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Stratigraphy and Erosional Landforms of Layered Deposits in Valles Marineris, Mars

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The complex stratigraphy of layered deposits suggests a diversity of origins, ages, and post-depositional modification histories. The complexities within some layered deposits indicate changes in the dominant source materials in space and time. The stratigraphy of layered deposits in the isolated Martian chasmata Hebes, Juventae and Gangis is not well correlated. This indicates that at least these chasmata had isolated depositional environments resulting in different stratigraphic sequences. Separated layered deposits in Ophir-Candor and Melas Chasmata might have been a single continuous deposit in each chasma. Chaotic terrains are found in conjunction with layered deposits in Juventae, Gangis and Capri-Eos Chasmata. In these chasmata, layered deposits unconformably overlie chaotic terrains. Chaotic terrain formation may have provided water to form paleolakes, and lacustrine deposition of thick layered deposits may have occurred if the canyons were closed. A very thick sequence of the layered deposits has been exposed by erosion. A combination of gradual processes such as evaporation of ice and eolian and fluvial transport in addition to structural processes may be responsible for this erosion. Another alternative is that catastrophic water release under the layered deposits disrupted and initiated erosion of the layered deposits. Newly identified units of anomalous color are confined to the depressions or reentrants in western Candor Chasma. The difference in color between these units and the surrounding terrain is most consistent with a somewhat greater content of bulk crystalline hematite in these anomalous units. The presence of the Candor units is a result of original and/or secondary deposition which is different from the primary and dominant formation of the layered deposits.

INTRODUCTION

The layered deposits in Valles Marineris are of great interest because of their relationships to canyon evolution, their generally great thicknesses, and their implications for depositional and erosional histories in the canyon. A variety of sources and depositional environments have been proposed to explain the layered deposits, including non aqueous eolian deposition [Peterson, 1981], non aqueous volcanic deposition [Peterson, 1981; Lucchitta, 1981], and lacustrine volcanic, eolian, or canyon wall-derived deposition [McCauley, 1978; Lucchitta, 1982; Nedell et al., 1987; Squyres, 1989]. Nedell et al. [1987] described in detail the deposits mostly in Ophir-Candor Chasmata and their geographic distribution, compared them with other canyon materials, determined the thickness of several individual layers, derived a depositional time sequence, and critically evaluated a variety of possible origins and depositional environments. They concluded that the deposits were most likely of sedimentary origin deposited in a low-energy lacustrine environment by one or more uncertain processes. Because the deposits are relatively young, they assumed essentially present-day climatic conditions requiring the lakes to be ice covered during sedimentation.

More recently, McKay and Nedell [1988] speculated that the layered deposits may be carbonate minerals precipitated from atmospheric CO_2. Spencer and Fanale [1990] suggested reprecipitation of carbonate from the excavated canyons. McKay and Nedell's attempt to detect carbonate rocks from Mariner 6/7 infrared spectral data in the wavelength region between 2 and 6 microns was unsuccessful. However, they speculated that the lack of detection may be caused by eolian mantling.

Erard et al. [1991] examined multi spectral images acquired by the ISM imaging spectrometer on Phobos II, and noted that layered deposits have stronger 3 microns water absorptions than materials of comparable albedo on the plateau, and are interpreted to be more hydrated. Murchie et al. [1992] used the same data sets to detect compositional variations in the layered deposits of Ophir, Candor and Melas Chasmata. They found spectral heterogeneity among the layered deposits. The pyroxene absorptions differ between the layered deposits, and none of the major layered deposits has pyroxene absorptions that closely match the pyroxene absorption in the wall rock or on the plateau plains. Capping strata in Melas Chasma is dark with weak water absorption bands (weak 3 microns water absorption). Layered materials in Melas and Eos Chasmata are dark and have a large fraction of incorporated water (strong 3 microns water absorption). In Candor and Ophir Chasmata, the deposits are bright and have a large fraction of incorporated water (strong 3 microns water absorption). The deposits seem to be of mafic composition with different amounts of incorporated water and ferric iron. No carbonates were detected in these deposits at a spatial resolution of about 22 km. In this paper, we attempt to stratigraphically correlate various layered deposits in all chasmata, identify new stratigraphic relationships within individual deposits, re-examine the erosional processes and history of the deposits, and incorporate new Viking spectral information that bears on their origin.

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Thirteen major layered deposits have been identified in Valles Marineris. They are shown in Figures 1a and 1b modified from Nedell et al. [1987]. They occur in Gangis, Juventae, Hebes, Ophir-Candor, Melas and Capri-Eos Chasmata. Although they are widely distributed in the canyon system, they are present only in wider sections of the canyon. It is possible that dust or debris slides have obscured other deposits rendering them unrecognizable.

GENERAL DESCRIPTION

Altitudes in Hebes, Ophir, Candor and Melas Chasmata and of their interior deposits were obtained from the U.S. Geological Survey [1986]. Those in Gangis, Juventae and Capri-Eos Chasmata were obtained from the U.S. Geological Survey [1989], while the heights of their interior layered deposits were estimated by comparing Viking stereoscopic pairs with the topographic map. The base of most layered deposits is uncertain because of younger surrounding floor deposits. However, the base is clearly defined where deposits unconformably overlie chaotic terrain.

Except for Capri-Eos Chasmata, where the average image resolution is about 200-300 m/pixel, the deposits were imaged at resolutions between 30-80 m/pixel. At least two or three images of different viewing geometries were available for each deposit.

Gangis Chasma. The Gangis Chasma layered deposit (Figure 2) is located in the western part of the chasma. It is about 110 km long and 30-50 km wide with an average height above the canyon floor estimated to be 1-2 km. The deposit seems to overlie unconformably the chaotic terrains. This deposit has two major units. The heavily fluted lower unit appears to be more massive, but contains a dark layer which is tilted toward the west at a shallow angle to the upper unit (Figure 2). This tilted dark layer is truncated by the upper unit suggesting the boundary between the two units is an angular unconformity (Figure 2). In the upper unit are many near-horizontal benches which are probably layers (Figure 3a). On top of the upper unit are several domes and ridges of low albedo [Komatsu and Strom, 1990] (Figure 3a). These structures are associated with a broader low albedo area. The eastern portion of the deposit contains two blocky slabs leaning against the main deposit (Figure 3b). These slabs contain wavy light layers suggesting they originated by slumping.

Juventae Chasma. Juventae Chasma has two layered deposits (Figure 4). The northern deposit is about 50 km long, 10-20 km wide with an average height estimated to be less than 1 km. It appears to be massive with pronounced erosional dissection (Figure 5). The central portion of this deposit has a channel-like feature that may be the result of fluvial action, although structural and/or eolian origins are also possible. The deposit unconformably overlies chaotic terrains on the canyon floor. The southern deposit occurs about 25 km south of the northern one. It is about 25 km long, 10 km wide, and thinner and at a lower elevation than the northern deposit. The upper two-thirds of this deposit is

Fig. 1. 1a. Viking mosaic of central and eastern Valles Marineris (orbit number 1334). The image was provided by A.S. McEwen (orbit number 334, survey mission).

characterized by numerous thin, narrow alternating light and dark bands which appear to be albedo features or benches depending on the viewing geometry (Figures 6a and 6b), whereas the lower one-third appears to be more massive.

Hebes Chasma. The Hebes Chasma layered deposit occupies the center of the closed chasma (Figures 1a and 1b). It is about 130 km long, 20-40 km wide and 4-5 km high. This deposit consists of two major units (Figure 7). The lower unit is thick, and heavily fluted, with possibly discontinuous two dark layers near the middle and one near the top. These dark layers are not well-fluted, indicating that they are more resistant than the other layers [Peterson, 1981]. The upper cap unit appears massive and is up to 1 km thick. It does not have fluting, and thus differs in its erosional style from the unit below. This cap layer shows two horizontal dark layers at or near its base (Figure 15a).

Ophir-Candor Chasmata. There are four major layered deposits in these chasmata (a, b, c and d in Figure 1b). At least deposits b, c, and the western part of d appear to have two major units; an upper nonfluted thinly bedded unit, and a lower heavily fluted unit. The upper units of c, d deposits show convincing evidence of thin lithologic layers characterized by ledges and indentations representing alternating resistant and weak strata (Figures 8 and 9). Upper portion of deposit b has fine layers exposed as light and dark bands [Nedell et al., 1987]. These upper layers are apparently absent from the eastern part of deposit d, and may have been completely eroded away or never deposited. Although more obscure than the upper unit, the lower unit also has layering at several locations but seems coarser than in the upper unit [Nedell et al., 1987]. Deposits c and d clearly cover part of an extension of the canyon wall separating Ophir from Candor Chasma [Lucchitta, 1982; Lucchitta and Ferguson, 1983] (Figure 1a). Deposit b shows near-horizontal erosional benches (Figure 10).

