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Magnetic stratigraphy of the Apollo 15 deep drill core

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Abstract—The $< 45\ \mu m$ fraction of 51 soil samples from the lower half of the Apollo 15 deep drill (122–242 cm depth) was subjected to magnetic analysis at room temperature. The variations of the Fe°/Fe^{2+} ratio with depth reflect a nonlinear accumulation rate of the regolith. Five major depositional units are recognized. Two of them show a partially reworked inverted section attesting to the local origin of most of the regolith. Data on grain size separates of four soils show that the $< 45\ \mu m$ fraction has a considerably higher Fe°/Fe^{2+} ratio than the remainder of the sample.

INTRODUCTION

THE APOLLO 15 DEEP CORE was drilled at the ALSEP station about 1.5 km away from Hadley Rille. It penetrated to a depth of 242 cm below the present lunar surface and consists of six sections labeled 15001 through 15006. A detailed optical description of the core has been given by Heiken *et al.* (1973). We report here on magnetic measurements on 51 samples from the lower three drill stem sections: 15001, 15002, and 15003 which cover the depth range between 122 and 242 cm. These samples have previously been analyzed in terms of grain size parameters by Lindsay (1973) and were sieved into size fractions at $\frac{1}{2}\phi$ intervals. (Note: ϕ is defined as size (mm) $= 2^{-\phi}$. Thus $\phi = 0$ corresponds to 1 mm, and $\phi = 4.5$ corresponds to 45 μm which is the smallest sieve size used.) Magnetic measurements were carried out on all size fractions of four samples, of the remaining samples only the $< 45\ \mu m$ fraction was analyzed. The reason for this restriction is the enormous workload required to measure all size fractions (some 600 samples!). At the time of this writing the project has not been completed and this paper should be viewed as a progress report. Specifically, the exact weight of the samples has not been determined so that only relative values can be reported.

VARIATIONS OF MAGNETIC PARAMETERS WITH GRAIN SIZE

The four samples on which the magnetic measurements were performed on all size fractions were selected on the basis of maximum weight for increased accuracy and for maximum spread in their mean grain size. Their mean grain sizes are 15001,193 $\phi = 2.689$ (155 μm); 15001,148 $\phi = 3.650$ (80 μm); 15001,164 $\phi = 3.963$ (64 μm); 15003,222 $\phi = 4.117$ (58 μm). This compares with an overall mean grain size for all 51 samples of $\phi = 4.019$ or 62 μm (see also Fig. 3).

The room-temperature hysteresis curves were obtained with a vibrating sample magnetometer. The maximum applied field was 18 kOe for the samples

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from 15001 and 15002, and 22 kOe for the samples from 15003. From the hysteresis curve one obtains the redox ratio, Fe°/Fe^{2+}, and the ratio of the saturation remanence to saturation magnetization, J_{rs}/J_s. The procedures and significance of these parameters have been discussed by Nagata *et al.* (1972) and Pearce *et al.* (1973, 1974). Measuring at room temperature rather than liquid helium temperature limits the accuracy since very fine iron particles (< 40 Å) are not properly determined (Nagata *et al.*, 1971; Pearce and Simonds, 1974). Depending on the amount of these grains the ratios could be low as much as 10%.

Figure 1 shows the Fe°/Fe^{2+} ratio as a function of grain size. In spite of the very different mean grain sizes all four samples exhibit essentially the same behavior. The finest size fraction (< 45 μm) which constitutes about half the sample by weight has the highest redox ratio. The next size range (45–63 μm) and all coarser fractions have a considerably lower Fe°/Fe^{2+} ratio. It would be interesting to further separate the fine fraction to determine the exact grain size at which the dramatic increase in the redox ratio occurs. The Fe°/Fe^{2+} ratio of ~ 0.01 for the > 45 μm fraction of sample 193 is typical for mare basalts (e.g. Nagata *et al.*, 1974; Pearce *et al.*, 1974). Preliminary studies indicate that this very coarse

