LARGE-SCALE STRUCTURAL MANIFESTATIONS OF PHYLLOSILICATE GENERATION AND DEPOSITION IN EARLY MARTIAN HISTORY.

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Introduction: Recent detections of phyllosilicate (clay) minerals in ancient terrains [1-3] have revolutionized our understanding of early hydrothermal activity on Mars. The spectral signatures of phyllosilicates are seen exclusively in Noachian-aged outcrops and not in Hesperian or Amazonian materials [1-3]. Phyllosilicates are inferred to have been widely emplaced during a period of time (termed the "Phyllosian" in [2]), that overlaps with, but ends before the end of, the Noachian. Afterward, conditions (such as pH) changed such that phyllosilicate formation was inhibited; instead, materials such as sulfates were favored. The potential existence of extensive phyllosilicate deposits low in the stratigraphic column has enormous implications for the structural evolution of materials emplaced higher in the column. Clay layers are often zones of low strength, enabling enhanced deformation and slip in terrestrial settings, such as fault zones, accretionary wedges, and basal decollements beneath volcanoes [4-8]. The low hydraulic diffusivity of clays also makes lateral transport of pore water difficult, thus facilitating the buildup of high pore pressures in a decollement [9-11].

Here we develop the idea that ancient phyllosilicate deposits, generated by vigorous hydrothermal activity early in Martian history [e.g., 12] and concentrated by sedimentary processes, may constitute decollement zones that facilitate movement and deformation of younger superposed structures, such as large volcanic edifices, wrinkle ridge provinces, and thrust belts.

Flank Movements at Large Volcanic Edifices: The 23 km tall, 600 km wide Olympus Mons edifice exhibits several characteristics of volcanic spreading, including concave-upward lower flank topography, faulting (both extensional and compressional), and a large basal scarp, sectors of which constitute the headscarps of giant landslides (the Olympus Mons aureoles) [13-15]. These features have been attributed to motion along a basal decollement rooted in a thick basal clay layer [15]. The asymmetric distribution of topography and tectonics seen at the Olympus Mons edifice, scarp, and aureole described are best explained by a gradient in basal friction beneath the edifice, increasing toward the southwest (e.g, with proximity to the Tharsis rise) [15]. Such a gradient is consistent with a decrease in sediment thickness with increasing elevation, as would be expected if sediments are transported from sources (highlands) to sinks (lowlands and basins).

If Noachian sediments were distributed preferentially in lowlands, then volcanoes at low basal elevations elsewhere on Mars are the most likely to have basal detachments. Large volcanoes in the lowlands are generally lacking, but Apollinaris Patera (AP), like Olympus Mons, is located at the highland-lowland transition. AP has several features consistent with Olympus Mons-style basal spreading: concave-up flank slopes and a partial basal escarpment with distributed broken-up terrain beneath and surrounding it (a potential aureole analog). AP is near the mouth of Ma'adim Valles, which may have yielded a large supply of sediments from the highlands to the base of AP. The Tharsis Tholus edifice northeast of Tharsis exhibits throughgoing faulting that has been attributed to deformation of a ductile basal layer [16]. The current basal elevation is ~+2 km, higher than that of our other examples, but estimates of 0.5-3.5 km of flank burial by voluminous lavas from higher on the Tharsis rise [16-17] imply a somewhat lower original base for Tharsis Tholus, consistent with a sediment-covered lowlands base and resulting decollement.

Conversely, the bases of the Tharsis Montes are at very high elevations on the Tharsis Rise, and therefore unlikely to exhibit significant thicknesses of phyllosilicate sediment. This inference is consistent with the absence of spreading-related structures (scarps, aureoles); the abundant extensional features on these edifices are likely to be related to intrusion [e.g., 18-19] rather than spreading. Similarly, highland paterae and shields are based at relatively high elevations, rendering them unlikely locations for large accumulations of sediment. The older ages of these structures relative to the Tharsis volcanoes also suggests that construction of edifices may have started well before the end of phyllosilicate production.

Wrinkle Ridge Formation in Solis and Lunae Plana: Narrow crenulated ridges with sinuous planforms, called wrinkle ridges, deform volcanic plains units in many regions of Mars, but are particularly well expressed in the Solis Planum and Lunae Planum regions east of Tharsis. While wrinkle ridges are uniformly recognized as manifestations of compression, the subsurface fault depth and geometry that produces the observed surface structures are controversial; both thick-skinned [e.g., 20] and thin-skinned [e.g., 21] models have been proposed. In particular, a thin-skinned model for Solis and Lunae Plana [21] postulates a decollement at shallow depth (~4.5 km) that focuses deformation and produces the characteristic arches and wrinkles. We propose that overpressurized clay layers could provide such a decollement beneath volcanic plains regions like Solis and Lunae Plana.

Thrust Belt Orogeny in Thaumasia: The Thaumasia Region comprises a ring of elevated terrain of Hesperian and Noachian age to the south and east of central Tharsis. Scenarios for producing the elevated terrain include broad-scale thrusting and volcanism [e.g., 22]. The thrust belt scenarios require some sort of mechanically weak basement material. One scenario [23] invokes ductile deformation of evaporites (sulfate and other salts), consistent with potential salt tectonic features in Valles Marineris [24]. Under this scenario, proposed sulfate evaporites outcropping from layers in the walls of Valles Marineris are the local expression of massive and widespread evaporites underlying the whole of Solis Planum and the Thaumasia rises [23], allowing generation of the wrinkle ridges and fringing mountain belts in those regions, respectively.

