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Topography of Valles Marineris: Implications for erosional and structural history

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Abstract. Compilation of a simplified geologic/geomorphic map onto digital terrain models of the Valles Marineris permitted an evaluation of elevations in the vicinity of the troughs and the calculation of depth of troughs below surrounding plateaus, thickness of deposits inside the troughs, volumes of void spaces above geologic/geomorphic units, and volumes of deposits. The central troughs north Ophir, north and central Candor, and north Melas Chasmata lie as much as 11 km below the adjacent plateaus. In Ophir and Candor Chasmata, interior layered deposits reach 8 km in elevation. If the deposits are lacustrine and if all troughs were interconnected, lake waters standing 8 km high would have spilled out of Coprates Chasma onto the surrounding plateaus having surface elevations of only 4-5 km. In this case, interior deposits above about 4 km in the central troughs would not be lacustrine. They could be volcanic. On the other hand, the troughs may not have been interconnected at the time of interior-deposit emplacement; they may have formed isolated ancestral basins. The existence of such basins is supported by independent structural and stratigraphic evidence. The ancestral basins may have eventually merged, perhaps through renewed faulting, to form northern subsidiary troughs in Ophir and Candor Chasmata and the Coprates/north Melas/Ius graben system. The peripheral troughs are only 2-5 km deep, shallower than the central troughs. They may have formed from a combination of erosional collapse and structural activity. Chaotic terrain is seen in the peripheral troughs near a common contour level of about 4 km on the adjacent plateaus, which supports the idea of release of water under artesian pressure from confined aquifers. The layered deposits in the peripheral troughs may have formed in isolated depressions that harbored lakes and predated the formation of the deep outflow channels. If these layered deposits are of volcanic origin, they may have been emplaced beneath ice in the manner of table mountains. Areal and volumetric computations show that erosion widened the troughs by about one-third and that deposits occupy one-sixth of the interior space. Even though the volume eroded is larger than the volume deposited, topographic and geologic considerations imply that material eroded from trough walls was probably part of the interior layered deposits but not their sole source. Additional material may have come from subterranean piping, from reworking of local disintegration products on the floors, such as chaotic materials, or from eolian influx. But overall it is likely that the additional material is volcanic and that it forms mostly the upper, more diversely bedded layers of the interior deposits.

Introduction

When the Mariner 9 spacecraft first glimpsed the Valles Marineris troughs, their origin became an immediate question. An erosional origin found favor with most early workers, who envisioned removal of material by thermokarst processes combined with the action of water and wind [*McCauley et al.*, 1972; *Sharp*, 1973a; *McCauley*, 1978]. However, thermokarst processes would have required unrealistically large amounts of segregated ice, whose formation would have been difficult [*Sharp*, 1973a], and slope-stability considerations rule out the presence of massive ice in the walls bordering the troughs [*Spencer and Croft*, 1986]. Therefore, the thermokarst idea was never fully accepted. Alternative origins proposed were collapse due to withdrawal of subsurface magma [*McCauley et al.*, 1972; *Sharp*, 1973a; *Schonfeld*, 1979] or collapse into voids created at depth by tension fractures [*Tanaka and Golombek*, 1989], but the first idea was never fully explained and the second has volumetric difficulties. Overall, a possible tensional tectonic origin for the chasmata as large grabens or rifts [*Sharp*, 1973a] remained a favored hypothesis because the chasmata were influenced by obvious tectonic features: they lie on the flanks of the Tharsis rise, they are radial to its center, they are paralleled by many shallow grabens, and they are bordered by straight fault scarps with triangular facets [*Blasius et al.*, 1977; *Masson*, 1977, 1980; *Wise et al.*, 1979; *Banerdt et al.*, 1982; *Plescia and Saunders*, 1982; *Sleep and Phillips*, 1985].

Interior layered deposits, like the troughs, were first recognized on Mariner 9 images, and a lacustrine origin for them was suggested by *McCauley* [1978] because of the

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great lateral extent of apparently evenly bedded layers and the cyclicity of some layers [*Nedell et al.*, 1987]. The near absence of channels flowing into the troughs, however, makes a sedimentary origin questionable unless one invokes subterranean piping or derivation of all sedimentary deposits from eroded wall materials. Because of these problems, alternative origins were also considered; foremost was the idea that the interior deposits are built of stacks of volcanic rock [*Peterson*, 1981; *Nedell et al.*, 1987; *Lucchitta*, 1990].

Overall, many problems remain concerning the Valles Marineris. This study addresses some of the problems from the point of view of elevations of surfaces, depths of troughs, areas occupied by units, and volumes of both the deposits and the void spaces above them. The surface elevations of deposits inside the troughs give clues to their thickness. The surface elevations of these deposits and those of surrounding plateaus permit inferences concerning the stand of possible former lake levels. The depth of troughs relates to their erosional or structural evolution. The areas and slopes of trough walls indicate the extent of erosional widening of the troughs and enable an estimate of the amount of material removed by backwasting. Thus one can determine whether the interior deposits came from the walls.

Method

The method used in this study had four steps. (1) We prepared a simplified geologic/geomorphic map of the Valles Marineris, transferred it to existing topographic maps, and digitized and coregistered it with the digital terrain models (DTMs) of the topographic maps. (2) We calculated areas occupied by the individual map units. (3) We calculated the depth of troughs and the volume of void spaces above individual units by obtaining the difference between the elevations of the DTMs and those of a restored surface linking contours on the adjacent plateaus across the troughs (Figure 1). The resulting "lid" reflects surface elevations of the plateaus in the vicinity. (4) We calculated volumes of interior deposits by obtaining the difference between elevations of the DTMs and those of a designated "floor" under the deposits (Figure 1). (5) Finally, we analyzed the results in regard to erosional and structural implications for the history of the Valles Marineris.

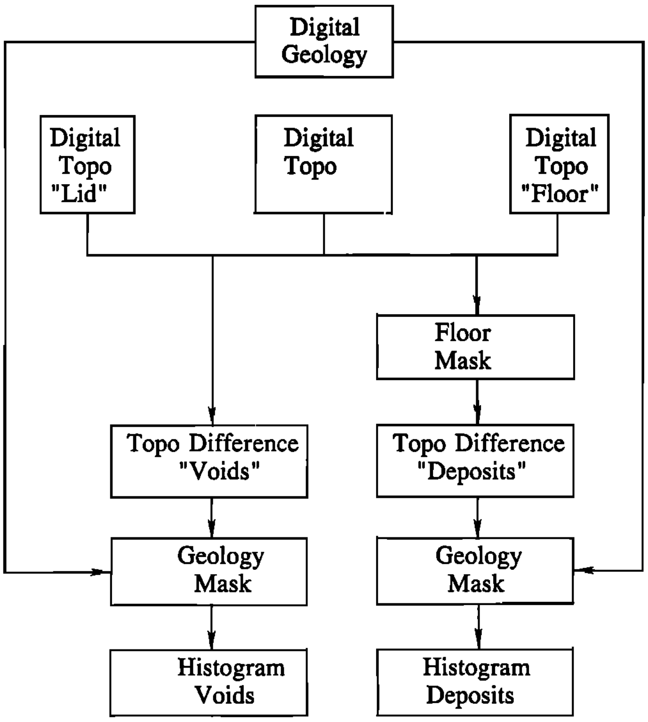

Figure 1. Flow chart giving procedural steps of the study. "Topo" is topography based on digital terrain models (DTMs). "Lid" is restoration of the original surface across the top of Valles Marineris by linking contours on adjacent plateaus. "Floor" is estimated level of original floor beneath interior deposits. "Mask" is outline of designated feature.

Geologic/Geomorphic Map

Units of the geologic/geomorphic map (Plate 1) were simplified and modified from *Witbeck et al.* [1991] (Table 1). The units were chosen to give information concerning both the structural and geomorphic development of the Valles Marineris.

Floor materials were subdivided to give information on the original floor, which may be composed of plateau material lowered tectonically or by collapse, or it may be an erosional surface on deep-seated material. Therefore, we mapped exposures on the trough floors of wall rock, plateau rock, and chaotic material. We considered exposures of plateau rock and chaotic material as reflecting "original floor" lowered tectonically or by collapse; we considered wall-rock exposures as "original floor" that resulted from either erosion or tectonic lowering. In addition, shallow fill on floors was mapped where only a thin cover, perhaps of eolian materials, seems to be present (as suggested by many nearby outcrops of the original floor). Undivided floor material was mapped where the thickness and origin of the floor material were unknown. We mapped floor material of enclosed depressions as a separate unit to distinguish the material inside chain craters or coalesced chains from that of the troughs; this material could not have readily contributed to deposits inside the troughs.

Landslides were subdivided into young landslide material, composed of slides with well-developed scars and, where unconfined, longitudinally ridged and grooved aprons [*Lucchitta*, 1979]; and old landslide material, composed of irregular deposits in wall reentrants, whose identity is more questionable.

Interior deposits that are likely to have substantial thickness were subdivided into four units. (1) Thick fill on floor was mapped where rolling topography combined with absence of nearby outcrops of original floor material suggests the presence of thick deposits. This unit is of questionable origin; it could locally be composed of downfaulted interior layered deposits or low-lying irregular materials. (2) Dark material may reflect the elevation and thickness of underlying units, because it is commonly thin and occurs on top of other deposits. (3) Irregular material has diverse surface characteristics and moderate to high albedo. It is very young and unconformably overlaps structurally disturbed and eroded older layered deposits and, locally, landslides. (4) Interior layered deposits mostly form mesas or underlie benches resting against wallrock.