The deposit in western Candor Chasmata (a), as well as the eastern part of deposit d, is much more heavily eroded than the others. The upper part of deposit a displays thin, narrow albedo bands or benches which appear to be enhanced layers (Figure 11). It is surrounded and partially covered by younger hummocky material [Lucchitta, 1990] which may be covering the lower heavily fluted unit seen in nearby deposits.

Melas Chasma. There are three separate but closely spaced layered deposits in this chasma (Figure 1b). The thickness of each is about 1-3 km, and the tops are 3-5 km lower than surrounding plateaus. The two largest deposits show erosional benches which may represent internal layers. At least one dark layer occurs in each deposit at about the same stratigraphic position (Figure 12).

Capri-Eos Chasmata. Two large deposits (300 and 60 km across and about 2-3 km high) occur in this canyon system. Because of the lack of high resolution coverage of this chasma, it is impossible to determine whether these deposits are layered. However, their erosional style, geological setting and spectral

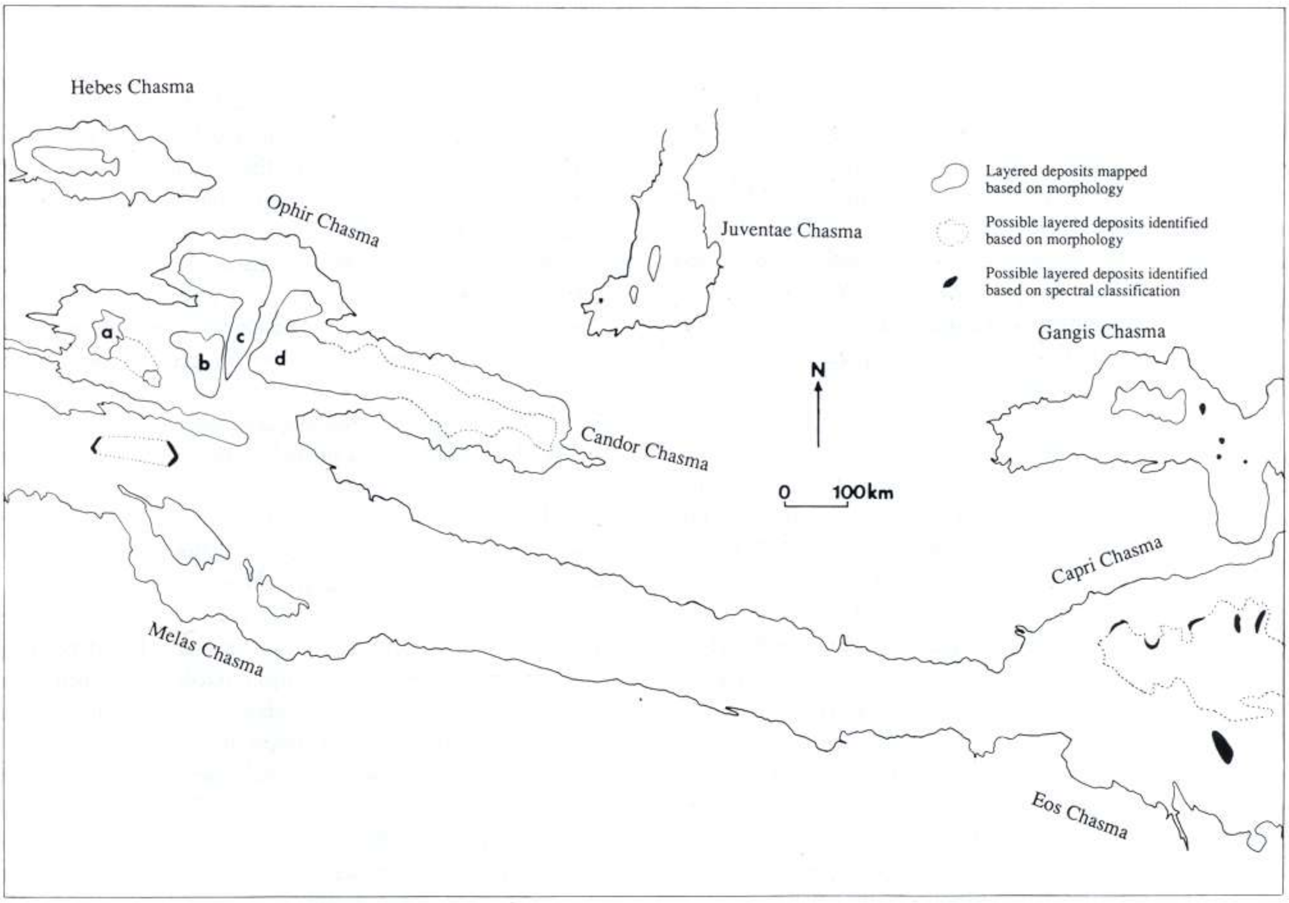

Fig. 1b. Location of layered deposits in Valles Marineris modified from Nedell et al. [1987]. Layered deposits in Ophir-Candor Chasmata are labeled a, b, c, and d for discussion. See text.

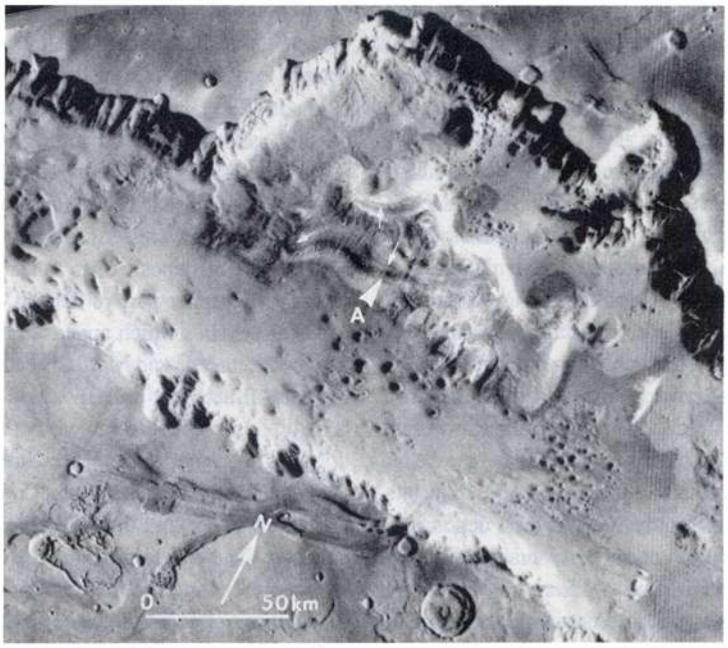

Fig. 2. Gangis Chasma layered deposit (Viking frame 610A13). A possible angular unconformity is observed, shown by a tilted dark layer (A) truncated by overlying strata (boundary indicated by small arrows).

properties are similar to other layered deposits (Figure 1b). They appear to unconformably overlie chaotic terrains (Figure 13).

STRATIGRAPHIC CORRELATION

Important issues are depositional environment, source and erosional history of the layered deposits. To address these questions, we compared the stratigraphy and spectral characteristics of deposits at various locations in Valles Marineris by using texture, albedo, color, thickness and erosional style. In Figure 14, the altitudes of canyon floors, surrounding plateaus and layered deposits are compared schematically. We note that it is often difficult to distinguish between albedo bands and benches (e.g., Figure 6a and 6b). Benches give the impression of multiple layers, and were so interpreted by Nedell et al. [1987]. However, this depends on their origin. They could be due to differential erosion of multiple layers with different lithologies by a variety of processes including eolian, masswasting, weathering, fluvial, wave-cut, or ice-shoving processes, or in some cases they could be wave-cut or ice-shoving shorelines [Komatsu et al., 1991]. We can be sure about a presence of internal layers only when they are observed as albedo features (e.g., Figures 2, 7, and 12), or characterized by ledges and indentations (e.g., Figures 8 and 9). Therefore, in the stratigraphic correlations discussed below we avoid using benches alone as evidence of internal layers.

The two largest deposits in Melas Chasma have similar erosional styles, thicknesses, colors, and a dark layer at the same stratigraphic position. The other deposit is situated between the large deposits but is much smaller and highly eroded. This may be an erosional remnant of these larger deposits, and all three deposits could have once been connected.

The deposits in Ophir-Candor Chasmata are probably erosional remnants of a once larger deposit. In at least three deposits (b, c and d) the erosional style (fluting of the lower unit) and multiple layers in the upper unit are similar (Figure 14), suggesting a common origin. It is not clear whether deposit a has the same stratigraphy as the other deposits. The benches of deposit a could represent multiple layers similar to those seen in the upper unit of the other deposits. Furthermore, the base of this deposit has been covered with younger deposits possibly masking the fluted lower unit. The largest distance separating the four deposits is about 70 km between deposits a and b. The minimum distance separating deposits b, c and d is only 5-10 km. These deposits have clearly been separated and it would be remarkable if they were not once part of a single deposit. It is uncertain whether these deposits were once part of the Melas Chasma deposits, or were separated by a segment of the canyon wall that subsequently has been eroded away.

