ORIGIN OF VALLES MARINERIS AND NOCTIS LABYRINTHUS, MARS, BY STRUCTURALLY CONTROLLED COLLAPSE AND EROSION OF CRUSTAL MATERIALS; **Kenneth L. Tanaka,** U.S. Geological Survey, Flagstaff, AZ 86001; ktanaka@flagmail.wr.usgs.gov

Introduction. Early analysis of Valles Marineris (VM) by Sharp [1] indicated that VM had an enigmatic origin, with ground-ice deterioration, magma withdrawal, and lateral spreading (rifting) cited as leading possible, though problematic, explanations. Later, Tanaka and Golombek [2] proposed that VM formed by tension fracturing and the removal of water-saturated debris along fractures, a mechanism consistent with the geomorphologic relations observed among numerous narrow grabens, pit chains, trough coalescence, and channels emanating from pits in the Valles Marineris region. Recently, some workers have further developed the rifting hypothesis for the VM troughs [3-6]. In spite of the obvious structural control of the troughs, I argue that the troughs of VM and Noctis Labyrinthus (NL) formed primarily by collapse and erosion, for the following reasons: (1) the troughs include widespread collapse and slump features, whereas evidence for normal faulting is limited to narrow plateau grabens and local trough-interior scarps, (2) magma withdrawal and tectonism in VM and NL probably occurred mainly prior to the majority of trough development, (3) other highly extended areas of Mars either are devoid of large grabens or include large grabens of much less offset, (4) troughs in VM and NL, nearby chaotic and knobby terrain, outflow channels, and interior layered deposits, and debris deposits in the northern plains appear to be temporally and spatially related, and (5) collapse and mass-flow features commonly occur in high-relief, volcanotectonic settings on Mars, indicating that appropriate crustal materials, erosional and debris-transport processes, and triggering mechanisms have been available to facilitate large-scale mass movements in regions like VM and NL.

Trough geomorphology. Previous work is replete with descriptions and images showing the clear development of collapse features in VM [1-2]. Many pit features occur within narrow grabens; others form alignments not connected by surface structure and presumably linked by fractures at depth [2]. Linear pit chains coalesce and grade into aligned troughs in VM, and crustal blocks densely faulted by narrow grabens have collapsed into cross-cutting, septated troughs in NL. However, narrow, shallow grabens (<5 km wide and 10s to 100s of m deep) are not observed to enlarge or coalesce into wide grabens having >1 km offsets on the plateaus surrounding the troughs (admittedly, such evidence may have been destroyed within the troughs), nor can normal faulting explain the collapse process. Half grabens have been proposed to explain the Ius/Melas/Coprates canyon system [3], but the plateaus and canyon floors involved show no appreciable tilting to indicate half-graben development (see profiles in [3-4]).

The geologic record. Geologic mapping indicates that plateaus cut by VM and NL are mainly made up of Upper Noachian to Upper Hesperian lava-flow plains [7-9]. North of central VM, a few rille channels suggest that adjacent ridged plains material originated as thin sheet lavas from central VM [9]. Local sets of narrow grabens parallel with and at other orientations to VM and NL formed during the Noachian and Hesperian. At VM, grabens formed only in close proximity with some of the western and central troughs during the Hesperian, as north-trending wrinkle ridges dominated elsewhere around VM during the Late Noachian and Early Hesperian due to Tharsis-centered stress [10]. Trough formation at VM and NL occurred mainly during the Late Hesperian and Early Amazonian [11].

The timing of ridged plains volcanism indicates that magma withdrawal largely predated trough formation; in addition, other large outcrops of ridged plains material on Mars show no or little caldera development (compare Hesperia and Syrtis Major Plana), suggesting a minor role at best for magma withdrawal in trough formation.

Crater-density data has been used to suggest that the floor of Coprates Chasma is the same as adjacent plateau material [3], which, if true, would demonstrate a large fault offset. However, given the standard error of the crater densities and estimated cratering-flux rates during the Hesperian [12], the data could also permit tens or even hundreds of millions of years of age difference between the units. Moreover, close inspection of impact craters on the floor of Coprates Chasma indicates that many of them superpose structural and erosional features in the canyon and thus postdate trough formation (e.g., a 23-km-wide crater, at 12.7°S., 65.2°W. partly excavated an eroded ridge within Coprates and buried part of a debris flow on the canyon floor), but none clearly predates trough formation. Although Ius/Melas/Coprates Chasmata have been proposed as a large, single graben structure to explain its depth from terrestrial fault length vs. offset relations [6], other highly extended areas on Mars of similar length either have not developed any broad graben structures (e.g., Ceraunius Fossae/Alba Patera) or formed broad grabens that attain maximum depths of only 1.5 km (at Claritas and Tempe Fossae) [7, 13].

Geomorphic associations with erosional features. For a collapse and debris-flow erosional mechanism to be viable, collapse structures should connect with conduits through which debris has been removed, and abundant deposits should exist at the ends of and perhaps within the conduits. All of these relations exist for VM and NL, although subsurface structural character must be conjectured (as is also true for the rift hypothesis). In addition, all the pertinent features are similar in age--Late Hesperian to Early Amazonian [7, 9, 11].

Abundant pits and troughs, landslides, and patches of chaotic and knobby terrains and layered and massive deposits throughout VM indicate pervasive collapse and deposition of wall-rock debris [1-2, 14-15]. Outflow channels form the most obvious surface conduits for the removal of erosional debris and connect with much of the VM canyon system, as well as nearby chaotic terrains. Eastward-heading debris flows cover parts of Ius and Coprates Chasma; earlier such flows may have transported VM debris through Eos and Capri Chasmata and Simud and Tiu Valles into the northern plains. At present, Eos and Capri are choked with chaotic terrain derived locally. Many smaller troughs and pit chains throughout VM and the adjacent Noctis Labyrinthus, including at least one larger trough (Hebes Chasma), form enclosed depressions (i.e., they have no surface drainage outlets). Because geomorphic relations show that these depressions formed mainly by collapse, the material likely was removed through subsurface conduits that connected to surface channels. Such conduits are suggested by the common alignment of pits showing no connecting surface structure (e.g., east of Hebes, Ophir, and Candor Chasmata and south of Coprates Chasma) and linear as well as broad zones of collapsed (warped but uneroded) terrain that connect to chaotic terrain and outflow channels (e.g., south of the head of Shalbatana Valles).

Fluidization and erosion common on Mars. Mars is replete with extensive occurrences of landforms produced by fluidization and long-distance transport of rock material. Proposed examples include chaotic terrains and outflow channels [16], debris flows and associated mud volcanoes below in the northern plains [17-18], and landslides in Valles Marineris [e.g., 14]. These features and processes indicate that much of the martian crust is made up of volatile-rich, poorly consolidated materials that may be triggered by seismic or volcanic events [19-20].

Conclusion. Stratigraphic, structural, and geomorphologic relations indicate that the Valles Marineris troughs began their development in the Noachian as narrow grabens in response to Tharsis-centered stress and local magmatism. Following an apparent waning of VM tectonism during the Early Hesperian, the major trough-forming episode ensued during the Late Hesperian and Early Amazonian due to fluidization, collapse, and erosion of water-saturated, poorly consolidated crustal rocks through channels and subsurface conduits. For the Ius/Melas/Coprates trough, large-scale tectonic development appears inconsistent with various local topographic, geomorphic, and stratigraphic relations and the structural character of other highly extended regions on Mars; however, normal offsets of as much as ~1-2 km along interior scarps seem plausible.

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