Valley Systems on Tyrrhena Patera, Mars: Earth-Based Radar Measurements of Slopes

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Received July 8, 1991; revised January 10, 1992

Eight new topographic profiles across the Martian volcano Tyrrhena Patera have been obtained between latitudes 20.0°S and 25.1°S from radar data collected by the JPL Goldstone Radar System in 1988. These profiles, which have a reproducible accuracy of better than 150 m, show the volcano to rise ~1.5 km above the plains of Hesperia Planum to the east, and to have an average height-to-diameter ratio of ~1:340. The maximum slopes of the flanks appear to be ~3.0°. The slopes on the northern flanks of Tyrrhena Patera (0.2 to 3.6°) bear little correlation with the width (1.7 to 5.2 km) or depth (~200 to 300 m) of valley systems found in that area. This suggests that erosion by gravity-driven flows was not responsible for valley formation and that other factors, such as spatial or temporal variations in the volume of ground water released by sapping, or strength differences in the materials comprising the surface units of the volcano, controlled the geometry and locations of the valleys. © 1992 Academic Press, Inc.

I. INTRODUCTION

Tyrrhena Patera (21.5°S, 253.2°W) is one of several heavily dissected volcanoes in the southern highlands of Mars (Peterson 1978, Plescia and Saunders 1979, Greeley and Spudis 1981). Recent geologic mapping by Greeley and Crown (1990) suggests that the volcano is composed of four or five principal units, the oldest and most areally extensive of which are thought to be ash flows on the basis of their morphology and erosional characteristics. Tyrrhena Patera and the other highland patera may represent the earliest examples of central-vent volcanism on Mars, and may reflect a transition from flood-style eruptions to activity from individual vents relatively early in the preserved history of Mars (Greeley and Spudis 1981, Scott and Tanaka 1986). Like several other Martian volcanoes (e.g., Hadriaca and Apollinaris Paterae, Hecates Tholus), Tyrrhena Patera lacks prominent lava flows on its flanks, but is instead dissected by a valley system.

Tyrrhena Patera offers the best opportunity to investigate the influence of local slopes on the development of the valleys, because it has the most evolved valley system of any Martian volcano (Reimers and Komar 1979, Gulick and Baker 1990). One currently favored model for the formation of the flanks of the volcano involves the emplacement of gravity-driven pyroclastic flows (Greeley and Crown 1990). The runout distances of these volcanic flows, and the azimuthal symmetry of the volcano, are thought to depend on both the topography of the surrounding plains of Hesperia Planum (which define the preexisting regional slopes), and the geometry of the summit area of the volcano. To help refine our knowledge of the volcano's height and slope characteristics, and hence the mode of formation of the valleys, we have collected a new set of Earth-based radar topographic data for Tyrrhena Patera, obtained during the 1988 Mars opposition.

II. NEW OBSERVATIONS

Between August 30th and November 13th, 1988, as part of a much larger radar ranging experiment, we collected eight new topographic profiles across Tyrrhena Patera at
FIG. 1. Viking Orbiter photomosaic of Tyrrhena Patera, showing the location (white lines) of each radar profile collected in 1988 across the volcano. From top to bottom, these profiles are located at 20.0°S (August 30 and August 31, 1988), 20.2°S (September 30, 1988), 21.9°S (October 8, 1988), 22.3°S (October 7, 1988), 22.4°S (October 8, 1988), and 25.1°S (November 13, 1988). Note that, depending on the radar roughness of the surface, the elevation measurements in each profile may be derived from a point as much as 60 km on either side of the nadir ground track (Simpson et al. 1978). Dot-dashed rectangle marks the area of the northern summit shown in Fig. 3. Area of coverage extends from 16.5 to 26°S, 247 to 260.5°W. Base image is part of the digital image of Mars produced by the U.S. Geological Survey at Flagstaff, AZ.

latitudes between 20.0° and 25.1°S using the Goldstone, California radar system. Our data were obtained between longitudes 245° and 260°W at X-band (3.5 cm) for latitudes 20.0°, 21.7°, 21.9°, 22.3°, 22.4°, and 25.1°, and at S-band (12.6 cm) for latitudes 20.0° and 21.7°S (Fig. 1). These data were reduced by an abbreviated subset of the methods described by Downs et al. (1975). As is mentioned below, the accuracy of the topographic data is independent of the wavelength. In the present case, only topographic information has been extracted from the raw radar data and to date we have made no attempt to obtain reflectivity or roughness values. Details of the data reduction process are given in the Appendix.

