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Modelling possible chemical evolution pathways during crystallisation and re-mobilisation of brines in Europa's ice shell

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Constraining the composition of Europa's ocean is a vital step in understanding its geochemical evolution and habitability. Salts of potential endogenous origin have been observed on Europa's surface, indicating that ocean-surface exchange must take place, and hinting at a potentially rich record of ocean chemistry that both Europa Clipper and JUICE aim to study. New frameworks for understanding the relationship between endogenous ice-bound salts in Europa's ice shell and the composition of the fluid they originated from are therefore urgently required. Using a thermodynamic modelling approach, we explored the salt hydrate mineral assemblages produced across a wide chemical parameter space of hypothetical ocean compositions, where the abundances of possible major ions Na, Mg, Ca, K, Cl and SO₄ were varied independently over several orders of magnitude. Our aim was to identify ocean compositions compatible with observed ice shell mineral assemblages and provide a framework for interpreting improved estimates of ice shell mineralogy when available from upcoming missions. Informed by experimental studies, we explored a variety of equilibrium and fractional crystallisation scenarios.

We found that remarkably similar mineral assemblages form across our parameter space of hypothetical oceans, but that the presence of specific phases, such as Mg-chloride and N-sulfates, indicate important differences in the source fluid that could distinguish between geochemical evolution scenarios. For example, we found that for equilibrium crystallisation scenarios, Mg-chloride minerals only form from oceans where initial Mg > SO₄, regardless of the initial concentration of other ions. Because potentially endogenous Mg-chloride salts have been observed on Europa's surface, our models imply that these must form from an ocean where sulfate is less abundant than magnesium, provided that observed mineral assemblages have not experienced significant fractional crystallisation. For a subset of compositions, Na-sulfates do form at intermediate temperatures, but redissolve upon Na-chloride precipitation (Fig. 1). The identification of Na-sulfates and Mg-chlorides together in endogenous mineral assemblages would therefore indicate that some fractional crystallisation had occurred. Finally, we explored the expected composition of partial melts resulting from re-mobilised brines within Europa's ice shell. We show how very similar compositions of partial melts should be expected across a vast ocean chemical parameter space, unless heating is significant enough to mobilise less soluble salt phases such as sodium or calcium sulfates. Accounting for the compositional evolution of brines within Europa's icy shell will allow better understanding of ice shell processes, and more accurate constraints on Europa's ocean chemistry that can continue to be refined in response to new observations.

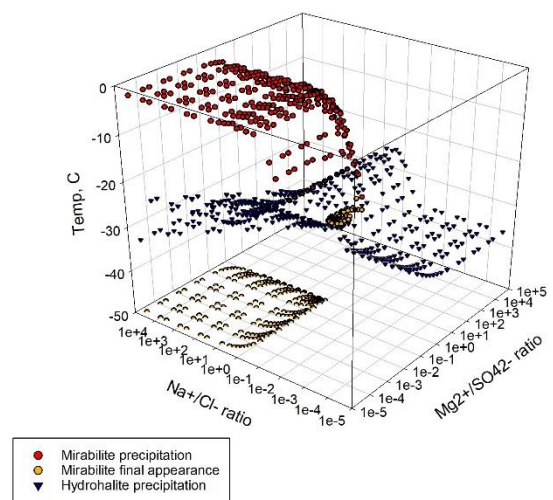


Fig. 1. Mineral precipitation as a function of temperature across Na-Mg-Cl-SO₄ parameter space.