INITIATION OF SUBDUCTION ON EARTH AND VENUS BY EPISODIC LARGE-SCALE MANTLE OVERTURN; D.L. Herrick and E.M. Parmentier, Department of Geological Sciences, Brown University, Providence, RI 02912

The difficulty of identifying forces large enough to create new subduction zones on the Earth has inhibited the development of a complete dynamic theory of plate tectonics. An important related question is why Venus, a planet similar to the Earth in bulk properties, should lack clear evidence of lithospheric recycling found on Earth. Models proposed to date (e.g., 1,2) have led to the conclusion that ridge-push or gravity-sliding forces cannot overcome the fault plane friction that results from the weight of the overriding plate on the subducting plate. The most desirable model would explain the initiation of subduction at many points in the Earth's history, as well as pinpoint the salient differences from Venus that render the case for venusian subduction much less obvious.

We have considered the possibility of initiating subduction by the thermal subsidence of a diapir located immediately below the trench. The structural model consists of an elastic lithosphere atop an anelastic thermal boundary layer, which in turn overlies an infinite fluid substrate. The density contrasts among the layers are assumed to result solely from temperature differences. Because the boundary layer is cooler and denser than the substrate, a diapir begins to grow downward from the interface between these fluids. The source region for this diapir, taken to be spherical, is modelled as a cone located directly above the diapir. Following the development of Whitehead and Luther (3), we derive an expression for the maximum radius achieved by the diapir before it pinches off and sinks into the substrate. At separation the compressive stress transmitted to the overlying elastic plate should be nearly maximized. We estimate this stress, and find it to be roughly two orders of magnitude less than the compressional strength of the plate for both Earth and Venus. The conclusion is that a sinking thermal diapir of the size generated by an unstable thermal boundary layer cannot generate sufficient viscous drag on a lithospheric plate to initiate subduction. It appears that a larger horizontal scale of convective motion would be required.

We explore the possibility that large scale compositional stratification in planets can generate such convective motions. Primitive mantle material is expected to have both a higher Fe/Mg and more radioactive heat producing elements than mantle which has previously melted to generate crust. Mantle with higher Fe/Mg has a larger density. If a layered planet consisted of these two types of mantle material, perhaps corresponding to the upper and lower mantles of the Earth, then the combined density differences due to composition and thermal expansion could create episodic overturn of the mantle in the following way. Compositionally denser material in the lower mantle will heat up due to radioactivity and become thermally less dense than the upper mantle. Then large scale overturn would occur. Once it is in the upper mantle, the compositionally denser, more radioactive material will cool because it loses heat more efficiently than when it formed the lower mantle.
Cooling will make it denser and it can again sink to form the lower mantle, completing one cycle of large-scale overturn.

A simple model is developed to examine this mechanism. Temperatures within two convecting layers are calculated using energy conservation in which the heat flux is related to thermal boundary layer thicknesses and the temperature differences across them. For layered thermal convection, the thermal boundary layer thicknesses are calculated from the appropriate thermal Rayleigh number for each layer. The rate of heat production in the more primitive mantle material is assigned a constant value corresponding to the amount needed to create the Earth's present surface heat flux (4). Temperature as a function of time in each layer is calculated by numerical integration. When the lower layer becomes less dense than the top by an amount that depends on a critical Rayleigh number, the two layers are adiabatically interchanged. The thermal evolution is allowed to continue in this new material configuration until the layering again becomes unstable. If such large-scale overturns were not considered, the thermal evolution for a this case would be as illustrated in Figure 1. The evolution when the possibility of mantle overturn is included is shown in Figure 2. Several overturns are observed to occur on geologically significant timescales.

It is conceivable that such dramatic events might stress lithospheric plates to the extent necessary to induce trench formation and the development of new subduction zones. Differences between Earth and Venus that may be relevant to this model have not yet been identified.

References: (1) D.P. McKenzie, in A.G.U. Ewing Series 1, 57, 1976. (2) D.L. Herrick and E.M. Parmentier, Rep. Planet. Geol. Geophys. Prog., 1990. (3) J.A. Whitehead Jr. and D.S. Luther, J. Geophys. Res. 80, 705-717, 1975. (4) D.L. Turcotte and G. Schubert, Geodynamics, 1982.

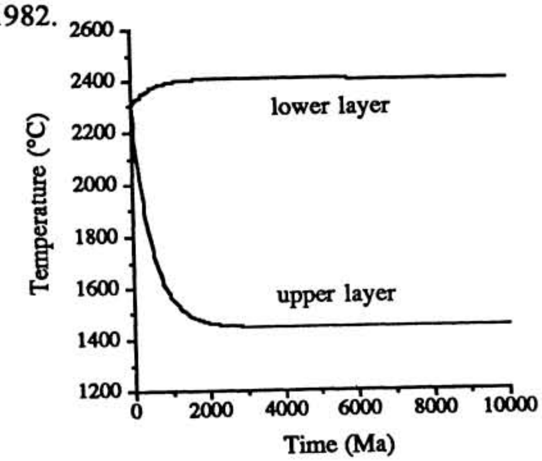

Figure 1. Thermal evolution calculation for a two-layer mantle neglecting large scale overturn. Both layers start out at 2300 °C, and the lower layer is compositionally 2.9% denser than the upper layer. A constant viscosity of 10^{22} Pa-s is assumed. A steady-state temperature structure is achieved after a few billion years.

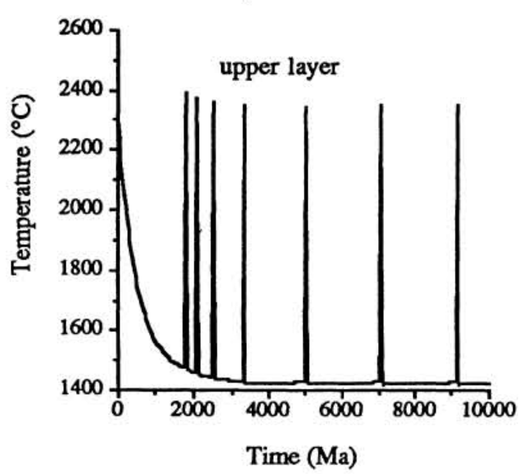

Figure 2. Thermal evolution of the upper layer, allowing for mantle overturns at a critical Rayleigh number of 10000. All other parameters are the same as in Figure 1. The upper layer is defined here as the layer that is on top at a given time, so that discontinuities in temperature reflect the fact that different material assumes the identity of the upper layer after each overturn. A plot of the lower mantle temperature would be somewhat of a mirror image of this plot.