The 1988 data have yielded elevation profile measurements relative to the 6.1-mb pressure surface of Mars with a vertical reproducible accuracy of ~150 m peak-to-peak. An example of the consistency of the data can be seen from inspection of Fig. 2. Profiles collected on two successive days (August 30 and 31, 1988) covered the same nominal ground track with X-band and S-band radar measurements. The greatest difference between the radar elevations over these independently processed tracks is about 150 m, which occurs near 256°W.

The actual location on the planet of the radar-measured value of elevation is not so simple to determine (cf., Pettengill et al. 1969, Simpson et al. 1978, Roth et al. 1989). The 1988 Goldstone measurements have a representative weighted mean spatial resolution of ~5 km in longitude and ~60 km in latitude. The data are deliberately processed to search for the highest topography in a resolution
FIG. 2. (A) Perspective view of the 1988 radar-derived topographic profiles across Tyrrhena Patera between 248° and 258°W. Radar measurement cell size is ~6 km in longitude and ~60 km in latitude (see text and Appendix for a discussion of the derivation of the radar footprint). (B) Same data as those presented in A except here the eight profiles are directly compared to enable elevations and longitudes to be seen more clearly.
TOPOGRAPHY OF TYRRHENEA PATERA, MARS

The 1988 radar data augment the 1971 and 1973 topographic profiles presented by Downs et al. (1975), which cross the northern flanks of Tyrrhena Patera at 17.3°, 18.2°, 18.3°, 19.8°, and 20.4°S. The 1988 data include one profile that nearly crosses the summit of the volcano at 21.9°S, as well as two other profiles somewhat further south at 22.3° and 22.4°S. From the 1988 profiles we observe that the maximum radar-measured elevation for Tyrrhena Patera is 4.7 km above the 6.1-mb datum at 21.9°S, 253.9°W (Fig. 2B). Moving away from the summit caldera (which we take to be ~44 km in diameter and bounded by the circumferential fracture), the radar-derivative mean slopes for the upper flanks of the volcano are ~1.2° over a distance of ~40 km to the east and ~0.6° for a distance of ~60 km west of the summit. The preexisting plain on which the volcano was constructed is interpreted to start east of Tyrrhena Patera at 250°W (which is the break in slope when the profile is measured at 21.9°S and 22.3°S). To the west of the volcano, the boundary between the volcano and the surrounding plains is less clear due to the gradual slope that extends to ~258°W at 21.9°S. From our inspection of the radar profiles taken at 20.0°, 20.4°, and 21.9°S (Fig. 2B) we interpret the summit to be at 255°W. At 21.9°S, the eastern plain is ~0.4 km lower in altitude than the plain on the western side of the volcano (~3.1 km above datum compared to 3.5 km above datum). The maximum height variation as one ascends the volcano on the eastern flank is ~1.5 km along the profile at 21.9°S between 250° and 254°W (Fig. 2B). This gives an average flank slope of ~0.43° over a distance of 220 km.

To the west of the summit, the change in elevation is ~1.1 km over a distance of 220 km (average slope 0.30°) between 254° and 258°W. Although the center-line profile of our measurements does not exactly cross the central portion of the summit caldera (Fig. 1), the radar echo is most probably obtained from one of the highest points on the caldera rim, based on the arguments presented above. At latitude 21.9°W (the closest profile to the summit) we infer Tyrrhena Patera to have a height-to-diameter ratio of ~1:340 (mean height ~1.3 km, basal diameter ~440 km). This value compares to 1:25 to 1:56 for shields in the Tharsis region (e.g., Olympus, Ascaerus, and Pavonis Montes) and 1:240 for Alba Patera (Schaber 1991). Our radar topography measurements thus confirm earlier stereogrammetric data of the volcano (U.S. Geological Survey, 1989), which indicate that Tyrrhena Patera is a low-relief and broad shield constructed on relatively flat plains materials.