The deposits in Hebes, Juventae, and Gangis Chasmata show distinctive characteristics and modes of occurrence that set them apart from the other deposits described above. Unlike other deposits the layered deposit in Hebes Chasma occupies an isolated enclosed canyon and consists of two major units each with multiple, thick, dark layers. The deposit in Gangis Chasma shows at least one unconformity, only one thick dark layer, and occupies a canyon that is open only at its eastern end. The deposits in Juventae also occupy an isolated canyon that is partly open to the north. Because the Hebes deposit occurs in a closed canyon and is stratigraphically distinct from the others, it was surely formed in a depositional environment isolated from those of the other layered terrains. The correlation of the stratigraphy of the Gangis and Juventae deposits with other deposits is uncertain, but their relative isolation and restricted openings suggest that they were also formed in isolated depositional environments.

In summary, the layered deposits in Ophir-Candor, and Melas Chasmata were possibly once a single deposit laid down in each

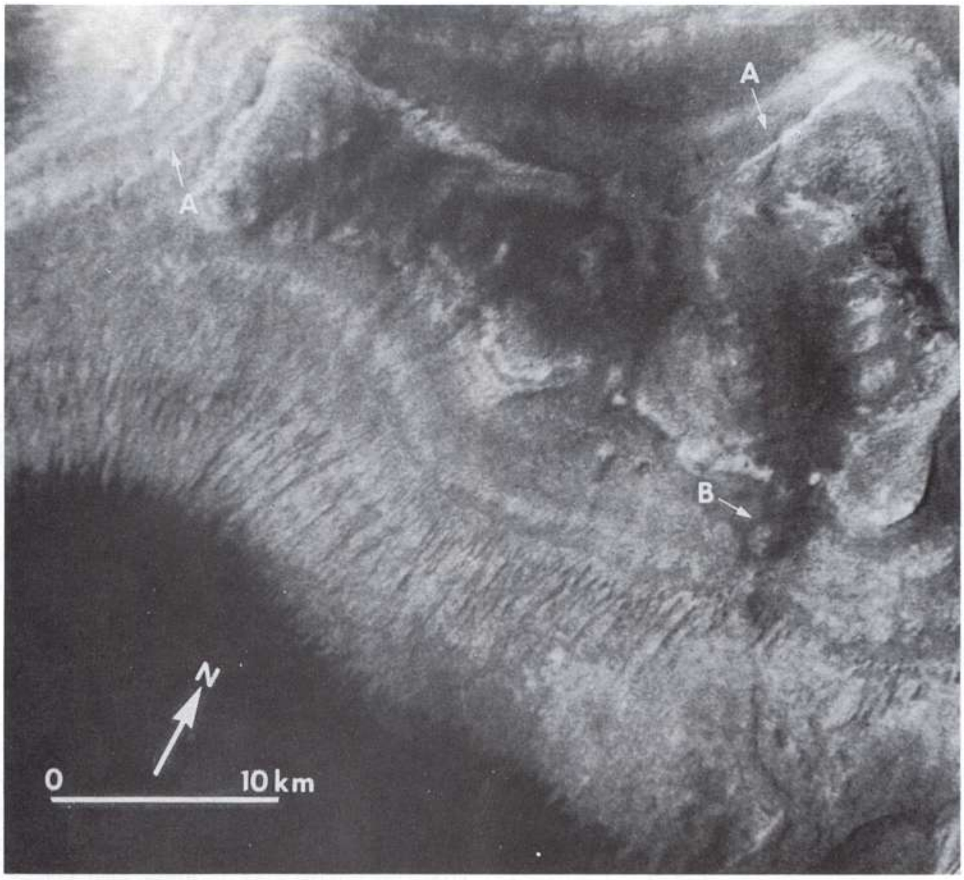

Fig. 3a. Mariner 9 high resolution image of Gangis Chasma layered deposit (Mariner 9 frame 9017619). The arrow (A) shows erosional benches. The arrow (B) shows a dome-like structure which may be an eroded volcanic remnant.

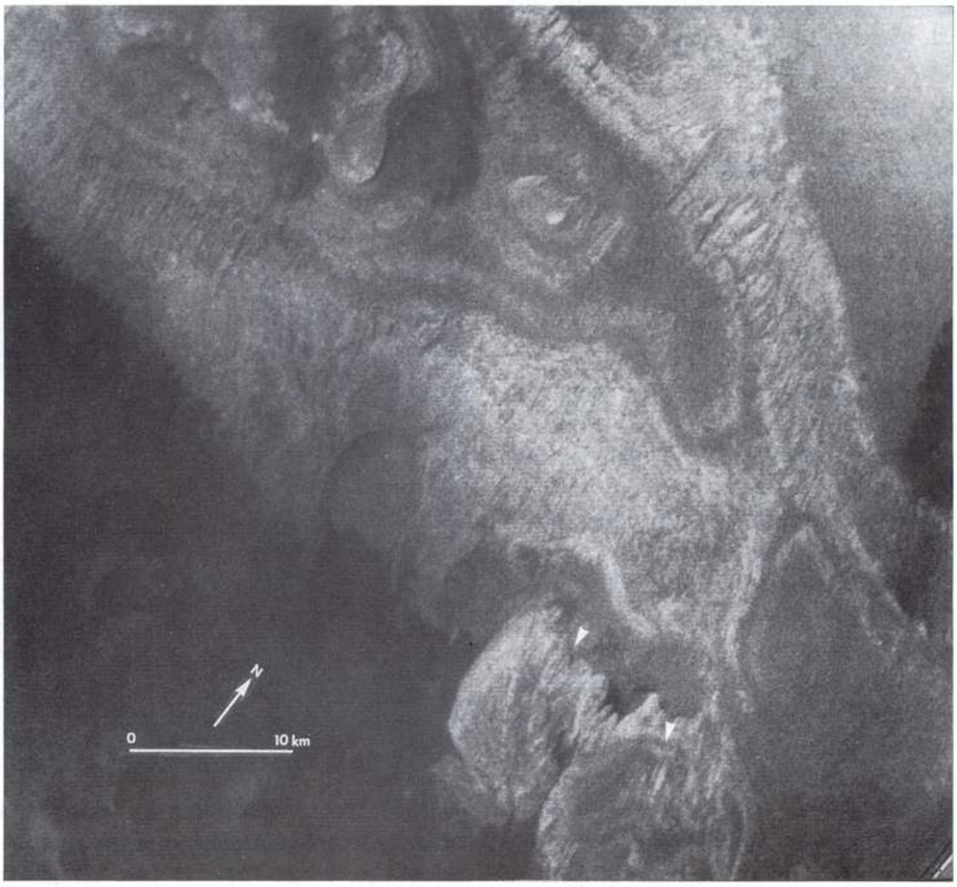

Fig. 3b. Mariner 9 high resolution image of Gang's Chasma layered deposit (Mariner 9 frame 1049263). The arrows show blocky slabs and wavy light layers.

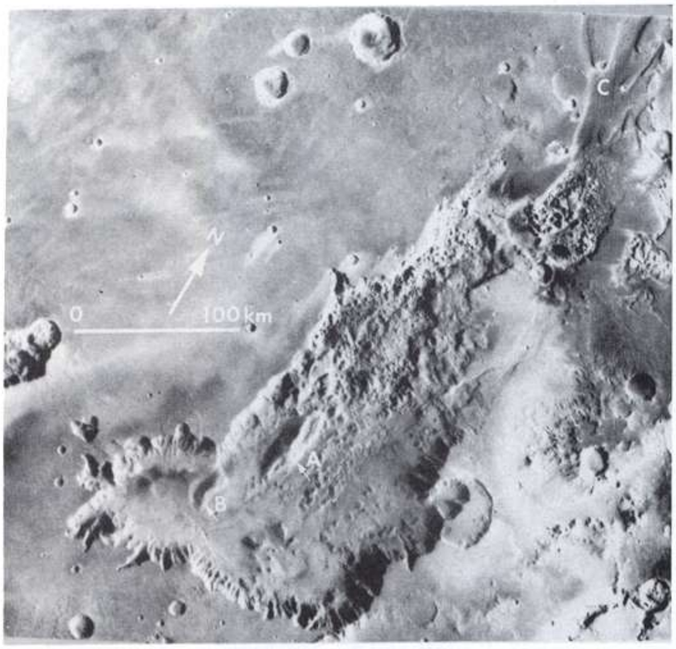

Fig. 4. Juventae Chasma and layered deposits (Viking frame 684A49). Northern deposit (A) is located about 25 km north of southern deposit (B). Juventae Chasma is a source for the outflow channel (C) to the north.

chasma. Whether this canyon system was closed or open to the south at the time of deposition is unknown. The deposits in Hebes, Juventae, and Gangis Chasmata were probably each deposited in isolated segments of the canyon under closed depositional conditions. Major differences in the stratigraphy between these deposits suggest that their sources and history were controlled by local or regional factors different from those in other parts of Valles Marineris. This further suggests that global eolian processes were not the sole or dominant source of the sediments; otherwise the sedimentary sequences should be similar in all parts of the canyon.

