THE LITHOSPHERE OF VENUS HAS BEEN BROKEN AND, IN PLACES, MOBILE.

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Introduction: There is no evidence for Earth-style, oceanic plate tectonic motion on Venus. Rather, the planet is interpreted to possess a "stagnant lid" [1], i.e., a lithosphere coupled to a highly viscous mantle and inhibited from major lateral motions [2]. Nonetheless, the planet continues to lose interior heat, and some surface mobility may be imparted by mantle convection [3]. Venus also exhibits widespread tectonic evidence for crustal extension, shortening, and strike-slip faulting in almost all parts of the planet [e.g., 2,4–6]. Here, we compare structural mapping of tectonic systems on Venus with model results for mantle convection to explore the prospect for motion of discrete blocks of lithosphere.

Tectonic Observations: In places, tectonic strains are broadly distributed spatially, for example, at tesserae; in other areas, deformation is concentrated into narrow curvilinear zones [7]. For example, bands of shortening structures that accommodate crustal thickening are termed "ridge belts" [e.g., 8] and are Cytherean cognates of Earth's mountain belts. These bands are typically manifest as a broad, linear rise a few hundred meters tall, tens of kilometers in width, and many hundreds of kilometers long [8]. The extensional counterparts to ridge belts are long rift zones (variously labeled "fracture belts" or "groove belts") [8,9]. Although most examples have dimensions comparable to those of the ridge belts, some groove belts combine to form arrays thousands of kilometers long that may be underlain by dikes swarms [e.g., 9].

Ridge and groove belts often delimit low-lying areas that are infilled with smooth plains (likely some combination of volcanic and sedimentary deposits, and interpreted as among the youngest units on the planet [9]); these plains clearly superpose the lower portions of ridge belts in some instances. Distributed across Venus, some belt-bound lowlands are but a few hundred kilometers across, whereas others extend laterally for more than 1000 km (such as those we term Nuwa and Lada Campi, discussed in this same volume [10]). The plains are themselves typically deformed by parallel sets of wrinkle ridges, but the interiors of the lows do not otherwise appear disturbed, in contrast to the intensely deformed perimeter belts. Nonetheless, some strain-compatible structures from the surrounding highly strained margins cross-cut the smooth plains infill and thus presumably post-date the emplacement of those plains.

Many of these bounding belts display evidence for transpression and/or transtension: that is, these systems have accommodated lateral shear in addition to crustal extension or shortening. For example, some ridge belts display secondary sigmoidal structures arranged in en echelon patterns, which morphologically resemble positive flower structures formed in restraining bends along strike-slip faults on Earth. Similarly, groove belts are frequently associated with smaller fractures that curve into the main system, indicating rotation during shearing parallel to the belt, as well as lozenge-shape depressions akin to pull-apart basins at releasing bends in strike-slip settings.

Notably, ridge and groove belts commonly intersect to form a regional network of polygonal, low-lying plains. One such example is Lavinia Planitia [e.g., 7], where multiple ridge belts demarcate a set of lows largely free of tectonic deformation. Numerous other examples occur across Venus, including near Artemis Chasma and adjacent to Vedma Dorsa. Indeed, we identify at least a dozen more such belt-defined networks of polygonal lows across the planet (**Figure 1**). Most of these examples are spatially collocated with free-air gravity and geoid lows, and are situated at mid- to high latitudes in the northern and southern hemispheres; almost no sites occur near the equatorial rift system that spans much of the planet's circumference (**Figure 1**).

Together, these observations imply that the smooth plains overlie mechanically coherent blocks that have moved relative to one another, akin to jostling pack ice [10], with that motion accommodated by the highly strained transpressive and transtensive belts that demarcate block margins. The strains recorded in the bounding belts imply both block translations and rotations, with lateral motions of up to several tens of kilometers in places. Moreover, the superposition of smooth plains units upon ridge belts, and of extensional structures emerging from groove belts and cross-cutting these deposits, point to deformation that both preceded and followed plains formation in at least several sites across Venus.

