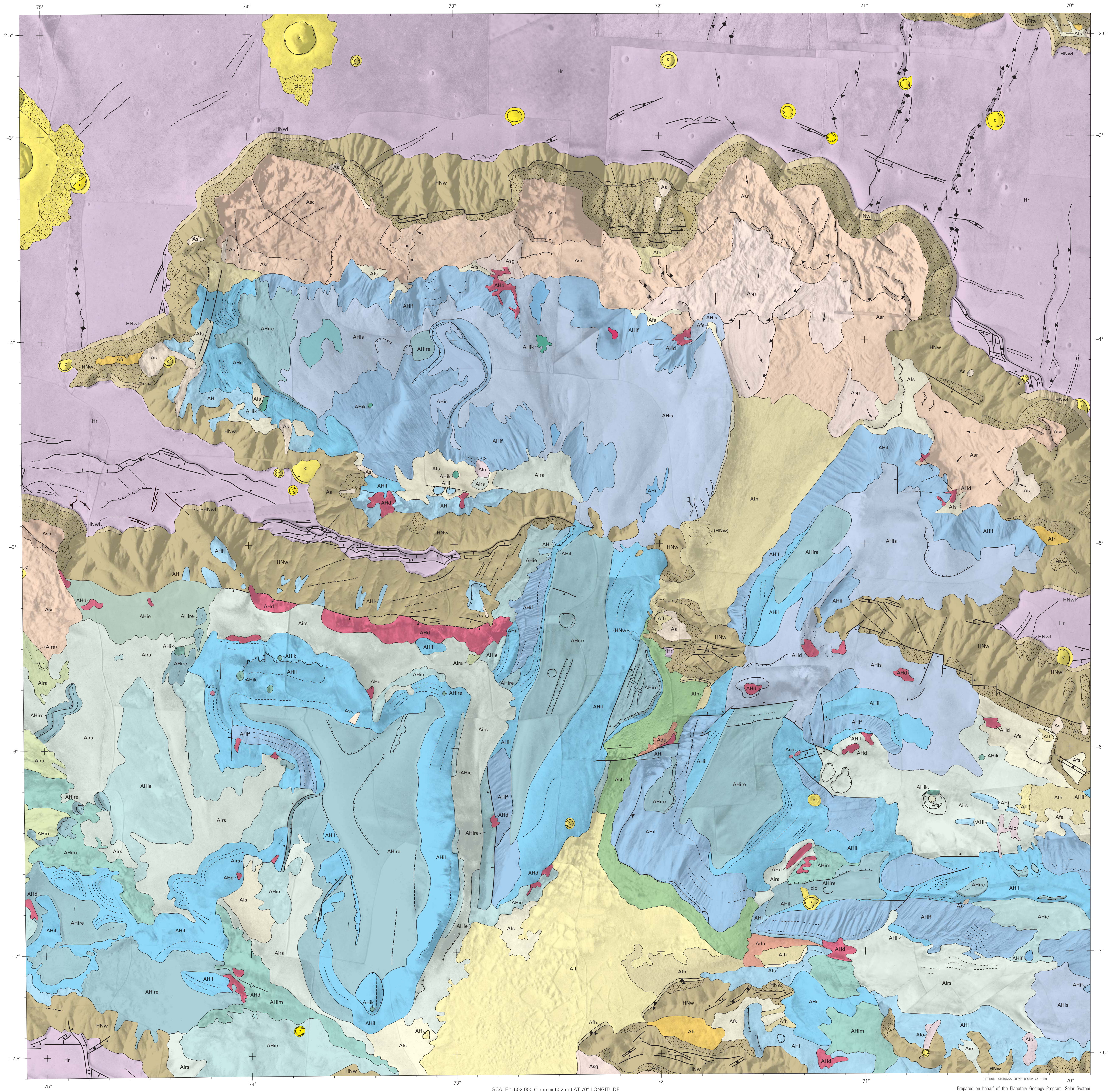
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ATLAS OF MARS
1:500,000 GEOLOGIC SERIES
OPHIR AND CENTRAL CANDOR CHASMATA
M 500k –5/72 G, 1999
MAP I–2568



SCALE 1:502 000 (1 mm = 502 m) AT 70° LONGITUDE
TRANSVERSE MERCATOR PROJECTION

Prepared on behalf of the Planetary Geology Program, Solar System Exploration Division, Office of Space Science, National Aeronautics and Space Administration

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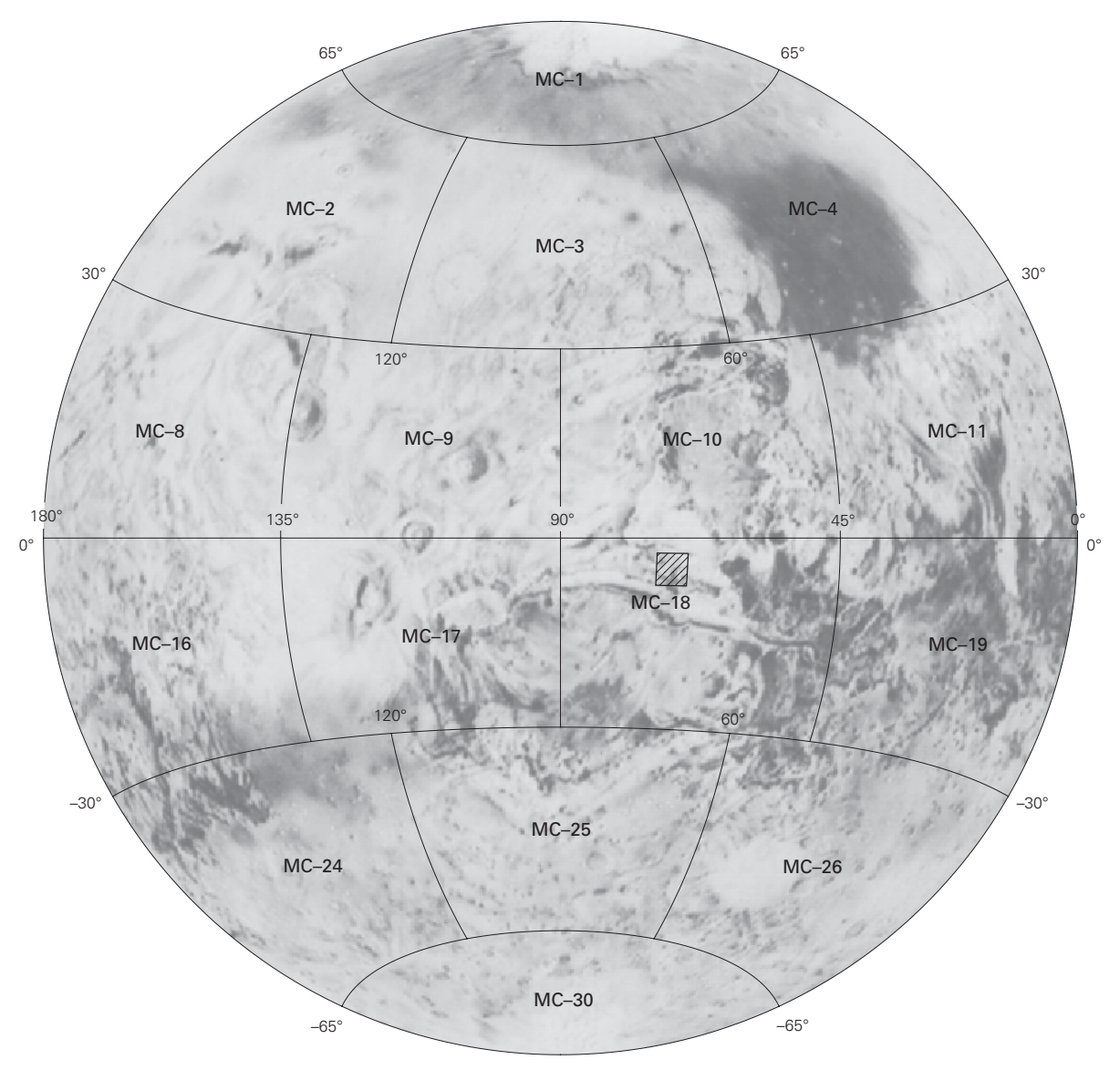


QUADRANGLE LOCATION
Photomosaic location is shown in the western hemisphere of Mars. An outline of 1:5,000,000-scale quadrangles is provided for reference.

