

PRODUCTION OF SUPERPARAMAGNETIC Fe^0 ON THE LUNAR SURFACE

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Inclusions of Fe^0 , some tens of nm in size, are formed in the amorphous rims of lunar regolith grains from solar-wind-reduced indigenous Fe^{++} , by either radiation-induced lattice rearrangement, or micrometeorite-induced vaporisation and recondensation, or both. This leads to surface correlation of the resulting FMR signal. Subsequent regolith maturation transfers that metal into agglutinitic glass, generating a volume-correlated FMR component. Typical lunar regolith contains a mixture of both components.

Even before the Apollo 11 landing, it was recognised that solar-wind irradiation probably leads to chemical reduction of the lunar surface [1,2,3]. Subsequent analysis of Apollo regolith samples confirmed this prediction [4,5]. Furthermore, it was found that agglutinates in the lunar regolith contain very fine metallic Fe particles [6] and that at least a fraction of these are single-domain, superparamagnetic grains, i.e., <30nm in diameter, thereby yielding a characteristic ferromagnetic resonance (FMR) signal [7]. As the proportion of agglutinates builds up during maturation of the regolith, the FMR intensity, I_s , increases, the parameter I_s/FeO being an excellent quantitative measure of regolith maturity [7]. Microscopically visible metal grains, and presumably also submicroscopic grains, are concentrated in the glass that binds each agglutinate together [8]. It has been generally accepted that such grains are produced during melting of precursor regolith minerals by micrometeorite impact, with reduction of lunar Fe^{++} being effected by solar-wind H previously implanted in the mineral surfaces [7,8]. However, the exact sequence of events involved in the production of superparamagnetic Fe^0 has not been clear. In particular, it was found [9] that in some immature soils the superparamagnetic Fe^0 was apparently surface correlated, Fig. 1, leading to speculation that in some way micrometeorite impact initially caused either the proportion of agglutinitic glass, or the density of fine-grained metal in that glass, or both, to vary inversely with regolith particle size [9]. The physical basis of this scenario seems questionable, even though the distribution of maturity-dependent properties among different grain-size fractions is not well established, but a plausible alternative has been lacking. However, observations [10,11] of 10-200nm-sized inclusions of Fe^0 in the amorphous rims of mineral grains from the lunar regolith provide an explanation for this phenomenon.

Previous studies of the amorphous rims that characterise most lunar regolith grains have concluded that those rims result solely from the intense radiation damage that the solar wind inflicts on the outermost lunar surface [12]. Thus, the rims were regarded as being effectively glass with the same chemical composition as the underlying grain interiors [13]. However, results of Auger and ESCA spectroscopy suggested that the surfaces of lunar regolith grains are enriched in Si and Fe, with some of the excess Fe being in the metallic state [14]. Furthermore, it was established that regolith S is surface correlated [15,16], and from isotope systematics it was possible to infer that regolith grain surfaces are depleted in O, i.e., reduced [17]. Consequently, although reduction of Fe^{++} to Fe^0 , by solar-wind-induced sputter ejection of O [18], was consistent with a purely solar-wind radiation-damage origin for the amorphous rims, enrichment of those rims in S, Si and possibly Fe^{++} appeared to require either an additional or an alternative process, such as condensation from impact-generated vapor [10,19,20]. Direct analyses of such rims in silicate [10] and ilmenite [11] grains have recently confirmed the enrichments in S and Si (though revealing depletion of Fe^{++}); however the Ti contents of the ilmenite rims demonstrate that the rims are not solely produced by vapor deposition but result from a combination of vapor deposition and radiation damage [11]. Whether vapor deposition is involved in the reduction of

LUNAR REGOLITH METAL PRODUCTION

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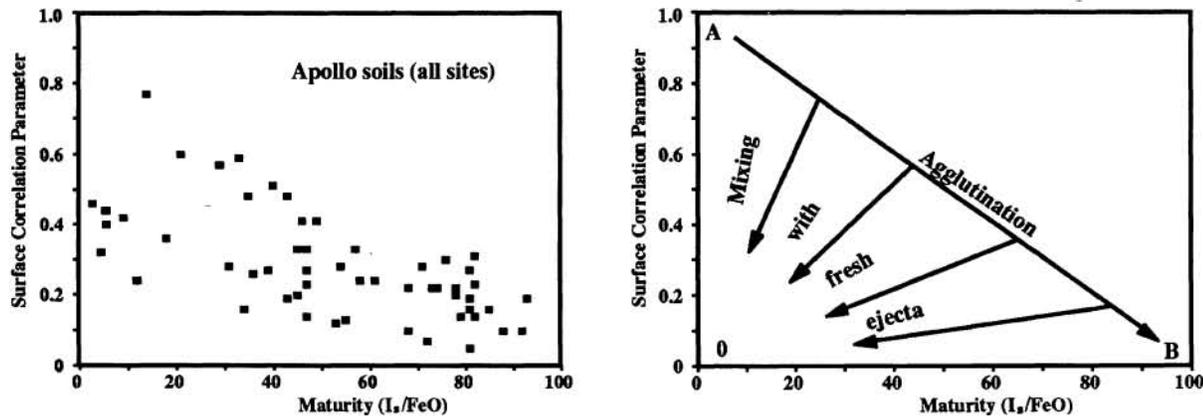


Fig.1 (left). Surface correlation parameter for intensity of ferromagnetic resonance, I_s , as a function of maturity for lunar soils. The surface correlation parameter is the negative of the slope of a log-log plot of I_s vs. grain size. A value of 1 connotes a pure surficial component; a value of 0 a pure volume component. After [9]. Fig. 2 (right). Schematic representation of evolution of the surface correlation parameter with increasing regolith maturity.

Fe^{++} to Fe^0 is presently unknown.

Despite uncertainty concerning the possible role of vapor deposition in their production, the observation of ultrafine Fe^0 inclusions in the rims of regolith mineral grains leads to the following semi-quantitative model to explain the data in Fig. 1. This is illustrated by means of Fig. 2.

Solar-wind sputtering of surfaces of Fe^{++} -bearing mineral grains leads to production of Fe^0 which generally remains as isolated atoms or small clusters within the increasingly metamict mineral lattice. Such material would plot at the origin in Fig. 2. Aggregation of Fe^0 clusters into inclusions tens of nm in size then occurs within the amorphous rims, either as a result of further irradiation damage (possibly involving higher-energy solar particles) leading to substantial rearrangement of the atoms comprising the rim, or as a result of micrometeorite-induced vaporisation of reduced surficial material and recondensation onto surfaces of neighboring mineral grains, or both. Regolith at this stage would plot at point A in Fig. 2. Subsequent impacts further modify this material in two ways: fusing of fine lithic grains into agglutinitic glass, and mixing with pristine rock. These two effects lead to trends towards points B and O, respectively, in Fig. 2. Production of the melt that forms the agglutinitic glass probably results in further reduction of Fe^{++} by solar-wind H liberated during fusion, and further aggregation into superparamagnetic Fe^0 . However, the earlier stages will continue to operate throughout the process so that which stage dominates in production of superparamagnetic Fe^0 is not yet clear.

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