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Layering in the wall rock of Valles Marineris: intrusive and extrusive magmatism

Jean-Pierre Williams, David A. Paige, and Craig E. Manning
Dept. of Earth and Space Sciences, Univ. of California, Los Angeles, USA

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[1] High-resolution images of the walls exposed in Valles Marineris reveal variations in appearance and degree of layering indicating various lithologies comprise the Tharsis plateau. The layered wall rock has been proposed to result from effusive flood basalt volcanism or interbedded sediments and volcanics. We present observations of unlayered rock that indicate layering extends to a greater depth in the western half of Valles Marineris and is confined to the Tharsis plateau, a region of thickened, uplifted crust resulting from prolonged intrusive activity. Consistent with this view, we propose that the observed layering may be a manifestation of intrusive rocks resulting from crystal fractionation of intruded basaltic magmas. Terrestrial layered plutons provide analogs for comparison such as those of the North Atlantic Igneous Province (NAIP) a large igneous province associated with crustal rifting and exposures of thick sequences of layered flood basalts and intruded layered cumulates. *INDEX TERMS:* 5480 Planetology: Solid Surface Planets: Volcanism (8450); 6225 Planetology: Solar System Objects: Mars; 8450 Volcanology: Planetary volcanism (5480). **Citation:** Williams, J.-P., D. A. Paige, and C. E. Manning, Layering in the wall rock of Valles Marineris: intrusive and extrusive magmatism, *Geophys. Res. Lett.*, *30*(12), 1623, doi:10.1029/2003GL017662, 2003.

1. Introduction

[2] One of the most significant early discoveries made by the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) was the observation of pervasive, meter-scale layering within the wall rock of the Valles Marinaris canyon system extending the entire depth (>8 km) of the chasma wall [*Malin et al.*, 1998]. *McEwen et al.* [1998] discussed the possibility that the layering is caused by thick sequences of voluminous, low-viscosity flood basalts. Subsequently, *Malin and Edgett* [2000] with further observations noted that the stratigraphy of the wall rock is more complex and heterogeneous than initially indicated by the MOC images. They suggested that the canyon walls expose sediments interbedded with impact craters and lavas. The surface units that cap the surrounding plateaus are thin (<1 km) Hesperian flood basalts [*DeHon*, 1988]. Presumably, the deeper outcroppings of layered wall rock are exposures of early Hesperian and Noachian terrains, and the lack of a thick regolith results from a sufficiently high magma effusion or sedimentation rate toward the end of heavy bombardment.

[3] High-resolution MOC images of the Valles Marineris walls (45 to 90°W longitude) were analyzed encompassing images released from aerobraking to extended mission subphase 06 along with Mars Orbital Laser Altimeter (MOLA) topographic profiles. Meter-scale, horizontal layering in exposed spurs of the wall rock are discernable in the images as described initially by *Malin et al.* [1998] and *McEwen et al.* [1998]. Variations in the appearance of the wall rock however, is evident not only laterally at differing locales, but vertically, as seen within single MOC images, including portions of wall rock that appear unlayered at MOC resolution indicating a more complex, less homogeneous formational history than was perhaps appreciated prior to MGS.

2. Observations

[4] Variations in the appearance of layering, as has been suggested by *McEwen* [1999], may result from variations in: Illumination, image resolution, degree and style of erosion, eolian burial, and modification from tectonics and mass wasting. We observe however, variations in the appearance of the wall rock that we interpret as genuine variations in lithology. Figures 1a–c provides an example of variability in wall rock appearance within a single MOC image. Rhythmic, meter-scale layers are evident immediately beneath the cap rock (Figure 1a) but are confined to a depth of less than a kilometer. At lower elevations (Figure 1b) the layering is no longer evident and the wall rock possesses a massive, blocky appearance with large boulders being shed onto the apron of dust flanking the exposed spur. Layering, if present, is not visible at the resolution of the MOC frame (4.25 m/pix) indicating a transition has occurred in which layers are no longer visible regardless of whether they are present of not. At greater depth (∼3.5–6 km below the plateau) irregular light and dark bands are visible (1.5–15 m in thickness assuming a slope of 10–30°) on a spur amongst wall rock that appears to have a higher albedo relative to the unlayered rocks higher up section implying another transition in lithology occurred (Figure 1c).

