corresponds to a silica composition in the dacite-rhyolite range. This composition is far more evolved than the typical Martian surface as determined by surface measurements (*e.g.*, Clark et al. 1982; Foley et al. 2003; McSween et al. 2006), remote sensing (*e.g.*, Mustard et al. 1997; Christensen et al. 2000; Bandfield 2002), or represented in the Martian meteorite suite (*e.g.*, McSween 1994). Although a few rare instances of higher silica materials have been detected in an isolated crater (Bandfield 2006) and in a patch of bright soil at the Mars Exploration Rover (MER) Spirit site (Yen et al. 2007), the Martian surface appears dominated by relatively lower silica constituents. Linear unmixing of 1/4° averaged Thermal Emission Spectrometer data at the VL2 site indicates a mix of basaltic (Type I) and andesitic (Type II) lithologies in the ratio of about 1:2. Therefore, rather than indicating the presence of Martian dacites and rhyolites at the VL2 site, these low densities are more likely indicative of the presence of vesicles or void spaces within the interior of these rocks.

An obvious caveat to these Viking measurements is that the uncertainty is significant: the largest source of error is the coarse resolution of the pushing forces exerted by the sampling arm. The recorded forces are quantized into 25 N increments; an uncertainty estimate that is halfway between the nominal value and adjacent values would be ±12.5 N. Using the rock Notch as an example, this translates into an uncertainty that is about ±50% of the calculated bulk density. The actual uncertainty may be even larger, closer to ±19 N depending on whether the motor is in a loading or unloading condition. Also significant are the uncertainties in the volume estimates (~10-20%) and vesicularity estimates (~5-10%). The error bars given in Figure 3 reflect all of these sources of uncertainty.

If the bulk densities of the rocks could be determined with high enough precision, the density of the silicate portion of the rocks could be estimated if the vesicularity is taken into account. Figure 3 gives the densities of the silicate portions of the rocks. At face value, these results suggest a rock composition of basalt to basaltic andesite, which is consistent with previously determined surface compositions in the northern plains (Clark et al. 1982; Foley et al. 2003). However, making the link from density to composition with these Viking measurements is equivocal because the error bars in Figure 3 cover almost the entire compositional range.

If rock compositions were known by other means (*e.g.*, alpha proton x-ray spectrometer (APXS) measurements), an alternative procedure would be to compute the vesicularity of a rock using the density measurements. For example, if a rock's position on the abscissa of Figure 3 could be determined, the difference between the measured and predicted densities would provide an estimate of the internal void space.

Conclusions

The results of the rock-pushing campaign at the Viking 2 landing site have illustrated a means to estimate both the density and possibly the composition of rocks on Mars. Although hampered by the low force resolution of the sampling arm and the lack of complete stereo coverage of the rocks moved, the results nonetheless are consistent with low-density rocks. If the rocks indeed possess a low density, this would suggest that they contain vesicles in their interiors and that their surface textures retain a strong primary component (although some degree of overprinting by chemical weathering and/or eolian abrasion is certainly possible). Mars Orbiter Laser Altimeter topographic data are consistent with a sedimentary veneer atop a wrinkle-ridged plain of possible volcanic origin in Utopia Planitia and the VL2 site (Thomson and Head 2001). Thus blocks at the landing site could be impact-disrupted lava flows and/or impact-melt breccias formed from local regolith (Schultz and Mustard 2004). Further research is necessary to distinguish between these two possibilities (*e.g.*, Thomson and Schultz 2003).

Density measurements inferred from rock pushing activities have the advantage that they are not affected by the presence of weathering rinds, surface coatings, or atmospheric interference. They should be included in future Mars missions wherever possible, for they could be complementary to other more direct compositional measurements, as well as provide needed constraints for thermophysical measurements and upcoming ground-penetrating radar (GPR) instruments. The Mars Phoenix Scout mission (Smith 2003), which landed successfully in May 2008, is a lander with a robotic arm similar in design to that on the ill-fated Mars Polar Lander (Bonitz et al. 2001). This arm is capable of exerting a force of 80 N on rocks within reach (~1.5 to 2 m). In addition, an arm-mounted camera is able to image rock texture at a spatial resolution of up to 23 μm (Keller et al. 2001). This arm camera also can allow stereo imaging of the rear portions of rocks, thus improving volume estimates over what was possible with the Viking Landers. Although mass and budgetary constraints prohibited placing an APXS on Phoenix, density and first-order compositional measurements could still be obtained from the rock pushing procedure outlined above. Calculating the potential uncertainty on a Phoenix arm rock pushing motion is difficult since the arm has four degrees of motion (shoulder yaw, and shoulder, elbow, and wrist pitch), and the exact configuration used will depend on the relative positions of the arm and a candidate rock. However, motor currents will be sampled at 0.2 sec intervals with a current resolution that will be an order of magnitude better than was possible with Viking (Bonitz et al. 2001), lending confidence that more accurate densities of any pushed rocks could be obtained by the Phoenix arm.

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