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).

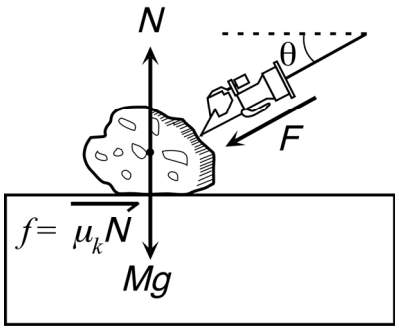

Figure 1. Block diagram of lander sampling arm in contact with a rock. Rocks were pushed radially away from the lander by extending the sampling arm boom.

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