Venus, Earth's Divergent Twin: Observations Constraining the Transition from a Mobile Lid Planet to a Stagnant Lid Planet

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Introduction: Mantle convection inside Venus today is widely considered to exist in the stagnant lid regime, with a thick thermal lithosphere and limited surface motions [e.g., 1]. However, Venus in the past may have had a more Earth-like, mobile surface. The transition from mobile lid to stagnant lid may have been driven by changing climate, because loss of water in the form of pore fluids increases friction on faults [2]. Recent studies suggest that climate change and changes in mantle convection style may be strongly coupled: the transition from mobile lid to stagnant lid convection results in strong, transient fluctuations in volcanic outgassing of the greenhouse gas CO_2 [3, 4], while climate evolution models are facilitated by these spikes of enhanced volcanism [5]. In this abstract, we summarize evidence for a transition in convective style from mobile lid in the past towards stagnant lid at present on Venus.

Mobile Lid Past

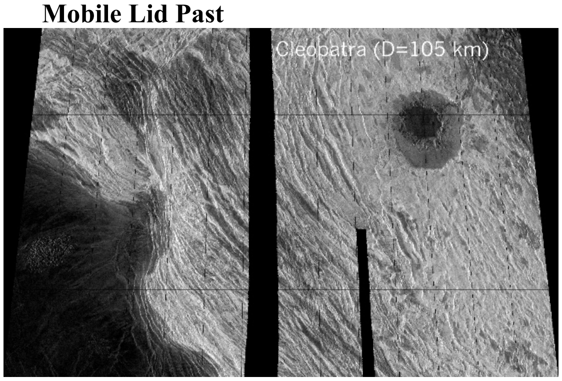

Figure 1: Folded mountain belts in Maxwell Montes. The image is 625 km across. The circular object at upper right is the crater Cleopatra.

The strongest evidence for mobile lid mantle convection at some point in the history of Venus is the Ishtar Terra highland. Ishtar consists of Lakshmi Planum, a flat central plateau, surrounded on most sides by mountain belts. Lakshmi is typically about 3.5 km above mean planetary radius, while the mountain belts are 6-10 km in elevation [6]. Tectonic structures in the mountains (Figure 1) indicate an origin by compressional deformation, possibly as fold-and-thrust belts [7-9]. Gravity data suggests that much of Ishtar is supported isostatically [10] by crust that is roughly double the thickness in the surrounding plains [11].

The thickened crust and folded mountain belt morphology are best explained by crustal convergence driven by convective flow in the mantle, indicating that Venus preserves evidence for a past epoch of mobile lid convection in its present-day surface. Structural relationships in Tellus Regio have been interpreted as forming due to lateral transport and assembly of several distinct tessera blocks [12], providing additional evidence for a mobile lid convection epoch.

A Convective Transition

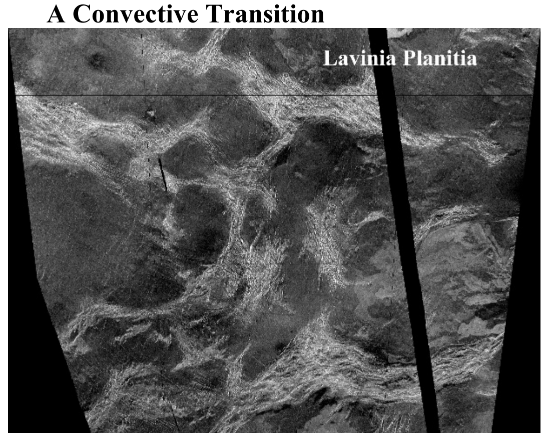

Figure 2: The Lavinia Planitia ridge belt system. The image is 1500 km across.