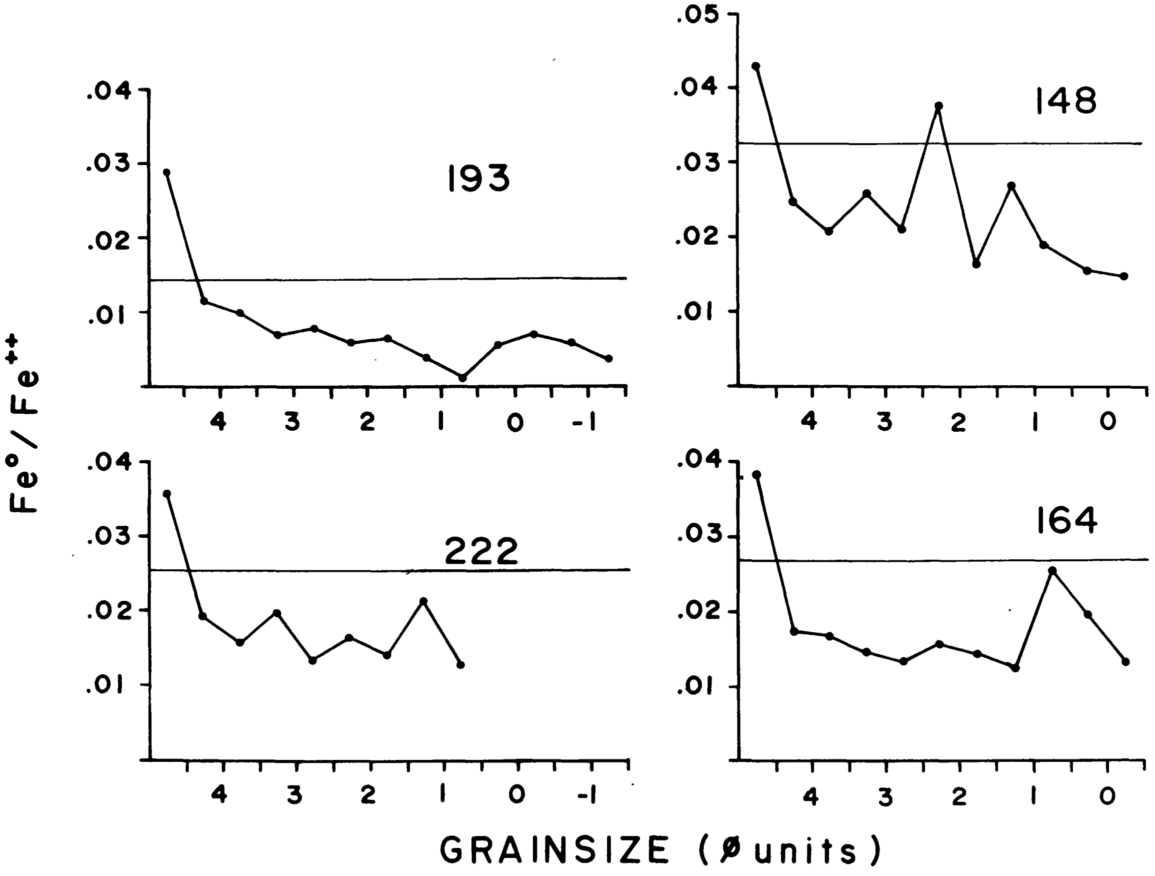

Fig. 1. Variations of the Fe°/Fe^{2+} ratio as a function of grain size. Horizontal line represents mean value. The depths of these samples are: 193 at 229 cm, 164 at 213 cm, 148 at 207 cm, 222 at 130 cm. Note: 4.5 ϕ = 45 μm, 0 ϕ = 1 mm.

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sample is indeed mainly a crushed basalt whereas the other three samples contain considerable amounts of microbreccias.

The value of the Fe°/Fe^{2+} ratio in these samples is mainly controlled by the Fe° content. Thus the high ratio of the fine fraction confirms that most of the excess iron is at least $< 45\ \mu m$ in size. The excess iron resides largely in the glass (e.g. Housley *et al.*, 1973) which constitutes an appreciable part of the agglutinates. It, therefore, follows that the bulk of the agglutinates is $< 45\ \mu m$ in size. McKay *et al.* (1974) use the agglutinate content of the 90–150 μm size range as one measure of soil maturity. In view of our data such an interpretation should be treated with caution until it has been established whether or not the agglutinate content in a particular size range is proportional to the total agglutinate content.