[5] Exposures of irregular unlayered and layered rock of varying albedo have been imaged by MOC within the lower portions of wall rock in Coprates Chasma. Figure 1f provides an example of contiguous, relatively high and low albedo rock units. Irregularly oriented dark fractures and/or dikes are clearly visible within the brighter unit along with dark parallel layers attributable to layered cumulates of a sill or layered sequence of a fossilized magma chamber. The talus eroded from these units also reflect the relative albedo difference between the rocks as lighter talus slopes appear to originate from lighter wall rock and visa versa.

[6] As MGS continues to accrue images, a first order picture is starting to emerge-that layering extends to a

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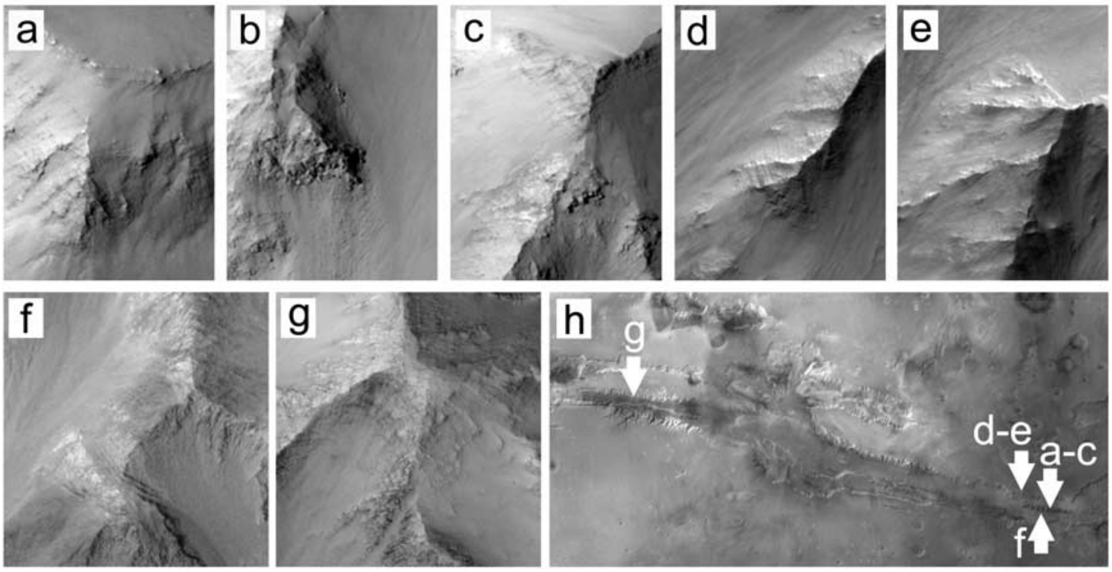

Figure 1. (a) Layered cap rock below which (b) layers are no longer visible although (c) irregular layers and higher albedo rock outcrops at deeper levels (central horst of Coprates Chasma, portions of m0403869, figures 1.1 km across). (d) Layering is clearly evident within top ~2 km of wall rock and below ~2 km depth (e) layering is no longer evident (portion of m2101517, figures 1.1 km across). (f) Example of high and low albedo massive bedrock with fractures and/or dikes interjected with a layered unit (portion of m0807133, 1.5 km across). (g) Typical layering observed in western half of Valles Marineris (north wall of Ius Chasma, portion of m1000126, 1.5 km across). (h) MOC atlas with arrows indicating locations of (a–g) (NASA/JPL/MSSS). North is to the top in all frames.

greater depth in the western half of Valles Marineris than the eastern half. Layering in Figure 1g, typical of wall rock in Ius Chasma displays rhythmic layers ~2–20 m in thickness, and is observed to extend to the deepest exposures of wall rock (>5 km depth). Rhythmic layering of similar thickness is observed in the eastern portion of Coprates Chasma, however it appears confined to the upper few km of the plateau. Figures 1d–e provides an example of wall rock that is definitively unlayered at >2 km depth in comparison to the distinctly layered overlying cap rock.