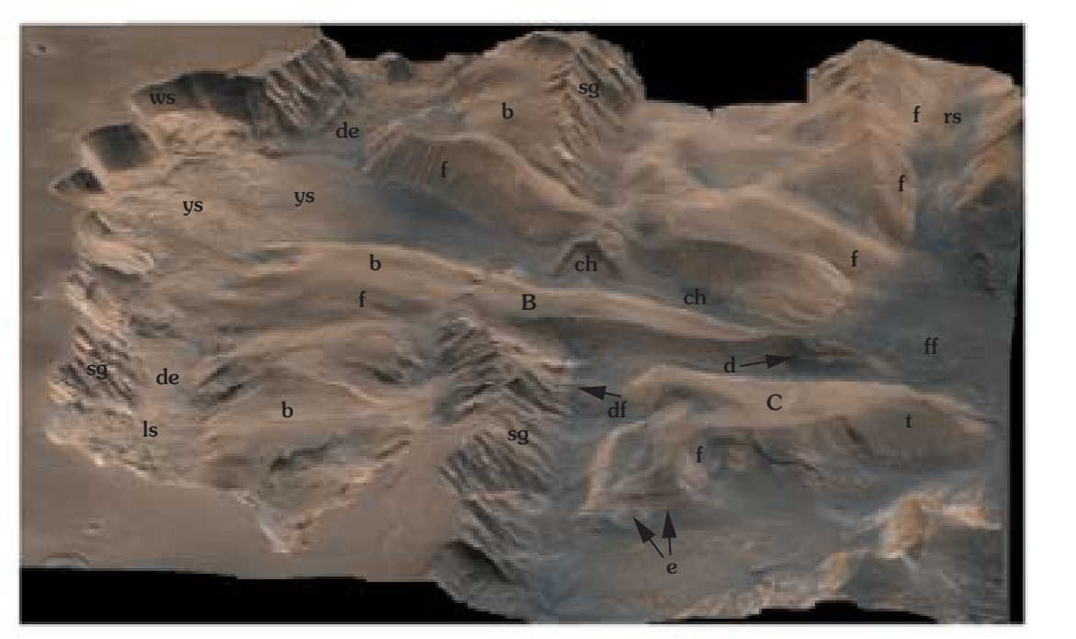


Figure 1. Ophir (left) and central Candor (right) Chasmata viewed from west. Image about 200 km wide. Trough walls and ridge separating Ophir from Candor Chasmata display wall rock with spur-and-gully morphology (**sg**) and are overlapped by interior deposits, displaying fluted morphology (**f**). Northern part of Ophir Chasma forms depression (**de**) into which landslides (**ls**) fell. Youngest landslides (**ys**) give rise to channel (**ch**). Note smooth wall rock at head of scars (**ws**). Southern part of Ophir Chasma forms bench (**b**) underlain by older interior deposits, as are mesas of Candor (**C**) and Baetis (**B**) Mensae. Mesa caprock is tilted at **t**. Younger interior deposits lap up onto mesa (unevenly edged material at **e**) and fill low areas (rolling and smooth interior deposits at **rs**). Dark outcrops represent necks or vents of mafic vocanic rock at **d** and band of dark material along fault scarp at **df**. Other windblown dark material thinly mantles floor, particularly fractured floor at **ff**. Mosaic of Viking Orbiter images of orbit 912 to 917 combined with topography by Wu (unpublished map, scale 1:500,000) (Bertolini and McEwen, 1990). Vertical exaggeration 2×.

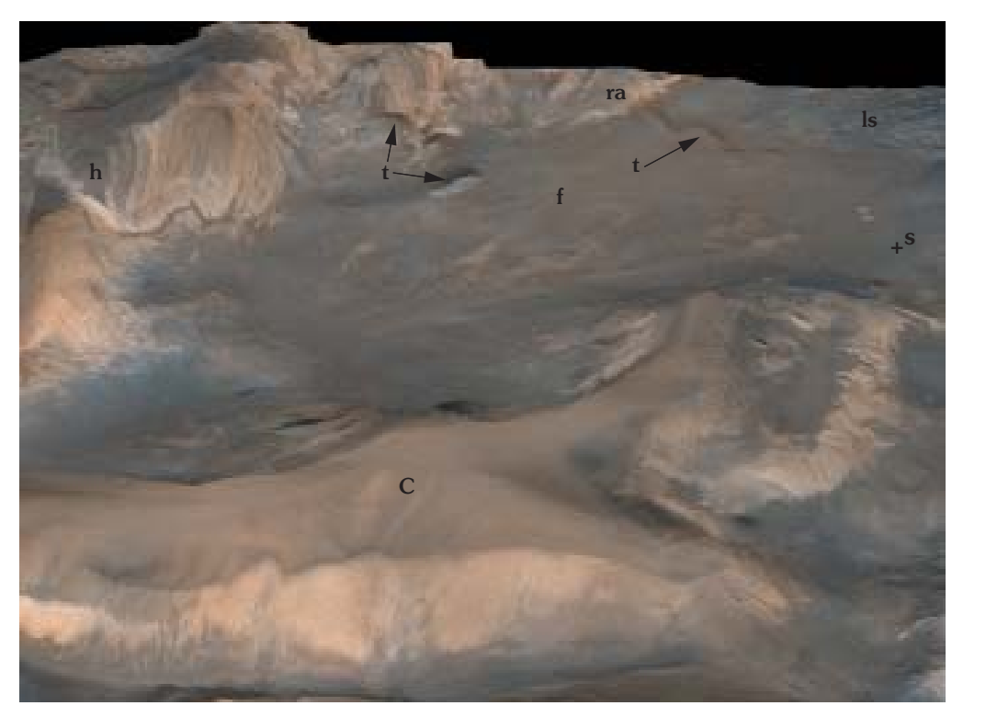


Figure 2. West Candor Chasma viewed from east. Image about 100 km wide. Candor Mensa (**C**), in foreground, underlain by older interior deposits. Hogbacks at **h** (lat 6.9° S., long 74.7°) show that older interior deposits are deformed in places and locally include dark layers. Tilted beds (**t**) form erosional remnants on trough floor (**f**). Young interior raked material (**ra**) unconformably overlaps floor and tilted beds. Landslide at ls. Potential landing site (fig. 3) at **s**. Excerpt of mosaic Viking Orbiter images of orbit 912 to 917 combined with topography by Wu (unpublished map, scale 1:500,000) (Betolini and McEwen, 1990). Vertical Exaggeration 2×.

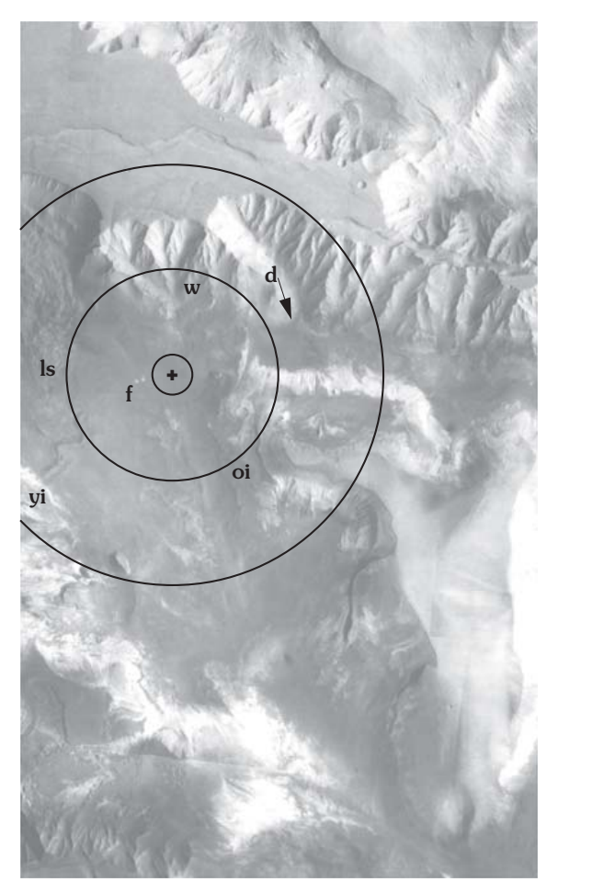


Figure 3. Candor landing site 1 (lat 5.5° S., long 74.5°). Circles represent 5-km, 25-km, and 50-km radius from proposed landing site. 50-km radius permits access to floor material (**f**), ancient wall rock (**w**) in north, possibly young dark material (**d**) in northeast, older interior deposits (**oi**) in east, younger interior deposits (**yi**) in west, and landslide material (**ls**) in northwest. This suite of rocks covers wide span of martian ages and materials.

