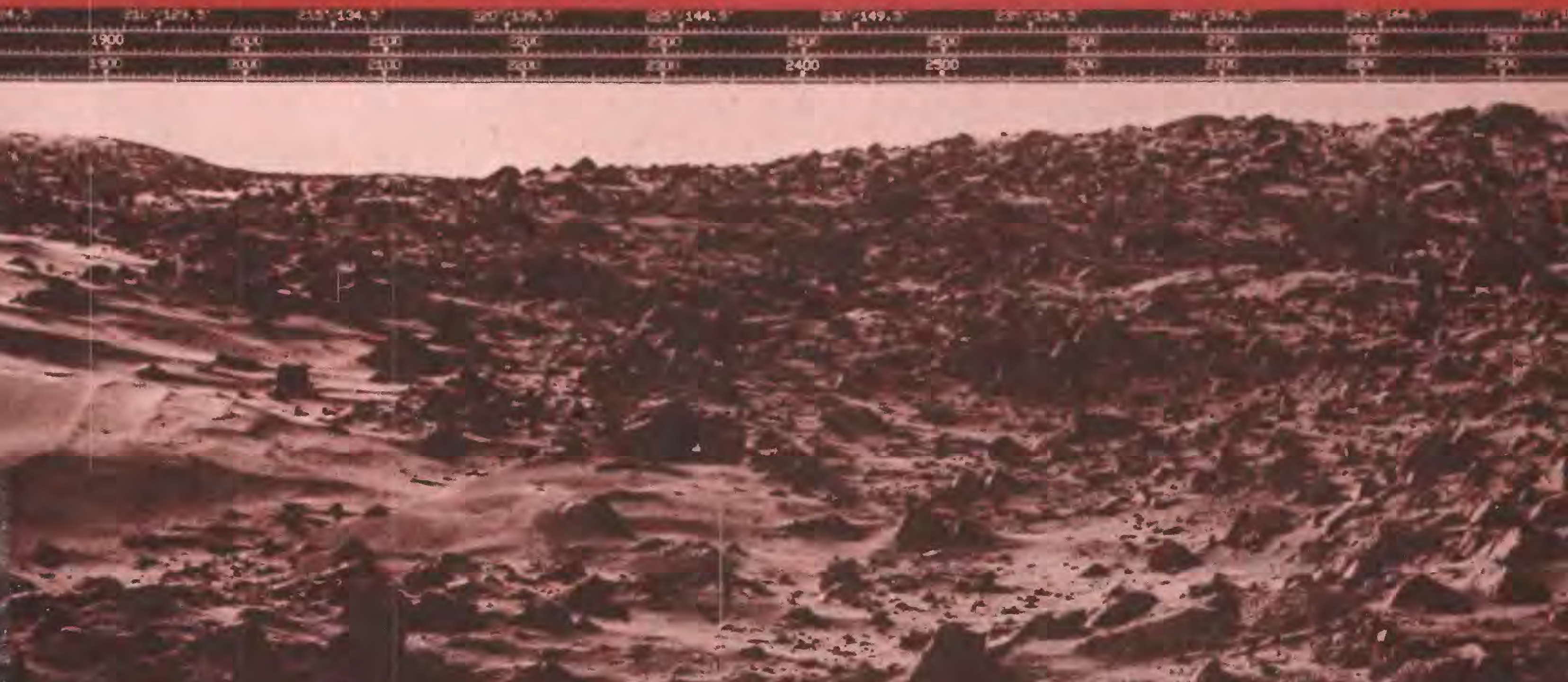
Rock Pushing and Sampling under Rocks on Mars

Prepared on behalf of
the National Aeronautics
and Space Administration



GEOLOGICAL SURVEY PROFESSIONAL PAPER 1081

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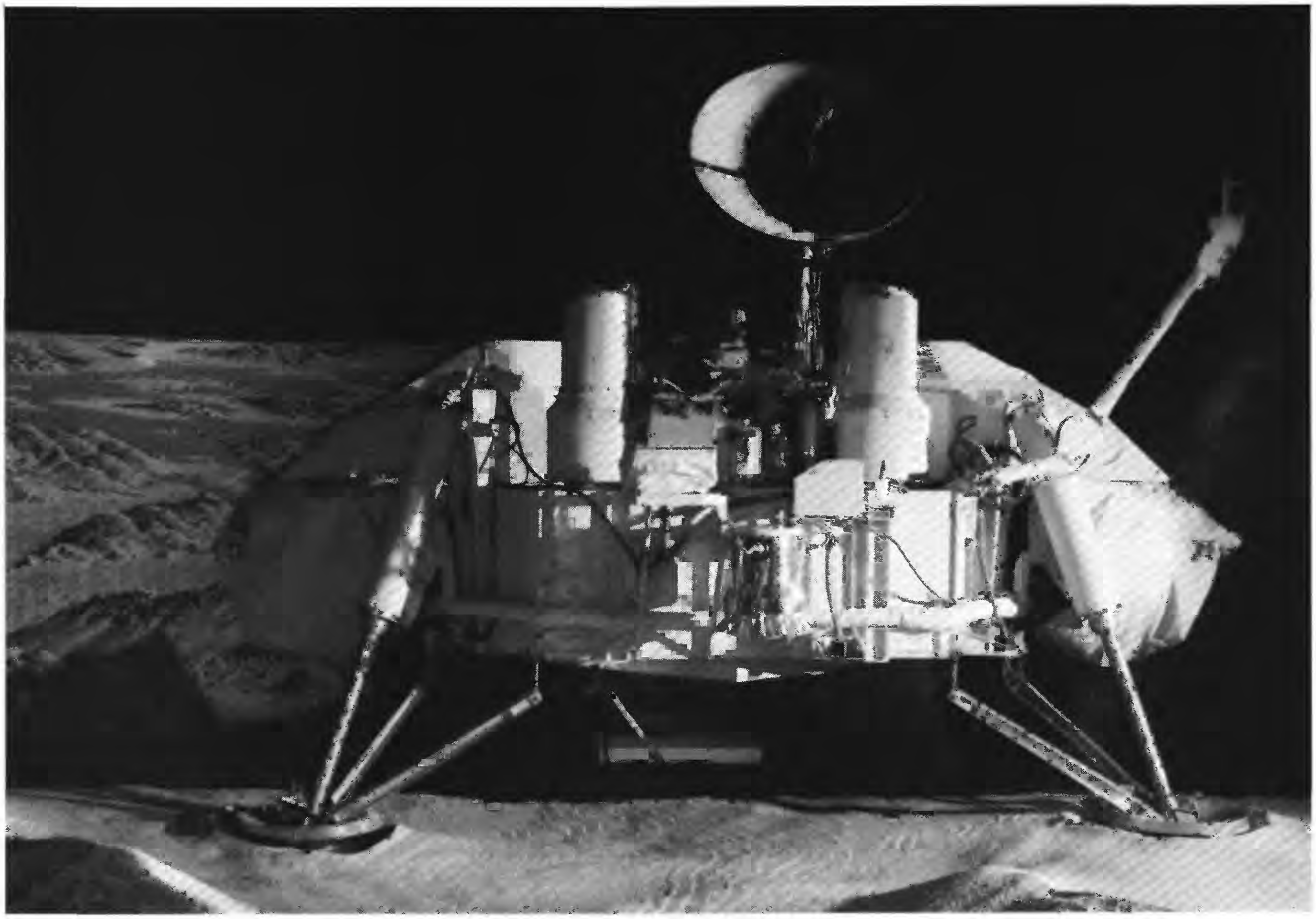

VIKING SCIENCE TEST LANDER

This full-scale model with fully operational lander camera and surface-sampler subsystems was installed adjacent to a large sand box representing the area in reach of the surface sampler. The Science Test Lander was used during the mission to develop and verify surface-sampler commands. Circular S-band radio antenna of lander is 0.76 meter across. Locations of cameras and surface-sampler subsystems are shown in figure 1.

Rock Pushing and Sampling Under Rocks on Mars

By H. J. MOORE, S. LIEBES, JR., D. S. CROUCH, *and* L. V. CLARK

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ROCK PUSHING AND SAMPLING UNDER ROCKS ON MARS

By H. J. MOORE,[1] S. LIEBES, JR.,[2] D. S. CROUCH,[3] and L. V. CLARK[4]

ABSTRACT

Viking Lander 2 acquired samples on Mars from beneath two rocks, where living organisms and organic molecules would be protected from ultraviolet radiation. Selection of rocks to be moved was based on scientific and engineering considerations, including rock size, rock shape, burial depth, and location in a sample field. Rock locations and topography were established using the computerized interactive video-stereophotogrammetric system and plotted on vertical profiles and in plan view. Sampler commands were developed and tested on Earth using a full-size lander and surface mock-up. The use of power by the sampler motor correlates with rock movements, which were by plowing, skidding, and rolling.

Provenance of the samples was determined by measurements and interpretation of pictures and positions of the sampler arm. Analytical results demonstrate that the samples were, in fact, from beneath the rocks. Results from the Gas Chromatograph-Mass Spectrometer of the Molecular Analysis experiment and the Gas Exchange instrument of the Biology experiment indicate that more adsorbed(?) water occurs in samples under rocks than in samples exposed to the sun. This is consistent with terrestrial arid environments, where more moisture occurs in near-surface soil under rocks than in surrounding soil because the net heat flow is toward the soil beneath the rock and the rock cap inhibits evaporation. Inorganic analyses show that samples of soil from under the rocks have significantly less iron than soil exposed to the sun.

The scientific significance of analyses of samples under the rocks is only partly evaluated, but some facts are clear. Detectable quantities of martian organic molecules were not found in the sample from under a rock by the Molecular Analysis experiment. The Biology experiments did not find definitive evidence for Earth-like living organisms in their sample. Significant amounts of adsorbed water may be present in the martian regolith. The response of the soil from under a rock to the aqueous nutrient in the Gas Exchange instrument indicates that adsorbed water and hydrates play an important role in the oxidation potential of the soil. The rock surfaces are strong, because they did not scratch, chip or spall when the sampler pushed them. Fresh surfaces of soil and the undersides of rocks were exposed so that they could be imaged in color. A ledge of soil adhered to one rock that tilted, showing that a crust forms near the surface of Mars. The reason for low amounts of iron in the samples from under the rocks is not known at this time.

INTRODUCTION

During the Primary Viking Mission,[5] Lander 2 acquired soil samples from beneath two rocks, where any living organisms and organic molecules would be protected from ultraviolet radiation. The acquisition of the samples required that the rocks be pushed away exposing the surface beneath them. Pushing rocks by remote control amid a dense field of other rocks (Shorthill and others, 1976; Moore and others, 1977a) some 363 million km away is a complex feat. Few people expected such a profusion of rocks on Mars, and the soil sampler was not designed for pushing rocks. Some of the rocks presented obstacles to the sampler and others were targets; consequently a detailed accurate knowledge of the topography and rock locations within reach of the sampler was mandatory for successful operations.

The purpose of this paper is to (1) describe the procedures used to push the rocks and the problems encountered, (2) show that the samples did, in fact, come from under the rocks, and (3) indicate the scientific value of acquiring samples from under the rocks.

ACKNOWLEDGMENTS

The authors are indebted to the National Aeronautics and Space Administration and countless individuals who made the Viking Mission a resounding success. The Viking Project was managed by James S. Martin and his staff at NASA Langley Research Center, Hampton, Virginia and the Viking landers were built by the Martin Marietta Corp., Littleton, Colo. Work was partly performed under NASA order L-9714 (H. Moore) and contract NAS-1-9682 (S. Liebes).

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[5] The Primary Mission is defined by the interval of time from the landing of Viking 1 on Mars, 20 July 1976, to 11 November 1976; the Viking spacecraft have continued to operate during the Extended Mission which ends in April 1978 (Soffen, 1976).

SURFACE SAMPLER SUBSYSTEM COMPONENTS

One of the major subsystems aboard the two Viking Landers is the Surface Sampler Subsystem (frontispiece and fig. 1). This subsystem was designed to acquire, process, and deliver surface material samples to the Biology, Molecular Analysis, and Inorganic Analysis experiments and to provide support for the Surface Physical and Magnetic Properties investigations (Soffen and Snyder, 1976). Biological analyses are conducted using three instruments (Klein and others, 1972, 1977): (1) Pyrolitic Release, (2) Labeled Release, and (3) Gas Exchange. The Gas Exchange instrument measures gases evolved from soil in the presence or absence of an aqueous nutrient, using gas chromatography. Molecular analyses are conducted using a Gas Chromatograph-Mass Spectrometer (GCMS) (Biemann and others, 1976, 1977). Inorganic analyses are conducted using an X-ray Fluorescence Spectrometer (XRFS) (Clark and others, 1976).