A radar profile at 18.2°S obtained by Downs et al. (1975) shows that the Hesperia Planum ridged plains to the north of the volcano are almost flat at a mean elevation of ~3.2 km above the datum of 6.1°S. One of the 1988 profiles, taken at 25.1°S (Fig. 2B), shows that the plains to the south of Tyrrhena Patera are at an elevation of 2.9 km. Taking the summit of the volcano to be at 21.9°S, 253.9°W, the average gradient from the summit heading 215 km due north is 0.4°, compared to 0.6° from the summit heading 185 km due south. These values can be compared directly to two slope estimates of Greeley and Crown (1990) that were made from the 1:15M topographic map of Mars (U.S. Geological Survey, 1989); their slope “C”, which they estimated to be 0.2° and we measured to be 0.4°, and their slope “D”, which was estimated to be 0.4° and we measure as 0.6°. We can also approximate the measurement of slope “F” of Greeley and Crown (1990), which they estimated to be 0.2° and is corroborated by the 1988 radar data to be 0.2°.

III. EROSION SURFACES ON TYRRHENEA PATERA

Use of four closely spaced radar profiles collected in 1973 and 1988 between 19.8° and 20.4°S enables us to investigate the slopes of the deeply dissected flanks of Tyrrhena Patera (Fig. 3). Numerous valleys are found on the flanks of the volcano (Greeley and Spudis 1981, Gulick and Baker 1990), extending for more than 150 km away from the summit in certain cases. These valleys typically have widths of ~2 to 3 km and, by comparison with the summit caldera scarp (measured by Robinson (1990) to be ~400 m high), are interpreted to be as deep as ~200 to 300 m.

The new radar data enable us to measure the gradients for several representative valleys on the volcano. These data show that the slopes of the surfaces in which the valleys have been carved are typically ~0.5° over horizontal distances of 25–50 km (Table 1). The steepest slopes calculated are 1.0° for a 35-km segment (5 in Fig. 3b) and 3.0° for a 13-km segment of the northern flanks (4 in Fig. 3b). These values compare to the 0.1°–0.4° slopes estimated for Tyrrhena Patera over distances varying from 304 to 634 km (Greeley and Crown 1990). Our results also compare favorably to the photoclinometric measurements of Robinson (1990), who determined a maximum slope of 3.6° ± 0.5° for the eastern flank of Tyrrhena Patera at ~21.9°S. From the radar data, we find no obvious difference in the slopes of valleys that are either deeply incised (slope of 0.7°) or relatively shallow (slopes be-
FIG. 3. (A) Location of radar profiles (dashed lines) at 19.82°S (November 1, 1973), 20.0°S (August 30, 1988), 20.2°S (September 8, 1988), and 20.4°S (November 5, 1973) across the northern flanks of Tyrrhena Patera. Slope estimates for the flanks (Table 1) were derived from these radar profiles. This is a geometrically rectified version of Viking Orbiter image 87A14, provided by M. Robinson. (B) Geomorphic sketch map of units on the northern flanks of Tyrrhena Patera, showing prominent valleys (open outlines), shallow valleys (dashed), and the locations of the radar-derived slopes (dashed lines number 1 to 6 are keyed to Table 1). Two erosion surfaces (the two different shadings) exist on the flanks of the volcano. Closed circles with inner barbs mark locations of prominent impact craters.
The primary mechanism by which the valleys were carved, for the Tyrrhena Patera volcanoes, is unlikely to be a valid model of dissection by the decrease in sediment load. In channels with cohesive banks and no marked downstream variation in bank erodability, the downstream rate of width increase has been found by Knighton (1974) to be principally a function of discharge, while at a single site the rate of change of channel morphology was largely controlled by bank material composition (particularly the silt-clay content). At Tyrrhena Patera and, possibly, other Martian highland volcanoes, we therefore infer that the degree of dissection of the flanks may thus be related less to the local slopes than to other physical properties of the materials (e.g., degree of welding, stratification, or postplacement fracturing) that compose the volcano. Further work involving the radar scattering properties of the surface (i.e., the 1971 and 1973 C-factor and radar reflectivity values; Downs et al. 1975) and quantitative measurements of valley depths from photoclinometry (Robinson 1990) may permit such relationships to be investigated in the future.

