CHEMICAL COMPOSITION OF ERUPTED BRINES ON EUROPA.

Elodie Lesage[1], Samuel M. Howell[1], Mariam Naseem[2], Julia W. Miller[1,3], Justine Villette[4], Marc Neveu[2,5], Mohit Melwani Daswani[1] and Steven D. Vance[1]. [1]NASA Jet Propulsion Laboratory, California Institute of Technology (elodie.lesage@jpl.nasa.gov). [2]University of Maryland College Park. [3]University of California, Los Angeles. [4]Laboratoire Planétologie et Géosciences, Université de Nantes. [5]NASA Goddard Space Flight Center.

Introduction: Liquid water reservoirs in Europa's icy crust, if they exist, could represent accessible liquid water bodies in the outer solar system. Previous studies have demonstrated that freezing cryoreservoirs might trigger eruptions due to the pressurization associated with volume change as liquid water expands to become water ice [1, 2]. Cryovolcanic eruptions could bring water and non-water materials to Europa's surface, informing about the subsurface composition and activity, and potentially transporting biosignatures. Locating and characterizing potentially stored and erupted brines is key for the exploration of ocean worlds and the search for habitable environments and life beyond Earth.

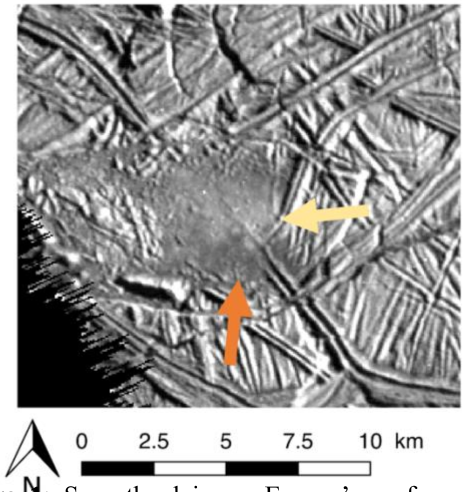

Figure 1: Smooth plain on Europa's surface whose morphology is consistent with eruption of liquid cryolava [1]. The yellow and orange arrows indicate two areas of different albedos, which may have been emplaced by two eruptive events of brines of different composition. NASA Galileo image 9352r.

Here, we aim to numerically model the coupled chemical evolution and pressurization of freezing brines stored in Europa's ice shell to predict the composition of erupted cryolava. We use current best estimates of the oceanic composition [3] as starting compositions, which could be particularly relevant in the case where liquid reservoirs are emplaced by the intrusion of oceanic material in the ice shell. This composition varies with time, as salts concentrate during freezing [4], which could lead to erupted brines of varying composition depending on the reservoir frozen fraction when the eruption is triggered. This could explain the variations of albedo observed around features potentially associated with cryovolcanism, for example smooth plains, as shown in Fig. 1.

Methods:

Cryomagma chemistry. Whether they are formed by in-situ melting [5] or intrusion of oceanic water [6], the best estimate for cryomagmatic fluid composition is provided by models of evolution of Europa's interior and ocean. We use five different cryomagma compositions corresponding to recent endmember estimates of Europa's ocean chemistry calculated by Melwani Daswani et al. [3]. An example cryomagma composition used in our model ("MC-Scale" from [3]), in wt.%, is 99.0% H_2O, 0.32% Na, 0.28% Cl, 0.16% bicarbonate, 0.21% sulfate, 0.027% K, 0.013% Ca, and 0.002% Mg.

The freezing of oceanic brines is modeled using the software PHREEQC [7] to obtain the composition of the aqueous solution, formed ice and precipitated salts as a function of the temperature (see [4] and abstract #1672 by Naseem et al. for details). Depending on the freezing rate, i.e. the temperature gradient between the reservoir and the surrounding ice, freezing takes place in different regimes [4]. If the freezing is slow and the chamber is well mixed, salts are rejected from the formed ice and continue to participate in the solution chemistry (equilibrium freezing endmember). If the freezing is fast, or if the chamber is poorly mixed, salts are entrapped in the formed ice (fractional freezing endmember). Here, both equilibrium and fractional freezing are simulated and resulting compositions are used as input in the cryoreservoir pressurization model described below. This way, we can transition from fractional to equilibrium freezing as freezing slows down with time.

Model principle. Previous studies [1, 2] demonstrated that internal overpressure increases in potential freezing cryoreservoirs as cryomagma transitions to the less-dense solid phase. The critical freezing time τ_c required to break the reservoir and trigger an eruption is a function of the reservoir chemical and physical parameters (see example in Fig. 2 for a spherical 500 m radius reservoir located 2 km below the surface and filled with pure liquid water [1, 2]). The cryomagma chemical evolution during freezing affects the solution and formed ice densities, and can make the critical freezing time different from what was calculated by previous studies. We thus need to model the cryomagma and ice compositions and internal overpressure as coupled variables. By doing so, we will be able to predict a realistic critical freezing time to trigger eruptions, as well as the cryomagma composition when the eruption begins.