Wall rock was subdivided into two units: wall rock on the

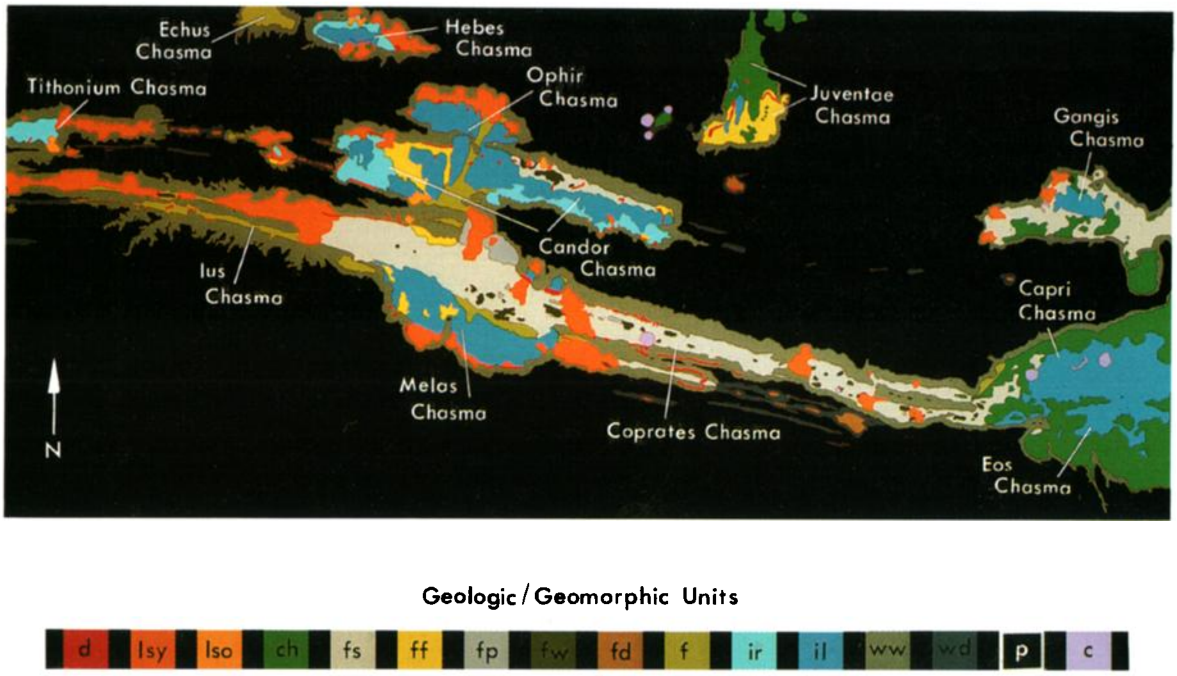

Plate 1. Geologic/geomorphic map of Valles Marineris. Modified after *Witbeck et al.* [1991]. Here d, dark material; lsy, young landslide material; lso, old landslide material; ch, chaotic material; fs, shallow fill on floors; ff, thick fill on floors; fp, plateau rock on floor; fw, wall rock on floor; fd, floor material in enclosed depressions; f, undivided floor material; ir, irregular deposits; il, interior layered deposits; ww, wall rock on main trough walls; wd, wall rock in enclosed depressions; p, plateau material; c, crater material.

Table 1. Generalized Geologic/Geomorphic Units

Map Symbol	Map Units
	Floor Units
fs	thin (shallow) fill on floor
fp	plateau rock on floor
fw	wall rock on floor
fd	floor material in enclosed depressions
f	undivided floor material
ch	chaotic material
	Landslides
lsy	young landslide material
lso	old landslide material
	Interior Deposits
ff	thick fill on floors
d	dark material
ir	irregular deposits
il	interior layered deposits
	Wall Units
ww	wall rock of main troughs
wd	wall rock in enclosed depressions
	Other Units
c	crater material
p	plateau material

main trough walls, which may have furnished eroded debris to the troughs; and wall rock on walls of enclosed depressions, which did not contribute debris to the troughs.

The remaining mapped units are materials of craters >20 km in diameter and plateau material. The latter served as a digital mask for the outline of the Valles Marineris: by blocking out this unit, we were able to consider only units inside the troughs.

The map (Plate 1) shows that interior layered deposits occur dominantly in the central troughs and in the peripheral troughs Juventae, Gangis, and Eos/Capri Chasmata that give rise to outflow channels. In Ophir, east Candor, and Melas Chasmata, interior layered and irregular deposits occur only in benches on their south sides. In Hebes, west Candor, Juventae, Gangis, and Capri/Eos Chasmata, these units form mesas. By contrast, the entire Ius/north Melas/Coprates Chasma system is devoid of interior layered deposits. Instead, its floor shows many "islands" of wall or plateau rock and old craters apparently downdropped together with the plateau rock [*Schultz*, 1991].

Most dark material lines the base of trough walls. It also occurs as patches that follow distinct trends parallel to the main troughs, indicating structural control of dark-material emplacement [*Lucchitta*, 1990]. Dark material also appears to be more common in the northern, lower trough segments of Ophir and Candor Chasmata than on the higher, southern benches. The conspicuous elongated exposure of dark material in the south wall of Coprates Chasma is a dark layer within wall rock [*Witbeck et al.*, 1991].

Chaotic material occurs in the troughs that merge with outflow channels (Juventae, Gangis, and Coprates/Eos Chasmata). In these troughs, chaotic material is locally buried by interior layered deposits.

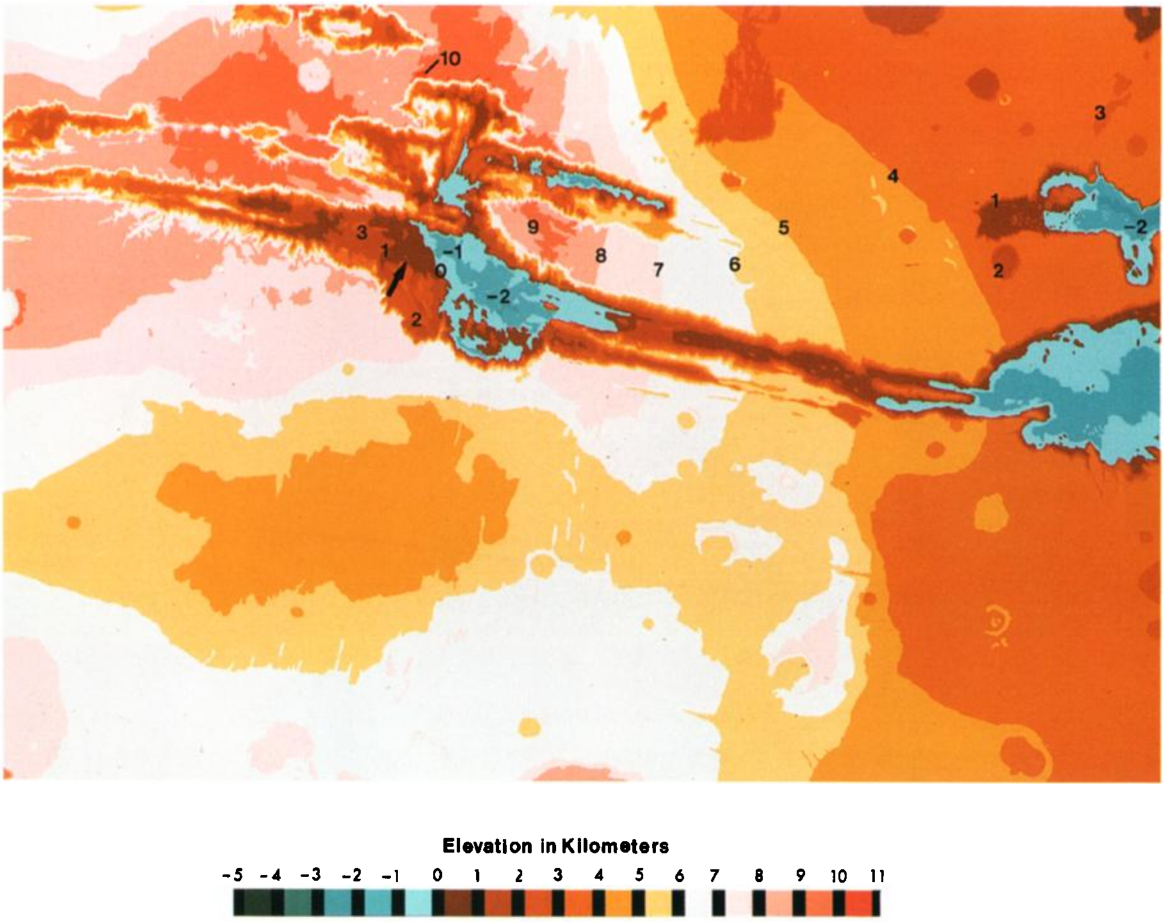

Plate 2. Elevations of Valles Marineris and vicinity, based on digital terrain model of *Wu et al.* [1991]. Contours in 1-km increments. Arrow points to straight fault scarp separating central from south Melas Chasma. For trough names see Plate 1.

Topographic Maps

The geologic/geomorphic map was transferred to the topographic maps MC18 NW [*U.S. Geological Survey*, 1986] and MC18 NE and SE (unpublished). The scale of these topographic maps is 1:2,000,000 and their contour interval is 1 km. They had been digitized previously [*Wu et al.*, 1991] and are now available as DTMs in sinusoidal equal area projection at a resolution of 1/64°, or 0.925 km per picture element (pixel) (Plate 2). These DTMs interpolate linearly between the 1-km contour intervals at a minimum increment of 2 m. Thus, a distance of 10 pixels between 1-km contours would give increments of 100 m/pixel, and a distance of 500 pixels or more would give increments of 2 m/pixel. The digitized geologic/geomorphic map was coregistered with the DTMs.

