OVERVIEW OF THE MARS PATHFINDER MISSION ANI) ASSESSMENT OF LANDING SITE PREDICTIONS

M. P. Golombek[1], R. A. Cook[1], T. Economou[2], W. M. Folkner[1], A. F. C. Haldemann[1], P. H. Kallemeyn[1], J. M. Knudsen[3], R. M. Manning], H. J. Moore[4], T. J. Parker[1], R. Rieder[5], J. T. Schofield P. H. Smith[6], and R. M. Vaughan[1]

[1] Jet Propulsion Laboratory, California institute of Technology, Pasadena, CA 91109

2 University of Chicago, Enrico Fermi Institute, Chicago, IL 60637

[3]Niels Bohr Institute, University of Copenhagen, Denmark

[4]U. S. Geological Survey, Scientist Emeritus, Astrogeology Team, Menlo Park, CA 94025

[5] Max Planck Insitute for Chemistry, Mainz, Germany

6 Lunar and Planetary Laboratory, [University of Arizona, Tucson, AZ85'721

Data returned by Mars Pathfinder indicates some rocks may be high in silica implying differentiated parent materials. Rounded pebbles and cobbles and a possible conglomerate suggest fluvial processes that imply liquid water in equilibrium with the atmosphere and thus a warmer and wetter past. The moment of inertia indicates a central metallic core of 1300-2000 km in radius. Composite airborne dust particles appear uniformly magnetized by freeze dried maghemite stain or cement that may have been leached from crustal materials by an active hydrologic cycle. Remote sensing data at a scale of generally greater than -1 km and an Earth analog correctly predicted a rocky plain safe for landing and roving with a variety of rocks deposited by catastrophic floods that are relatively dust free.

Dear Colleague: This is the overview and landing site paper for the special Mars Pathfinder 30-Day Report submitted to Science after revisions on 10/31/97. Because of the agreement with Science, please do not distribute this paper and under no circumstances show it or any part of it to the press

Note for reviewers and editors: Common Plates for Pathfinder papers referred to in this paper are: Plate 1 a-Full color panorama: f'late 1 b- Anaglyph stereo panorama: Plate 3-Map with rover traverses; Plate 4-Geomorphic sketch map of site; Plate 5-Map of rock sizes: Plate 6-Rock names; Plates 8, 9 and 10-Rock size-t'requcncy distribution plots.

Introduction

Mars Pathfinder landed on the surface of Mars on 4 July 1997 (Figs. 1 and 2), deployed a small rover (Fig. 3), and collected data from three science instruments (imager for Mars Pathfinder, IMP; alpha proton X-ray spectrometer, APXS; and atmospheric structure instrument/meteorology package, ASI/MET) and technology experiments in one of NASA's most popular missions *(1)*. In the first month of surface operations the mission has returned about 1.2 Gbits of data, which includes 9669 lander and 384 rover images and about 4 million temperature, pressure and wind measurements. The rover has traversed a total of about 52 m in 114 commanded movements, obtained 10 chemical analysis measurements of rocks and soil, performed soil mechanics and technology experiments, and explored over 250 m^2 of the martian surface.

Pathfinder is the first mission to use a rover, carrying a chemical analysis instrument, to characterize the rocks and soils in a landing area over hundreds of square meters on Mars, which provides a calibration point or "ground truth" for orbital remote sensing observations *(1)*. The combination of spectral imaging of the landing area by the IMP, chemical analyses by the APXS aboard the rover, and close-up imaging of colors, textures and fabrics with the rover cameras offers the potential of identifying rocks (petrology and mineralogy). Prior to Pathfinder, knowledge of the kinds of rocks present on Mars was rudimentary and was based mostly on the SNC meteorites (all mafic igneous rocks) and inferences from Viking data. In addition, small valley networks in heavily cratered terrain on Mars have been used to argue that the early martian environment may have been both warmer and wetter (with a thicker atmosphere), at which time liquid water may have been stable.

The Ares Vallis landing site (Fig. 4) was selected because it appeared acceptably safe and offered the prospect of analyzing a variety of rock types expected to be deposited by catastrophic floods, which enable addressing first-order scientific questions such as differentiation of the crust, the development of weathering products, and the nature of the early martian environment and its subsequent evolution *(2)*. Selection of the Mars Pathfinder landing site took place over a two and a half year period in which engineering constraints were identified, surface environments and safety considerations were developed (for the robust lander), and the potential science return at different sites was considered. Sites (100 by 200 km target ellipses) were considered safe if they were below O km elevation, were free of obvious hazards (high-relief surface features) in high-resolution (<50 m/pixel) Viking orbiter images and had acceptable reflectivity and roughness at radar wavelengths, high thermal inertia, moderate rock abundance, low red to violet ratio, and low albedo. In selecting the Ares Vallis site using the remotely sensed data and the geologic setting, a number of predictions of the surface characteristics of the site were made (2), which are tested later in the paper.

Launch, Cruise, Entry, Descent and Landing

The spacecraft was launched on 4 December 1996 and had a 7 month cruise to Mars, with four trajectory correction maneuvers. The vehicle entered the atmosphere directly following cruise stage separation. Parachute deployment, heatshield and lander separation, radar ground acquisition, airbag inflation and rocket ignition (Table 1) all occurred before landing at 2:58 AM true local solar time (9:56:55 AM PDT). The lander bounced at least 15 times up to 12 m high without airbag rupture, demonstrating the robustness of this landing system. The radio signal from the low-gain antenna was received at 11:34 AM PDT indicating successful landing. During entry, descent and landing science and engineering accelerometers, pressure, and descent temperature sensors allowed the atmospheric temperature, pressure and density to be reconstructed (3).

Soils near the lander that had been disturbed by retraction of the airbags appear to be a darker red-brown than the surrounding undisturbed soils (Plate 1 a). Similar patches can also be found at up to 15 m away from the lander to the east and southwest. Those to the southwest resemble airbag retraction marks, lie along an arc centered to the southwest of the lander, and appear to indicate that the airbag-enclosed lander rolled gently up and back down a slight rise (see around the rover petal in Plate 1a). Dark patches extending away from the lander are probably (he spacecraft's last few bounce marks as the lander bounced to its present location from the east or east-southeast (notice disturbed soil to the east at end of petal with meteorology mast in Plate I a). These marks are distinct from the roll marks and airbag retraction marks in that they are separate patches rather than continuous swaths. Those closest to the lander also show sharp, linear troughs that fade toward the edge of the disturbed patch. These may be impressions of creases in the airbags that were imprinted into the soil as the lander bounced and compressed the airbag lobe in contact with the ground.