The ratio of the saturation remanence to saturation magnetization, J_{rs}/J_s, depends on the iron metal grain size distribution and sphericity (Pearce *et al.*, 1973, 1974; Nagata *et al.*, 1972). Large values (~ 0.05) imply abundance of stable single-domain iron particles (150–300 Å diameter), whereas small values generally occur in samples where most iron is multidomain. Let us first consider sample 193 (Fig. 2). Again, the $< 45\ \mu m$ fraction is distinctively different from the remainder of the soil having very high J_{rs}/J_s values. The $> 45\ \mu m$ fractions have J_{rs}/J_s ratios typical of mare basalts (e.g. Pearce *et al.*, 1974) and predominant multidomain iron grains are inferred based on results on other mare basalts. (No values for grains $> 710\ \mu m$ are given. The values are very small but due to the minute sample size (1–3 mg), J_{rs} could not be determined with an accuracy equal to the other samples.)

The J_{rs}/J_s data on soil samples 148 and 164 (Fig. 2) exhibit similar behavior for grains $< 355\ \mu m$. For coarser fractions, however, J_{rs}/J_s increases again. This reflects an increasing amount of microbreccias in the coarse fraction. It has been shown (Gose *et al.*, 1972) that the low- to medium-grade breccias contain abundant single-domain iron. It is not clear, however, whether this increase is truly representative of these soils since the coarse fractions used consist of only a few grains. The low J_{rs}/J_s values in the range 45–355 μm could conceivably be due to superparamagnetic iron, but the predominance of multidomain iron seems to be more likely based on experience with other samples. This uncertainty will be removed in the near future.

VARIATIONS OF MAGNETIC PARAMETERS WITH DEPTH

Within the lower three drill stem sections Heiken *et al.* (1973) optically recognized 26 distinct layers, some of which are further subdivided (Column 1 of Fig. 3). The grain size analysis of 51 samples by Lindsay (1973) reveals a general decrease in mean grain size toward the top (Fig. 3). Except for the four samples discussed above, our magnetic analyses were performed on the $< 45\ \mu m$ fraction only which represents about half of the total sample. The variations in weight of the $< 45\ \mu m$ fraction (Fig. 3) follow and sometimes accentuate the variations in mean grain size attesting to a rather symmetrical grain size distribution, i.e. the

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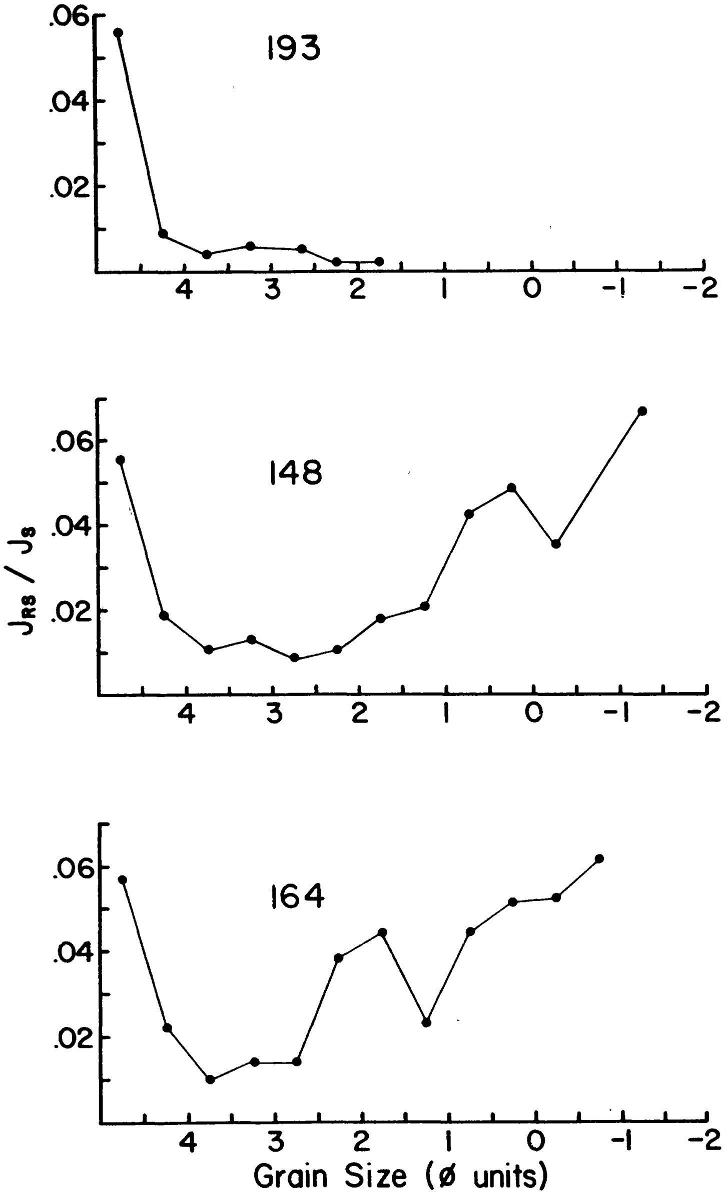

Fig. 2. Variations of saturation remanence to saturation magnetization with grain size.

mean and the median of the population are similar. Therefore, the trends observed should be representative of the total sample.

