THE IMPORTANCE OF BRITTLE DEFORMATION IN MODELS OF ICY SATELLITE TECTONICS.

M. T. Bland[1] and W. B. McKinnon[1], [1]Department of Earth and Planetary Science and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130.

Overview: One of the greatest challenges in simulating planetary tectonics is in formulating a continuum model of brittle deformation that realistically reflects the physical behavior of the lithosphere. Here we describe a case study (folding of an ice lithosphere) that illustrates some of the uncertainties in modeling plastic (i.e., brittle) deformation. The choice of cohesion, yield criterion, and plasticity theory (i.e., associated or non-associated) can change the simulated deformation amplitudes by more than an order of magnitude. While the results are specific to this case study, the implication apply to models of planetary tectonics in general.

The Nominal Model: Our numerical experiment consisted of a visco-elastic-plastic finite element model of plane-strain contraction of an ice lithosphere, as described in [1]. The domain was 80 km long, 24 km deep, with square, 167-m elements. Viscous and elastic parameters were appropriate for ice I. Plastic deformation was modeled with a Drucker-Prager yield criterion with a nominal cohesion of 3.4 MPa and an angle of internal friction of 30^o. The thermal gradient was imposed through the viscosity structure, the nominal strain rate was 10^{-13} s^{-1}, and maximum strains were 10%. A small, random initial topographic perturbation was imposed on the surface to allow folding to initiate. The result of each simulation was long-wavelength folding of the lithosphere. Such a model can be used to infer the conditions of the lithosphere at the time observed folds (like those on Europa) were formed [1], but only if the mechanical properties of the lithosphere are properly simulated. Below we discuss how these properties can affect simulations of planetary tectonics, using our simulations of folding as a case study.

The Role of Cohesion: One of the most fundamental (and the best constrained) parameters controlling the plastic behavior of the lithosphere is the cohesion (often defined as the shear stress required for sliding in the absence of normal stress (e.g., [2]). The cohesion of rocks and ice can be measured experimentally, but the relevance of those measurements to large scale tectonics is uncertain (e.g., [3]). The cohesive strength of ice has been measured to be 1 MPa, but may actually be much less [4]. The effect of cohesion on simulated tectonics is profound. Figure 1 illustrates that, for large thermal gradients, an order of magnitude change in cohesion (say from 1 MPa to 10 MPa) results in roughly two orders of magnitude change in fold amplitude.

The Yield Criterion: The choice of yield criterion also strongly affects the results of tectonic simulations. Models of geologic deformation commonly use a Mohr-Coulomb (MC) yield criterion. MC-like criterions are often numerically approximated by Drucker-Prager (DP) yield criterions, which result in smoothly varying yield envelops in stress-space. The approximation is not exact, however, and the modeler must choose whether the DP criterion should inscribe the MC envelope (i.e., underestimate some parts of the envelope), or circumscribe the MC envelope (i.e., overestimate some parts) (see [5]).

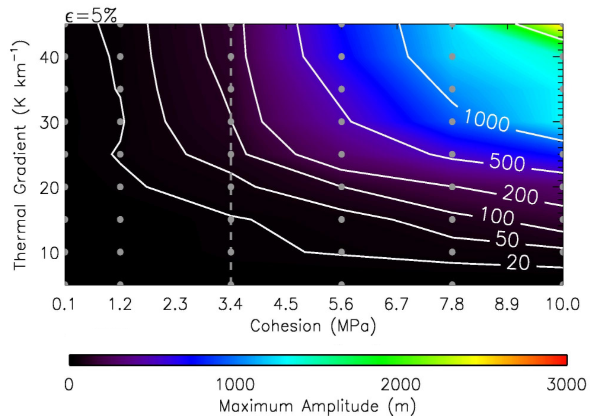

Figure 1: Contours of maximum fold amplitudes as a function of cohesion and thermal gradient. Grey dots indicate a set of simulated conditions.

Figure 2 shows the strength of the lithosphere (parameterized as the square root of the second deviatoric stress invariant (J_2)) for two identical simulations, but using the two different DP assumptions (inscribed and circumscribed). Also shown is the surface deformation after 5% strain for the two simulations. Using the circumscribed criterion results in fold amplitudes roughly four times larger than the inscribed criterion. Distinguishing which simulation is more "correct" is not straight forward. Rather, the two assumptions should be viewed as end-member cases, with the true lithospheric behavior somewhere in between.

Associated or Non-Associated Plasticity: Models of plastic deformation must also choose whether the plasticity is "associated" (the plastic strain rate is a function of the yield criterion) or "non-associated" (the plastic strain rate is independent of the criterion). Associated models of plasticity are generally simpler, but can result in unrealistic dilation (i.e., volume increase); non-associated plasticity can avoid large dilations but requires additional unknown parameters.