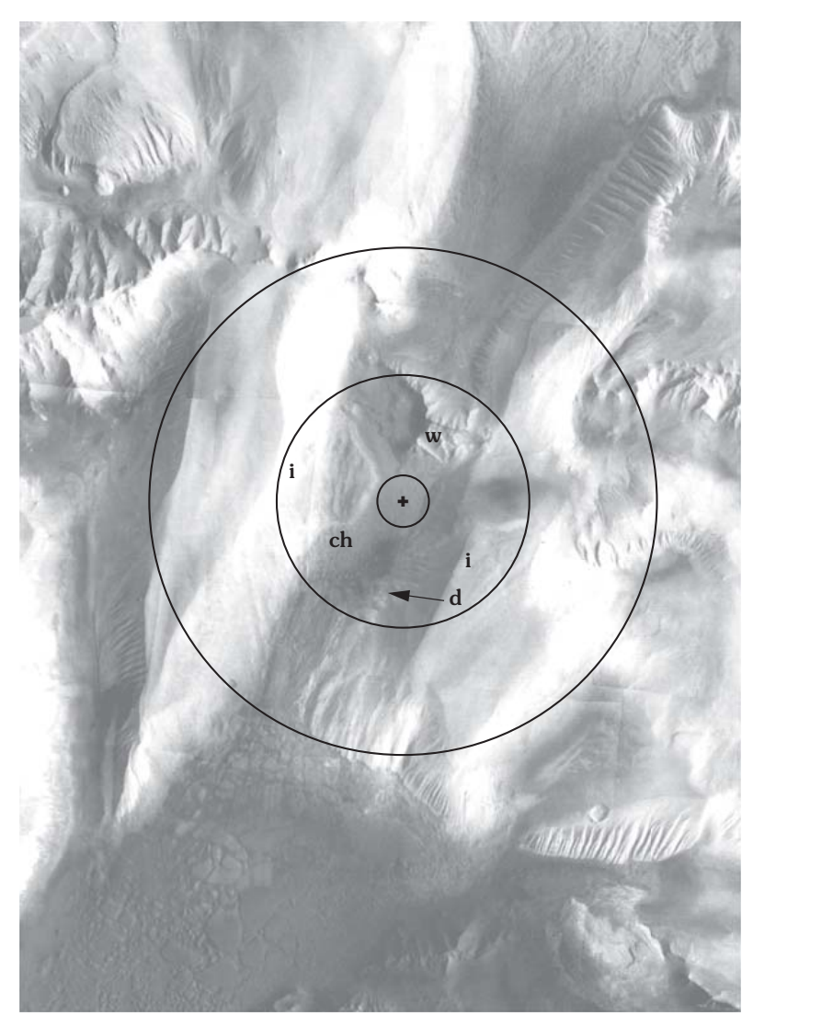
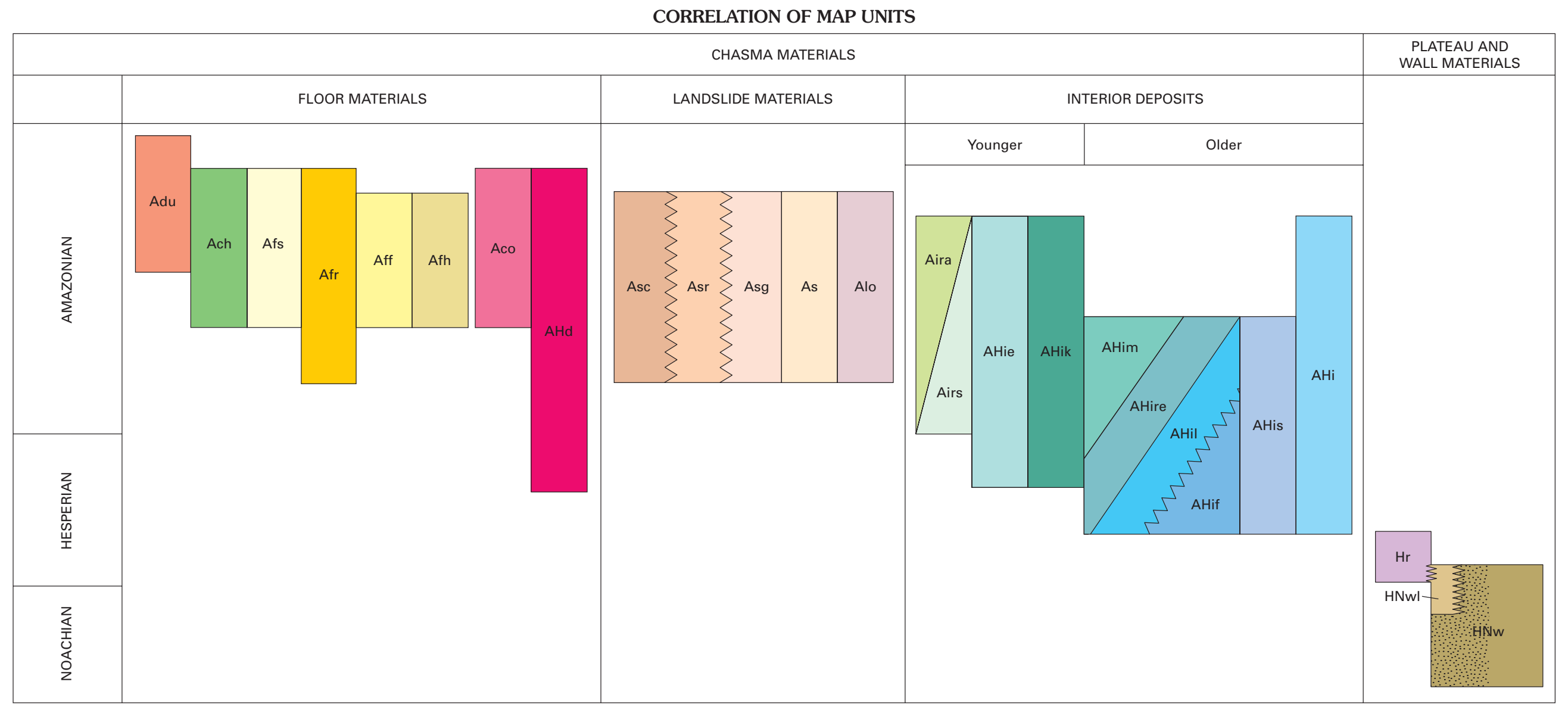


Figure 4. Candor landing site 2 (lat 5.7° S., long 71.9°). Circles represent 5-km, 25-km, and 50-km radius from landing site. 50-km radius permits access to ancient wall rock (**w**) in north, older interior deposits (**i**) in west and east, and wind-blown, dark mafic material (**d**), perhaps derived from local vents, in south. In addition, landing site is located in channel (**ch**) and may provide answers concerning channeling processes and volatile history of Mars.