The Surface Sampler Subsystem consists of four major components: (1) the Acquisition Assembly, which acquires the samples and delivers them to the desired experiments; (2) the GCMS Processor, which receives samples from the Acquisition Assembly, grinds the material to a particle size less than 300 μm, and delivers metered 1-cm^3 samples to the GCMS; (3) the Biology Processor, which accepts samples from the Acquisition Assembly, sieves the material to a particle size less than 1,500 μm, and delivers metered 7-cm^3 samples to the Biology experiments; and (4) the Control Assembly, which receives digital commands from the spacecraft computer and controls the operation of and handles the data from the other three components. Samples are delivered to the XRFS through a funnel with a 1.25-cm screen. The Acquisition Assembly, with its control electronics, and the spacecraft computer were the major components involved in the rock-pushing sequences.

The Acquisition Assembly consists of a boom unit and collector head. The boom unit consists of (1) an extendable and retractable furlable boom capable of extending the tip of the collector head to a maximum of 3.45 m from the boom housing and (2) an integral gimbal capable of 288° horizontal (azimuth) movement and 74° vertical (elevation) movement. The collector head (fig. 2) consists of a stationary lower jaw for digging into the surface and a movable upper jaw for retaining the sample. The collector head can deliver a bulk sample directly to the appropriate experiment in the upright position, or it can be rotated 180° and the upper lid (in the inverted position) vibrated at 4.4 or 8.8 Hz to deliver the sample through a 2-mm sieve in the collector head lid.

The Surface Sampler Subsystem is automatically controlled by the spacecraft computer and Surface Sampler control electronics. Typical sampling sequences generally require that 40–100 discrete commands be executed; the longest sequence to date required the execution of 344 commands. Real-time command control and camera monitoring of the boom is impossible due to the one-way radio transmission time between Earth and Mars, which was about 20

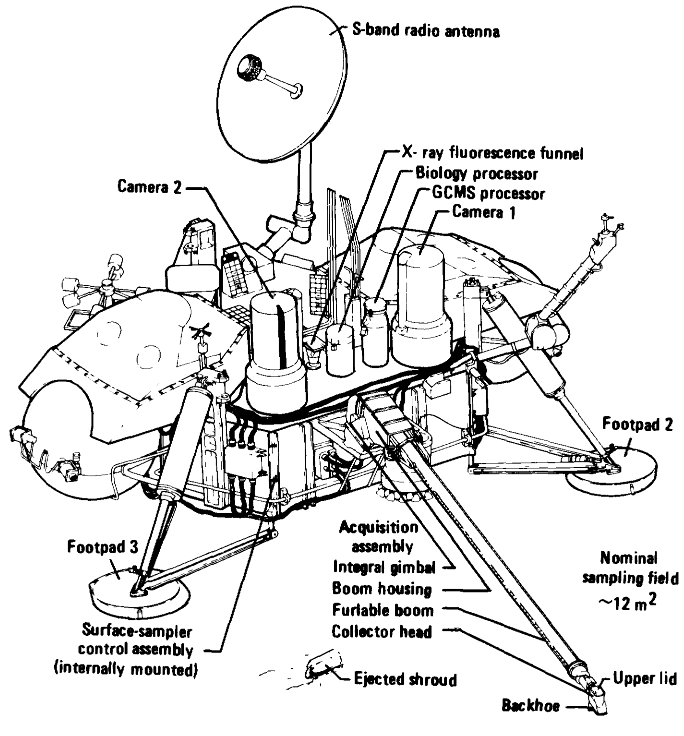

FIGURE 1.—Surface Sampler Assembly components and camera locations.

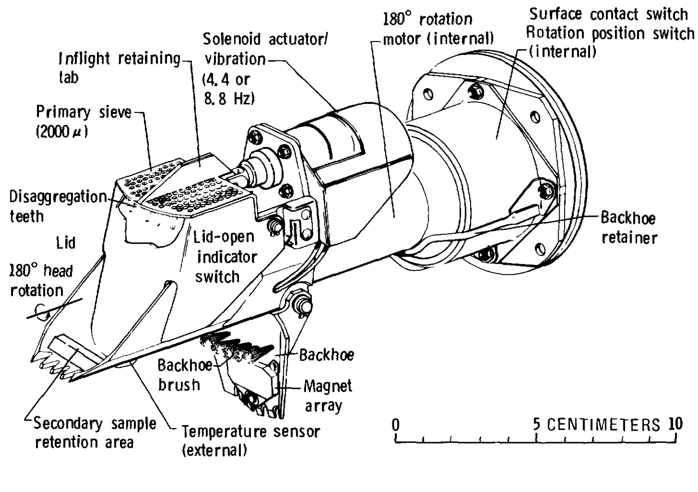

FIGURE 2.—Surface-sampler collector head.

minutes during the Primary Mission. Therefore, the entire sequence to be executed must be generated and verified on Earth, transmitted to the spacecraft, and stored in the lander's computer until the specified execution time. When the sequence is executed, the computer sequentially transmits each coded digital command and waits a specific interval of time (precomputed to allow sufficient time for execution) before issuing the next command. If the command is not successfully completed, or a "no-go" signal is generated by an unsafe operation, the computer terminates power to the Surface Sampler and stops the sequence until corrective commands are transmitted from Earth.

Surface samples are acquired by moving the boom to the desired azimuth and extension distance and lowering it until the collector head contacts the surface. At that point, the collector head pivots about a ball joint, which activates a switch and terminates the downward movement. Sampling is then carried out by opening the collector head lid, extending the boom forward 15–20 cm, closing the lid, and delivering the sample to the desired experiment by another series of commands.

STEREOPHOTOGRAMMETRY

The prompt generation of accurate and suitably formatted topographic information was a prerequsite for choosing sample sites and rocks to be pushed and for planning sampler sequences. An interactive computerized video-stereophotogrammetric system (Liebes and Schwartz, 1977) was used for this purpose. The system, created to support the Viking Lander Imaging Team and to serve general project needs, was developed by one of the authors (Liebes) in collaboration with A. A. Schwartz of the Jet Propulsion Laboratory.

The primary input to the system was the digitally encoded imaging data returned by the Viking lander cameras (Huck and others, 1975; Mutch and others, 1972). Figure 3 schematically illustrates the nominal locations of the camera photogrammetric reference points, the placement and articulation of the surface sampler boom or arm, and the alignment of the Lander Aligned Coordinate System.

The stereophotogrammetry system consists of three basic elements: (1) computer hardware, (2) computer software, and (3) a stereo station. The computer hardware is that of the Interactive Image Processing Facility (Levinthal and others, 1977) at the Jet Propulsion Laboratory. A computer software applications program, called RANGER, supports the system. The stereostation is illustrated schematically in figure 4. A pair of video monitors face one another from opposite ends of a table. Images displayed on the monitors are simultaneously viewed through a centrally located scanning stereoscope. The left and right members of a stereoimage pair are routed, under the control of RANGER, to the left and right video monitors, respectively. The stereoscope enables a photogrammetrist to fuse the image pair into an apparent three-dimensional image of the martian scene.

Camera geometric calibration files developed by M. R. Wolf of the Jet Propulsion Laboratory (Patterson and others, 1977) help RANGER to accurately associate a viewing vector in the Lander Aligned Coordinate

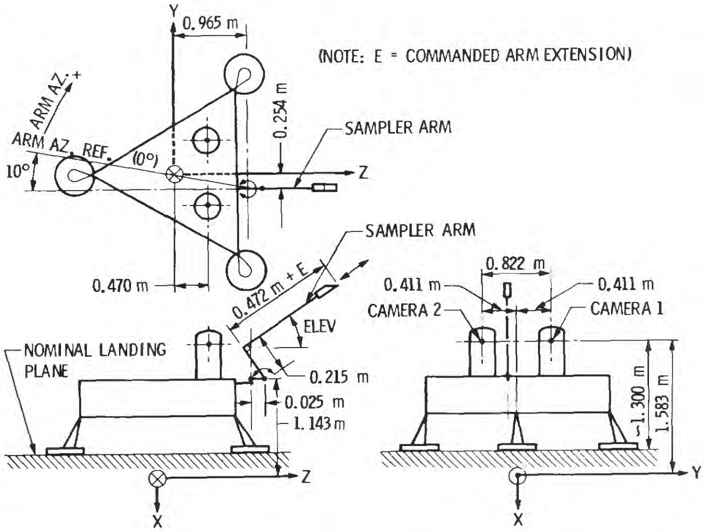

FIGURE 3.—Schematic illustration of a Viking lander indicating location of cameras, sampler arm or boom, and Lander Aligned Coordinate System.

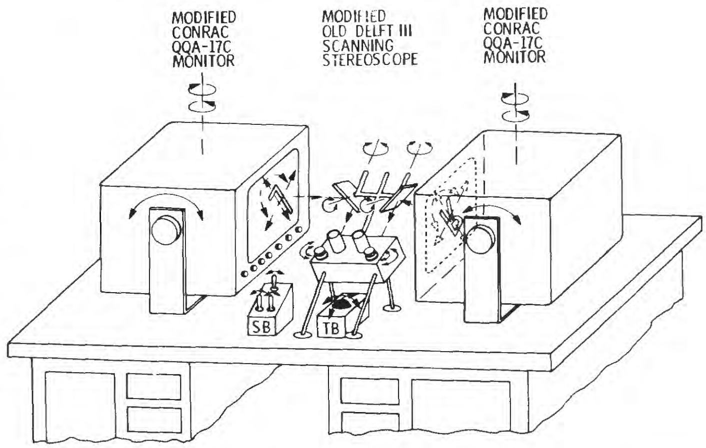

FIGURE 4.—Schematic illustration of interactive video-stereophotogrammetry station. Video monitors rest on table. Left and right camera stereoimage data are directed from computer to left and right monitors, respectively. Three-dimensional cursor is controlled by trackball device (TB). Video image routing and analog image are controlled by switchbox (SB).

System with each image point. RANGER provides the photogrammetrist with an artificial "3-space mark" consisting of an appropriately coupled pair of point cursors overlayed on the two video images. The pair of marks fuse to produce a single mark in the apparent three-dimensional image. The photogrammetrist can move the mark in a continuous manner through the martian scene. RANGER can be commanded to constrain the mark to any surface, which enables the photogrammetrist to generate arbitrary profiles of the relief such as elevation contours, vertical profiles, transverse profiles, etc.

Support for the sampler activities was invariably provided in the form of sets of profiles (called V-Profiles) representing the intersections of the martian relief with planes containing the azimuth axis of the sampler boom. The profile data were stored in computer data sets. Products consisted of photographs of the stereoimage pairs and overlaid profiles, and plots of the V-Profiles. Figure 5 illustrates a stereopair recorded after the sampler nudged Notch rock. The white lines represent 10 profiles that were generated along boom azimuth intervals of 0.5° to quantify the results of the nudge, to provide a basis for planning the subsequent attempt to displace Notch substantially, and to acquire a sample for Biology from beneath the rock. Figure 6 is a plot of the fifth profile from the left in figure 5. Sets of such V-Profiles enabled constraints such as the area accessible to the sampler (sample field) and detailed rock shapes to be established. The commands required to execute any desired sequence would be determined directly from these plots (Clark and others, 1977). The profile formatting program (implemented by R. N. Philips of the Jet Propulsion Laboratory) operated under multiparameter control that permitted variable grid intervals, measurement systems, and scales. Full-size V-Profiles were frequently plotted to aid modeling of sample areas in front of the Science Test Lander, which is discussed in the following section.

The cameras can record at resolutions of either 0.04° or 0.12°. The curves in figure 7, which illustrates theoretical uncertainty of range, apply to a pair of 0.04° images. Uncertainties will be two times as great when one image is at 0.04° and the other is 0.12° resolution, and three times as great for a pair of 0.12° resolution images. Uncertainty at any field point is here defined to be the radial dimension in plan view of the diamond-shaped region of overlap of wedges radiating out from each of the cameras, with wedge apex angles equal to the camera resolutions. Error caused by the calibration data and by thermal movement of the

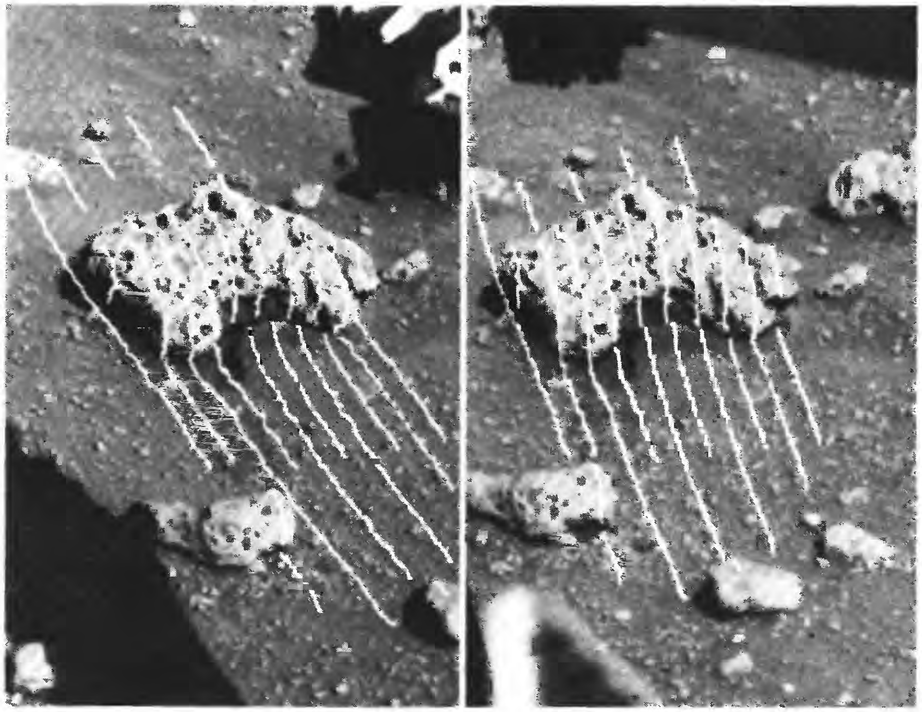

FIGURE 5.—Stereopair of pictures of Notch rock after nudge. Notch rock is about 25 cm wide and 11 cm high. Profiles (white lines) are in planes radiating from the azimuth gimbal axis spaced 0.5° apart. These reproductions have been subjected to differential enlargement and relative rotation to facilitate stereoviewing. Sampler boom visible at top with its shadow below. Vertical bar in left image is artifact of transmission.

cameras and shifts of the lander amount at most to 0.06° of image displacement, suggesting that a reasonable measure of operational ranging error is typically that shown in the figure. Within the stereoportion of the sample field, this uncertainty is typically about 2 or 3 cm.

