MAKING ISHTAR TERRA, VENUS: MOBILE LID TECTONICS, CONTINENTAL CRUST, AND IMPLICATIONS FOR LIQUID WATER AND PLANETARY EVOLUTION
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Introduction

Present-day Venus is very different from Earth. Mantle convection on Venus is currently in the stagnant lid regime, with very little surface motion [1]. Due to the 470 °C temperature, liquid water is not currently stable on the surface of Venus. But is it possible that Venus was once more Earth-like? In this work, I present evidence that the Ishtar Terra highlands on Venus require thousands of kilometers of crustal convergence and thus imply that mantle convection on Venus once operated in the mobile lid regime. A mobile surface requires faults that fully penetrate the brittle lithosphere. In the absence of such faults, the temperature dependence of mantle viscosity results in a globally continuous, thick, high viscosity layer that enforces stagnant lid convection [2]. Liquid water facilitates fault development by lowering pore pressures and also lowers the coefficient of friction of materials in the fault zone. For these reasons, water has been commonly invoked as mechanism for creating weak plate boundary faults [e.g., 1, 3-6], although other mechanisms may also be possible [7, 8]. Low density, silica-rich crust, similar to continental crust on Earth, may also form portions of Ishtar Terra and would also imply the presence of water within the Venus mantle [9]. Measurement of seismic receiver functions from a small (minimum 2 station) seismic network, supplemented by existing gravity observations, can distinguish between basaltic and felsic crust in Ishtar.

Crustal Convergence Model

Ishtar Terra consists of a flat, central plateau, Lakshmi Planum, surrounded on most sides by mountain belts. Lakshmi is typically about 3.5 km above mean planetary radius, whereas the mountain belt peaks are frequently at 6 to 10 km elevation. The overall structure is about 2700 km (East-West) by 1800 km (North-South); these dimensions do not include Fortuna Tessera to the east or Itzpapalotl Tessera to the north [10]. Tectonic structures within the mountain belts indicate an origin by compressional deformation, possibly as fold-and-thrust belts [11-13]. Gravity observations indicate that most of Ishtar Terra is compensated at sufficiently shallow depths that the topography may be supported mostly isostatically by thickened crust [4, 10]. There is a long-wavelength gravity component, comparable in length to the plateau, that suggests some deeper support is also present [10, 14].

One way to produce the necessary thickened crust is in a crustal convergence zone driven by convective flow in the mantle. Such a model is also consistent with the mountain belt tectonics. We can quantify the amount of convergence required by a simple Airy isostasy calculation. Based on limited geochemical measurements, the lowlands plains crust on Venus is basaltic [15]. Assuming crust and mantle densities of 2900 and 3300 kg m⁻³, the average 3.5 km elevation of Lakshmi Planum requires 29 km of crustal thickening in order to be supported isostatically. The average crustal thickness is estimated to be ~30 km in the plains [16], so the Lakshmi crust is roughly double the global mean crustal thickness. Given the size of Ishtar, doubling the thickness of crust by means of crustal convergence implies ~2000 to 3000 km of crustal convergence. For flow velocities similar to present-day plate velocities on Earth (2-10 cm/yr), the necessary amount of crustal convergence could occur in ~10⁸ years. If the relevant density contrast for the isostasy calculation is between the crust and a mantle melt residue [14], δρ will be smaller than calculated here, requiring a greater degree of crustal thickening and crustal convergence to produce Lakshmi.

The mountain belts such as Maxwell Montes are significantly taller and their formation by this mechanism would therefore require greater degrees of crustal convergence. However, the phase transition from basalt to dense eclogite limits the total thickness of basaltic crust that can form on Venus [17, 18]. An alternative model is that the mountain belts are formed at least in part from more felsic material such as granite [18]. The lower density of this material reduces the required amount of crustal thickening and crustal convergence. Because the mobile lid convection scenario being considered here likely requires liquid water, felsic igneous material might have formed on Venus over the sites of mantle downwelling by a process similar to subduction zone volcanism on Earth.

Implications

The considerations outlined above suggest that a crustal convergence model may explain the high topography, gravity, and tectonics of Ishtar Terra. This model requires that Venus once existed in a mobile-lid convective regime, in which the surface experienced substantial motion, but does not necessarily require the rigid plate rotations that characterizes plate tectonics on Earth. Moreover, it is possible that Venus only existed in the mobile lid regime on an intermittent basis [19]. Other investigators have previously proposed models involving thickening of either the crust or a near-surface keel of mantle melt residuum over a man-
tle convergence zone, but these earlier studies were done prior to the recognition of the importance of stagnant lid convection, and thus the earlier studies did not emphasize the possible implications of these models for liquid water on Venus [14, 20-22].

This model may help to explain observations of $^{40}$Ar in the atmosphere of Venus. $^{40}$Ar is a radioactive decay product of $^{40}$K and is degassed from the mantle to the atmosphere over time. Measured on the basis of per unit mass of planet, Venus has about half as much $^{40}$Ar in its atmosphere as Earth does [23]. This suggests that averaged over the age of the solar system, volcanic degassing has been about half as effective on Venus as on Earth. Assessments of the present-day volcanic resurfacing rate on Venus vary considerably [e.g., 24, 25], but if Venus spent a portion of its history in the mobile lid convection regime, volcanic outgassing during that period of time would make an important contribution to the atmospheric argon record.

Several highland structures on Venus, such as Beta Regio and Atla Regio, appear to be best explained as hot, rising mantle plumes [26, 27]. On Earth, similar plumes such as Hawaii produce prominent chains of volcanos and seamounts that can be used as a record of past plate motions. If Venus convected in the mobile lid regime for a significant period of time, one might expect that lithospheric motion over upwelling plumes would create similar chains of volcanos on Venus. Such volcano chains are not observed, which is a potential problem for the mobile lid hypothesis. Can volcanic resurfacing during the transition from mobile lid to stagnant lid convection obscure the record of prior volcanic chains?

### A Possible Seismic Test

A seismic sensor that functions at Venus’s ambient atmospheric temperature is currently in development [28]. A seismic experiment with a small number of stations could measure both the thickness and average composition of the Ishtar Terra crust and thus test the hypothesis advanced here. Receiver functions are a method used to study crustal structure on Earth, sometimes with a very small number of seismic stations. When seismic waves cross a discontinuity in seismic velocities, such as at the crust-mantle interface, new seismic waves are created by mode conversion (from P to S or from S to P). The receiver function method measures the arrival time of both the original wave and the converted wave; the difference in travel time is related to the ratio of the seismic velocities, Vp/Vs, and to the thickness of the crust [29]. The need to separate the effect of the velocity ratio from the effect of the layer thickness introduces ambiguity to the interpretation. An effective way to resolve the ambiguity is to measure phases that have bounced multiple times between the surface and the base of the crust [30], but the initial seismometers available for high temperature measurements may not be sufficiently sensitive. An alternative approach to resolving the ambiguity is to incorporate ancillary constraints into the model [31]. In the case of Ishtar, a possible constraint is the difference in crustal thickness between Ishtar and the lowland plains, as constrained by gravity. Such an approach would also require a seismic station in the lowlands. One can use existing databases to relate seismic velocity, density, and rock composition [32] to formulate the joint gravity-seismology analysis.

### References