[7] An initial attempt to constrain the depth of the layered to unlayered wall rock transition has been made although MOC coverage is sparse and observations of any contact are hampered by obscuration from eolian mantles, talus slopes, and landslides that destroy the spur and gully morphology, making further acquisition of images along the walls of Coprates Chasma of use in future studies. Using MOLA tracks registered to MOC narrow angle images; the depth of clearly discernable layered and unlayered rock within a frame was determined. Figure 2 shows the results for the north wall of Coprates Chasma. Plots of the south wall and the central horst of Coprates coincide with these results. The plot does not represent a contact but rather is an estimate of the depths at which layering is unambiguous and depths at which wall rock is clearly exposed with no apparent layering at MOC resolution. The wall rock in between represents a transition from a layered morphology to an unlayered morphology in which layers are ambiguous or wall rock is obscured. This transition zone may encompass many stratographic horizons and various lithologies.

[8] Unlike images in Ius Chasma that reveal layering to the lowest observed depths (e. g. Figure 1g), layering depth in Coprates Chasma appears to correlate with the topography and gravity. The shallowing of layer depth at longitude ~295–300° corresponds with a region in which the chasm transects north-south trending mountains of Nectaris Fosse, a ~3 km arcuate mountain belt that forms the eastern edge of the Thaumasia Plateau. The deeper layering to the east (lon ~300–304°) corresponds with a negative free-air gravity anomaly adjacent to the mountain belt and identifiable in Ophir Planum to the north [*Zuber et al.*, 2000] and may represent a portion of the crust composed of lower

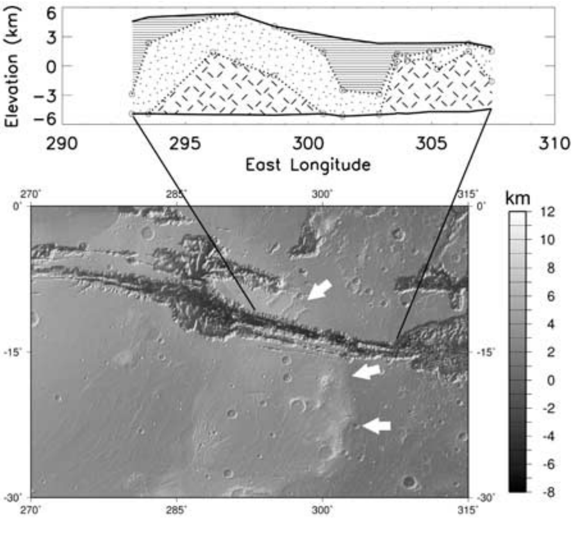

Figure 2. Layered-unlayered transition in rock of the north wall of Coprates Chasm. Shallow layering between east lon ~295–300° correlates with the transection of an arcuate mountain belt highlighted with arrows on topography map.

density materials, perhaps infill of a flexural moat created by the mountains and high-standing plateau to the west. Layering then shallows again implying that regions distal to the Tharsis Plateau are not necessarily layered to great depths. The chasma radiate along the eastern flank of Syria Planum, the center for most of the stress and strain of Tharsis, and represents the locus of the thickened, uplifted crust of the plateau [*Zuber et al.*, 2000]. This would explain the proximal confinement of the deep layering to the western portion of Valles Marineris. Further, the volcanic and tectonic features, high topography, thickened crust, lack of large shield volcanoes and ample evidence of subsurface magma ice interaction in the region are consistent with prolonged intrusive activity [*Dohm and Tanaka*, 1999].

