Ancient and modern slopes in the Tharsis region of Mars

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The directions of lava flows in the Tharsis region of Mars are used to identify regional palaeo-slopes, vent areas and local topography. A comparison is made between these flow directions and the present day radar-measured topography; good agreement between these data sets indicates that little intra-regional tectonic deformation has occurred following the emplacement of the preserved lavas.

As the youngest centre of constructional volcanism on Mars, the Tharsis region has been the focus of considerable attention directed towards gaining an understanding of the geophysical, geochemical and volcanological evolution of the area. Debate has centred on the relative importance of regional tectonic uplift versus constructional volcanism as the primary mechanism for the production of the observed relief, together with the attendant implications that such hypotheses would hold for lithospheric structure and crustal–mantle petrology. Until recently, it was believed that the centre of the broad Tharsis dome was located close to the three Tharsis Ridge volcanoes, where the surface rose to nearly 10 km above the martian datum. New Earth-based radar measurements have shown, however, that Tharsis is much lower on average, with the mean elevation only 2–4 km above the 6.1 mbar reference surface. In addition, the centre of the dome is evidently located further to the south-east than previously believed and is now centred on Syrtis Planum.

Nevertheless, considerable local topography (including numerous volcanic constructs) exist within Tharsis by virtue of the many outpourings of lava which characterize the area. As a consequence of the changing lithospheric load associated with this volcanic activity, deformation of areas such as the base of Olympus Mons would be expected if the lithospheric thickness was >150 km (ref. 13). In an attempt to search for recent tectonic deformation of this kind within Tharsis, we compare here the ancient slope directions (deduced from the orientations of lava flows) with the present-day slopes (derived from Earth-based radar measurements). Due to their propensity to flow parallel to the direction of slope, the eruptions of lava provide information on the characteristics of the local topography at the time of flow emplacement. In addition, the travel directions and areal extent of the flows can be used to describe further the nature of the volcanic activity within Tharsis because they permit the different eruptive centres and their relative volumes of lava to be recognized.

Flow measurements

Individual lava flows within Tharsis were mapped either from high resolution (20–150 m per pixel) Viking Orbiter images or from the new medium resolution (200 m) orthophotomosaics prepared by the US Geological Survey. The positions of these lava flows are shown in Fig. 1, with the exception of those flows which are located on the high flanks of the shield volcanoes. A few flow units in addition to those mapped may also exist, particularly to the west of Ulysses Patera and north of Noctis Labyrinthus, where only poor photographic coverage exists due to atmospheric opacity; some lobate flow edges are visible in these regions, but the boundaries cannot be traced for sufficient distances to infer their direction of travel.

Fig. 1 Distribution of all lava flows included within this analysis. Length of arrow is equal to the length of the lava flow and shows the direction of travel. Volcanoes are shown in black where: ARM, Arsia Mons; ASM, Ascraeus Mons; BP, Biblis Patera; CT, Cerberus Tholus; JT, Jovis Tholus; OM, Olympus Mons; TT, Tharsis Tholus; ULP, Ulysses Patera; UP, Uranus Patera; UT, Urranias Tholus. Also shown are the highland boundary in Memnonia (lower left), Valles Marineris, the Olympus Mons aureole (north-west of the volcano) and Echus Chasma (EC).
A total of 475 lava flows longer than 20 km have been mapped (Fig. 1). These flows have typical widths of 5–10 km on the higher slopes of the volcanoes and 15–35 km on the lower flanks. Additional lava flows that spread out over wide areas and have widths greatly in excess of 40 km were deliberately excluded from this analysis because they were deemed unsuitable for the determination of their flow directions. In certain instances, particularly to the west of Arsia Mons, this has also proved difficult to map the total extent of each flow, since many flow segments are either partially buried by superposed younger units or their boundaries have become indistinct as more subdued relief is encountered close to their vents. Thus, while the flows measured here rarely exceed 200 km in length, previous estimates of 300–400 km appear to be quite plausible\(^4,15\), while flow length maxima of ~1,000 km may also be possible for fissure eruptions originating at low elevations. For the flows included with this analysis, independent estimates of the flow thicknesses made from shadow measurements\(^4\) indicate values between ~5–20 m for the steeper slopes and ~20–65 m for the generally flatter surrounding terrain.