SCIENCE TEST LANDER

An important simulation facility was available at the Jet Propulsion Laboratory during the Viking mission for developing and verifying all of the commands to be executed on Mars by the Viking surface sampler.

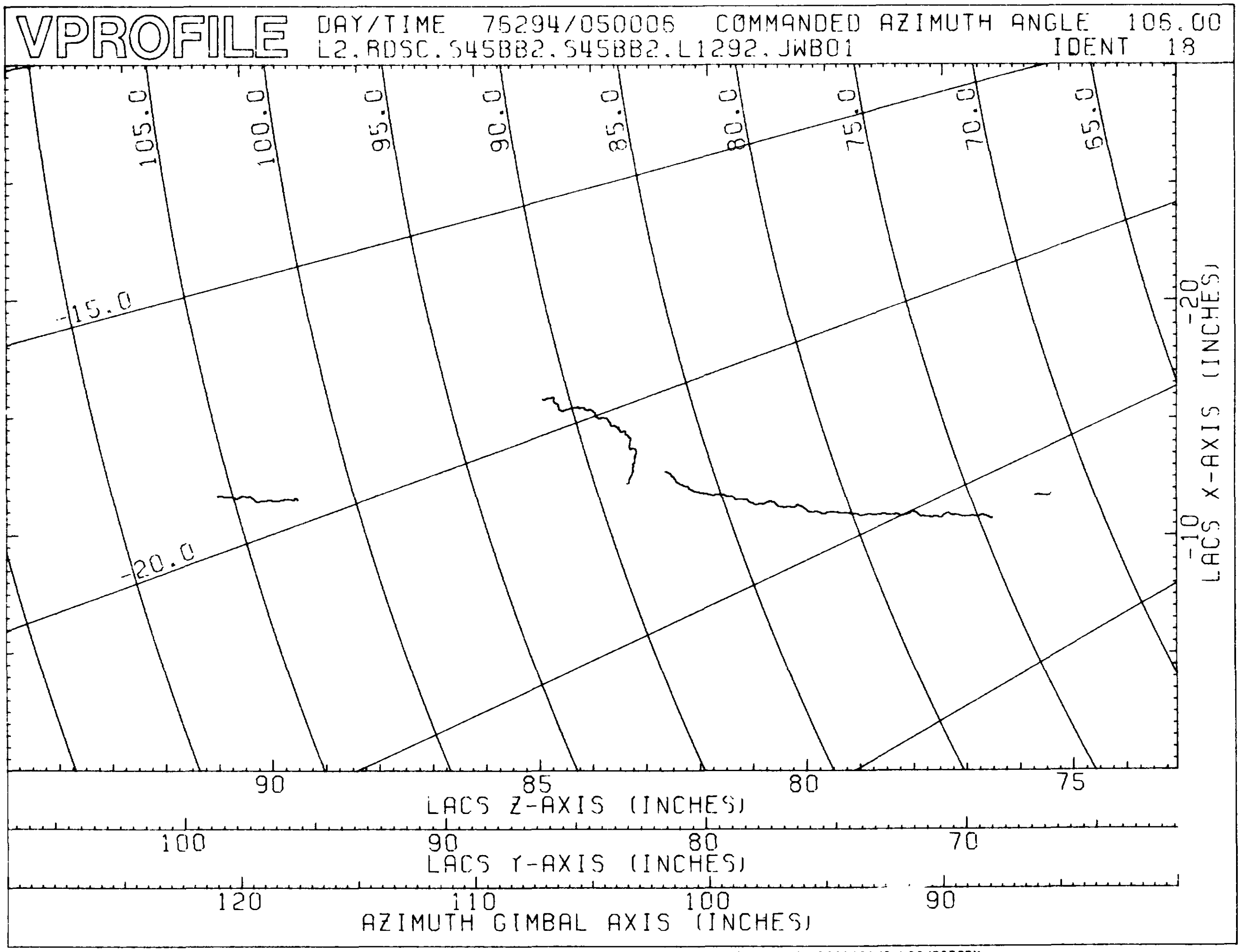

FIGURE 6.—Plot of fifth V-Profile from the left in figure 5. Gaps in profile correspond to regions not visible to both cameras. Note that the fillet at the base of the rock was not disturbed during the nudge. Sampler commands of azimuth, extension, and elevation required for subsequent rock push and sample acquisition were derived from such plots. The "range data set name" for the family of profiles appears beneath the Julian day and time in the top margin. The "IDENT" number designates the particular profile member of the set. The boom azimuth associated with the profile plane is indicated in the upper right corner. The X, Y, and Z coordinate scales appear in the plot margins. The Y and Z scales plotted on the V-Profile are azimuth-angle dependent (see fig. 3). The perpendicular distance in the Y–Z plane from the axis of the azimuth gimbal is indicated at the bottom. Each of the concentric curves denotes the position of the collector head tip at a given extension distance; that is, the curve the tip would describe as the boom is raised and lowered. These curves are here labeled with the associated extension distance (in inches). The diagonal fan of rays indicates the path of the collector head tip as the boom is extended at the indicated elevation angles.

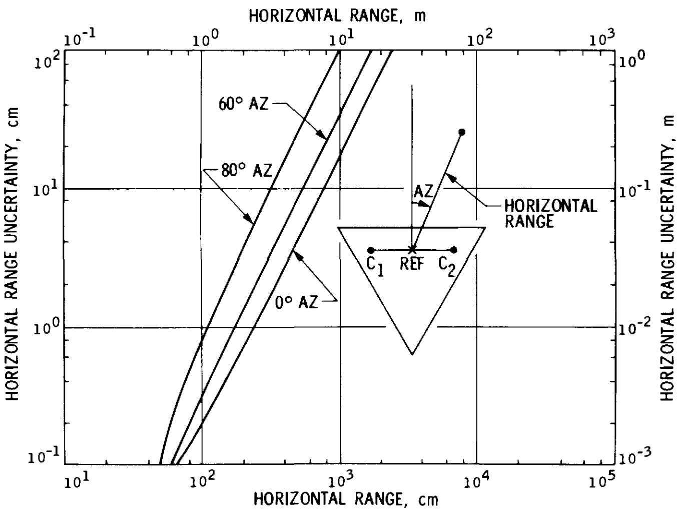

FIGURE 7.—Range uncertainty with horizontal range for paired 0.04° resolution images.

The key element of this facility, the Science Test Lander, was a full-scale Viking lander with fully operational cameras and surface sampler (frontispiece). The Science Test Lander was installed adjacent to a large sandbox which represented the area on Mars within reach of the sampler (the sample field). The subsystems were manually controlled by test equipment and, in the case of the surface sampler, by a small programmable computer. Two 10-kw tungsten-carbide lights were available for simulating martian lighting conditions during imaging tests.

Computer control of the sampler was essential to simulate and validate each sampler sequence. The sequences could thus be witnessed by scientists as well as engineers and managers responsible for assuring the safety of the sequence. The computer also provided data like that which would be returned during execution of the sequence on Mars. Surface-sampler data include commanded and achieved boom positions, discrete measurements of motor current and temperature, and switch positions. Although the surface-sampler data do not contain any timing information, it was possible to determine timing from a detailed analysis of the lander computer's memory as a continuous timed-tagged record of command and data traffic. This record permitted determination of the rates of travel of all motors, considered a measure of subsystem health. It was also a valuable diagnostic tool for understanding anomalous behavior of the sampler subsystem, and it was especially useful for evaluating the results of rock-pushing sequences.

After the landing of Viking Lander 1 on July 20, 1976, the Science Test Lander was configured to simulate as closely as possible the conditions at the site. The modeling was done by personnel of the U.S. Geological Survey using the images returned from the lander and photogrammetric analyses of the images. A sand mixture was used for the soil, and the simulated rocks were made of styrofoam. An accurate representation of the surface topography including rock locations was considered essential to developing and verifying safe and meaningful sampler sequences. Support imaging was also validated using the Science Test Lander. The real-time imaging display was particularly useful during the modeling work.

The Science Test Lander was reconfigured after the landing of Viking Lander 2 on September 3, 1976. Simulation of the second landing site took on an added importance when it was decided to search for martian organic matter and biota by acquiring samples from under rocks instead of from the exposed surface material. This necessitated an extensive program to develop rock-push sequences. The sample field was carefully surveyed for candidate rocks that met certain scientific and boom-capability criteria. Three rocks were selected for the sampler to attempt to move. Full-scale V-Profiles and contour maps of the target rocks were provided to the NASA/Manned Spacecraft Center's Lunar Receiving Laboratory, which prepared two models of each rock (one of plaster of paris and the other of epoxy resin) simulating extremes of their estimated weights on Mars. The rocks were positioned in front of the Science Test Lander using full-scale V-Profiles. These rocks were used in exhaustive tests to develop the proper techniques for rock pushing.

CRITERIA FOR ROCK SELECTION

Rocks that were eligible for pushing were limited to the sample field (fig. 8), which was defined using sampler extensions less than 279 cm (110 in.), angles of boom elevation greater than −38.1°, and boom azimuths between 90° and 250° (fig. 3). This excluded a number of promising rocks because they were either too far away, too close to the spacecraft, or on the left edge of the sample field. Five rocks (Nos. 1 through 5 in figs. 8 and 9) were considered first because they had been imaged by both cameras in high resolution early in the mission, whereas high-resolution coverage in stereo was not available in other areas. Each rock was rated from 1 to 4 in each of 11 factors, and each factor was weighted by importance.

The eleven factors were defined as follows: (1) Rollability: Was the rock deeply buried or near the surface so that it would move when pushed? (2) Obstructions: Were there objects behind the rock that might interfere with its motion? (3) Size: Was the weight of the rock small enough for it to be moved? (4)