Numerical procedure. We implemented a three-layer (ice-brine-ice) 1D model to simulate a reservoir embedded in the ice shell. The thickness of each layer varies to accommodate heat flux at the ocean interface, at the reservoir top and bottom and at the surface. We use the finite differences method to solve for heat and energy transfer. Keeping track of the amount of energy leaving the reservoir allows us to link the thermal state of our reservoir with the PHREEQC data. At each time step, we update the cryomagma frozen fraction and we vary the composition of the formed ice and remaining aqueous solution based on the PHREEQC output. We modify the solution freezing temperature and the liquid and solid densities accordingly. Using the cryomagma frozen fraction through time, we calculate the internal overpressure in the reservoir and the tangential stress it generates on the wall. If the tangential stress exceeds the ice tensile strength, the ice is fractured and an eruption starts. As soon as the ice Maxwell time is exceeded, we consider that the reservoir cannot erupt anymore (as demonstrated in [2]) and we end the simulation. Finally, as an output of the model, we obtain the composition of the erupted brines at each eruption.

Cyclic eruptions. After the first eruption, the cryoreservoir may keep freezing and trigger several successive eruptions as described in [8]. We added the possibility to continue freezing and trigger several eruptions to our numerical simulation so that we can observe the evolution of erupted brines composition from one reservoir through time.

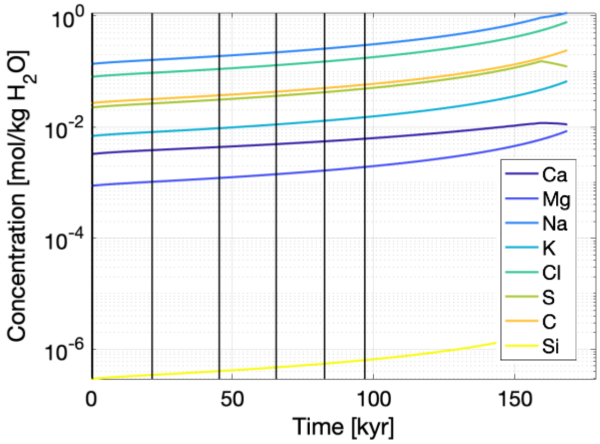

Figure 2: Composition evolution of a freezing cryomagma. Fifty eruptions take place between each vertical black line. We simulated the slow (equilibrium) freezing of the oceanic composition "MC-scale" from [3].

Preliminary Results: We show on Fig. 2 the composition evolution of a cryomagma freezing at equilibrium (slow freezing endmember). Each vertical black line on Fig. 2 represents a 50-eruption cycle. For this simulation, we used the input oceanic composition "MC-scale" from [3] and a 2 km radius reservoir embedded 2 km deep in a 25 km thick purely conductive ice shell. Salts concentrate in the solution throughout the freezing and their concentration is multiplied by 2 to 4 between the first and last eruption. We predict a total erupted volume of 30 km^3 before the reservoir stops being active approximately 100 kyr after its emplacement.

Other signatures of the reservoir presence are also predicted by our energy-conservative model. 50 kyr after the reservoir emplacement, we observe a surface thermal anomaly of +0.7 K. In the case of a 10 km thick ice shell, we also observe a 1 km local thinning of the ice shell below the reservoir after 150 kyr.

These results will inform the upcoming missions JUICE (ESA) [9] and Europa Clipper (NASA) [10] on the spectral, thermal and geophysical signatures that could indicate the presence of shallow sub-surface cryoreservoirs and provide information on their activity.

Acknowledgments: Portions of this research were carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). This work was supported by NASA's Solar System Workings program (grants #80NM0018F0612 and #80NSSC20K0139). The PHREEQC routine is available at https://github.com/MarcNeveu/frezchem.

References: [1] Lesage E. et al. (2020) *Icarus*, 335, 11336, [2] Lesage E. et al. (2022) *The Planetary Science Journal*, 3(70), [3] Melwani Daswani et al. (2021) *Geophysical Research Letters*, 48(18), [4] Naseem et al. (submitted) *The Planetary Science Journal*, [5] Kalousová et al. (2016) *Journal of Geophysical Research: Planets*, *121*(12), 2444-2462, [6] Craft K. L. et al. (2016) *Icarus*, *274*, 297-313, [7] Parkhurst, D. L. (1995). *User's guide to PHREEQC: A computer program for speciation, reaction-path, advective-transport, and inverse geochemical calculations*, [8] Lesage et al. (2021) *Icarus*, 361, 114373, [9] Grasset O. et al. (2013) *Planetary and Space Science*, 78, 1-21, [10] Howell S. M. and Pappalardo R. T. (2020) *Nature Communications*, 11, 1311.