GEOLOGIC MAP OF OPHIR AND CENTRAL CANDOR CHASMATA (MTM –05072) OF MARS

By
Baerbel K. Lucchitta
1999

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

CHASMA MATERIALS

FLOOR MATERIALS

Adu **Dune material**—Forms patches of dark material topped by sickle-shaped or irregularly curved narrow ridges. Locally ridges have gentle rises on one side, steep slopes on the other. *Interpretation:* Mafic, sand-size material that moved by saltation, became concentrated by wind, and formed transverse dunes

Ach **Channel-floor material**—Forms 5- to 10-km-wide hummocks and knobs on flat-floored, curvilinear valley. Includes doughnut-shaped structures that resemble terrestrial kettle holes (visible only in high-resolution images). Superposed on fractured floor material. *Interpretation:* Water-transported material, probably emplaced in a flood that rafted kilometer-size ice blocks. Flood waters and ice blocks derived from landslide materials at head of Ophir Chasma or from breached, ice-covered lake dammed behind wall rock ridge at lat 5.5° S., long 71.7°

Afs **Smooth Material—**Forms smooth, flat areas filling low places mostly on trough floors. Varying albedos. *Interpretation:* Surficial deposits of diverse origins. May be mass-wasted colluvium, alluvium reworked from adjacent materials, or eolian cover

Afr **Rough material**—Forms irregularly shaped hills and ridges as much as 1 km in size, occurring mostly between converging talus slopes on the floors of tributary canyons or enclosed linear depressions. *Interpretation:* Mostly material mass wasted from adjacent walls

Aff **Fractured material**—Forms crudely polygonal, low-albedo plaques of flat-lying material separated from one another by linear depressions. Size of plaques ranges from small isolated mesas to 10-km-diameter plateaus. Gradational with and locally including interspersed patches of hummocky material. Occurs at lowest elevations in quadrangle near bottom center of map area. Resembles chaotic terrain in other regions of Mars. *Interpretation:* Most likely alluvium deposited by water discharged from landslides or other materials. May have formed in lakes or playas. Structure probably from settling, contraction upon freezing, sublimation, and desiccation. Emplaced after troughs had nearly reached their present configuration. Low albedo from eolian cover

Afh **Hummocky material**—Forms irregularly dispersed small hills of <100–500 m diameter, occurring in low areas having flat to slightly undulating surfaces. Locally associated with fractured material. Includes large area of valley fill (centered at lat 4.6° S., 71.4°) gradational with landslide materials at head of Ophir Chasma. Also forms narrow ridge bordering base of wall rock along south side of fractured material (lat 7.2° S., long 72° and lat 7.35° S., long 72.3°). Gradational with fractured material in places. *Interpretation:* Diverse origins. (1) Same as fractured material but more disintegrated. (2) Colluvium from trough walls and landslide materials. (3) Valley fill, gradational with Ophir Chasma landslides, appears to have formed from debris flows emanating from landslides. (4) Narrow hummocky ridge along wall rock may be strand line marking higher stand of fractured material before settling

Aco **Cone material**—Forms small dark conical hills, 1–3 km across. One cone (lat 6.05° S., long 71.4°) has small central depressions and occurs along fault. Another cone (lat 5.75° S., long 74.15°) has larger central depression and dark halo. *Interpretation:* Cone along fault probably cinder or spatter cone. Others could be erosional remnants of older volcanic rocks or impact craters ejecting dark substrate

AHd **Dark material**—Forms diffuse patches, streaks, or knobs. Some patches occur preferentially along faults or on lower spurs of wall rock. In places superposed on landslide materials. Locally gradational with mottled material. *Interpretation:* Diverse origins. Material on top of landslide materials and associated with faults probably young, mafic volcanic material. Elsewhere, may be older dikes, necks, or material shed from freshly exposed dark layers in trough walls and interior deposits. Probably includes material concentrated by wind

LANDSLIDE MATERIALS

Asc **Coarse material**—Disordered mountainous material at head of landslides. Traversed by many linear or curvilinear scarps. Occurs mostly within and just below curved reentrants in wall rock. Superposed on older interior deposits. At lat 5.5° S., long 75° covered by young interior deposits. *Interpretation:* Composed of competent, probably upper parts of wall and plateau materials that collapsed cataclysmically. Emplaced after the troughs had nearly reached present configurations

Asr **Ridged material**—Forms curvilinear ridges, as much as 1 km wide, generally trending perpendicular to direction of movement. Gradational with coarse material. *Interpretation:* Probably composed of less competent material from middle and lower parts of wall rock

Asg **Grooved material**—Lobate aprons of grooved, ridged, or lineated materials having wavelengths of as much as a few hundred meters. Trend of grooves generally parallel to direction of movement. Aprons extend as much as 70 km from slide scar. Gradational with ridged material. *Interpretation:* Similar to ridged landslide material, but unimpeded runout facies. Grooves develop along shear zones between debris traveling at different speeds

As **Undivided material**—Forms mostly thin lobate deposits below small landslide scars or alcoved wall rock gullies. Lobes may have hummocky or longitudinally striated surfaces. Occurs mostly on wall rock. *Interpretation:* Similar to other landslide materials

Alo **Lobate material**—Forms long, narrow, light-colored lobes that are locally superposed on one another. Differs from other landslide materials by being more distinctly leveed. Lobes originate at interior deposits or wall rock. *Interpretation:* Relations seen outside map area in MTM –05067 and MTM –05077 suggest volcanic origin. Alternatively, landslide material

INTERIOR DEPOSITS

Younger Interior Deposits

Aira **Raked material**—Forms light-colored lobate deposit dissected by fine flutes. Embays resistant material and superposed on rolling and smooth interior deposits and landslide materials. Occurs only along west margin of map area. *Interpretation:* Material that apparently flowed across trough floors relatively late in the trough's history. Volcanic material or remobilized older interior deposits

Airs **Rolling and smooth material**—Forms slightly rolling plains of intermediate albedo on trough floors. In very high resolution images, seems to be composed of layers of light-colored material, thinly covered by intermediate-albedo dust. Overlaps eroded older interior deposits with angular unconformity at lat 7.05° S., long 70.4°. Also associated with nested set of oval and round depressions, 5 to 7 km wide, at lat 6.3° S., long 70.7°. Locally transitional to unevenly edged material. In places, difficult to distinguish from smooth older interior deposits. *Interpretation:* Thick deposit of unknown origin. Could be airfall tuff or exceptionally thick eolian deposit. West of Baetis Mensa could also be downfaulted older interior deposits

AHie **Unevenly edged material**—Forms patches of material whose surfaces display numerous low and irregular scarps and thin, sharp-crested ridges. High to intermediate albedo. Occupies large area on floor of west-central Candor Chasma; embays wall rock and in places superposed unconformably on older interior deposits, such as at lat 6.8° S., long 70°. *Interpretation:* Different origins possible: (1) Young volcanic material of unknown composition. (2) Where draped over sides of interior mesas: tilted older interior deposits, young volcanic material, or mass-wasted material. (3) Smooth interior deposits (unit AHis) downfaulted onto trough floors

AHik **Knob material**—Forms mostly light-colored knobs measuring 1–3 km across base. *Interpretation:* Young volcanic constructs of unknown composition or eroded volcanic necks associated with emplacement of interior deposits. Alternatively, erosional remnants of other resistant rock

Older Interior Deposits

AHim **Mottled material**—Forms mottled dark and light patches having irregular outlines. Light patches locally have wispy and feathery appearance. Occurs near southwest corner of map area. *Interpretation:* Dark layer eroded irregularly to permit underlying light layer to show through. Alternatively, mixture of young mafic material and light-colored tuffs or light-colored alteration products

AHire **Resistant material**—Forms smooth surfaces of intermediate albedo on interior mesas and steeply sloping mesa rims. Unit dissected to hummocks or knobs in places. Questioned where identity uncertain. *Interpretation:* Competent uppermost layer and caprock of mesa-forming older interior deposits. Possibly volcanic origin. Alternatively, indurated sedimentary layer of lacustrine origin. Probably overlain by thin sheet of eolian material. Emplacement predates major structural disturbance and erosional dissection of older interior deposits

AHil **Layered material**—Forms layers of varying thickness and competence exposed in mesa slopes. Minor fluting occurs in places. Generally intermediate to high albedo but has a few conspicuous low-albedo layers in places. Occurs mostly in upper parts of mesas, just below resistant caprock, but locally also in lower slopes. Vertically and laterally gradational with fluted material. *Interpretation:* Combination of volcanic, lacustrine, eolian, and mass-wasted materials. Possibly volcanic material erupted into a lake (Nedell and others, 1987)

AHif **Fluted material**—Has subparallel troughs and ridges with smoothly tapering ends, mostly on slopes of interior mesas. Occurs dominantly as massively bedded units, beds having alternating light and intermediate albedos (seen in high-resolution images). Occurs mostly in lower to middle sections of mesas. Vertically and laterally gradational with layered materials. *Interpretation:* Similar to layered material. Thicker bedding suggests more lasting processes or faster emplacement rates. Shape of ridges resembling yardangs suggests grain sizes susceptible to wind erosion. Perhaps larger contribution of mass-wasted material, tuffs, or massive eolian deposits than in layered material

AHis **Smooth material**—Forms smooth surfaces of intermediate to high albedo. Locally, where scoured, reveals stepped benches. Covers broad regions on mesas where resistant caprock is absent or poorly developed. Mapped mostly where resistant, layered, and fluted materials could not be distinguished. May include rolling and smooth younger interior deposits in places. Superposed unconformably on gullied wall rock. *Interpretation:* Same as resistant, layered, and fluted materials

AHi **Undivided material**—Exposures of light-colored interior deposits that cannot be readily assigned to other units. Mostly occurs as small patches in wall rock gullies or as irregular light to mottled deposits in or along lower spurs on trough walls. *Interpretation:* Mostly erosional remnants of other interior deposits. May be remnants of oldest interior deposits where it occurs in spurs on lower trough walls

PLATEAU AND WALL MATERIALS

Hr **Ridged plains material**—Forms smooth to slightly rolling surface of moderate albedo traversed by grabens (generally trending westerly) and wrinkle ridges (generally trending northerly). Thin, sharp, steep lip at upper trough edge included in unit. Superposed structures locally subdued. Forms regional unit described in Witbeck and others (1991). *Interpretation:* Competent caprock on plateau. Most likely composed of mafic lavas, but compositions as cemented sediments cannot be ruled out. Plateau materials and superposed structures thinly blanketed in places, probably by eolian deposits. For detailed interpretation see Witbeck and others (1991).