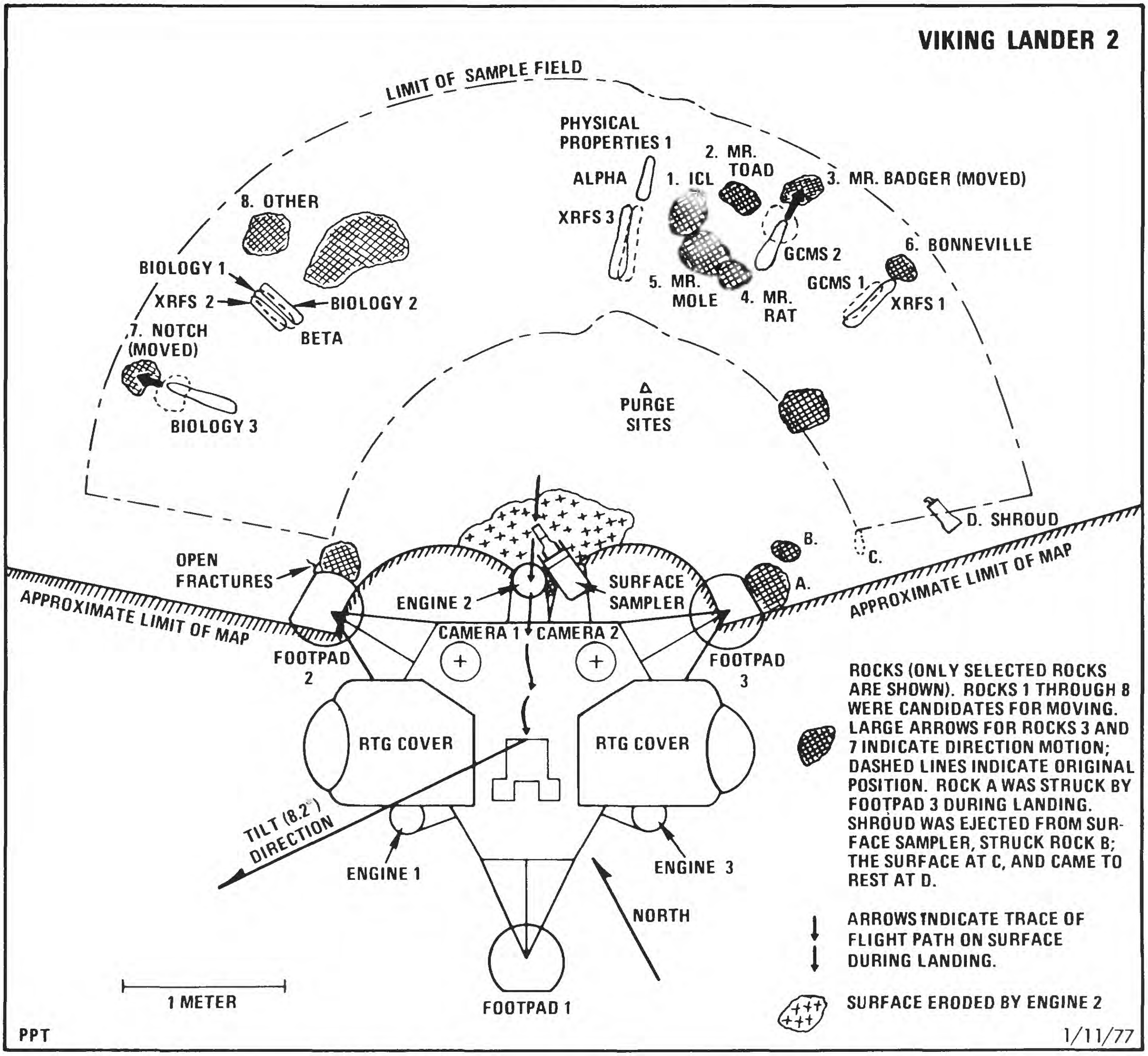

FIGURE 8.—Plan view of Viking Lander 2 and status of sample field at end of Primary Mission. Locations of selected rocks, sample acquisition trenches, and ejected shroud are shown. Original positions and positions of rocks 3 and 7 after pushing are indicated. Plane of plan view is parallel to upper surface of lander body (spacecraft Y–Z plane).

Accessibility: Were there objects in front of the rock that would interfere with the ability of the surface sampler to reach the rock or the area exposed after it moved? (5) Grippability: Was the character of the surface of the rock such that the surface sampler would not slip off? (6) Breakability: Would the rock break when moved? (7) Purchase: Was the shape and orientation of the rock on the surface favorable for moving? (8) Sampleability: Would the exposed surface be easily sampled? (9) Visibility: Would the exposed surface be visible to the cameras? (10) Surface area: Would the newly exposed area be large enough to collect samples unmixed with surface materials previously exposed to solar ultraviolet radiation? (11) Iconoclasticity: Were there any emotional reasons why the rock should be moved?

Each factor was weighted by relative importance (fig. 10), and surface area, visibility, and sampleability received the largest weightings because of their scientific importance. Large surface areas reduce the

FIGURE 9.—Camera 2 picture showing first rocks considered for pushing: (1) ICL, (2) Mr. Toad, (3) Mr. Badger, (4) Mr. Rat, and (5) Mr. Mole. Rock 6 (Bonneville) was considered for pushing later in the mission. Dimensions of rocks given in figures 10 and 12.

FACTOR	RATING WT	NAME / NUMBER				
		ICL 1	Mr. TOAD 2	Mr. BADGER 3	Mr. RAT 4	Mr. MOLE 5
1. Roliability	4	3 (12)	4 (16)	3 (12)	2 (8)	1 (4)
2. Obstructions	3	3 (9)	4 (12)	4 (12)	4 (12)	4 (12)
3. Size	4	3 (12)	4 (16)	4 (16)	4 (16)	1 (4)
Mass		16.7 kg	11.5 kg	11.5 kg	9.9 +kg	25.9 +kg
4. Accessibility	3	4 (12)	2 (6)	4 (12)	4 (12)	4 (12)
5. Grippability	2	3 (6)	4 (8)	4 (8)	3 (6)	4 (8)
6. Breakability	1	3 (3)	3 (3)	3 (3)	1 (3)	2 (2)
7. Purchase	2	2 (4)	4 (8)	3 (6)	4 (8)	1 (2)
8. Sampleability	5	4 (20)	2 (10)	2 (10)	4 (20)	4 (20)
9. Visibility	5	4 (20)	2 (10)	1 (5)	4 (20)	4 (20)
10. Surface Area	5	4 (20)	1 (5)	2 (10)	2 (10)	3 (15)
cm^2 (cm)		648(18 x 36)	225(15 x 15)	360(24 x 15)	306(18 x 17)	810(30 x 27)
11. Iconoclasticity	1	4 (4)	1 (1)	1 (1)	1 (1)	1 (1)
TOTAL SCORE (140 IS PERFECT)		122	95	95	116	100

FIGURE 10.—Factors, scores, and weightings used in selection of rocks to be moved for acquiring samples under rocks. Rock 1 (ICL) received the highest scores because of large weighting of scientifically important factors: surface area, visibility, and sampleability. Iconoclasticity, a humorous factor, did not affect the outcome.

chances of mixing and contamination of the under-rock sample with material that had been exposed to the sun. Good visibility allows an opportunity to assess the results of the sampling. Sampleability is the fundamental scientific requirement. The three rocks nearest the spacecraft (ICL, Mr. Mole, and Mr. Rat,[6] in figs. 8 and 9) received high scores in visibility and sampleability because the newly exposed surfaces would be favorably oriented to the cameras and the surface sampler if they moved (fig.10). Because of their location and orientation on the surface, their surface areas could be determined. ICL clearly had the largest surface area—18 cm at right angles to the surface-sampler azimuth plane and 36 cm along it, so that the chances of acquiring an unmixed sample from beneath it would be good. Rocks farther from the spacecraft generally had low scores, partly because of their location and partly because of their orientation on the surface, which reduced the observer's ability to estimate the dimension of the rock away from the spacecraft. Mr. Toad (rock 2) had the smallest estimated surface area because of its narrow base (fig. 9); considering width alone, it was too small. Visibility and sampleability were scored low because Toad was relatively far from the spacecraft, and the upper surface of the rock was barely visible, showing it was tilted away from the spacecraft. Mr. Badger (rock 3) had low scores for the same reasons. The visibility score for Badger was lowest of all because its orientation indicated the exposed surface would be difficult to view and dimensions difficult to estimate. Evidence for this unfavorable orientation was fourfold: (1) V-Profiles showed the surface adjacent to the rock was inclined and could not be viewed, (2) the upper surface of the rock was invisible, (3) the visible upper edge of the rock was convex upward and parallel to a crude layering midway in the rock, and (4) the undersurface of the rock was visible at the tip nearest the spacecraft. This orientation resulted in low scores for sampleability and a conservative estimate of its dimension in a direction away from the spacecraft.

Rock size (weight) and rollability were the chief engineering considerations. Estimates of the weight of rock that could be pushed were made assuming frictional sliding (fig. 11). For frictional sliding and boom angles constrained by the local surface and sampler capabilities, rocks as heavy as 90 and 160 Newtons (N) could be pushed. If moderate plowing occurred, the weights might be about 40 N less. Rock weights were

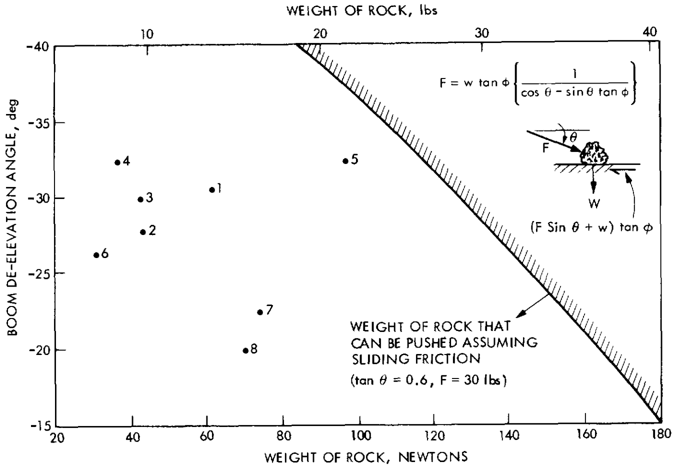

FIGURE 11.—Estimates of weights of rocks that could be pushed by the sampler assuming frictional sliding.

estimated from the dimensions, shapes, and an assumed density of 3,000 Kg/m^3. Such a density is reasonable for massive mafic rock (Baird and others, 1976) but is somewhat excessive if the rocks are, in fact, vesicular. As an example, ICL's estimated weight was about 62 N assuming an ellipsoidal shape and should have moved provided that excessive plowing (because of burial) would not be required. With the exception of Mr. Mole (rock 5), the other four rocks would move if excessive plowing was not required. Mole was not only heavier than about 97 N, but it was also deeply buried (fig. 9) and would require plowing; thus it received low scores on rollability and size. Toad was clearly the most rollable because of its small base compared to its upper part. Mr. Rat (rock 4) appeared to be partly buried. In the other factors, only Toad scored low in accessibility because Mole and Rat would interfere with sample acquisition. ICL scored low in obstructions because there were two small rocks behind it. The curved and relatively smooth surfaces of Rat and ICL indicated the surface-sampler collector head might slip while pushing, but there were some pits on the surface so that the teeth of the collector head would probably grip and stay with the rock. Because many of the rocks appeared to be vesicular, it was possible that they might be fragile and break if they did not move when the sampler pushed them. Thus, partly buried rocks, such as Rat and Mole, received low scores in breakability. High scores for purchase were given to Toad and Rat because their large height-to-base ratios would provide mechanical advantage for rolling. In contrast, Mole scored low because of its small height-to-base ratio. The fact that Badger was tilted away from the lander resulted in a relatively high score for purchase.

[6] Names were assigned to rocks in order to aid memorization of the geometry of the sample field. Rocks 2 through 5 were named after characters in Kenneth Grahame's book *The Wind in the Willows* (1961), and others were simply named. The origin of the name of rock 1 (ICL) is noted later, in footnote 7.

The weighted scores tipped the balance in favor of ICL rock as the first choice. Here, the factors weighted on scientific goals were important. ICL's high score in "iconoclasticity," a factor introduced to help many tired members of the Viking Flight Team retain their sense of humor and relax, did not affect the outcome.[7]

Subsequent rock selections considered the same 11 factors as well as others (fig. 12). Bonneville (rock 6) and Notch (rock 7), two of three new candidates, were selected to be nudged (fig. 8). Bonneville had moved previously during a sample acquisition for the Inorganic Analysis experiment, and the surface that would be exposed after it moved would be shaded at the planned time of sample acquisition for Biology. The rock was in an area where the boom housing obscured the field of view of camera 1, and so there was no stereoscopic coverage. Notch won out as the push candidate because its location was well-known, its shape provided favorable grippability, its location provided good visibility, and the surface in front of it was not disturbed by previous acqusitions (as was the case for Bonneville), which reduced chances of contamination. Surface area, visibility, and sampleability were ample for Notch.

ROCK-PUSHING STRATEGY

The Acquisition Assembly was not designed for moving rocks on Mars. Therefore, when the request was made to obtain samples from under rocks after the Mars landing, appropriate sequences using the existing capabilities of the Acquisition Assembly had to be developed rapidly.

Two ways of moving rocks were considered: (1) positioning the collector head on the rock in such a manner that the backhoe could be used to drag the rock when the boom was commanded to retract and (2) positioning the collector head in front of the rock and pushing the rock forward by extending the boom. The boom can push or pull with a force of approximately 178–213 N before the motor load capability is exceeded causing decoupling of its magnetic clutch.

Tests using the Science Test Lander indicated the pushing technique was the most feasible. The major difficulty encountered was the accuracy required to push the rock at an optimum point judged from imaging to be the center of gravity. The command resolution of the boom is 0.6° in azimuth and elevation, and 0.6° cm in the extend and retract directions. Additionally, gear backlash and gravitational and thermal deflection of the boom increased the possible aiming inaccuracies. Although the gravitational deflection could be calculated, the thermal bending of the thin-walled steel boom could not be predicted with sufficient accuracy to guarantee that the collector head would not contact the surface in front of the rock and push exposed surface material into the sample site during the forward thrust.