### IV. CONCLUSIONS

The 1988 Mars Opposition provided the opportunity to collect new topographic information for the volcano Tyrrhena Patera, permitting the slopes of valleys on the flanks to be investigated in detail for the first time. Using these radar data we have confirmed that the volcano has present Martian conditions, but Gulick and Baker (1990) have recently suggested that some Martian volcanoes may once have been snow-capped, thereby providing a potential source of water if the snow was present at the start of an eruption.

Although the details of groundwater sapping in any specific environment on Earth are not fully understood (but see Kochel and Piper (1986) for a discussion of Hawaiian valleys formed by sapping, and their attempts to model this process in the laboratory), the Tyrrhena Patera valleys have at least two base levels, and this implies a complicated internal structure to the volcano with respect to the groundwater system. Dikes or impermeable layers of welded ash are believed to generate perched water tables in Hawaiian volcanoes (Stearns and Macdonald 1946), and multiple base levels for sapping may also have been generated by multiple episodes of activity at Tyrrhena Patera. Because these impermeable layers need not bear a relation to the gradient of the surface, it is therefore not surprising that the valleys with the greatest degree of dissection are not correlated with the steepest slopes. During the surface flow of water, the morphology of a channel carved in sediment reflects the strength of the bed and bank materials, which in turn is influenced by particle size, shape, and cohesion (James 1991). For a specific terrestrial channel carved in mining sediment, the rate of incision was found by James (1991) to be encouraged by increased topographic gradients and by the decrease in sediment load. In channels with cohesive banks and no marked downstream variation in bank erodability, the downstream rate of width increase has been found by Knighton (1974) to be principally a function of discharge, while at a single site the rate of change of channel morphology was largely controlled by bank material composition (particularly the silt-clay content). At Tyrrhena Patera and, possibly, other Martian highland volcanoes, we therefore infer that the degree of dissection of the flanks may thus be related less to the local slopes than to other physical properties of the materials (e.g., degree of welding, stratification, or postplacement fracturing) that compose the volcano. Further work involving the radar scattering properties of the surface (i.e., the 1971 and 1973 C-factor and radar reflectivity values; Downs et al. 1975) and quantitative measurements of valley depths from photoclinometry (Robinson 1990) may permit such relationships to be investigated in the future.

### TABLE I

Slopes for Representative Erosion Surfaces on the Northern Flank of Tyrrhena Patera

<table>
<thead>
<tr>
<th>Slope</th>
<th>Min. width (km)</th>
<th>Slope (deg)</th>
<th>Measured length (km)</th>
<th>Relative depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.2</td>
<td>0.3</td>
<td>62</td>
<td>Medium</td>
</tr>
<tr>
<td>2</td>
<td>3.9</td>
<td>0.2</td>
<td>32</td>
<td>Shallow</td>
</tr>
<tr>
<td>3</td>
<td>N/A*</td>
<td>0.4</td>
<td>24</td>
<td>Shallow</td>
</tr>
<tr>
<td>4</td>
<td>2.6</td>
<td>3.0</td>
<td>13</td>
<td>Medium</td>
</tr>
<tr>
<td>5</td>
<td>5.2</td>
<td>1.0</td>
<td>34</td>
<td>Shallow</td>
</tr>
<tr>
<td>6</td>
<td>1.7</td>
<td>0.7</td>
<td>45</td>
<td>Deep</td>
</tr>
</tbody>
</table>

* Location of each measured slope is given in Fig. 3b.

