INTERIOR — GEOLOGICAL SURVEY, RESTON, VA—1998 SCALE 1:502 000 (1 mm = 502 m) AT 70° LONGITUDE Base from U.S. Geological Survey, 1984. Prepared on behalf of the Planetary Geology Program, Solar System Exploration TRANSVERSE MERCATOR PROJECTION Division, Office of Space Science, National Aeronautics and Space Administration Edited by Derrick D. Hirsch; cartography by Mike Dingwell Manuscript approved for publication December 2, 1993 CORRELATION OF MAP UNITS overlying plains material; few craters; locally superposed by ornamented in Coprates Chasma by dark subcircular or irregular Direction of movement of slide or flow material landslide material and material of older interior deposits. patches and by scarps or shallow grooves oriented parallel to Impact crater materials—Symbol c denotes crater rim and apron MATERIALS OF FLOOR SURFICIAL Interpretation: Material eroded during or following formation of trough axis; northern and southern margins defined by faceted N(1) SYSTEM* materials. May include rim crest (hachured, dotted where buried) AND TROUGH-TROUGH INTERIORS MATERIALS MATERIALS trough depressions; probably Noachian impact crater ejecta and scarps; smooth, higher albedo surface in Melas Chasma. and materials of central peak complex. Materials of craters smaller WALL MATERIALS igneous materials showing apparent Amazonian crater age due to Interpretation: Surface material of former plateau caprock

U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

MC-8

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.

Noachian

*System and series boundaries from Tanaka (1986)

DESCRIPTION OF MAP UNITS

Smooth plains material—Flat; craters mostly lack visible ejecta

leposits; abundant northwest-trending scarps and troughs.

Relatively low albedo; marked by south-southwest oriented streaks

of darker material originating at craters and scarps. Closely

in Candor Chasma and faceted in Melas and Coprates Chasmata;

sloping trough walls marked by linear gullies below ribs in

rom trough-floor material of Coprates Chasma; basal part eroded

[Unit symbol in parentheses indicates buried unit]

PLAINS AND TROUGH-WALL MATERIALS

of plains material exposed by erosion

oversteepened wallrock

spaced, subvertical ribs within 1-2 km of plateau surface occur Forms contact in places. U, upthrown side; D, downthrhown side about 1–2 km across; locally rough or lobate appearance; embays along erosional margins; commonly in fault contact with cratered trough-wall materials. Interpretation: Same as smooth material; ______ Major fault—larger offset plateau material. Interpretation: Possibly lava flows of relatively lobate appearance may indicate flow lobes; etched appearance may indicate erosion of depressions in finely layered material by — Minor fault—smaller offset low viscosity covered by veneer of eolian material; ribs mark layers Narrow graben—Dotted where concealed rough-wall material, smooth—Forms steep, smooth slopes in FLOOR MATERIALS rough walls below smooth plains material, typically above Scarp—Line at top of scarp; hachures point downslope Afs Smooth floor material—In Melas Chasma and westernmost Coprates landslide headscarps. Interpretation: Rocks of basal sliding Scarp—Line at base of scarp; barb points downslope; dotted where Chasma. Surface undulatory, albedo relatively high. surfaces of landslides left exposed by downslope transport of Interpretation: Surficial mantle composed dominantly of eolian material that drapes over craters and bedrock of trough floor Trough-wall material, gullied—Separates smooth plains material

elimination of craters by protracted erosion

MATERIALS OF TROUGH INTERIORS

YOUNGER INTERIOR DEPOSITS

characteristics to debris or mud flows

volcanic origin

volcanism

GEOLOGIC MAP OF THE WESTERN OPHIR PLANUM REGION (MTM –10067) OF MARS

Richard A. Schultz

Al Lobate material—In Candor Chasma. Forms a digitate mass;

Ah Hilly material—In southeastern Melas Chasma above topographic rise

OLDER INTERIOR DEPOSITS

Cratered plateau material—On eastern part of Ophir Planum.

Moderately rugged, undulate; degraded craters, channels, and

scarps. Interpretation: Possibly complex of lavas, intrusives, and

unconformably overlies smooth and fluted materials; no

superposed craters. Interpretation: Mobilized material that

emanated from interior layered deposits; similar in flow

separating it from western Coprates Chasma. Forms domical

mound about 2 km high with irregular, hilly surface; no

superposed craters; cut by scarps. Interpretation: Local deposit of

them by scarps. Layering visible in many places. *Interpretation*:

Possibly layered sedimentary rocks produced by erosion or

uted material—In Candor Chasma. Characterized by subparallel

chutes oriented downslope; layering observed in places; contact

with etched material gradational. *Interpretation*: Same as smooth

tched material—In Candor Chasma. Irregular surface marked by pits

material; fluted appearance attributed to wind erosion of friable

mooth material—In Candor Chasma. Forms tops of interior layered

material; grades into fluted and etched units or is separated from

Lineation—Probably trace of layering on exposed slopes rough floor material—Mostly in western Coprates Chasma and northern Melas Chasma. Flat. Several craters that lack discernible ejecta; underlies interior layered and slide materials. Locally Rimless depression—Presumably of collapse origin

lowered by normal faulting and partially buried by sediments and

landslides; dark deposits near center of Coprates floor may be

dunes composed of mafic volcanic sand trapped in depressions;

smooth appearance in Melas Chasma probably due to thin

massive; similar in appearance to smooth plains; mesa margins

contact with wall materials at junction of Melas and Coprates

material erupted from vents along faults; redistributed downslope

Planum. Fan-shaped deposits have ridges and blocks near their

heads and radial grooves along aprons; thin; a few superposed

craters that lack visible ejecta. Interpretation: Landslides and

Slide material—Along northern and southern margins of Ophir

Fault—Dotted where concealed; bar and ball on downthrown side.

slumps mobilized by failure of plateau walls

materials. No superposed craters. Interpretation: Possible mafic Peulvast and Masson, 1993b).

and surface commonly faceted or grooved. Interpretation:

Material of isolated floor mesas—Relatively flat topped, resistant.

