STRIKE-SLIP ON EUROPA: VISCOELASTIC MODELING OF TIDALLY DRIVEN DISPLACEMENT.

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Background: Since the initial discovery of displacement along Astypalaea Linea [1], strike-slip displacement (SSD) along cracks has been shown to be common and widely distributed on Europa [2,3,4]. The observed strike-slip displacement can be explained by the diurnal cycle of tidal stress, via a process analogous to walking [2]: A given crack opens, then shears along its length, then closes, and then the tendency to shear back is resisted by friction. Thus, over each Europan day, the crack takes a step in strike-slip displacement.

The tidal walking model was developed under the assumption that opening and closing of the crack is uninhibited by coupling to the deeper interior, as would be the case if the crack penetrates through to liquid water. Such penetration is consistent with the observation that SSD is found only along faults lined by double ridges [4], which may be formed by pumping of oceanic slush during diurnal tidal working of the crack [5]. Thus tidal walking suggests that many cracks in Europa's crust penetrate through to the ocean.

During initial formation of a crack, overburden pressure within the ice below the surface may limit downward propagation of the crack. However, quantification of such a limit is difficult because of uncertainty about the dynamics of the cracking process and the character of the material [6]. Hence, evidence that cracks have penetrated to liquid [5,7] does not imply a specific value to the ice thickness. It is puzzling that an Icarus editorial [8] incorrectly cited [5] as having argued for ice being only 1 km thick. Tectonic evidence suggests that cracks penetrate to the liquid ocean, not any particular value of the thickness of the ice.

While the tidal walking model assumes a decoupling layer under the crust, it is reasonable to ask whether a viscous layer, such as the warmer ice under the cold brittle-elastic "lithosphere", would be adequate to allow SSD. Indeed, a numerical model [9] with a crack that penetrated only a couple of km into much thicker ice showed SSD growing just as fast as in [2]. This result seemed to show that the prevalence of SSD did not necessarily imply that cracks penetrate to the liquid ocean. Moreover, viscous heating in the warm ice below the crack was invoked to explain ridge formation without requiring crack penetration to the ocean [9].

However, in that numerical model [9], the rapid rate of SSD was imposed as an input condition, using the rate derived in [2] for very different model conditions. In [2] the crack penetrated to the liquid layer, so it was inappropriate to impose that rate in [9] where the crack only penetrates part-way down through the ice. The computed heating rates in [9] are only possible because the driving force was assumed to supply however much energy was needed to maintain the specified speed against the strong viscous resistance.

We have begun to model the response to tidal strain of a crack in Europa's shell, and the crust, taking into account the visco-elastic resistance of the ice. Crustal distortion and shear displacement along the fault are output, not specified as input. In this way we may begin to understand the range of sub-surface models that may be consistent with observed strike-slip faults. In addition to the thickness of the ice layer and crack depth, the response to tidal driving depends on assumptions about the temperature profile with depth, the rheology of the ice (as a function of temperature), and the conditions under which friction allows or resists slip along the walls of the fault. None of these characteristics is known for Europa, but continued modeling of strike-slip displacement and comparing results with observations may constrain the range of possibilities. Here we summarize a first attempt at constructing such numerical simulations.

Numerical modeling: The general principle of tidal walking has been developed analytically, yielding successful predictions about the resulting strike-slip displacement [2]. However, to extend our understanding of the process, to explore the interrelated processes involved in stressing a three-dimensional system with a complicated and uncertain rheology, and to consider cases where the crack penetrates only partway through the ice, a numerical simulation is needed. We have applied the finite-element code Tekton [10] to the following system, which contains the essential elements needed for the tidal walking process: A rectangular ice crust floats on a liquid layer, with a vertical crack penetrating down from the surface. We assume that the state of the system at any time is independent of the position along the direction of the crack, simplifying the finite-element simulation.