Surface Operations

After receiving data indicating a healthy spacecraft, commands were sent to unlatch the IMP and high-gain antenna. Images returned at 4:30 PM PDT included a panorama to determine how well the airbags had been retracted, stereo images of both ends of the rover petal to determine if it was safe to deploy the rover ramps, and a partial color panorama of the martian surface and sky beyond the rover (Fig. 1). After further retraction of the airbags, requiring the rover petal to be partially closed and then reopened, the ramps were deployed at 9:30 PM and the rover was commanded to stand up. A full panorama of the surface around the lander was returned during the last downlink of the first sol (the first martian day, 24.6 hrs, of surface operations). The rover was driven down the rear ramp on sol 2. After acquisition of a number of lossless panoramas, the IMP was deployed on its 0.8 m high mast at the end of sol 2. Following some communication difficulties between the rover and lander on sols 1 and 2, the rover placed the APXS against Barnacle Bill on sol 3 (see rock names in Plate 6).

Operations during the first week focused on returning a full stereo lossy (compressed 6:1) panorama to support rover operations and end of day images of the rover to allow traverse planning for the next sol. A full three color lossy (compressed 6:1) panorama was acquired on sol 10 and a nearly lossless three color stereo with 9 color filter panorama was begun on sol 13. This panorama and images acquired for sub-pixel scale resolution represent the complete set of images for characterizing the landing site. The rover was sent in a clockwise traverse around the lander (Plate 3) to enable APXS measurements of rocks in the Rock Garden, which could not be accessed from the other direction.

location of the Lander

Five prominent horizon features, including 3 knobs, one large crater on the horizon and two small craters have been identified *in* lander images and in the high-resolution Viking orbiter

images (Fig. 5), which allows the lander to be located with respect to other surface features. Based on azimuths to the features, the location of the lander in the Viking images can be determined to within a few pixels (about 100 m). Within the USGS cartographic network *(4)* the lander is located at 19. 17°N, 33.2 1°W, but a revised cartographic network *(5)* for the local area and the two-way ranging and Doppler tracking *(6)* results in inertial space suggest that the USGS network is displaced about 19 km to the north and 7 km to the west (Figs. 4 and 5).

Science Overview

Science results from the Pathfinder mission are described within seven science areas; all are described and discussed in more detail in the companion papers describing the preliminary science results of the mission (.?, 6, 7, 8, *9,* /0).

Geology and Geomorphology

Many characteristics of the landing site are consistent with its being shaped and deposited by the Ares and Tiu catastrophic floods (7). The rocky surface is consistent with its being a depositional plain (16% of the area is covered by rocks, Plates 5, 8, 9, 10) with rounded to semi-rounded pebbles, cobbles and boulders that appear similar to depositional plains in terrestrial catastrophic floods (see later discussion). The Twin Peaks appear to be streamlined islands in lander images, which is consistent with interpretations of Viking orbiter images of the region that suggest the lander is on the flank of a broad, gentle ridge trending northeast from Twin Peaks (Fig. 5). This ridge, which is the rise to the north of the lander, is aligned in the downstream direction from the Ares and Tiu Vanes floods, and may be a debris tail deposited in the wake of the Twin Peaks. Rocks in the Rock Garden (Shark, Half Dome, and Moe, Plate 6) may be imbricated blocks generally tilted in the direction of flow (Fig. 1). Channels visible throughout the scene (Fig. l and Plates l b and 4) may be a result of late stage drainage. Large rocks appear tabular, semi-rounded, and many appear perched consistent with deposition by a flood. Smaller angular darker rocks and blocks may be ejecta from a nearby crater *(7)*. Evidence for eolian activity at the site includes wind tails behind rocks and wind streaks of what appears to be very fine grained bright red drift material. Dirt covering the lower 5-7 cm of several rocks suggest that they have been exhumed (7). Some rocks appear to be fluted and grooved by saltating sand size particles in the wind and sand dunes have been imaged in the trough behind the Rock Garden by the rover.

Mineralogy and Geochemistry

In general, rocks are dark gray with discontinuous coatings of bright red dust and/or weathered surfaces (7). Undisturbed dark soil and dark red soil, which appears in areas disrupted by the rover and airbags, have colorations between the bright red and dark gray. A very bright red material (e. g., Scooby Doo) may be an indurated soil, because its composition is similar to soils elsewhere at the site (8). Soil compositions are generally similar to those measured at the Viking sites. Thus this soil may be a globally deposited unit on Mars *(8)*. The similarity in compositions among the soils implies that the differences in color may be due to either slight differences in iron mineralogy or differences in particle size and shape.

The analyzed rocks are consistent with basaltic to andesitic parent materials on Mars *(8)*. The high silica content of some of the rocks appears to require crustal differentiation of mantle derived parent materials. These rocks have compositions that are distinct from those of the SNC meteorites (believed to have come from Mars). Analyses of lower silica rocks appear rich in sulfur implying that they are covered with dust or weathered. Rover images show some rocks appear vesiculated and may be volcanic. Soils cannot have formed from the measured rocks at the landing site because their compositions are chemically distinct (8).

Magnetic Properties and Surface Material Properties

Airborne magnetic dust has been progressively deposited with time on most of the magnetic targets on the lander (9). The dust is bright red and has a magnetization consistent with composite particles with a small amount of maghemite as stain or cement. Interpretation of these results suggests that the iron was dissolved out of crustal materials in water, suggesting an active hydrologic cycle on Mars. and the maghemite is a freeze-dried precipitate *(9)*.

Observations of wheel tracks and soil mechanics experiments suggests that compressible, drift, cloddy and indurated surface materials are present *(10)*. Bright red drift material and others may be very fine grained materials (dust); most arc composed of poorly sorted fines, clods, and small rocks. Angles of repose and internal friction are like those on Earth and imply bulk densities of surface materials between 1.2 and 2 g/cm^3. Rover images show a large number of loose spherically rounded pebbles and cobbles on the surface. One small rock in front of Shark (Plate 6) shows reflective hemispheric pockets or indentations and rounded pebbles, implying that the rock is a conglomerate *(10)*. Conglomerates require running water to smooth and round the pebbles and cobbles and to deposit the materials and argues for a warmer and wetter past in which liquid water was stable and the atmosphere was thicker.