The digital terrain model is based on contours obtained by analytical photogrammetry. In the equatorial area the error is evaluated to be of the order of ±1 km [*U.S. Geological Survey*, 1991]. However, as many of our measurements are based on local relief of as much as 10 km, the proportional error is lessened. On a regional scale, the areas and volumes of units and their differences are large enough that inaccuracies resulting from the errors should not severely affect our conclusions.

Areas and Volumes

Areas of individual units inside the Valles Marineris were readily obtained by summing the pixel numbers occupied by each unit. We disregarded the units inside enclosed depressions (except for Hebes Chasma) because they are not important to this study. The areas were rounded to the nearest 10 km^2 because uncertainties in mapping and coregistration make greater accuracy unrealistic. The results are shown in Table 2 and Figure 2.

To obtain the local depth of troughs (1-km contours, Plate 3) we calculated the difference between a restored surface across the Valles Marineris and ground elevations of the DTMs. We designed this surface by connecting contours on the adjacent plateaus across the Valles Marineris. To obtain the volume of void spaces above individual units inside the Valles Marineris, we applied a "geology mask" (Figure 1) derived from the digitized geologic/geomorphic map (Plate 1). We then summed all pixels per unit and all elevation differences per pixel between the restored surface ("lid" of Figure 1) and the ground elevations. Again, we eliminated the units inside enclosed depressions. Void-space volumes above individual units are given in Table 3 and Figure 3.

We calculated volumes of interior deposits by obtaining the difference between the elevations of the DTMs and those of a designated "floor" under the deposits. This floor, on which the interior deposits presumably rest and whose real position is unknown, was determined by projecting under the deposits the elevation of adjacent floor units that are thought to approximate the original trough floor, such as exposures of wall rock, plateau rock, or chaotic material. In reality the original floor may lie even deeper, because some underlying deposits are not accounted for. The true volumes of interior deposits are therefore probably larger than our estimates. The reverse case, where the true volume would be smaller

Table 2. Sizes of Areas Underlain by Geologic/Geomorphic Units in Valles Marineris

	Area, km^2	Area, %
Floor units		
fs	123,730	15.8
fp	5,300	0.7
fw	6,650	0.8
f	29,540	3.8
ch	90,370	11.5
Landslides		
lsy	80,390	10.2
lso	2,960	0.4
Interior deposits		
ff	23,120	2.9
d	6,080	0.8
ir	27,360	3.5
il	135,370	17.2
Wall rock of main troughs		
ww	249,690	31.8
Crater material		
c	4,050	0.5
Total	884,600	

Percentages are of total area inside troughs. Unit symbols defined in Table 1.

because the floors lie higher than our estimate, does not appear to be common: we see no outcrops of apparent floor materials in the middle slopes of free-standing mesas or along the sides of benches composed of interior layered deposits; possible floor materials are seen only near the base. The designated floor-elevation levels (Figure 4) are flat surfaces with integer increments. They were established only for areas where measurable deposits occur inside the trough-boundary faults. The purpose of this restriction is to obtain volumes only for those deposits located inside the original, unenlarged troughs. Thus landslide deposits in landslide reentrants were excluded, as were materials located on trough walls or in tributary canyons.

Deposit thicknesses are shown in Plate 4. Only partial troughs are visible, as only areas occupied by deposits are shown in the figure. The volume of material in the geologic/geomorphic units was obtained by summing the thicknesses per unit. Deposit volumes are given in Table 4 and Figure 5.

Results

Areas

Sizable areas in the Valles Marineris are occupied by wall rock, interior layered deposits, thin floor material, chaotic material, and young landslides (Figure 2, Table 2). Wall rock (32% of the total) occupies the largest area of any unit inside the troughs. The wall-rock area reflects widening by erosion, confirming the observation by *Schultz* [1989] that the troughs have been enlarged substantially. Interior layered deposits occupy 17%. Thin floor deposits (16%) are also sizable because they cover the large expanse of the floors of Coprates and Melas Chasmata. The total area inside the troughs that has thin cover is compared with the total area that has thick cover and with the total wall area in Table 5 and Figure 6. In this comparison landslides are grouped with thin deposits because they are thin relative to the depths of the troughs. The comparison shows that areas underlying thick deposits are less extensive than areas underlying thin deposits (or areas free of deposits), and that wall rock, reflecting sites of erosion, is approximately equal in area to sites of deposition.

Trough Depth and Void-Space Volumes

Plate 3 shows trough depths relative to the surrounding plateaus. The deepest troughs are north Ophir, north Candor, central Candor, and north Melas, as well as a north-trending low connecting Ophir and Candor Chasmata. Also deep are the eastern part of Ius and the western part of Coprates. The former contains landslide deposits, whereas the latter is largely free of them (Plate 1). The similar depths suggest that the landslide deposits are not very thick. Coprates Chasma becomes shallower toward the east and merges with the relatively shallow peripheral troughs that in turn merge with outflow channels. In Ophir, Candor, and Hebes Chasmata, the depth is reduced where interior layered and irregular deposits build high mesas and benches. The top surface of interior layered deposits in Hebes Chasma is within 1 km of the elevation of the surrounding plateau. The only other large area in which interior layered deposits reach nearly to plateau height is Gangis Chasma.

From Table 3 and Figure 3 it is apparent that the largest void spaces occur above wall rock, thin floor deposits, and

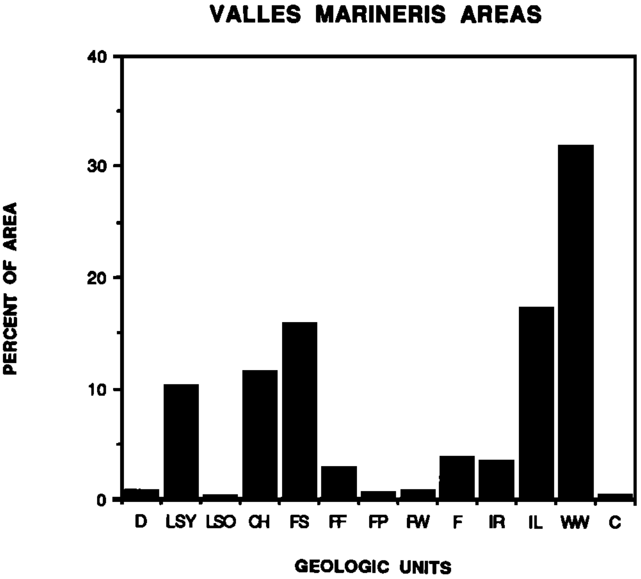

Figure 2. Areas of geologic/geomorphic units inside Valles Marineris. Percentages are those of total area (about 885,000 km^2) inside troughs. Unit symbols defined in Table 1, unit values given in Table 2.

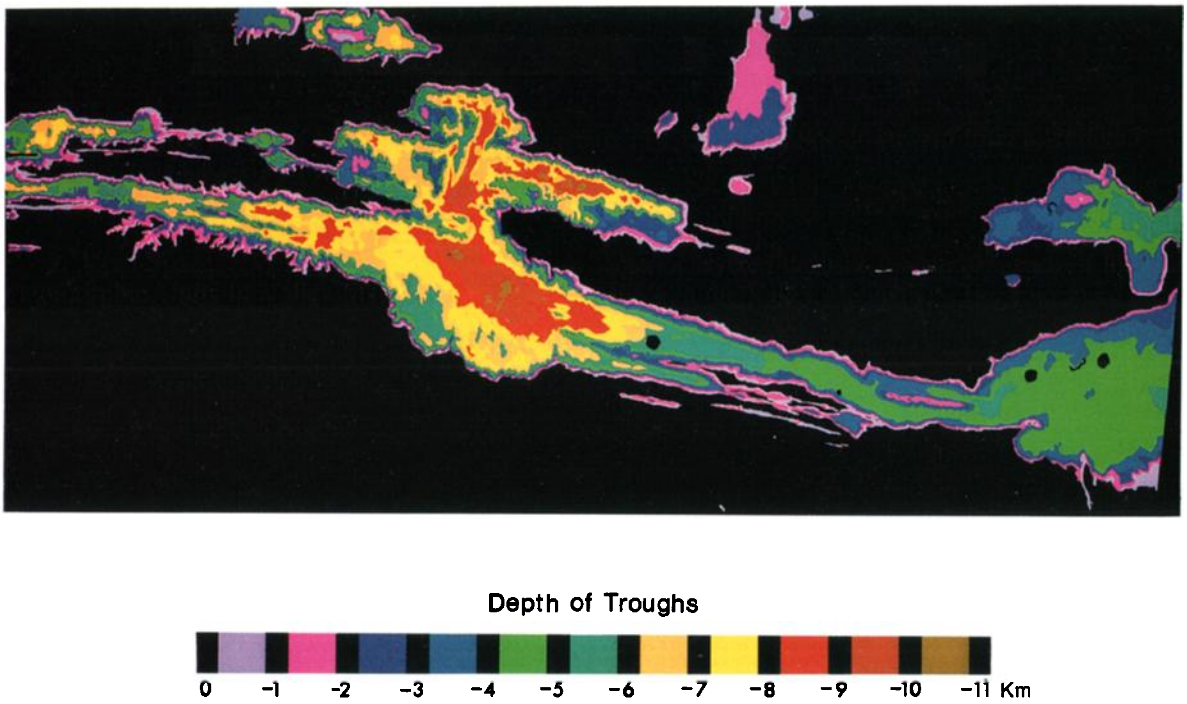

Plate 3. Depths of Valles Marineris troughs. Contours in 1-km increments downward from a "restored" surface across top. For trough names, see Plate 1.

