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Extracting scientific results from robotic arm support operations: A technique for estimating the density and composition of rocks on Mars

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Abstract

Background: Robotic arms on landed spacecraft are typically designed to either (a) retrieve surface samples for analyses by the main spacecraft or (b), bring a mobile instrument package into contact with surface components. Yet the engineering data returned by a robotic arm while conducting these science support operations can themselves be used to investigate the physical properties of surface materials. The Viking Lander 2 (VL2) displaced several nearby rocks with its sampling arm to obtain regolith samples from the protected environment beneath them.

Method: The masses of displaced rocks are estimated using measurements of the pushing force exerted by the sampling arm by assuming a basic block-sliding model. Rocks densities are estimated by dividing the mass estimates by rock volumes determined from stereo pairs of images.

Conclusion: Although the precision of the VL2 sampling arm motor current records is insufficient to derive unambiguous results, the bulk densities of pushed rocks appear to be low (≤2.6 g/cm^3), consistent with rocks that are vesicular throughout their volumes (*i.e.*, vesicular impact or volcanic glasses). If the bulk density and vesicularity are known with high enough precision, the method demonstrated here can roughly constrain rock composition. Although the Viking measurements are ultimately inconclusive, the robotic sampling arm on the Mars Phoenix lander could execute a similar pushing strategy on nearby rocks to obtain more accurate density and compositional estimates.

Introduction

The primary purpose of a robotic sampling arm on a planetary lander is to provide support for other instruments, for example by excavating trenches, acquiring surface samples, sieving material, and delivering samples for further analyses. At the Viking 2 Lander (VL2) site in Utopia Planitia, a rock pushing campaign was undertaken to obtain samples of Martian fines from beneath rocks (rock pushing activities were also undertaken at the Viking 1 Lander site but were generally less successful than at VL2; Moore et al. 1987). These sub-rock regolith samples, which were shielded from the harsh ultraviolet radiation environment at the Martian surface, were considered prime biological targets in the search for living organisms or organic molecules (Shorthill et al. 1976). Although no definitive evidence of biologic activity was detected (*e.g.*, Biemann et al. 1977), the rock pushing activity can be used to provide information about the nature of the rocks themselves.

The Physical Properties Team of the Viking mission made detailed analyses of the position, topography, and burial state of the candidate rocks. A bulk density of 3.0 g/cm^3 was assumed for the rocks to assess the engineering feasibility of rock pushing (Moore et al. 1978). Once the pushing sequences were executed, the actual bulk densities of the rocks were not back calculated. Rock density is a fundamental geologic parameter that has yet to be determined *in situ* on Mars. In this work, we calculate both the bulk densities and densities of the silicate portions of rocks, and we show how the latter could be used to estimate their compositions. Unfortunately, the precision of these measurements precludes us from making any firm

Table 1. Rock pushing activity at the Viking Lander 2 site

Rock name	Sol[†]	Boom angle (°)	Extension (cm)	Force (N) above nominal	Comments
Bonneville	29	29.0	16.3	50	Rock (inadvertently) nudged during XRFS sample acquisition. Rock displaced upwards about 0.4 cm.
ICL	30	30.6	8.1	200+	Rock did not move, break, or chip
Badger	34	30.0	30.7	25-50	Rock translated 6.5-7.0 cm, tilted, and rotated. Surface sampler deflected clockwise and went under rock.
Badger	37	28.1	30.7	n/a	2nd Badger push attempt, motor currents not sampled. Rock translated 12-15 cm.
Bonneville	45	26.2	9.9	50	Rock nudged roughly 0.5 cm, front face moved upward roughly 1 cm, rock returned to near pre-nudge position after retraction.
Notch	45	22.4	9.4	25	Rock nudged, left edge of rock displaced about 3.8 cm.
Notch	51	21.8	28.7	50	Rock pushed, translated 24-27 cm and rotated clockwise.
Snow White	471	27.5	5.0	n/a	Rock was pushed 4-6 cm, boom decoupled and failed to reach commanded extension.

[†]Sol refers to Martian day measured from start of mission (Sol 0).

