ROLE OF HYDROTHERMAL GEOCHEMISTRY IN THE GEOPHYSICAL EVOLUTION OF ICY BODIES. J. C. Castillo-Rogez[1], D. L. Matson[1], J. S. Kargel[2], S. D. Vance[1], T. B. McCord[3], T. V. Johnson[1], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109. E-mail: Julie.C.Castillo@jpl.nasa.gov, 2 Department of Hydrology and Water Resources, Univ. of Arizona, Tucson, AZ. [3]The Bear Fight Center, P.O. Box 667, 22 Fiddler's Road, Winthrop, WA 98862.

Introduction: Clues that some icy bodies, such as Europa and Enceladus, could host liquid water at depth have prompted the development of chemical evolution models for these potential seas or oceans [*e. g.* 1, 2]. However current geophysical models for these icy objects have not included the consequences of hydrothermal geochemistry on the geophysical evolution of these icy objects. Hydrothermal alteration of the silicate phase results in the redistribution of major elements from the core to the hydrosphere. Importantly, this includes the long-lived radiogenic isotopes. Depending on the extent of the hydrothermal alteration of the silicate phase (surficial alteration of the core at its cool [3] vs. extensive hydration during the differentiation phase [4, 5, 6]) the models possible for these icy objects can be very different. Here we address some of the consequences of the geochemical changes resulting from hydrothermal activity in icy objects (meteorite parent bodies, icy satellites, Kuiper belt objects) and discuss the factors determining the extent of hydrothermal activity in these objects.

Chemical Consequences of Hydrothermal Activity

The interaction of "dry" silicates with water produces hydrated minerals and oxides [8], and leaches "mobile" elements that form salt hydrates, carbonates, chlorine and other water-soluble compounds. Such silicate "serpentinization" is accompanied by a significant release of heat, as well as H_2.

Leaching of the Long-Lived Radioisotopes: Expanding on what we already know from terrestrial environments, geochemical models of icy objects [1, 2, 9, 10, 11] show that the alteration of a chondritic core enriches the fluids in salt and carbonate compounds in the form of hydrates, the major species bearing magnesium, sodium, and potassium. Zolotov and Shock [1] show that in the extreme case of full leaching of the silicate phase potassium would be concentrated in Europa's ocean at a level up to ten times its concentration in the CV-chondrites. Structural evolution models of Europa's ocean [11, 12] show that a dense salt hydrate layer will settle at the interface at the top of the core. Related phenomena are apparent in some carbonaceous chondrites displaying veins of evaporite minerals [13]. These features may reflect the conditions near the interface of the core and hydrosphere in meteorite parent bodies. Under such conditions we expect the concentration of potassium to be as much as two orders of magnitude greater than in "primordial" material. Uranium and thorium can be very mobile in hydrothermal interactions. They tend to follow the behavior of potassium Uranium is also known to behave coherently with magnesium [14]. There are many examples in terrestrial hydrothermal areas (*e. g.* geysers, mid-oceanic ridges of enrichment of U- or Th- bearing compounds [*e. g.* 14, 15, 16]. Depending on the conditions, these metals could be concentrated as oxides at the surface of the core [5] or as salts at the bottom of the ocean.

Gas Production: Hydrothermal conditions also offer the prospect of gas chemistry. Enceladus's geysers and Titan's atmosphere indicate the production of compounds such as the production of molecular nitrogen from ammonia decomposition [17, 18] and of methane from CO or CO_2, analogous to terrestrial mid-oceanic ridges, volcanic areas associated with subduction zones [19], or hydrothermal areas [20]. Also note that ^{40}Ar produced from ^{40}K decay in the ocean can also be stored in the ocean in clathrate hydrates, as suggested by the stability field of that gas [18]. Radiogenic Xe and Kr isotopes, while not expected to be abundant enough to be of geological consequence, may also be stored in clathrates. Finally, ^{4}He, while commonly not considered to be a clathrate forming molecule, indeed does form a clathrate-like hydrate phase that could be a storehouse of radiogenic helium in large icy satellites [21]. These noble gases could be produced *in situ* within an ocean or icy shell from leached radioisotopes, or it could be carried from the rock mantle by rising aqueous fluids, or diffuse as separate fluid phases.