The map of Tharsis lava flows (Fig. 1) enables both the regional slopes and the individual eruptive centres at the time of flow emplacement to be recognized. In agreement with the general observations of Schaber et al.\(^6\), our analysis shows that the major palaeo-slope within Tharsis was down towards the north-west, with a high point present between Arisia and Pavonis Montes and a low located near to Olympus Mons.

From the distribution of the flows, the linear extent of this north-west slope was at least 2,500 km, and there were also downhill gradients which extended away from Pavonis and Ascareus Montes towards the north-east for 2,000 km, south-east from Syria Planum for 1,200 km and westward from Arsia Mons for ~1,000 km. While most of the flows originated from the four major shield volcanoes\(^14,16\), additional lava flows were erupted in areas which lack obvious volcanic constructs (Fig. 1); Syria Planum and an area to the west of Ceraunius Fossae (25°N, 110°W) are two such examples. In these localities, several small cones of probable volcanic origin exist\(^17\), but their significance as source regions for large volumes of magma had not previously been recorded. Lava flows >100 km in length originate from each of these two areas, indicating the existence of well-developed fissure systems which were distinct from the conduits which supplied the magma to the major volcanoes.

**Local deformations**

In addition to illustrating the regional slopes within Tharsis, the orientations of the lava flows permit deformational features on a scale of a few hundred kilometres to be identified. Prominent amongst these is a circumferential depression, or peripheral trough, which surrounds the southern half of Olympus Mons\(^11\). Extending to distances of 300–350 km beyond the basal escarpment of the volcano, this depression has acted as a funnel to redirect lavas which consequently either flowed northward towards Arcadia Planitia or westward towards Amazonis Planitia. Segments of the aureole material to the east of Olympus Mons have been emplaced and partially buried by lavas from both central Tharsis and Olympus Mons, while the much more extensive portions of the aureole to the north and west of the volcano, despite being down the regional slope\(^12\), have remained unburied. From our investigation of the preserved record of volcanic activity, none of the lava flows erupted from Olympus Mons contributed to the lava pile which now constitutes central Tharsis (such as the area around Biblis and Ulysses Paterae); all the lava flows from the volcano travelled either to the north or west. This implies that the peripheral trough around Olympus Mons has been in existence for an extended period of time, rather than being a relatively recent response to crustal loading by the volcano after most of the lavas had been emplaced.

In contrast to Olympus Mons, the other three Tharsis shield volcanoes are noteworthy for the lack of preserved deformational features within the surrounding plains materials. A slight topographic rise ~330 km west of Ascraeus Mons, together with the tangential flow direction of lavas at the base of the volcano, suggest that a local depression may exist around this volcano, although subsequent infilling by lavas makes this identification uncertain. No similar evidence exists from the orientations of preserved lava flows for depressions around either Arisia or Pavonis Montes; flows from these two volcanoes travelled in almost radial directions from the summit calderas and adjacent fissure zones.

Only one example of surface deformation after lava flow emplacement can be found in the Tharsis region. To the north-east of the Olympus Mons peripheral trough, relatively old lava flows from the south-east have been partially buried and modified by more recent volcanism. In one instance, a sinuous lava channel was formed along a radial directed towards Olympus Mons and this lava channel contains the old flows almost at right angles to the original flow direction (Fig. 2). Our interpretation of this dual flow direction is that after their emplacement, the older flows were tilted towards the south-west before the formation of the lava channel. Lithospheric loading of the area by the continuing construction of Olympus Mons could be the cause of this tectonic movement.

**Present-day topography**

Earth-based radar measurements of elevations on Mars have recently been referenced to the 6.1-mbar pressure surface\(^11\). These data provide height information for the southern flanks of Arisia Mons and Syria Planum for latitudes 14–21°S. Data resolution for this area is ~10 km in longitude, 80 km in latitude and 100 m in altitude\(^10\). Using this radar-derived topography, it is therefore possible to compare the present day regional gradients with the observed flow directions (palaeo-slopes) to search for regional deformations which may have occurred after the cessation of the volcanic activity. Such tectonic deformation would be expected to be present if the lithosphere beneath Tharsis was thinner than ~150–180 km (refs 13, 19) due to the changing load associated with the protracted eruption of large volumes of lava\(^20,21\).

