

dependent viscosity with the help of a recently developed approach [8] and the thermal evolution of Venus with melting and differentiation is calculated.

The model predicts that only a small amount of melt is extracted in the first period of evolution; however, this would result in a strong depletion in radioactive elements and devolatilization of a part of the upper mantle. Independently of the thickness of this differentiated layer, only about a 300-km layer contributes to the crust formation (a depth below which the melt is supposed to be denser than the surrounding rocks). A small buoyancy of this depleted layer is sufficient to stabilize this layer with respect to the undifferentiated mantle. This prevents supply of the undifferentiated material to the melting region. Convection occurs eventually in both layers. The lower, undifferentiated layer is heated from within. The upper, differentiated layer is mainly heated from below. The temperature increases and reaches the anhydrous solidus only after several billion years depending on the rheological model. The young basaltic crust observed on Venus is produced by melting of the anhydrous layer. This melting and the crust growth are weak mainly because of the lower heat flux consisting of the radiogenic heat production in the undifferentiated lower layer and almost not contributed from the secular-cooling heat flux from the core (it is even negative) and the remaining radioactivity in the differentiated layer. An additional consequence of the model is that the magnetic field was never generated in venusian history.

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THE TECTONICS OF VENUS: AN OVERVIEW. Sean C. Solomon, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge MA 02139, USA.

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 [1-3], the radar images from Magellan constitute an improvement in resolution of at least an order of magnitude over the best previously available [4]. A summary of early Magellan observations of tectonic features on Venus has been published [5], 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 95% 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 [6].

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 the younger impact craters and associated ejecta. Most of the surface, during at least some period over approximately the last 500 m.y. [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 in the Ishtar region should spread under self-gravity by ductile flow of the weak lower crust on time scales less than about 10 m.y. [11]. Thus the processes that build relief and steepen slopes must have been active within the last 10 m.y. Further, a number of features produced by geological processes that have operated more or less steadily during the past 500 m.y. show evidence of subsequent tectonic activity. About one-third of all preserved impact craters on Venus have thoroughgoing 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 500 m.y. 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 Somerville Crater 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 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] now seem 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; such trenches may be the products of limited underthrusting or subduction of lithosphere surrounding large coronae [19]. Elsewhere, however, chasm systems of somewhat lesser relief display more linear segments and

more nearly symmetric topographic profiles, such as Devana Chasma, and on the basis of small-scale morphology 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 unraveling 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 at least the larger 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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THE SPATIAL DISTRIBUTION OF CORONAE ON VENUS.
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Coronae on Venus are large, generally circular surface features that have distinctive tectonic, volcanic, and topographic expressions. They range in diameter from less than 200 km to at least 1000 km. Data from the Magellan spacecraft have now allowed complete global mapping of the spatial distribution of coronae on the planet. Unlike impact craters, which show a random (i.e., Poisson) spatial distribution [1], the distribution of coronae appears to be nonrandom. We investigate the distribution here in detail, and explore its implications in terms of mantle convection and surface modification processes.

Figure 1 shows the distribution of coronae and corona-related features on Venus, in a simple cylindrical (Plate Carrée) projection. The map gives the locations of 311 features identified in all of the Magellan data taken to date. These features include coronae; they also include radially fractured domes, which are believed to be coronae in an early or arrested stage of development [2]. The map gives the qualitative sense that the distribution is nonrandom, with distinct areas of clustering and sparseness. However, this assertion requires testing, especially because there are some significant gaps in the Magellan data that artificially introduce areas of sparseness in the corona distribution.

In order to test for nonrandomness, we apply a simple nearest-neighbor test. In this test, we measure the distance, r , of each feature from its nearest neighbor on the planet. The percentage of points with a nearest-neighbor distance greater than r is then plotted as a function of r in Fig. 2. The next step is to compare this result to the result expected for a spatially random distribution. There exist theoretical treatments for a nearest-neighbor curve of the sort in

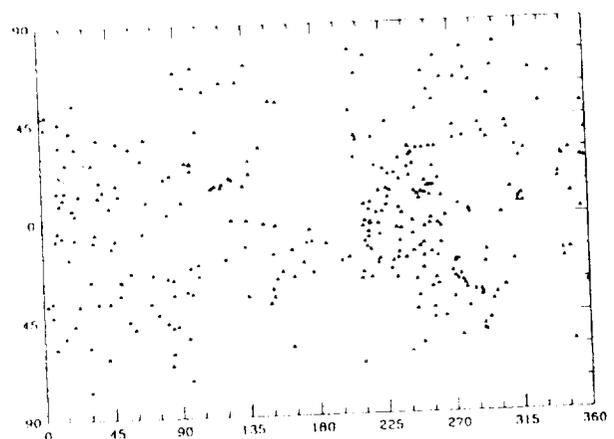


Fig. 1. Map showing the distribution of coronae and related features on Venus.