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3-D Spherical Modelling of the Thermo-Chemical Evolution of Venus' Mantle and Crust

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Several first-order aspects of the dynamics of Venus' mantle remain poorly understood. These include (i) how it loses its radiogenic heat despite the presence of stagnant lid convection. Hypotheses that have been advanced (summarised in [Turcotte, JGR 1995]) are conduction through a thin lithosphere, episodic overturn of the lithosphere, magmatic heat transport, and concentration of almost all heat-producing elements into the crust, but there are problems with all of these taken individually. (ii) The relatively long-wavelength distribution of surface features, which is surprising because numerical models and analogue laboratory experiments of stagnant-lid convection produce relatively short-wavelength convective cells. (iii) The inferred (from crater distributions [Hauck et al., JGR 1998]) relatively uniform surface age of 500-700 Ma. (iv) Whether the highlands are above mantle downwellings as on Earth or above mantle upwellings [Bindschadler et al., 1992].

To study these questions, we are performing integrated thermo-chemical convection modelling of Venus' evolution over 4.5 billion years, in 3-D spherical and 2-D spherical annulus [Hernlund and Tackley, PEPI 2008] geometries. These models include "laboratory" rheological parameters based on [Karato and Wu, Science 1993; Yamazaki and Karato, Am. Min. 2001] and plastic yielding based on Byerlee's law, which might cause changes in tectonic regime (e.g., episodic plate tectonics). Crustal formation and the resulting crust-mantle differentiation are modelled using a self-consistent melting criterion. Phase transitions in both the olivine system and pyroxene-garnet system are included. The concentration of heat-producing elements is assumed to be the same as in bulk silicate Earth and decreases with time, and cooling of the core is tracked using a parameterised core heat balance. Geoid and surface topography are calculated using a self-gravitating formulation. Thus, the model constitutes an attempt to incorporate as much realism as is presently feasible in global-scale 3-D spherical simulations. Simulations are performed using StagYY, which uses a finite volume multigrid solver on the Yin-Yang spherical grid [Tackley, PEPI 2008]. Model results are compared to observations of surface topography (hypsometric distribution), geoid (admittance ratios), mean surface age and distribution of surface ages, crustal deformation rates [Grimm, JGR 1994], crustal thickness and the time evolution of heat flux through the CMB. Of particular interest is whether a smooth evolution can satisfy the various observational constraints, or whether episodic or catastrophic behaviour is needed, as has been hypothesised by some authors.

Simulations in which the lithosphere remains stagnant over the entire history indicate that over time, the crust becomes as thick as the mechanical lithosphere, with delamination occuring from its base, and magmatism being the dominant heat transport mechanism. A thick crust is a robust feature of these calculations. Higher mantle viscosity results in larger topographic variations, thicker crust and lithosphere and higher admittance ratios; to match those of Venus, the upper mantle reference viscosity is about 10ˆ20 Pa s and internal convection is quite vigorous. Several large plumes persist throughout the model history, as the core does not cool as much as in Earth due to the lack of slabs arriving at the CMB. The most successful results in matching observations are those in which the evolution is episodic, being in stagnant lid mode for most of the evolution but with 2-3 bursts of activity caused by lithospheric overturn. If the last burst of activity occurs $\sim$1 Ga before present, then the present day displays low magmatic rates and mostly conductive heat transport, consistent with observations.