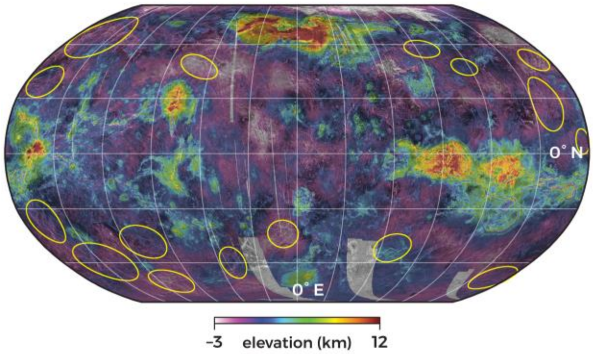

Figure 1. *The distribution of networks of belt-bound crustal blocks on Venus, shown with color-coded topography.*

Terran Analogs: This interpreted style of tectonics is similar to that seen within continental interiors on Earth. For example, the Tarim basin in northwestern China is a mechanically rigid crustal block that is physically distinct from its surroundings and has moved into its present location as an accreted exotic terrain [10]. The basin interior is relatively undeformed [11]; lateral motion of this block has mainly been taken up by the Altin Tagh and Tian Shan mountain ranges that define its southern and northern perimeters, respectively [10,12,13]. Similar crustal block motion accounts for the Sichuan basin in southeastern China [14], as well as the Amadeus basin in central Australia, the Moesia block in Bulgaria and Romania, and the Black Sea and South Caspian basins.

The lithospheres of Venus and Earth's continents likely have similar strength profiles [2,15], with a weak zone at some relatively shallow depth (i.e., ~13 km for Venus and ~50 km for Earth: [2,10,16]). This weak zone within Venus may therefore permit the transmission of subcrustal stresses to the near surface. Of course, lateral motion of crustal blocks on Earth arises in response to plate tectonics, driven primarily by slab pull and ridge push. Clearly, the driving mechanism for block motion on Venus is different. Yet the recognition of "subsumption" on Europa [17] raises the prospect that interior motion as evinced by tectonic structures on planetary surfaces may occur in a range of styles and thus be more common than once thought.

Regions of low topography on Venus are often spatially collocated with gravity and geoid lows and are thought to reflect areas of downwelling mantle [e.g., 18]. It may even be that such downwelling could produce tractions at the base of the crust sufficient to drive minor lateral motion. We therefore tested this inference for Venus, by comparing the stresses predicted from mantle downwelling with estimates for the yield strength of the planet's lithosphere [2].

Mantle Convection Stresses: We used a propagator matrix calculation to calculate dynamic flow kernels for a viscous sphere, from which stresses in the lithosphere were obtained [19]. The calculation methodology is described in elsewhere [19], but both lateral variations in isostatic crustal thickness and basal tractions from mantle convection were considered. We find that, in both cases, compressive stresses broadly correlate with low-lying terrains, whereas the highlands experience tensile stresses. There is a trade-off between stress and lithospheric thickness: a thicker lithosphere allows stresses to be distributed more broadly and reduces the stress magnitude at any given point.

Nonetheless, stresses over mantle downwelling appear to be substantial: the von Mises stress at Atalanta Planitia, for example, exceeds 100 MPa for any lithosphere thinner than 300 km [19]. The stresses from mantle tractions are generally an order of magnitude larger than those from isostatic crustal stresses, so mantle convection is likely the more important driver of tectonics. And, of note, such stresses are substantially greater than the expected yield strength of the lower crust at Venus [2], providing a basis by which interior motion could plausibly be transferred to the surface.

Outlook: Our results indicate that mantle motion on Venus may be reflected in the tectonic deformation recorded on the surface. Further, superposition relationships between tectonic structures and plains units indicate that this deformation may have taken place relatively recently. Perhaps, then, there is a continuum of styles between (partially) coupled interior–surface deformation, with Earth's "mobile lid" tectonics at one end, the "stagnant lid" tectonics of Mars, Mercury, and the Moon at the other, and Venus somewhere in between.

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