EUROPA'S EXSOLVED PROTO-OCEAN.

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Introduction: Jupiter's moon Europa hosts a >100 km deep liquid water ocean beneath its 3 – 30 km ice shell [e.g. 1]. Key to understanding the past and present habitability of Europa's ocean is its composition and evolution. Water, solutes and possible oxidants in Europa's ocean may have been indigenous to Europa's accreting material and produced endogenously by chemical reactions, or delivered in time by meteoritic influx. The young surface age of the ice <40 – 90 Myr [e.g. 2] suggests periodic resurfacing, and that a mechanism for surface – ocean material exchange through the ice shell may exist. Sufficiently large bodies (0.5 – 5 km, for ice shell thicknesses 5 – 40 km) would puncture through with a frequency of ≲250 Myr [3], and surface features are suggestive of subduction-like processes in geologically recent times [4], although geodynamic models find that subduction of the ice shell may be severely limited at present [5].

Here we explore an endogenous origin for Europa's earliest ocean and constrain the components that may have been dissolved in it and may yet remain. Specifically, we consider ocean build-up by volatile exsolution from volatile-bearing minerals, caused by thermal metamorphism during planetary differentiation and thermal excursions in the rocky interior caused by Europa's tidal-orbital evolution in the Jovian system.

Methods:

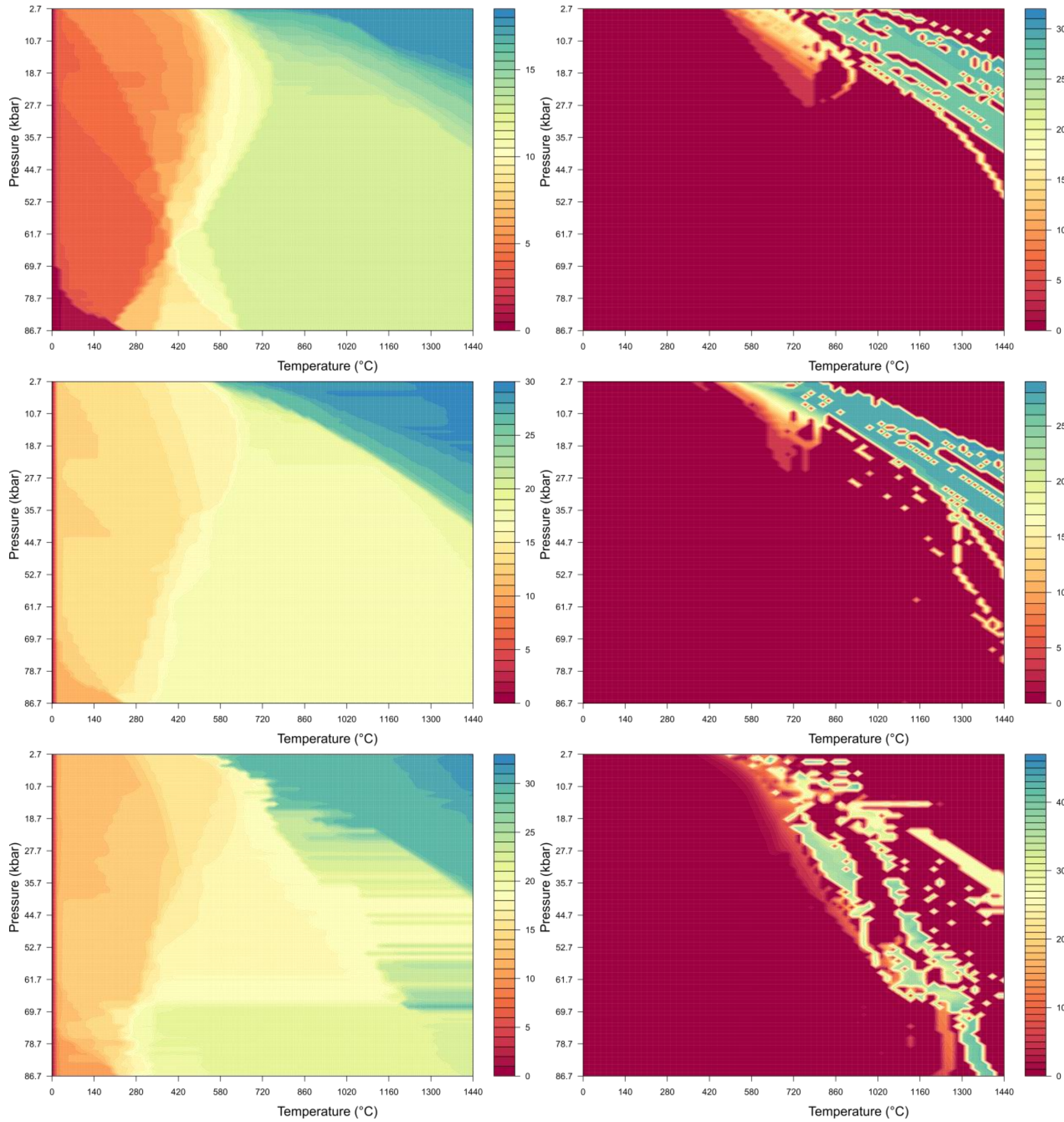
Bulk composition of Europa. Constraining the composition of Europa's exsolved ocean requires that we make simplifying assumptions about the initial bulk composition of the accreted body. We have built a simple accretion model (AccretR; https://github.com/mmelwani/AccretR) to constrain the composition of a variety of satellitesimals (CI, CV, CM, CR, CK and CO chondrites, and comets of 67P/Churyumov-Gerasimenko's composition). We also consider the thermal evolution of endmember CM and CI bulk compositions.