HNwl **Layered wall material**—Forms regularly fluted cliff, about 1 km high, lining plateau in upper part of trough walls. Visible only on steep exposures, such as landslide scars. In many places several distinct layers visible, expressed as bands of differing albedo or competence. Laterally gradational with upper part of gullied wall rock. *Interpretation:* Probably flood basalts, representing lower layers of ridged plains unit. Possibly cemented sediments

HNw **Wall rock, stippled where smooth**—Characterized by spur-and-gully morphology, interrupted locally by steep, smooth sections. Spur-and-gully morphology consists of shallow to deeply incised gullies and downward-bifurcating sharp-crested irregular spurs. Spurs have slopes of 15° to 20°, gullies as much as 30°. Outcrops show no major discontinuity in vertical sections. Includes material having poorly developed spurs and gullies, especially in semidetached blocks on trough walls or gullied mounds on trough floors. Smooth wall rock (stippled) is mostly at angle of repose near 30° and occurs predominantly on landslide scars, in gullies above the head of small landslides, on tributary-canyon walls, and on fault scarps. *Interpretation:* Uppermost parts of spur-and-gully walls may include layered wall rock that is not morphologically distinct. Middle and lower sections probably massively bedded material, most likely impact breccia from numerous overlapping ejecta blankets. Semidetached blocks and mounds on floor probably wall rock detached by slumping or faulting. Smooth sections are mostly talus slopes composed of wall rock

Contact—Dashed where approximately located, dotted where buried. Also separating lobes in slide and lobate materials

Layer

Approximate strike and dip directions—Crossed where vertical

Sharp scarp—Line at top, hachures point downslope. Dashed where subdued. Forms contact in places

Scarp base—Barb points downslope

Wrinkle ridge

Ridge—Diverse origins

Direction of movement in landslide material

Fault—Bar and ball on downthrown side. Dashed where inferred. Forms contact in places

Graben—Broad to narrow

Lineation

Depression

Crater rim—Showing crest

Buried crater rim—Showing crest

c **Crater materials**—Includes floor, rim, and eject blanket of impact craters of all ages. Lower size limit is 2 km for rim-crest diameter

clo **Outer ejecta lobe on some impact craters**

INTRODUCTION

The geologic map of Ophir and Central Candor Chasmata is one of a series of 1:500,000 scale maps prepared for areas on Mars that are of particular scientific interest and may serve as potential future landing sites. This map is also part of a set that includes east Candor Chasma, west Candor Chasma, and Melas Chasma. The geologic interpretations are based dominantly on medium- and high-resolution Viking images, many of them stereoscopic, and supplemented by lower resolution apoapsis and other color images. A strip of very high resolution stereoscopic images (~20 m/pixel) crosses the central part of the quadrangle from northwest to southeast and served to clarify detailed relations not obvious on other images. A topographic map with contour intervals of 200 m was also used, as were multidirectional oblique images derived from merged image mosaics and topography (fig. 1) (Bertolini and McEwen, 1990). Geologic relations and interpretations are based on the entire central Valles Marineris map set. The map area is included in the Valles Marineris map of Witbeck and others (1991), but units were defined independently. Age assignments, however, were integrated with those by Witbeck and others and Scott and Tanaka (1986).

PHYSIOGRAPHY

The Valles Marineris system includes a series of troughs just south of the martian equator that trends N. 70° W. for a distance of about 3,000 km, from about longitude 45° to 95°. The troughs are paralleled by many shallow grabens; the entire system appears to be radial to central Tharsis (Carr, 1974; Blasius and others, 1977). Individual troughs are generally 50–200 km wide, but in the central part they merge to form a low region 600 km wide. This map covers most of Ophir and central Candor Chasmata, located in the northern half of this low region. As figure 1 shows, Ophir Chasma is divided into a narrow northern depression and a southern, higher bench. Central Candor Chasma is dominated by two mesas (Candor and Baetis Mensae) rising 6 km above the valley floor. A narrow, northerly trending valley connects Ophir and central Candor Chasmata.

The Lunae Planum Plateau, into which Ophir and Candor Chasmata are entrenched, is at an elevation of 8 to 10 km above Mars datum. The interior mesas locally reach levels only 500 m below the plateau rim (Lucchitta and others, 1994). Trough-floor elevations in the map area range from 2 km, where partly filled by landslide material, to –1 km where near the apparent structural floor. Thus, original trough depths may have been as much as 10 km.

STRATIGRAPHY

INTRODUCTION

Units in the map area are divided into four major groups: (1) materials forming the trough walls and the surrounding plateaus, (2) materials forming the benches and mesas and some trough floors, (3) landslide materials, and (4) trough-floor materials composed of relatively thin surficial deposits. The sequence of emplacement of units has been established with reasonable confidence by superposition and cross-cutting relations, but the composition of units remains conjectural.

PLATEAU AND WALL MATERIALS

Hesperian and Noachian wall rock (unit HNw) (fig. 1) forms the trough walls and locally occurs on the floors in isolated mountain ranges. It displays dominantly spur-and-gully morphology (fig. 1) but is smooth locally, such as on landslide scars. The unit likely consists of impact breccia of the megaregolith (Woronow, 1988), an inference based on the wall rock's stratigraphic position in the upper part of the martian crust (Carr, 1979, 1986). The morphologic uniformity over a depth of several kilometers also suggests that the megaregolith is thick or that the transition from megaregolith to fractured basement (MacKinnon and Tanaka, 1989) is gradual and results in rocks of similar competence. Water or ice may be trapped in pores in the breccia (Carr, 1979).

Thermal-inertia measurements (Skinner and Zimbelman, 1986; Zimbelman and others, 1987) show that wall rock has intermediate thermal inertias, corresponding to fine sand; thus, the walls may be mantled by relatively fine grained materials. Broad-band spectral data provided by Viking color images (Geissler and others, 1990) show that wall rock is nearly as red as the surrounding plateaus; both may be mantled by reddish dust, or the dust on the plateaus may be derived from wall rock and other exposures of similar crustal material.

Wall rock is conspicuously different from interior deposits; it generally shows layers only in the upper 1 km, displays no evidence of wind erosion, and has spur-and-gully morphology in many places (fig. 1). Also, it typically gives rise to extensive landslides. The crest lines of most wall-rock ridges (for example lat 5° S., long 73°–74°) extending from the plateaus into the troughs are marked by dense fault zones. The zones appear to be more competent than the wall rock elsewhere; they may have been intruded by dikes or may have been lithified by fluids percolating along the faults (Lucchitta, 1987a).

Spurs and gullies on wall rock (Lucchitta, 1978) formed early in the history of the Valles Marineris (Lucchitta and others, 1992), as they were already well developed when they became overlapped by older interior deposits (fig. 1). Whether spurs and gullies are forming now is conjectural; they do not occur on young wall surfaces such as landslide scars (fig. 1) and fault scarps, and transitional forms between them and smooth talus slopes (unit HNw, stippled) are scarce, suggesting a change in erosional regime. Perhaps the spur-and-gully morphology is an older erosional form related to a different climate (Lucchitta, 1984) or a different local environment, such as a subaqueous setting. On the other hand, spur-and-gully formation may be an ongoing process, but the smooth talus slopes on landslide scars or fault scarps are so young that they have not yet developed spurs and gullies.

