The Thermal Evolution of Venus as Recorded by Surface Tectonics

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The Venus impact crater record suggests that the planet experienced a resurfacing event of virtually global proportions roughly 400 million years ago. The catastrophic resurfacing hypothesis holds that minimal volcanic and tectonic activity has occurred in the interim; a parallel argument is that the lithosphere has cooled and thickened in the post-catastrophic period. We evaluate this postulate by examining correlations between the relative ages of tectonic features and their inferred thermal gradients. Using an instability growth model, we find a high geotherm is necessary to explain the deformation wavelengths of tessera, among the oldest terrains on Venus. Flexure and gravity modeling of coronae and large volcanoes, structures of intermediate age, indicate lower geotherms at the time of formation. Artemis Chasma—a zone of lithospheric underthrusting—is believed to be relatively young; it displays coherent, plate-like tectonics and an extraordinarily low temperature gradient. Together these observations favor the monotonic cooling and thickening of the venusian lithosphere in the past few hundred million years.

Tessera Deformation and Plateau Highlands

The plateau highlands are characterized by extensive units of tessera [1], the oldest stratigraphic terrain on Venus [2]. We have examined the mechanical implications of observed ridge wavelengths in tessera using an instability growth model for a plastic layer overlying a viscous substrate [3]. Viscosity increases exponentially with depth in the layer, and decreases exponentially with depth in the halfspace. Observed ridge spacings in Ovda, Thetis, Alpha and Tellus Regiones are tightly clustered between 10 and 15 km, with 80% of all measurements lying within this range (inclusive). These short deformation wavelengths are indicative of a layer thickness of only ~3–4 km, assuming an anhydrous diabase rheology [4]. To translate the thickness into a thermal gradient, we define the layer as the compressional brittle–ductile transition in yield stress. For strain rates of at least 10^{-16} s^{-1}, inferred temperature gradients are greater than 25 K km^{-1}.

The thermal gradient estimated for the tessera at the time of formation is comparable to that predicted by scaling from Earth [5], but it should be evaluated in the context of the shortening environment for which it is derived. If the strain rate (and crustal thickening rate) was relatively rapid (~10^{-15} s^{-1}) compared to the thermal reequilibration rate, isotherms would have been advected downward as deformation proceeded. Therefore, the nominal geotherm for unthickened lithosphere would have been higher. At Ovda, for example, if the crust was thickened from 30 to 45 km [6], the ambient geotherm would have been ~60% higher (~35 K km^{-1}) than the temperature gradient reflected in the fold wavelengths. This would imply an unusually high heat flux for the planet, or perhaps that tesserae were associated with anomalous heating.

Alternatively, a very low strain rate (~10^{-17} s^{-1}) would imply a prolonged evolution for tessera; the lithosphere could reequilibrate as it thickened, meaning the derived temperature gradient would be representative of the pre-deformation thermal state. The impact crater record provides a useful constraint on the strain rate, given that no craters on tessera are deformed by shortening [7]. The strain time must have been only a fraction (~10%) of the crater retention age (~400 Ma), yielding a strain rate of at least ~10^{-15} s^{-1} [8]. This estimate is supported by a statistical consideration of the probability of no craters being formed in the time required to wipe out all existing ones. Therefore, thermal reequilibration was probably outpaced by tectonic thickening, suggesting a high ambient heat flow.

Recent Thermal Evolution of Venus

In contrast to our findings for tesserae, the thermal gradient at most other, younger features on the planet is significantly lower than 25 K km^{-1}. Unlike terrestrial oceanic lithosphere, we cannot accurately trace changes in heat flow with time for Venus because we lack exact ages for any surface features. However, crater counts of specific geologic provinces (plains, coronae, volcanic rises, rifts) [9,10] and stratigraphic relations [2] combined with geodynamic modeling permit a broad assessment of the thermal evolution.

Tessera, the oldest unit both stratigraphically [2] and based on its crater population [11], is associated with weak crust and a high thermal gradient. These conditions might not have been typical of Venus if they were related only to processes responsible for forming tesserae and plateau highlands, but tessera is widespread, and such high heat flows have evidently not occurred anywhere in the ensuing period. Tessera represents an era in which the mantle did not contribute to lithospheric strength; the lithosphere was soft and confined to the crust, allowing pervasive deformation (Figure 1).

Coronae, large volcanoes, and rifts have crater densities less than that of the planet as a whole [9,10], indicating relative youth. This inference is reinforced by the stratigraphy [2]. Thermal gradients of 6–25 K km^{-1} have been deduced from flexural modeling of the topography around several coronae [12,13]. Admittance and coherence studies of volcanic rises suggest temperature gradients of 5–10 K km^{-1} [14,15]. The thermal state of the lithosphere at these features may have been "contaminated" by the heating associated with their formation; these estimates therefore represent upper bounds on the geotherm of unaffected lithosphere. Impact craters were emplaced continuously in the time since the global resurfacing, and provide a space- and time-averaged view of lithospheric strength. Large craters exhibit no flexural rebound of their floors, indicating a lithospheric geotherm less than 20 K km^{-1} [16]. The scatter in the cited values may be attributed to lateral variations of surface heat flow, different ages of the features (and changes of heat flux over time), as well as variable amounts of heating associated with the features themselves. Both the crust and mantle were involved in the mechanical lithosphere during this period; lithospheric strength may have been stratified, producing multiple deformation wavelengths [17] (Figure 2).

Artemis Chasma is one of the most striking structures on Venus: the convergence, lithospheric underthrusting, and strike-slip motions evident at Artemis resemble plate boundaries on Earth, but on a much more limited scale [18]. This deformation style implies a rigid, thick lithosphere, dominated by mantle strength, and lacking any significant stratification (Figure 3). Artemis crosscuts some nearby rifts, and it is probably relatively young. Flexural studies demonstrate that the lithosphere being underthrust at Artemis is extraordinarily cold: geotherms are below 4 K km^{-1} [12,19].

The correlations between age and heat flux support a gradual, conductive cooling of the venusian lithosphere. Despite the magmatism involved with coronae and volcanoes, these features formed in lithosphere with a geotherm substantially below that of tessera crust and an Earth-scaled heat flow. The Artemis thermal gradient reflects the mechanical lithosphere of today: strong, cold, and over 100 km thick. A conductively cooling lithosphere cannot attain a geotherm much lower than ~3–4 K km^{-1} on Venus, corresponding to a thermal lithosphere over 300 km thick.

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