The material is assigned a viscoelastic rheology based on best evidence for water ice, with the temperature dependent non-linear (i.e. non-Newtonian) relationship between stress and strain rates (e.g. [11] and elastic parameters the same as [2]. In contrast, a newtonian relationship was assumed in [9]. We use a conventional temperature profile in Europa's ice crust, increasing liearly with depth from the surface temperature of 100°K, down to a depth (here taken as 2 km) that represents the base of a layer dominated by thermal conduction. Below that depth we assume a uniform temperature of 260°K representing a convection zone down to the base of the ice. The actual temperature profile is certain to be more complex and variable, but given the uncertainty in the actual rheology, the assumed temperature profile is a relatively unimportant factor.

Tidal walking is a cumulative response of a crack in the ice to the periodic change in the strain state of the region around it, which is part of the global response of the ice shell of Europa to the continually changing shape of the underlying tidal figure, giving a strain amplitude ~10^{-5} [5] assuming a global ocean exists. For our simulations, we model the regional strain by driving displacement of the simulations' boundary planes farthest from the crack in the 80 hr. sequence of tension, shear, compression, and reverse shear that generates tidal walking.

Results of initial simulations: We first confirmed that tidal walking generates SSD for the case of a crack penetrating completely through a relatively thin ice crust with a conductive (linear) temperature profile [2]. The viscous behavior near the base of the ice helps the walking process by inhibiting the material from snapping back when the crack opens during the tension phase, thus allowing net displacement with each cycle. Moreover, non-elastic relaxation over the adjacent region prevents the build-up of elastic stress which would inhibit tidal walking beyond a certain displacement. The SSD rate is a few km in ~10^4 yr. That rate is consistent with observed faults, the likely duration over which a crack may be actively worked, and a plausible formation time for ridges [7].

For cases with only partial penetration though the ice, overburden pressure plays a critical role. Deeper than a couple of hundred meters, the walls of the fault are always squeezed together under compression. (This issue is not critical where a crack penetrates to liquid, because the fluid neutralizes the overburden.) In order to have the alternating locking and unlocking required for tidal walking, we need to specify a maximum compression value that will allow the fault surfaces to slide freely. In general, we find tidal walking is negligible, unless this critical parameter is tuned to a very specific value, selected specifically so that the locking-unlocking cycle occurs only near the bottom of the crack. Thus walking is possible for a crack that penetrates only as far as warm ice in a thick crust, but only under special conditions, which would be coincidental and improbable, but cannot be ruled out. Such special conditions are not needed for SSD if the crack penetrates to the underlying ocean.

In these simulations, including all cases that yield significant SSD, viscous heating was negligible, less than a few degrees. The periodic strain amplitude throughout the material represented in all cases is comparable to the global scale tidal distortion. Thus throughout most of the volume of the material the heating rate is no greater than the general background tidal heating of Europa's ice shell. Even in the case that generated the most local heating at the base of the crack (a hypothetical case with parameters chosen to artificially speed up SSD), comparison of the heating rate with the rate of conduction away from that site yields a maximum temperature change of 3°K. Our results contrast with the considerable heating reported in [9], largely because the viscous resistance that dissipates energy also slows the displacement.

Further simulations may shed light on conditions under which friction and viscous dissipation from strike-slip displacement might play a role in local heating on Europa, just as they will expand our understanding of the range of conditions under which tidal walking might operate. The initial cases reported here suggest that tidal walking likely yields SSD only if cracks penetrate to a liquid layer. Previous reports of significant tidal heating during SSD on Europa, and any attempts to apply such results to Enceladus should be interpreted with caution. Our numerical model confirms the viability of the tidal walking mechanism under conditions likely on Europa.

Acknowledgments: J. Melosh and E. Turtle provided the tectonics simulation code Tekton and helped us use it. Alyssa Sarid and Rory Barnes provided technical support and fruitful scientific discussions. L. Prockter provided comments that resulted in substantial improvements. This work is supported by NASA's Outer Planets Research program.

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