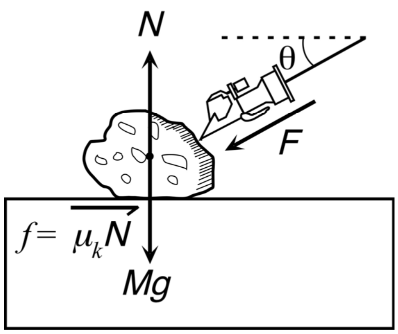

Figure 1. Block diagram of lander sampling arm in contact with a rock. Rocks were pushed radially away from the lander by extending the sampling arm boom.

conclusions about the Viking results. These results are nonetheless tantalizing, and the next generation of Mars landers may be able to execute a similar strategy with greater success.

Obtaining density and compositional estimates

Rock mass determination

The procedure to move rocks involved locating the sampling arm boom in front of a candidate rock, nudging the rock to verify its movability, and then pushing the rock away from the lander by extending the boom. The boom was commanded to extend 7-8 cm in the first test nudge and 20-25 cm in the second push. Motor currents were sampled every 0.19 sec with a current resolution of 0.039 A. This translates into a force resolution of about 25 N (Moore et al. 1978). The boom could push with a force of about 200 N before its magnetic clutch decoupled to prevent the motor from overloading.

The geometry of the sampling arm in contact with a rock is given in Figure 1. Assuming simple frictional sliding with negligible plowing (creation of a furrow or groove along the ground), the mass of the rock can be obtained using equation 1:

$$M = \frac{F(\cos\theta - \mu_k \sin\theta)}{\mu_k g}. \quad (1)$$

In equation 1, M is the mass of the rock, F is the applied force of the sampling arm, θ is the boom angle, g is the force of gravity on Mars, and μ_k is the coefficient of kinetic friction (assumed to be equal to 0.6 [Moore et al. 1978]). Friction coefficients are empirically determined system properties; a value of 0.6 is appropriate for rough surfaces (*e.g.*, Byerlee 1978). One way to consider plowing is to divide the resistance to sliding into two parts, one part due to friction (μ_k) and another due to the force required to displace softer material from the path of a harder sliding object (μ_p) (Bowden et al. 1942). Since additional pushing force is required to overcome the effects of plowing, non-negligible plowing during a rock push would result in an overestimation of the rock's mass. For example, if plowing component of friction added 10% to the total friction ($\mu_{tot} = \mu_k + \mu_p = 0.6 + 0.06 = 0.66$) for the rock Notch, this would decrease the actual rock mass estimate by 12% relative to the case where the plowing component is neglected. As is demonstrated in the Results section, uncertainty in the friction coefficient is not the dominant source of uncertainty. But regardless, ideally these parameters should be determined by experiment using a test setup of the system in question. Images acquired during and after a rock-pushing maneuver is executed can be used to determine if significant plowing occurred. On this basis, plowing was deemed minimal ($\mu_p \approx 0$) in the successfully displaced rocks at the VL2 site (Moore et al. 1978).

The lander's sampling arm attempted to move five rocks at the VL2 site (see Figure 2a). Table 1 summarizes the rock pushing activities. Two rocks, Notch and Badger, were successfully pushed, and one was slightly displaced (Bonneville). One rock, ICL, did not move despite a force of about 200 N exerted upon it by the sampling arm before the clutch decoupled. The last rock, Snow White, shifted only slightly before the clutch again decoupled due to an overload. Given that the teeth of the lower portion of the collector head have a collective contact surface area roughly