SURFICIAL MATERIALS

Dark surficial material—Along faults separating Coprates Chasma

sedimentary and (or) eolian mantle

Chasmata

by gravity and wind

Relative ages of photogeologic map units are determined from stratigraphic and structural relations and crater statistics. The mapped units provide a framework for determining the magnitudes of stratigraphic offsets along the major troughbounding normal faults. The oldest unit recognized in the map area is the cratered plateau material (unit NpI). Comparable with that mapped previously by Scott and Tanaka (1986) and Witbeck and others (1991), this material occurs on the eastern part of Ophir Planum. It is undulatory or hilly topography having a high crater density; crater counts (fig. 1) suggest an Early to Middle Noachian age.

Probably downfaulted remnants of plateau caprock; locally in fault in an en échelon array that is unique along the Valles Marineris.

edges diffuse. Material concentrated in gullies; locally overlies slide several processes that have shaped the troughs (Lucchitta and others, 1992;

Valles Marineris troughs.

than 3 km in diameter not mapped

Key aspects of the deformation sequence of the Valles Marineris trough

system can be clarified by relations observed in the map area. For example, the

the trough floor (Lucchitta and Bertolini, 1989; Schultz, 1991; Lucchitta and

STRATIGRAPHY

Prepared for the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Trough walls are divided into three units. From bottom to top, they are gullied wall material (unit Nwg), smooth wall material (unit Nws), and smooth plains material (unit Hp). Gullied wall material exhibits the classic spur-and-gully morphology typical of wall-rock erosion (Lucchitta, 1978). Little bedding can be discerned in this material, although the existence of tilted beds in the north wall of Coprates Chasma near lat 11° S., long 66° may be suggested by inverted V-shaped erosional patterns of the material. Also mapped as this unit are massifs at about lat 11.4°-12.2° S., long 65.2°-67°, which commonly lack flat tops and may be downfaulted blocks of trough-wall material, although the distinction is not everywhere clear. Smooth wall rock is mapped, in part, above large landslides where downslope movement of material has resulted in smooth and relatively steep scallops in the

The two lower trough wall materials stratigraphically underlie Ophir Planum caprock; they also underlie, or are continuous with, cratered plateau material (unit Npl). These relations imply a dominantly Noachian age for the two lower wall-forming materials, although their upper parts may be Lower Hesperian. Superposition of very few craters on wall materials implies that erosion of trough wall slopes has continued to relatively recent time, giving an Amazonian modification age. No contact can be discerned on Ophir Planum between cratered plateau material and gullied wall material, so the two materials may be the

The smooth plains material forms the caprock of western Ophir Planum and steep ribbed or layered slopes extending 1 km or so immediately below the caprock surface. The exposed section of caprock correlates with "layered wall material" mapped in other troughs northwest of the map area by Lucchitta (1998). Because the cumulative crater density of this plains material (fig. 1) is statistically distinct from that of Lower Hesperian ridged plains material (outside the map area; see Witbeck and others, 1991), but indistinguishable from that of Upper Hesperian Syria Planum Formation southwest of Valles Marineris (Schultz. 1991), the plains material appears to be Late Hesperian in age. The smooth plains material was mapped previously as "ridged plains" by McCauley (1978) and Witbeck and others (1991) and as "younger fractured material" by Scott and

Tanaka (1986). Both of these materials are of Early Hesperian age (although the younger fractured material can also be of Late Hesperian age, Tanaka, 1986). However, no wrinkle ridges are observed in high resolution images of western Ophir Planum, so the appellation "ridged plains" for this material is inappropriate. In the eastern part of the map area, plains material was mapped by Witbeck and others (1991) as "smooth material" (their unit HpI₃) of Early Hesperian age. Ridged plains material may underlie the plains material, although none is identified in the map area. The plains material locally embays cratered plateau material (unit NpI), which has a Noachian crater age (fig. 1); elsewhere, these materials appear to be

in fault contact. The margins of Ophir Planum are defined by erosional slopes. Trough floor material (unit Hf) is characterized by a relatively flat surface having moderate crater density; the unit is commonly in apparent fault contact with gullied wall material. The floor material is covered in places by a veneer of eolian and (or) sedimentary material, particularly in Melas Chasma, although this veneer may be thin or absent in Coprates Chasma. More resistant material of isolated mesas (unit Hfi) in Coprates Chasma forms irregular to rectangular blocks aligned parallel to the north bounding scarp and overall trend of the trough.