A strategy of rock pushing was ultimately selected that provided the best way to move the rock without contaminating the sampling site. The accuracy of azimuth positioning was improved by comparing the boom-command coordinates of previously excavated trenches with the V-Profile azimuths of the centerlines of the trenches measured using the camera stereoimages. Appropriate command corrections were made as required. The azimuth backlash effect was predictable because the lander is tilted 8.2° in a westerly direction (Shorthill and others, 1976; fig. 8). Thus, the azimuth backlash consistently produced actual boom azimuths that were about 0.6° smaller than the commanded azimuths. Backlash in the extend and retract directions was negligible. The relatively large potential errors in the elevation axis (boom thermal bending, gravitational deflection, and overtraveling after motor cutoff) were eliminated by first commanding the boom to the surface until movement was terminated by actuation of the ground contact switch. This command was followed by an elevate command which was controlled by timing rather than by position achieved. Knowledge of the elevation rate of travel enabled calculation of the time required to lift the collector head tip above the surface a known amount. This technique nullified the effect of boom deflections in the upward direction. The final sequence adopted for the mission consisted of the following steps generally performed over a period of 10–15 Martian days:

1. Swing the boom to the desired azimuth (as determined from V-Profile data and corrected for calibration and lander tilt).
2. Extend the boom such that the tip would be positioned approximately 2–3 cm in front of the rock after lowering it (as determined from V-Profile data).
3. Deelevate the boom to activate the surface contact cutoff switch.
4. Elevate the boom (usually for 1–2 seconds) to position the collector head at the correct vertical position in front of the rock.
5. Extend the boom approximately 7–8 cm to verify "moveability" of the rock by subsequent imaging and boom telemetry data.

[7] ICL rock was named after an acronym for Initial Computer Load. Prior to landing, the spacecraft computers had stored commands for an automatic mission in the event that the lander could not be commanded. Had this occured, the spacecraft would have tried to collect a sample from a point just beyond ICL, but would have failed. Thus, ICL was an "iconic clast" that deserved to be pushed.

NAME / NUMBER	Mr. RAT 4	BONNEVILLE 6	NOTCH 7	OTHER 8
SIZE Width Depth Height Mass	18 cm 17 cm 11 cm 9.9 kg	22 cm 15-22 cm 5-6 cm 6-8.4 kg	25 cm 25 cm 11 cm 10.7-20.3 kg	25 cm 25 cm 13 cm 9.5-19.1 kg
ADVANTAGES	Has V-Profile data stereoscopic coverage	Appears to have moved during XRFS Sol 30 dig Newly exposed area shaded at 0600	Appears to be unburied Has V-Profile data stereoscopic coverage	Has V-Profile data stereoscopic coverage
DISADVANTAGES	Near ICL rock (1) which didn't move Partly buried	Monoscopic coverage Area in front of rock "messed-up" by GCMS (Sol 21) and XRFS (Sol 29, 30) trenches		Rock along SSAA gimbal axis presents possible hazard
Iconoclasticity	1	0	0	0

FIGURE 12.—Additional considerations for selection of rocks to be nudged or pushed for the second sample acquisition beneath a rock for the Biology Experiment.

6. Position the boom such that the rock and collector head could be stereoimaged and subsequent V-Profiles could be generated showing the new position of the rock.
7. Position the collector head at the new relative position (steps 1 through 4).
8. Extend the boom 20–25 cm (depending on dimensions of rock) to completely displace rock from original site. Verify rock movement by imaging and repeat steps 7 and 8 if required.
9. Perform a backhoe sequence at the original site of the rock to remove possible exposed material, followed by performance of a normal sampling sequence.

Details of the rock-push sequences used on Mars are listed in table 1.

SAMPLER MOTOR CURRENTS AND ROCK MOVEMENT

Motor currents, inferred from variations in lander bus currents, were sampled at a rate of 4 kilobits per second in the engineering data format (Format 5). This resulted in a current sample every 0.19 seconds and a current resolution of 0.039 amperes. Typical motor currents have a base current of about 0.2 amperes, normally a high current transient at motor start, a no-load condition during a gear transfer, and then a rise in current due to extension. Currents are converted to force by subtracting the base current of 0.2 amperes from the total motor current measurements, calculating the wattage from known voltages (typically 31.8 Vdc) and then using calibration data (Crouch, 1976) which gives ≈20 Newtons/watt. Thus, the resolution in force is about 25 N.

Motor currents during nudging, pushing, and sampling correlate with movements of the sampler and the rocks as viewed and measured using the pictures. This correlation is vividly illustrated by the Sol 29 acquisition for the Inorganic Analysis experiment (fig. 13). The acquisition stroke extended to the buried base of Bonneville, which was displaced upward about 0.4 cm as shown by comparison of pre- and post-sample pictures of the rock. The surface sampler extends at a rate of about 1 in. (2.54 cm) per second. The duration of high current (≈ 6.7 s, fig. 13) represents an extension near 6.7 in. (17 cm), which is in good

TABLE 1. *Sample sequences used for rock pushing and sampling under rocks*

[Engineering units are reported in inches because of use during mission and in final surface-sampler report (L. V. Clark and others, 1977). CW, clockwise; CCW, counterclockwise as viewed in fig. 8; est., estimated]

Rock	Sol[1]	Command description	Position achieved	Comments
ICL	30	Azimuth CW	186.6°	To nudge rock.
		Extend	75.4 in.	Est. distance to rock 77.4–78.0 in.
		Deelevate	(−) 33.2°	Surface contact.
		Elevate	(−)30.6°	By timing.
		Extend	78.6 in.	Sampler commanded to 83.1 in.; motor clutched: est. force 200 N. Rock did not move.
Badger	34	Azimuth CW	201.1°	To push rock, first try.
		Extend	84.4 in.	Est. distance to rock 87.4 in.
		Deelevate	(−)30.6°	Surface contact.
		Elevate	(−)30.0°	By timing.
		Extend	96.5 in.	Rock translated, tilted, and rotated; surface sampler deflected CW and went under rock.
		Retract	82.0 in.	Trench produced because rock leaned on surface sampler.
Badger	37	Azimuth CW	200.5°	To push rock, second try.
		Extend	89.1 in.	Est. distance to rock 90.6 in.
		Deelevate	(−)29.4°	Surface contact.
		Elevate	(−)28.1°	By timing.
		Extend	101.2 in.	Rock at extension of 97–98 in. along 200.5°; may have had larger tilt during push than afterwards.
Badger	[2]37	Azimuth CW	201.1°	To acquire sample.
		Extend	93.0 in.	Est. distance to rock 95 in.
		Deelevate	(−)28.8°	Surface contact.
		Retract	84.1 in.	Trench to clear away any surface contaminants.
		Elevate	(−)20.5°	
		Extend	87.0 in.	
		Deelevate	(−)30.0°	Surface contact.
		Extend	93.6 in.	Sample acquisition.
Bonne-ville	45	Azimuth CW	217.5°	To nudge rock.
		Extend	99.1 in.	Sol 29 XRFS extension of 99.4 in. moved rock.
		Deelevate	(−)25.6°	Elev. indicates surface sampler contact on rock.
		Elevate	(−)26.2°	Images show collector head tilted back and on rock.
		Extend	103.0 in.	Rock fell back after extension. Points on front surface moved 1 cm upward.
Notch	45	Azimuth CCW	105.8°	To nudge rock.
		Extend	84.1 in.	Est. distance to 86.2 in.
		Deelevate	(−)23.1°	Surface contact.
		Elevate	(−)22.4°	By timing.
		Extend	87.8 in.	Left edge of rock displaced about 1.5 in. (3.8 cm).
Notch	51	Azimuth CW	106.4°	To push rock.
		Extend	86.7 in.	Est. distance to rock 87.7–88 in.
		Deelevate	(−)21.8°	Surface contact.
		Elevate	(−)21.8°	By timing.
		Extend	98.0 in.	Rock translated and rotated clockwise.
Notch	51	Azimuth	107.1°	To acquire sample.
		Extend	93.6 in.	
		Deelevate	(−)20.5°	Surface contact.
		Retract	78.1 in.	Trench to clear away debris.
		Elevate	(−)15.5°	
		Extend	88.0 in.	
		Deelevate	(−)21.8°	Surface contact.
		Extend	94.6 in.	Sample acquisition.

[1] Sol is martian day from start of mission; day of touchdown is Sol 0. The duration of a martian day is about 24.65 hours.

[2] Sequence was repeated because of failure to obtain level full indication; achieved elevations were (−)29.4° and (−)30.6° for surface contacts; level full indication was obtained prior to second delivery. Elevation increase indicates shallow 1.2 in. (3 cm) depth for sample trench.

agreement with the commanded extension of 6.4 in. (16.3 cm). Thus, the increase in current at the end of the Sol 29 sample acquisition is certainly due to the interaction of the surface sampler and soil with Bonneville rock. The current increase corresponds to a force of about 50 N, a value about twice the estimated weight of the rock (22–31 N). At a deelevation angle of −29°, the horizontal component of force is about 44 N. Because the rock moved upward, a lifting force of about 22–31 N was required. The horizontal force vector along a line sloping 30° toward the surface sampler is 37.5 N, and its vertical component is 22 N, or near the estimated weight of the rock.

During the nudge of Bonneville, surface contact was made on the rock as shown by the deelevation angles (table 1) and by the pictures (fig. 13), which show the collector head resting on the rock after it extended. The high motor currents during the last part of the nudge lasted about 0.2 seconds, which represents about 0.5 cm of travel. This is consistent with about 1 cm upward motion on the face of the rock which was estimated from the pictures and suggests a pivot point on edge of the rock, which is about half as high as wide, farthest from the spacecraft. After retraction, the rock returned approximately to its prenudge position causing debris from plowed material in the rim of the previous trench to fall into that trench (fig. 13).

ICL, the first choice candidate, did not move, as demonstrated by comparing[8] prenudge and postnudge images taken by the same camera, photogrammetric measurements, and motor currents. Relatively small motor currents were measured for about 3 seconds, after which they rose to a value corresponding to a force of about 200 N above the normal extension current. The current duration compares favorably with the estimated 2–2.5-in. (5–6.4 cm) distance to the rock. Two hundred Newtons is close to the decoupling force for the sampler motor (178–213 N). The maximum horizontal component of force on ICL was 153–183 N. Because ICL was estimated to weigh 62 N, only about 67 N should be required to push it if simple sliding is assumed (see equation in fig. 11). If the sin θ term in the equation is ignored, 37 N should be required to push the rock. Thus ICL must be cemented or more deeply buried than initial interpretations indicated. It is noteworthy that there was no evidence for chipping, spalling, or scratching of ICL as a result of the attempt to push the rock. The individual teeth of the lower jaw of the collector head have an area near 1 mm^2, and so stresses of the order of 10^8 N/m^2 were exerted by the collector head. Thus, it appears that the surface of the rock is strong.

[8] Viewing of two pictures taken of the same object at different times by one camera is a sensitive way of detecting motion of the object.