The following comparison of these present and past slopes within southern Tharsis (Fig. 3) points to a strong agreement between the two data sets. The radar elevations corroborate that a regional slope extends downward from Arisia Mons towards Memnonia; the total change in elevation amounts today to ~8 km. A slight (~500–1,000 m) high is associated with the Claritas Fossae fractures, while Syria Planum represents the
centre of a regional dome located at the western end of Valles Marineris\textsuperscript{12}. Almost all the mapped lava flows cross the present day contour lines within about 10° of the local gradient (Fig. 3). Considering that the aforementioned resolution of the radar data provides only the general characteristics of the local topography, there is also good agreement between the regional slopes and the paths of the flows (such as those associated with the "bending" of the flows south of Arisia Mons between latitudes 17°–22°, longitudes 110°–122°W). Essentially all of the observed lava flows are seen to travel generally down the present topographic gradient for their entire length. Close to the summit of Arisia Mons, however, where a parasitic shield is thought to be located\textsuperscript{23}, some flows do not follow the maximum slope. This may, on the other hand, be a consequence of the shallowness of the slopes (see below) and the relative thickness of the flows (~25 m [ref. 14]), which could have funnelled the younger flows around pre-existing units in a manner comparable to the diversion of certain terrestrial eruptions (ref. 23, p. 421).

Although the radar data set lacks sufficient areal coverage to compile a complete topographic map, scattered elevation values for parts of northern Tharsis are available\textsuperscript{11} and permit the determination of the present-day slopes north of the equator. We have measured 14 slopes within Tharsis (all of which parallel the lava flow directions for distances of 150–1,250 km using the radar data [Fig. 4]). In each case, it is evident from the slope estimates (Table 1) that the lava flows travelled along paths that are consistent with the modern down-slope directions. All the radar-measured slopes seem to be very shallow, ranging from 0.75° for the southern flanks of Arisia Mons (profile L–L') to 0.04° for a section of the Olympus Mons peripheral trough (profile C–C'). These slopes are, however, only best estimates from the radar data because each elevation estimate is an average of several measurements made within a 2° longitude sample bin\textsuperscript{11}. Typically, 7–13 measurements are included in each sample, and the resulting standard errors for the averages range from 70 to 700 m (Table 1). Over the measured horizontal distances considered here, the maximum error in the slope determination would be about ±0.17°, while typical errors would be <±0.1°. Under these circumstances, only in the case of profile C–C' could the down-slope direction of the profile change; although the absolute slopes would be different, all the remaining modern gradients are consistent with a down-slope movement of the lava flows even allowing for the resolution of the radar system.

Such a close match between the ancient and modern regional slopes indicates appreciable lithospheric stability within Tharsis. Although the absolute ages of the lava flows are not known, at least 14 distinct eruptive sequences of flows have been identified in this area\textsuperscript{14} and these surface units have large differences in their superposed crater densities\textsuperscript{21}. Crater counts give number densities ranging from 1.22 \times 10^3 to 9.08 \times 10^3 craters >1 km diameter per km$^2$ respectively for the Tharsis Montes unit 3 (tm) and Olympus Plains (op) units of Scott and Tanaka\textsuperscript{21}, suggesting a wide age range. It appears, therefore, that there was relatively little tilting of geological units during (or after) the extended period of Tharsis volcanism represented by the currently exposed lava flows. This in turn implies that the lithospheric structure beneath Tharsis was rigid enough to support the changing load associated with volcano construction, suggesting that the lithosphere may indeed have been thicker than ~130–180 km (refs 13, 19, 20).

**Volcanology**

In addition to the slope information, subtle differences in the style of Tharsis volcanism are also indicated by the distribution of the observed lava flows. From the large number of flows located between the three Tharsis Ridge volcanoes (Fig. 1), it is evident that large volumes of magma were also erupted at these localities from saddle fissures (in addition to the magma erupted from the summit calderas). Furthermore, a change in eruptive style from true shield volcanism (most of the magma erupted from near-summit vents) to flank activity (most of the magma finding egress at the saddle crests) evidently took place on both Ascreaus and Pavonis Montes late in their evolution, because no flows from their summit calderas extend across the saddle flows. Eruptions from Arisia Mons also display a similar change in vent location, with large eruptions of magma from the parasitic cone\textsuperscript{22} postdating the near-summit activity. This sequence of vent relocations for these volcanoes is at least qualitatively consistent with the inferred history of the calderas of the Tharsis volcanoes\textsuperscript{24}.