We argue that a clay-based overpressurized decollement is a more likely scenario for mobilizing compressional features within Thaumasia. The mountainous rim of Thaumasia is among the oldest terrain associated with the margins of Tharsis, with ages spanning the Noachian and Early Hesperian [22]. The highest, oldest terrain dates from the mid-Noachian; thus, material beneath it must be comparably old or older. Our current understanding of hydrothermal systems on Mars [1-3] indicates that conditions favored phyllosilicate formation and prevented formation of sulfates during the required time (mid-Noachian or earlier). Thus, it is unlikely that sulfate evaporites are driving the formation of the margins of Thaumasia, and, similarly, hydrothermally altered materials at depths 5-15 km beneath the surface of Solis Planum are more likely to be materials produced during the early to mid-Noachian (clays) than later (sulfate-containing evaporites). Futhermore, salt beds are buoyant with respect to dense volcanic rocks; in tectonically active systems, salt tends to ascend via diapiric instabilities and exploitation of faults as conduits [25-26], leading to an expectation of exposure of such materials at the surface above a pervasive and laterally extensive deposit. No such evidence is seen at the surface in Solis Planum or Thaumasia.

Several objections to decollement-based deformation have been raised on the grounds of the purportedly unrealistic pore pressure magnitudes required for gravity to move a wedge with such a low surface slope [23, 27]. However, a number of accretionary wedges with high basal pore fluid pressures in sealed decollements (approaching lithostatic, or pore pressure/lithostatic pressure ratio $\lambda_f \sim 1$) occur on Earth, [e.g., 5]. Such a system accommodates gravitationally driven spreading along passive margins in the Niger Delta [e.g., 25, 28]. Furthermore, a pressurized decollement provides a natural source of water for formation of channels observed on the outer margins of Thaumasia [29].

Discussion: Vigorous hydrothermal circulation early in Martian history [12] likely accounts for the widespread evidence of phyllosilicates in Noachian terrains [1-3]. The implied abundance of water also suggests that erosional transport and deposition of phyllosilicates was vigorous in this epoch. Given that the Tharsis rise has been elevated since the early Noachian [30], erosion should favor collection of Tharsis-derived, clay-dominated sediments in the lower regions surrounding the rise. Thus, it is no surprise that a number of tectonic manifestations of stratigraphically low sediment-based decollements should occur in the regions surrounding Tharsis. Clay sediments may play an important role in controlling the geologic and tectonic history of the circum-Tharsis region, and other regions where topographic gradients favor accumulation of sediments, such as the dichotomy boundary under Apollinaris Patera.

References: [1] F. Poulet et al., *Nature, 438*, 623, 2005; [2] J.-P. Bibring et al., *Science, 312*, 400, 2006; [3] J. F. Mustard et al., *Nature, 454*, 309, 2008; [4] J. D. Byerlee, *Pure Appl. Geophys., 116*, 615, 1978; [5] D. Davis et al., JGR, 89, 10,187, 1984; [6] P. Vrolijk, *Geology, 18*, 703, 1990; [7] D. S. Cowan et al., *GSA Bull., 115,* 1230, 2003; [8] R. P. Denlinger and P. Okubo, *JGR, 100*, 24,499, 1995; [9] J. Arch and A. Maltman, *JGR, 95*, 9035, 1990; [10] R. M. Iverson, *JVGR, 66*, 295, 1995; [11] G. C. Rawling et al., *Geology, 29*, 43, 2001. [12] S. P. Schwenzer and D. A. Kring, *Workshop on Modeling Martian Hydrous Environments* (this volume), abstract 4015, 2009; [13] A. Borgia et al., *JGR, 95*, 14,357, 1990; [14] P. J. McGovern et al., *JGR, 109*, doi10.1029/ 2004JE002258, 2004; [15] P. J. McGovern and J. K. Morgan, *Geology, 37*, 139, 2009. [16] J. B. Plescia, *Icarus, 165*, 223, 2003; [17] M. Robinson, Dissertation, University of Hawaii, 1993; [18] L. G. J. Montesi, *GSA Spec. Pap. 352*, 165, 2001; [19] P. J. McGovern et al., *JGR, 106*, 23,769. 2001; [20] L. G. J. Montesi and M. T. Zuber, *JGR, 108*, doi: 10.1029 /2002JE001974, 2003; [21] T. R. Watters, *Icarus, 171*, 284, 2004; [22] J. M. Dohm and K. L. Tanaka, *Planet. Space Sci., 47*, 411, 1999; [23] D. R. Montgomery et al., *GSA Bull., 121*, 117, 2009; [24] D. R. Mongomery and A. Gillespie, Geology, 33, 625, 2005; [25] M. G. Rowan, et al., in *K.R. McClay, ed., Thurst Tectonics and hydrocarbon systems: AAPG Memoir 82*, 157, 2004; [26] M. R. Hudec and M. P. A. Jackson, 2007, *Earth Science Reviews, 82*, 1, 2007; [27] A. L. Nahm and R. A. Schultz, *LPSC XL*, abstract 1069, 2009; [28] P. R. Cobbold, et al., *Petroleum Geoscience, 15*, 3; DOI: 10.1144/1354-079309-784, 2009; [29] K. L. Tanaka et al., *JGR, 103*, 31,407, 1998; [30] R. J. Phillips *et al., Science, 291*, 2587, 2001.