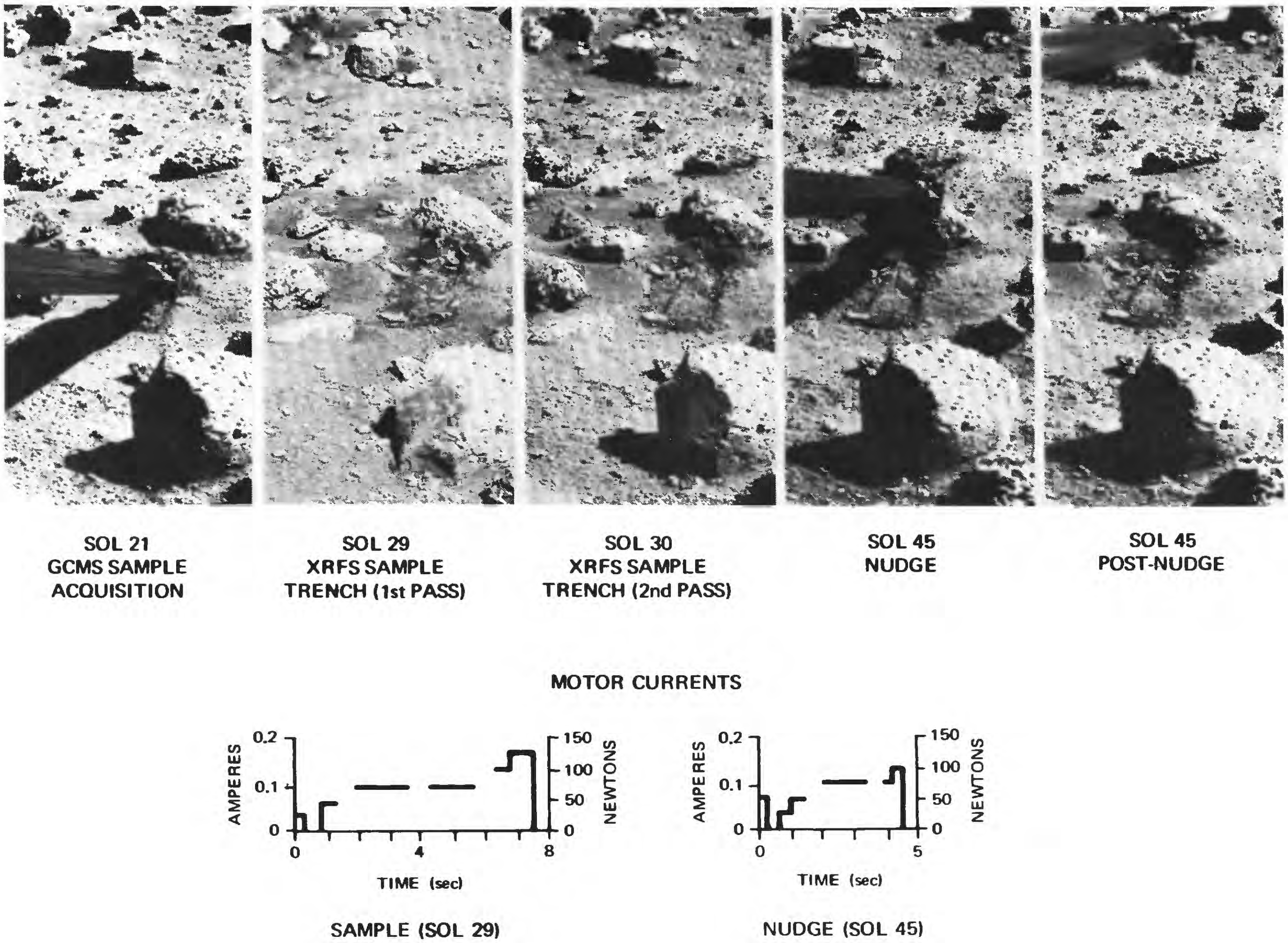

FIGURE 13.—Sequence of events at "Bonneville Salt Flats." Bonneville (rock 6) is just beyond surface sampler in the left picture (Sol 21). Left picture shows sampler acquiring sample for the Molecular Analysis (GCMS) experiment on Sol 21. Next picture shows trench formed during the first pass of acquisition for XRFS on Sol 29; comparison of pre- and post-acquisition pictures shows Bonneville was displaced 0.4 cm upward; motor currents show increase at end of acquisition stroke and correspond to upward displacement of rock. The Sol 30 picture (center) shows the second pass acquisition for XRFS; note trench has been cleaned of platy debris. Sol 45 picture (to right) shows collector head on Bonneville during nudge; note trench produced on Sol 30 is still clear of debris. Final picture at right shows sampler (upper center) and Bonneville after nudge; note debris propelled into trench by rock falling into its original position. Trenches are about 10 cm across. Motor currents for nudge (lower right) near end of stroke are larger than those for beginning of sample acquisition.

Despite the initial setback of ICL, the sampler moved on to Badger (chosen over Toad). The weight of science considerations was relegated to lesser importance, a marginal decision in view of reduced visibility and sampleability. More importantly, Badger moved in a complicated way (figs. 14 and 15). Motor currents for the Sol 34 push of Badger correlate with the results. The rock was about 3 in. (7.6 cm) from the collector head tip at surface contact, which correlates with the duration of initially low currents (3 s). This was followed by large currents for 2.5 seconds, correlating with the estimated translation of 2.6–2.8 in. (6.5–7.0 cm), which may have been accomplished by tilting, rather than sliding. Subsequent currents oscillate and correlate with the interval during which the sampler slipped down off the rock surface causing the rock to lean on it as it completed its extension (fig. 14). Most of the measured 69° counterclockwise rotation of the rock probably occurred in this last interval. Because the rock was leaning on the sampler as it retracted after the push, the collector head dug a trench along an azimuth oblique to the commanded azimuth. Badger did not move far enough on the first push, therefore a second push was executed on Sol 37. Unfortunately, motor currents were not obtained during this push. The pictures show two smooth tracks where

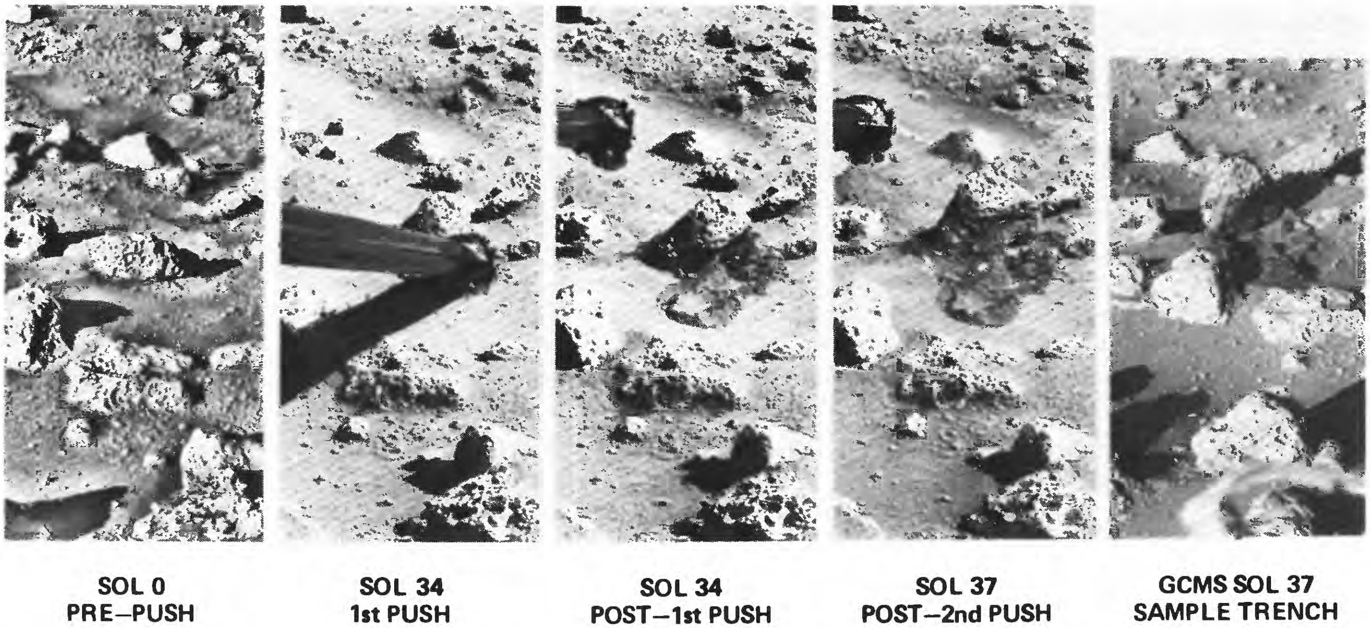

FIGURE 14.—Sequence of pictures showing history of Badger (rock 3). At left is rock prior to first push on Sol 34. Next picture (Sol 34) shows Badger leaning on sampler which is fully extended and has been driven clockwise (to right); a small unplanned trench in front of rock was produced during push. Center picture (Sol 34) shows the trench excavated as sampler retracted; azimuth of trench is oblique to azimuths through gimbal axis. Note thin "water line" ledge of soil adhering to left side of rock. Fourth picture (Sol 37) shows Badger after second push; note skid marks produced by sliding. Final picture shows second pass acquisition trench for sample under Badger; note floors of retraction trench (to clear contaminants) and acquisition trench are not visible because local surface slopes away from observer. Only end of sample trench is visible.

the rock simply slid on the surface. The Sol 37 push was followed by a sample acquisition. Motor currents for this acquisition are relatively low and oscillatory when compared with other acquisitions (compare figs. 13 and 15).

As noted above, the orientation of the surface with respect to the sampler was not expected to be favorable because it sloped away from the lander. Thus, the small motor currents measured during sampling are compatible with shallow trenching ($\approx$ 3.5 cm deep) through an irregular surface inclined away from the lander.

The nudge and push of Notch (rock 7), followed by the acquisition, was the culmination of the under-the-rock sampling activities during the Primary Mission (figs. 16 and 17). On Sol 45, Notch was nudged by pushing on a protuberance on the left edge of the rock so that it would rotate to avoid early exposure. As planned, Notch rotated about an axis on the right center side of the rock. This movement displaced the protuberance about 3.8 cm (figs. 5, 6, and 16). The motion may have been jerky, judging from the oscillating motor currents. The push before sunrise on Sol 51 was accompanied by about 47° of rotation and 9.5–10.5 in. (24–27 cm) of translation. The duration of high motor currents was about 10.5 seconds. A rapid rise in motor currents within 1 second shows that the sampler contacted the surface within 1 in. (2.5 cm) of the rock. Motor currents for the push were about 50 N larger than those during the sample acquisition. Periodically, they were 75–100 N larger. This may be compared with the estimated weight of the rock (40–76 N). Since the higher estimate assumed a rectangular rock, it is probably too large. The lower weight allows for rounded edges but may be somewhat low. For simple sliding with a friction coefficient of 0.6 and using the equation of figure 11, a rock weighing 31 N could be pushed. If the sin θ term, which allows for an increase in normal force by the sampler, is ignored, a rock weighing 40 N could be pushed. At times forces as large as 100 N were exerted and may correspond to some plowing, which is seen to be the case from the pictures.

SAMPLING RESULTS

Judgment on the provenance of the samples was relatively straightforward for Notch rock because it fulfilled the criteria of surface area, visibility, and sampleability, but this was not the case for Badger. The surface beneath Notch could be viewed directly on high-resolution pictures taken by both cameras. Direct views showed that the trenching designed to

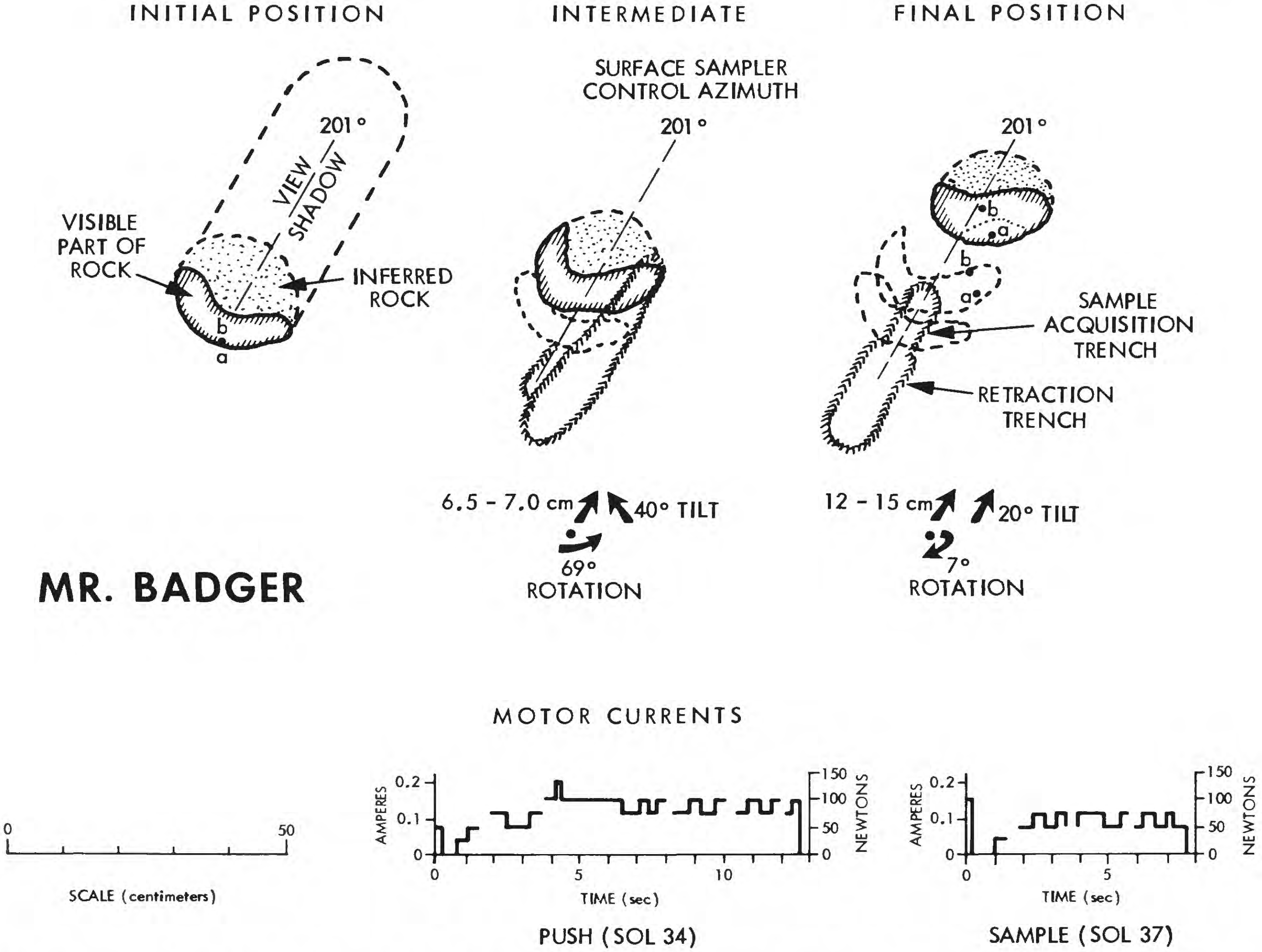

FIGURE 15.—Plan view showing movement of Badger (rock 3). Left is Badger before movement; note view shadow and area of inferred rock; 201° is azimuth through sampler gimbal axis; a and b are points on rock. Center, Badger after first push; dotted line is original position; note short trench excavated by surface sampler while extending to rock; large trench produced during retraction while Badger leaned on surface sampler; note trench is oblique to commanded azimuths; arrows below indicate motion; motor currents show approach to rock (0.6–4 s); the push (4–6.5 s); and push while Badger leaned on surface sampler (6.5–12.6 s). Last diagram shows final position of Badger; trench to clear contaminants; acquisition trench; arrows indicate motions; motor currents below are unusually low for sample acquisition.

clear away possible contamination was successful and that the acquisition occurred in the correct place. Achieved positions of the sampler were in complete accord with interpretations of the pictures. For the sample beneath Badger, judgment was at best difficult. Visibility and sampleability were not as favorable as at Notch because of the slope of the surface. The situation was more seriously affected by the post-sample acquisition pictures, one of which was a low-resolution (blue diode) picture and the other a high-resolution picture. Both were taken at low sun elevation angles, which caused extensive shadowing. The chief evidence that the sample came from beneath the rock was provided by comparing the history and locations of the rock along the azimuth axis of the sampler gimbal with achieved commands (fig. 18). Since this comparison indicated the sampler achieved the correct positions, the best estimate was that the sample did indeed come from soil originally beneath the rock. The outcome indicates that the low rating given to sampleability was appropriate. Two acquisition sequences were automatically performed because a "level full" signal was not obtained immediately after the first acquisition. Such a signal was obtained during the second acquisition sequence just before sieving of the sample into the Molecular Analysis soil delivery system.

