RAYLEIGH-TAYLOR INSTABILITY-DRIVEN PLUME TECTONICS AND THE RHEOLOGY OF THE ARCHEAN, VENUSIAN, AND MARTIAN CRUSTS. Daniel Mege¹, Dominique Chardon² and Vicki L. Hansen³,
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Summary: Structural patterns of the Dharwar greenstone belts and Venuvian crustal plateaus have both been interpreted to result from Rayleigh-Taylor (R-T) instability developing in a crust heated by a mantle plume [1-4]. Analog experiments scaled for gravity allows evaluating the thermomechanical conditions for R-T instabilities to develop at a crustal scale. The results put constrains on the rheology of the Archean crust (depth of the brittle-ductile transition, BDT; and thermal regimes), and support the interpretation that mantle plumes were involved in the deformation of Venuvian crustal plateaus. On Mars, surface observations tend to suggest that the BDT may not have been shallow enough since 3.9 Ga, i.e. the geotherm may not be steep enough, to allow significant R-T instabilities to develop. However, the magnetic anomalies recently detected in the highlands are consistent with such a mechanism, which provides an alternative to the plate tectonics hypothesis [5,6]. They do not need to be older than 3.9 Ga if the R-T instabilities occurred in the deep crust.

Introduction: The tectonics of permanent topographic swells above modern mantle plumes produced by vertical accretion of magmatic rocks to the crust is dominated by extension, sometimes leading to rifting [e.g. 7]. "Modern" plume tectonics can induce compressive tectonics, though this is seldom observed [8]. In Archean terrains, particularly in South India, widespread dome-and-basin folding and thrusting is interpreted as a consequence of crustal scale R-T instabilities above ancient plumes [2] that thermally softened the lithosphere [9]. "Modern" plume tectonics is observed at Tharsis and Elysium on Mars [10,11] and at volcanic rises on Venus [e.g., 3]. In this work we investigate the occurrence of Archean-type, "softly" driven plume tectonics in the ancient Martian and Venuvian crusts.

Dharwar greenstone belts: The 2.8–2.6 Gy-old Dharwar greenstone belts of southern India show some of the thickest and best exposed Archean mafic volcanic traps that erupted on a 3 Gy-old segment of continental crust [2]. The base of the greenstone pile coincides with a decollement layer allowing the mechanical decoupling between the greenstones and their continental basement. Structural and kinematic analysis point to the centripetal displacement of the volcanics downward with respect to the basement and toward the center of the greenstone belts, resulting in widespread folding. Fold axes converge toward the area of supposed maximum sinking. Such kinematics is consistent with the sinking of the dense volcanic rocks into the continental crust and relative basement uplift in response to the development of R-T instabilities between the volcanic traps and the underlying continental crust. Mid- and deep crustal gravity-driven dome-and-basin structures [12] are deep counterparts of the same R-T system affecting the shallower Dharwar volcanics [2].

Crustal plateaus: Venesian crustal plateau (2000-km diameter quasi-circular, steep-sided, flat-topped, regions that host most tessera terrain) display distinctive tectonic fabrics composed of (a) early formed ribbons, a periodic extensional fabric of narrow ridges and troughs [3], (b) broad gentle marginal folds (λs of 1-30 km) and short variably oriented interior folds, (c) late local graben, and (d) intratessera volcanic basins [14]. The plateau-extensive composite fabric records intimate tectonic and volcanic temporal relations, and an increase in depth to crustal BDT [4,13,15]. Tectonic patterns correlate with plateau topography and gravity indicating crustal thickening, responsible accompanied tectonism and volcanism [4].

Although preliminary SAR analysis lent support to plateau formation via downwelling [16], this model cannot accommodate: shallow BDT across thousands of km2; early widespread pervasive extension, c) increasing depth to BDT; minor shortening recorded by gentle folds; accompanying volcanism; plateau topography [14]. However, a magmatic-accretion model in which a local, deep-mantle plume impinges on globally thin lithosphere accommodates each of these relations [4,14]. Folding is interpreted to result from subsidence of dense volcanic materials into a lighter crust in response to crustal R-T instability.