SPECTRAL CHARACTERISTICS

In general, the steep slopes of layered deposits are similar in color and albedo to nearby canyon wall rock in low-resolution apoapsis Viking Orbiter color images produced from the 0.45 (violet), 0.53 (green) and 0.59 (red) micron filters. As noted by Lucchitta et al. [1992], these slopes have been exposed by erosion and are presumably free of thick mantling dust deposits. Although limited in spectral range and resolution, the color observations exclude any gross compositional difference between the layered deposits and the surrounding plains materials which might be distinguished at visible wavelengths [Lucchitta et al., 1992] (Figures 15a and 15b). For this reason, multispectral mapping techniques such as employed by Geissler et al. [1990] cannot by themselves uniquely discriminate between layered deposits and isolated plateaus of plains within the canyons. However, some of the units identified here to be spectrally similar in the Viking color to the layered deposits (Figure 1b) were also mapped as "possible layered chasma deposits" by Nedell et al. [1987] based on distinct mottling, fluting, and texture, and this may indicate a genetic relationship between these units and layered deposits.

Two of the layered deposits show color variations in Viking multispectral images indicative of compositional differences either within the layered deposits themselves or between the layered deposits and wall rock. A thick, dark gray unit is interbedded in the sediments comprising the central plateau of Hebes Chasma (Figure 15a) but is absent from the nearby canyon walls. The three-color spectrum of this material (Figure 15b) indicates that it is relatively unoxidized, similar to dark materials in Ophir-Candor Chasmata presumed to be of volcanic origin [Lucchitta, 1990; Geissler et al., 1990]. Erosion of the central mesa leaves an accumulation of mobile dark sands in the "moat" surrounding the interior deposit, which occasionally blow over the rim of Hebes Chasma.

A spectrally anomalous region occurs in the western Candor Chasma [P.E. Geissler et al., An unusual spectral unit in West Candor Chasma: Evidence for agueous or hydrothermal alteration in the Martian canyons, submitted to Icarus, 1993]. Here two depressions or reentrants in heavily eroded layered deposits correspond to a spectral unit distinctively redder at visible wavelengths than surrounding bright materials of similar albedo (Figures 11, 15a, and Plate 1). Viking three-point spectra (Figure 15b) show that the unit has a higher red/green ratio than elsewhere in the canyon; relative to the violet and red values, the green filter reflectance is lower than observed for surrounding regions. The unique hue of the unit at visible wavelengths is consistent with an interpretation of a relatively higher abundance

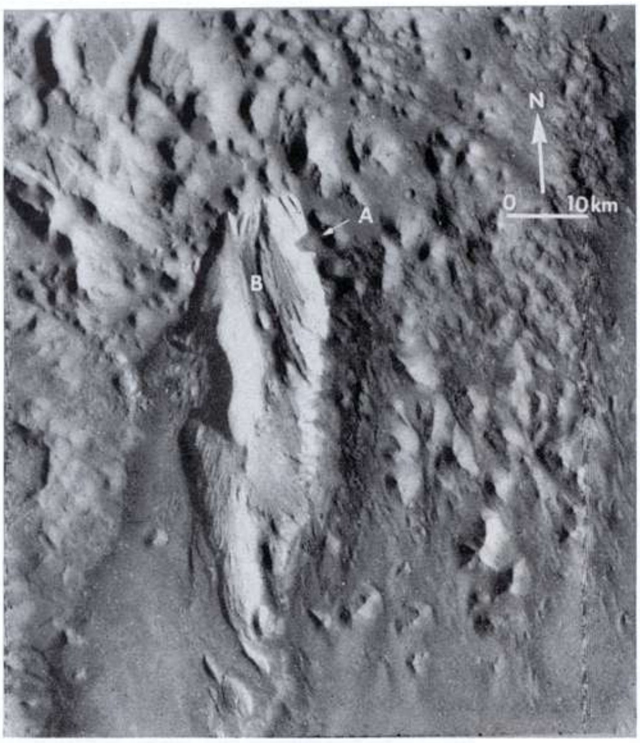

Fig. 5. Northern Juventae Chasma layered deposit (image frame 906A06). It unconformably overlies chaotic terrain (A). The channel-like feature (B) may have formed by fluvial erosion, although other possibilities (e.g., structural, eolian) are possible.

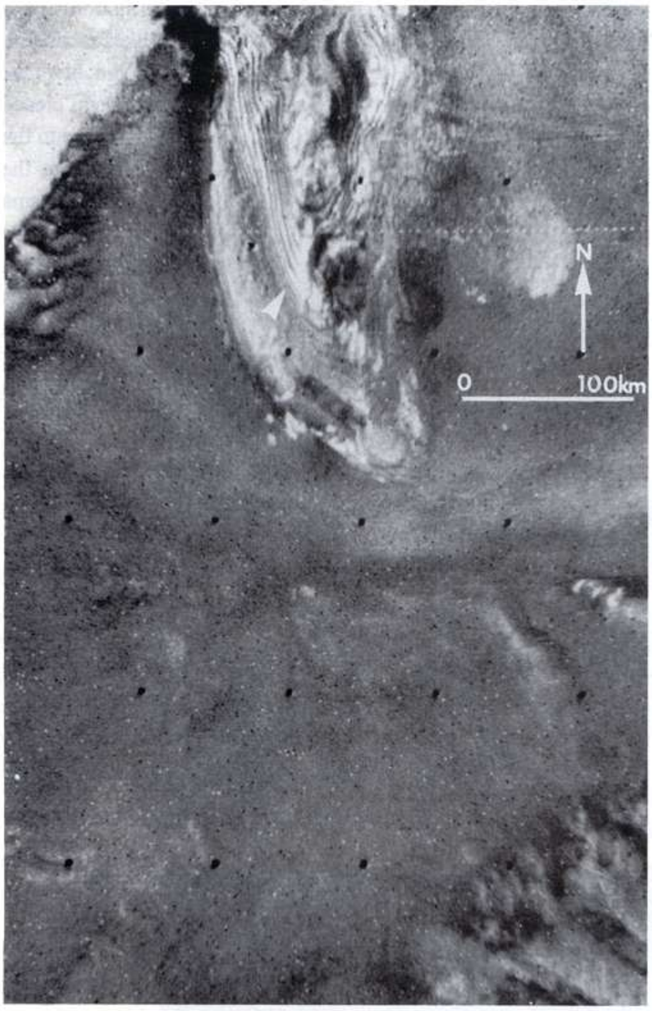

Fig. 6a. Southern Juventae Chasma layered deposit. In (a), Viking frame 081A15, it seems to have thin layers appearing as albedo features.

of bulk crystalline hematite in this region. The near-infrared spectral reflectance as measured by the ISM instrument on Phobos II indicates a local enrichment in ferric oxides or oxyhydroxides in the region and suggests the presence of a phase additional to hematite (P.E. Geissler et al., submitted manuscript, 1993; R.B. Singer et al., manuscript in preparation, 1993).

DISCUSSION

Depositional Environment

Recent studies of paleolakes and sedimentary basins [Goldspiel and Squyres, 1991; Scott and Chapman, 1991; Scott et al., 1992], and possible ancient oceans in the northern plains [Parker et al., 1989; Baker et al., 1991] indicate that Mars could have had large bodies of surface water in its recent geologic past. This evidence includes sediments, shoreline features, and source channels draining into the basins. The circumstantial evidence seems to support the paleolake hypothesis or at least hydrological activity for Valles Marineris. Lucchitta [1982] pointed out that the spur and gully topography of canyon walls resembles subaqueous slope topography. The chaotic terrains identified in central and eastern Candor Chasma by Lucchitta and Ferguson [1983] were interpreted to be where pools of water formed. Also absorbed water was detected in the layered deposits by Phobos II ISM Imaging Spectrometer [Murchie et al., 1992]. The hydration could be a result of hydrothermal activity, or eruption of volcanics into ground water/ice or an aqueous environment. Nedell et al. [1987] consider the deposits to have been laid down in an aqueous (lacustrine) environment based on the thin layering which is consistent with a low-energy regime [McCauley, 1978], and by showing that other environments were less likely. Lacustrine deposition is not an absolute necessity, but is consistent with the paleolake hypothesis.

