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RIFT SYSTEMS ON VENUS: AN ASSESSMENT OF MECHANICAL AND THERMAL MODELS.

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Introduction. The formation and distribution of major tectonic features on Venus are closely linked to the dominant mechanism of lithospheric heat loss [1]. Among the most spectacular and extensive of the major tectonic features on Venus are the chasmata, deep linear valleys generally interpreted to be the products of lithospheric extension and rifting [2-5]. Systems of chasmata and related features can be traced along several tectonic zones up to 20,000 km in linear extent [5]. In this paper we apply mechanical and thermal models for terrestrial continental rifting to the rift systems of Venus. The models are tested against known topographic and tectonic characteristics of Venus chasmata as well as independent information on the physical properties of the Venus crust and lithosphere.

Chasma Characteristics. Major systems of chasmata, readily identified from Pioneer Venus topographic data [2,3], are located in the Beta and Phoebe highland regions [4] and along the Aphrodite-Beta and Themis-Atla tectonic zones in the Venus equatorial highlands [5]. Smaller chasms have been identified elsewhere on the basis of radar imaging data [6]. Among the principal highland regions of Venus [7], Ishtar Terra may be distinguished as the only large highland area apparently lacking major rift structures.

Topographic profiles across major chasmata have similar characteristics from region to region [2-5]. The rift valleys are typically 75-100 km in width. The floors of the chasmata are up to 2.5 km deeper than ambient terrain levels, and the rims of the rifts are generally raised by 0.5 to 2.5 km. Because of the large footprint and spacing of the altimetry data [3], the rift widths may be slightly overestimated, and the maximum relief of rims and chasma floors may be somewhat greater than indicated here.

A major question is the relative contribution of volcanic construction and uplift to the observed rim heights. New high-resolution radar images of the rift system in central Beta Regio have allowed the tentative identification of a number of individual volcanic constructs along the boundaries of the rift [8] and an assessment of their relationship to local topography [4]. On the basis of these new data, the regions of maximum rim height appear to coincide with volcanic constructs. Rim heights are no more than 1-1.5 km in areas without discernible constructional contribution [8].

Graben Model. The first model proposed in the literature to explain the characteristics of Venus chasmata was the Vening-Meinesz graben model [5]. For this model [9] to predict the correct width of the rift valley or graben, however, the local thickness of the elastic lithosphere must be 45-70 km [5]. Such a great thickness for the elastic lithosphere of Venus is extremely unlikely; on the basis of laboratory data and the high surface temperature of Venus, the elastic lithosphere can be shown to be no more than a few kilometers in thickness [10].

Lithospheric Stretching Models. The failure of the graben model to explain the topographic characteristics of highland rifts on Venus led to the proposal of a lithospheric stretching model [11]. Such models have been applied successfully to explain the structures and subsidence histories of continental basins and rifted continental margins on Earth [12-14]. The simplest of these models are locally one-dimensional and involve either uniform lithospheric stretching or different degrees of stretching for the crust and the thermal lithosphere. According to the two-layer stretching model of Turcotte [13], for instance, a crust of thickness C_0 and density ρ_c and a lithosphere of thickness L_0 (including the crust) is stretched under extension to new crustal and lithospheric thicknesses C and L. There is a resulting subsidence

$$s = \frac{(\rho_m-\rho_c)}{\rho_m} C_0 \left(1 - \beta_c\right) - \frac{\alpha}{2} \left(T_m - T_0\right) L_0 \left(1 - \beta_L\right) \qquad (1)$$

where $\beta_c = C/C_0$ and $\beta_L = L/L_0$ are thinning factors for the crust and lithosphere, T_m and ρ_m are the temperature and density of the asthenosphere, T_0 is the surface temperature, and α is the volumetric coefficient of thermal expansion for the lithosphere. The first term in (1) represents the isostatic result of crustal thinning; the second term represents the thermal result of lithospheric thinning.

