed that most Zn is volatized from Apollo 17 soil grains between 800 and 900 °C. At the other extreme, there is no petrographic evidence for melting or sintering of the soil of Unit C, suggesting that the temperature did not exceed about 1000°C.

We can only surmise the sequence of events leading to the apparent resetting of I_s/FeO and loss of Zn. The heating was almost certainly caused by an impact. From the asymmetry of the profiles for I_s/FeO and Zn in Unit C, it seems unlikely that the heating event occurred in situ after the deposition of Unit C at its present location. One possibility is that Units A, B, and C were deposited in one event on top of Unit D. The leading edge the ejecta, i.e., Unit C, was subjected to hot gas from the impact. In this scenario, the impact that deposited Unit C also supplied the heat. Alternatively, several subsequent impacts may have redistributed (and mixed) the anomalous soil since the time of impact that reset the maturity parameters. A problem with any scenario relying on an impact to supply the heat is that the lunar regolith has been formed by countless impacts. Why is this the first time that we have observed an apparent resetting event like this? The implication is that only a small fraction of the volume of regolith redistributed by an impact encounters the requisite conditions. As noted above, the only high-ΔH samples we have previously observed at Apollo 16 have been regolith breccias. This suggests that the soil of Unit C might possibly represent either a disaggregated regolith breccia or an incipient regolith breccia, i.e., soil that experienced conditions similar to those of the immature regolith breccias discussed above, but with temperature or shock pressure insufficient to cause lithification.

6. SUMMARY AND CONCLUSIONS

The drive tube core 68001/2, taken in the southern portion of the Apollo 16 site, contains regolith typical of the local Cayley plains throughout its 0.6 m length. Contrary to premission expectations, there is no evidence in the core, except perhaps for a minor inflection in the profile of I_s/FeO at 3 cm depth, of any ejecta or influence from South Ray crater. Based on the maturity parameter I_s/FeO, the upper 27 cm of the core is mature throughout (I_s/FeO = 60–89). Maturity generally decreases with depth between 27 and 42 cm and remains nearly constant to the bottom of the core (61 cm) at the operational boundary between immaturity and submaturity (i.e., I_s/FeO = 30). We have identified five units, designated A–E, of compositionally distinct soil in the core, but there is no strong evidence that any of them correspond to discrete depositional units. If old surfaces occur in the core, they most likely occur at 42 cm depth, between Units C and D (where there are strong discontinuities in the profiles for Zn and I_s/FeO) or at 53 cm (where there are discontinuities in the profiles for Sc and Fe). We can account for the compositional differences among the units in terms of variation in the relative abundances of lithologies in the soil. For example, Unit B (33–37 cm) appears to be slightly enriched in some lithology of anorthositic norite composition and Unit D (42–53 cm) may contain a slightly greater proportion of dimict breccia compared to the average for the core. There is compositional evidence that Unit E (53–61 cm) contains a small excess proportion (up to 3.5%) of some component compositionally similar to Apollo 14 sample 14321.

The most unusual feature of the core occurs in Unit C in a narrow band of bluish-gray soil between 39 and 42 cm depth. Two parameters that correlate with regolith maturity, I_s/FeO and Zn concentration, decrease to very low values (<2 units and 7 μg/g), implying that the soil is highly immature, i.e., that it is composed of disaggregated rock with virtually no surface exposure. However, the abundance of agglutinates, which is also measure of maturity, is typical of soil with I_s/FeO $\approx$ 30, i.e., an immature to submature soil. There is also compositional evidence that the unusual soil, like the more normal soils that are stratigraphically adjacent, is a complex mixture of many lithologies, including micrometeorite material, and, thus, that it has undergone gardening (Morris, 1978a) at the lunar surface. We believe that the anomalous soil was once a submature soil that was subsequently heated by an impact event to temperatures hot enough to evaporate the surface-correlated Zn and agglomerate the nanophase metal giving rise to the I_s/FeO signal but not to sufficiently high temperatures to destroy the agglutinates by sintering or melting or to volatize Na or Au. Although impact heating must be a common occurrence in the lunar regolith, this is the first evidence that we have observed in lunar soil for decoupling of some maturity parameters (I_s/FeO and Zn concentration) from others (agglutinate abundance).

