Explosive energy considerations for Europa’s chaos terrain geometries: Implications for plume generation. C. C. Walker¹, B. E. Schmidt², C. J. Chivers³, ¹Woods Hole Oceanographic Institution, Department of Applied Ocean Physics and Engineering, Bigelow Laboratory, 98 Water St., Woods Hole, MA 02543, cwalker@whoi.edu; ²Cornell University, Department of Astronomy, 404 Space Sciences Building, Ithaca, NY 14853, britneys@cornell.edu; ³Woods Hole Oceanographic Institution, Department of Applied Ocean Physics and Engineering, 98 Water St., Woods Hole, MA 02543, chase.chivers@whoi.edu

Introduction: Europa is thought to be recently or currently geologically active [1], and over the last ~decade, several different observational techniques suggested the presence of water vapor plumes emanating from the surface of Europa [2-8]. The source was initially suggested to be long surface fractures in the area of interest [2], the opening of which would be controlled by tidal stress, similar in fashion to the tiger stripes of Enceladus [9, 10]. The distinct observations so far, across a variety of positions, combined with null results during other observing times, imply that the plumes may not be persistent; they are independent of orbital position; and/or that the successful detections correspond to exceptionally strong events [3]. It may be that non-detections simply represented lower abundances of plume material [11]. That the putative plumes, assumedly, emanate from geologically active regions spurs our interest in how they might be related to chaos terrains, a Europa surface terrain type that has been suggested to be recently/currently active [1]. The likelihood that shallow water [1, 12, 13] might underlie these features, and is dynamically involved in their formation, is the basis for our inquiry into whether or not observed plume activity and spatiotemporal distribution could be related to chaos formation and evolution.

Background: The possibility that active cryovolcanism and plumes could be present on Europa has been considered previously [14, 15] to explain the existence of low-albedo surface features. In that work, the greatest height expected for modeled Europa plumes was ~100 km, with eruption velocities of ~600 m/s for gas-dominated plumes; heights between 1-25 km for more realistic values of plume composition. Initial observations of the putative plumes [2-8] suggested heights of ~200 km and eruption velocities of ~700 m/s, which would require surface temperatures of over 130 K above Europa’s ~100 K mean surface temperature. The amounts of water implied by each of the observations were similar in magnitude. The locations attributed to the plume sources lend themselves to the notion that they are not tied to a single location on the surface; two 2014 observations occurred at similar latitudes to the 2012 observation, though at different sublongitude points; the third 2014 observation was located at a location closer to the equator, near Pwyl crater, as was the 2016 detection [5]. The expectation that the activity correlated with orbital location was determined to be invalid [4], suggesting that the large, currently-remotely-observable plumes may be transient phenomena. Of course, the possibility that smaller plumes (~10s of km) may exist that are tidally-modulated has been suggested [11], and such smaller-scale plumes have been postulated to be the source of dark deposits along some of Europa’s lineaments, margins of some chaos terrains, etc. [14-16].

The youngest features (observed thus far) on Europa are its ubiquitous chaos terrains. While most are found in the mid-to-low latitudes, chaos terrains are spatially distributed around the surface. It has been suggested that the eventual appearance of the varied chaos terrains is determined at least in part by the pre-existing fracture density of the localized background terrain [1]. It is likely that their formation involves a surface deformation phase, and an eventual background phase, with the ice lid collapsing into the melt lens, driving potentially violent mixing upon its rupture [1, 12]. While questions as to what mechanism drives formation of the water lens in the first place remain, we propose that, agnostic to this unknown process, the breakup of any material into pieces of its former self can be characterized in terms of its energetics to determine properties of the processes that went into creation of the resulting system, using fragmentation theory. We hypothesize that by characterizing the size distribution of surface fragments, we can better constrain the physical properties of the ice shell ice, in addition to characterizing the magnitude of the energy required to create the features we observe. Upon collapse or disordering of a material, as is evident to have happened from chaos morphology, explosive energy is transformed into several primary components released below, within and above the surface [17].