The crater age of trough floor material in western Coprates Chasma can be established

by examining its cumulative crater density (Schultz, 1991). The Coprates floor here has an area of 6,915 km², is relatively flat, and has 14 craters exceeding 1 km in diameter that define a Hesperian crater age for the material (fig. 1). This age is substantially greater than that reported for the landslides (Lucchitta, 1979) that are superposed on the floor, but it is comparable with, or perhaps somewhat greater than, that of smooth plains material within the statistical uncertainties. Therefore, smooth plains material on Ophir Planum and trough floor material in Coprates Chasma are likely correlative. The crater counts, similar morphologies, and apparent structural juxtaposition identified in the map area imply that the trough floor material is caprock formerly continuous with that on western Ophir Planum and adjacent plateaus to the south, but which is preserved at a lower structural position. The material of isolated floor mesas (unit Hfi), cropping out in resistant mesas and blocks scattered throughout Coprates and Melas Chasmata, was previously interpreted as trough wall (or slope and bedrock) material (McCauley, 1978; Scott and Tanaka, 1986; Witbeck and others, 1991). Witbeck and others mapped several mesas as "high floor material" that was left relatively high standing due to lowering of adjacent trough floor material. The absence on these mesas of spur-and-gully topography characteristic of trough wall material (Lucchitta, 1978), the relatively flat surfaces, and the apparent fault contact of the isolated mesa material with massifs of wall material suggest that the two materials have different lithologies. The distribution and shape of the mesas suggest that they may be erosional or faulted remnants of a formerly more extensive deposit. ough material of isolated floor mesas may be interpreted as sedimentary

morphology and structure of the mesas are comparable with those of remnant blocks of Lower Hesperian "ridged" plains material (unit Hr of Scott and Tanaka, 1986) west of the map area on the floor of Melas Chasma and to the north on the floor of Candor Chasma (B.K. Lucchitta, oral commun., 1990). These similarities and the structural setting on trough floors of mesa-forming materials in Coprates and Melas Chasmata suggest that the materials probably are downfaulted pieces of smooth plains material, as postulated by Witbeck and OLDER INTERIOR DEPOSITS

Interior deposits, found in parts of Coprates and Melas Chasmata, resemble interlayered sedimentary or volcanic beds similar to those identified by Lucchitta (1998) in other troughs. The older deposits are mapped as three units: etched material (unit AHe), fluted material (unit AHf), and smooth material (unit AHs). The etched material forms the base of the sequence and grades laterally and (or) upward into the fluted material, which correlates with that defined elsewhere by Lucchitta (1998). Layering can be identified in places within both etched and fluted materials. A somewhat more resistant cap of the sequence is smooth material that is locally faulted, particularly in Candor Chasma. The older interior deposits appear to be Late Hesperian through Middle Amazonian in age (Lucchitta and others, 1992). The contact between older interior deposits in Candor Chasma and the trough wall material beneath Ophir Planum appears to be a depositional unconformity. Exposures of older interior deposits within the map area in Candor Chasma are comparable stratigraphically and morphologically with those in other troughs in Valles Marineris (for example, Komatsu and others, 1993). Isolated exposures of these materials are locally buried by slide material (unit As) on the north wall slope of western Coprates Chasma (lat 10° S., long 69.5° and 10.4° S., long 68.6°). Here, the deposits rest on a relatively smooth surface about 4 km below the caprock surface on Ophir Planum (and 5 km above the trough floor). This smooth surface may be a more resistant horizon within the wall rock. Layering in these exposures is particularly prominent. Because the deposits are not found elsewhere in Coprates Chasma or in the adjacent part of Melas Chasma, they probably are either an erosional remnant of a formerly more extensive sequence, similar to that found in other troughs, or materials emplaced near a local source. However, their close similarity to the older interior deposits found in other troughs suggests that they are a remnant. This interpretation is supported by the presence of younger, amphitheater-shaped reentrants into the surface that underlies the interior deposits. The reentrants mark the sites of slope failures and landslides (Ophir Labes) that demonstrate truncation of the older interior deposits by structural lowering of trough floors and slope instabilities. YOUNGER INTERIOR DEPOSITS

Materials occurring stratigraphically above the older interior deposits imply both erosion and mobilization of the older materials as well as deposition of other, more localized materials. The erosional materials appear unique to the map area, whereas the depositional materials are similar to those recognized in other parts of the Valles Marineris. Although failure of wall-rock materials in the form of landslides is well documented (for example, Lucchitta and others, 1992), down-slope mobilization of material making up the older interior deposits can also occur. One well-developed occurrence near lat 8° S., long 66° in Candor Chasma displays several digitate lobes that emanated from a source in the upper part of fluted material and flowed into an arcuate depression. The digitate, multi-lobed morphology of this material (unit AI) distinguishes it from younger interior deposits in other troughs that may have been emplaced as volcanic flows (Lucchitta, 1990). Also, its morphology suggests that the older interior deposits were mobilized more as a series of mud slides or debris flows than as landslides. This interpretation implies that some process, such as overpressurization by water or melted interstitial ice, seismic shaking, or acoustic fluidization, caused the bulk flow of the fluted material (for example, see Johnson, 1970;

The hilly interior material in southeastern Melas Chasma (unit Ah) overlies relatively flat, moderately cratered trough floor material that is less mantled to the north and west and is 1 to 2 km lower in elevation than the trough floor in western Coprates Chasma (U.S. Geological Survey, 1986). The hilly material exceeds 2 km in thickness but appears to thin markedly to the west and east. Its crudely domical form, restricted lateral extent, and occurrence over a significant northeast-trending topographic offset suggest a local origin, perhaps as volcanic material erupted along a fault associated with the topographic offset. This origin is comparable with that suggested by Lucchitta (1990) for morphologically similar material in other troughs.

