THE FORMATION OF WRINKLE RIDGES ON VENUS VIA CLIMATE CHANGE: A THERMOMECHANICAL FINITE ELEMENT ANALYSIS. Andrew J. Dombard (rew@wurtzite.wustl.edu), Sean C. Solomon, Mark A. Bullock, Roger J. Phillips, and David H. Grinspoon, 1 Dept. of Earth & Planetary Sciences, Washington University, Saint Louis, MO 63130, 2 Dept. of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd., NW, Washington, DC 20015, 3 Dept. of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 426, Boulder, CO 80302.

Introduction: Climate changes on Venus may have tectonic repercussions. For example, changes in atmospheric greenhouse gases and radiative properties of the clouds, due to volcanic outgassing, may generate surface temperature excursions lasting many hundreds of Myr, with magnitudes approaching 200 K [1]. As these surface temperature changes diffuse into the interior, the material will accordingly expand or contract, producing climatically induced thermal stresses that can reach upwards of 100 MPa [2]. While often sufficient to deform the near-surface rock, this stress state has no preferred horizontal orientation, although it can be augmented by regional stresses, giving it a preferred direction. Such a mechanism has been postulated for the formation of the wrinkle ridges on Venus [3], features ubiquitous to the lowland plains.

Solomon et al. [3] used a simple elastic model to describe the mechanical response of the shallow lithosphere to surface temperature change. Here, we extend this model by employing an uncoupled thermomechanical, finite element analysis to examine the stress and strain distributions with depth and in time. In this model, thermal stresses are limited by a plastic yield strength, and/or relaxed towards a stress-free state by time-dependent ductile creep. We use the same surface temperature profile as in [3], and discuss how this model predicts that wrinkle ridges formed via shallow thrust faulting (a discussion not permitted previously). Input parameters are also varied, in order to identify those parameters that most strongly affect plastic strain at the surface, the most easily identifiable consequence of this mechanism that can be observed in Magellan imagery.

Surface Temperature Profile: The profile is calculated from an atmospheric model that tracks the sources and sinks of greenhouse gases during a volcanic event, and includes the effect of clouds [1]. A plains-emplacing volcanic history is approximated by an abrupt increase in flux, followed by exponential decay with an e-folding time of 100 Myr. The integrated volume is equivalent to a global layer 500 m thick. Under this model, this volcanic history results in a temperature increase of ~60 K over 100-200 Myr, a plateau in surface temperature for 300-400 Myr, followed by a decrease of ~110 K over ~100 Myr. The accompanying thermal stresses are thus expected to be compressive then tensile [3].

Fixed Plate Analytic Model: For this analysis, we employ a fixed-plate boundary condition, because it is assumed that each individual column of material is surrounded on all sides by neighboring columns of similarly deforming material. The inability of the material to horizontally expand or contract results in generation of stresses: \( \Delta \sigma = -E \alpha \Delta T(z,t)/(1 - v) \), where \( \Delta \sigma \) is differential (horizontal minus vertical) stress (positive stresses are extensional), \( E \) is Young’s modulus, \( v \) is Poisson’s ratio, \( \alpha \) is the linear thermal expansion coefficient, and \( \Delta T(z,t) \) is temperature change, a function of depth, \( z \), and time, \( t \). The thermal stresses depend on depth only in the sense that the temperature change depends on depth, because under a fixed-plate condition, a thermally stressed block of material cannot apply any tractions to vertically adjacent blocks of material. (As will be shown below, viscous and plastic strains can alter the vertical distribution of stress.) The fixed-plate condition will not be satisfied locally around a forming wrinkle ridge; however, we are presently concerned with the continuum response of the near surface to thermal stresses.

The elastic model of [3] employed a free-plate condition with no plate bending, to approximate, though not model, stress release around wrinkle ridges. (Tractions can be transmitted in a free plate, so near surface stresses will decrease as a temperature change diffuses deeper into the material.) This approximation is not needed here, because stress-releasing mechanisms (creep and plasticity) are included.