As has been discussed earlier, the ratio J_{rs}/J_s is sensitive to the grain size of the metallic iron. The large values observed (Fig. 3) reflect the abundance of single-domain particles, i.e. particles between about 150 and 300 Å in diameter. This is in agreement with results obtained from surface soils (e.g. Pearce *et al.*, 1974). In view of the following discussion it is critical to note that this ratio is essentially constant throughout the core (no values have been obtained for the samples from 15003). This implies a rather similar iron metal size distribution in all samples. Thus, performing the experiment at low temperatures to thermally stabilize the superparamagnetic grains will not change the trends of the Fe°/Fe^{2+}

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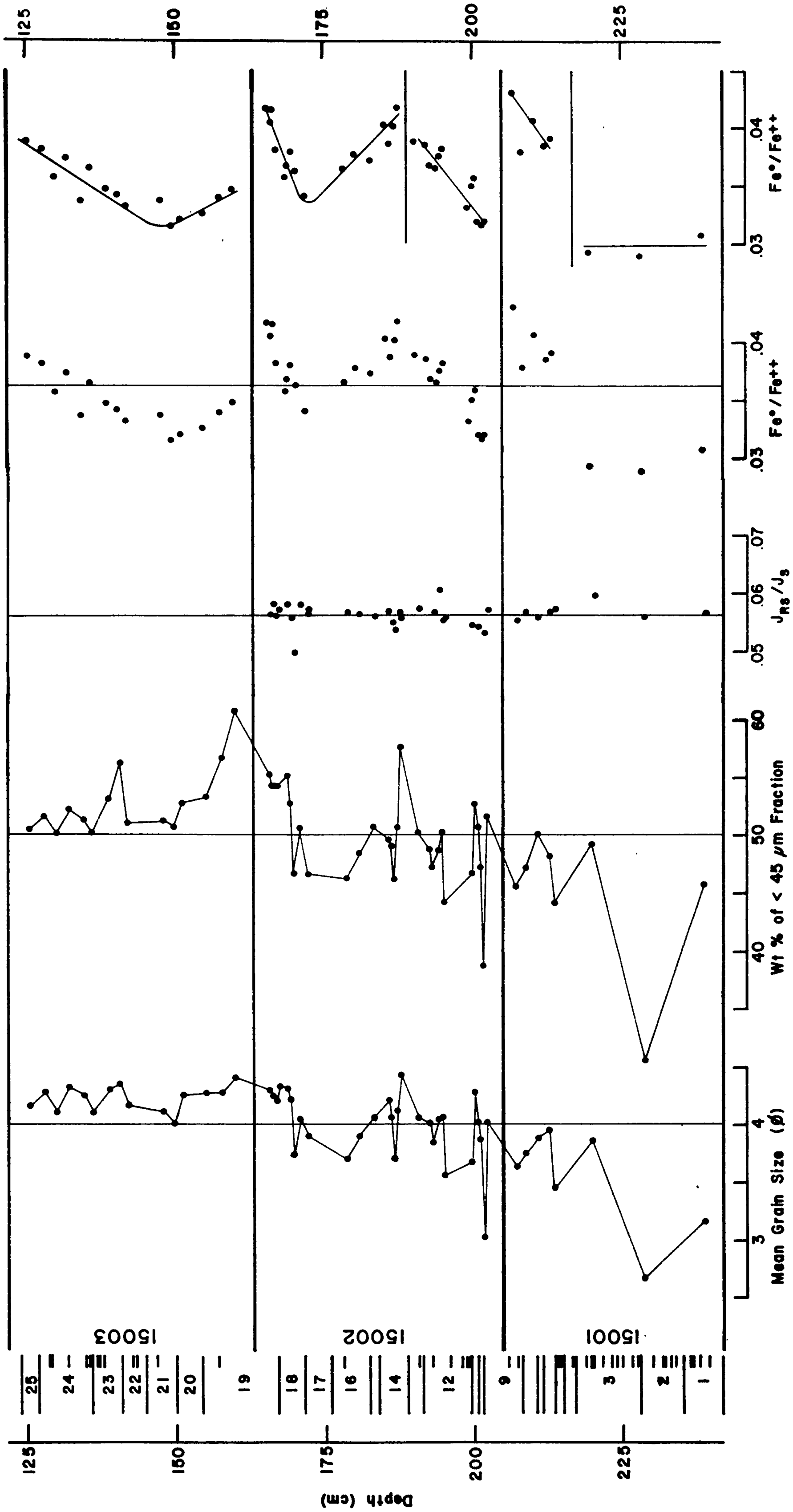