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![Fig. 3](image-url)  
Comparison of radar-derived topography and lava flow directions for the southern portion of the study area. Radar data give contours in 1-km intervals and are referenced to the 6.1-mbar pressure surface of Mars. Contours were hand drawn by P.M.M. from elevation measurements made in 1971 and 1973 between 14° and 21°S.

![Fig. 4](image-url)  
Location of the surface slopes measured from Earth-based radar data (see Table 1). Each slope is coincident with the lava flow directions shown in Fig. 1, with the downslope measurement denoted by the superscript bar. Base map abbreviations are the Ihsame as those in Fig. 1.
All the small volcanic constructs of the Tharsis region (Biblis, Ulysses and Uranus Paterae and Tharsis, Uranus, Jovis and Cenaria Tholi) show evidence of partial burial by lava flows which conform to the regional slopes identified in this analysis. The absence of minor deviations from a straight-line path, which most of the flows follow, indicates that there are no additional topographic rises within central Tharsis which could be the source of low-volcanoes. Thus, it seems that the entire sequence of lava plains in this region was constructed by a few major volcanic centres (not all of which were associated with the large shields); eruptions of masma were evidently confined to large, frequently reactivated fissure systems, rather than many small widely dispersed vents, during the period of activity presently exposed at the surface.

Comparing the size and number of the flows originating from Arisia Mons (42 > 100 km long) and Olympus Mons (3 > 100 km long) indicates that it was likely that these two volcanoes had appreciably different magma supply rates from their respective source regions. If it is assumed that these mantar shields had eruption characteristics comparable to terrestrial volcanoes (that is, lava flow length was related to magma effusion rates, the longer and more numerous flows from Arisia Mons would imply higher effusion rates than for Olympus Mons. Variations in effusion rate are also likely for different parts of Olympus Mons, because relatively long flows are only common on the eastern and southern flanks of the volcano while the aureole material to the north-western area is almost devoid of embaying lavas. Thus, the traditional view that Olympus Mons is the largest volcano in the Solar System may not be correct, because Arisia Mons does not have a larger caldera. But this analysis also appears to have higher magma effusion rates and represents a topographic high which dominates the surrounding region for radar distances >1,000 km in any direction from its caldera. In comparison to both Arisia and Olympus Mons, the mass eruption rate for individual flow fields on Pavonis (seven flows longer than 100 km) and Ascraeus (nine flows longer than 100 km) were probably intermediate between these two extremes.

Conclusions

The use of lava flow directions as palaeo-seismic indicators and Earth-based radar measurements of present topography demonstrate that little deformation of the Tharsis region has occurred over an extended period of time. Very few deformational features attributable to subsidence around the volcanoes can be recognized from the flow directions; a peripheral trough surrounds Olympus Mons and there is some evidence for a similar feature to the west of Ascraeus Mons. Only one example of surface tilting after lava emplacement has been found (to the north-east of Olympus Mons), suggesting that the increasing lithospheric load due to progressive buildup of the lava pile had little influence on local topography. It is therefore postulated that early in the evolution of Olympus Mons, the lithosphere was <150 km thick, thereby permitting the formation of the peripheral trough. For much of the period in which the preserved volcanic activity took place, however, lithospheric thickness has evidently been >150–180 km (refs 13, 19), as evidenced by the lack of local or regional deformation between the time of these eruptions and the present day.

Although regional slopes are very shallow today, if they truly reflect the gradients present at the time of volcanic activity, they nevertheless controlled lava flow distances over distances in excess of 1,000 km. In this respect, the rise associated with Syria Planum has controlled the flow directions of many of the Tharsis lavas, while Claritas Fossae was also a local high at the time that Arisia Mons was active. It is evident that the style of volcanic activity was quite diverse within the region, with fissure eruptions from the saddles between the Tharsis Ridge volcanoes contributing large volumes of lava to the surrounding plains. In this connection, it is proposed that Arisia Mons, with its extensive lava flows and great relief, should supersede Olympus Mons for the title of the largest known volcano in the Solar System.

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