Finite Element Model: We use the commercially available MARC finite element package (MARC Research Corp., Palo Alto, CA) to perform an uncoupled thermomechanical analysis. The term “uncoupled” is employed because while the thermal solution affects the mechanical response, mechanical deformation does not affect the thermal solution. That is, advective terms are assumed negligible, a reasonable assumption because strains are small (a temperature change of the order of 100 K and a thermal expansion coefficient of \( 10^{-5} \) results in strains of the order of 0.1%). Because there is no lateral dependence in the modeled thermal or mechanical response, the finite element mesh is a single column, 15 km deep.
**Thermal Simulation.** The sides of the mesh are restricted to no heat flux, while a flux of ~75 mW m$^{-2}$ is applied at the bottom. This flux, and an assumed conductivity of ~3 W m$^{-1}$ K$^{-1}$, results in a linear thermal gradient of 25 K km$^{-1}$, a fairly high gradient expected for Venus [4]. A thermal diffusivity of 1 mm$^{2}$ s$^{-1}$ is assumed. The variable surface temperature is imposed as a top boundary condition. Results from this simulation are used as input in the mechanical simulation.

**Mechanical Simulation.** A density of 2900 kg m$^{-3}$, a surface gravity of 8.87 m s$^{-2}$, and an atmospheric pressure of 95 bars provide “overburden” stresses. Initial stresses are adjusted to equal the overburden and produce zero differential stresses at the start of the simulation. Thermal stresses are produced via temperature changes and a (linear) thermal expansion coefficient of 10$^{-5}$.

An elastoviscoplastic rheologic model, an extension of Maxwell viscoelasticity, is used. Total strain in elastoviscoelasticity is a linear summation of the elastic, viscous, and plastic strains. For the elasticity, we adopt a Young’s modulus of 65 GPa and a Poisson’s ratio of 0.25 [see, e.g., 5]. For the viscosity (to simulate solid-state ductile creep), we adopt parameters for power-law flow determined specifically for application to Venus from a thoroughly dried sample of Maryland diabase [6]. Plasticity, a continuum approximation of discrete, brittle faulting, is based on “Byerlee’s rule”. We assume an angle of internal friction of 40°, and a cohesion of 10 MPa. This cohesion is selected to be intermediate between the strength of intact igneous rock and the cohesion against frictional slip along a pre-existing fracture.

**Results:** In these simulations, climate-induced changes in surface temperature occur on a time scale sufficiently long that thermal stresses appear to be applied almost uniformly with depth, at least at our time resolution (the diffusion time for 15 km of material is < 10 Myr). Slowing the thermal propagation by decreasing the diffusivity results in more sluggish application of the thermal stresses at depth; however, stresses and associated strains at the surface are unchanged.

The distribution of strain also reveals details of the style of wrinkle ridge formation. The thermal stresses are taken up as elastic strain. If the plastic yield strength is exceeded, any additional strain is plastic. At the surface, plastic strains are zero in compression, and only approach ~0.06% in extension, as much of the tensile stress goes into unloading unrelied compressive stresses. That is, for this set of input parameters, wrinkle ridges are not predicted from the thermal stresses alone. However, larger thermal stresses or reduced resistance to plasticity (i.e., a lower cohesion) can result in greater amounts of plastic failure.

Acting concurrently, ductile creep relaxes stress, converting elastic strain to creep strain. This process generally occurs more rapidly at depth, where temperatures are highest. Consequently, the surface zone of active plastic failure tends to be separated from a deep zone of appreciable creep by a relatively stable elastic region (see Fig. 1). (A lower, potentially more plausible thermal gradient [4] would only result in expansion of this elastic region.) This phenomenon strongly indicates that, presuming wrinkle ridges formed as a result of thermal stresses, their creation likely did not involve folding of the lithosphere. (Lithospheric folding requires a ductily weak substrate to accommodate deflections in a strong surface layer.) Instead, these simulations are more consistent with a shallow thrust fault mode of formation, with the periodicity provided by local stress release.

**Discussion:** This model demonstrates the time-dependent, continuum behavior of a planetary surface subjected to climate-induced temperature change. It indicates that the magnitude of the thermal stress and the resistance to faulting most strongly control surface deformation, and that shallow thrust faulting is the preferred mechanism for wrinkle ridge formation on Venus, although a more sophisticated finite element analysis is needed to directly model their creation.


![Fig. 1. Differential stress versus depth at two different times. The curve at ~50 Myr shows how stresses are applied almost uniformly, with lower stresses at depth resulting from ductile creep. Because the plastic yield strength is not exceeded, the stable, elastic region extends to the surface. At ~550 Myr, the elastic region lies between the surface plastic and deep creep zones.](image-url)