Hesperian ridged plains material (unit Hr) caps the adjacent plateaus and is crossed by grabens and wrinkle ridges. It is discussed in detail by Witbeck and others (1991). This material crops out on the uppermost walls in steep slopes, forming the brink of the walls. Below the brink occur layers or bands of differing albedo or competence (unit HNwl) (Lucchitta, 1978). Four layers can be recognized in many places, and as many as eight can be seen locally. Many of the layers are extensive, and some can be traced for hundreds of kilometers. The layers are only visible on steep, clifflike wall sections of smooth wall rock, and they laterally butt into walls having spur-and-gully morphology. The uppermost part of the spur-and-gully walls also include these layers, even though they are not visible and were not mapped.

The layers are probably the exposed edge of basalt that resurfaced the Lunae Planum plateau; they may represent lower layers in the ridged plains unit (Scott and Carr, 1978; Greeley and Spudis, 1981; Scott and Tanaka, 1986; Scott, 1992). However, the basalt may underlie only one-half of the upper 1 kilometer of steep slope (De Hon, 1985; Frey and others, 1989; Davis and Golombek, 1990); the discontinuity at the base of this slope may mark the base of the cryosphere rather than that of the basalt (Fanale, 1976; Rossbacher and Judson, 1981). In this case, differences in mechanical or chemical weathering processes may have caused the break in slope at the base of the steep section (Soderblom and Wenner, 1978; Davis and Golombek, 1990).

INTERIOR DEPOSITS

Amazonian and Hesperian interior deposits form two sequences, an older one, mostly underlying the mesas and benches, and a younger one, embaying or overlapping the older mesa-forming deposits with disconformities or angular unconformities (fig. 1). Major structural and erosional activity apparently separated the two sequences.

Older Interior Deposits

The materials were emplaced unconformably on trough floors either concurrent with or shortly after the earliest troughs were formed. The deposits are more or less layered throughout, but the layering varies in thickness and competence and is therefore more conspicuous in some sections than in others. Yardanglike fluting appears to be more common on massive, uniformly bedded units but is also found on more finely layered units in places. It was mapped wherever fluting is pronounced, even if occurring on layered units. Therefore, fluted and layered materials are intergradational in places. Overall, fluted units are more common at the base of the section (unit AHif), followed upwards by less fluted and more finely layered materials of differing competence (unit AHil) and topped by resistant caprock (unit AHire). Mottled material (unit AHim) occurs on top of the resistant unit in adjacent quadrangles, but in the map area it occurs only on trough floors. Therefore, it could have been either downfaulted from higher up in the section or emplaced directly on the floor. In the latter case it would be part of the younger interior deposits.

Fluted material may be composed of sequences of alternating light and slightly darker layers, such as in east Candor Chasma (lat 7° S., long 71°), where Nedell and others (1987) found the layers to be about 300 m thick. (Thickness values were derived photogrammetrically.) In general, most of the flutes are on slopes and trend roughly downhill, but some occur on flat surfaces. Wind erosion apparently created these parallel, yardanglike flutes, perhaps by transforming irregular mass-wasting gullies into parallel ridges and troughs. Fluted material is commonly light colored (fig. 1). Thus, light-colored material apparently is susceptible to wind erosion and may be composed of eolian deposits or tuff. The fluting occurs only on interior deposits; it is not seen on wall rock and thus it helps to distinguish interior deposits from wall rock.

Layered material in Candor Mensa averages 100 to 200 m per bed in thickness (Nedell and others, 1987) and is varied in albedo and competence. Dark layers are conspicuously interbedded in places (fig. 2). Exposures of dark beds are as much as 30 km long and locally the beds form resistant ledges and benches that shed talus. Light layers are more difficult to trace, perhaps because they are less resistant to erosion or because they blend in with Mars' general color and albedo. The unit is highly deformed near the southwest corner of the map area (fig. 2).

Resistant material, occurring at the top of the mesa sections, is also locally deformed. On the west side of Candor Mensa, it extends as a tilted layer from the top of the mesa to the adjacent trough floor (fig. 1). In the southwest of the map area the unit forms undulating surfaces (fig. 1), suggesting perhaps the presence of domal uplifts, anticlines, or synclines. The observations suggest that tectonic activity deformed the mesas after the older interior deposits were emplaced. Accordingly, units covering the trough floors in the western part of the map area may actually be downfaulted older interior deposits. The deformation could be tectonic, but it could also be the result of collapse due to loss of material at depth (Tanaka and Golombek, 1989).

Smooth material (unit AHis) forms the surface unit exposed over most of southern Ophir Chasma and also underlies broad expanses of mesa surfaces elsewhere. It may include fluted, layered, and resistant material and is mapped where these units could not be distinguished because of the lack of steep slopes having good exposure. The undivided unit (unit AHi) was mapped where exposures are too small or indistinct to be assigned more definitely. In places this unit may be younger interior deposits.

Spectral data from color images (Geissler and others, 1990) show that the older interior deposits are relatively red and among the brightest materials in the troughs and that the spectral signature of these units is within the range of those of wall rock. These observations suggest either that both units are mantled by similar reddish atmospheric fallout or that at least some of the layered deposits are composed of reworked wall material.

Thermal inertia measurements of older interior deposits (Skinner and Zimbelman, 1986; Zimbelman and others, 1987) indicate that the mesa surfaces are fine-grained or mantled by fine-grained atmospheric fallout; the thermal inertia values on mesa slopes are similar to those on wall rock, supporting the color observations that suggest similar compositions.

At least five hypotheses have been proposed for the origin of the older interior deposits (Lucchitta and others, 1992): The deposits may be (1) erosional remnants of the same material that makes up the canyon walls, (2) eolian deposits, (3) mass-wasted material, (4) lacustrine material, or (5) volcanic material.

The hypothesis that the deposits are erosional remnants of the canyon-wall material (Malin, 1976) is weakened because of superposition relations, the lack of similar layering in the canyon walls, and the different erosional styles of the two materials (Peterson, 1981; Nedell and others, 1987). The hypothesis of a purely eolian origin (Peterson, 1981) is flawed because some of the deposits are much too regularly bedded and too diverse in albedo, competence, and erosional characteristics to be formed by this mechanism alone. However, trapping of eolian materials on ice-covered lakes and foundering of the ice cover (Nedell and others, 1987) may have occurred.

An origin only by mass wasting from wall rock (Sharp, 1973) is also unlikely because the deposits are more diverse in albedo and competence than wall rock, which appears to be fairly uniform in composition. However, mass wasting probably provided some of the material for the deposits (Lucchitta and others, 1994).

The lacustrine hypothesis readily explains the horizontal bedding and lateral continuity of individual layers, and at the time of canyon formation, substantial subsurface aquifers may have provided large quantities of water (Sharp, 1973; Carr, 1979). However, the likelihood of purely lacustrine deposits is diminished because no channels are seen to empty into the troughs, channels that may have carried the large amount of sediments needed to form the thick layered deposits.

Also not to be ruled out is a volcanic origin of the older interior deposits (Peterson, 1981; Lucchitta, 1990; Witbeck and others, 1991). Compatible with such an origin are the diversity of layers, the low albedo and high competence of some layers (suggesting basalts), and the fluting on light-colored deposits that is similar to fluting on tuffs in terrestrial desert regions. For tuffs, an ash-flow origin appears more likely than an origin by airfall because the layered deposits are restricted to the inside of the troughs. The main evidence against a volcanic origin is the apparent regularity and continuity of the deposits and the lack of obvious vent edifices or calderas (Nedell and others, 1987). However, the continuity and horizontality of the layers could have come from subaqueous volcanic eruptions.

Younger Interior Deposits

These deposits overlie eroded wall rock, older interior deposits, and, locally, landslides, attesting to the presence of a second major unconformity in the troughs (Lucchitta, 1990). The deposits were emplaced after the troughs had nearly reached their present configuration, and they consist of three major units: unevenly edged material (unit AHie); rolling and smooth material (unit Airs), and raked material (unit Aira).