Trough floor material in Melas Chasma west of the Ophir Labes group of landslides and wall-rock massifs and centered at about lat 11° S., long 69°, contains several craters larger than about 3 km in diameter in its northern part. However, it appears to be mantled by a veneer of smooth, high-albedo material mapped as smooth floor material (unit Afs). This veneer was also mapped as smooth floor material and interpreted as alluvial and eolian material by Witbeck and others (1991), although they did not distinguish an underlying bedrock unit.

OTHER MATERIALS

Mass wasting of trough walls has produced small, fan-shaped slumps or rock avalanches (Selby, 1982) in Candor Chasma and large landslides in Melas and Coprates Chasmata. These landslides overlie trough wall material, older interior deposits, and trough floor material. Curiously, material of large landslides (unit As) south of Ophir Planum occurs only in Melas and western Coprates Chasmata. The largest landslides in Coprates (Ophir Labes and Coprates Labes) reach more than 50 km in length but have only 1 to 2 km of relief, so the locally greater relief south of Ophir Planum by itself probably did not control the locations of these landslides. Instead, they may have formed preferentially where trough fault geometry becomes complex. For example, no large landslides occur in Candor Chasma where complex faulting is not apparent or in eastern Coprates where the normal faults are straight and parallel. The junction of Melas and Coprates Chasmata is marked by massifs, arcuate and intersecting normal faults, and large landslides. The landslides may have nucleated as wedge failures (Brady and Brown, 1993) in these areas. Patches of dark surficial material (unit Ad) occur throughout the map area, but their characteristics and implied significance differ with location and geologic context, Irregular

patches of dark material typically occur as linear chains along faults in Coprates Chasma. These patches suggest recent mafic pyroclastic eruptions (Lucchitta, 1987a) from vents developed along both the main trough-bounding faults and parallel structures inferred within the trough wall. The dark materials are superimposed on landslides of Ophir Labes, suggesting volcanic activity more recent than these large slope failures. Other patches of dark material in Candor Chasma near lat 8° S., long 65.1° are interpreted by Lucchitta (1990) as material erupted from vents along fractures. This interpretation suggests that dikes intruded the older interior deposits in Candor Chasma and locally breached the surface. Other patches of dark material in the map area are larger, more diffuse, and conform to slopes, in addition to small circular patches on trough floor in Coprates Chasma; these occurrences may represent materials transported and redeposited by wind. The main development of spur-and-gully modification of plateau margins postdates formation of grabens on Ophir Planum (for example, Blasius and others, 1977), giving a maximum age for this erosional process of Late Hesperian. Onlap of older interior deposits naving Late Hesperian through Middle Amazonian ages implies that formation of spur-andgully topography was restricted in time, in part coeval with some older interior deposits, perhaps suggesting that Amazonian or contemporary climatic conditions were not conducive to spur and gully growth. Indeed, landslides eroded plateau margins after The map area, in the Coprates 1:2,000,000-scale quadrangle MC-18 NW, deposition of older interior deposits but spur-and-gully topography was not reestablished on lies in the heart of the Valles Marineris trough system. The western part of Ophir the landslide scars. On the other hand, spur-and-gully modification of head scarps may not Planum (36,660 km²) occupies 40 percent of the map area; parts of Candor, have had sufficient time to develop since the formation of the landslides (Lucchitta, 1978). Melas, and Coprates Chasmata make up the remainder. The troughs contain Faceted scarps that also have smooth slopes along the north wall of Coprates Chasma distinctive landslide deposits, normal faults, possible young volcanic rocks, and indicate truncation of spur-and-gully topography by normal faulting that was geologically layered materials. Ophir Planum plateau is deformed by normal faults and grabens recent (Blasius and others, 1977) or that continued over time. The width of plateau-margin erosion and backwasting varies in the map area. In

The Valles Marineris troughs have been mapped by many workers, including Candor Chasma, the trough wall increases in width from 10 km in the east to 20 to 30 km McCauley (1978), Scott and Tanaka (1986), and Witbeck and others (1991). in the west. These values are minimal estimates because the base of the wall is not exposed. Topical studies of the trough system have emphasized regional structure or The southern plateau margin of Ophir Planum retreated 25-50 km; the change in width tectonics (Sharp, 1973; Carr, 1974; Blasius and others, 1977; Frey, 1979; (widler toward the west) occurs where trough-bounding faults change trend and large Masson, 1985; Schultz, 1991; Tanaka and others, 1991; Mège, 1994; Schultz, landslides form, at the junction of Melas and Coprates Chasmata. Greater width of erosion floor from wall materials and within Candor and Melas Chasmata. 1995, 1997) or erosional modification of the troughs (for example, Sharp, 1973; west of this junction may be associated with enhanced headward sapping, ground-water Low albedo; commonly forms subcircular or elongate patches
Lucchitta, 1979; Kochel and others, 1985; Peulvast and Masson, 1993a). These
migration, and transport of material downslope along northwest-trending faults (for spaced 5 to 10 km apart along scarps; patches distinct but their studies have provided both the general geologic framework and useful detail on example, Kochel and others, 1985). Faulting of Ophir Planum appears to have changed the