Fig. 3. Stratigraphic variations of grain size and magnetic parameters.

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ratio measured at room temperature but it would increase the numerical values.

The Fe°/Fe^{2+} ratio (Fig. 3) cannot be directly compared with published data since it was obtained from the $< 45\ \mu m$ fraction. However, a reasonable estimate can be made in using the data from the four samples discussed above (Fig. 1). In those samples the reduction ratio of the total sample is approximately 70% of the value of the $< 45\ \mu m$ fraction. Using this conversion factor, the Fe°/Fe^{2+} ratio of the core is seen to vary between 0.02 and 0.03. These values are higher than those for the mare basalts, but also are clearly lower than the ratios in surface soils (e.g. Pearce *et al.*, 1973, 1974). We shall return to this point later.

Particularly interesting are the uniform trends of the Fe°/Fe^{2+} ratio over depth intervals of tens of centimeters as indicated in the last column of Fig. 3. First consider the data for 15002. In the lower part of this drill stem the ratio generally increases, i.e. the higher layers are more reduced. This behavior is readily explained—indeed it was predicted—by depositional models such as presented by Quaide and Overbeck (1975). Independent of the exact meteoroid flux, including even a constant rate of crater production, the growth of the regolith will always be nonlinear, i.e. individual regolith layers of identical thickness represent progressively longer accumulation periods the higher their position in the stratigraphic column. Thus younger layers have been more severely reworked and, thereby, have a larger Fe°/Fe^{2+} ratio since the addition of iron metal is clearly associated with the regolith accumulation process. i.e. degree of reworking and exposure. This is true irrespective of the mechanism of iron production (Housley *et al.*, 1973, 1975; Yin *et al.*, 1975; Pearce *et al.*, 1973). The expected variation of the Fe°/Fe^{2+} ratio are schematically depicted in Fig. 4.

The remainder of 15002 is interpreted as one depositional unit which was laid down in inverted stratigraphy. It is thought that the redox ratio immediately after deposition decreased systematically throughout this unit. The

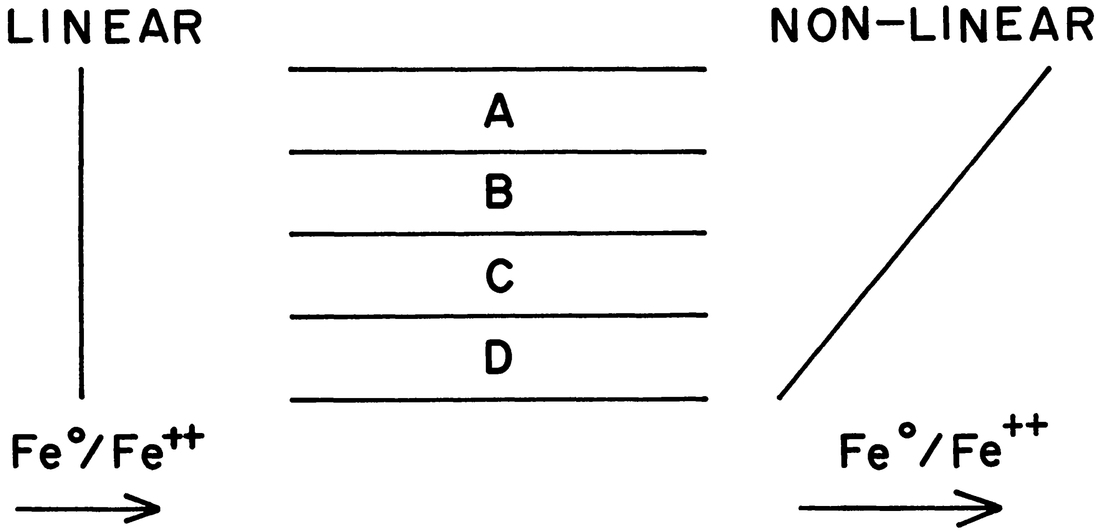

Fig. 4. Expected variation of the Fe°/Fe^{2+} ratio for a linear and nonlinear regolith accumulation.