Table 3. Void-Space Volumes over Geologic/Geomorphic Units in Valles Marineris

	Void-Space Volume, km^3	Void-Space Volume, %
Floor units		
fs	790,240	22.2
fp	19,570	0.5
fw	46,650	1.3
f	191,450	5.4
ch	310,450	8.7
Landslides		
lsy	476,840	13.4
lso	18,020	0.5
Interior deposits		
ff	113,280	3.2
d	33,760	1.0
ir	128,350	3.6
il	691,790	19.4
Wall rock of main troughs		
ww	731,070	20.5
Crater material		
c	15,440	0.4
Total	3,566,910	

Percentages are of total volume inside troughs. Unit symbols defined in Table 1.

interior layered deposits (about 20% each of the total void space in the Valles Marineris). The void space above wall rock corresponds to the wall material that has been eroded from the walls. However, our calculated volumes represent the vertical space above geologic units. If we assume that the troughs are tectonic rifts, this geometric configuration implies vertical faults. The attitude of the planes of trough-bounding faults is still unknown; estimates range from dips

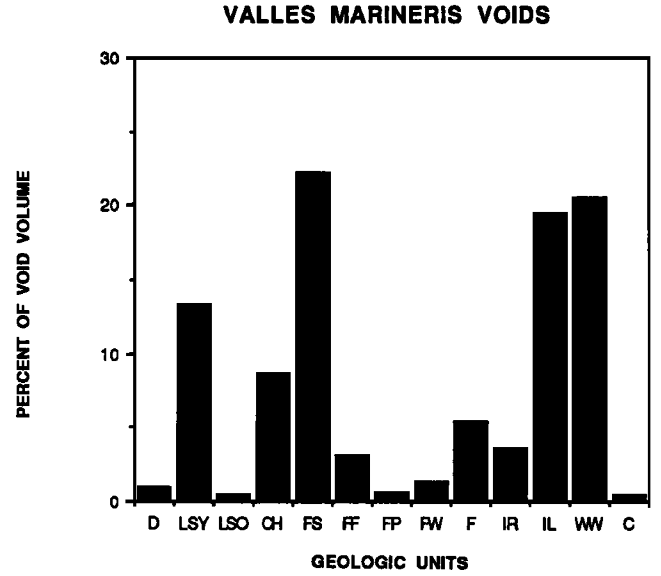

Figure 3. Volumes of void spaces above geologic/geomorphic units inside Valles Marineris. Percentages are those of total void volume (about 3,567,000 km^3) inside troughs. Volume measured between restored surface across top of Valles Marineris and ground level. Unit symbols defined in Table 1, unit values given in Table 3.

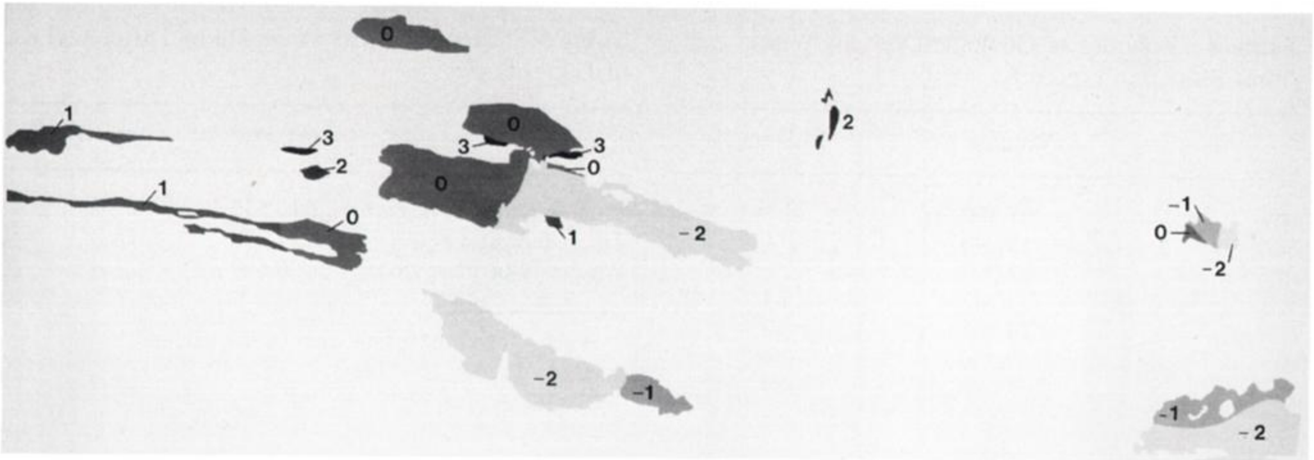

Figure 4. Designated floor elevations, in increments of 1 km or more, inside Valles Marineris. They were obtained by projecting under interior deposits the elevations of adjacent floor units thought to approximate the original trough floor. Only areas occupied by deposits are shown. For trough names, see Plate 1.

near vertical to less than 60° [*Carr*, 1981; *Davis and Golombek*, 1990; *Chadwick and Lucchitta*, 1992]. In this study we assume near-vertical faults, but if the fault planes dip 60°, as is common at simple grabens, the material removed from the walls would be about one-third less than calculated.

The large void-space volume above thin floor deposits (Figure 3) reflects mostly the occurrence of thin deposits in the deep and largely empty troughs of north Melas, Coprates, and northern east Candor (Plates 1 and 3). Also substantial are void spaces over young landslides (13%), which occur mostly in deep parts of the troughs. The large void space over interior layered deposits (Figure 3) shows that many of these deposits do not stand high inside the troughs.

Deposit Volumes

Plate 4, which gives the thickness of deposits, is to some extent the inverse of Plate 3, which gives the depth of the troughs downward from a hypothetical ceiling. Plate 4 shows that the interior layered deposits and irregular deposits (Plate 1) are as thick as 9 km in the mesas and benches of Hebes, Ophir, and Candor Chasmata but are much thinner in south Melas and Capri/Eos Chasmata. If the irregular layered deposits and dark materials are only a thin veneer, their indicated thickness may reflect the combined thickness of the interior layered deposits and the superposed irregular or dark materials. The volume of the interior layered deposits (about 60% of the total deposit volume, Table 4 and Figure 5) vastly exceeds the volumes of all other individual

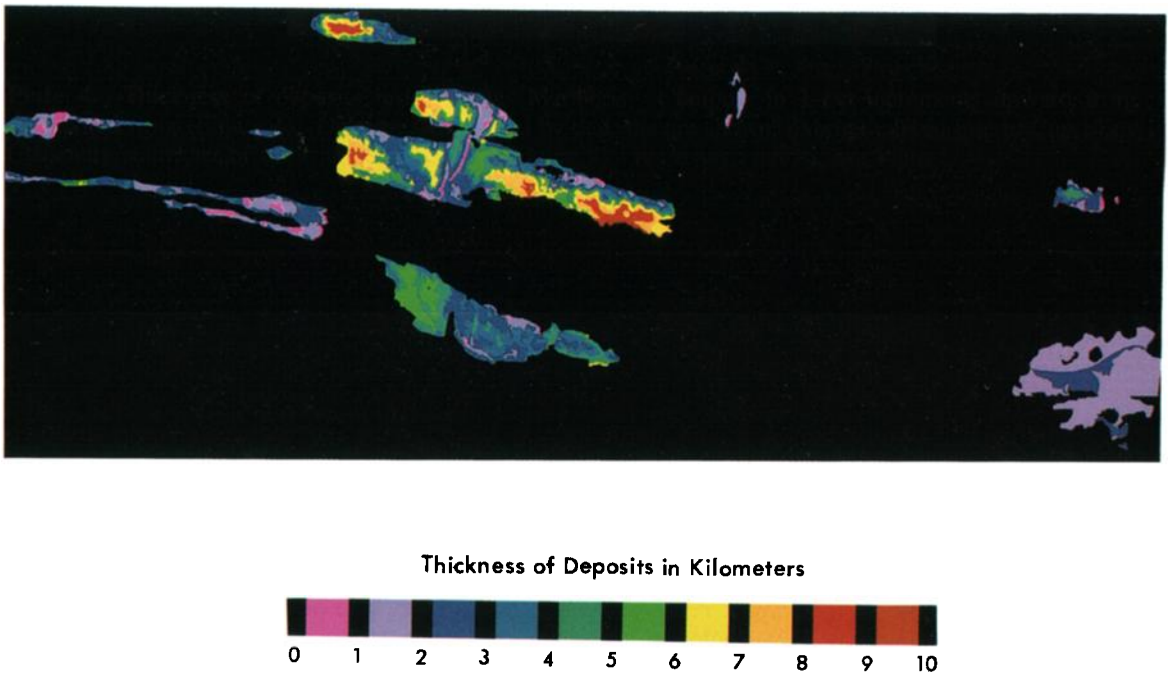

Plate 4. Thickness of deposits inside Valles Marineris. Contours in 1-km increments upward from designated floor (Figure 4). Only areas occupied by deposits are shown. Abrupt curved line in Capri/Eos Chasmata is artifact of floor-level assignment (Figure 4). For trough names, see Plate 1.

Table 4. Volumes of Geologic Deposits Within Areas Shown in Figure 4

	Volume, km^3	Volume, %
lsy	67,490	11.3
lso	2,240	0.4
fs	12,390	2.1
f	23,440	3.9
ff	24,780	4.2
d	2,560	0.4
ir	108,860	18.3
il	352,950	59.3
Total	594,690	

Percentages are of total volume inside area shown in Figure 4. Unit symbols defined in Table 1.

units. If the irregular deposits (18%) and the dark material are indeed only a thin veneer, the interior layered deposits may make up as much as 80% of all deposits. Most floor units are not voluminous, in accordance with expectations for thin blankets on the original floor. Similarly, young landslides appear to be thin veneers because they make up only about 10% of the deposits.

Discussion

Interpretations of the geologic/geomorphic map combined with information on depths of troughs, elevations of units, and volumes of void spaces and deposits, have led to some tentative conclusions on the erosional, sedimentary, volcanic, and structural evolution of the chasmata. Particularly addressed are relations between putative lakes, interior layered deposits, and outflow channels. Also addressed are the possibilities that the interior deposits are derived from the walls and that they are volcanic.