Composition during thermal evolution. We use Gibbs energy minimization code Perple_X to compute the compositional changes of Europa's rocky interior. Perple_X calculates the state of thermodynamic equilibrium of a system, phase relations, mineralogy, and elastic and caloric properties [7], together with the Deep Earth Water thermodynamic database [e.g. 8] to obtain volatile (i.e. liquid and gas) composition.

For each resulting bulk composition considered above, we model a 0-dimensional heating pathway throughout the solid interior; we examine a 1D column spanning the radius of undifferentiated Europa composed of an arbitrary number of vertical cells that experience isobaric heating. (In the figures below, temperature increases from left to right. The rock column undergoes petrologic changes and volatiles may be exsolved from the destabilization of volatile-bearing minerals.)

Approximating the build-up of an ocean. Volatiles exsolved from volatile-bearing minerals in the rocky interior do not necessarily migrate into the ocean: some proportion may be retained as a separate phase but in equilibrium with the rock. We explore different amounts of volatiles retained in the interior versus the amounts that migrate to form the proto-ocean (retained-to-extracted ratio, or R/E). Thus, we do not assume any particular mechanical properties pertaining to the rocky interior, which could be completely permeable, partially permeable, or impermeable to fluid flow. Additionally, Europa's ocean accounts for ~8 – 10 % of its mass, so the upper limit of total mass extracted from the interior cannot exceed this amount.

Temperature limits of thermal metamorphism in Europa. Europa's interior composition and core – mantle differentiation are inferred by its measured and calculated density, size, shape and quadrupole gravitational coefficients. These data do not provide direct evidence, but it is widely held that the segregation of a dense, largely metallic body and a silicate-rich mantle was caused by the heat from accretion, radioactive decay and tidal dissipation within the solid interior. Geodynamic processes during Europa's evolution allowed the redistribution of elements into the core, mantle and ocean reservoirs. A number of sources could have supplied the energy and heat requirements for these processes. The decay of short-lived radionuclides ^{26}Al and ^{60}Fe in the accreting material could have supplied some of the heat to partially melt the silicate interior and segregate silicate and metal. Regardless of the source of heat, in order to produce eutectic Fe-FeS, a temperature of ~1250 K must be reached [e.g. 9], which sets the minimum temperature the interior of Europa experienced during differentiation, and the maximum temperature in our thermal metamorphism models before the onset of core formation.



Results in figure: Compositions of volatiles exsolved appear to have a larger dependence on the R/E ratio than the bulk undifferentiated composition. We illustrate this with three examples in the figure, which show the thermal evolution of (a + b) CM chondrite bulk composition, with R/E = 1:100; (c + d) CI chondrite with R/E = 1:100; (e + f) CI chondrite with R/E = 1;10. The first column shows the bulk cumulative volatiles extracted into the ocean in mass %. The second column shows the mass % of carbon in the extracted volatiles.

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