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The Distribution of Particulate Material on Mars

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The surface materials on Mars have been extensively studied using a variety of spacecraft and Earth-based remote-sensing observations (1-7). These measurements include: 1) diurnal thermal measurements, used to determine average particle size, rock abundance, and the presence of crusts; 2) radar observations, used to estimate the surface slope distributions, wavelength-scale roughness, and density; 3) radio emission observations, used to estimate subsurface density; 4) broadband albedo measurements, used to study the time variation of surface brightness and dust deposition and removal; and 5) color observations, used to infer composition, mixing, and the presence of crusts. Remote sensing observations generally require some degree of modeling to interpret, making them more difficult to interpret than direct observations from the surface. They do, however, provide a means for examining the surface properties over the entire planet and a means of sampling varying depths within the regolith. Albedo and color observations only indicate the properties of the upper-most few microns, but are very sensitive to thin, sometimes emphemeral dust coatings. Thermal observations sample the upper skin depth, generally 2-10 cm. Rock abundance measurements give an indirect indication of surface mantling, where the absence of rocks suggests mantles of several meters. Finally, radar and radio emission data can penetrate several meters into the surface, providing an estimate of subsurface density and roughness.

For an assumed smooth, homogeneous surface, the average particle size can be determined from the thermal inertia using diurnal temperature measurements (3). For typical geologic materials in the martian environment, thermal inertia is primarily controlled by the thermal conductivity. Variations in conductivity are due to differences in particle size, porosity, or the degree of bonding, with laboratory measurements providing the link between thermal inertia and these parameters (8). Conductivity, density, and therefore thermal inertia, are lowest for small particles with small cohesion, such as loose dust, and highest for solid rock. It is important to note, however, that thermal inertia is a bulk property, such that unimodal, medium sand, a mixture of fine sand and pebbles, or crusted fines could all have identical thermal inertias.

Some of the ambiguity in thermal inertia can be resolved by incorporating multi-wavelength thermal observations to resolve the surface materials into fine and rock components. This modeling is based on the fact that the temperatures of high-thermal-inertia rocks and low-thermal-inertia fines differ by up to 60 K at night. The energy emitted from a surface of materials at different kinetic temperatures is not blackbody in nature, and the observed thermal spectrum can be inverted to determine the fraction of the surface covered by each temperature component. To keep the number of free parameters in this model small, yet provide useful surface information, only two components are assumed: rocks (~10-15 cm in diameter and larger) and fines. This model is only weakly sensitive to the exact size of the rocks, and provides an estimate of the total fraction of the surface covered by rocks greater than 10 cm in diameter.

Thermal data reveal the presence of large low- and high-inertia regions in the northern hemisphere, with much of the south covered by material of moderate inertia. Substantial regions in Tharsis and Arabia appear dust covered, suggesting active accumulation of deposits 1-2 m thick (6). Results from the rock modeling indicate that the modal surface rock cover is 6%, with abundances ranging from several percent to ~35%. The rock abundances of the regions surrounding the Viking 1 and 2 landing sites, determined from this model, are ~10% and 20% respectively, in good agreement with the rock abundances observed from the landers, as discussed previously. Thus, in retrospect, it can be seen that both sites have above average rock abundances, and the VL2 site is one of the rockiest regions on the planet.

Radar observations of Mars from Earth and from Mars orbit provide information on surface reflectivity and dielectric constant, and fine-scale roughness on a scale of the radar wavelength and smaller. The reflectivity may be used to estimate the dielectric constant (ε) of the surface materials (e.g. 10). Variations in ε are primarily due to changes in the bulk density of the surface, with lower density material generally having a lower ε and lower reflectivity . Downs et al. (10) reported an "average" reflectivity for Mars of 6.4% based on an extensive series of measurements in the south equatorial region (14-22° S). They noted considerable variation, however, in particular the extremely low reflectivities in Tharsis and the region to the west, corresponding to densities of approximately 1.5 g/cm^3, consistent with powdered rock values, and high values (ε=4) in Syrtis Major (11) , suggesting the presence of solid rock at the surface.