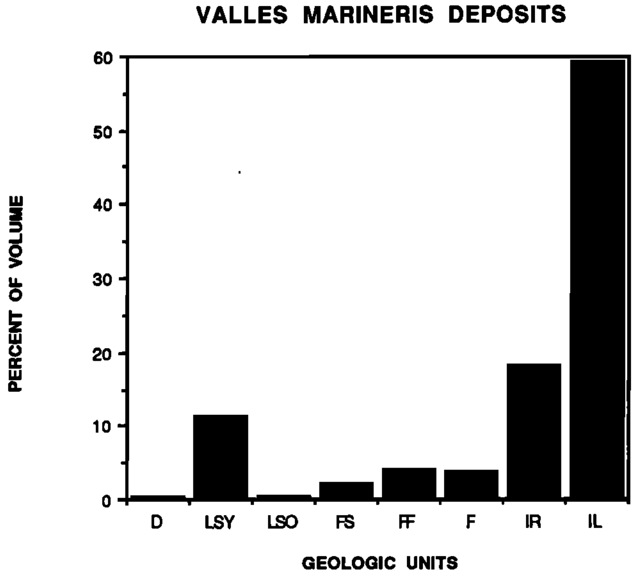

Figure 5. Volumes of geologic/geomorphic units inside troughs of Valles Marineris (only eight units shown). Percentages are those of total deposit volume (about 595,000 km^3) inside troughs. Volumes measured between designated floor (Figure 4) and deposit surface. Unit symbols defined in Table 1, unit values given in Table 4.

Table 5. Extent of Areas Occupied by Different Types of Deposits

	Area, km^2	Area, %
Thin or absent deposits*	319,530	40.7
Thick deposits†	221,470	28.2
Wall rock of main troughs	249,690	31.8

Percentages are of total area inside troughs. Unit symbols defined in Table 1.

*Units lsy, lso, ch, fs, fp, fw, c

†Units ff, f, d, ir, il

The Central Troughs and Interior Layered Deposits

The interior layered deposits are generally considered to be lacustrine sediments [*McCauley*, 1978; *Nedell et al.*, 1987]. The layered deposits in the central troughs (Plate 1) locally rise to elevations less than 1 km below the surrounding plateau rim (or to absolute levels of as much as 8 km above Mars datum) (Plate 2). During the last stages of deposition of the interior layered deposits, postulated lake levels must have been at those elevations. If the troughs were interconnected then as they are now, lakes rising to those levels could not have been sustained; their waters would have spilled onto the surrounding plateau in the vicinity of Coprates Chasma, where the plateau surface is less than 8 km high. Even lakes with surface levels as low as about 4 km could not have been contained in the central troughs, because such lakes would also have spilled, except farther east along Coprates Chasma. (Only a lake in Hebes Chasma could have been sustained at a high level.) Therefore, if the ancient troughs were inter-connected, lakes could not have risen above the 4-km level, and the upper layered deposits could not be lake sediments. A likely alternative is that they are volcanic material.

However, the central troughs of Ophir, Candor, and south Melas may not have been interconnected; they may have formed isolated ancestral basins that were not linked to the present north Melas and Coprates Chasmata. Or, if they were interconnected, they had no outlet to the east. In these cases, lakes could have formed in the central troughs with water levels at high elevations.

The Central Troughs and Ancestral Basins

The idea that ancestral isolated basins may have existed in the central troughs is supported by structural and stratigraphic evidence [*Lucchitta and Bertolini*, 1990]. The elongate, east-trending trough of east Candor Chasma is divided lengthwise into southern and northern segments. The southern segment, extending across one-half to two-thirds the width of the chasma, is filled with interior layered deposits that form a high-level bench (Plate 1). The bench has

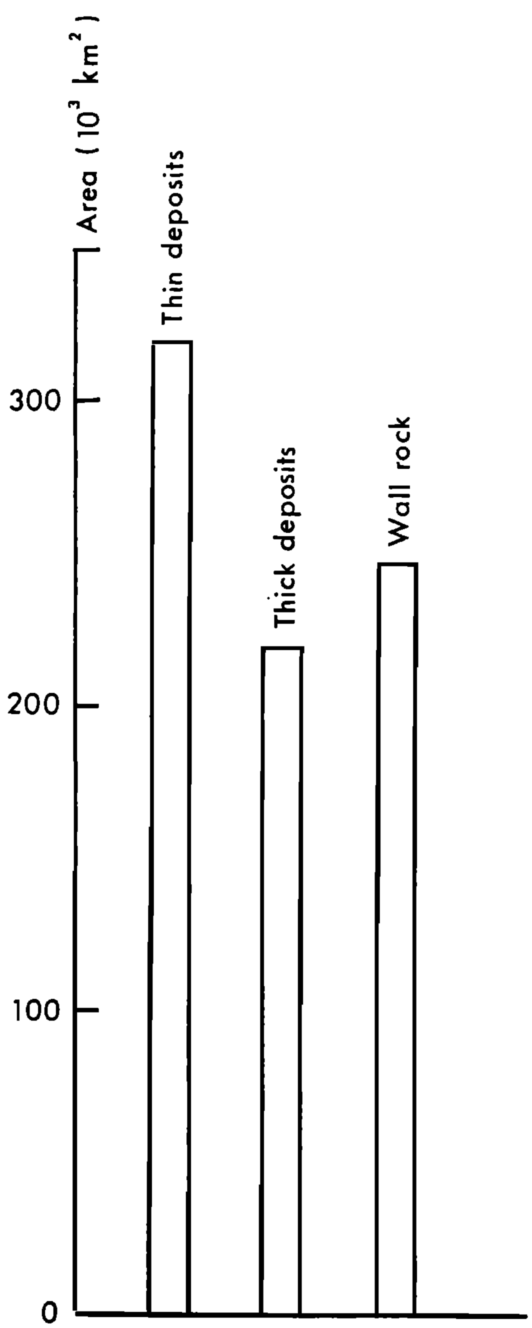

Figure 6. Extent of areas occupied by thin (or no) deposits, by thick deposits, and by wall rock. Unit values given in Table 5.

surface elevations about 4-6 km above Martian datum (Plate 2), and to the south it abuts and buries walls already eroded into spurs and gullies. The northern chasma segment is lower, having surface elevations of 0 to -2 km, and it forms a subsidiary trough generally more than 5 km lower than the southern bench. This trough is bounded on its north side by walls showing conspicuous triangular facets, which are usually taken to be fault scarps. Only interior layered deposits are seen in the south wall of this subsidiary trough, indicating that these deposits extend all the way to its bottom. The trough also contains several erosional remnants on its floor displaying spur-and-gully morphology, which is characteristic of chasma wall rock but not of interior deposits, and no layered interior deposits crop out within the trough. These observations suggest that this subsidiary trough is underlain dominantly by wall rock, whereas the southern bench is underlain by interior deposits to a depth at least as great as that of the northern trough. The outcrop relation of mutually exclusive rock types in the two trough segments, separated by a relatively straight scarp, suggests a fault contact. The most likely explanation for this topographic and stratigraphic setting is that the original Candor Chasma may have occupied only the area of the southern bench, forming an ancestral trough that became filled with interior deposits. The northern trough segment apparently dropped after deposition ceased, as no interior deposits are seen on its floor. The ancestral southern trough, before it became filled with deposits, may have been deeper than the still empty, subsidiary northern trough.

The configuration of Ophir Chasma is similar. Again, the southern two-thirds of the chasma is occupied by interior deposits; the northern third is deeper and forms a linear trough between interior deposits and chasma wall. No wallrock remnants are seen on the floor of this depression, however, because its floor is buried by young landslide deposits. The setting suggests that Ophir Chasma may have developed similarly to Candor Chasma in that the depression along the north side of Ophir Chasma is also a later subsidiary structural trough.

The Coprates/north Melas/Ius system, which is virtually devoid of interior layered deposits, may also be a late fault trough. This system cuts across Melas Chasma, which, like the troughs mentioned above, has interior layered deposits on its south side but no well-defined layered deposits in its central part. The south boundary of this system is obvious where Melas and Ius Chasmata merge. Here the boundary is a pronounced linear scarp on the chasma floor (Plate 2). The entire system is deep, ranging from a depth below adjacent plateaus of more than 6 km in the west to as much as 11 km in the center and about 5 km in the east (Plate 3). The troughs in this system are thought to be grabens because their walls have triangular facets and Coprates Chasma shows downdropped plateau material on its floor. (The latter observation is supported by the existence of large, ancient, plateau-type craters on the trough floor and by crater-density counts [*Schultz*, 1991]. Ius Chasma looks like Coprates Chasma except that its floor is covered by landslides, similar to the floor in the north half of Ophir Chasma (Plates 1, 2, and 3).

From these observations it appears that ancestral isolated basins developed in Hebes, south Ophir, south Candor, and perhaps south Melas Chasmata. The basins were filled with interior layered deposits and therefore may have harbored lakes. Faulting that followed the emplacement of layered deposits eventually widened the ancestral basins and formed deeper and younger northern trough segments (Plate 3). The Coprates/north Melas/Ius graben system probably also developed during this time of renewed tectonic activity.

The late-stage development of subsidiary troughs had two possible major consequences. (1) The putative lakes in isolated basins of the central ancestral trough were eventually breached, and the water spilled through Coprates and Capri/Eos Chasmata into Simud and Tiu Valles to the east of the chasmata, perhaps forming a major flood. However, no flood features are seen inside Coprates Chasma, making this hypothesis less likely. Also, the ancestral basins were probably already filled with layered deposits at the time of breaching, and the lakes had dried up long before, so that no floods would have ensued. (2) The formation of young, deep, subsidiary fault troughs, perhaps combined with the emptying or drying of the putative lakes, may have caused major instabilities in the walls, resulting in the young landslides that now cover the floors of north Ophir, Coprates, and Ius Chasmata (Plate 1).

