ACTIVE CHAOS REGIONS AS THE SOURCE OF WATER VAPOR PLUMES ON EUROPA. C. C. Walker and B. E. Schmidt, NASA Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109 (catherine.c.walker@jpl.nasa.gov) 2Georgia Institute of Technology, School of Earth and Atmospheric Sciences, 311 Ferst Dr., Atlanta, GA 30332 (britneys@eas.gatech.edu)

Introduction: Europa and Enceladus are active ocean worlds that are prime targets in the search for life in the solar system. While Enceladus has demonstrated constant activity since the initial detection of its south polar ice-vapor plumes [e.g., 1], it is only recently that potential plume-like activity has been observed at Europa [2, 3]. The eruptions on both bodies have been linked to tensile forces stemming from tidal effects that control the opening of the rifts [4, 5, 6]. Rift opening is highly dependent on assumptions of ice shell thickness (and subsurface liquid reservoir depth), surface and interior stresses, and ice properties.

Enceladus’ plumes emanate from the Tiger Stripe fractures at its south pole [1], which are long, deep linear fractures [5, 6]. The putative plume activity on Europa has initially been attributed to the opening of large tensile fractures in the southern hemisphere [2], based upon low-resolution images of Europa’s surface fractures and tidal modeling. This theory is relying upon the assumption that, like Enceladus’ Tiger Stripes, these Europan fractures reach a subsurface ocean or reservoir. However, there is no evidence yet that shows fractures at Europa’s surface can fully penetrate the ice shell thickness, and as such the assumption that Europa’s plumes are produced through the same mechanism as observed at Enceladus may not be appropriate. This is an especially important point when noting that other areas on the surface, the chaos regions, have been identified as active or recently-active. We suggest these regions may be more likely to be the source of the observed plume activity.

Europa’s chaos terrains are the youngest features found on Europa, overlying and interrupting older fractures and ridges. They likely formed above shallow water lenses formed by melting in near-surface regions of the ice shell [7]. While most are found in the mid- to low latitudes, chaos terrains are spatially distributed around the moon, as are the putative plume sources. Recent work suggests that the eventual appearance of the chaos terrain is determined in part by fracture density within the background terrain [7]. It is likely that their formation involves a dramatic deformation and eventual collapse of the ice lid above the forming melt lenses along with potentially violent mixing upon its rupture [7, 8]; this process is likely analogous to the collapse of terrestrial ice shelves.

Approach: It is our goal with this study to determine the likelihood that what was observed using Hubble Space Telescope represented observations of dynamics associated with chaos terrain formation and evolution, rather than continuous tidally-controlled geysers. Ice dynamics expected within chaos terrains could better explain why the plumes were not consistently observed at times expected by tidal models. Additionally, the location of detected plumes on the surface is near spots of known chaos terrain.

Fig.1. Left: cartoon shows expected ice lid response to water-filled cavity. Right: Early results from particle model showing (half of) deforming ice lid. Blue line denotes water level assuming hydrostatic equilibrium.

“Ice dolines” describe depression features observed in Antarctic ice [9], often found nearby surface meltwater ponds. Field measurements have suggested that such features form due to the existence of a water-filled cavity in the subsurface [e.g., 10]. Deformation of an ice lid or “roof” over a 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 [e.g., 11, 12]. This lessens structural integrity due to propagation of subsurface fracture arrays [e.g., 13, 14]. Once an ice lid is sufficiently fractured and ruptures, the water within the lens may create sufficient pressure within fractures to drive water upwards, aiding vertical fracture propagation (Fig. 1). Of course, whether or not the cavity is over- or underpressurized makes a difference in the resulting topographic signature, but can also derive from the local topography [7]. Where the ice lid-to-cavity ratio is large, i.e., the cavity exists relatively close to the surface, basal breakup leads to catastrophic collapse of the lid in both cases. As observed in collapses of such
ice-capped melt reservoirs on Earth, in addition to large floating sections of glacier ice, water and icy material can be churned up and ejected during the process (e.g., Fig. 2). While trajectory profiles of the material in terrestrial collapses are small, consideration of differences between Earth and Europa’s surface gravity and atmosphere alludes to the production of significant material plumes at the latter. To estimate the likelihood that we could observe such materials, we must understand the geometry of the system and the energy contained in it.

![Image](image1.jpg)

Fig. 1. Snapshots from video of Jakobshavn glacier collapse into an ice mélange-filled fjord, where basal fractures lead to detachment of icebergs (top) and their capsize, which causes icy material and water from below to be ejected into the air (bottom). Credit: Jason Amundson, U. of Alaska Fairbanks.

**Methods:** We use observations of Europa’s surface by Galileo, analytical experiments and a numerical model that simulates ice as a matrix of interacting particles [8, 15] to predict breakup and overturning during chaos formation and ice-water dynamics. It was shown for terrestrial ice that highly-damaged ice, as might be expected for the ice shell of Europa, can be accurately modeled as a granular material [e.g., 16]. Our numerical model represents ice layers as a matrix of closely packed, bonded circular particles that interact through elastic frictional forces. Each individual ice particle obeys Newton’s equations of motion and are allowed to rotate and interact with adjacent particles through elastic collisions and bonds, and frictional buoyancy and gravitational forces. Additionally, these ice particles respond to forcing by water “particles” below to demonstrate ice-water interactions at the interface, a new function of the model. We can use the observed geometry of chaos terrains (e.g. 7, 17) as well as models of rising geothermal plumes [e.g. 7, 18] and post-collapse refreeze of the water source to calculate the hydrostatic forces and overburden pressure acting upon the ice and water source. Thus, we can model the motion of water through any crack for the ice and water source.

**Results:** We will present analytical and numerical results demonstrating that chaos formation/activity is a likely source region for the putative Europa plumes. While the tensile through-fracture argument depends upon the moon being at the right orbital position to explain the opening of the rifts due to stress, this chaos solution relates to a process that can take place throughout the orbit with little dependence on or enhancement from tides, and may better explain the putatively short duration of Europa’s plumes. We explore two end members of the likely source events: first, the expulsion of overpressurized water through basal fracture propagation and roof collapse; second, we assess the effects of secondary iceberg overturn/undersize on water motion in the near-surface. We will show the limitations of cavity shape and size on the likelihood of observable plume creation. Both shape and size of the cavity, in addition to its location within the ice shell (depth of “roof”), have effects on the energy of the system, which in turn places limitations on the energy available for fracture propagation and water expulsion through cracks and iceberg capsize.