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unit was then partially reworked resulting in an increasing Fe°/Fe^{2+} ratio for the surface and near-surface materials, owing to the more frequent occurrence of small impact events as compared to large ones (Gault *et al.*, 1974) (Fig. 5). Before the entire unit was reworked the next layer was deposited, namely 15003 in its entirety. Again, 15003 is considered to show a partially reworked inverted section. An alternate interpretation of the lazy V shape variations of the Fe°/Fe^{2+} ratio is that it represents two units, one with inverted and one with normal stratigraphy. This interpretation seems less likely because it requires that the inverted section was covered sufficiently fast to prevent any reworking.

Inverted sections are a natural result of impact crater formation. It has been observed both experimentally (e.g. Gault *et al.*, 1968; Moore, 1971) and in terrestrial impact craters (e.g. Shoemaker, 1963; Roddy *et al.*, 1975) that the original stratigraphic sequence is overturned during excavation and deposition of ejecta and is especially well preserved on the crater rim and may extend as far as one crater radius. The occurrence of inverted units in the core is a further manifestation that much of the lunar regolith is of very local origin. This statement is also supported by the total iron content of the drill section which we determined magnetically to be between about 12 and 16 wt.% FeO, i.e. typical of mare basalts. The addition of material from the Apennine Front must be minimal, although it is only a few kilometers away (see also Schonfeld, 1975).

The basal part of the core does not exhibit any variations in the Fe°/Fe^{2+} ratio. There are only three data points and the result may be fortuitous. However, units 1, 2, and 3 form one superunit (Heiken *et al.*, 1973; Nagle, personal communication) which is distinctively different from the rest of the core; it could have been deposited in a single impact event.

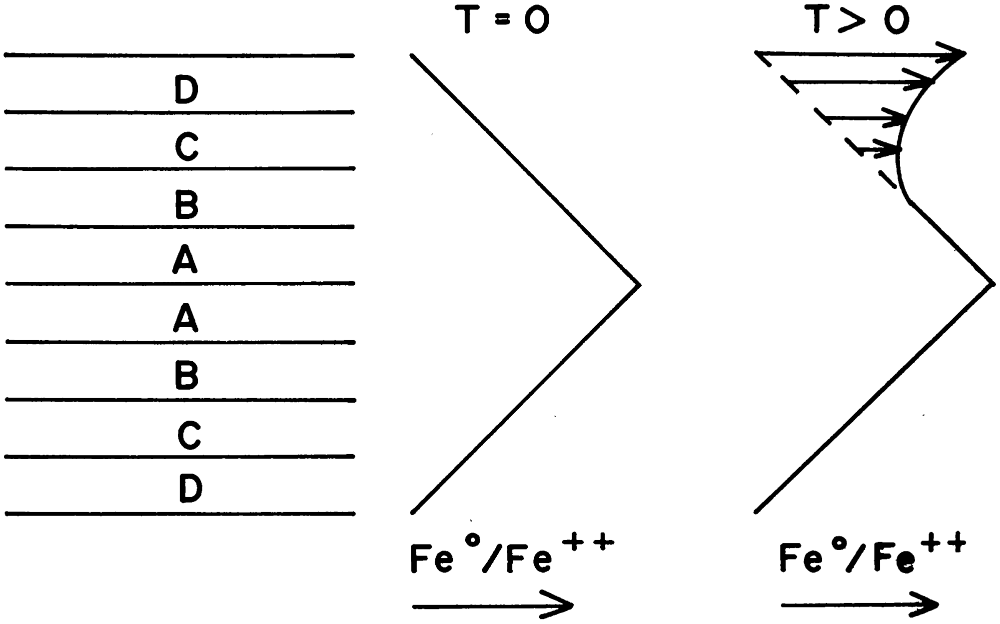

Fig. 5. Schematic variation of the Fe°/Fe^{2+} ratio in an inverted section immediately after the impact ($T = 0$) and at some later time ($T > 0$).