Peripheral Troughs and Chaotic Materials

Chaotic material occurs only in peripheral troughs, in Juventae, Gangis, and Capri/Eos Chasmata (Plate 1). (The patches in Hebes Chasma are of questionable origin.) These troughs merge with outflow channels, have less regular outlines than the central troughs, and are shallower (generally only 2-5 km deep) (Plate 3).

Many researchers have shown that chaotic material is genetically linked to the origin of outflow channels [*Sharp*, 1973b; *Baker and Milton*, 1974; *Masursky et al.*, 1977]; in fact, withdrawal of water and ground ice in the chaotic regions is thought to have led to the observed collapse and to the floods that formed the channels. Accordingly, the peripheral troughs would have formed largely from collapse and less from structural downdropping.

Evidence supporting a collapse origin is illustrated in Figure 7, which shows a depression south of Gangis Chasma filled with fractured, slumped, and tilted plateau material, which gradually merges northward with true chaotic material. Clearly, this chaotic material is the product of collapsed plateau material. Faulting probably augmented the depth of the peripheral troughs, as suggested by many straight wall segments cutting the base of spurs and gullies and by the alignment of these segments with regional structural trends. Overall, our observations support the idea that the peripheral troughs formed by a combination of faulting, collapse, and erosion, which probably extended to some degree along preexisting structural lines of weakness.

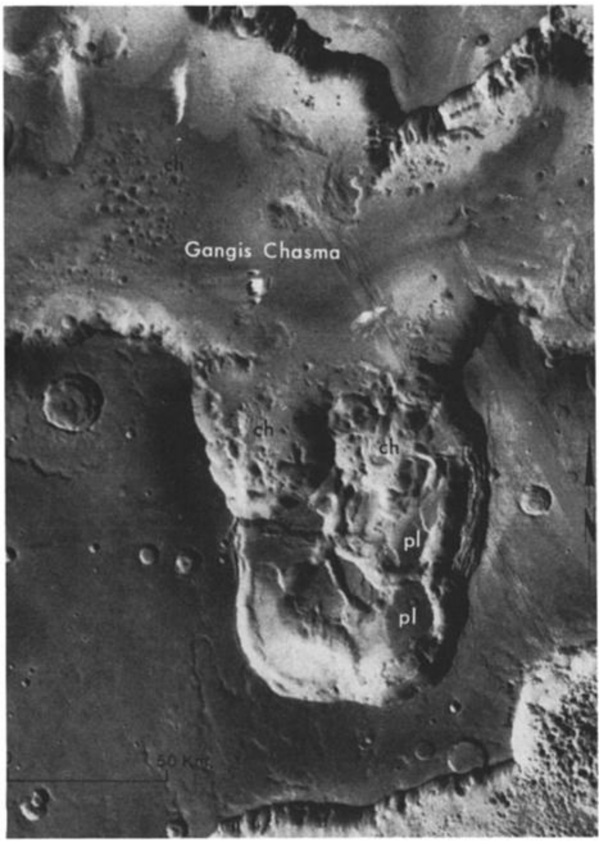

Figure 7. Depression south of Gangis Chasma. Tilted and fractured plateau material (pl) inside depression merges northward with chaotic material (ch). Part of 1:2,000,000-scale photomosaic Coprates NE (unpublished).

The origin of chaotic materials can be further explained by the observation that they (Plate 1) appear on the trough floors near the 4-km contour on the surrounding plateaus (Plate 2). The similarity in elevation supports the proposition that the outflow channels erupted from confined aquifers [*Carr*, 1979]: the liquid in the aquifers could have attained the necessary head near this 4-km elevation. A postulated 1- to 2-km-thick layer of ground ice in the equatorial area [*Fanale*, 1976; *Rossbacher and Judson*, 1981] is also consistent with the depth below plateau level of about 2 km at which chaotic material appears on the floors in the upper regions of Juventae and Gangis Chasmata (Plate 3). This depth may be the depth of the postulated aquifers.

Peripheral Troughs and Interior Layered Deposits

The interior layered deposits in Gangis, Capri/Eos, and Juventae Chasmata are 1-4 km thick (Plate 4) and overlie chaotic materials [*Witbeck et al.*, 1991; *Lucchitta et al.*, 1992; *Komatsu et al.*, 1993]. Therefore formation of chaotic terrain must have predated formation of the lakes that received the layered sediments. Chaotic terrain presumably formed by flushing of rock, water, and ice from the area, giving rise to outflow channels [*Carr*, 1979].

In order to fill these lakes, dams must have blocked the channels. However, there is no evidence for such dams. A likely alternative is that they were formed of ice [*Kochel and Miller*, 1990], but the resulting lakes would be temporary. It is difficult to envision the formation of 4-km-thick-layered sediments, such as those in Gangis Chasma, in lakes filled to the brim behind temporary dams.

Alternatively, the layered deposits could have formed in isolated lakes in regions of chaotic terrain, as noted by *Komatsu et al.* [1993]. These lakes must have predated the deep outflow channels currently observed, and the lakes would have drained only after deposition of the layered deposits. *Howard* [1991] envisioned the existence of such lakes. He suggested that chaotic terrain may have formed where confined aquifers formed "frozen hydrolaccoliths," or locally even sills of liquid water. The sills could have caused collapse of the uplifted roof to form chaotic terrain and lakes; the ice laccoliths could have melted or sublimed. Overall, the deposition of layered sediments on top of chaotic material suggests that the peripheral troughs also formed first as isolated ancestral basins, perhaps harboring lakes, as is suggested for the central troughs.

On the other hand, the layered deposits in the peripheral troughs may be volcanic [*Komatsu et al.*, 1993], as is perhaps true for the upper layers in the central troughs. A volcanic composition is suggested by the shape of the free-standing mesas of layered deposits in Gangis and Juventae

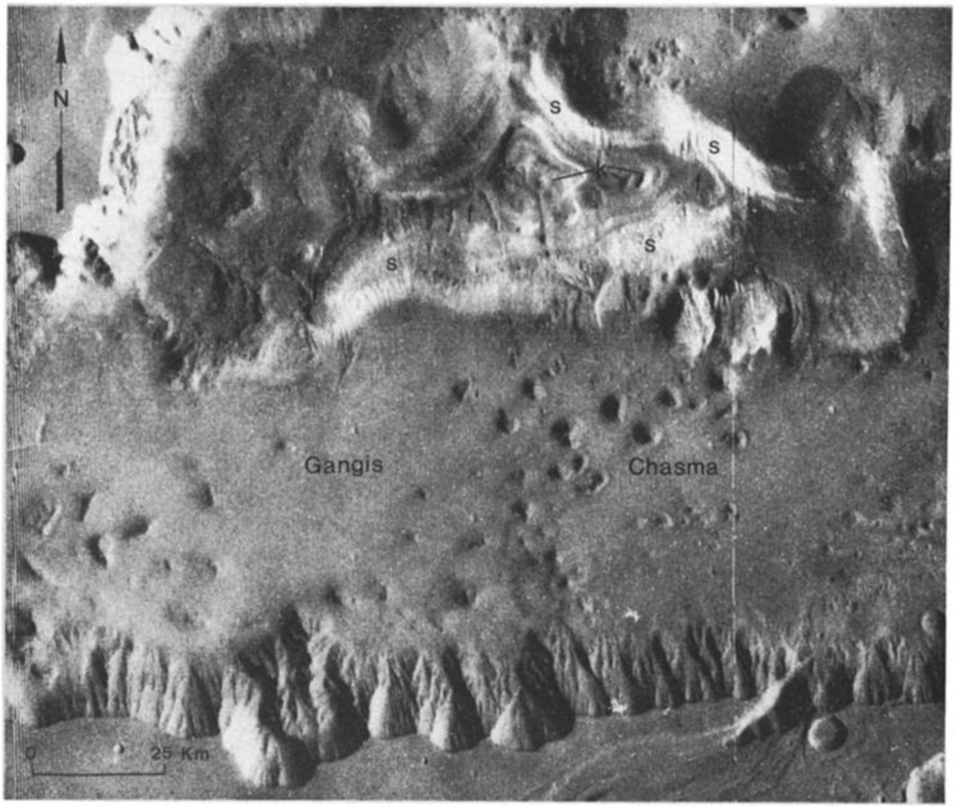

Figure 8. Layered deposits in Gangis Chasma. Flat tops (f) surmounted by knobs (k) are flanked by steep slopes (s). The configuration is compatible with those of table mountains formed of volcanic material erupted under ice. Part of Viking Orbiter image 897A40.

Chasmata. The mesa in Gangis Chasma (Figure 8) has steep sides on which light and dark layers are exposed and a relatively flat top surmounted by knobs. Mesas in Juventae Chasma are similar. Such configurations are like those of table mountains, which are mounds formed of volcanic material erupted beneath ice [*Van Bemmelen and Rutten*, 1955]. Table mountains also have steep sides, where the erupting flows were confined by the surrounding ice, and they may have volcanic constructs at the top, where the volcanic fluids rose above the ice. In the peripheral troughs, volcanic material could have been intruded into ice laccoliths [*Howard*, 1991], which are analogous to gigantic open-system pingoes [*Washburn*, 1973] and which thus could have formed large masses of segregated ice [*Sharp*, 1973a,b]. Alternatively, the volcanic material could have been intruded into relatively shallow lakes that were completely frozen. The steep sides on the mesa in Gangis Chasma are about 2 km high, consistent with the depth to which water may have been frozen in the equatorial area [*Rossbacher and Judson*, 1981]. If the isolated mesas in the peripheral troughs are indeed table mountains, the light and dark layers could be palagonitic tuffs and mafic flows, compositions common in table mountains in Iceland [*Van Bemmelen and Rutten*, 1955]. According to this scenario, the mesa shape would be a constructional rather than an erosional feature, and the lack of deposits surrounding these mesas would be explained. An origin as a table mountain has also been proposed by *Croft* [1990] for the layered mesa in Hebes Chasma.