Atmosphere Science and Imaging

The atmospheric opacity has been about 0.5 since landing on Mars (7), in late northern summer (Ls of 1430). Slightly higher opacity at night and early in the morning may be due to clouds, which have been imaged, and fog. The sky has been a pale-pink color (Fig. 1), similar to what was seen by the Viking landers. Particle size (roughly a micron) and shape and water vapor (about 10 precipitable microns) in the atmosphere are also consistent with measurements made by Viking. The upper atmosphere (above 60 km altitude) was relatively cold, although this may be consistent with seasonal variations and entry at 3 AM local solar time (compared with the warmer upper atmosphere measured by Viking at 4 PM local solar time). The multiple. peaks in the landed pressure measurements and the entry and descent data are indicative of dust uniformly mixed in a warm lower atmosphere, again similar to that measured by Viking *(3)*.

The meteorology measurements show repeatable diurnal and higher order pressure and temperature fluctuations (3). The barometric minimum was reached at the site on sol 13 indicating the maximum extent of the winter south polar cap. Temperatures fluctuated abruptly with time and between 0.25 and 1 m height in the morning. These observations suggest that cold morning air was warmed by the surface and convected upward in small eddies. Afternoon temperatures, after the atmosphere has been warmed do not show these variations. Winds have been light (<10 m/s) and variable, peaking at night and during daytime. Dust devils have been detected repeatably in the early afternoon (3).

Rotational and orbital Dynamics

Daily Doppler tracking and less frequent two-way ranging during communication sessions between the spacecraft and Deep Space Network antennas have resulted in a solution for the location of the lander in inertial space and the direction of the Mars rotation axis (6). Combined with earlier results from the Viking landers, this gives a factor of three improvement in the Mars precession constant. The estimated precession rate is consistent with the hypothesis that the non-hydrostatic component of the polar moment of inertia (0.3653 ±0.0056) is due to the Tharsis bulge (6). The estimated precession constant rules out warm interior models with mantle compositions similar to Earth and cold, highly iron enriched models. If the (iron-enriched) Shergotite meteorites are typical of the mantle composition, then the mantle must be warmer than Earth's (for the same pressure level) and the core radius must be larger than -1300 km (but no larger than -2000 km for other mantle compositions).

Tests of Predictions for the Landing Site

Pathfinder has provided tests of the validity of remote observations from Earth, orbit, and the surface *(2)*. As predicted, the average elevation of the center of the site was about the same elevation as Viking Lander 1 relative to the 6.1 mbar geoid (Table 2), based on delay-Doppler radar measurements *(13)* and on tracking results *(14)*; the Doppler tracking and two-way ranging estimate for the elevation of the spacecraft (6) is only 45 m lower than the Viking 1 Lander and within 100 m of that expected, which is within the uncertainties of the measurements. After landing, surface pressures and winds (5-10 m/s) were found to be similar to expectations based on Viking data, although temperatures were about 10 K warmer (3). The temperature profile below 50 km was also roughly 20 K warmer. As a result, predicted densities were 5% higher near the surface and up to 40% lower at 50 km, but within the entry, descent and landing design margins. The populations of craters and small hills and the slopes of (he hills measured in high-resolution (38 m/pixel) Viking orbiter images and the radar derived slopes of the landing site are all consistent with observations of these properties in the lander images (Table 2).

A rocky surface was expected from Viking Infra-Red Thermal Mapper (IRTM) observations and comparisons with the Viking landing sites *(15, 16, 17)*. The observed cumulative fraction of area covered by rocks With diameters greater' than 3 cm (Plate 9) and heights (Plate 10) greater than 0.5 m (potentially hazardous to landing) at Arcs is similar (Table 2) to that predicted by IRTM observations and models of Viking lander rock size-frequency *distributions* (2, *18)*. The IRTM prediction postulated an effective thermal inertia of 30 (10-3 cgs units) for the rock population *(15)*, but we obtain a slightly different effective thermal inertia for the rock population.

The validity of interpretations of radar echoes prior to landing are supported by a simple radar echo model *(19*, 20), an estimate of the reflectivity of the soil from its bulk density (2, *21*, 22), and the fraction of area covered by rocks (Table 2). In the calculations, the soil produces the quasi-specular echo and the rocks produce the diffuse echo. The derived quasi-specular cross section is comparable to the cross-sections and reflectivities reported for 3.5-cm wavelength observations (Table 2). The model yields a diffuse echo that is modestly larger than the polarized diffuse echo reported for 3.5-cm wavelength observations. At 12.5-cm wavelength, similar rock populations at Ares and the Viking 1 site were expected because the diffuse echoes are comparable *(23)*, but the large normal reflectivities suggests that bulk densities of the soils at depth are greater than those at the surface. We also obtain a fine-component inertia near 8.4 which agrees with the fine-component inertia of 8.7 (in 10^{-3} cgs units) estimated from thermal observations from orbit by the IRTM *(24)*; for this estimate, wc used a bulk thermal inertia of 10.4 for the landing site (25) , an effective thermal inertia near 40 (10^{-3} cgs units) for the rock population *(26)*, and a graphical representation of Kieffer's model *(27)*.

Color and albedo data for Ares suggested surfaces of materials at Ares Vallis would be relatively dust free or unweathered prior to landing *(2)* compared with the materials at the Viking landing sites. This suggestion is supported by the abundance of relatively dark-gray rocks at Ares and their relative rarity at the Viking landing sites, where rocks are commonly coated with bright red dust *(28)*. Finally, the 40 km long Ephrata Fan of the Channeled Scabland in Washington state, which was deposited where channelized water flowing down the Grand Coulee filled the Quincy Basin, was suggested as an analog for the landing site *(29)* because the overall geology and geomorphology of the landing site, as inter preted from orbital images prior to landing, are compatible with such a deposit ional plain (2). The geology anti geomorphology of the landing site (discussed earlier) is similar to such a depositional plain and the abundance and size of pebbles, cobbles and boulders are consistent with the expected general decrease in clast size from the mouth of the channel *(2, 30)*.

Perspective

Data returned by Pathfinder have significantly changed our understanding of Mars. Taken together, the rounded pebbles, cobbles and the possible conglomerate, the abundant sand- and dust-sized particles and models for their origin, and the high silica rocks, all appear consistent with a water rich planet that may be more Earth like than previously appreciated, with a warmer and wetter past in which liquid water was stable and the atmosphere was thicker.