That part of the radar echo that can not be attributed to mirror-like reflection from large facets is called the "diffuse" component. It arises from scattering by irregular structure in the surface, perturbations on the facets, and from multiple scattering, typically at scales of 0.3 to 3 times the radar wavelength. This scattering results in a depolarized echo in addition to the quasi-specular, polarized return. Dual-polarization radar observations at 12.6 cm have detected the diffuse reflection, with a concentration of data in the Tharsis region at 20-25° N. These data indicate that the Tharsis region has very large concentrations of surface to near surface roughness elements (12). These observations appear to conflict with the thermal results, but can be reconciled by a model of high-radar-reflecting rocks buried by 1-2 m of dust.

Albedo observations have been used to study the composition, particle size, packing, porosity, and macroscale roughness of the uppermost microns of the surface using broadband Viking IRTM reflectance measurements (4). IRTM observations have also been used to determine the spatial and temporal variations of the albedo of the martian surface and atmosphere throughout the Viking mission (4,8). The northern hemisphere atmosphere was dustier during storms, consistent with south-to-north transport of dust. Northern-hemisphere dark regions were also brighter following the storm, indicating the deposition of ~7 to 45 μm of dust per year. These surfaces subsequently darkened over the following months, suggesting active removal of material.

On a global basis there is a strong anticorrelation between inertia and albedo, a correlation between inertia and rock abundance, and, over much of the planet, a correlation of radar-derived density with inertia (13). The correlation between density and inertia might be due to the presence of subsurface crusts which would simultaneously increase both of these properties. Viking Orbiter color data indicate the presence of three major surface materials: low-inertia, bright-red material that is presumably dust; high-inertia, dark-grey material interpreted to be lithic material mixed with palagonite-like dust; and moderate-inertia, dark-red material that is rough at sub-pixel scales and interpreted to be indurated. Observations from the Viking landing sites show rocks, fines of varying cohesion, and crusts. These sites have indications of aeolian erosion and deposition in the recent past. Large rocks have been exhumed from beneath fines, suggesting one or more cycles of deposition and erosion. Taken together, the remote and *in-situ* data suggest that much of the surface can be characterized by four basic units. Unit 1 is covered by fine, bright dust, with few rocks exposed at the surface. Radar observations indicate that much of this unit is very rough, suggesting a rough surface that is mostly buried beneath several meters of fine dust. This unit may be a recent deposit, whose location may be linked to periodic climate changes. Unit 2 is also active, with the motion of particles keeping the surface free of dust, resulting in a dark, coarse-grained surface with abundant rocks. Unit 3 has intermediate inertia, albedo, and color, and is interpreted to be a rough, indurated surface. Unit 4 is a relatively minor unit, but it contains both Viking landing sites. It is characterized by relatively high inertia and high albedo, suggesting that a thin layer of dust may have accumulated. The landing sites appear to be representative of the types of processes that have occurred globally, but are not completely representative of the major units. They have not accumulated significant amounts of dust, nor are they experiencing active transport and erosion by sand-sized particles. Crusts are present, but not to the degree that may be present elsewhere. Numerous, recently-active processes are inferred from the surface characteristics, including dust deposition, erosion, aeolian transport and sorting, and crust formation. The available data suggest that cyclic changes in sedimentary processes may occur over several timescales associated with periodic climate changes. Large dust deposits presently occur in the north, with maximum winds and dust storm activity in the south. Under different environmental conditions these deposits may be eroded and transported elsewhere. Much of the present surface appears young and may have been continually reworked. The continued erosion and redeposition of this loose material, rather than erosion of fresh surfaces, may provide the material for the high rates of aeolian activity. As a consequence, much of the fine material on the surface may have been globally homogenized and essentially decoupled from the underlying bedrock.

Perhaps the most the most significant conclusion that can be drawn from our current understanding of the upper layer is that much of the present surface is young and has been continually reworked. The continued erosion and redeposition of this loose material, rather than erosion of fresh surfaces, may provide the material for the high rates of aeolian activity. As a consequence, much of the fine material on the surface may have been globally homogenized and may be essentially decoupled from the underlying bedrock.

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