Derivation of Interior Layered Deposits From Wall Rock

The origin of interior layered deposits as sediments has been questioned mainly because no major channels debouch into the central troughs, and only one is seen to spill into the peripheral troughs. Therefore, an alternative hypothesis has been considered: the sediments in the layered deposits may be derived from eroded wall rock [*Nedell et al.*, 1987; *Lucchitta et al.*, 1992]. The following quantitative analysis may shed light on this question.

In Figure 9 we compare the entire void space inside the Valles Marineris with the volume of all interior deposits, including landslides. As the figure shows, the void volume of the troughs is about six times the volume of the deposits, indicating that, overall, interior deposits are only a minor feature of the troughs.

In Figure 10 we compare the volume of material eroded from the walls with the volume of deposits inside the troughs, again assuming vertical fault boundaries. The volume of eroded material is larger than that of deposits. But, if the initial trough-boundary faults dipped near 60°, the volume of eroded wall material would be less by about one-third and would approximate that of the deposits. Both of these relations are consistent with the hypothesis that the material removed from the walls could form the interior layered deposits, and that no additional influx of material was needed. However, several observations lessen the validity of the argument. The true floor of the interior deposits is not known, and our designated floor is conserva-

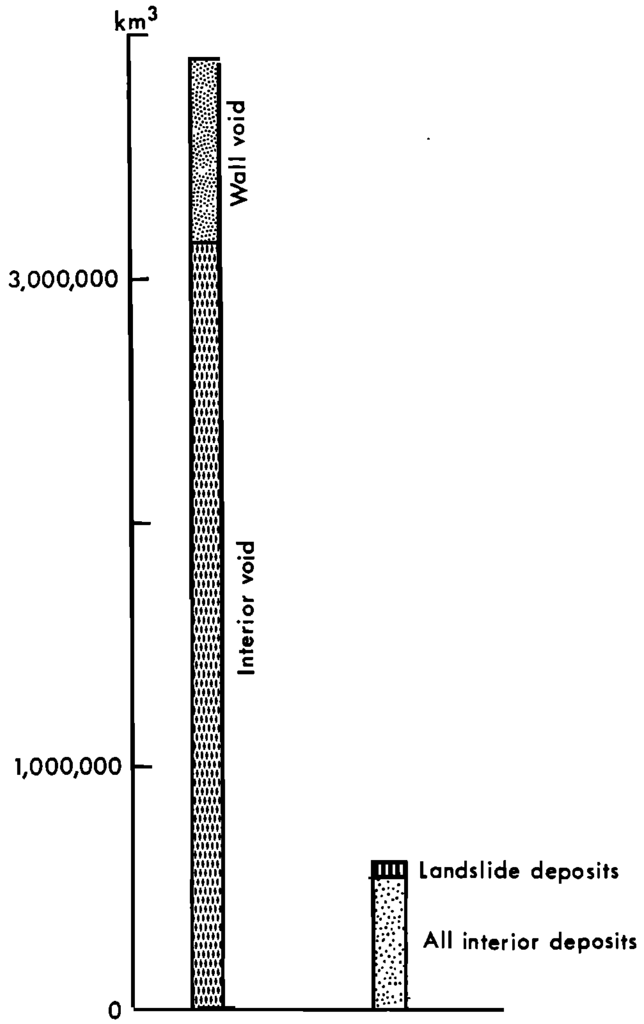

Figure 9. Comparison of volumes of void spaces (left) and deposits (right) in Valles Marineris. The void-space volume is about six times the deposit volume.

tive, and, therefore, most likely results in minimum values for the deposits. Thus, the deposit volume may exceed that eroded from the walls. Also, derivation of interior deposits entirely from eroded wall rock would be possible only if all the troughs were interconnected. As shown in the previous sections, the layered sediments were possibly emplaced in ancestral troughs that were isolated basins. In addition, the Coprates/north Melas/Ius system may not have existed when the layered deposits were emplaced. If so, the amount of material eroded from trough walls at that time would have been only about half as much as the estimated total (Table 6 and Figure 11).

Even if Ius and Coprates Chasmata had already existed, it would have been difficult to transport eroded wall material from these troughs through the low area in Melas Chasma and then uphill toward Ophir and Candor Chasmata to form the thick, high-level deposits there. Instead, the deposits should have come to rest in low-lying central Melas Chasma instead (Plates 2 and 3), but no major deposits are found in this area. Furthermore, all of this wall material would have to be transported not only toward the central troughs, but through the relatively narrow isthmus connecting Melas and Candor Chasmata (Plate 2).

We conclude that the interior layered deposits were probably not built entirely from mass-wasted wall rock, but that this rock contributed significantly to their formation. However this conclusion, even though generally true at the scale of our investigation, should be verified by a study of individual troughs. We attempted to apply our measurements to individual troughs, but we soon realized that for local,

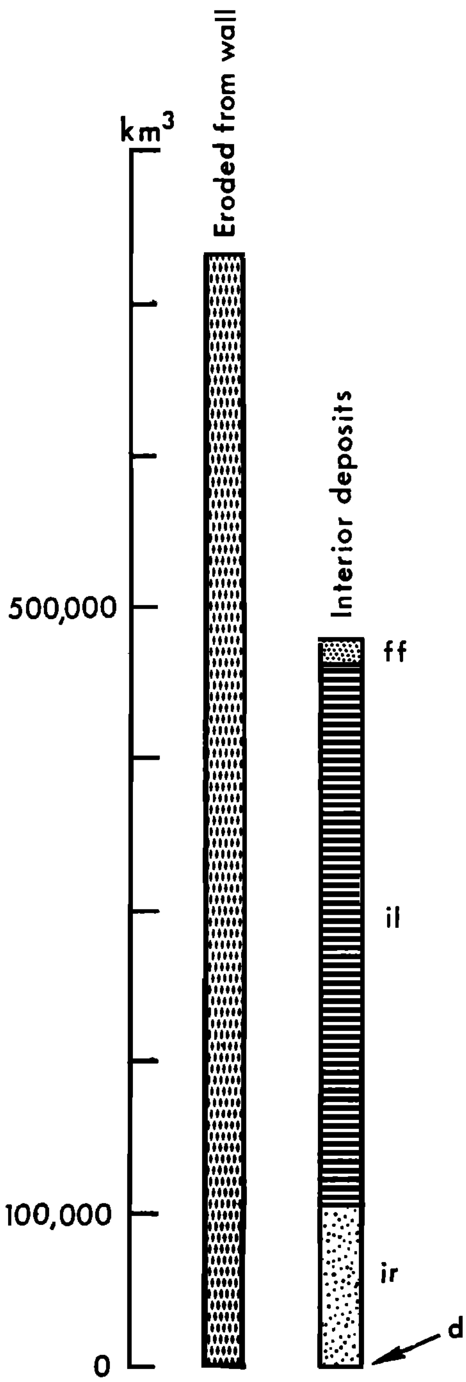

Figure 10. Comparison of volumes of eroded wall rock and of interior deposits. Void space above wall reflecting volume of eroded material is at left; volume of interior deposits composed of dark material (d), irregular material (ir), interior layered deposits (il), and thick fill on floors (ff) is at right. The material eroded from the walls exceeds the deposit volume by about one-third (see text for discussion).

Table 6. Volume of Wall Material Eroded From Individual Troughs

Chasma	Volume, km^3	Volume, %
Echus	6,800	0.93
Hebes	29,730	4.05
Juventae	7,340	1.00
Tithonium	55,760	7.60
Ius	167,100	22.79
Ophir	25,070	3.42
West Candor	29,100	3.97
Central Candor	31,980	4.36
East Candor	58,870	8.03
Melas	90,630	12.36
Coprates	173,280	23.63
Gangis	32,680	4.46
Capri/Eos	24,920	3.40
Total	733,260	

Percentages are of total eroded wall material.

detailed studies one needs refined, large-scale geologic/geomorphic maps and large-scale topographic maps with better vertical resolution.

Derivation of Interior Layered Deposits From Other Sources

If the ancestral central troughs were isolated basins containing segregated ice and water, and if, like the peripheral troughs, they formed mostly from erosional collapse, much of the material in the interior layered deposits could be disintegrated, in situ material reworked by wave or current action. The assumption is that lakes were present and that the climate was warm enough that the water was not frozen. In favor of the argument is the observation that the interior deposits occupy only one-sixth of the space inside the troughs; the material that occupied the space now void could have been condensed into deposits, and the rest could have evaporated or sublimated. Also in favor is the relatively irregular shape of south Melas Chasma, suggesting that collapse processes may have been active in the ancestral central troughs.

On the other hand, the central troughs in general are much deeper than the peripheral troughs and are bounded by straight walls, suggesting that the ancestral central troughs were already controlled by tectonism and that their floors were dropped structurally. Also, the south boundary of Melas Chasma may follow the structural imprint of an old crater rim, and its rounded shape may not necessarily indicate formation by erosional collapse. Another problem is that local reworking of preexisting material does not explain free-standing mesas such as the mesa in Hebes Chasma. In addition, in the peripheral troughs, where collapse processes were common and the existence of former lakes is more likely, we see little evidence that chaotic material, a disintegration product, was reworked into stratified deposits. In fact, the stratified deposits bury chaotic material [*Witbeck et al.*, 1991]. Therefore, it is more likely that the ancestral central troughs were largely formed by faulting, that erosional collapse was only a subsidiary process, and that most of the interior layered deposits are not composed of disintegration products reworked in situ.