The prediction of the important characteristics of the site for safe landing and roving indicates that remote sensing data at scales of kilometers to tens of kilometers can be used to infer surface properties at a scale of meters. The prediction that the site would be a plain deposited by a catastrophic flood is consistent with that found at the surface and implies that some geologic processes observed in orbiter data can be used to infer surface characteristics where those processes dominate over other processes affecting the martian surface layer *(16)*. Analyses of rock chemistry and close up rover images suggest that a variety of rock types are present, consistent with it being a "grab bag" of materials deposited by the flood *(2)*.

Mars Pathfinder has demonstrated a very robust landing design for rocky areas and other terrains on Mars. The landing site is among the rockiest parts of Mars (rockier than all but 5% of the planet at a scale of 100 km in IRTM,*15)* and the airbag encased lander protected the lander through multiple bounces without damage. Even in rocky areas of Mars, small rovers are excellent for placing instruments up against rocks and imaging their textures and fabrics up close. The Pathfinder landing system and its rover is suitable for the exploration of the wide variety of terrains and surface materials of Mars.

References and Notes

(1) M. P. Golombek, *J. Geophys. Res.* *102,* 3953 (1997). Mars Pathfinder is one of the first low-cost Discovery class missions. The mission captured the imagination of the public, garnered front page headlines for a week, and became the largest internet event in history with a total of about 566 million internet "hits" tor the first month of the mission (47 million "hits" on July 8th alone).

(2) M. P. Golombek R. A. Cook H. J. Moore T. J. Parker, *J. Geophys.* ***Res.*** 102, 3967 (1997)

(3) J. T. Schofield et al., *Science*, this issue.

(4) E. Howington-Kraus R. L. Kirk B. Redding L. A. Soderblom, in M. P. Golombek K. S. Edgett J. W. Rice Jr., eds., *Mars Pathfinder Landing Site Workshop II: Characteristics of the Ares Vallis Region and Field Trips in the Channeled Scabland, Washington*, Lunar and Planetary Institute Technical Report 95-01, Part 2, p. 38 (1995)

(5) T. C. Duxbury, in M. P. Golombek K. S. Edgett J. W. Rice Jr., eds., *Mars Pathfinder Landing Site Workshop 11: Characteristics of the Ares Vallis Region and Field Trips in the Channeled Scabland, Washington,* Lunar and Planetary Institute Technical Report 95-01, 1995, Part 2, p. 35-36, (1995).

(6) W. M. Folkner et al., *Science,* this issue

(7) P. H. Smith et al., *Science,* this issue.

(8) R. Rieder et al., *Science,* this issue.

(9) S. F. Hviid et al., *Science,* this issue.

(10) Rover Team, *Science,* this issue.

(II) D. A. Spencer and R. D. Braun, AAS/AIAA Paper 95-379 (1995) and D. A. Spencer pers. corn.

(12) A. S. Konopliv and W. L. Sjogren, *JPL Publ. 95-5,73* pp., Feb. 1995.

(13) A. F. C. Haldemann, D. L. Mitchell, R. F. Jurgens, M. A. Slade, D. O. Muhleman, *J. Geophys. Res.* 102, 4097, (1997)

(14) C. F. Yoder and E. M. Standish, *J. Geophys. Res.* 102,4065 (1997)

(15) P. R. Christensen, *Icarus* 68,217 (1986)

(/6) P. R. Christensen and H. J. Moore, in MARS edited by H. H. Kieffer, B. M. Jakosky, C. W. Snyder, M. S. Matthews, U. Ariz. Press, 686-727 (1992)

(17) H. J. Moore anti J. M. Keller, *Rep. Planet. Geol. Geophys. Prog.* - 1990, *NASA TM 4300, 160(1991)*

(18) M. Golombek and D. Rapp, *J. Geophys. Res.* 102,4 I 1 7 (1997)

(19) J. V. Evans and 1'. Hagfors *Icarus* 3, *15* l (1964): The model of Evans and Hagfors relates the total cross-section of the polarized echo (σ_{oc}) with the quasi-specular component (σ^{Q}_{oc})

anti the diffuse component (σ^D_{oc}): $\sigma_{oc} = \sigma^Q_{oc} + \sigma^D_{oc}$. The quasi-specular component (σ^Q_{oc}) is related to the normal reflectivity (p_o), the root-mean-square slope in radians (Θ_r), a number near unity, and the area (X) producing the quasi-specular echo. The diffuse component is related to the reflectivity of the wavelength scatters (p_r), the directivity, and the fraction of area of scatterers producing the diffuse echo:

$\sigma_{oc} = \rho_o\ (1 + n\ \Theta_r^2)\ X + \rho_r\ g\ (1\text{-}X)$

where $\rho_o = 0.06$, $\Theta_r = 4.8°$, $X = 0.839$, $\rho_r = 0.23$, and g=2.

(20) T. W. Thompson and H. J. Moore, *Proc. Lunar Planet. Sci. Conf.* 19th, 409, (1989)

(21) G. R. Olhoeft and D. W. Strangway, *Earth Planet. Sci. Left. 24,394, (1975)*

(22) J. K. Mitchell W. N. Houston R. F. Scott N. C. Costes W. D. Carrier 111 L. G. Bromwell, *Proc. Third Lunar Science Conf., Supple. 3, Geochim et Cosmochim Acta*, *3, 3235 (1972)*

(23) J. K. Harmon, *J. Geophys. Res. 102,4081* (1997).

(24) P. R. Christensen, *J. Geophys. Res.* 87, 9985 (1982); P. R. Christensen, *J. Geophys. Res.* 91, 3533 (1 986). Other models by R. M. Haberle and B. M. Jakosky, *Icarus* 90, 187 **(1991)**; J. N. Hayashi B. M. Jakosky R. M. Haberle, *J. Geophys. Res.* 100, 5277 (1995) report slightly smaller inertias.

(25) F. D. Palluconi and H. H. Kieffer, *Icarus* 45,415, (198 1)

(26) Our estimate of the effective thermal inertia is based partly on the work of B. M. Jakosky *Icarus* 66, 1 17(1986). We estimate of the thermal inertia of the rock population by summing the products of the thermal inertias and areas for each rock and dividing by the total area covered by the rocks; rocks greater than 0.26 m have inertias near 50 (IO-3 cgs units) and smaller ones vary as the 0.75 power of their diameter; 0.03 m rocks have inertias near 10.