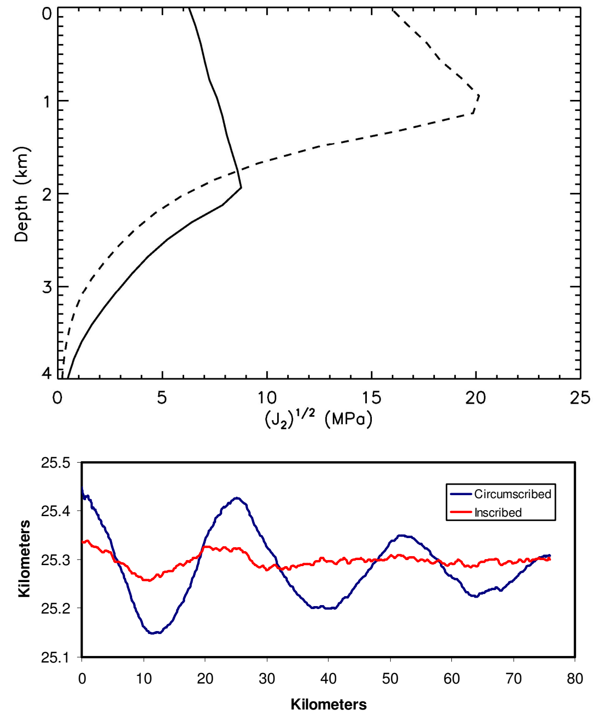

Figure 2: (Top) *The strength profile of the lithosphere for two different approximations of an MC criterion: (solid) inscribed DP, and (dashed) circumscribed DP.* (Bottom) *The surface deformation resulting from the two simulations shown above.*

Like the yield criterion, the choice of associated or non-associated plasticity strongly affects the simulation results. Figure 3 shows the lithospheric strength ($(J_2)^{1/2}$), and stress for two simulations: one with associated plasticity (in this case requiring definition of a dilation angle), and one with non-associated plasticity. Most notable is that (in this formulation, with dilation angle of 10^o) the associated case is nearly incompressible, while in the non-associated case the intermediate stress nearly equals the maximum stress. Also shown is the surface deformation for each simulation after 5% strain. Fold amplitudes are roughly three times greater when non-associated plasticity is used.

Non-associated plasticity is generally more realistic, but the results depend strongly on the dilation angle as shown in Figure 4. Large dilation angles (compressible behavior) result in modest fold amplitudes while small dilation angles (incompressible) result in large amplitudes. Maximum amplitudes vary by an order of magnitude or more.

Summary: While numerical models of tectonic deformation can provide valuable insight into the geophysical evolution of planetary bodies, care must be used when choosing (and reporting) how plastic (i.e., brittle) behavior is simulated. In the case study described here the choice of cohesion can result in a two orders of magnitude change in fold amplitude. The details of the yield criterion, and the choice of associated or non-associated plasticity have a factor of 3-4 affect on fold amplitudes, while the choice of dilation angle (in the non-associated case) changes fold amplitudes by nearly an order of magnitude.

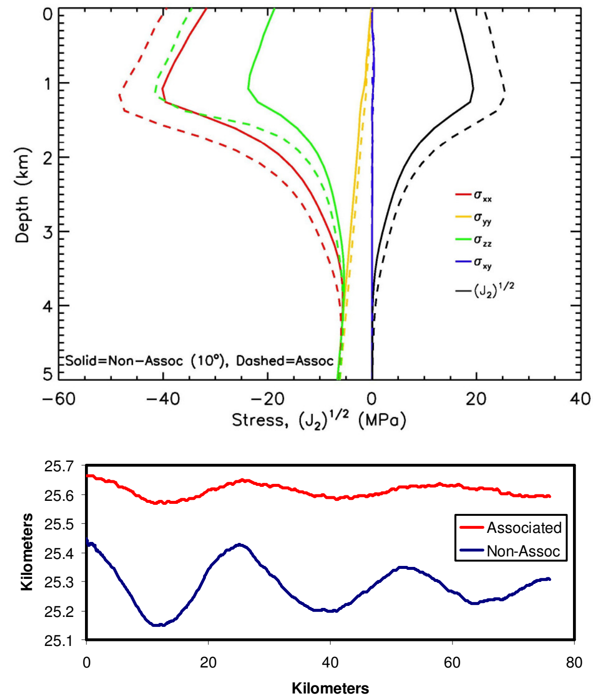

Figure 3: (Top) *Strength profile for two identical simulations, but one with non-associated plasticity (solid), and one with associated plasticity (dashed).* (Bottom) *Surface deformation after 5% strain for the two simulation shown above.*

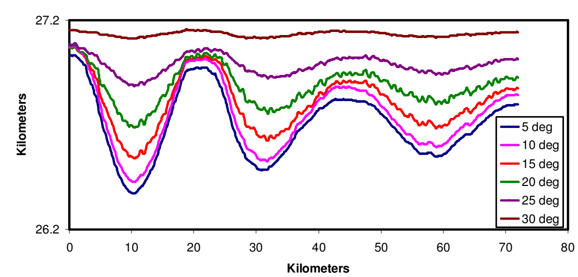

Figure 4: Surface deformation for a suite of identical simulations using non-associated plasticity with different dilation angles. Smaller angles result in more incompressible behavior and larger amplitudes.

References: [1] Bland M. T. and McKinnon W. B. (2010) *LPS XLI*, Abs. #2298. [2] Ranalli G. (1995) Chapman and Hall, pp. 97. [3] Kanamori H. (1994) *Ann. Rev. Earth Planet. Sci.* 22, 207-237. [4] Beeman et al. (1988) *JGR*, 93, 7625-7633. [5] Owen D. R. J. and Hinton E. (1980) Pineridge Press, pp.220.