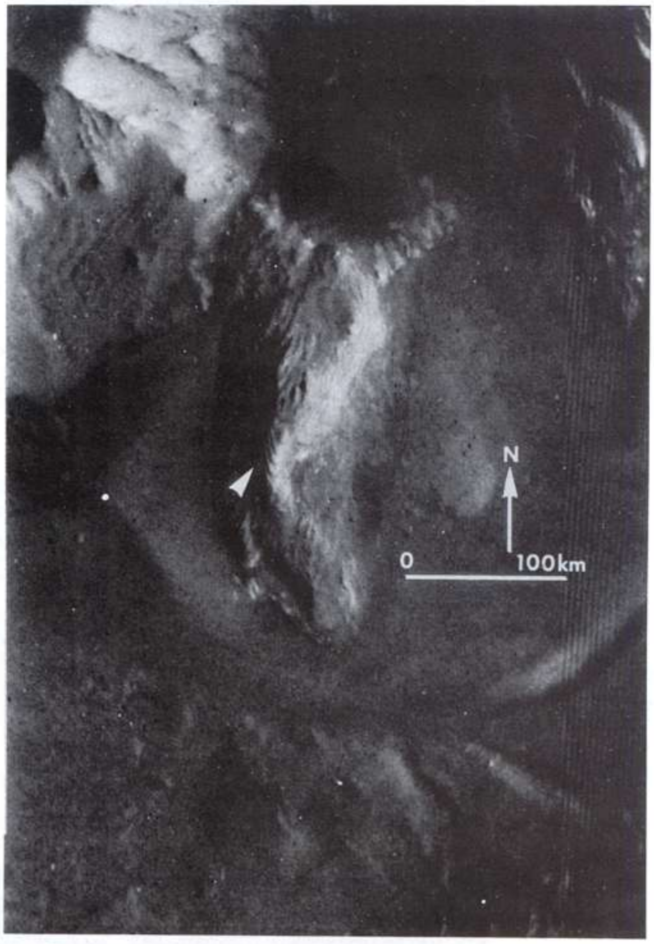

Fig. 6b. In (b), the light and dark bands that appear in (a) are possibly benches (Viking frame 907A05).

In applying a lacustrine origin to the layered deposits in Valles Marineris, the biggest questions are the sources of water and the topography of the canyons. Where canyon deposits and chaotic terrain occur together (in Juventae, Capri-Eos, and Gangis Chasmata), the deposits appear to unconformably overlie the chaotic terrains, and are probably younger. These relationships were also noted by Witbeck et al. [1991]. The chaotic terrain formation may have been a source of water for lake formation. However, the overflows had to be at much higher levels than current outflow channels, and the canyons had to be closed.

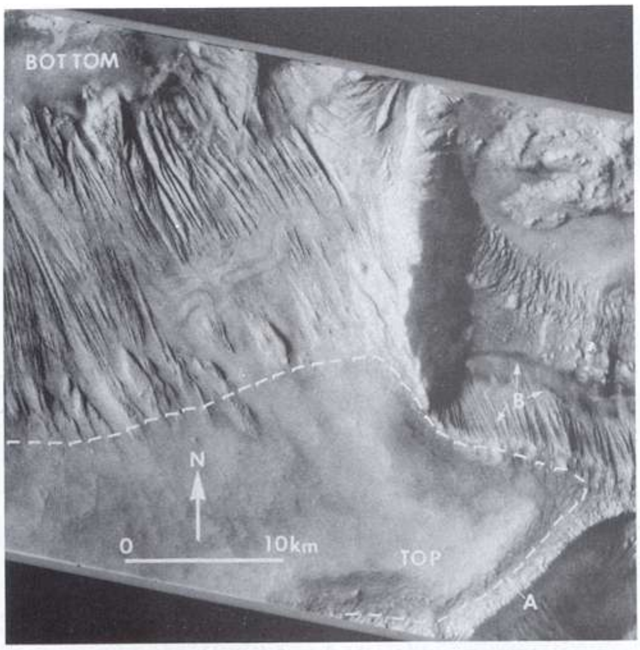

Fig. 7. Hebes Chasma layered deposit (Viking frame 738A71). The arrow (A) and dash lines indicate the boundary between the lower massive unit and the cap layer. The lower unit has three dark layers (B).

Otherwise, the lakes formed after chaotic terrain formation would never reach the tops of the layered deposits. This makes lacustrine deposition of very thick layered deposits difficult. The Juventae Chasma may not suffer from this problem since it is a semi closed basin. The chaotic terrains and outflow channels are limited to the northern and eastern canyons, although we can not rule out the possibility that the "chaotic terrains" identified in Candor Chasma by Lucchitta and Ferguson [1983] have a similar origin. So Hebes, Ophir-Candor, and Melas Chasmata may require a different source of water unless chaotic terrains are mantled by other materials. Although some runoff valleys are observed in Candor Chasma by Lucchitta and Ferguson [1983], it is not clear if these could have provided enough water. Sapping valleys could have drained a large amount of water into the canyon.

Source of Deposits

The source of the layered deposits is uncertain. The stratigraphy derived from Viking images alone cannot distinguish between possible origins, but it can place some constraints on the nature of the material. The diversified erosional style and differences in albedo of the layers suggest multiple sources [Lucchitta et al., 1992]. This is consistent with the observation by Murchie et al. [1992] of spectral heterogeneity among the layered

Fig. 8. Layered deposit (d, see Figure 1b) in Candor Chasma (Viking frame 815A58). The arrows indicate the boundary between upper thinly bedded (ledges and indentations) unit and lower more massive, fluted unit.

Fig. 9. Layered deposit (c, see fFgure 1b) in Candor Chasma (Viking frame 815A48). The arrows indicate the boundary between upper thinly bedded unit and lower more massive, fluted unit.

deposits. Although there were probably multiple sources, the great lateral extent of individual layers suggests that at any given time one source dominated in each chasma. The major divisions of layered units observed in Hebes, Gangis and part of Ophir-Candor Chasmata strongly suggest a major change in the depositional environments and/or supply of materials through time.

Volcanic materials may have been a major source for the deposits. We observe domes and ridges associated with dark materials in the Gangis layered deposit. These domes are difficult to explain by eolian or water-related processes and are interpreted to have a volcanic origin [Komatsu and Strom, 1990]. Also as shown by color comparison with Hebes Chasma, the dark layers in Gangis, Hebes and Melas layered deposits are probably mafic volcanic materials, such as basaltic lava flows or basaltic pyroclastic materials. They could be the source for dark eolian materials currently observed on the canyon floor [Geissler et al., 1990]. If the younger canyon floor materials are locally derived volcanics, then the older layered deposits could have been formed by a similar volcanic process [Lucchitta, 1990]. Also diversity of stratigraphy and erosional characteristics is consistent with a volcanic origin (Lucchitta et al., 1992). A volcanic contribution is consistent with the detection of pyroxine in dark canyon floor deposits by orbital spectroscopy [Murchie et al., 1992]

Sediments from the canyon wall are one possible major source if the canyon developed by mass wasting and sapping, although this alone could not explain the entire volume of deposits [Nedell et al. 1987]. Within the limited color range and resolution, the difference between steep slopes of layered deposits and nearby canyon walls is small (Figures 15a, 15b). Although this could be caused by mantling deposits of similar color, it may also be because canyon wall material was a supplier [Lucchitta et al., 1992].

Because eolian processes are long term and continuous, it is possible that eolian material formed at least a portion of the deposits. The canyons may have trapped a large volume of eolian material [Peterson, 1981], while surrounding plateaus remained relatively free of deposition. The diversity of stratigraphy and erosional characteristics [Lucchitta et al., 1992] and spectral properties excludes pure eolian origin. As pointed out previously, the lack of stratigraphic correlation in different chasmata precludes global eolian dust as the only dominant source. Also the current landscape of layered deposits is erosional, which is difficult to explain if eolian deposition is a continuous process in space and time. If eolian processes were responsible for both deposition and erosion, then the processes in the canyon system would have to have changed from one dominated by deposition to one dominated by erosion. This in turn would probably have required a significant climatic change relatively late in Martian history.

Fig. 10. Bench morphology (A) of deposit (b, see Figure 1b) in Candor Chasma (Viking frame 917A13). These benches are possibly enhanced internal layers. Fluting (B) occurs at approximately the same stratigraphic position as benches.

