Thermally-linked evolution model for cycling of hydrogen through Europa and the implications to ocean redox. E. M. Spiers1 and B. E. Schmidt1,1 Georgia Institute of Technology, Earth & Atmospheric Science; 311 Ferst Dr, Atlanta, GA 30318

Introduction: In coming decades, NASA missions will continue to investigate the Galilean satellite Europa. Current investigations of Europa have shown that it has a geologically young surface [1][2] and a liquid water sub-surface ocean in contact with a rocky mantle [3][4]. These factors suggest that Europa may contain not only the ingredients, but the energetic cycling capable of supporting a biosphere[5][6][7]. Investigating the bio-potential of Europa requires investigating the sources, sinks, and distributions of energy potential within the satellite. However, it is insufficient to look solely at the modern energy distribution within Europa when investigating bio-potential. Long term environmental stability is a factor that requires consideration.

Previous work has explored possible chemical and geochemical states of the interior of Europa. It has been proposed that if oxidants are delivered to the ocean through surface oxidation processes, an acid ocean would be anticipated [8]. However, it is further hypothesized that serpentinization, a low temperature hydrothermal process, could be viable at Europan seafloor conditions for the modern era [9][10][11] and would create an input of reducing hydrogen. The balance of the oxidants from the surface and reductants from hydrothermal reactions is an open question that would assist in defining the redox state and pH of the past and modern-day ocean. Since redox gradients drive metabolism on Earth, an exploration of the redox state and the long term stability of those gradients is critical to understanding potential habitable niches. However, the evolutionary link of the internal thermal state to the stability of the geochemical state lacks significant modeling in the literature. This work explores the link between Europa’s dynamic thermal and rheological history and how it drives, or ceases to drive, cycling of key redox ingredients within Europa. Specifically, we expand upon work done by [10][11] on hydrogen production at the seafloor, as well as look at additional sources and sinks for hydrogen in the global system.

Mass-Balance for a whole-moon model: Using a combination of seafloor-ocean and ice-ocean exchanges and maintaining a chemical mass balance for the entire satellite, we are able to explore the ocean redox history using box modeling. At present, the box model is a closed three-box system consisting of the upper rocky mantle, ocean, and ice shell. Though the model leaves room for expansion to an open system and to more boxes. While incorporation of additional chemical species will be required, we begin to lay the groundwork for a redox history, and subsequently bio-potential timeline for Europa.

Initial results: For low salinities, the rate of reaction is faster than the rate of rock exposure, Figure 1.

Figure 1: Rates of reaction products for serpentinization measured by mol of species per kg of exposed rock. The top graph is low salinity of 1 weight percent. The middle graph is 3.5 weight percent salinity, and the bottom graph is 5.5 weight percent salinity. All three graphs are run for the modern era of Europa from 4 Gy to 5.5 Gy. The rate of reaction is slower for higher salinity, and the production of hydrogen is slowed.

Whereas, for higher salinities, which are less probable, the rate of rock exposure is faster than the rate
of reaction. The result of this is that for more realistic, low salinities, the output of hydrogen and serpentinization heat increases rapidly until tapering off. Rates of new rock exposure dominate change with the internal heating values, and therefore the hydrogen production is directly dependent on the internal heat state. If rock exposure rates slow or stop for an extended period of time, then the rate of production of hydrogen also ceases. Values for modern day Europa agree with that of prior work [11]. Early Europa shows an initial high input of hydrogen from serpentinization reactions, but due to the higher thermal state the extent of available rock for hydration is small and the reaction slows and eventually runs out of new rock to react. This severely slows the rate of production of hydrogen being included into the ocean.

**Time-Sequencing:** We divide the history of Europa into three primary phases for modeling, based off of the work of Hussmann and Moore [12][13]. The first stage goes from post-differentiation of Europa at around 2.5 – 3.8 Gy. This period is characterized by high internal heating from radiogenic heat. The second time period is the “high-tide” period of Europa from 3.8 – 4.1 Gy. In this period, Europa’s heating goes into an oscillatory heating phase varying over a range of two orders of magnitude [12]. The third time period is the present era from 4.1 – 5.5 Gy. The present era is characterized by continuous cooling and having the least energetic state compared to most of the satellite’s history. However, despite the energetic low, it is the time period at which we will be exploring Europa with spacecraft, and therefore the most information rich to contextualize the satellite’s past.

**Seafloor-Ocean Exchanges:** The seafloor of Europa is one of the primary interfaces for chemical exchange and alteration to occur due to the water-rock interface.

**Serpentinization:** Building off of prior literature [10][11] we examine serpentinization at the seafloor of Europa. However, we implement an explicit incorporation of heat from thermal modeling of Europa [12][13], a salinity dependent rate of reaction for serpentinization [14], and a temporally variable depth of reaction. Tracking the depth and rate of serpentinization of the seafloor allows for a closer examination of hydrogen production at the seafloor due to hydration of olivine. This allows for an approximate, thermally dependent model for hydrogen input into the ocean. This is examined for each of the three aforementioned time periods.

**High Temperature Alteration:** The feasibility of high temperature hydrothermalism on Europa has been explored in literature [11][15]. These estimates would suggest that high temperature systems may have evolved at Europa, given a large enough temperature gradient and assuming lack of large sediment layering and rock permeability permit it. It has even been proposed that high temperature hydrothermal systems could have mass fluxes within an order of magnitude of Earth [15].

By examining the thermal time sequence of Europa and how it has affected seafloor temperatures and gradients, a model of combined low temperature and high temperature hydrothermal systems is explored. Examinations of seafloor temperature profiles for Europa’s history will be aided by thermal equilibrium studies, which predict a conductive lid for the mantle at Europa, even at more energetic periods [13][16].

**Ocean-Ice Exchanges:** We know little about the long-term history of the ice shell of Europa, making models of exchange rates between the ocean and ice-shell difficult. However we can assume that as the thickness of the ice shell has varied, the exchange rate has also varied. We look at models of Earth ice-ocean exchange, in addition to current literature estimates to bound the exchange of oxidants and reductants from the ice shell to the ocean.

**References:**