magnitude of stratigraphic offset along trough-bounding normal faults can be estimated given trough topography (U.S. Geological Survey, 1986) and the downfaulting of newly identified plateau material into lower structural positions at others, 1992). In support of the objective of understanding the structural development of Valles Marineris, the mapping presented here has emphasized the delineation of bedrock material rather than of surficial mantles. The kinematic significance of the distinctive en échelon graben array on western Ophir Planum, ———— Contact—Dashed where approximately located; dotted where as well as the possible relation of the array to faulting in the adjacent troughs, can provide constraints on various existing tectonic models for trough formation. Thus, I have investigated in some detail the sequence of faulting and analyzed its geometric characteristics in the map area. The geologic and structural evolution of western Ophir Planum, Coprates Chasma, and vicinity as documented on this map clarifies the fundamental role of normal faulting in the development of certain

CRATER DIAMETER, IN KILOMETERS Figure 1. Crater counts of materials in map area, from Schultz (1991). Shaded areas indicate reference values for surfaces of Early Hesperian (EH) and Late Hesperian (LH) crater ages from outside the map area (Tanaka, 1986). Age of cratered plateau material (unit NpI; open circles) is Early to Middle Noachian; age of trough floor material in western Coprates Chasma (unit Hf; open squares) is Early to Late Hesperian; age of smooth plains material (caprock, unit Hp; filled circles) is Late Hesperian. Points for cratered plateau material (bin diameters 4.0-5.7 km) and for trough floor

material (bins 4.0–11.3 km) omitted for clarity.

assisted erosion could proceed

STRUCTURE

Western Ophir Planum is a relict plateau surrounded in the map area on the north, west, and south by fault-bounded troughs and cut by abundant normal faults. In addition, well-defined fault scarps separate the plateau from the troughs along the northern trough margin. These faults are inferred from triangular facets that truncate trough wall material near its base (Blasius and others, 1977). No evidence was found in the map area for reverse or strike-slip faults, as suggested previously by Peulvast and Masson (1993a), although strikeslip faults do exist outside the troughs, south of easternmost Coprates Chasma (Schultz,

Several generations of normal faulting are identified in the map area. The oldest set is defined by northeast-trending scarps that transect plateau material but do not cut smooth plains material; thus, the localized crustal extension that produced these faults occurred in Noachian and perhaps Early Hesperian time. Other northeast-trending normal faults in the eastern part of the map area on Ophir Planum are members of the set of structures, discussed below, which make up an en échelon fault array. The grabens on Ophir Planum typically lack the graben-filling materials found west of the map area in Candor Mensa (Schultz and Fori, 1996), making crosscutting relations more difficult to determine. The second set of normal faults identified in the map area is typified by the graben that extends eastward from the elongate depression at the western margin of the plateau (lat 9.1° S., long 70.1°). The graben-bounding faults deform smooth plains material of Late Hesperian age and are visibly crosscut by northwest trending faults of the en échelon set.

other faults of this set occur in other places on western Ophir Planum. about 30° from the overall trend of the troughs (Schultz, 1991). Normal faults that define area. The orientations of the youngest set of faults on western Ophir Planum mirror this change, and the plateau faults locally merge with trough-bounding faults in northern Coprates Chasma. This change in complexity from linear to arcuate, concave-north fault geometry occurs near the junction of Melas and Coprates Chasmata, where large landslides

Planum and similar plateaus adjacent to the Valles Marineris troughs help to indicate the sequence of faulting in the trough region. Witbeck and others (1991) suggested that some of the normal faults and grabens near the southern plateau margin could have resulted at least in part from incipient gravity sliding of the plateau edge into the trough. Ophir Planum are consistently older than the impact craters that they intersect. The Late Hesperian crater age for the faulted smooth plains material then implies that the deformation occurred rapidly compared with the timescale of crater production. On the

relations indicate that normal faulting on western Ophir Planum predates at least some erosion of the plateau margin and perhaps occurred before significant lowering of adjacent trough floors, although plateau faults and trough-bounding faults could have been Normal faults and grabens of the young, en échelon set change trend systematically across Ophir Planum. East of the map area, grabens on the plateau are oriented subparallel to adjacent Coprates Chasma. In contrast, faults farther west change orientation by some 30° to northwesterly trends. The en échelon pattern of faults (for example, Pollard an others, 1982; Sempere and Macdonald, 1986; Schultz, 1991) indicates that the stress state

associated with the main trough faulting was also spatially heterogeneous. Several other normal faults and grabens within about 10 km of the southern margin of Ophir Planum may be related to localized failure and collapse of the plateau into the trough (Witbeck and others, 1991). Because the space occupied by Coprates Chasma would have had to be vacated before this type of failure could occur, these nontectonic faults are probably relatively young, perhaps of Late Hesperian or Amazonian age.