(27) H. H. Kieffer T. Z. Martin A. R. Peterfreund B. M. Jakosky E. D. Miner, F. D. Palluconi, *J. Geophys. Res.* 82, 4249 (1977)

(28) E. A. Guinness R. E. Arvidson M. A. Dale-Bannister R. B. Singer E. Bruckenthal, *Proc Lunar Planet. Sci. Conf. 17th, Part 2, JGR suppl.* E575 (1987); L. K. Pleskot and E. D. Miner, *Icarus* 45, 179 (1981)

(29) M. P. Golombek, K. S. Edgett, J. W. Rice Jr., eds., *Mars Pathfinder Landing Site Workshop II: Characteristics of the Ares Vallis Region and Field Trips in the Channeled Scabland, Washington*, September 28-29, 1995, Spokane, Washington, Lunar and Planetary Institute Technical Report 95-01, Part 1, 63 pp; Part 2,47 pp. (1995); J. W. Rice Jr. and K. S. Edgett, *J. Geophys. Res.* 102, 4185 (1997); K. S. Edgett and P. R. Christensen, *J. Geophys. Res. 102, 4107 (1997)*

(30) V. R. Baker *Geol.* Sot. *America Spec. Pap. 144,* 73 p. (1972); G. Komatsu and V. R. Baker, *J. Geophys. Res. 102,* 4151 (1997)

(32) The success of the Pathfinder mission resulted from the dedication of hundreds of engineers and scientists throughout the United States and in Germany and Denmark. The mission was managed, designed, built and operated by the Mars Pathfinder Project of the Jet Propulsion Laboratory, California Institute of Technology, which is the National Aeronautics and Space Administration's lead center for planetary exploration, with selected components contracted out to industry.

Figure Captions

Fig. 1. Panorama of the martian surface with dark rocks, red dust, and pale pink sky at Ares Vallis taken by the IMP on sol 1; the rover is still stowed on the lander petal. Airbags inhibited deployment of the rover ramps (the gold, silver edged cylinders at either end of the rover), and required the petal to be raised and the airbags to be further retracted, prior to rover egress on sol 2. Twin Peaks in the background is about 1 km to the west southwest and contributed to rapid location of the lander in Viking orbiter images. Color mosaic is made of 24:1 compressed red filter and 48:1 green and blue images.

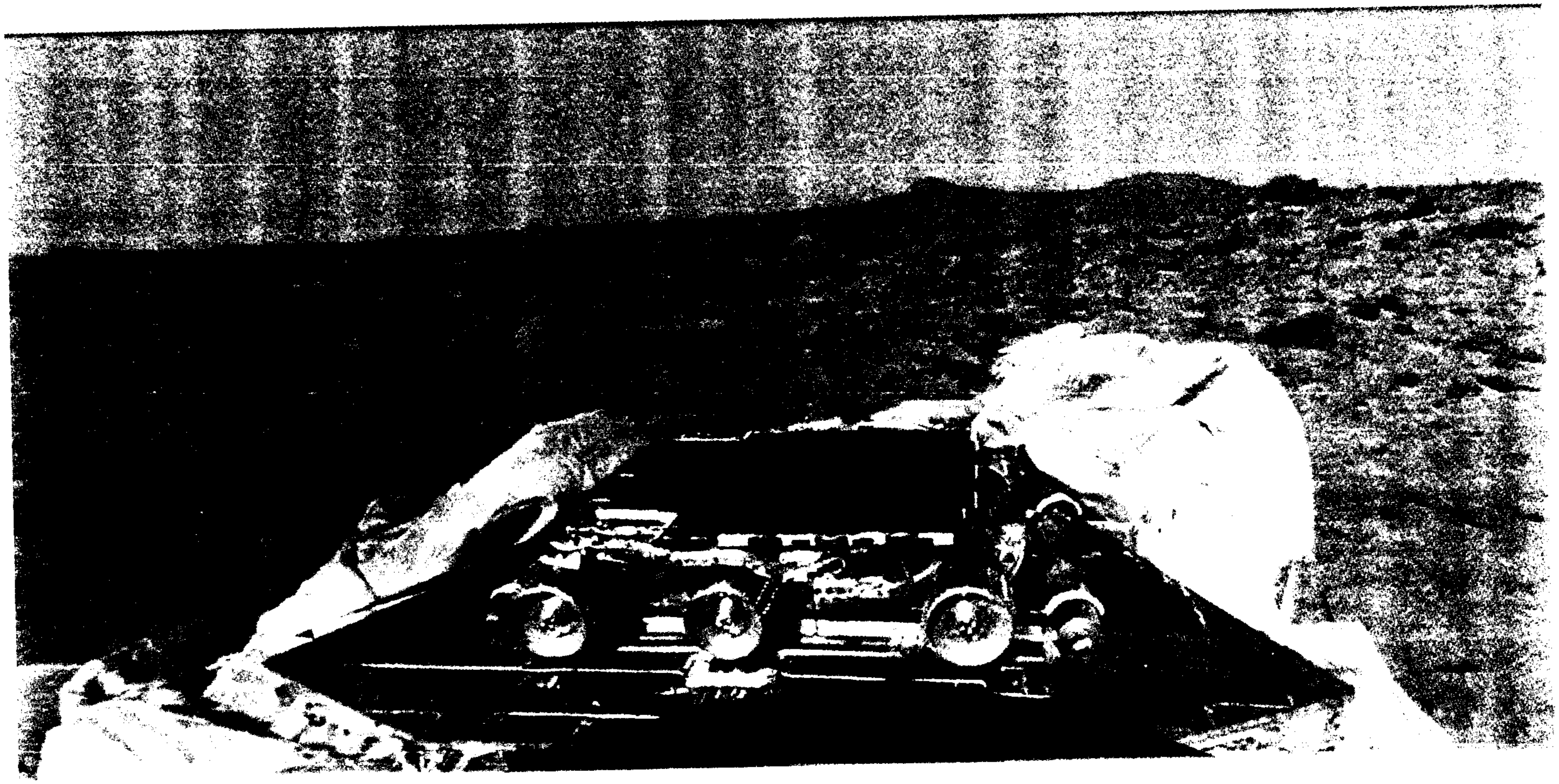
Fig. 2. Image of lander on Mars taken from rover left front camera on sol 33. The IMP (on the lattice mast) is looking at the rover. Airbags are prominent and the meteorology mast is shown to the right. Lowermost rock is Ender, with Hassock behind it anti Yogi (Plate 6) on the other side of the lander. JPL logo is visible on the side of the electronics box, adjacent to the American flag.