Implications: *(a) Heat Source Concentration:* In the most extreme case, the core of icy satellites strongly affected by hydrothermal activity could be depleted in long-lived radiogenic elements. The concentration of most of these elements in a relatively thin region at the interface between the hydrosphere and the core would constitute a significant heat source. Mechanisms for transferring this heat remain to be studied.

(b) Thermal Conductivity: standard icy satellites models consider a rock thermal conductivity of 3 W/m/K. However, the thermal conductivity of hydrated silicates, hydrates, and oxides are very different from typical rocks. Salts and clathrate hydrates have thermal conductivities that are lower by up to one order of magnitude than dry rock [*e. g.* 12]. On the other hand, oxides thermal conductivity can be higher, up to 80 W/m/K [22].

(c) Isolation of thermal Pockets: hydrate chemistry is very complex. An important point to be considered is

that different aqueous solutions freeze at different temperatures. For example, KCl (aq) freezes at 243 K versus 263 K for $MgSO_4$ [1]. Salt fractionation during freezing would result in compositional heterogeneity of the seafloor. For example, latitudinal variations in surface temperature might result in freezing from the poles to the equator and lead to the concentration toward the low-latitude regions of species with low-freezing points, such as KCl.

(d) Impact on Hydrothermal Circulation: Hydrated silicates as well as sulfur compounds released during hydrothermal interaction [23] tend to decrease rock permeability by precipitating in flow channels. A salt layer at the base of the ocean would also tend to limit the circulation between the ocean and the core. In other words, products released as a result of hydrothermal activity can counteract hydrothermal transport over the long term.

(e) *Future potential for radio-isotopic dating of cryovolcanic ices*: Kargel [24] previously considered the flux of radioactive isotopes of K and Rb into brines, icy crusts and possible oceans of icy satellites. The same schemes developed to date silicates and other rocky minerals can be utilized to date salts containing radioactive elements, especially considering the relatively low-temperatures for isotopic closure of these systems.

How much Hydrothermal Activity? The extent to which the processes mentioned above actually proceed in a given object depends on the extent and intensity of the hydrothermal activity. There are several possible contexts and locations for hydrothermal activity: (1) in planetesimals -- which already contained hydrated minerals when they accreted to form the icy objects [25, 26]; (2) in the upper layer of the rocky core -- which as it cools, contracts and cracks [3] (the long-term occurrence of this process is a function of the factors mentioned in the previous section); (3) during differentiation. In large satellites, accretion provides conditions for melting water and hydrating the silicate phase [23]. Short-lived radioisotope decay might also play a significant role in triggering differentiation and providing conditions suitable for silicate hydration taking place during differentiation [17, 18]. On the timescales for thermophysical evolution, differentiation is a relatively rapid phenomenon, but so is serpentinization. Meteorite parent bodies are expected to have formed early enough so that ^{26}Al played a significant role in their early history [25]. An icy body such as Enceladus or Ceres, forming as early as a meteorite parent body, is likely to undergo similar hydrothermal activity. If that body is broken apart, then it is reasonable to believe that part of its core will yield hydrated materials with veins of hydrothermally deposited minerals.

Prospects: Better modeling of hydrothermal activity (thermal and chemical) is crucial for assessing the long-term preservation of fluids in icy objects, and whether hydrothermal activity may be happening presently in satellites like Europa.

Coupling accurate geochemical and thermal evolution in objects affected by hydrothermal activity is a complex undertaking and might appear intractable considering the numerous, parameters involved in the modeling. However, the most important consequences of leaching long-lived radioisotopes from the silicate phase can be approached. It is possible to compare end-member models, depending on their degree of hydrothermal evolution. There is a trade-off between the degree of hydrothermal activity affecting the silicate during differentiation and the long-term evolution of the core. Focusing on Ceres, we investigate the role of localized heating in near-surface materials enriched in hydrates, including K-, U- and Th- salts. A possible outcome of this scenario is enhanced geological activity in regions with high concentrations of long-lived radioisotopes. In this case, Ceres's surface could be relatively young and active today. This possibility can be investigated by the *Dawn* spacecraft beginning in 2015.

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