The geologic units with anomalous color characteristics, discussed above, occur in western Candor Chasma. It is not clear whether they are the exposed lower strata of layered deposits or new material deposited in existing depressions. These spectral characteristics are most readily explained by a composition somewhat richer in bulk crystalline hematite than typical for weathered or altered soils on Mars [Singer, 1982; Singer and Miller, 1991]. Crystalline hematite displays a strong and diagnostic crystal-field absorption near 0.53 microns [e.g., Singer, 1982; Sherman, 1985], to which the Viking green bandpass is quite sensitive despite that filter's great width. While crystalline hematite is not the primary coloring agent for most soils on Mars there have been a number of observations consistent with its occurrence on the planet [Soderblom et al., 1978; Guinness et al., 1987; Morris et al., 1989; Bell et al., 1990; Singer and Miller, 1991]. We feel that the Candor units imply a greater hematite content than typical Martian soils, but probably still mixed with the ubiquitous poorly crystalline or nanophase ferric oxide-bearing material that dominates typical weathered soil. Hematite is also the thermodynamically most stable ferric oxide mineralogy under current Martian surface conditions [Berner, 1969; Gooding, 1978]. Crystalline hematite on Earth forms in a variety of environments through a number of mechanisms, including subaerial weathering of soils, hydrothermal alteration associated with volcanism or circulating mineralized fluids, and conversion of other previously formed ferric oxide minerals such as ferrihydrite and geothite. All of these mechanisms might have been viable on Mars as well, making it difficult at this time to pinpoint the genesis of hematite in the Candor units. Increased temperature tends to favor formation of hematite over other ferric oxides, as does decreased water content [e.g., Berner, 1969; Kampf and Schwertmann, 1983]. The Candor units may have formed through primary volcanic oxidation. They may also have formed through aqueous precipitation of ferrihydrite in receding lakes, consistent with the localized nature of these deposits. This ferrihydrite could have subsequently converted to hematite through drying and application

Fig. 11. Mosaic of images showing deposit (a, see Figure 1b) in Candor Chasma (Viking frames 65A27, 66A20 and 66A22). This deposit is deeply eroded into basins with albedo-banded or benched sides (A). This image also shows details of geologic units of anomalous color interpreted to be crystalline hematite (B). Compare with Plate 1. These units are confined in the topographic low.

of heat. The presence of the Candor units is a result of original and/or sencondary deposition which is different from the primary and dominant formation of the layered deposits.

Erosional History

The erosional characteristics of layered deposits provides some insight into their subsequent history. The current geometry of layered deposits does not represent the original size of the deposits because lower-most layers probably have been exposed by a variety of erosional processes. Assuming the gaps separating the layered deposits in Ophir-Candor Chasmata are erosional in origin, the minimum amount of material estimated to have been removed is about 1.5 x 10^4 km^3, and in Melas it is about 8 x 10^3 km^3. From all deposits, the amount eroded could have been orders of magnitude more. Layered deposits were possibly even more extensive than current distribution, if the small isolated hills identified to be spectrally (Figure 1b) similar to known layered deposits are indeed erosional remnants of the layered deposits. It is possible that eolian erosion removed a large amount of material. The layered deposits (upper Hesperian, Tanaka, 1986) should be younger than the end of heavybomberdment which is thought to be about 2 b.y. at the latest [Strom et al., 1992]. The erosion rate required to expose 4 km thick deposits in the maximum time scale, 2 b.y. is about ~ 10^{-4} cm/yr. This rate is much smaller than the experimentally estimated maximum abrasion rate 2.1×10^{-2} cm/yr in the vicinity of Viking Lander 1 [Greeley et al., 1982]. Although there are uncertainties (age of the layered deposits, resistance of the layered deposits, such as hardness, consolidation state, etc.), it is likely that eolian processes played some role in exposing a thick sequence of the layered deposits.

Water is capable of eroding and removing vast quantities of material over short or long periods of time. Although the catastrophic drainage of lakes may have aided such erosion, it is

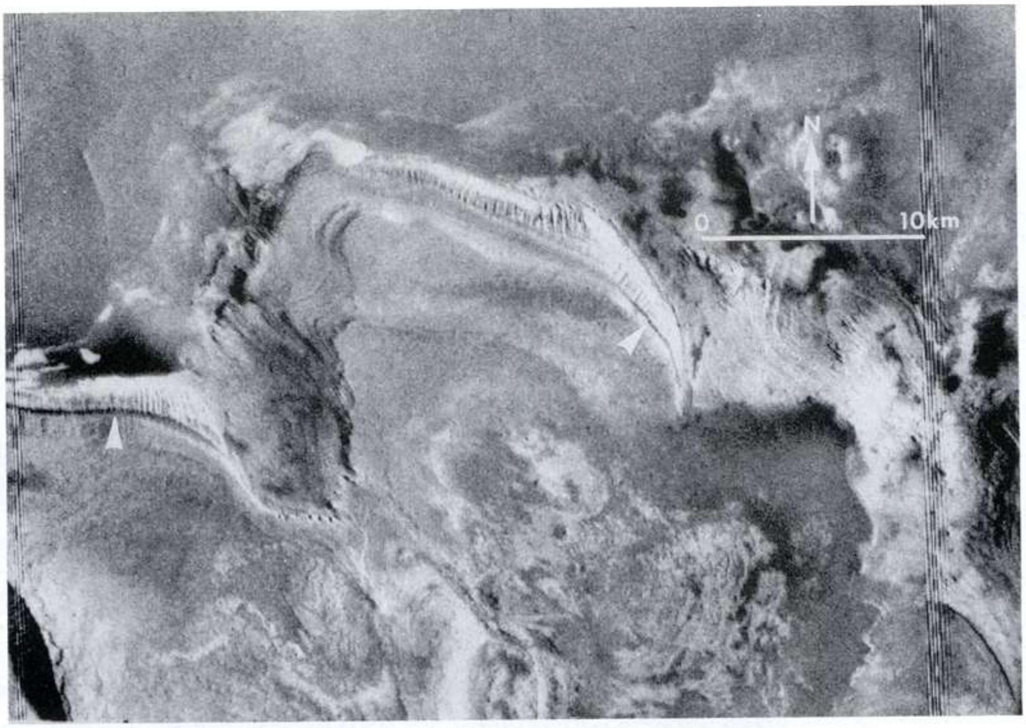

Fig. 12. Layered deposit in Melas Chasma (Viking frame 915A20). A dark layer, which is indicated by arrows, also appears to occur in a nearby deposit at about the same stratigraphic position.

unlikely to have been the major cause because the thickness of many deposits is almost as great as the depth of the canyon in some regions, i.e., Ophir-Candor Chasmata, Hebes, Gangis and Capri-Eos Chasmata. This suggests that if these parts of the canyon were filled with water at the end of sedimentation, then the water depth was very shallow (many times less than the thickness of the deposits). Erosion by lake drainage also does not explain the moats in closed canyons (Hebes Chasma). Furthermore, chaotic hills and streamlined forms that are commonly associated with water erosion on Mars have limited distribution in the canyons and formed only in peripheral troughs [Lucchitta et al, 1992]. One possible mechanism to account for the very large amount of erosion and removal of layered deposits on a short time scale is catastrophic water release under the layered deposits. The catastrophic release of water would severely disrupt the overlying layered terrain and permit the released water to deeply erode and sweep away large portions of it. This process would not work for Hebes Chasma because it is a completely enclosed basin and there is no signs of fluvial features on the canyon rim which could be expected if there was water and sediment flow over the canyon rim from such an event. The gaps between the deposits in these chasmata may have been created by more gradual processes, by a combination of processes involving evaporation of ice and eolian and fluvial transport in addition to structural processes [Lucchitta et al., 1992].

The layered deposits show at least two distinct erosional styles; downslope fluting, and near-horizontal benches. In layered deposits the fluted depressions locally show accumulations of debris at their bases suggesting they are debris chutes caused by the downslope movement of material. Alternate interpretations are that the fluted ridges were yardangs caused by eolian erosion, transformed mass-wasted gullies into parallel ridges and troughs [Lucchitta et al., 1992] or erosion by fluid seepage [Sharp, 1973]. In any event the response of the fluted material to erosion is very different from that of the non fluted material, suggesting different lithologies.