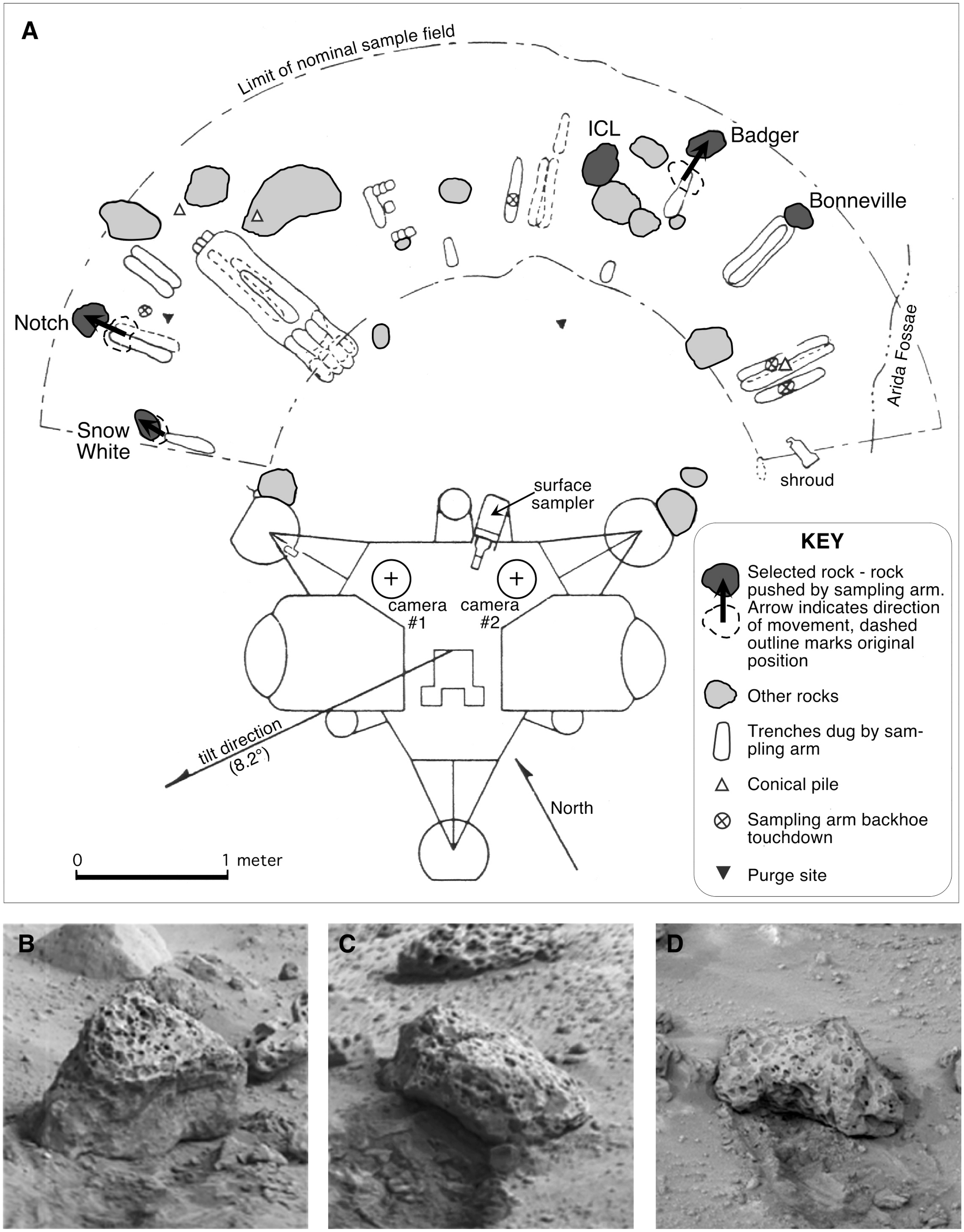

Figure 2. (a) Sketch of the sample field at Viking Lander 2 (after Moore et al. 1987). Rocks pushed by the sampling arm are dark gray. **(b-d)** Super-resolution composite images of Badger, Bonneville and Notch, respectively.

equal to 1 mm^2, stresses on the order of 10^8 N/m^2 were exerted on the surfaces of the two immobile rocks (Moore et al. 1987). The fact they did not chip, scratch, or spall indicates that the rock surfaces are strong and are not covered with mechanically weak weathering rinds, although more competent alteration fronts or rinds may be present. Mass estimates obtained for the three successfully pushed and displaced rocks are given in Table 2.

Table 2. Mass, volume, and density estimates

Rock name	Weight (N)	Mass (kg)	Volume[a] ($\times 10^3$ cm^3)	Bulk density (g/cm^3)
Badger	24 ± 12	6.4 ± 3.2	3.0 ± 0.6	2.1 ± 1.1
Bonneville	22[b]± 11	5.9 ± 2.9	2.3 ± 0.5	2.6 ± 1.4
Notch	29 ± 14	7.8 ± 3.9	3.3 ± 0.6	2.4 ± 1.3

[a]Ellipsoid shapes assumed. [b]Value given in Moore et al. (1978) page 12; rock displaced upward rather than pushed back.