Comparison: The Dharwar greenstone belts and crustal plateaus appear to express the same processes at depth: plume impingement at the base of the lithosphere generates volcanism that cannot be supported by the lithosphere, resulting in a dense, upper volcanic layer sinking into the ductile crust, formation of anastomosing folds toward areas of maximum subsidence, and coherent radial or concentric fold patterns.

Implications for crustal rheology:
Insights from crustal plateaus. Structural analysis allows quantifying variation in BDT depth with time. In Eastern Ovda Regio, Venus, the BDT was initially at an extremely shallow level (<10 m), or at the surface over a 500x600 km region. The BDT was <1 km deep across the 2000x3000-km plateau, increasing to >10 km during plateau formation.

Experimental approach. Scaled analog experiments designed to investigate the response of various lithospheres to loading by a dense plateau confirm these interpretations [1], and allows evaluation of possible thermal and rheological structures for the lithosphere consistent with development of R-T instabilities. A first set of experiments was designed to
test the role of the BDT and the extent of volcanic plateaus on R-T instabilities. Dry dense sand is used as an analog of the brittle upper crust or plateaus and silicone of various densities simulate underlying ductile layers. The experiments were only submitted to the normal gravity field (Figure 1). Our results follow. Entirely brittle plateaus do not develop instabilities. An upper brittle layer does not inhibit the development of R-T instabilities as long as the lower part of the plateau lies in the ductile field (below the BDT). The amplification of R-T instabilities between a 2 layer (B-D) plateau and its basement does not imply that the upper brittle layer of the plateau is deformed (Figure 1). Thus amplification of R-T instabilities is enabled only if the BDT lies within the thickness of the plateau.

Using temperature-dependence viscosity materials [17], we performed two-layer experiments driven by gravity alone, in which a vertical temperature gradient was maintained, allowing simulation of an unstable density gradient, thermal blanketing of the lower light layer, and a viscosity decrease with depth. The growth rate of the instabilities appears to be an exponential function of temperature gradient. This suggests that, for a continuous ductile crust (i.e., very shallow BDT), the triggering and development of R-T instabilities is strongly controlled by the geotherm and rheology of the unstable buoyant layer.

Mechanical aspects. The thermomechanical conditions required to trigger and amplify such crustal-scale gravity instabilities are: (a) a reverse density gradient between the volcanic pile and the underlying crust, (b) partial melting of the basement resulting from high heat supply from the lower crust combined with thermal blanketing of the crust by traps, and (c) a certain degree of alteration of greenstones [2,18,19,20]. To our view, only an intracontinental plume setting would provide such conditions simultaneously, considering that plume magmatism is responsible for the generation and emplacement of volcanic traps [e.g. 7,21].

Discussion: Implications for the rheology of the Martian crust: Field work and our experimental results suggest high heat supply (plume activity) and significant thermal blanketing of the crust by the plateau move the BDT upward in the crust and then facilitate development of R-T instabilities in the Archean Earth crust. Similar mechanism may have operated at crustal plateaus.

Plume tectonics on Mars as revealed by imagery and topographic data grossly resembles modern plume tectonics on Earth [10,11]. Most models of planetary thermal evolution predict that the number of mantle thermal anomaly decreases with time [22,23]. The lack of structural evidence for R-T instability-driven plume tectonics at the surface of Mars since the formation of the cratered highlands (3.9 Ga) tends to suggest that plume thermal anomalies and the blanketing effect of volcanic flows were unable to shift the BDT to a shallow enough level to affect the rheology of the brittle crust.

However, we propose that the magnetic lineaments recently identified in some intensely cratered terrains [5,6] are consistent with R-T instability-driven plume. "Greenstone belts" would be responsible for strong magnetic anomalies, whereas crustal basement would express weak anomalies. The anomalies may not be older than the cratered highlands if the R-T instabilities did not affect the surface (Figure 1). An advantage of this interpretation over the plate tectonics hypothesis is that it provides a better fit to the highly irregular geometry of the anomalies and their chaotic distribution.