Fig. 3. Lander image of rover near The Dice (three small rocks behind the rover) and Yogi (Plate **6)** on sol **22.** Color (red, green and blue filters at 6: I compression) image shows dark rocks, bright red dust, dark red soil exposed in rover tracks, and dark (black) soil. The APXS is in view at the rear of the vehicle and the forward stereo cameras and laser light stripers are in shadow just below the front edge of the solar panel.

Fig. 4. Mosaic of Ares Vallis showing different landing ellipses, with color insert of the Chryse Planitia region of Mars showing the outflow channels. The large blue ellipse (100 by 200 km) to the northwest is an ellipse in the USGS cartographic reference frame *(4)* designed to avoid streamlined islands to the south and east, craters to the north, and etched terrain to the west (this ellipse is shown in the color insert). The large yellow ellipse (100 by 200 km) displaced towards the southeast (by 20 km in longitude and 8 km in latitude) is the navigation target ellipse in the revised local cartographic reference frame (which are the latitude and longitude shown in the figure, 5). The elongate light blue ellipse (98 km by 19 km) is the navigation prediction as of late July 3rd and early July 4th; it includes part of the streamlined island in the southwest. The smallest (gold) ellipse (15 by 8 km) is the prediction with tracking through atmospheric entry. The second smallest, pink ellipse (41 by 15 km), which encloses the smallest ellipse (and the location of the lander), is the navigation result with dispersions added for atmospheric entry and descent. The blue X is the location of the lander with respect to surface features identified in Viking orbiter images (located at 19.33°N, 33.55°W in the local reference frame of 5). The location of the lander in inertial space (19.30°N, 33.52°W) from the two-way ranging and Doppler tracking of the lander *(6)* is at the very northwest edge of the crater, just 2.2 km to the south-southeast of the X. If the location of the lander in inertial space is forced to coincide with its location with respect to surface features, then the resulting cartographic frame is actually 2 km to the south and 0.8 km to the east of the local network. Color mosaic is part of the Oxia Palus Quadrangle (MC' 11) of Mars: black and white mosaic from Viking orbiter images of 38 m/pixel resolution; north is at the top.

Fig. 5. Mosaic of Viking Orbiter images illustrating the location of the lander (19.17°N, 33.21°W in the USGS reference frame) with respect to surface features. Five prominent horizon features visible from the lander have been given the informal nicknames: North Knob,

Southeast Knob, Far Knob, Twin Peaks, and Big Crater. Two small craters arc also visible in both the orbiter and lander views, one nicknamed Little Crater, the second, nicknamed Rimshot Crater, lies on the northwest outer flank of the rim of Big Crater. Because the lander is on the southeast-facing flank of a low ridge, very distant features to the south and east are in view, whereas relatively nearby features to the north are partially or completely obscured. Only the tip of North Knob, which appears larger in the Viking Orbiter images than the Twin Peaks, projects above the local horizon, and a 300 meter crater, 1.2 km to the northeast, is completely obscured. Viking stereo images O04A27 and 004A87 and 004A44 and 004A70. North is up; I km scale bar shown. Upper right insert shows detail of lander location. Other inserts are: upper left, North Knob from lander; lower left, Far Knob from lander; lower right, Southeast Knob from lander. The location of the lander in inertial space (19.30°N, 33.52°W) from the two-way ranging and Doppler tracking of the lander (6) is coincident with Rimshot Crater. Twin Peaks can be seen in Fig. 1.