One simple test of this model is to examine the implications of the topographic relief for the pre-rift thickness of the crust. If either the present rift significantly postdates the episode of extension [12,13] or the width of thinned lithosphere beneath a Venus rift is considerably greater than the width of the region of thinned crust [14], then the total rim-to-floor relief, excluding volcanic construction, across a rift on Venus is a measure of crustal thinning. Setting the first term in (1) equal to 3.5 to 4 km, and assuming $\rho_m = 3.4$ g/cm^3 and $\rho_m-\rho_c = 0.4$ g/cm^3, gives $C_0(1-\beta_c) = 30\text{-}34$ km. Since $\beta_c \geqslant 0$, a minimum thickness for the pre-rift highland crust on Venus is 30 km, a result at least consistent with available gravity and topographic data for Venus highlands, particularly highlands removed from the regions with the strongest signature of mantle dynamics in the long-wavelength gravity and topography fields [15,16]. A rift developed in a region of significantly thinner crust, perhaps including the Venus lowlands and midland plains [7], would be expected to display lesser relief than do the highland chasmata.

On the Origin of Raised Rims. A key issue for mechanisms of rift formation and evolution is the origin of the raised rims adjacent to Venus rift valleys. While localized topographic highs in Beta Regio may be identified from radar images as volcanic constructs [8], the constructional component of rim topography elsewhere along Venus chasmata is difficult to ascertain. A significant component of rim uplift appears to be generally present in terrestrial continental rift formation, an observation that has led to two-layer extensional models with the thermal lithosphere thinned over a zone of greater width than the region of crustal thinning [14]. Strictly kinematic models of this type do not conserve lithspheric mass; removal of the lower lithosphere by some mechanism (e.g., stoping) must be postulated. More complete thermal and dynamical models, however, yield rim uplift as a natural consequence of the lateral transport of heat following initial rifting, either by lithospheric conduction [17] or by the onset of convection in the heated lower lithosphere [18].

The simple two-layer stretching model of equation (1) may be tested against the implied thickness of the thermal lithosphere under the assumption that the raised rim of a Venus chasma is a response to lithospheric thinning and associated thermal uplift [19]. Setting the second term in (1) equal to 1 to 1.5 km, and adopting $\alpha = 3 \times 10^{-5}$°K^{-1} and $T_m-T_0 = 10^3$°K, gives $L_0(1-\beta_L) =$ 70 to 100 km. Since $\beta_L \geqslant 0$, the pre-rift thermal lithosphere is at least 70 km thick. Adding the thickness of the presumably unthinned highland crust external to the rift valley would give a lower bound of 100 km to the pre-rift thermal lithosphere. It should be noted that the uplift attributed here to lithospheric thinning is in addition to any thermal contribution to the broad topographic rise of highland topography in areas of active rifting [20]; i.e., the average thickness of the thermal lithosphere would have to exceed 100 km, perhaps by a considerable amount, if a portion of the topographic rise of a rifted highland is attributed to a broad area of heating and thinning of the thermal lithosphere. If the physical properties governing convection in the Venus mantle are similar to those in the Earth's mantle, this requirement of a thick thermal lithosphere beneath the Venus highlands may be sufficient to rule out this simple stretching model, at least for models not including the effects of lateral heat transport.

It is also important to consider non-thermal explanations for uplift of Venus rift valley rims. In terrestrial rifts, early thermal uplift of rift margins may be sustained well after the heating event by the flexural rigidity of the thickening elastic lithosphere [21]. Such a process is not likely to be important for Venus, however, because of the small value of elastic lithosphere thickness expected even in the absence of extension [1,11]. Dynamic models of extension of a ductile lithosphere can also yield uplifted rims by material flow [22]; the relative contributions of thermal uplift and flow uplift remain to be explored for such models, however.

Conclusions. Lithospheric stretching models can account at least broadly for the topographic characteristics of Venus rift structures. With additional assumptions, such models provide bounds on the thicknesses of the crust and thermal lithosphere in the Venus highlands. Unresolved is the causative mechanism for rift formation, but the great length of ridge systems points to global-scale tectonic processes. We favor the view that the uplift of the margins of Venus rift systems involves a significant thermal component, which would indicate that these global processes are currently active. The lack of major rift structures in Ishtar Terra provides additional support for the hypothesis [11] that the most recent tectonic activity in that highland area has been dominantly compressional.

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