FLEXURAL DYNAMICS AND FLOW IN NEAR-SURFACE ICE-WATER SYSTEMS AS DRIVERS OF PLUME ACTIVITY ON EUROPA. C. C. Walker1,2, B. E. Schmidt3, and L. C. Quick4, 1Woods Hole Oceanographic Institution (98 Water Street, Woods Hole, MA 02543, cwalker@whoi.edu), 2NASA Headquarters, Office of the Chief Scientist (300 E Street SW, Washington, DC 20024), 3Georgia Institute of Technology, School of Earth and Atmospheric Sciences (50 Ferst Street, Atlanta, GA 30332, britneys@eas.gatech.edu), 4NASA Goddard Space Flight Center, Planetary Geology, Geophysics, and Geochemistry Laboratory (8800 Greenbelt Road, Greenbelt, MD 20771, lynnae.c.quick@nasa.gov).

Introduction: The dearth of craters on the surface of Jupiter’s moon Europa indicates that it is geologically young. Several recent studies point to possible plume activity [e.g., 1-4], suggesting that Europa is currently active. Here, we undertake a coupled analog and remote observational study paired with analytical modeling to investigate the ways in which subsurface water affects the surface that we observe. In particular, we investigate the likelihood that Europa’s plume origins lie in features other than its long, linear fractures. Initially the plume was suggested to be sourced from linear surface fractures [1], similar in fashion to the tiger stripes of Enceladus [5, 6]. However, tensile fractures that penetrate from the surface to the subsurface ocean remain unproven [7]. We argue it is more likely that the plumes emanate from geologically active regions. One terrain type that has been recently/currently active is chaos terrain [8]. The likelihood that shallow water [8, 9] underlies these young surface features, and is involved in their formation, inspires our inquiry into whether or not the observed plume activity is produced via chaos formation and evolution.

Background: Here, we combine observations of two phenomena observed at Europa to determine both their individual evolution and their relationship to each other: chaos terrain and cryovolcanic plumes.

Chaos terrain. Observations suggest that the youngest features on Europa are its chaos terrains, which are spatially distributed on Europa. Chaotic terrain may form following melting in near-surface regions, and it is likely that their varied appearance is in part determined by the pre-existing fracture density of the local background terrain [8]. Chaos formation involves a surface deformation phase, resulting in the eventual collapse of the ice lid into the melt lens, along with potentially violent mixing upon rupture [6, 7].

Plumes. Modeled Europa plume heights range from 1-25 km for more realistic plume compositions to ~100 km for gas dominated plumes [10, 11, 13]. Plume observations [1] suggested heights of ~200 km and eruption velocities of ~700 m/s, which would require surface temperatures of 130 K above Europa’s ~100 K mean surface temperature. The locations attributed to the plume sources lend themselves to the notion that they are not tied to a single location on the surface. The expectation that the activity correlated with orbital location was determined to be invalid [2]; it has since been suggested that the plumes may be transient phenomena [3, 4]. However, it remains a possibility that smaller plumes (~10s of km), under the observation limit, could be tidally-modulated [12]. Such smaller plumes have been suggested as the source of dark deposits along some of Europa’s lineaments, margins of some chaos terrains, etc. [10, 11, 13].

Approach: Here, we argue that the geological and hydrodynamical processes associated with chaos formation, their geological youth, global spatial distribution, and timescales over which their formation occurs, match better with observed plume activity than large-scale, tidally-controlled linear fractures.

Flexural dynamics of ice over water. The deformation of ice surrounding a water-filled cavity, such as the melt lenses hypothesized for chaos formation [8, 9], can be influenced by both (1) overpressure (meltwater inflow, refreezing) and (2) withdrawal (drainage, additional melt above hydraulic head, bubbles) of a fluid encapsulated in the subsurface, which relate to an overloading or absence of hydrostatic support [e.g., 14, 15]. Overpressurization may drive hydraulic fractures upwards and cause rupture of the lid and drainage of the cavity. Conversely, a gathering of bubbles along the roof causes lessened hydrostatic support, enabling collapse inwards. Where the ice lid thickness-to-cavity ratio is large, basal breakup through either overpressure or withdrawal leads to catastrophic collapse [9]. One terrestrial analog that we study are “ice dolines”, enclosed water pockets that are formed by surface meltwater drainage into the ice layer, appearing as circular, domed features prior to breakup (Fig. 1).

Relationship to plume predictions. Terrestrial observations of collapse in ice-water systems have shown that water and icy material is churned up and ejected. While trajectories of water and icy particles in terrestrial events are low, the difference in surface gravity and atmospheric pressure between Earth and Europa suggests that this process would produce large material plumes at the latter. We suggest there are three phases/sub-phases within chaos formation that may be produce material plumes: (1) rupture of the surface, either by (a) overpressure OR (b) loss of hydrostatic...
support, during which the subsurface water pocket is exposed to space; and (2) following initial lid fragmentation by either process, “icebergs” developed during formation capsize and launch particles into the atmosphere (Fig. 2).

Figure 1. Top: doline on George VI ice shelf in Antarctica. Bottom: topography from ICESat-2.

Figure 2. Processes considered here: plume expulsion via ice lid breakup during chaos formation.

Methods: To determine if chaos formation could be the source of plumes on Europa, we use (1) observations of Europa’s surface and the geometry of chaos terrains from Galileo, (2) surface observations of terrestrial dolines and ice shelf breakup by ICESat-2 (altimetry for topographic evolution measurements) and Landsat imagery; (3) analytical models of ice fracture, energy release, and plume formation; and (4) a numerical model of ice as a matrix of closely packed, bonded particles that interact through elastic-frictional forces [9, 16]. Analytic solutions describing the flexure and stress regime of the isolated cavity may be adapted from the thin-plate treatment of various lithospheric flexure problems associated with oceanic plate volcanism. We initially consider ice as elastic, noting that our estimates are likely to be upper bounds, as viscous relaxation tends to reduce stresses associated with elastic response.

Figure 3. Initial results showing estimated plume heights (in km, y-axis) for an overpressurized cavity as a function of depth from the surface (x-axis) and efficiency of energy transfer in the ice fracture process.

Results: We explore three end member models for possible chaos formation/plume source events: (1) the expulsion of overpressurized subsurface water through basal hydraulic fracture propagation and roof collapse (e.g., Fig. 3); (2) the release of underpressurized subsurface water through roof collapse after loss of hydrostatic support, and (3) the effects of secondary iceberg overturn on water/matrix motion at the surface. We will present cavity shape and size constraints and their bearing on the creation of observable plumes. Both cavity size and shape, in addition to its the cavity’s depth within the ice shell (depth of “roof”), have efects 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.