The unevenly edged material may have different ages and origins in different places. It clearly overlaps an eroded bench of older interior deposits in east central Candor Chasma (lat 6.8° S., long 70°), where it is composed of two thin resistant ledges on top of one another and where it was apparently emplaced after significant erosion of the older interior deposits had taken place (Lucchitta, 1990, fig. 10); here, it may well be of volcanic origin. Elsewhere it occurs at the base of interior mesas or laps onto mesa slopes and its identity is unclear (fig. 1). It could be mass-wasted material from mesa slopes, tilted older resistant material, or young volcanic material. On the floor of west-central Candor Chasma, it could be downfaulted older interior deposits. Where it occurs along the south border of the map area in west-central Candor Chasma (lat 7.5° S., long 74°), it could be an ancient landslide deposit.

The rolling and smooth material occurs dominantly on Candor Chasma trough floors. It again may have different ages and origins in different places. In east-central Candor Chasma, the material overlies with angular unconformity dissected mesas composed of older interior deposits (lat 7.05° S., long 70.4°) (fig. 1). It is also associated with a peculiar nested set of rimmed craters (lat 6.35° S., long 70.7°) consisting of a circular crater about 10 km in diameter inside an oblong depression (Lucchitta, 1990, fig. 11). The inner crater is deep, but both craters lack the rugged ejecta blankets that might be expected around deep, young impact craters; these craters could be volcanic. Therefore the associated deposit may also be volcanic, perhaps airfall tuff. However, an origin as thick eolian materials cannot be ruled out. The rolling and smooth material on the trough floors in west-central Candor Chasma could be downfaulted older interior deposits. There the unit is overlapped by slide material (along the west border of the map area), suggesting that it may indeed be an older deposit.

Material as much as 3 km thick in the adjacent west Candor Chasma quadrangle has a raked appearance. There it embays tributary canyons and buries landslide deposits (Lucchitta, 1990, figs. 12 and 13). In central Candor Chasma the raked material occurs only near the westernmost border. The unit cuts across beds on the chasma floor that appear to have been previously tilted and eroded (lat 5.9° S., long 75°) (fig. 2). A dearth of superposed impact craters and superposition of the unit on landslides suggest that it is young. Its origin is unknown. It is not readily explained as lacustrine because it was emplaced relatively late in martian history, when the existence of water in the Valles Marineris was unlikely (Carr, 1983). A debris-flow origin is also questionable, because the material has no obvious source areas and buries other debris such as landslides. Lobate fronts and embayments suggest flow emplacement. A volcanic origin (Lucchitta, 1990) is suggested by the apparent flow lobes and by fine fluting similar to fluting on terrestrial tuffs in arid regions.

LANDSLIDE MATERIALS

Amazonian landslide materials occur dominantly in Ophir Chasma. Their scars form talus-covered curved reentrants in the walls. The slides typically have coarse slump blocks at their heads (unit Asc), transverse ridged material below (unit Asr), and, where unconfined, longitudinally grooved material in fan-shaped aprons toward their toes (unit Asg). Three conspicuous landslides on the north wall of Ophir Chasma have mutually overlapping lobes, indicating emplacement in several pulses.

The landslides were emplaced into low areas that formed when older interior deposits were eroded or structurally dropped; they abut the older interior deposits. Along the west map border, raked material overlaps a landslide, indicating that in places sliding occurred before emplacement of the younger interior deposits. According to crater counts on combined landslide deposits (Lucchitta, 1979), the age of the landslides is broadly equivalent to plains-lava emplacement on the Tharsis plateau to the west (Scott and Tanaka, 1981, 1986). However, the central landslides in Ophir Chasma have so few craters superposed that they may be considerably younger.

Whether the landslides were emplaced as dry-rock avalanches or as wet debris flows is unclear. McEwen (1989) found that the trend in the ratio of height of drop/length of runout decreased for martian landslides. This trend is parallel to, but lies above, that of terrestrial dry-rock avalanches. He argued that wet debris flows would be expected to plot below the trend for terrestrial dry-rock avalanches and that the martian landslides were probably not wet. On the other hand, the landslides apparently gave rise to mudflows and floods: debris from the landslides in Ophir Chasma seems to have merged with valley fill (unit Afh) (lat 5° S., long 71.5°) and a channel (unit Ach) (lat 6° S., long 72.1°) (fig. 1), whose fluids flowed for 250 km, negotiated several bends, and apparently contained blocks of ice (Lucchitta, 1987a, figs. 1 and 2). The water in the landslides must have come from the materials underlying the plateaus and must have been stored behind the trough walls.

Small aprons of lobate slide material (unit Alo) may also be landslides. However, in the adjacent quadrangles to the west and east, considerable thicknesses of similar lobate material are part of the younger interior deposits and may be of volcanic origin.

FLOOR MATERIALS

Amazonian and Hesperian dark material (unit AHd) occurs along faults or as aligned patches following structure trends (Lucchitta, 1987b). It also occurs as competent material in lower spurs (Lucchitta, 1990) (lat 5.5° S., long 73°) and near dark cone material (unit Aco) (lat 6.05° S., long 71.4°).

Viking Orbiter 3-color spectral measurements on similar dark material in Juventae Chasma and a dark layer in the wall of Coprates Chasma indicate that these materials have a reflectance below 5 percent and are relatively colorless, compatible with the signature of mafic rock or glass (Geissler and others, 1990). Some patches may be derived from older necks, dikes, or sills that are exposed in the chasma walls or interior deposits, and may be associated with interior deposit emplacement (fig. 1). Others may be erupted from young volcanic vents, as suggested by patches occurring along the northern chasma fault in Coprates Chasma (Lucchitta, 1987b).

Hummocky floor material (unit Afh) and smooth floor material (unit Afs) occur in patches throughout the map area. Hummocky floor material is generally associated with landslide deposits (see above) or with material that suggests an alluvial origin, such as fractured material (unit Aff). The latter occurs in the lowest area of the quadrangle, resembles chaotic material at the head of outflow channels, embays other materials, and appears to have a strand line (unit Afh at lat 7.2° S., long 72°). All this evidence points to an origin as alluvium, deposited in ephemeral lakes or playas—the water being derived mostly from wet landslides.

Dark eolian drift is concentrated in low areas (Thomas, 1982) on the trough floors. It is mapped separately only where thick enough to form dunes (unit Adu) (Lucchitta, 1990, fig. 6). The material apparently moved by saltation and thus is inferred to be composed of sand-sized grains (Cutts and Smith, 1973; Greeley and others, 1980). Elsewhere, dark material covers the trough floors with a thin mantle. The dunes (lat 6° S., long 72°) and dark mantle appear to be derived from dark, possibly mafic outcrops inside the troughs (Lucchitta, 1987b, 1990; Geissler and others, 1990). The thin dark mantle is readily visible in figure 1; it is not separately mapped.

Atmospheric fallout from local and intermittent dust storms temporarily obscures albedo markings in the Valles Marineris (McEwen, 1985). The dust may also form a permanent thin layer on other deposits. In some places atmospheric fallout may be thick enough to obscure underlying units.

STRUCTURE

Most evidence points toward a tectonic origin for the Valles Marineris. They lie along a structural trend radial to central Tharsis (McCauley and others, 1972; Sharp, 1973; Blasius and others, 1977), and linear boundary faults at the base of the walls extend for hundreds of kilometers and locally cut lower spurs to form triangular facets (Blasius and others, 1977).

In this quadrangle, the trend radial to Tharsis is expressed in shallow grabens on the plateau surface, in the direction of elongation of Ophir and Candor Chasmata, in wall-rock spurs that separate these two chasmata, and in the trough-boundary faults that occur at the base of wall rock throughout the map area. The trend of wrinkle ridges on the surrounding plateau material is generally perpendicular to that of the troughs and the shallow grabens (Watters and Maxwell, 1983, 1986; Chicarro and others, 1985). The trend of wrinkle ridges is reflected in the blunt west end of Ophir Chasma and in the northerly alignment of the deep trough east of Baetis Mensae; apparently older structural trends were reactivated when these later structures formed. In the northeastern map area ridges, visible on trough walls, occur along the trend of wrinkle ridges immediately above on the plateau. This observation suggests that the wrinkle ridges have structural expression at depth. An analysis of the shallow grabens and wrinkle ridges on the adjacent plateau suggests that, in early Hesperian time, the wrinkle ridges developed first, the grabens second (Watters and Maxwell, 1983, 1986), and the Valles Marineris either at the same time as the grabens or later (Schultz, 1991).