If the ancestral central troughs formed mostly by faulting, the void space in these troughs is largely due to the downdropping of the floor, and the previously discussed premise applies: not enough material was available from the eroded walls to build the layered deposits. As no major channels empty into the troughs, the additional material may have been derived from subterranean piping. *Croft* [1989] argued that the strings of chain craters in the region, evidently collapse features, point toward large underground flow. But such flow would produce carbonates, not detritus, and most sapping valleys occur in Ius Chasma, where no interior layered deposits are found; in Ophir, Candor, and Hebes Chasmata, where most of the layered deposits occur, the sapping valleys are scarcer. A possible origin of the interior deposits as carbonates has indeed been suggested by *McKay and Nedell* [1988], *Croft* [1989], *McEwen and Soderblom*

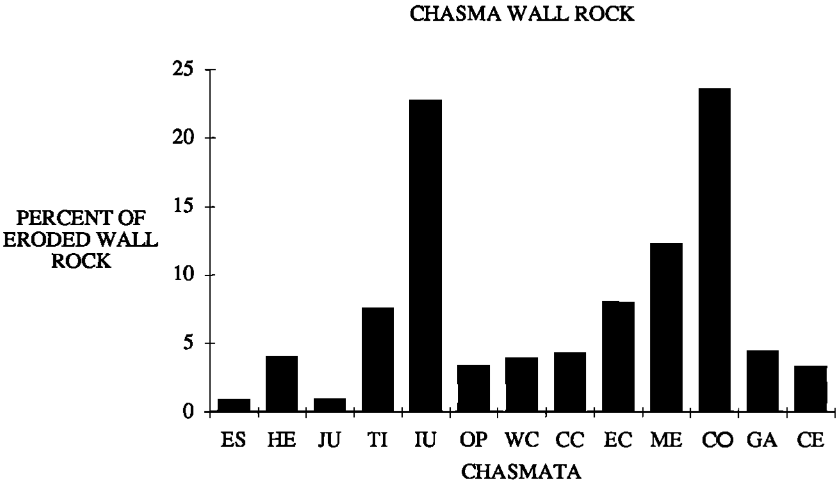

Figure 11. Volume percentages of material eroded from walls of individual chasmata. ES, Echus; HE, Hebes; JU, Juventae; TI, Tithonium; IU, Ius; OP, Ophir; WC, west Candor; CC, central Candor; EC, east Candor; ME, Melas; CO, Coprates; GA, Gangis; CE, Capri/Eos.

Figure 12. Interior layered deposits in east Candor Chasma. Dashed line separates massive lower deposits (l) from diversely bedded upper deposits (u) having different thicknesses and different resistance to erosion. Part of Viking Orbiter image 815A58.

[1989], and *Spencer and Fanale* [1990]; but no spectral evidence for carbonates was found by these workers. Winds probably also blew in material, which was trapped inside the Valles Marineris but not on the surrounding plateaus [*Nedell et al.*, 1987]. However, the diversity of the layers in most places suggests that eolian material is not dominant. The above arguments lead to the conclusion that another mechanism is needed to supply additional material. Again, it appears that volcanism is a likely alternative.

Images of the layered deposits in the central troughs suggest that they were emplaced by different processes. As Figure 12 shows, the lower beds in the depicted mesa of layered deposits are massive, and the upper beds are more diverse and include finely layered and resistant units. This configuration also seems to be present elsewhere in the central troughs [*Nedell et al.*, 1987; *Lucchitta et al.*, 1992]. It is possible that the lower massive units were deposited in ancestral lake basins and were built largely from mass-wasted material. This idea is supported by spectral investigations [*Geissler et al.*, 1990] showing that the signature of interior layered deposits is similar to that of wall rock. The appearance of the upper layered deposits is more compatible with that of volcanic rock, which could have topped the mesas in Ophir, Candor, and Hebes Chasmata. Of course, these observations do not preclude the possible contributions of volcanism also to layers in the lower beds and of mass wasting to layers in the upper beds.

Summary and Conclusions

The topography of the Valles Marineris was analyzed to gain insights into the elevation and volume relations of trough floors, wall rock, and interior deposits. The purpose was to understand better the structural and erosional evolution of the troughs. To this end, we compiled a simplified geologic/geomorphic map on the digital terrain model of the Valles Marineris. Then we evaluated elevations in the vicinity of the troughs and calculated the depth of troughs below the adjacent plateau rims, the thickness of deposits inside the troughs, the volumes of void spaces above geologic/geomorphic units, and the volumes of deposits.

The area underlain by trough walls is about one-third that of the total area of the troughs. North Ophir, north and central Candor, and north Melas are the deepest chasmata, lying as much as 11 km below the adjacent plateaus. The void space inside the Valles Marineris is about 6 times the volume occupied by deposits.

Central Troughs

The favored hypothesis for the origin of the interior layered deposits is that they are sediments emplaced in lakes. However, in Ophir and Candor Chasmata, lakes could not have been sustained if all the troughs were interconnected; lake waters in these troughs would have to reach 8-km elevations to lay down the uppermost layered deposits. These high-standing lakes would have spilled out of Coprates Chasma onto the surrounding plateaus that have surface elevations of only 4-5 km. If the lakes were interconnected, their levels inside the central troughs could not have been higher than about 4 km. Thus, the upper interior layered deposits cannot be lake sediments. A likely alternative is that they are volcanic.

On the other hand, the troughs may not have been interconnected but may have formed isolated basins when the interior layered deposits were emplaced. As also shown by independent structural and stratigraphic evidence, these ancestral basins occupied the southern parts of Ophir, Candor, and Melas Chasmata [*Lucchitta and Bertolini*, 1990]. The northern parts of these troughs and the entire Coprates/north Melas/Ius graben system may have formed later, after deposition of the interior layered deposits.

Peripheral Troughs

The peripheral troughs Juventae, Gangis, and Capri/Eos Chasmata, reaching depths of 2-5 km, are shallower than the central troughs. Our investigation showed that they most likely formed from a combination of erosional collapse and structural activity. Furthermore, the presence of chaotic material in these troughs at similar elevations (near the 4-km contour on the adjacent plateau surfaces) supports the idea that the chaotic material may have indeed formed from release of confined artesian water [*Carr*, 1979]. In the peripheral troughs, the interior layered deposits bury chaotic material, indicating that lakes formed after the chaotic collapse of the surface (if the layered deposits are indeed lake sediments). The lakes were apparently breached only later to form the presently observed outflow channels [*Komatsu et al.*, 1993]. However, the layered deposits in these troughs may not be lake sediments at all; they may be volcanic materials, as is perhaps true for deposits in the central troughs. A volcanic composition is suggested because in Gangis and Juventae Chasmata the layered deposits occur in free-standing mesas that have the shape of Icelandic table mountains [*Van Bemmelen and Rutten*, 1955], a form supporting the idea of emplacement beneath ice. The volcanic materials could have been erupted below segregated ice masses postulated for those areas [*Howard*, 1991], or they could have formed in shallow, completely frozen lakes. The main scarps of the mesas rise about 2 km above the trough floors, a thickness consistent with the approximate depth of frozen ground in the equatorial area [*Rossbacher and Judson*, 1981].

Interior Layered Deposits as Redeposited Wall Rock

The troughs were significantly widened by erosion, but volumetric comparisons and topographic and geomorphic analyses show that material eroded from trough walls may not have been sufficient to be the sole source of interior layered deposits. Even though the total eroded and deposited volumes match approximately, to fill Ophir and Candor Chasmata with eroded wall material from Coprates and Ius Chasmata would have required uphill transport of material into the central troughs, an improbable concept. Also, the Coprates/north Melas/Ius system may not have existed when the layered deposits were emplaced; if it did not, the amount of material eroded from trough walls at that time would have been only about half as much as the estimated total. Because of these considerations, it is likely that other material contributed to the formation of layered deposits. Some may have come from subterranean piping, some from reworking of material disintegrated in situ (if the ancestral troughs were formed largely by collapse), some from trapping of lofted sediments. But, because these processes probably did not furnish enough material, volcanism again remains as a possible major contributor. Perhaps the lower massive deposits are dominantly redeposited wall rock and other mass-wasted material, whereas the upper thinner bedded units are dominantly volcanic.

History

A brief history of the Valles Marineris, based on the above observations, can be envisioned as follows. In the region of the central troughs, ancestral deep basins formed partly from collapse, but mostly from structural adjustment along previous structural alignments. These basins, which may have contained lakes, were filled mostly with mass-wasted material near the bottom and with volcanic material near the top. Probably at the same time the peripheral troughs formed, mostly by collapse due to eruption of artesian water. In these troughs, layered deposits were emplaced in ancestral lakes, which were eventually drained by the outflow channels we see today. Later, the central basins were widened and deepened by the addition of subsidiary northern grabens. The Ccprates/north Melas/Ius graben system cut the entire region, including the ancestral Melas Chasma. These new grabens connected the troughs with one another and with the peripheral troughs in the east. When all the troughs merged, a major flood may have emptied the central troughs. However, it is more likely that no flood ensued because lakes in those troughs had already vanished, and the troughs were filled with sediments and volcanic material.

Alternatively, all troughs were interconnected early in their development. No deep lakes formed, and thus the layered deposits are probably largely of volcanic origin. Volcanic material in the peripheral troughs may have been emplaced as table mountains.

Even though both scenarios are within the constraints of the topographic analysis, a combination of them is probably closer to reality. Lakes were more likely to have existed in the peripheral troughs than in the central trough, and volcanic materials were more likely present in the upper than in the lower interior deposits.

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