One east-trending graben on Ophir Planum in the western part of the map area is associated with an elongate depression near the plateau margin; only the east end of the depression is within the map area (lat 9.1° S., long 70.1°). It is interpreted to be a tributary canyon (Lucchitta, 1987b) produced by headward sapping by fluids (for example, water) and collapse along structures. In this case, the structure is a graben that is shown to predate the main en échelon set of grabens on the plateau by the presence of younger, crosscutting, northwest-trending faults. A set of five rimless depressions 1 to 2 km in diameter is 2 km north of this graben near its intersection with the northwest-trending faults. The depressions locally coalesce; their long axes parallel the older graben. The depressions differ in morphology from impact craters of similar size in that they lack raised rims and ejecta blankets and have irregular, noncircular shapes. These pit craters are thought to be collapse structures related to migration of fluids in the subsurface along the faults. Although the type of fluid is difficult to identify from pit morphology alone, headward collapse of the tributary canyon along the same graben to the west may suggest that lateral, subsurface flow of water, not magma, contributed to formation of the pit craters if they and the canyon are related. Apparently, fluids in the shallow subsurface of western Ophir Planum were still migrating after structural lowering of eastern Melas Chasma and erosion of the western

Candor Chasma, and aligned patches of dark surficial materials (Lucchitta, 1987a) are commonly associated with scarps of these faults. The patches embay the wall-rock slope that forms the north edge of Ophir Planum in Candor Chasma without evidence of faulting, so the deformation of older interior deposits was apparently not a simple reactivation of previous trough faulting. Instead, the faults in the interior deposits are typically short (a few kilometers long) and discontinuous, and they range widely in orientation, suggesting either mild or nontectonic deformation of the deposits (for example, settling). The aligned patches of dark materials in eastern Candor Chasma that are not associated with obvious fault scarps may mark the surface expression of dikes that intruded the older interior deposits.

margin of the plateau.

of the Valles Marineris troughs (for example, Watters and Maxwell, 1986). Because the smooth plains material on Ophir Planum in the map area is somewhat younger than ridged plains material adjacent to many troughs, we can hypothesize that wrinkle ridges that might have formed on Ophir Planum may have been buried by later deposits. However, as much as 1 km of material would be necessary to bury large ridges (Watters, 1988). The burial hypothesis requires that a substantial thickness of material be deposited preferentially on Ophir Planum at a high enough rate for a Late Hesperian crater age (fig. 1) to be established on this material. Similar burial of wrinkle ridges is observed southwest of Valles Marineris, where the Syria Planum Formation embays ridged plains material (Scott and Tanaka, 1986). This scenario requires that faulting on Ophir Planum and in the troughs postdate emplacement of the Upper Hesperian smooth plains material, which in turn predates most of the structural lowering of adjacent troughs such as Coprates Chasma.

COPRATES CHASMA AS A GRABEN The cross-sectional geometry of Coprates Chasma is inferred from several lines of evidence. Stratigraphic offsets, O_s, along the normal faults that separate Coprates from the adjacent plateaus appear to increase slightly across the trough from south ($O_c \approx 7$ km at the southern margin of Coprates Chasma) to north ($O_s > 8$ km near Ophir Planum), as determined from available topographic data (see fig. 10, Schultz, 1991). Crater counts indicate a Hesperian age for the Coprates trough floor material, comparable with that of materials capping the adjacent plateaus (fig. 1). The trough floor itself is relatively flat and

Remnants similar in morphology and structure to the smooth plains caprock on Ophir Planum (unit Hp) survive on the floors of Coprates and Melas Chasmata. These remnants, discussed above as material of isolated floor mesas (unit Hfi), commonly occur in apparent fault contact with massifs of gullied trough wall material (unit Nwg). If these materials are remnants of Ophir Planum caprock, their positions define the magnitude of stratigraphic offset across the bounding normal faults. The present elevations of these remnants also indicate about 8 km of vertical offset between plateau surface and trough floor. The observations presented above are consistent with the hypothesis that Coprates Chasma is a large graben bounded on its north and south sides by inward-dipping normal faults (Schultz, 1991, Fig. 10; Lucchitta and others, 1994). The northern parts of Candor and Melas Chasmata may also be grabens, because the relations of their structure and topography are generally similar to those of western Ophir Planum and Coprates Chasma (Peulvast and Masson, 1993b; Lucchitta and others, 1994; Mège, 1994; Schultz, 1995; Mège and Masson, 1996). This interpretation of large-scale trough structure supplements previous suggestions for smaller depressions of various nontectonic origins that include

see also Spencer and Fanale, 1990). NORMAL FAULTING IN WESTERN COPRATES CHASMA

Subtle normal faults and shallow grabens transect trough floor materials in the southwestern part of the map area. These faults, best developed near lat 12° S., long 70°, extend into Melas Chasma from west of the ridge of Noachian wall material that runs the length of western Coprates Chasma. Because the structures are visible in moderateresolution images, either they deform the Amazonian mantle in Melas Chasma or the mantle is exceedingly thin. The faults also occur in the area that divides moderately cratered trough floor in northern Melas Chasma (Blasius and others, 1977) from the southern, semicircular part of Melas Chasma that also contains thick interior deposits. These faults may mark the surface expression of deeper normal faults that define the southern margin of a large graben that extends through Ius Chasma and central Melas and Coprates Chasmata, as suggested previously by some workers (Blasius and others, 1977; Spencer and Fanale, 1990; Schultz, 1991; Lucchitta and others, 1994).

erosional transport of the older interior deposits along the trough floors (Lucchitta and others, 1994), it appears that the northern trough floors represent a later stage of faultcontrolled subsidence that defines a single, large, composite graben in the northern parts of Coprates, Melas, and Ius Chasmata (Peulvast and Masson, 1993b; Lucchitta and others,

