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RHEOLOGY, TECTONICS AND THE STRUCTURE OF THE VENUS LITHOSPHERE;

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Given the absence of ground truth information on seismic structure, heat flow, and rock strength, or short wavelength gravity or magnetic data for Venus, information on the thermal, mechanical and compositional nature of the shallow interior must be obtained by indirect methods. Using pre-Magellan data, theoretical models constrained by the depths of impact craters [1] and the length scales of tectonic features [2,3,4] yielded estimates on the thickness of Venus' brittle-elastic lithosphere and the allowable range of crustal thickness and surface thermal gradient. The purpose of this study is to revisit the question of the shallow structure of Venus based on Magellan observations of the surface and recent experiments that address Venus' crustal rheology.

Both models of viscous relaxation of impact crater topographic relief and the wavelengths of tectonic features made identical assumptions about the composition of the Venus crust and mantle. These include: (1) the Venus mantle is similar in composition to Earth's mantle and therefore the primary constituent is olivine, and (2) the crust in areas where observed impact and tectonic structures used in previous studies are located is similar to the that determined for the Soviet Venera and Vega landers, and is best described by diabase [*cf.* 6]. Knowledge of both the brittle and ductile deformational behavior of these materials is an essential component of these models. Numerous experiments on terrestrial rocks indicate that the brittle strength of near-surface rocks is essentially independent of rock type, strain rate and grain size [7]; strength is dependent almost solely on pressure (depth) and is described in a simple linear relation by Byerlee's Law. The ductile strength of crustal and mantle materials is significantly more problematical, as ductile strength is sensitive to temperature, strain rate, composition, and modal mineralogy. Because of its importance with regard to flow in Earth's mantle, the ductile rheology of single crystal olivine is relatively well-understood [8,9,10], albeit for strain rates 10 or so orders of magnitude greater than characterize the mantle. For Venus, experiments on olivine performed at exceptionally dry conditions are applicable. In contrast, the rheologies of multiphase mineral assemblages such as diabase are not at all well characterized, due in part to the sensitivity of derived flow laws to grain size and mineralogy [11]. Previous studies of the structure of the Venus lithosphere utilized both of the flow laws for diabase that were available at that time [12,13,14], as well as one for websterite [15], although none of these experiments were performed at dry conditions. The results of models based on both impact craters and tectonic wavelengths indicated a range of Venus crustal thicknesses of ~10-30 km and associated thermal gradients of <25^{o}K km^{-1}. For the assumed rheologies, the shallow Venus lithosphere consisted of a region of brittle flow in the crust to a depth of 2-4 km, underlain by a weak lower crust and a strong brittle or ductile upper mantle (*cf.* Figure 1a).

Fortunately, new experimental data on the rheology of diabase has recently become available [16]. These experiments were carefully performed on thoroughly dried samples of Columbia and Maryland diabase, with these rocks chosen on the basis of their gross similarity to chemical compositions at the Venera and Vega lander sites [6]. The results of these experiments indicate that the rheology of the Venus crust may be much stiffer than previously assumed, with a brittle-ductile transition at a depth of 6-8 km rather than 2-4 km. If this is the case, then the depth averaged strength of the crust may be much more similar to that of the mantle than previously thought. For the new diabase data, depending on the rheology of olivine used, the "strong-weak-strong" rheology illustrated in Figure 1a is much less distinct than indicated by previous experiments (Figure 1b).

A stiffer Venus crust is intuitively appealing given the large values of elastic thickness indicated by Magellan topographic profiles suggestive of lithospheric flexure in association with coronae and other surface loads [17]. However, significant evidence for a ductile lower crust (or other weak subsurface rheological layer) is also present in Magellan images of the surface. Numerous occurrences of tectonic features with multiple tectonic wavelengths are observed -- short wavelength features with spacings of km to tens of km occur pervasively over the planet [18,19,20]. The length scales of these features have previously been interpreted to have been controlled by the depth of the brittle-ductile transition in the crust [3]. Features that display much longer length scales include, for example, the width of the Beta Regio Rift and the width and spacings of ridge belts, which may be controlled by the depth and thickness of a strong upper mantle (or other strong subsurface rheological layer) [3]. The existence of multiple wavelengths of tectonic deformation and their relationship to various rheological wavelengths is well documented on Earth [*e.g.* 21,22]. In addition, the width of terrestrial continental rift zones [30-60 km; 23] are controlled by the depth of the brittle-ductile transition in the crust [24]. In contrast, the width of Beta Regio is much greater than that of terrestrial rift zones and must be controlled by either a much thicker or deeper layer. The short wavelength faulting on the floor of the rift [19], is may be evidence for a "strong-weak-strong" vertical rheology. Long wavelength deformation on Venus has alternatively been attributed to be a consequence of small-scale convection [25,26,27]. However, while this mechanism can explain the regular development of structures in some ridge belt regions, it cannot explain the width of the Beta Regio Rift.

Further insight into the nature of the structure of the Venus lithosphere will require careful re-evaluation of observations, theoretical models, and experimental data. First, tectonic wavelengths and impact crater depths should be re-measured using Magellan data. Refined observational constraints should be evaluated in models based on the most recent experimental data. Improvements in treatment of the vertical distribution of lithospheric strength in the theoretical models [28] should also be implemented. In addition, for tectonic features, the relationship between tectonic length scales and strong layer thickness should be evaluated for fracture as well as continuum deformation scenarios [29]. Finally, experiments relevant to the ductile strength of the Venus lithosphere should be performed for a broader range of modal mineralogy and grain size, as well as for larger strains. For example, the experiments in [16] were run out to only 1-2% strain. If higher strains characterize relevant tectonic features, such as some Venus mountain belts [8-20%; V. Hansen, pers. comm.], then significant strain softening of the crust is possible [*e.g.* 30]. In addition, the diabase flow laws are highly sensitive to grain size and the feldspar content of the deformed samples [31]; different values could produce significantly different strengths. Consideration of all of these factors will be required to derive a clearer picture of the thermo-mechanical structure of Venus.

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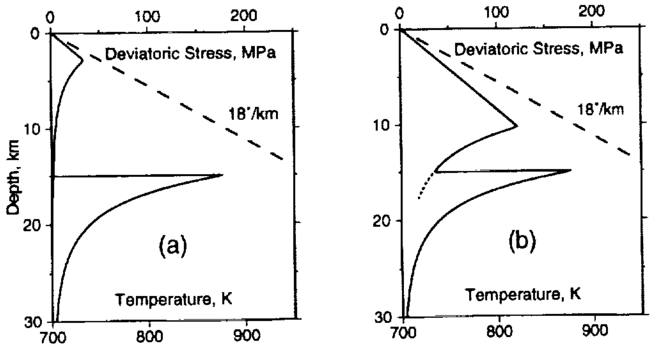

Figure 1. Strength of Venus lithosphere in extension. Ductile strength of crust based on [13] for (*a*) and [16] for (*b*). Both profiles assume ductile strength of olivine from [9], a15-km thick crust, a strain rate of 10^{-14} s^{-1}, and $dT/dz=18^{O}K$ km^{-1}.