Approach: We postulate that the likely processes associated with chaos formation, their global spatial distribution, and timescales over which their formation occurs, support the likelihood that plume activity may be related to stages of the chaos formation lifecycle, rather than related to tidally-controlled deep ice shell rifts.

The release of buried explosive energy and its impacts on fragment size, crater/retarce and surrounding morphology are well-studied, in particular in the field of weapons testing and resource mining/blasting efficiency
The physics of buried blasts have already been invoked on the planetary scale as well, for example, in describing cometary outbursts, short-lived phenomena involving jets of mass loss from the near-surface [19-23]. Several comet outbursts have been unambiguously linked to quasi-circular sinkholes and surface debris subsequently visible on the surface [e.g., 23]. Several models of the distribution and speed (kinetic energy) of the expelled gas-dust jets suggest an explosive origin for the activity, either by surface collapse or buildup of subsurface pressure due to crystallization of ice [21, 22]. These are processes that we might expect leading up to or during Europa’s chaos formation as well. On Earth, deformation of an ice lid or “roof” over a water-filled cavity can be caused by overpressure in- or withdrawal of a fluid encapsulated in the subsurface, due to an overloading or absence of hydrostatic support leading to subsurface fracture propagation at the base of the lid [e.g., 24, 25]. Once the lid is significantly damaged, structural integrity of the lid is sufficiently lowered, and overpressure or drainage in the subsurface cavity may drive fractures further upwards and cause a surface rupture. On Earth, the ice lid-to-cavity ratio is large, and basal breakup leads to catastrophic collapse of the lid. Terrestrial observations of such events have shown that water and icy material is churned up and ejected during the process. While trajectories of such water and icy bits in terrestrial events are small, consideration of differences between surface gravities and atmospheres of Earth and Europa alludes to the producibility of significant material plumes at the latter. We suggest that there are two phases within the process of chaos formation that may be capable of producing such large “clouds” of material: (1) initial breach or rupture of the surface, during which the subsurface water pocket is “popped” by mechanical failure of the overlying lid, depressurizing explosively; and (2) following initial lid fragmentation, “icebergs” developed during formation capsize and launch particles into the atmosphere.

To estimate how such processes could produce an observable plume event, we must understand the system geometry and energy contained in it.

Methods: To examine these possible energy scenarios, we use (1) observations of Europa’s surface and geometry of chaos terrains by Galileo, (2) analytical models of material fragmentation under explosive loads, and (3) a numerical model that represents ice as a matrix of closely packed, bonded circular particles that interact through elastic-frictional forces [12, 26].

Fragment size distributions of several chaos terrains are used to determine energy required to produce them, using fragmentation theory. We use the Grady energy balance model [27], which derives from calculating local energy equilibrium at the fragment scale. For example, the energy required to produce the average fragment size in Conamara Chaos is $0.05 - 0.35$ J/m, dependent upon an assumption of ice yield strength. Depending on assumed energy partitioning and transfer efficiency, we find that resultant plume heights can reach between 10-150 km.

Second, when a large iceberg forms during rupture, it has the potential to capsize. There is some evidence to suggest that we observe some cap sized fragments. In this scenario, energy is again transferred into the water and icey matrix material. Capsize energy can be calculated as:

$$P_{E_{i-w}} = \rho g H^2 \varepsilon (1-\rho_i/\rho_w)/2.$$  \hspace{1cm} (1)

Here, $\rho_i$ and $\rho_w$ are ice density, $g$ is acceleration due to gravity, $H$ is initial iceberg thickness, and $\varepsilon$ is the ratio of initial iceberg width to thickness. Dependent upon assumed values, capsize can produce “splash” plumes on the order of 10s of km.

Results: In this study, we explore two end members of the likely source events: first, the release of explosive energy resulting from the collapse phase of chaos formation; second, we assess the effects of secondary iceberg overturn/capsize on water motion in the near-surface. We will discuss the explored parameter space and the limitations of cavity shape and size on the likelihood of observable plume creation.