Ancestral basins in Valles Marineris are troughs having irregular shapes, 3-5 km of apparent subsidence (Lucchitta and others, 1994), and either chaotic terrain (Komatsu and others, 1993) or smooth floor underlying thick sequences of older interior deposits. These basins ("moats" of Lucchitta and Bertolini, 1989) also include Capri and Eos Chasmata east of the map area. Two possible ancestral basins are identified in the map area. The first, in southern Candor Chasma and identified by Lucchitta and Bertolini (1989), contains thick sequences of older interior deposits, evidence for localized faulting of and perhaps dike emplacement in these materials, and mobilization of both older interior deposits and trough wallrock. The second likely ancestral basin in the map area, near lat 10.4° S., long 68.6°, is the site of erosional retreat of plateau rocks, remnants of older interior deposits, and landsliding into Coprates Chasma. The southern margin of this basin is defined by a topographic break associated with the major normal fault that bounds the deeper part of Coprates Chasma in this area.

material properties relevant to ground water flow from isotropic to transversely isotropic, because the faults appear to have been conduits or zones of weakness along which water-Erosional widths of troughs adjacent to Ophir Planum are typically much greater than their structural widths (Frey, 1979). For example, the distance between Ophir Planum caprock and the crest of a ridge of trough wall material just south of the large landslide (Ophir Labes) in Coprates Chasma (lat 12.3° S., long 68°) is about 100 km, whereas the distance between opposing faults bounding the Coprates trough floor is 55 to 65 km. Thus, the structural width of Coprates Chasma in this area is only 60 percent of its erosional width

NORMAL FAULTING ON WESTERN OPHIR PLANUM

The older, east-trending set of faults roughly parallels the trend of troughs such as Tithonium Chasma in eastern Valles Marineris (northwest of the map area, extending from long 77° to 92°) but this older fault set does not parallel either the eroded margin of western Ophir Planum or the faults that bound western Coprates Chasma directly to the south. Several The most recent period of tectonic extension on western Ophir Planum is characterized by a distinctive array of normal faults and grabens whose orientations differ by the northern margin of Coprates and Melas Chasmata, along the trough floors, change strike from nearly east-west in Coprates Chasma to northwest in the central part of the map

such as Ophir Labes have eroded plateau walls. The relative age and local kinematic significance of normal faults and grabens on Ophir

Superposition relations indicate that normal faults in the en échelon array on western other hand, the faults are truncated by the eroded margin of western Ophir Planum. These

associated with the deformation was spatially heterogeneous, in that the direction of extension (normal to the fault trace) changed systematically from trough-parallel east of the map area to oblique. This result is interesting, in part because the change in trend occurs near the intersection of several troughs that include Coprates, Melas, and Candor Chasmata. The change in trend of the plateau grabens is also comparable to that of the main troughbounding fault in western Coprates Chasma to the south, suggesting that the state of stress

DEFORMATION OF OLDER INTERIOR DEPOSITS Normal faults locally transect at least the upper part of the older interior deposits in

LACK OF WRINKLE RIDGES ON WESTERN OPHIR PLANUM Wrinkle ridges are observed on other plateaus of Early Hesperian age north and south

structurally continuous, although differential subsidence of perhaps a few hundred meters is

collapse into subsurface voids (for example, Schonfeld, 1979; Tanaka and Golombek, 1989;

ANCESTRAL BASINS Lucchitta and Bertolini (1989) suggested that large parts of the Valles Marineris trough system subsided earlier than the "rectangular" troughs such as Coprates Chasma. This interesting hypothesis, supported by detailed work by Peulvast and Masson (1993b) and Lucchitta and others (1994), is based in part on the presence of large, high-standing remnants of older interior deposits in southern, irregularly shaped troughs (such as Melas Chasma) and in the southern parts of rectangular troughs such as Candor Chasma. Because the northern parts of troughs such as Candor and Coprates Chasmata stand at lower elevations than the adjacent older interior deposits, and given a lack of evidence for

1994: Schultz, 1995, 1997, 1998).

Figure 2. Topographic map of Valles Marineris region showing relation between ridge of presumed uplift and Valles Marineris, from Schultz (1991). Topography from U.S. Geological Survey (1989); contour lines indicate kilometers above martian datum. Outlines of Valles Marineris (unpatterned), Noctis Labyrinthus (NL), Ius Chasma (I), Melas Chasma (M), and Coprates Chasma (C) after Scott and Tanaka (1986).

OBSERVATIONS OF FAULTS VERSUS MODEL PREDICTIONS Several models, either quantitative or conceptual, have been proposed to account for the locations, trends, and significance of normal faults in and near Valles Marineris. Models evaluated in this section concern local uplift in the central trough region, concentric faulting about the Chryse multi-ring impact basin, and regional extension associated with Tharsis.