Benches were interpreted by Nedell et al. [1987] as thin layers enhanced by erosion. This would be true if they were caused by differential erosion of different lithologic units, which could be the case in most instances. The differential erosion may have been caused by eolian processes, assisted by masswasting, weathering and ice-related processes. These are the most likely processes under current Martian climatic conditions. However, fluting and benches are very different erosional forms that sometimes occur at the same lateral position in the same layer (Figure 10). It is difficult to understand why radically different erosional styles would occur adjacent to each other, if the strata has a laterally uniform chemical and mechanical composition. Furthermore, relatively thin multiple layers recognized by alternating weak and resistant strata evidenced by ledges and indentations, do not display benches (Figures 8, 9). It is difficult to understand why some layers appear as benches and others do not. Some benches might be shorelines resulting from wave actions, as in the case of the bench morphology identified in Elysium Basin (Figure 8 in Scott and Chapman [1991]). The lake level must have been lower than the deposits for this process to occur. Benches could be formed in both layered and massive deposits. The benches could be caused by wave-cutting in ice-free lakes, or by ice shoving in ice-covered lakes which periodically freeze and thaw. Another possibility is fluvial processes, both gradual and catastrophic

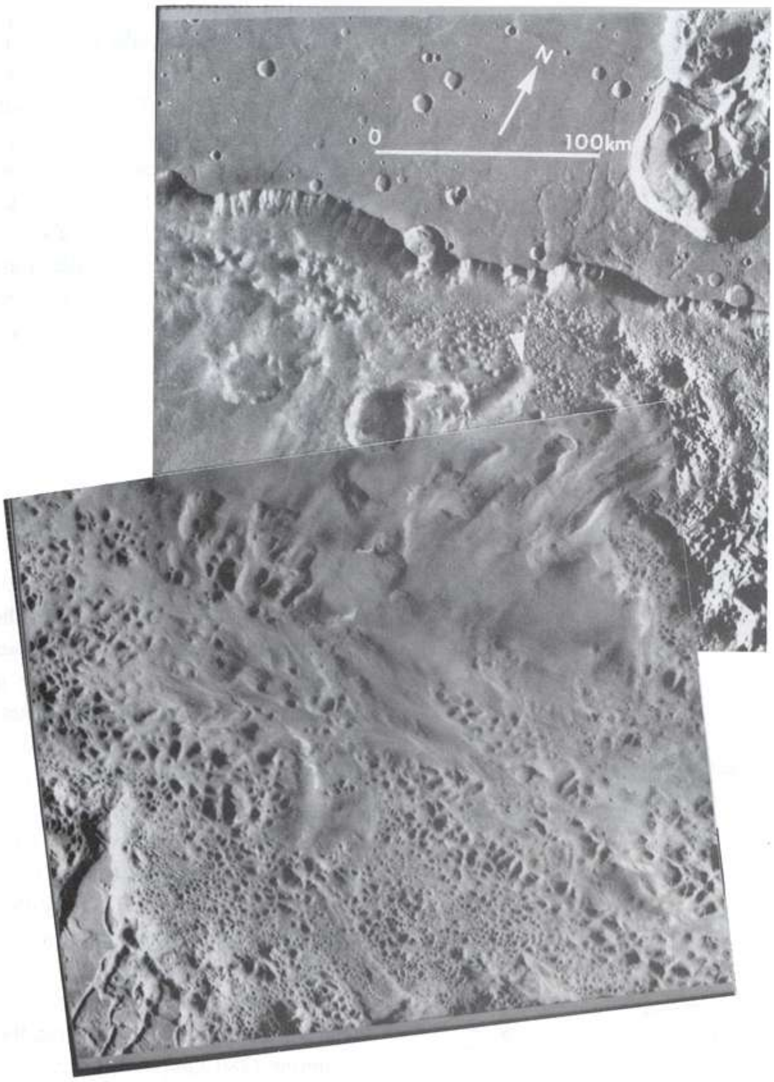

Fig. 13. Layered deposits in Capri-Eos Chasmata (Viking frame 610A31 and 649A57). These deposits unconformably overlie the chaotic terrains indicated by the arrow.

processes which strip layers away. This type of bench morphology and scale is identical to that interpreted as fluvial terraces associated with outflow channels (Figure 6.8 in Baker [1982]).

Geologic History

Tanaka [1986] inferred the age of the layered terrains as upper Hesperian or younger based on stratigraphic relationships. Because of the small area of the canyon floor and the low crater densities, it is difficult to distinguish the age differences between chasmata. However, they seem to lie in the range of Hesperian to. Amazonian. Chaotic terrain formation and catastrophic outburst flooding may have been the source of the water for paleolakes in some cases as discussed before. There may have been multiple episodes of chaotic terrain formation and thus a cyclic supply of water; consistent with the multiple discharge history of outflow channels [Rotto and Tanaka, 1991]. The angular unconformity observed in Gangis layered deposits suggests at least two episodes of deposition separated by a period of tectonic movement and erosion in this part of the canyon. Later chaotic terrain formation could have led to layered terrain disruption and erosion in some parts of the canyon as explained above.

A plausible explanation for the formation and erosion of layered terrain involving multiple episodes of chaotic terrain formation in Juventae Chasma follows:

1. Formation of chaotic terrain causing the collapse of the surface to form the incipient Juventae Chasma and the catastrophic release of water filling the depression.

2. Lacustrine deposition of interior deposits.

3. A second episode of chaotic terrain formation resulting in the enlargement of the Chasma, disruption and heavy erosion of the lacustrine deposits, and transportation of the eroded material to areas both inside and outside the Chasma. The channel-like feature on the northern deposit (Figure 5) was probably formed by fluvial erosion due to water release. Some of this eroded material was probably carried over the northeastern rim of the canyon through the channel that occurs there (Figure 4), while some was probably deposited on the floor forming the blanket of smooth

material in the southern part of the Chasma (Figures 4 and 5).

4. Lowering of the lake with eventual concentration of water in the deeper southern part of the Chasma (See Figure 14 for current estimated profile). The very regularly spaced bands on the southern deposit (Figure 6), and not on the northern deposit, may be erosional benches caused by wave-cutting action due to a more gradual lowering and dissipation of this last part of the lake.

It is not clear whether the above scenario involving lacustrine deposition and erosion by water from chaotic terrain formation is applicable to in other chasmata. Chaotic terrains are limited to the eastern canyons (Gangis and Capri-Eos) in addition to the Juventae Chasma, also it is not clear if these eastern canyons were closed to hold lake water. Central (Ophir-Candor and Melas) and northern (Hebes) canyons do not exhibit clear evidence of chaotic terrains.

OBSERVATIONS REQUIRED TO ANSWER KEY QUESTIONS

There are a number of observations required to resolve key questions regarding the history of the layered deposits. Some of them may be answered by Mars Observer.

Each layered deposit should be imaged at high resolution to detect fine-scale depositional structures such as cross-bedding, unconformities, and change in lithology, and large scale embedded clasts. Mars Observer Camera has a very high spatial resolution (1.4 m/pixel, narrow-angle [Malin et al., 1992]) that may enable us identify such structures. A combination of the camera and Mars Observer Laser Altimeter (foot print spacing 300 m along track, vertical accuracy, 1.5 m [Zuber et al., 1992]) could be used to derive more accurate stratigraphy and its relationship to bench and other erosional geometry.

The chemical and mineralogical compositions of the layered deposits are critical to evaluating their origins. Thus low spatial resolution (280 km/pixel) Gamma Ray Spectrometer [Boynton et al., 1992] together with Thermal Emission Spectrometer (spatial resolution, 3 km/pixel [Christensen et al., 1992]) may be used to distinguish compositional variation between the layered deposits.

CONCLUSIONS

The complex stratigraphy of layered deposits suggests a diversity of origins, ages, and post depositional modification histories. The stratigraphic units are identified based on albedo and erosional styles. In general, the stratigraphy of layered deposits in the isolated chasmata Hebes, Juventae and Gangis are not well correlated. Hebes and Juventae Chasmata are isolated basins detached from the main canyon system, while Gangis is only indirectly connected. This indicates that at least these chasmata had isolated depositional environments resulting in different stratigraphic sequences. The stratigraphic correlations indicate that the layered deposits in Ophir-Candor, and Melas Chasmata could have been connected together in each chasma.

The complexities within some layered deposits indicate changes in the dominant source materials in space and time. The color spectra of dark layers in the Hebes deposit are similar to those of dark canyon floor material interpreted to be mafic volcanics. Therefore, volcanic material may form a significant portion of the deposits. Similarly, other dark layers in Gangis and

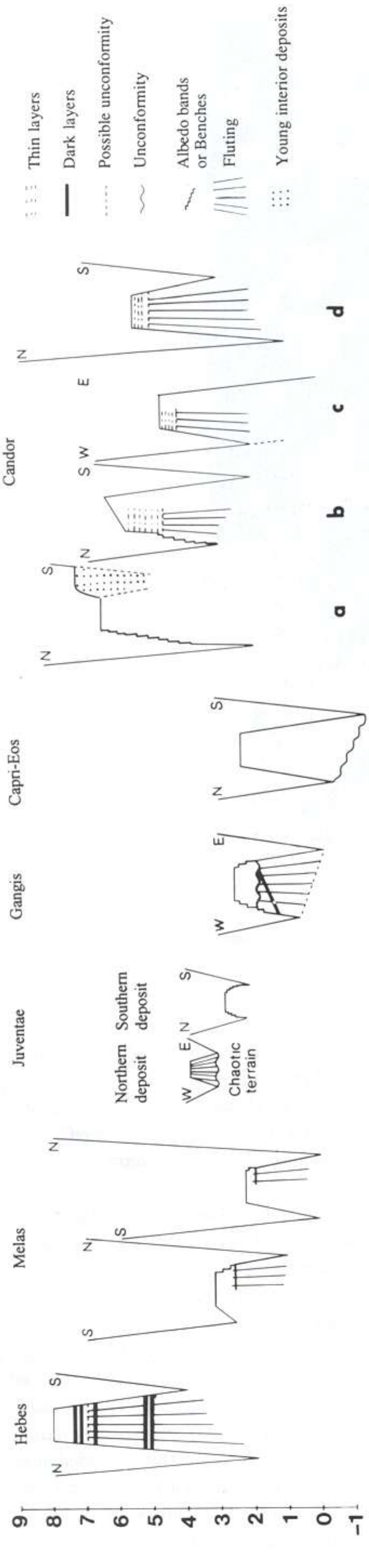

Figure 14. Idealized stratigraphic profiles of layered deposits. Horizontal and vertical dimensions are not the same scale. These profiles were constructed from the USGS topographic maps, I-1712, I-2030 and with Viking stereo images. The error associated with estimation of altitudinal profiles is about 1 km.