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It, therefore, appears that the lower half of the Apollo 15 deep drill reflects five or possibly seven separate cratering events which range in thickness of material deposited from about 10 to 40 cm. These units seem to represent individual ejecta blankets. Their thickness coupled with the evidence of reworking and preirradiation (e.g. Pepin *et al.*, 1974; Crozaz *et al.*, 1972) implies that they were formed by local craters confined to the regolith, i.e. craters between about 2 and 20 m diameter (Moore, 1971). As a consequence, such units may have horizontal extents of tens of meters.

The magnetically derived core stratigraphy needs not be in contradiction with the results of the detailed core description by Heiken *et al.* (1973) who recognized 26 units with many more subunits (see also Fig. 3). The difference may simply reflect impact events of different scales. The magnetic stratigraphy is the result of larger impacts whereas the fine structure is the consequence of local reworking by micrometeorites. The latter should, therefore, be observable only over very small distances, say less than 1 m. Such an interpretation was also arrived at theoretically by Quaide and Overbeck (1974) and Arnold (1975). This result is of great significance, because utmost caution is necessary to reconstruct depositional histories based on the observed fine structure. It is not correct to assume that their present stratigraphic position reflects a continuous depositional history.

DISCUSSION

The suite of samples used in this report allowed for the first time a detailed magnetic study of lunar soils. While more work needs to be done some trends are quite evident. In the four samples in which several size fractions were analyzed the $< 45\ \mu m$ fraction has a considerably larger Fe°/Fe^{2+} ratio than the remainder of the soil and the metallic iron present is predominantly in the stable single-domain size range. However, neither these soils nor the other soils from the core have as large a redox ratio as any of the true surface soils. This observation gives strong support for a nonlinear accumulation rate of the regolith as theorized by Quaide and Overbeck (1975) and Lindsay (1972, 1975).

The variations in the Fe°/Fe^{2+} ratio with depth result in a magnetic stratigraphy which seems to define major depositional units. The occurrence of two partially reworked inverted sections implies a local origin of most of the soils. The magnetic stratigraphy which indicates five or possibly seven depositional units is not in contradiction to the observations of Heiken *et al.* (1973) who describe 26 layers in this part of the core nor does it conflict with the neutron fluence data of Russ *et al.* (1972) which seem to imply that the core has remained undisturbed for the last half billion years. Rather it appears that the three techniques are complementary, each looking at a different scale of the evolution of the regolith.

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REFERENCES

Arnold J. R. (1975) A Monte Carlo model for lunar surface properties (abstract). In *Lunar Science VI*, p. 18–20. The Lunar Science Institute, Houston.

Cisowski C. S., Dunn J. R., Fuller M. D., Rose M. F., and Wasilewski P. J. (1974) Impact processes and lunar magnetism. *Proc. Lunar Sci. Conf. 5th*, p. 2841–2858.

Crozaz G., Drozd R., Hohenberg C. M., Hoyt H. P., Ragan D., Walker R. M., and Yuhas D. (1972) Solar flare and galactic cosmic ray studies of Apollo 14 and 15 samples. *Proc. Lunar Sci. Conf. 3rd*, p. 2917–2931.

Gault D. E., Quaide W. L., and Overbeck V. R. (1968) Impact cratering mechanics and structures. In *Shock Metamorphism of Natural Materials* (editors B. M. French and N. M. Short), p. 87–99. Mono Book Corp., Baltimore.

Gault D. E., Hörz F., Brownlee D. E., and Hartung J. B. (1974) Mixing of the lunar regolith. *Proc. Lunar Sci. Conf. 5th*, p. 2365–2386.

Gibbons R. V., Hörz F., Thompson T. D., and Ahrens T. J. (1975) Controlled shock experiments of lunar analogues (abstract). In *Lunar Science VI*, p. 284–286. The Lunar Science Institute, Houston.

Gose W. A., Pearce G. W., Strangway, D. W., and Larson E. E. (1972) Magnetic properties of Apollo 14 breccias and their correlation with metamorphism. *Proc. Lunar Sci. Conf. 3rd*, p. 2387–2395.

Heiken G. H., Duke M., McKay D. W., Clanton U. S., Fryxell R., Nagle J. S., Scott R., and Sellers G. A. (1973) Preliminary stratigraphy of the Apollo 15 drill core. *Proc. Lunar Sci. Conf. 4th*, p. 191–213.