3. Regional Geology

[9] Based on our observations, we propose that intrusive rocks are a component of the wall rock material of Valles Marineris, an interpretation that is consistent with the overall geologic setting of the region. The canyon system transects the Tharsis plateau, a volcanotectonic province of thickened, uplifted crust that dominates the western hemisphere of the planet [*Zuber et al.*, 2000; *Dohm and Tanaka*, 1999]. The extensive system of faults and grabens throughout the hemisphere attest to a prolonged and extensive tectonic history. Detailed mapping of the tectonic features and geologic units by *Dohm et al.* [2001a] and *Anderson et al.* [2001] reveal various volcanotectonic centers in the region with activity peaking during the Noachian and persisting with declining intensity into the Amazonian.

[10] Most large igneous provinces on Earth are associated with mantle plumes and lithospheric extension which result in both extrusive and intrusive volcanism as upwelling of asthenospheric material results in the generation of large quantities of melt [*White and McKenzie*, 1989]. Based on paleotopographic reconstructions on a synthesis of published geologic information and high-resolution topography, *Dohm et al.* [2001b] propose that Late Noachian and Hesperian magmatic-driven activity at central Valles Marineris, which includes uplift, tectonism, volcanism, dike emplacement, and possibly hydrothermal and outflow channel activity, exposed stacked sequences of lavas and possible interfingering sedimentary deposits of a Europe-sized, Noachian drainage basin. Therefore, Magmatic intrusion is expected to have occurred and we propose that intrusive rocks should be taken into consideration as a constituent rock material.

4. Layered Igneous Intrusions

[11] Pristine samples of the ferroan anorthosite and Mg-suite lithologies of the lunar highlands acquired by Apollo posses cumulate textures and imply that layered cumulate rocks are a common and inevitable constituent of planetary crusts and require special circumstances such as rifting to expose them. The lunar crust, having experienced relatively little geologic activity since its formation, is generally preserved in its initial configuration. The formation of the anorthositic crust can be explained by crystal fractionation within a primordial magma ocean [*Wood et al.*, 1970] and the more mafic rich Mg-suite samples likely originate from large layered plutons formed by subsequent intrusions into the primary crust by ascending magma produced by partial melt in the underlying mantle [*James*, 1980]. Fruitful comparisons have been made between the lunar anorthosites and those that occur in mafic layered intrusions such as the Stillwater complex in the Western United States which exhibit similar mineralogic trends and may have formed in an analogous manner [*Raedeke and McCallum*, 1980].

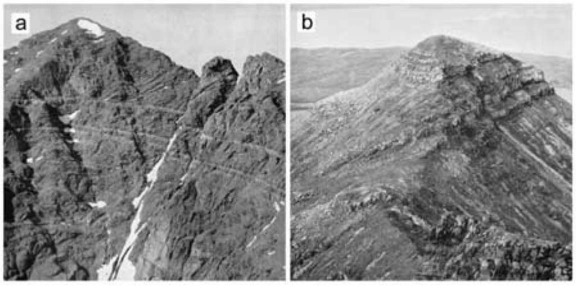

Figure 3. Layered intrusive outcrops. a) Skaergaard intrusion, East Greenland and b) Rhum igneous complex, Scotland. From: Layered Igneous Rocks by L. R. Wager and G. M. Brown © 1967 L. R. Wager and G. M. Brown. Used with the permission from of W. H. Freeman and Company.

[12] Large intrusions of basaltic magma within the Earth's crust are known to produce plutonic rocks with layering as pervasive and distinctive as stratification resulting from sedimentary layers [e.g., *Irvine*, 1982]. Layering within terrestrial cumulate rocks can vary from tens of meters to centimeters. Though the origin of layering in intrusions is poorly understood, it is generally interpreted to result from fractional crystallization and sedimentary processes during crystallization in cooling magma chambers. Examples of processes giving rise to igneous layering include size sorting of the cumulate grains, and varying concentrations of mineral phases such as plagioclase, pyroxene, and olivine, which often create dark-light bands. Cumulate layers also possess features associated with sedimentary deposition such as cross-bedding, channelization, and slump structures, implying that the cumulate grains are deposited within a magma chamber by processes analogous to sedimentary deposition upon the Earth's surface [*Wager and Brown*, 1967].