Fig. 15a. Locations of spectra extracted in Figure 15b from Viking color data. (1) anomalous spectral unit in western Candor Chasma; (2) Baetis Mensa, a more typically hued layered deposit in central Candor Chasma; (3) canyon wall rock; (4) dark layer in Hebes Mensa; (5) dark, floor covering materials interpreted by Lucchitta [1990] as possibly volcanic in origin; (6) Floor-covering materials in Hebes Chasma which probably derived from erosion of Hebes Mensa.

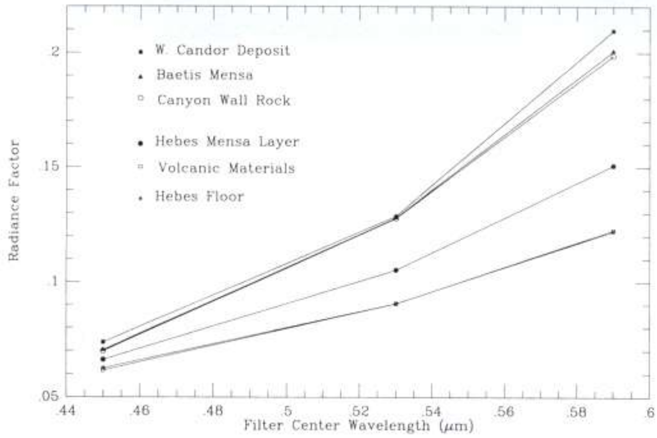

Fig. 15b. Three-point Viking spectra of Valles Marineris layered deposits. Colors of spectrally exceptional materials in western Candor and Hebes Chasmata are compared with more typical units in Viking Orbiter 1 data acquired on orbit 583. The unusual coloration in western Candor Chasma is due to the reduced green filter reflectance, relative to red and violet, when compared with spectra from more typical layered materials in Ophir Chasma (which is similar to the canyon wall rock). Because of the large pixel size, the spectrum of the dark layer in the central plateau of Hebes is probably mixed with that of adjacent brighter materials; the spectrum of the undiluted dark material accumulated in the moat surrounding the mesa closely approximates that of dark floor-covering materials in Ophir Chasma previously interpreted to be of volcanic origin.

Melas Chasmata could have the same origin. Within the limited spectral range and resolution, steep slopes of the layered deposits have a similar spectral signature to that of nearby canyon walls. This may indicate that materials derived from the canyon walls could have been a source of layered deposits. Eolian deposition could have been a continuous part of the sedimentation processes.

Chaotic terrains are found in conjunction with layered deposits in Gangis, Juventae, and Capri-Eos Chasmata, but not in Ophir-Candor, Melas, and Hebes Chasmata. The layered deposits unconformably overlie chaotic terrains. Lacustrine deposition is not an absolute necessity. However, thick layered deposits could have formed in the lakes if the canyons were closed at the time. Chaotic terrains could have been a source of water for the paleolakes. In Juventae Chasma, water released from the chaotic terrains could have formed temporal lakes deep enough for the deposition of layered deposits. For Hebes, Ophir-Candor, and Melas Chasmata, water must have come from other sources, unless the chaotic terrains are currently covered by more recent

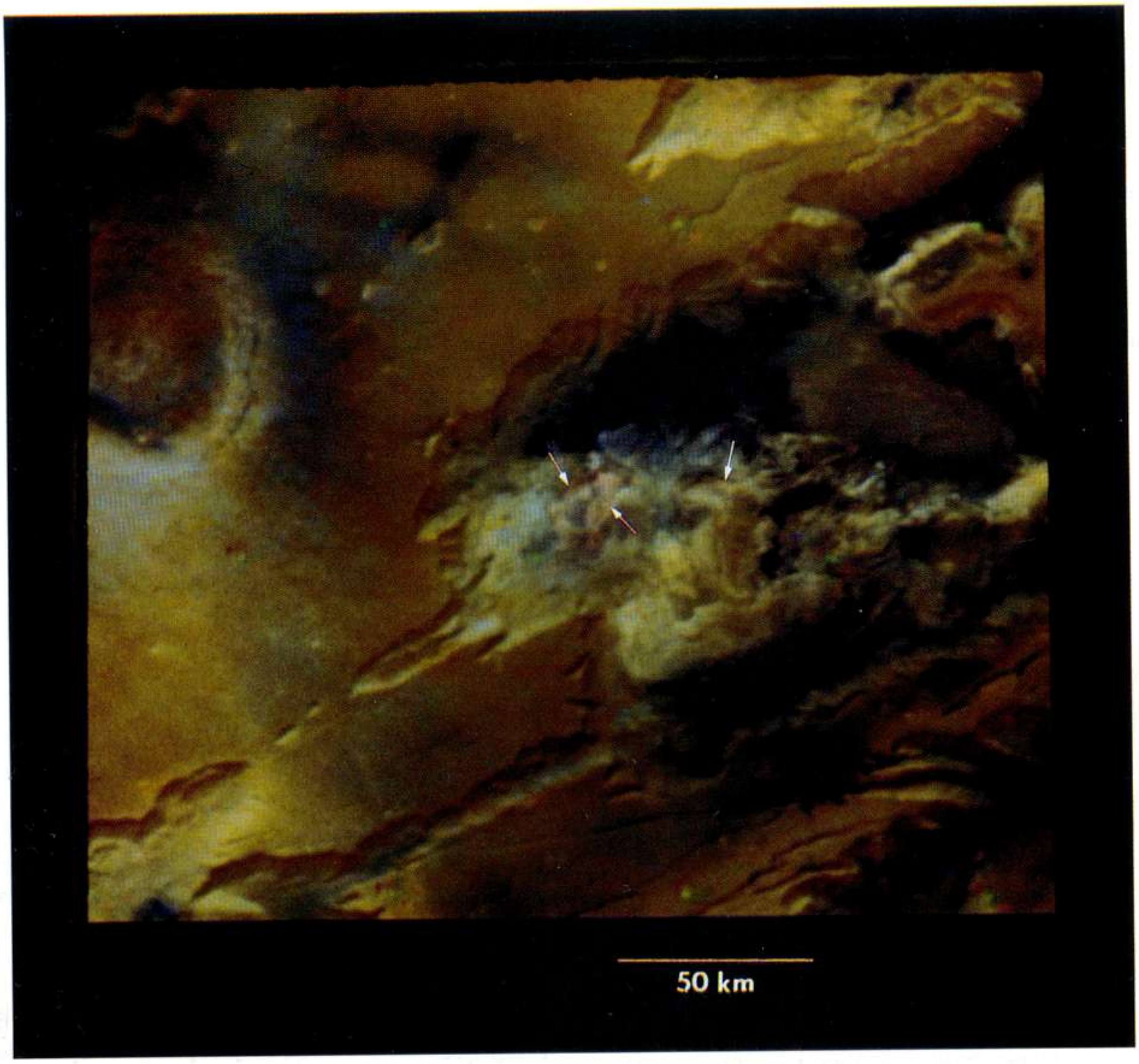

Plate 1. Viking multispectral image of western Candor Chasma (Viking orbit number 583). The arrows indicate the positions of deposits which have an anomalous color. They have a higher red (0.59 microns) /green (0.53 microns) band ratio than elsewhere in Valles Marineris. These spectra are consistent with an interpretation of a relatively higher abundance of bulk crystalline hematite.

floor deposits. The very thick sequence of the layered deposits has been exposed by erosion. A combination of gradual processes may be responsible for this erosion, or later episodes of catastrophic water release under the layered deposits may have disrupted and eroded the layered deposits.

Newly identified units of anomalous color are confined to depressions or reentrants in western Candor Chasma. The difference in color between these units and the surrounding terrain is most consistent with a somewhat greater content of bulk crystalline hematite in these anomalous units. The presence of the Candor units is a result of original and/or sencondary deposition which is different from the primary and dominant formation of the layered deposits.

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