Analytical results of the samples by the Molecular

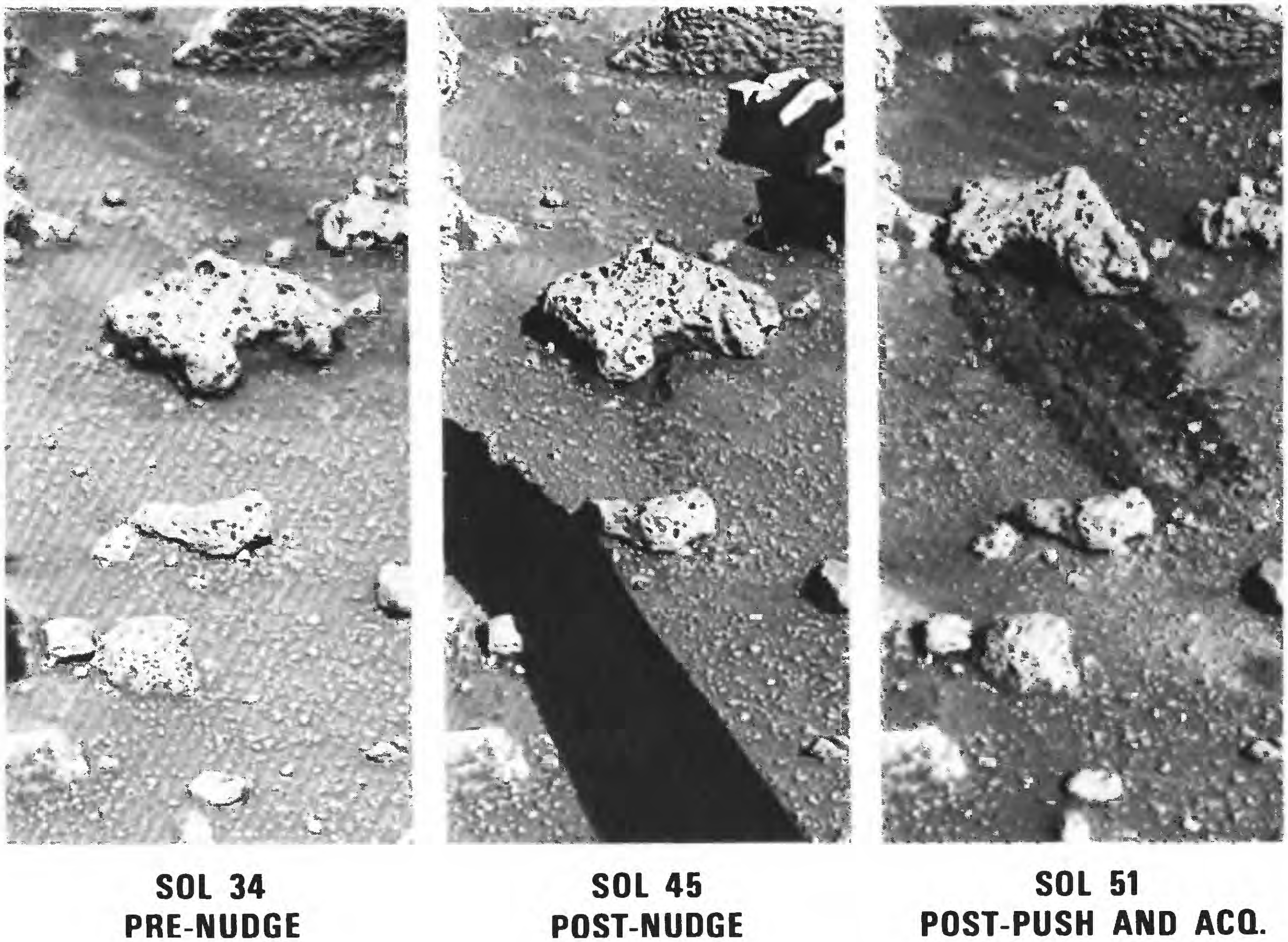

FIGURE 16.—Sequence of pictures showing Notch (rock 7). At left is rock prior to nudge on Sol 45. Next picture shows rock after nudge; note small displacement at protuberance on left side of rock. Third picture shows Notch after push and sample on Sol 51; note backhoe trench walls, plowing marks, and sampled area, which was originally under rock.

Analysis Experiment and Biology Experiment are compatible with the judgment that the samples came from beneath the rocks. The amount of water evolved during heating from 50–200°C of material from beneath Badger is much larger (0.2 percent) than that evolved from the sample exposed to the sun and heated in one step to 200°C ($\approx$0.05 percent)(Biemann and others, 1977). Heating of both samples to 350°C and then 500°C evolved comparable amounts of water during each heating step (Biemann and others, 1977). The results of the Gas Exchange instrument of the Biology experiment are also compatible with relatively large amounts of water. Evolution (desorption) of N_2, Ar, CO_2, and O_2 from soil humidified in the presence of the nutrient in the Gas Exchange Instrument varies inversely with the mean water content of the original sample environment (Oyama and Berdahl, 1977). Reduced desorption of N_2, Ar, and CO_2 from the sample under Notch is attributed to larger amounts of adsorbed water (Oyama, 1977). Reduced O_2 evolution is attributed to the hydration of alkaline-earth and alkali-metal superoxides to produce hydrated peroxides.

By terrestrial analogy, larger amounts of water should be expected under rocks (Moore and others, 1977b). Field and laboratory studies show that soil beneath rocks in a field of soil in an arid environment has detectably more adsorbed water at depths of 2.5–5.0 cm than soil exposed to the sun and atmosphere (Jury and Bellantuoni, 1976a, b). These studies indicate the net heat flow is toward the soil beneath the rocks, and so water vapor moves under the thermal gradient toward the area beneath the rocks. The rock cap inhibits evaporation. Also, ultraviolet radiation may dehydrate exposed soils (Huguenin, 1976).

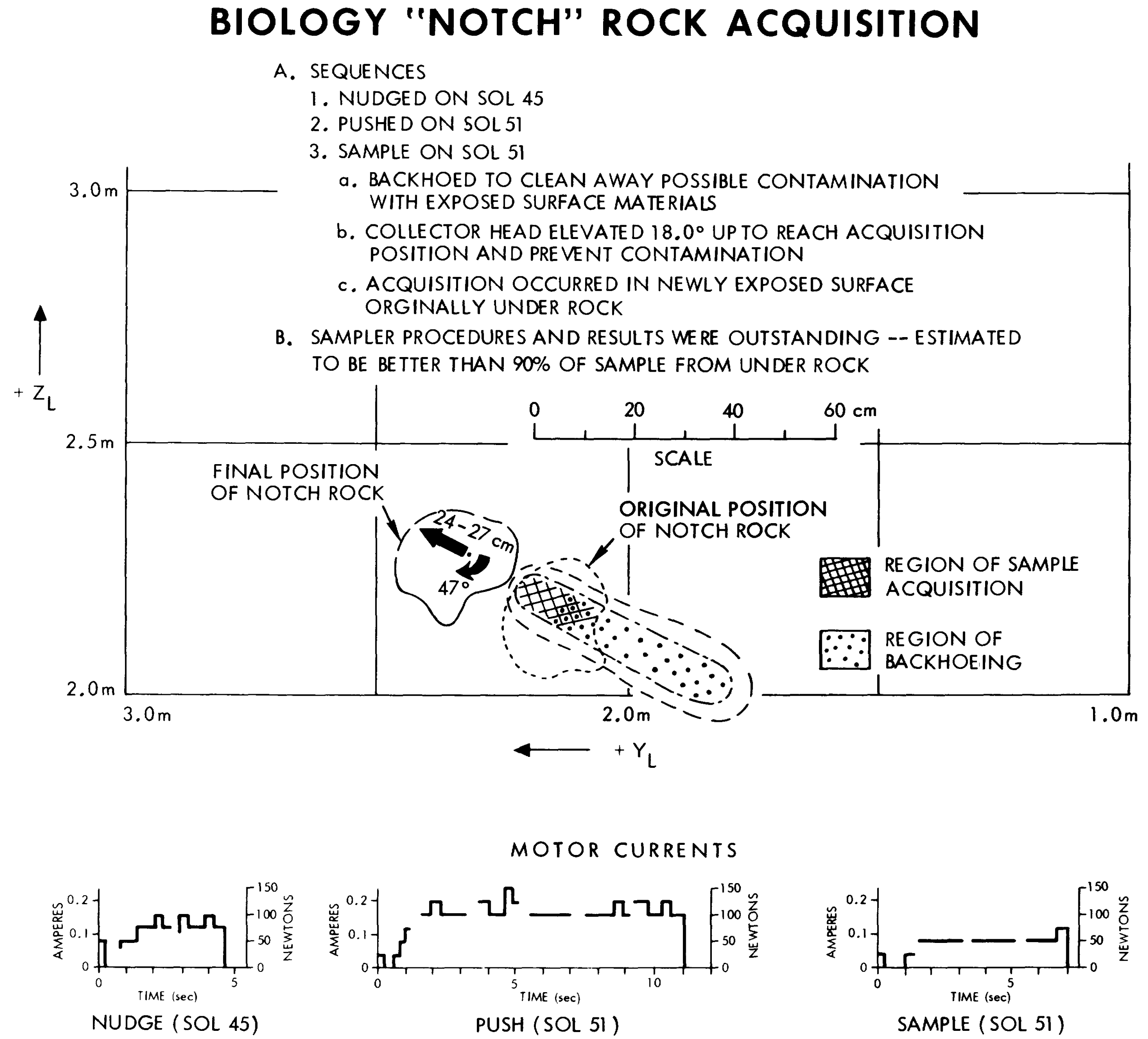

FIGURE 17.—Plan view showing movement of Notch (rock 7). Short dashed lines indicate original position of rock, solid line indicates final position of rock. Arrows show motion of rock. Motor currents are plotted at bottom. Note motor currents during push (center) are larger than those for nudge (left) and sample (right).

SCIENTIFIC VALUE

The scientific value of the samples from under the rocks was considerable (see table 2).

