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Modelling water-rock interactions in the subsurface environment of Enceladus. R. E. Hamp, S. P. Schwenzer, M. Fox-Powell, K. Olsson-Francis and V. K. Pearson, AstrobiologyOU, School of Physical Science, The Open University, Milton Keynes, MK7 6AA, UK (rachael.hamp@open.ac.uk)

Introduction: The subsurface of Enceladus is a potentially habitable environment, with a global subsurface ocean [1] and ongoing hydrothermal activity [2]. Geochemical reactions on Enceladus occur at the rock-water interface and reaction products are transported in the water column to the ice-ocean interface [2]. They are then ejected into space, *via* the plumes in the South Polar Region, and have been detected by instruments onboard the Cassini spacecraft. The analysis of these plumes and the ice grains in the E-ring have provided information on the internal chemical and physical conditions on Enceladus. Further understanding of the internal environment on Enceladus is crucial for assessing the moon's potential habitability.

Here, we present thermochemical modelling of the subsurface environment, from different starting conditions, to calculate a theoretical modern day ocean composition, and to assess the changes in ocean chemistry from water-rock interface to detection by Cassini.

Methods: From the data collected by Cassini [3,4], and estimates of the starting conditions of the subsurface ocean on Enceladus, we have modelled the interaction between the silicates and fluid at the ocean floor.

We have assumed the silicate composition is that of a CI carbonaceous chondrite [5], based on the analysis of the ice grains within the E-ring and the plumes, which suggests the presence of Mg-rich and Al-poor minerals [6] as well as organic species [7]. We then used thermochemical modelling (CHIM-XPT) [8] to predict the chemical composition of a sub-surface ocean in equilibrium with the silicates. We investigated two starting fluids of differing compositions over range of physical conditions:

Dilute NaCl Solution. This fluid composition was included to investigate the possibility that the ice shell of Enceladus was initially formed of pure water, and therefore represents the primary sub-surface ocean [9]. CHIM requires ions for charge balance; we used NaCl as the charge balance since both ions have been detected in the plumes of Enceladus and the E-ring of Saturn, and are assumed to be present in the modern day subsurface ocean. However, the concentration of NaCl added was much less than that detected by Cassini, so it was anticipated to have minimal influence on the final output chemistry. The models run with this fluid also act as a baseline to compare to the results of the second fluid composition, and provide an insight into what chemical species, if any, originated from the accreted primordial ices rather than the interaction of the water with the silicate interior.

Cometary Ice Fluid. This fluid composition assumes that the water originated from a cometary source [10] and was based upon data collected from 67P [11]. The dominant species within the starting fluid are H_2O, NaCl, NH_4^+, HCO_3^-, HS^- and SO_4^{2-}.

Physical Conditions. The models were run at 50, 90 and 120 ℃, and pressures of 50 and 80 bar. These values are representative of the ocean floor conditions of Enceladus. It has been determined that a minimum temperature of 90 ℃ is required to form the SiO_2 particles that have been measured in the stream believed to originate from Enceladus [2], therefore we ran the model at 90 ℃, and compared this to both a higher temperature scenario and lower temperature models (50 ℃). The pressure hypothesized for the water-rock interface is 80 bar, based upon the combined depth of the subsurface ocean and ice crust, along with gravitational data measurements [2]. Further modelling was carried out at both higher temperatures (up to 250 ℃) and higher pressures (up to 150 bar), to explore reactions that may occur deeper within the porous silicate interior.

Cooling and Freezing model. Using the outputs from the water-rock thermochemical models, we used CHIM-XPT to cool the subsurface ocean fluid from the temperatures in regions of hydrothermal activity (90, 120, 250 ℃) down to 25 ℃. This was to understand any changes in the chemistry of the fluid as it ascends from the ocean floor to the ice-ocean interface. Finally, we used FREZCHEM [12] to freeze the cooled modern day subsurface ocean fluid, thus simulating its delivery to the surface environment.

Results/Discussion: *Subsurface ocean fluid.* All of the water-rock interaction models produce fluid chemistries that are in agreement with data from Cassini, where the dominant chemical species observed were Na^+, Cl^-, K^+, CO_3^{2-}/HCO_3^- [6]. This suggests that CI chondrites are a good analogue for Enceladus' silicate composition. The variations between the models lie in the relative concentration of these species, with the chemical species in the fluid being more concentrated in the cometary starting composition. The cometary fluid models at 90 and 120 ℃ and 80 bar produce fluid compositions that are most comparable to the concentration of the chemical species detected by Cassini [13]. All models produce aqueous SiO_2, which agrees with the detection of solid SiO_2 in the stream particles.

The pH of the fluid generated from both fluid compositions predominately lies between values of 8.5-10 at the rock-water interface. For the higher temperature runs (250 °C), the pH was lower, approximately 7-8. The pH for the ocean on Enceladus has been calculated to lie between 8.5-9 [14]

Gases and minerals. The results from all model runs show that the gases generated at the rock-water interface remain dissolved in solution. The gas results from both fluid compositions include, H_2O, CO_2, CH_4 and H_2, all of which have been detected in the plumes by the INMS [15]. The key difference between the two fluid compositions is that NH_3 is only produced in the cometary fluid run. Given that NH_3 has been detected in the plumes of Enceladus [15], our findings support the idea that the primordial ice could originate from a cometary source.

For both fluid compositions and at all physical parameters, serpentine is the dominant mineral precipitated, accounting for approximately 50 wt.% of the minerals produced. This supports the suggestion that serpentinisation reactions are ongoing on Enceladus.

Cooling/Freezing. The models show that, as the subsurface ocean fluid cools, the pH of the ocean reduces, therefore the pH is approximately 8.5-9 at the ice-ocean interface for the model runs at 90 and 120 °C. This is consistent with the new constraints based on plume gas and carbonate analysis [14].

During the cooling and freezing process, solid species (salts, amorphous silica, carbonates and sulfides/sulfates) are predicted to precipitate out as the fluid infiltrates above the ice-ocean interface into the ice layer.

Summary: Our results show that fluid equilibria between cometary derived fluid and CI chondrite silicates explain much of the major chemical characteristics of Enceladus's present day ocean, including the alkaline pH of ~9 and the abundance of salts and carbonates.

We will present the outcomes from this modelling, which includes a theoretical composition for a modern day subsurface ocean. We will also present findings from modelling of the cooling of ocean fluids as they are transported from the ocean floor to the ocean/ice interface and above, into the ice shell itself; this will include the precipitation of mineral species, which may become incorporated into the icy shell, or into icy plume particles sampled by Cassini.

References:

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