Housley R. M. and Grant R. W. (1975) Reduced Fe observed in ESCA studies of lunar surface chemistry (abstract). In *Lunar Science VI*, p. 399–401. The Lunar Science Institute, Houston.

Housley R. M., Grant R. W., and Paton N. E. (1973) Origin and characteristics of excess Fe metal in lunar glass melted aggregates. *Proc. Lunar Sci. Conf. 4th*, p. 2737–2749.

Lindsay J. F. (1972) Development of soil on the lunar surface. *J. Sed. Pet.* **42**, 876–888.

Lindsay J. F. (1973) Evolution of lunar soil grain size and shape parameters. *Proc. Lunar Sci. Conf. 4th*, p. 215–224.

Lindsay J. F. (1975) A steady state model for the lunar soil. *Geol. Soc. America Bull.* In press.

McKay D. S., Fruland R. M., and Heiken G. H. (1974) Grain size and the evolution of lunar soils. *Proc. Lunar Sci. Conf. 5th*, p. 887–906.

Moore H. J. (1971) Craters produced by missile impacts. *J. Geophys. Res.* **76**, 5750–5755.

Nagata T., Fisher R. M., Schwerer F. C., Fuller M. D., and Dunn J. R. (1971) Magnetic properties and remanent magnetization of Apollo 12 lunar materials and Apollo 11 lunar microbreccia. *Proc. Lunar Sci. Conf. 2nd*, p. 2461–2476.

Nagata T., Fisher R. M., and Schwerer F. C. (1972) Lunar rock magnetism. *The Moon* **4**, 160–186.

Nagata T., Sugiura N., Fisher R. M., Schwerer F. C., Fuller M. D., and Dunn J. R. (1974) Magnetic properties of Apollo 11–17 lunar materials with special reference to effects of meteorite impact. *Proc. Lunar Sci. Conf. 5th*, p. 2827–2839.

Pearce G. W. and Simonds C. H. (1974) Magnetic properties of Apollo 16 samples and implications for their mode of formation. *J. Geophys. Res.* **79**, 2953–2959.

Pearce G. W., Williams R. J., and McKay D. S. (1972) Magnetic properties and morphology of metallic iron produced by reduction of synthetic Apollo 11 composition glasses. *Earth Planet. Sci. Lett.* **17**, 95–104.

Pearce G. W., Gose W. A., and Strangway D. W. (1973) Magnetic studies of Apollo 15 and 16 lunar samples. *Proc. Lunar Sci. Conf. 4th*, p. 3045–3076.

Pearce G. W., Strangway D. W., and Gose W. A. (1974) Magnetic properties of Apollo samples and implications of regolith formation. *Proc. Lunar Sci. Conf. 5th*, p. 2815–2826.

Pepin R. O., Basford J. R., Dragon J. C., Coscio M. R., and Murthy V. R. (1974) Rare gases and trace elements in the Apollo 15 drill core fines: Depositional chronologies and K–Ar ages, and production rates of spallation-produced ^{3}He, ^{21}Ne, and ^{38}Ar versus depth. *Proc. Lunar Sci. Conf. 5th*, p. 2149–2184.

Quaide W. and Overbeck V. (1975) Development of the mare regolith: Some model considerations. *The Moon*. In press.

Roddy D. J., Boyce J. M., Colton G. W., and Dial A. L. (1975) Meteor Crater, Arizona, rim drilling,

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volume, thickness, depth, and energy calculations (abstract). In *Lunar Science VI*, p. 680–682. The Lunar Science Institute, Houston.

Russ G. P., Burnett D. S., and Wasserburg G. J. (1972) Lunar neutron stratigraphy. *Earth Planet. Sci. Lett.* **15**, 172–186.

Schonfeld E. (1975) Component abundances in Apollo 15 soils by the mixing model technique (abstract). In *Lunar Science VI*, p. 712–714. The Lunar Science Institute, Houston.

Shoemaker E. M. (1963) Impact mechanics at Meteor Crater. In *The Moon, Meteorites, and Comets* (editors B. M. Middlehurst and G. P. Kuiper), p. 301–336. University of Chicago Press.

Yin L. I., Tsang T., and Adler I. (1975) Electron spectroscopic studies related to solar-wind darkening of the lunar surface. *Geophys. Res. Lett.* **2**, 33–36.

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