1. There was no evidence for large quantities of organic molecules in the sample from the sun-shielded soil beneath Badger (Biemann and others, 1977).
2. Results from the Biology experiments did not produce convincing evidence for Earth-like living organisms that thrived in the protected environment beneath Notch (Horowitz and others, 1976, 1977); the possibility for life on Mars has not been excluded, however (Levin and Straat, 1976, 1977).
3. Results of the Inorganic Analysis experiment indicate substantially less iron in the samples from under Badger and Notch than in samples exposed to the sun and atmosphere (B. C. Clark and others, 1977). The reason for the difference in iron content is not understood at this time; it may be the result

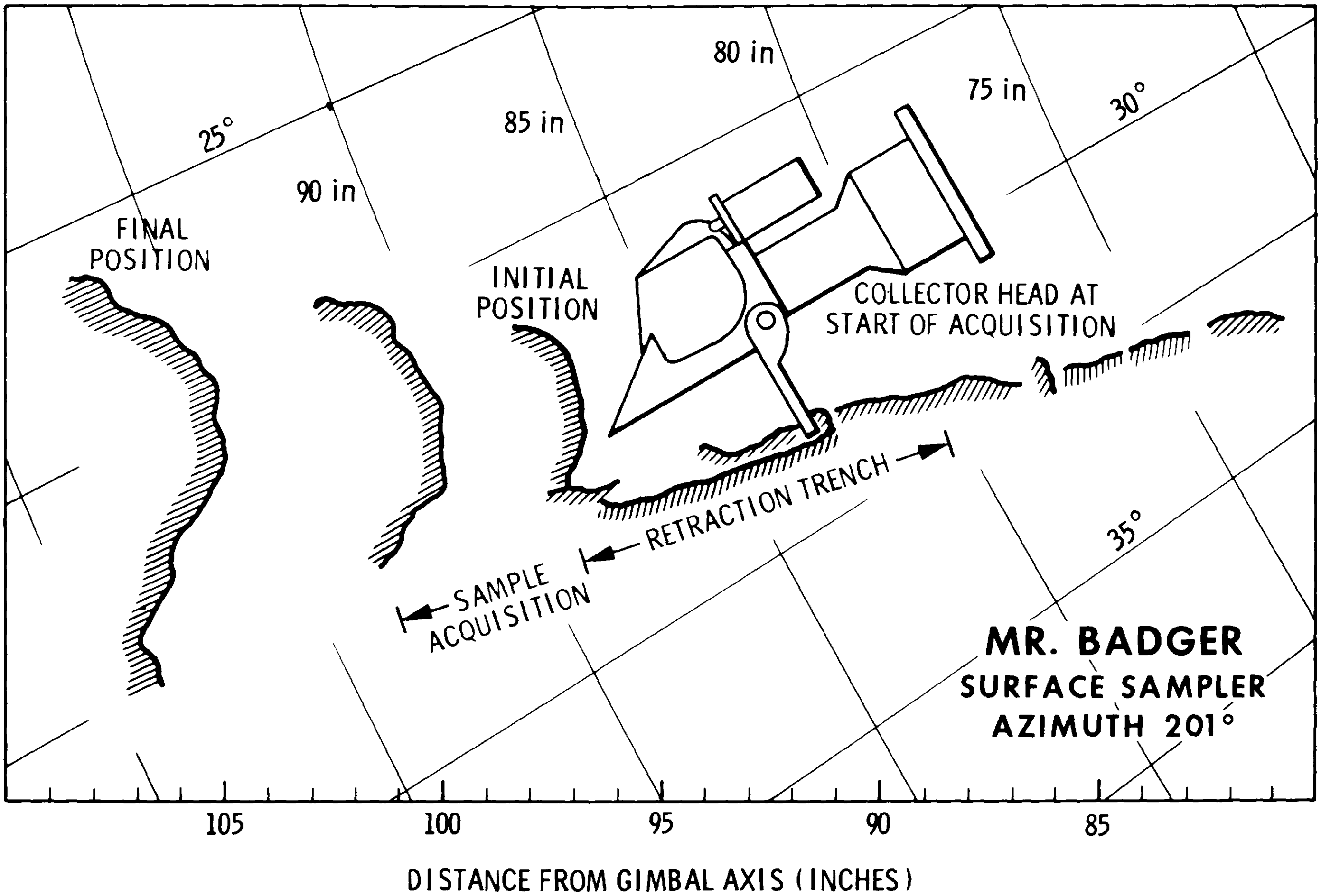

FIGURE 18.—V-Profile along sampler arm azimuth of 201° showing surface and original location of Badger (rock 3), location after Sol 34 push, and location after Sol 37 push. Surface sampler collector head is at position just before acquisition stroke; sample area and backhoe trench areas indicated by arrows. Sloping lines indicate deelevation angles; arcs are sampler extensions.

of sedimentation of magnetite-rich fine material from the atmosphere (Pollack and others, 1977) on exposed surfaces but not on covered surfaces.

4. The large amount of water (for Mars) evolved during heating of the sample from under Badger to 200°C may represent adsorbed water. If this is the case and Mars is like the Earth, adsorbed water may be present at greater depths, where it is cooler. Such a result lends strong support to models of Mars and its atmosphere requiring adsorbed water (Fanale, 1976).
5. The response of the exposed and shielded soils to the Gas Exchange instrument is providing valuable insight on the chemical environment at the surface of Mars.
6. The surface sampler did not scratch, chip, or spall the rocks, showing their surfaces are hard.
7. Color pictures were obtained of freshly exposed soil beneath Badger as well as the underside of the rock.
8. The "water line" ledge of soil adhering to the side of Badger (fig. 14) provides clear evidence of a near-surface crust.

SUMMARY AND CONCLUSIONS

The dense field of rocks on Mars was not anticipated before the Viking landings, and pushing rocks was not in the plans. Successful pushing of the rocks and sampling from the newly exposed soils beneath them required the development of imaginative procedures based on a thorough understanding of scientific requirements and the variables related to the surface sampler. Of equal importance was an accurate knowledge of the locations of the rocks within the sample field.

The endeavor to collect samples from under rocks was entirely successful. Four lines of evidence support this: (1) The pictures show that samples came from soils originally beneath the rocks; (2) the sampler positions indicate that samples came from soils originally beneath the rocks; (3) by terrestrial analogy,

TABLE 2.—*Comparison of scientific results from samples acquired from under rocks and samples directly exposed to the atmosphere and sun*

Experiment	Observed quanitities or items	Under-rock samples	Exposed samples (Lander 2)	Exposed samples (Lander 1)	Comments
Biology:					
Gas Exchange	predicted Ar(nmols)	39	49	62	Predicted and observed nanomoles (nmols) of gas desorbed by humidification (Oyama and Berdahl, 1977; table 2). Differences in the Ar and N_2 found in samples are attributed to amount of adsorbed water vapor, which is largest for under-rock sample and smallest at VL–1 site; amount of O_2 evolved attributed to reaction of water vapor with superoxides and peroxides; O_2 from under-rock sample probably near 70 nmols; low O_2 evolved because there was more water under Notch (rock 7).
	found Ar	6	4	13	
	predicted N_2	60	76	96	
	found N_2	13	30	83	
	predicted O_2	2.7	3.4	4.4	
	found O_2	70–270	190	790	
	predicted CO_2	6,110	7,750	9,800	
	found CO_2	6,110	7,750	9,800	
Pyrolytic Release	$^{14}CO_2$ (disintegrations per minute).	---	---	---	Results from this instrument are poorly understood at this time; a biological interpretation of results is unlikely (Horowitz and others, 1977).
Labeled Release	$^{14}CO_2$ (counts per minute).	---	---	---	Results from this instrument are consistent with a biological response and restrict possible chemical reactions that might produce the results (Levin and Straat, 1977).
Molecular Analysis	Water (percent)				No organic compounds related to the soil of Mars were detected; water analyses for Lander 1 were omitted because they are, at best, crude estimates (Biemann and others, 1977).
	heated to— 50°C	<0.01	---	---	
	200°C	0.2	0.05	---	
	350°C	0.3	0.3	---	
	500°C	0.8	1.0	---	
	500°C	0.6	0.25	---	
Inorganic Analysis	Iron (percent)	≈11.6–12.8	14.2	12.7–13.1	Data on samples from under rocks not yet available; sample from under Badger (rock 3) contains 18 percent less iron than exposed samples at VL–2 site; sample from under Notch (rock 7) contains 10 percent less iron than exposed samples at VL–2 site (B. C. Clark and others, 1977); values for under-rock sample taken as 10 and 18 percent less than 14.2 percent.

TABLE 2.—*Comparison of scientific results from samples acquired from under rocks and samples directly exposed to the atmosphere and sun*—*Continued*

Experiment	Observed quanitities or items	Under-rock samples	Exposed samples (Lander 2)	Exposed samples (Lander 1)	Comments
Physical properties:					
Rock strength	Pictures and forces inferred from motor currents.	---	---	---	ICL (rock 1) did not scratch, chip, or spall when forces of 200 N and stresses near $10^8 N/m^2$ were exerted on it; this indicates rock is strong and does not have a weak weathered rind.
Soil structure (crust)	Pictures of disturbed rocks.	---	---	---	Ledge of soil adhering to Badger (rock 3) proves the existence of thin crust near surface.
Lander Imaging Color	Pictures of rock and soil.	---	---	---	Color data not reduced; there are no obvious differences in color between under-rock and exposed soils.

more adsorbed (?) water should be in soils under rocks than in soils exposed to the sun; (4) soils from under the rocks contain less iron than those exposed to the sun and atmosphere.

The larger amount of water evolved during heating to 200°C from soil beneath the rock than from soil exposed to the sun and atmosphere as well as the Biology experiment results on the sample from under a rock lends strong support to theories requiring storage of water and volatiles in the martian regolith. Eventually, the results may lead to a reasonable assessment of equilibrium conditions between the water vapor in the atmosphere and the water in the regolith. Although not understood at this time, the difference between the amount of iron in soils from under the rocks and soils exposed to the sun and atmosphere should be explicable.

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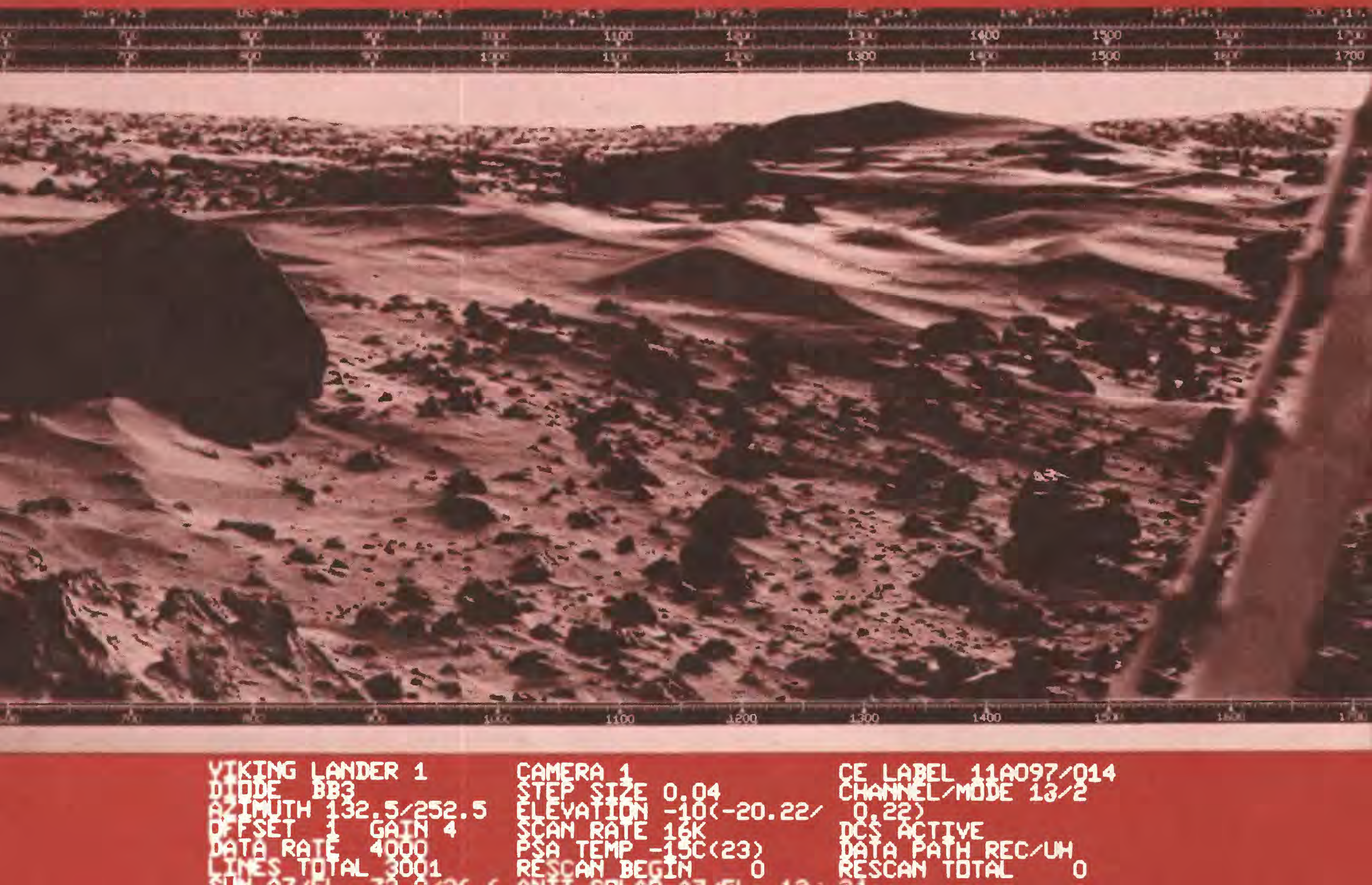
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SCAN RATE 16K
PSA TEMP -15C(23)
RESCAN BEGIN 0
CE LABEL 11A097/014
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DCS ACTIVE
DATA PATH REC/UH
RESCAN TOTAL 0