Figure

Sojourner atop

Pathfinder

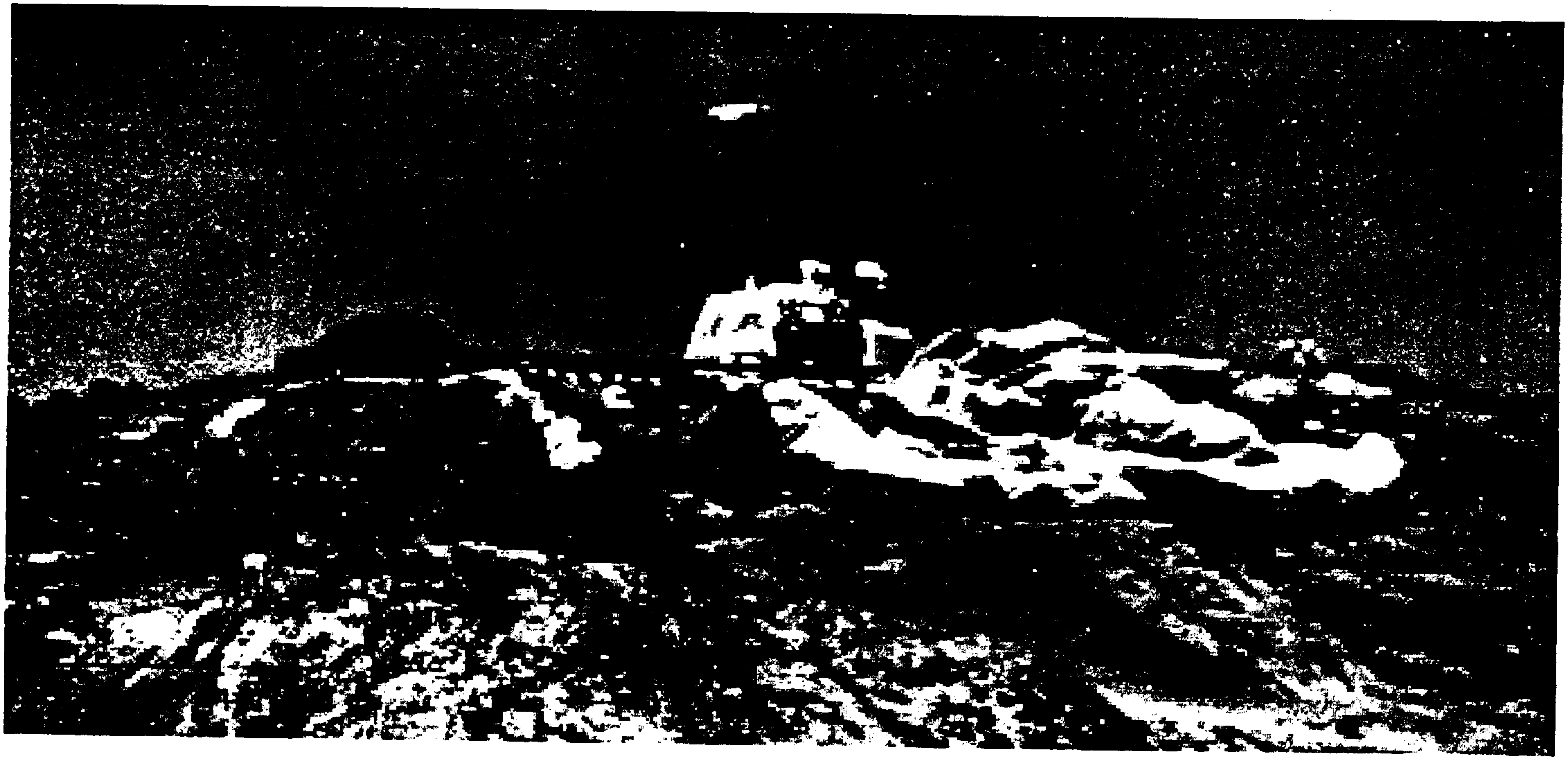


Figure 2

Golombek et al

Pathfinder

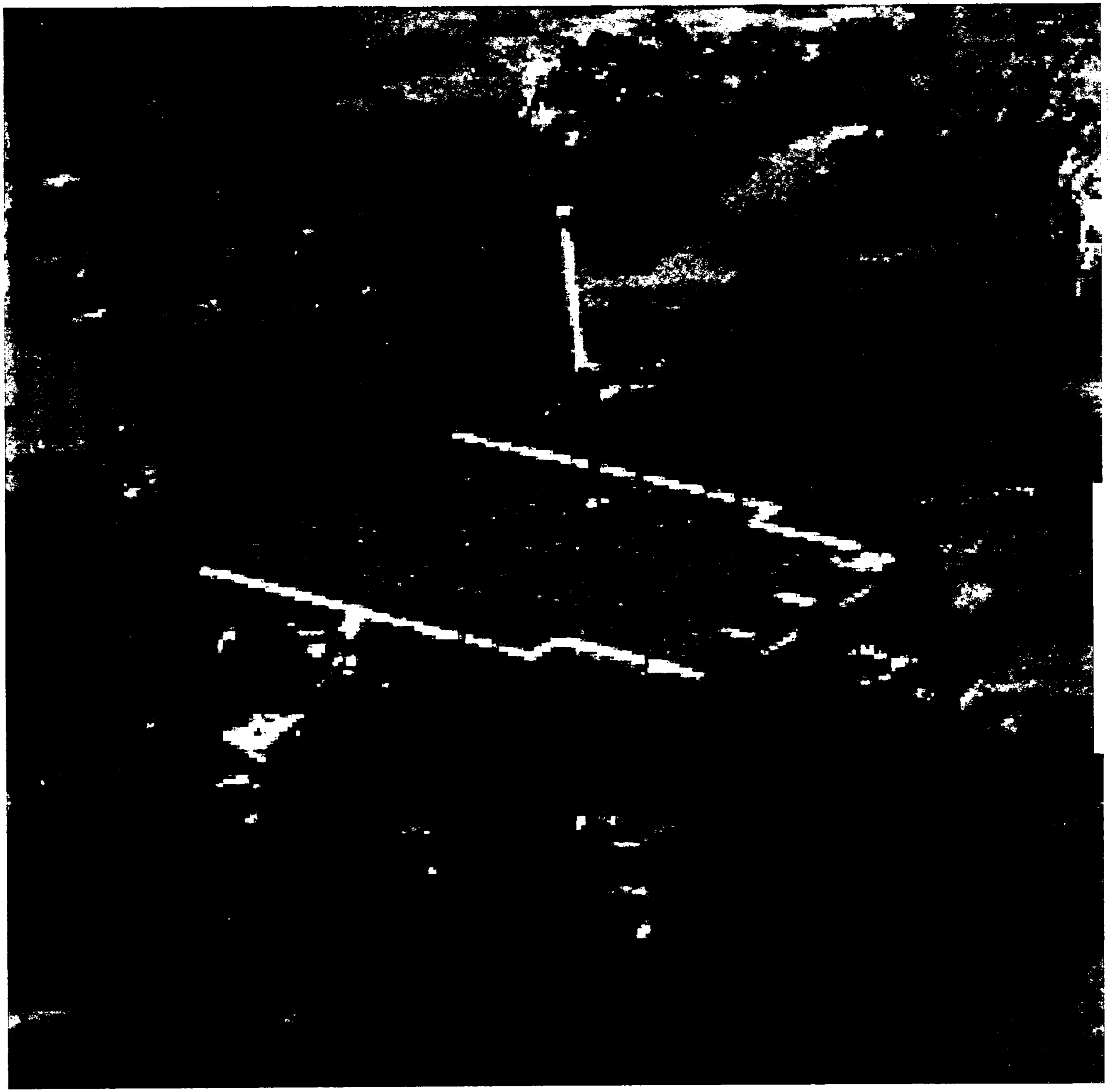


Figure 8