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APPENDIX

Below, we justify the assignment of units based on composition and summarize some observations made during core processing; these observations are described in more detail in Schwarz (1993, 1994). Our placement of boundaries between units is somewhat arbitrary, and in some cases the boundaries could be relocated a centimeter up or down without changing the interpretations. Most of the compositional features discussed below are evident in Table 1 and Figs. 2–5.

Unit A (0–33 cm depth), which includes all of the 68002 section and the top few centimeters of 68001, is uniformly dark in color and nearly uniform in composition; the standard deviation for those lithophile elements that are associated with major silicate mineral phases (e.g., Na, Ca, Sc, Eu) is of the same magnitude as the analytical uncertainty, 1–2% (Table 1). There is some slight systematic variation with depth, however. Concentrations of elements associated with mafic phases (Fe, Sc, and Cr), ITEs (incompatible trace elements, e.g., Sm and Th), and Na are all about 2–3% lower at the bottom of the unit than at the top and the decrease with depth appears continuous. Concentrations of Eu also decrease with depth, but the rate of decrease accelerates below the boundary between the core sections at 27 cm depth. Friable clods are abundant between 9.5 and 14.5 cm depth. Because there is no compositional anomaly in this region, these clods are probably soil breccias that are not significantly different in composition from the fine-grained material. The sharp change in I_s/FeO and Eu concentration at the core section boundary may in part be related to the lateral offset of 1–2 cm between the first dissection pass (68002, more toward center of tube) and third dissection pass (68001, more toward perimeter of tube).

Unit B (33–37 cm) is characterized by low concentrations of ITEs and Eu, leading to distinctly lower Sm/Sc ratios and a higher Na/Eu ratios than other units of the core. There is no color change at the A-B boundary, but compared to the bottom of Unit A, dark soil breccias and soil clods are larger in Unit B and the abundance of black, fine-grained glassy particles is greater.

Unit C (37–42 cm) is intermediate in composition to Units A and D and not distinct or unusual in any way with regard to lithophile elements. The only characteristic compositional feature of Unit C is a steady and significant decrease with depth in Zn concentration to the lowest values observed in the core at 41 cm, with a slight increase at the bottom centimeter of the unit; the minimum in I_s/FeO occurs at the same depth. The upper part of Unit C (~36–39 cm) is light gray in color and contains light gray clods and soil breccias; anorthosites are rare and black glassy particles are fairly numerous. Macroscopically, the region of minimum I_s/FeO and Zn (~39–42 cm) appeared darker and bluish gray during core dissection. The >1 mm particles in this interval are coherent (no friable soil breccias), consisting mostly of breccias and small black, glassy fragments, with some anorthositic fragments and glass shards and spheres.

Unit D (42–53 cm) is demarcated at the top by a distinct color change at the C-D boundary, with the top (42–48 cm) of Unit D being brownish-gray. However, there is no abrupt change in the concentration of any lithophile elements. The top of Unit D is loose and coarse-grained, with the >1-mm material consisting of coherent particles. A thin finger of light gray material containing white fragments extends about two-thirds the diameter of the core at about 45 cm depth. This gray soil probably corresponds to the local minimum in Sc and Sm concentrations at 46 cm in the profiles. About halfway through Unit D at 48 cm and continuing to the bottom of the core the soil is lighter brown and more coherent. This zone contains soil breccia particles that are both friable and coherent as well as fine-grained black glassy fragments. There is no inflection in any element profiles corresponding to the change in color and coherency at 48 cm depth. Zn concentrations return to values typical of Unit A.

Unit E (53–61 cm) is characterized by a discontinuous increase in the concentrations of Sc, Fe, Cr, and, to a lesser extent, some other elements. The Cr/Sc ratio also changes discontinuously and significantly at the D-E boundary. However, we observed no change in color or other parameters at the D-E boundary during core dissection.

The La/Sm ratio, which is sensitive to mare-derived material, is constant throughout the core with no hint of inflections or regions of anomalously low values that would signify an enrichment in mare-derive material (Korotev, 1991), although the average ratio for Unit E is slightly greater than for the other units. There is no indication of any systematic variation in siderophile-element concentrations with depth, except that Unit B has a lower average concentration than the other units. As we have observed in other Apollo 16 cores (Korotev et al., 1984; Korotev, 1991; Korotev and Morris, 1993), some individual samples are anomalously enriched in Fe, Co, Ni, Ir, and Au from nuggets of $Fe_{94}Ni_6$ metal of meteoritic origin.