Other scenarios for trough formation and faulting, such as collapse, are discussed above and by Schultz (1991) Some previous work suggested only a general relation between the "fractured terrain" and either uplift near Valles Marineris or loading in Tharsis (for example, Blasius and others, 1977; Scott and Tanaka, 1986; Witbeck and others, 1991). Localized uplift beneath the central trough region was postulated as a mechanism for producing or augmenting lithospheric extension and normal faulting in Valles Marineris (for example Witbeck and others, 1991; Banerdt and others, 1992; Mège, 1994), although the region containing the troughs may overlie thicker crust than the martian average (Kiefer and others, 1996). Although the trough system is near a region of high topography, an assessment of the contribution of uplift to faulting in the troughs is not as straightforward as might be supposed. The region of high topography includes a northeast-trending ridge, and any normal faulting resulting from uplift and deformation of the crust to produce this ridge would be near its crest (the area of maximum bending stresses) and oriented parallel to the axis of uplift. However, the troughs do not lie along the crest of high topography (fig. 2), as would be expected if uplift contributed directly to faulting. In addition, the topographic axis trends northeast from Syria Planum, whereas the troughs trend southeast. Coprates Chasma, one of the largest troughs in the Valles Marineris system, is not only far from the axis of high topography but is oriented nearly perpendicular to the topographic contours. None of the above-mentioned relations is consistent with the notion that topographic uplift, and associated bending stresses in the lithosphere, directly produced the normal faulting in the troughs. Indeed, constructive volcanism and preexisting relief may be mechanisms for producing the topography that are at least as admissible as uplift. I

hypothesize that the troughs probably did not form solely in response to presumed uplift in the region. However, although not yet demonstrated, such uplift may have influenced the trends of, and displacements along, normal faults in the trough system. Schultz and others (1982) and Wichman and Schultz (1989) suggested that faulting in Valles Marineris may have been influenced by Chryse basin structure. In this hypothesis, an outer ring-fracture (tensile cracks and normal faults) system concentric to the basin center could be reactivated by some later stress system to produce trough-bounding structures. Various inferred locations for this ring system are in the western part of Ophir Planum in the map area. However, the mapping supplies no evidence that would support a concentric ring-fracture system in this area, confirming the finding of Witbeck and others (1991). On the contrary, the geometry of Coprates Chasma is linear, not concave northward, as would be required in this scenario, and the change in trend of grabens and trough-bounding normal faults in the western Ophir Planum-Coprates Chasma region can be more convincingly attributed to the merging of Coprates and Melas Chasmata, rather than to basin structure. Because the intensity of deformation associated with impact basins decreases radially away from their centers, and because basin rings are characteristically discontinuous (Schultz and Frey, 1990), the influence of Chryse basin structure on Valles Marineris is considered to have probably been minor.

Valles Marineris troughs have been thought to be associated with volcanotectonic activity at Tharsis (for example, Carr, 1974; Blasius and others, 1977; Banerdt and others, 1982; Plescia and Saunders, 1982; Tanaka and others, 1991), in part owing to their relative proximity and in part because the general orientation of the trough system is subradial to the center of the Tharsis load (Willemann and Turcotte, 1982). In particular, the good correspondence between the orientation of the trough system and calculated principalstress trajectories obtained from Tharsis-deformation models (Banerdt and others, 1982, 1992) suggests that major normal faults in many troughs such as Coprates Chasma developed in response to Tharsis-induced stresses.

The stress trajectories, and hence the basis for relating Valles Marineris to Tharsis, can be compared only to the largest structures (longer than 500 to 1,000 km) because of scale limitations inherent in the models. Smaller structures, such as those mapped and investigated in this map area, cannot be related directly to Tharsis tectonism, either by orientation or by model. More detailed models will be required to explain the heterogeneous stress states inferred for many areas, including western Ophir Planum during the time of trough formation and growth of en échelon fault arrays on the plateau and the localized deformation of older interior deposits.

GEOLOGIC SUMMARY

After emplacement of Noachian bedrock throughout the map area, higher standing parts of the bedrock were locally cut by northeast-trending normal faults. During Hesperian time this irregular Noachian surface was resurfaced or embayed by fluid mafic lavas. An extensive set of normal faults and grabens striking dominantly east to northwest grew across the map area shortly after emplacement of the smooth plains material. Large irregularly shaped depressions perhaps 4 km deep formed peripheral to Ophir Planum, defining the ancestral troughs. During Late Hesperian through Middle Amazonian time, thick sequences of sedimentary or volcanic materials partly filled the ancestral basins in southern Candor. Melas, and Coprates Chasmata, encroaching on backwasted slopes. Later, structural lowering of large blocks along normal faults progressed to form grabenlike troughs while a crater population of Late Hesperian age, or younger, was accumulating. Erosional backwasting along the trough-bounding normal faults gradually reduced the area of western Ophir Planum and formed characteristic spur-and-gully topography along its margins. The floors of Coprates and northern Melas Chasmata appear to be thinly covered, downfaulted Ophir Planum caprock, implying either a period of significant erosion, or more likely nondeposition, of the older interior deposits in these areas. Along the northern margin of Coprates Chasma (and probably Melas), normal faults that cut spur-and-gully topography on trough walls indicate either Amazonian reactivation of older faults or, perhaps more likely, continued faulting since the Hesperian. In contrast, the major faulting and lowering of trough floors in southern Coprates and Melas Chasmata were mostly completed before or during emplacement of older interior deposits, although some normal faulting of older interior deposits occurred locally. Landslides and slumps along plateau margins indicate renewed erosion of the plateau margins that largely postdates significant faulting in the troughs. Possible mafic pyroclastic deposits were erupted from vents along normal faults, or above dikes, in Candor and Coprates Chasmata. Wind streaks and dunes are evidence for the redistribution of surficial materials through relatively recent times.

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