Relative depth is a qualitative assessment of the average depth of the valley over the measured slope. This depth estimate is based on the length of shadows apparent on Viking Orbiter image 87A14.

Erosion surface No. 3 is a spur between two valleys. The minimum widths of these valleys are 2.8 km and 3.1 km.

tween 0.2° to 1.0°). Indeed, the steepest slope (3.0°) is associated with a valley that is of average width and depth (Slope 4, Table I).

The lack of correlation between valley slope and degree of dissection indicates that the dissection was not strongly dependent on the slope of the volcano. This observation raises the question of the mode of formation of the valley systems on both Martian and terrestrial volcanoes. Several alternative mechanisms exist for the formation of valleys on volcanoes: (1) scouring during the emplacement of lava flows or pyroclastic flows; (2) erosion during the emplacement of mudflows (lahars); or (3) down-cutting during the release of water by sapping. Although few quantitative data for any of these three processes exist for terrestrial volcanoes, some general characteristics can probably be extrapolated to Mars. We consider that erosion of the flanks by volcanic density currents similar to the kind proposed by Reimers and Komar (1979) is unlikely to be a valid model for the Tyrrhena Patera valleys. Were density currents the primary mechanism by which the valleys were carved, preferential channeling of the flows down the steepest sides of the volcano should have occurred since, by analogy with terrestrial density currents (Sparks et al. 1978), we would expect these flows to be controlled by near-vent topography. For lahars formed during the 1984 eruptions of Mayon Volcano, Philippines (Rodolfo 1989), preexisting topography had little initial influence on the path of the flows, but once a channel was established the lahars were highly erosive and down-cut their channel, generating more than 50% of their solid content through erosion. In the terrestrial case, lahars are most often generated by eruptions on snow-capped volcanoes (e.g., Nevado del Ruiz; Naranjo et al. 1986) or by tropical rainfall (Mayon Volcano; Rodolfo 1989). Neither of these mechanisms appear likely under
an average elevation of ~1.3 km above the surrounding plains of Hesperia Planum. Compared to volcanoes in the Tharsis and Elysium regions of Mars (Pike and Clow 1981, Schaber 1991), Tyrrhena Patera is a lower-relief shield that is steeper to the south and east than to the north and west. We note that the southern side of the volcano is the direction in which most of the late-stage effusive activity has been directed (Greeley and Crown 1990), suggesting the possible role that the topography of the volcano, or the underlying slope, has played in the location of recent activity and the distribution of relatively young lava flows. However, we find no obvious explanation for the nonsymmetric distribution of the valleys on the eastern and norther flanks, where similar slopes should have promoted the formation of valleys of comparable dimensions.

Analysis of the radar profiles on the northern flank of the volcano shows that the depth and width of the valleys in this area are independent of the local topographic slope at a horizontal scale of 10 to 50 km. This independence suggests that scouring (by, for instance, volcanic density currents) was not responsible for the formation of the valleys. Because of this lack of correlation between valley dimensions and slope, a plausible alternative erosional process may be groundwater sapping at the upper elevations of the volcano, with the volume of the water released responsible for the width and depth of the valley. In part, the degree of incision of the valleys may be controlled by the physical properties of the materials comprising the volcano, or by the internal structure (e.g., the location and orientation of dikes). This groundwater sapping model is consistent with the occurrence of amphitheater headwalls at the up-slope ends of the valleys on Tyrrhena Patera (Gulick and Baker 1990); headwalls on Mars with this morphology are believed to be a product of groundwater sapping (Howard et al. 1988).

