

## VENUS TECTONICS: AN OVERVIEW OF MAGELLAN OBSERVATIONS;

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*Introduction.* While the Pioneer Venus altimeter, Earth-based radar observatories, and the Venera 15-16 orbital imaging radars provided views of large-scale tectonic features on Venus at ever-increasing resolution [1-4], the radar images from Magellan constitute an improvement in resolution of at least an order of magnitude over the best previously available [5]. A summary of early Magellan observations of tectonic features on Venus has been published [6], but data available at that time were restricted to the first month of mapping and represented only about 15% of the surface of the planet. Magellan images and altimetry are now available for more than 90% of the Venus surface. Thus a more global perspective may be taken on the styles and distribution of lithospheric deformation on Venus and their implications for the tectonic history of the planet.

*Generalizations.* Tectonic features on Venus are widespread and diverse, and comparatively few regions are undeformed. Areas lacking tectonic features at Magellan resolution are restricted to relatively young volcanic deposits and impact craters and associated ejecta. Most of the surface, during at least some period over approximately the last 400 My [7,8], has experienced horizontal strain sufficient to fault or fold near-surface material.

Tectonic activity on Venus has continued until geologically recent time, and most likely the planet is tectonically active at present. Several arguments support this inference. The great relief and steep slopes of the mountains and plateau scarps of Ishtar Terra and of the equatorial chasm systems are difficult to reconcile with long-term passive support by crustal strength. Because of the high surface temperature on Venus, temperatures at which crustal rocks fail by ductile flow should be reached at much shallower depths than on Earth [9,10]. Numerical models suggest that areas of high relief and steep slope should spread under self-gravity by ductile flow of the weak lower crust on time scales less than 1-10 My [11]. Thus the processes that build relief and steepen slopes must have been active within the last 1-10 My. Further, a number of features produced by geological processes that have operated more or less steadily during the past 400 My show evidence of subsequent tectonic activity. About one third of all preserved impact craters on Venus have throughgoing faults and fractures, and 1 in 12 are extensively deformed [8]. The longest lava channel on the plains of Venus does not progress monotonically to lower elevations downstream, indicating that differential vertical motions have occurred since the channel was formed [12].

Compared with the Earth, horizontal displacements on Venus over the last 400 My have been limited. Most of the tectonic features require modest strains and horizontal displacements of no more than a few tens to perhaps a few hundreds of kilometers. Plains thousands of kilometers across record horizontal strains of order  $10^{-2}$  or less. The great rift systems of Beta and Atla Regiones need have extended no more than a few tens of kilometers, on the basis of topographic profiles, extended features such as the crater Somerville in Devana Chasma, and analogy with continental rifts on Earth [13]. For compressional features, the amount of crustal thickening can be estimated from topographic relief and isostatic considerations, but this approach provides only a lower bound on horizontal displacements if any crustal material is recycled into the mantle at zones of underthrusting. For ridge belts 100 km in width and with up to 1 km of relief, horizontal displacements of no more than 100 km are required for crustal thicknesses of 10-20 km beneath the adjacent plains [14,15]. Mountain belts are exceptional in that greater horizontal displacements are required. For a two- to four-fold thickening of the crust beneath the 500-km width of Maxwell Montes, the implied minimum horizontal displacement is 1000-2000 km.

Unlike the Earth, Venus does not show evidence for a global system of nearly rigid plates with horizontal dimensions of  $10^3$ - $10^4$  km separated by narrow plate boundary zones a few kilometers

to tens of kilometers across. Predictions prior to Magellan that Aphrodite Terra would show features analogous to terrestrial spreading centers and oceanic fracture zones [16] are now seen to be incorrect. Evidence for shear is present in the ridge and fracture belts and in the mountain belts, but the shearing tends to be broadly distributed and to accompany horizontal stretching or shortening. Few clear examples have yet been documented of long, large-offset strike-slip faults such as those typical of oceanic and many continental areas on Earth; two such features have been identified in the interior of Artemis Corona [17]. A number of the chasm systems of Venus have arcuate planforms, asymmetric topographic profiles, and high relief [18] and have been likened to deep-sea trenches on Earth [17]. These include Dali and Diana Chasmata [17] and the moat structure of Artemis Corona [19]. Elsewhere, however, chasm systems with similar relief and small-scale morphology, but with more linear segments and more nearly symmetric topographic profiles, such as Devana Chasma, are clearly extensional rifts.

Much of the tectonic behavior on Venus appears to be more reminiscent of actively deforming continental regions than of oceanic regions on Earth. In particular, as in tectonically active continental areas, deformation is typically distributed across broad zones one to a few hundred kilometers wide separated by comparatively stronger and less deformed blocks having dimensions of hundreds of kilometers. On Earth, the continental lithosphere in tectonically active areas is weaker than typical oceanic lithosphere because of the greater thickness of more easily deformable crust. As noted above, because of the higher surface temperature on Venus, the likely comparable lithospheric thermal gradients on Venus and Earth [20,21], and the strong temperature dependence of ductile behavior, the lithosphere on Venus should behave in a weak manner for crustal thicknesses less than are typical of continental regions on Earth.

*Status of Models.* A major challenge in unravelling the tectonic evolution of Venus is to understand the interaction between mantle convection and the lithosphere. The hotspot [22] and coldspot [23] models for the formation and evolution of major highlands on Venus are distinguishable on the basis of the predicted sequence of events and the time-dependent relationship between topography and gravity. Both models face difficulties in their present forms, however, at least partly because both the rheology of the upper crust of Venus and the observed patterns of magmatism and deformation are more complex than current models for the deformation and magmatic response of the crust to mantle flow. Any global tectonic model, of course, must also consider the formation and characteristics of the lowlands, including the large apparent depths of isostatic compensation [22] and relatively recent lowland volcanism [24]. All dynamical models to date require special pleading to explain Ishtar Terra. Both the rifted, volcanically active highlands and coronae are generally regarded as sites of upwelling mantle flow and magma generation by pressure-release partial melting of mantle material. These two classes of features, however, have very different tectonic and morphological manifestations at the Venus surface. If both are products of mantle upwelling, then multiple scales of mantle convection are indicated and the different morphologies of the two classes of features must be related to differences in the geometry, buoyancy flux, or duration of flow in the two types of upwelling regions. The assessment of existing dynamical models for the tectonic evolution of Venus and the development of the next generation of models will require an understanding of geological relationships at all scales, from the highest resolution available to global patterns. High-resolution measurements of the global gravity field later in the Magellan mission will provide key data for testing and refining models.

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