[13] Extensive flood basalts and numerous layered gabbroic intrusions in Eastern Greenland [*Nielsen et al.*, 2001] and the Northwest British Isles [*Chambers and Pringle*, 2001], provide terrestrial examples of rift-related volcanism resulting from extension and uplift of the continental crust prior to initiation of the North Atlantic ocean basin and the passage of the Iceland hotspot (~55 Ma) [*Wager and Brown*, 1967]. The Skaergaard intrusion (Figure 3a), one of the most intensively studied mafic intrusions on Earth, intruded Tertiary flood basalts. The top of the intrusion was no more than 2–3 km below the surface, based on pyroxene-silica phase equilibria [*Lindsley et al.*, 1969]. At its present level of exposure, the intrusion measures ~6 by 11 km in map view with a vertical section displaying rhythmic layering of more than 3.5 km accessible to direct examination.

[14] Similarly, the Rhum complex of Scotland, comparable in size to the Skaergaard intrusion, is comprised of

striking terraced features produced by layers of ultramafic peridotites. For example, the mountain Hallival (Figure 3b) exhibits resistant feldspar-rich cumulates interlayered with olivine-rich cumulates [*Wager and Brown*, 1967].

[15] The thicknesses of layering in many terrestrial examples are of the same scale as those observed in the wall rock of Valles Marineris. For example, the feldspar-rich layers at the summit of Hallival forming the higher albedo resistant layers (Figure 3b) are of the order 6 to 20 m in thickness. Seismic-reflection profiles also reveal strong, sub-horizontal reflectors in the lower part of the continental crust that can be explained by internal layering within igneous intrusions which provide appropriate impedance contrasts at appropriate length scales providing evidence that large parts of the lower continental crust consist of layered intrusions [*Singh and McKenzie*, 1993]. Further, most of the SNC meteorites also possess cumulate textures that suggest an intrusive origin [*McSween*, 1994]. Having presumably originated from various regions of Mars, this implies that the near surface crust of Mars may be composed of intrusive igneous rocks, and that perhaps the extrusive lava flows and sediments only represent a carapace upon the planetary crust.

5. Discussion

[16] Distinguishing between the various origins of layering is difficult as layers resulting from sedimentation, extrusion of flood basalts, and crystal fractionation of a magma body can all result in layering that is potentially indistinguishable in MOC images. Layered cumulate rocks is proposed here as a viable working hypothesis that should be considered as an end member possibility for layered rock formation on Mars but is by no means an exclusive hypothesis as layered plutons can be expected to intrude any crustal material including layered flood basalts and sedimentary rocks. Variations in wall rock appearance provide evidence that various mechanisms of rock formation have occurred and the apparent confinement of the deep layering to the proximity of the volcanotectonic centers of Syria Planum and central Valles Marineris [*Anderson et al.*, 2001] imply a complex history that most likely included an intrusive component.

[17] Large igneous provinces on Earth have effusively erupted flood basalts accompanied by intruded layered gabbros and provide analogs for comparison. East Greenland and the Northwest British Isles provide an example of layered intrusive rocks and flood basalts resulting from the initial rifting of the crust prior to, and contemporaneous with, the opening of the North Atlantic and the passage of the Iceland hotspot. Extrusive and intrusive volcanism resulted as melt buoyantly ascended through the crust where it effusively erupted at the surface and ponded at depth forming numerous magma chambers oriented parallel to extension when upward movement was arrested. Incipient rifting of the proto Valles Marineris would have generated similar volcanism in the region and as a result, the layering observed to great depths in the walls should not be expected to be indicative of the crustal structure elsewhere on the planet.

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J.-P. Williams, D. A. Paige, and C. E. Manning, Dept. of Earth and Space Sciences, Univ. of California, Los Angeles, USA.