Much remains to be learned about the physical nature of the flanks of Martian highland volcanoes such as Tyrrhena Patera, particularly the spatial variations in the strength of the materials from which the flanks were constructed. Some valleys may be unusually deep compared to other shallower valleys because they were carved in less consolidated materials. Such an idea is supported by the observation of layering in the deposits surrounding the summit of the volcano (Greeley and Crown 1990), which may indicate the existence of multiple flow units or cooling units in ash deposits that could have different mechanical strengths. Related issues are the structure of Tyrrhena Patera and the type(s) of eruptions that produced the edifice. A hydromagmatic origin is favored by Greeley and Crown (1990), although the radar topography data show that the volcano is nonsymmetric in shape. This asymmetry may be due either to the nonuniform growth of the volcano or to its subsequent modification by tectonism. We favor a nonsymmetric mode of formation due to the lack of landslide deposits or tectonic features (wrinkle ridges to the east and/or graben to the west) that would be expected to form if deformation has taken place. Modeling the effects of, for instance, the geometry of the summit caldera on the flow and erosional characteristics of various volcanic flows (e.g., Wilson and Heslop 1990) may also help explain the areal variations in the morphology of the volcano and further constrain the models of origin and evolution. Such analyses may have to await the derivation of local topography at a higher spatial and vertical resolution than can be achieved with Earth-based radar measurements. We therefore expect that the new kilometer-scale information on the topography derived from the upcoming Mars Observer Laser Altimeter (MOLA) will be crucial for refining such models of the evolution of Tyrrhena Patera and the other highland paterae on Mars.

APPENDIX—RADAR TOPOGRAPHY DATA PROCESSING

All the radar topography measurements described here were made using standard range-Doppler radar methodology. A pseudorandom pulse-coded signal was transmitted, having 6-µsec bauds with 60 bauds per code cycle, resulting in a mapped frequency width (at X-band, 8495 MHz) of 2645.5 Hz on the planet, equivalent to about 5.51° of longitude. The frequency window for the S-band measurements was approximately the same width in longitude.

The echoes were oversampled at 2 samples/baud or 128/code cycle, giving a resolution (sample spacing) of 0.043° in longitude. At X-band a range window of 37 range samples was recorded, limited by the speed of the hardware; the S-band window was twice as deep (74 samples). Echoes were sorted in range and Fourier-transformed in real time, resulting in a series of $128 \times 37$(74) range-Doppler maps of the leading edge profile of the planet. These maps were then summed for $\pm 5$ sec and the resulting $128 \times 37$(4)-pixel map written to tape. The output maps were monitored by the telescope operators and the time-delay of the range window adjusted manually to keep the leading edge of the planet properly located within the window.

The processing of these data into elevation profiles was carried out on the JPL Radar VAX in Pasadena. In a single range-Doppler map the center column gives the echo strength profile as a function of range for the sub-Earth longitude on the planet, and similarly the 63 columns to either side give profiles for earlier and later longitudes. Each recorded map was disassembled into fixed-longitude columns and the time-delay corrected to an assumed spherical planetary surface. For each column the peak echo strength was noted and the elevation was calculated from the time of the earliest echo that is >0.3 times the peak. Columns with low signal/noise were rejected.

Successive maps for that day's observations were processed in this way and then sorted into 0.05° longitude bins. Finally, the mean elevation for each longitude was calculated, referred to the 6.1-mbar datum for Mars, and stored. Refinements of this processing scheme are possible, wherein column data are weighted for their distance from the center of the longitude bins, and a more elaborate fitting procedure can be attempted for determining the elevation in each map column. However, the current data appear to be in good agreement with previous (1971 and 1973) radar results, where there are overlapping measurements.

ACKNOWLEDGMENTS

We thank Mark Robinson for his thoughtful and pertinent comments and suggestions on an earlier version of this manuscript. Mark Rob-
inson also processed the Viking Orbiter mosaic used in Fig. 1, using
digital data supplied by the Astrogology Branch, U.S. Geological
Survey, Flagstaff, AZ. Formal reviews by David Crow and an
anonymous person are also acknowledged. This paper presents
the results of one phase of the research carried out at the Jet Propulsion
Laboratory, California Institute of Technology, under contract with
NASA. Support to S.H.Z. came from JPL Contract 598601, and to
P.M.M. under NASA Grant NAGW-437 from the NASA Planetary
Geology and Geophysics Program. This is Planetary Geosciences
Paper No. 676 and the School of Ocean and Earth Science and
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