CRACKING UP-WARDS: AN INVESTIGATION INTO THE MECHANICAL FAILURE OF ICE ON EUROPA. C. C. Walker[1] and B. E. Schmidt[1], [1]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, 311 Ferst Drive, Atlanta, GA 30332 (cat.walker@eas.gatech.edu).

Introduction: The observation of water plumes from Enceladus' south pole of Enceladus [1] and the recent discovery of putative vapor plumes on Europa [2] hint at the possibility of deep, ice-penetrating fractures in--and subsurface reservoirs below--the thick ice shells of the outer planet satellites. The eruptions have been linked to tensile forces stemming from tidal effects that control the opening of the rifts [3, 4, 5]. The study of crack penetration is highly dependent on assumptions of ice shell thickness (and subsurface liquid water ocean), surface and interior stresses, and ice properties. Tidally-induced stresses for Europa and Enceladus, specifically, have been studied in terms of their ability to open rifts to sufficient width in order to allow for escape of subsurface material.

Enceladus' and Europa's surfaces are both riddled with fractures, which betray a long history of geophysical activity. With an ~100 km deep ocean atop a silicate interior (e.g. [6], [7], [8]), Europa is an intriguing target for astrobiological study. Ice cycling may provide nutrients to the putative Europan ocean, and pores, basal cracks, and grain boundaries in the ice may serve as harbors for life. Such ice shell-ocean interaction must occur over geologically short timescales in order for Europa to be habitable. One way in which this can occur is through disruption of the ice shell. Thus, areas of active geology have strong implications for the recycling of the ice shell, and the habitability of the ice shell itself.

Background: For subsurface water to erupt onto the surface, a surface- or bottom-initiated crevasse (crevasse is defined here as a crack in the ice that does not extend the full thickness of the ice) must vertically propagate and penetrate the entire shell thickness to create a channel from the liquid reservoir below to the surface. We consider two processes in the formation of terrains observed on Europa: the propagation of fracture systems and collapse/fragmentation.

Propagation of a basal fracture system: Initiation and penetration of a surface crevasse is driven by tensile forces at and near the surface. At depth, these forces are opposed by the overburden pressure from the weight of the ice (glaciostatic pressure). Tensile stresses at the surface and within the brittle surface layer must be great enough to overcome the overburden pressure at the base to allow for full penetration of the shell. Here, we investigate the role of highly-fractured materials in fracture propagation; i.e., we take into account the highly-fractured nature of the icy shells, and the possible interaction of rifts, a phenomenon observed both on Earth's ice shelves and in other media, such as wave-breaker walls, airplane propellers, Arctic permafrost, mud flats in Death Valley, and others [9]. Specifically, we model the propagation of cracks that initiate at the bottom of the brittle shell, and illustrate the parameters that might affect their propagation height towards the surface. We model water pressure within the crack dependent upon reservoir size and depth below the surface. The work of [10] showed that it is likely that Europa's chaos terrains formed after the surface above a perched water pocket flexed and allowed cracks to initiate at the base of the ice lid. We investigate the likelihood that the entire ice lid over water could break and the effect of water pressure on that process.

Fragmentation of collapsed lids: Recent work suggests that chaos terrain formation may include a collapse phase, and that the eventual appearance of the chaos terrain is determined in part by the fracture density within the background terrain [10]. In studying the size distribution of fragments in Europa's chaos regions, it is possible to back out physical properties of the ice, such as material strength and cohesion properties and most importantly, the energy necessary to create a fragmentation event using fragmentation theory. Fragmentation theory describes the breakage of a body into several pieces (e.g. [11]). Dynamic fragmentation modeling in elastic and plastic solids is primarily a statistical study of material behavior, and is categorized into three stages: (1) crack nucleation; (2) crack propagation; (3) fragment coalescence.

Through this approach, using our calculated size distributions from remote imagery, we determine time-to-failure for a given set of fracture patterns and estimate the strain rate profile and fracture energy released during the collapse event. Results from this analysis are important in recognizing the timescale and vigorousness of crustal overturn on Europa.