Golombek
et al.
Pathfinder

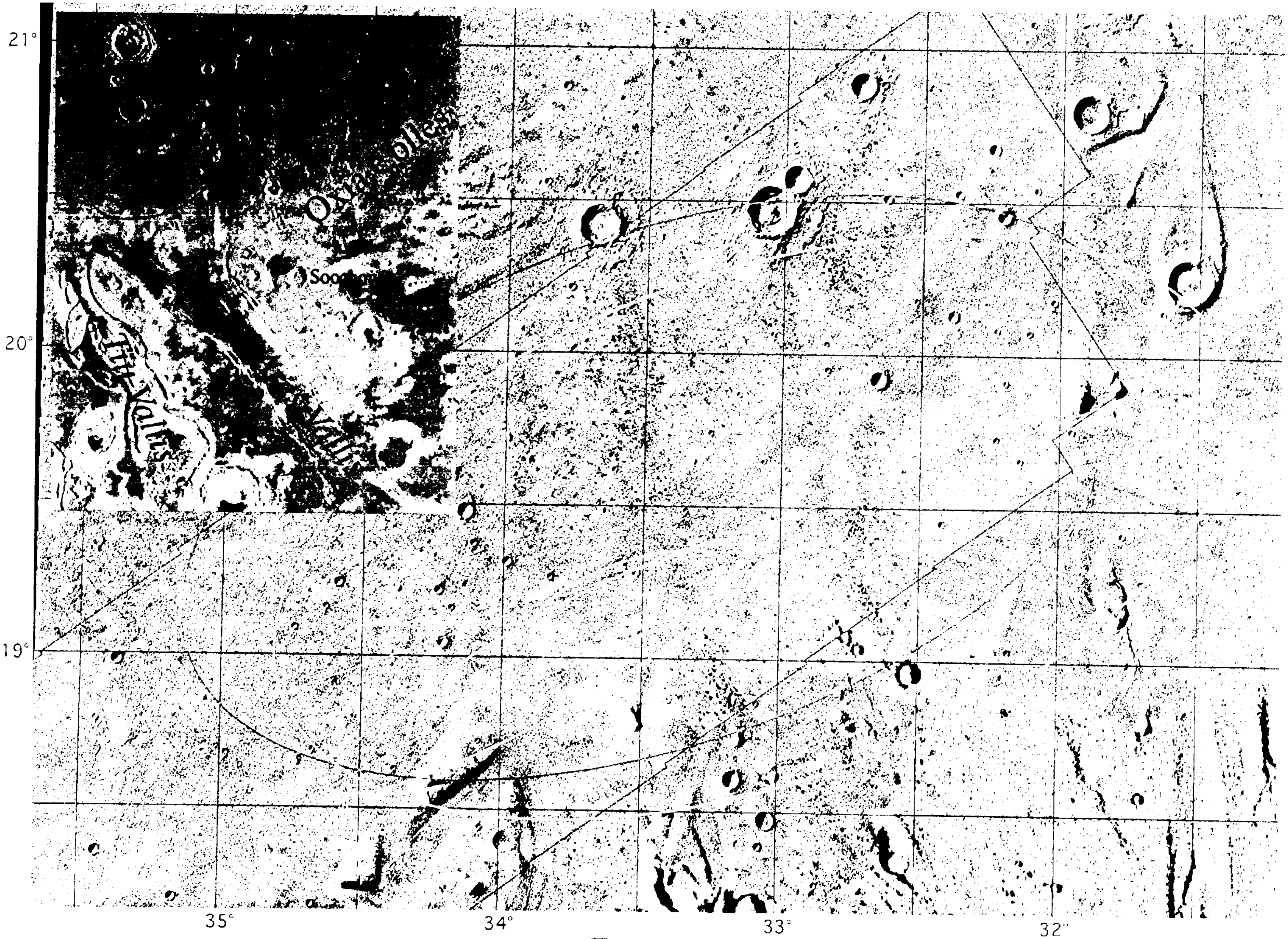


Fig 4 Golombek et a

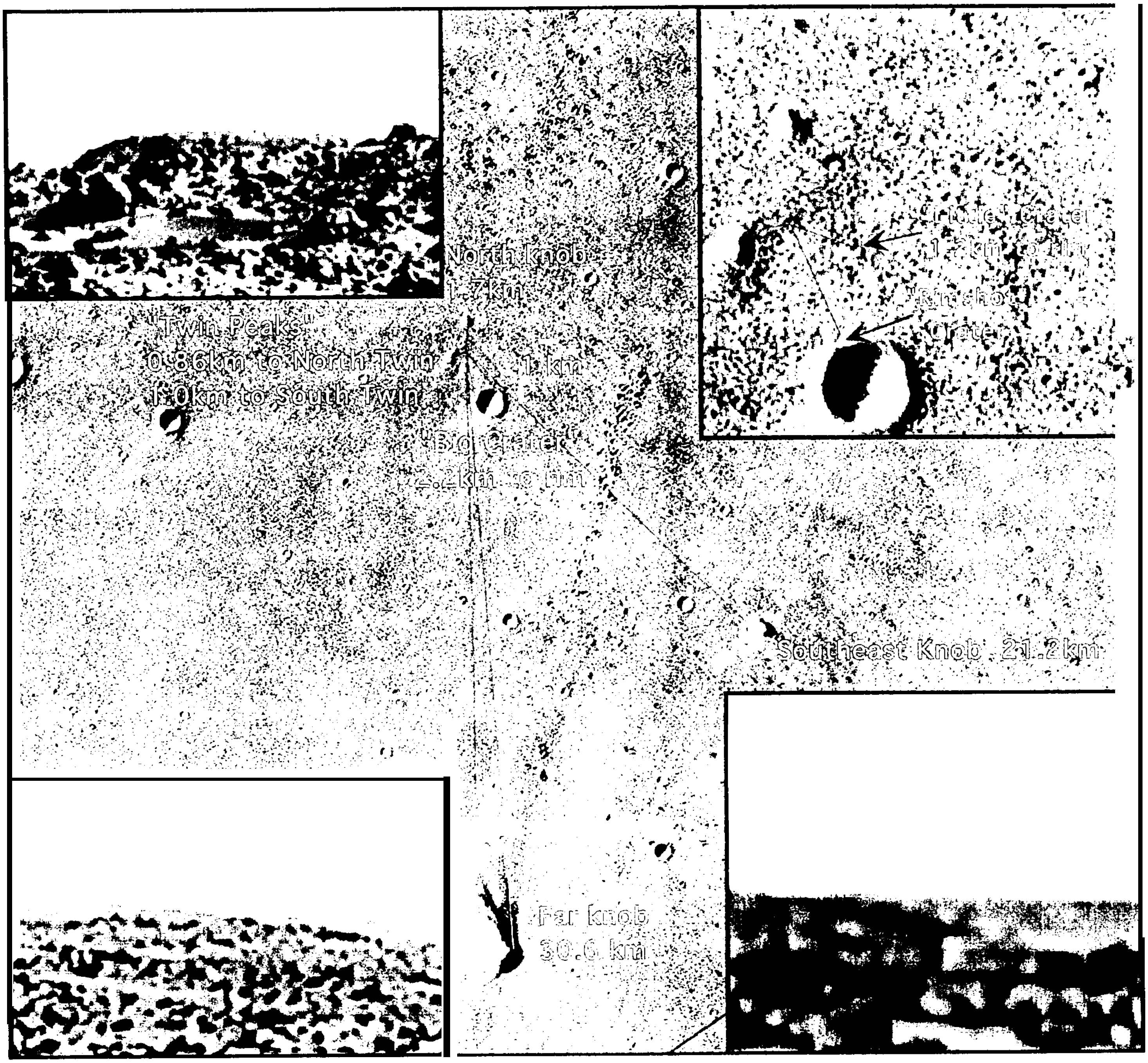


Figure 7
Golombek et al.
Pathfinder