Venus is dominated by lowland plains, which may record a transition between an early mobile lid epoch and the present-day sluggish/stagnant lid epoch. Ridge belt networks occur in some low-lying plains on Venus, such as Lavinia Planitia (Figure 2) and Vellamo Planitia [13, 14]. For example, Vedma Dorsa is ~1700 km long, with ridges that are typically 30-70 km wide but sometimes reach more than 200 km in width [6]. The Vedma Dorsa ridges are 0.5-1 km high and commonly asymmetric in cross-section. Ridge belts have been interpreted as due to thrust faulting and folding from crustal convergence over cold, downwelling mantle [13, 14], consistent with gravity data indicating dense mantle [15].

Ridge belts are prominent in radar imagery, but elastic fault dislocation models indicate that only 1-2 km of fault displacement is required in three representative study sites [14] in Vedma Dorsa. This indicates that the amount of horizontal deformation present in the plains is far less than in Ishtar Terra and the tessera, consistent with the possibility that the plains are from a transitional period in Venus history.

Ridge belts are distinct from wrinkle ridges [16, 17], which are ubiquitous on the Venus plains but typically less than 2 km wide and with limited topographic relief, suggesting very limited horizontal displacement. Stratigraphic relationships among the wrinkle ridges show that both the plains and the wrinkle ridges are not all the same age but instead formed over a period of several hundred million years [18].

Stagnant Lid Present

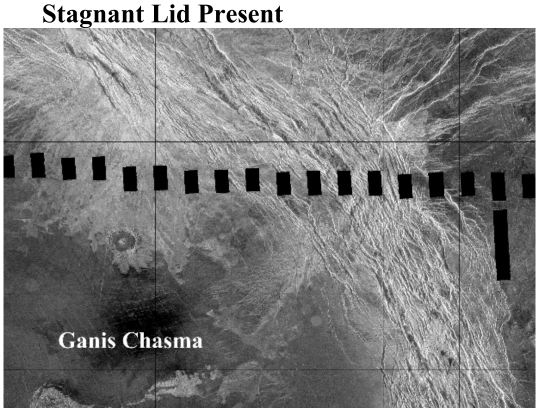

Figure 3: The Ganis Chasma rift is an analog to continental rifts on Earth. The image is 700 km across.

Both geophysical and geological evidence suggests that volcanic rises, rifts, and at least some coronae are young. Finite element simulations tested by long-wavelength geoid and topography observations show that Atla Regio and Beta Regio, the two largest volcanic rises, are dynamically supported by hot, rising mantle plumes [19]. Gravity and elastic flexure models also indicate that the Devana Chasma rift and large coronae such as Artemis, Diana and Dali Chasma, and Eastern and Central Eistla Regio are also dynamically supported by hot mantle [20-22]. Because these thermal anomalies will disappear within 100-200 million years if not actively maintained by convection, these structures all must be young. Although geophysical anomalies are not a common stratigraphic tool, they can sometimes be useful! The inferred young ages are consistent with the relatively low crater densities in these regions [23].

Extension at Balch Crater and structural mapping indicates typical extension of 4-8 km along Devana Chasma between Beta Regio and Phoebe Regio [24-27]. These values are typical of those found at continental rifts in the Rio Grande Rift and in East Africa [27]. The combination of geologic youth, as inferred from the geophysical observations, and limited horizontal extension is strong evidence that Venus mantle convection is currently transitioning into the stagnant lid regime; models indicate that this transition can take ~1 billion years [3], and Venus may not have completed the transition. Ganis Chasma in Atla Regio (Figure 3) has similar morphology and dimensions to Devana Chasma, suggesting that it too has limited total horizontal extension. The absence of clear hotspot tracks associated with the Atla and Beta plumes is another line of evidence favoring limited surface motions at present.

Gravity modeling of Artemis and Quetzalpetlatl suggests the presence of subduction at these two large coronae [28]. This does not disprove our hypothesis that Venus is transitioning from mobile lid to stagnant lid convection because modeling shows that such a transition is spatially and temporally complex, including for instance epochs in which one side of the planet temporarily has a mobile lid and the other side has a stagnant lid [3]. The overall evolutionary sense of the observations laid out here is from mobile lid convection towards stagnant lid, consistent with a possible climate-driven loss of pore fluids, resulting in an increase of fault friction.

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