Implications for stress and energy in the ice shell: We use fragment size ob-servations to determine stress and energy associated with fracture array evolution and chaos terrain for-mation.

Fracture array propagation: The interaction of rifts was observed in both the Amery Ice Shelf and Larsen Ice Shelf on Earth in surface and basal rifts [12], which, along with studies of other fractured media mentioned previ-ously, showed that the existence of other fractures nearby can affect and individual rift's propagation. This raises the question of the significance in the difference between the isolated crack model so often used versus modeling shell-penetrating cracks as part of an array of rifts. We follow the approach of [13], using results from [14] to model closely-spaced fractures on Enceladus and Europa. The result of multiple fractures is to reduce the net stress intensity factor concentrated at the rift tips, an effect that increases with smaller spacing. Because of this reduction in stress concentration, a larger tensile stress is necessary to allow for propagation deeper into the ice than has been previously suggested in single-fracture models, and we illustrate the likelihood of through-penetrating fractures from the base of the ice shell.

Fragmentation events: Different patterns of fragmentation can produce different estimates of material properties and the energy required to produce the fragmentation event, examples of which are shown in Fig. 2 and defined in [11]. A characteristic length scale is based on the local balance of kinetic and fracture energy and layout of fragments. In this theory, we consider a body to break apart into a certain collection of fragments. Each fragment takes kinetic energy as the object breaks up, and this energy goes into local expansion and rigid-body motion. Local kinetic energy then contributes to further failure. A characteristic length scale for fragmentation is based on the local energy balance of potential, kinetic, and fracture energies in a given material [11]. Through the balance of energies, [11] determined the energy driving fragmentation in two dimensions based on material density, strain rate, surface energy, propagation speed, and fracture toughness.

We used a simple statistical model [11] and a cohesive zone model to test the use of fragmentation theory on collapse features. We now present our estimate of the strain energy released and time-to-failure in chaos terrain collapse through application of fragmentation theory and iceberg capsize analysis. This approach allows us to understand the mechanism behind dynamic collapse of the ice shell as well as its potential for mixing material in the upper ~5km of the ice shell downward, providing input to a recycling ice shell. Thus, in determining the fragment size distribution, and the dynamic history of that ice, we will constrain physical properties of the ice shell, stress necessary for fracture feature formation, energy required for chaos formation, and their respective implications for Europa's habitability.

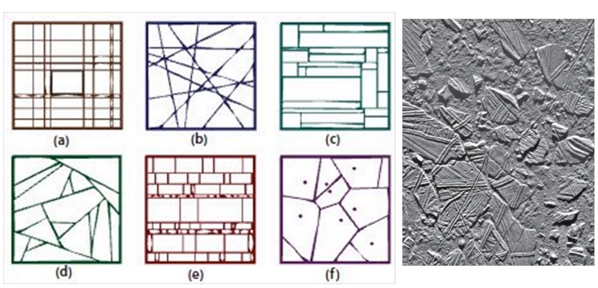

Figure 1. *Right: Common geometric fragmentation patterns, picture from [9]; Left: PIA01403 - chaos region on Europa taken by Galileo in 1998; (a) Random lines of equal length; (b) Pickup Sticks/Mott fragmentation; (c) Sequential Segmentation; (d) Same as (c) with conditions on shortest dimension; (e) Randomly distributed/oriented segments; (f) Voronoi-Dirichlet fragmentation. Each type is associated with specific length scales and fragmentation types.*

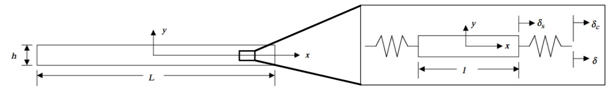

Figure 2. *Schematic illustrating core idea embodied in the cohesive zone model (Drugan, 2001). Bar (left) represents elastic material. Enlarged box (right) shows a prospective fragment within the elastic material for which the elastodynamic equations can be solved. δc and δs are its relative displacements with respect to the rest of the bar and to its neighboring fragments.*

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