In the quadrangle, boundary faults with triangular facets occur on the north walls of Ophir and east-central Candor Chasmata. In both places, when seen in detail, the boundary fault is offset along many cross faults. On the north side of west-central Candor Chasma, triangular facets are absent, and dark material (unit AHd) lines an inferred fault scarp instead (fig. 1). On the south side of Ophir and Candor chasmata, fault scarps are less obvious. Instead, deeply eroded spurs and gullies are overlapped by interior deposits.

Other faults within the troughs have diverse trends and displace floor materials and interior deposits. An example is the fault that offsets the mesa surface east of Baetis Mensa in central Candor Chasma (Lucchitta, 1990) (lat 5.8° S., long 71.5°). Tilted beds are best recognized on older interior layered deposits, such as in hogbacks in west Ophir Chasma (along long 74.1°), east-central Candor Chasma (lat 6.6° S., long 70.6°), and west-central Candor Chasma (lat 6.9° S., long 74.7°) (fig. 2). Tilted beds may also occur on some trough walls, where crudely developed hogbacks appear to be present (lat 3.7° S., long 74.3°), but the absence of distinct stratification in wall rock makes identification tentative. Undulations apparently occur on older interior deposits in the southwest corner of the map area, suggesting, perhaps, the presence of anticlines and synclines (fig. 1).

Locally, faulting apparently dropped internal subsidiary troughs parallel to the main ones (Lucchitta and Bertolini, 1989). Indeed, the interior benches and mesas may have formed by such faulting rather than by erosion. This idea is supported by the observation that faults (fig. 1) may locally displace the entire section of older interior deposits. Also, the northern depressions in both Ophir Chasma (fig. 1) and the adjacent east Candor Chasma quadrangle are devoid of interior deposits, suggesting that they formed after these deposits were emplaced. On their northern margins, these troughs have well developed faceted fault scarps, suggesting a young age. The southern benches, by contrast, are underlain by interior deposits that lap up onto well eroded scarps. Thus, Ophir and Candor Chasmata possibly developed in two episodes: early (Hesperian) faulting formed the south part of the chasmata and late (Amazonian) faulting formed the northern depressions (Lucchitta and others, 1994).

Structural relief, estimated from a block of downdropped wall rock on the floor of east-central Candor Chasma near the east map boundary at lat 5.9° S., long 70°, is about 7 to 9 km (U.S. Geological Survey, 1986). But considering that the troughs are locally filled with young interior and landslide deposits, structural relief in other places may attain 10-km depths.

GEOLOGIC HISTORY

The Valles Marineris troughs opened after most of the wrinkle ridges on the adjacent plateaus had formed. The opening may have coincided with the formation of parallel shallow grabens (Chadwick and others, 1994). All three structures apparently formed in response to Tharsis stresses (Banerdt and others, 1982; Watters and Maxwell, 1983, 1986). Ancestral troughs disrupted the Lunae and Syria Planum plateaus of early Hesperian age (Scott and Tanaka, 1986; Tanaka, 1986) and, accordingly, they are younger than this age (Dohm and Tanaka, 1995). After the opening of the ancestral troughs, the walls were eroded into spurs and gullies. At the same time or later, the older interior deposits were emplaced, embaying the walls and locally overtopping eroded wall rock. First emplaced were more massive, thick bedded, fluted units having cyclic layers of lighter and darker materials. Secondly emplaced were more finely layered beds of variable competence and albedo. The sequence was topped by resistant caprock. The older interior deposits may have been emplaced in lakes as sediments or volcanic rocks, with contributions of mass-wasted or eolian materials. Deposition of the older interior deposits may have extended through late Hesperian and perhaps into early Amazonian time. After the ancestral troughs were filled nearly to their rims by older interior deposits, a major episode of structural disturbance and erosion ensued, forming faults, grabens, and tilted beds (fig. 2). Subsidiary troughs formed on the north sides of the ancestral Ophir (fig. 1) and Candor Chasmata (Lucchitta and others, 1994). The disturbance left isolated mesas surrounded by benches bordered by newly formed depressions. Thus, the older interior deposits may have filled only the ancestral southern troughs; the more recent northern depressions are devoid of such deposits.

Formation of the new depressions heightened the relief of the trough walls, and landslides fell into the voids. In central Ophir Chasma, the landslides appear to have contained fluids and gave rise to a flood, forming a channel (fig. 1). Many small debris flows formed in wall-rock gullies, smoothed their head walls to form widened alcoves, and eradicated wall-rock spurs.

After some of the landslides were emplaced, a new unit of diverse materials, several kilometers thick in places, was deposited on the Valles Marineris floors. Some dark patches associated with this unit may be of mafic volcanic material; the origin of the remainder is unknown, but considerable evidence suggests that it may also be volcanic. Eventually, low areas of the chasmata were filled with colluvium from mass-wasted material and alluvium from fluids drained from late landslides. The latest activities are continued wind erosion, blanketing by light-colored atmospheric dust, and transport of dark-colored saltating material that locally forms dark dune fields on the trough floors. Tectonism apparently occurred throughout the history of the Valles Marineris. If some of the interior deposits are of volcanic origin, volcanism may have been similarly long lasting.

A CANDIDATE LANDING SITE

The Valles Marineris offer a potential surface-exploration site of unusual interest. Although the lack of extensive surfaces that can be dated by crater statistics is a detriment, other factors outweigh this disadvantage. Ideal sample sites on Mars would yield information on rocks in close proximity having a range of ages and compositions. Sites in the Valles Marineris fulfill this requirement. Noachian units are exposed in the lower walls. These rocks, if sampled, could furnish data on compositions and ages of rocks that are deep below the surface in most other places on Mars. The most commonly accepted hypothesis is that these rocks are lunar highland-type breccia (Carr, 1979). Wall rocks and plateau rocks of early Hesperian age could both be sampled in the landslide deposits that carried these rocks from the walls and the plateau surfaces to the trough floors. The plateau rocks may be composed of basalt (Scott and Tanaka, 1986). Intermediate-age rocks (Hesperian-Amazonian) form the older interior deposits. Their origin is uncertain. Sampling these rocks would illuminate an important segment of martian mid-history and shed light not only on the composition of these materials but also on the processes that operated at that time. If these deposits were emplaced in a lake, the discovery would have far-ranging implications on Mars' climate. If they incorporated carbonates, one might even discover fossil life.

Rocks of late Hesperian to Amazonian age form the younger interior deposits. Their origin is also unknown but may be volcanic. The dark materials are probably mafic rocks. The other materials have varied albedo and include light-colored rocks. If these were volcanic, an answer might be obtained to the important question whether felsic rocks are exposed on the surface of Mars. If so, sampling these rocks and obtaining their precise compositions and ages would be important to unraveling the thermal evolution of Mars.

Observations and samples would also give insights into martian processes. By studying the landslide deposits one might answer the question whether the slides were wet debris flows or dry rock avalanches and whether they contained ice blocks derived from wall rock. Thus, the role of volatiles would be evaluated. Wind deposits are abundant on the trough floors. Sampling dark dune material would shed light on the composition and ages of the source material and its mechanism of emplacement. Sampling light-colored reddish dust from atmospheric fallout may resolve the controversy whether dust-storm material and the ubiquitous blanket on Mars is composed of smectite clay (Clark, 1978), palagonite (Singer, 1982), or an as yet unknown substance.

Figure 3 shows a potential landing site that is located on relatively open, level ground and offers easy access to ancient (Noachian) wall rock on the trough wall to the north, intermediate age (Hesperian-Amazonian) older interior deposits on Candor Mensa to the east, younger (late Hesperian-Amazonian) interior deposits to the west, and a landslide incorporating Hesperian plateau rock also to the west (fig. 2). Examination of floor material at the landing site will answer questions pertaining to its origin as down-faulted older interior deposits, infilled younger interior deposits, or late eolian fill.

Figure 4 shows a potential landing site that is located in a relatively narrow slot on the floor of a channel. Even though both ancient wall rock and intermediate age older interior deposits are accessed easily, the main purpose of the site would be the exploration of younger materials and processes. The site offers insights into the nature of the flood and the involvement of mud, water, or ice in the formation of the channel and into the characteristics of the nearby dark dune deposits and possible late mafic volcanic vents.

In addition to being scientifically rewarding, the Valles Marineris would offer a spectacular backdrop for a manned landing. The Earth-like complexities of the local geology would be most suitable for investigation by man.

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