Rock volumes

The Viking Team made volume estimates of the rocks using the twin cameras of the Viking lander, which provided stereo coverage of the sampling field. Topographic profiles were manually generated with the assistance of image processing software (Liebes and Schwartz 1977). High-resolution vertical slices and contour maps of the sample field were compiled to create shape models of each of the candidate rocks. These topographic data was used to create plaster of paris and epoxy resin models for several candidate rocks and were used with the full-scale mock lander (Science Test Lander) in a sandbox to develop the pushing technique (Moore et al. 1978). Unfortunately, neither the model rocks nor the detailed topographic data used to create them were archived. We therefore approximated the rocks' volumes using the spatial dimensions of rocks in the catalogue compiled by Moore and Keller (1990) and published lower resolution topographic data (Liebes 1982; Wu and Schafer 1982). Even if the original topographic data used by the Physical Properties Team had been available, the volume estimates would still be subject to some uncertainty (~10-20%) due to the fact that rear portions of the rocks were out of view of the lander's cameras. The estimated volumes were combined with the mass estimates to obtain the bulk densities of the rocks given in Table 2.

Rock surface textures

Most rocks at the Viking 2 landing site are covered with small pits or vesicles. The exact mode of origin of this pitted surface texture has been a matter of some debate. Suggestions about the origin of the pits can be grouped into two general categories: primary textures and secondary textures. A primary surface texture would mean that the pits are vesicles—exsolved bubbles of volatiles quenched in a glass—implying that the rocks are either vesicular volcanic rocks (*e.g.*, Mutch et al. 1977) or vesicular impact melt breccias (Schultz and Mustard 2004). Alternatively, the surface texture has been suggested to be a secondary erosional texture formed by eolian abrasion (McCauley et al. 1979) or by chemical weathering (*e.g.*, Allen and Conca, 1991).

The distinction between a primary and a secondary pitted texture has important consequences for a rock's density. In the former case, the presence of vesicles or void spaces in a rock interior significantly lowers the overall density. If the pitted textures are limited to exterior surfaces, however, then the pits have a minimal effect on the bulk density. To accurately estimate the percentage of pits covering each pushed rock, we created super-resolution image composites after the method of Parker (1998) (Figures 2b-d). The resulting estimates are given in Table 3.

Table 3. Rock surface area covered by pits

Rock name	Vesicularity (%)
Badger	31 ± 2
Bonneville	24 ± 2
Notch	16 ± 1

Results

The uncorrected bulk densities reported in Table 2 are all ≤ 2.6 g/cm^3. To assess the type of Martian rock that corresponds to a given density, we use Martian glass compositional data from a series of crystallization experiments run on a primitive SNC basaltic starting composition by Minitti and Rutherford (2000). Glass densities were calculated according to the procedure outlined by Spera (2000) using standard Martian surface temperature and pressure (222 K, 6 mbar).

Comparing the bulk densities to the first-order predicted Martian rocks densities in Figure 3, it is evident that this

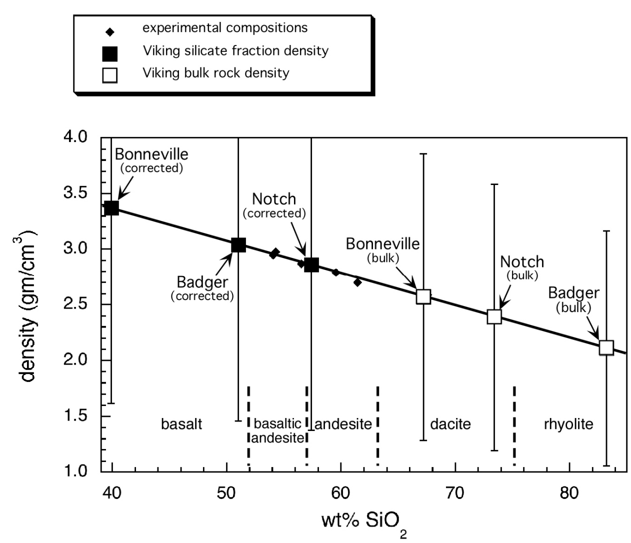

Figure 3. Density versus SiO_2 wt.% plot for Martian glasses. Trend line is a linear least-squares fit to data from anhydrous crystallization experiments using a primitive SNC basaltic starting composition (Minitti and Rutherford 2000). Solid diamonds represent the experimental data, open squares represent the bulk densities of Viking rocks, and filled squares represent the density of the silicate portion of the rocks (after correcting for rock vesicularity). Error bars indicate uncertainty dominated by coarse force resolution of sampling arm. Volcanic rock classification from Le Bas et al. (1986) TAS diagram, assuming low total alkalis.

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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