THE ROLE OF HYDROTHERMAL CIRCULATION IN THE EVOLUTION OF ICY SATELLITES. J. Palguta[1], G. Schubert[1,2] and B. J. Travis[3], [1]Department of Earth & Space Sciences, UCLA (595 Charles E. Young Drive East, 3806 Geology Building, Los Angeles, CA 90095; jpalguta@ucla.edu), [2]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, [3]Los Alamos National Laboratory (EES-2/MS F665, Los Alamos NM 87545).

Introduction: Several models involving subsurface liquid water oceans have been proposed to explain the current geologic activity on Enceladus and the chaotic terrain on Europa. We find that heating by both short-lived and long-lived radiogenic decay is sufficient for melting ice and driving hydrothermal activity in both icy satellites. Therefore, studies of hydrothermal activity provide insight on how water has shaped and modified these bodies. We investigate the role of hydrothermal processes in controlling the currently observed thermal and physical activity of both Europa and Enceladus.

Numerical Approach: The simulations use a spherical geometry and the code MAGHNUM. MAGHNUM determines the thermal histories of the bodies by solving the time-dependent governing equations of mass, momentum and energy conservation in spherical coordinates for a self-consistent gravity field [1,2,3]. We use temperature-dependent relations for thermal conductivity of ice, liquid water and rock mixtures and include conduction of heat as well as latent energy requirements. The Haar equation of state provides properties of water (e.g., density, internal energy, enthalpy, viscosity) as a function of temperature and pressure.

The various processes included in the simulations are hydrothermal convection, thermal diffusion, phase change, settling of particles, radiogenic heating, parameterized advection, and tidal dissipative heating in an ice shell. A velocity field in an ocean layer is approximated using simplified momentum equations. The numerical model automatically accounts for the various processes when conditions call for them. We let the thermodynamics determine where freezing or melting will occur as a function of time.

Thermal and Physical Properties: Enceladus is assumed to have accreted as a uniform mixture of ice and rock (71% ice and 29% rock volume fractions) with a density of 1608 kg m^{-3} and a radius of 250 km. The values used for the rock density, thermal conductivity and specific heat are 3300 kg m^{-3}, 3 W m^{-2} K^{-1}, and 750 J K^{-1} kg^{-1}, respectively. Ice and water properties are functions of temperature. A radiation boundary condition at the surface leads to a surface temperature of ~ 75 K. The radioactive elements ^{26}Al, ^{235}U, ^{238}U, ^{232}Th, ^{40}K, and ^{60}Fe provide heat to drive differentiation. Chondritic ratios are used for each of these radiogenic elements, and the abundances or mass fractions used are 50.0x10^{-8}, 2.64x10^{-8}, 0.86x10^{-8}, 5.21x10^{-8}, 66.0x10^{-8}, and 10.0x10^{-8}, respectively. A range of values for the ^{26}Al abundance has been suggested [2,4,5]. The longer the duration of formation of Enceladus, the less ^{26}Al would be included in the body's interior. A rapid accretion time would correspond to a large amount of ^{26}Al, which would then initially dominate the heating of the body and result in higher temperatures. The abundance of ^{60}Fe is less certain than ^{26}Al, but it has been upgraded to higher values, as have ^{26}Al concentrations [6]. Our simulations correspond to an Enceladus formation time 1.6 Myr after calcium–aluminum inclusion formation. Radionuclide concentrations in the simulations are reduced appropriately from calcium–aluminum inclusions abundances.

Overall, Europa's thermal evolution is most strongly governed by radiogenic decay and tidal dissipative heating. Both heat sources are included in the numerical simulations. We adopt a minimum tidal heating scenario in which the Laplace resonance among Io, Europa, and Ganymede formed ~ 500 Myr ago [7,8]. The radioactive elements included in the Europa model are the same as given for Enceladus. Radiogenic heating in the mantle is approximately 4.5 pW kg^{-1} [9]. Water heated radiogenically is released into the ocean at sites of hydrothermal venting as warm, buoyant plumes. These warm plumes can then be transmitted through the ocean to the base of the ice shell. The heat delivered to the ice shell by the plumes can contribute to local melting and thinning of the ice shell. The tidal dissipative heating included is similar to that of [10]. Tidal heating is a function of ice viscosity and pressure-dependent melt temperature and latitude. We assume tidal heating in the ice shell provides a total of 1 TW in a 30 km thick shell [11,12,13].

The permeability of Europa's upper silicate mantle is the most difficult parameter to determine. We use studies of terrestrial permeabilities at depth to help constrain our selected values. Permeability of rock is greatly enhanced by the presence of fractures, which are ubiquitous in buried rock [14]. Significant permeability has been found at depths up to 9 - 25 km on Earth [15]. Accounting for differing gravity, this scales to 68 - 187 km on Europa. Permeability can also arise from fracturing due to shear stresses [16,17]. Continual stressing of mantle material by gravitational tides, as well as occasional large-scale freezing and thawing that might be associated with changes in orbital resonance and long-term hydration/dehydration processes may allow significant permeability to exist despite the approximately 1 kbar confining overburden pressure at the mantle's surface. A limit on the depth of permeable mantle is taken to be 200 km below the mantle surface; at this depth, the mantle temperature is approaching melt temperature of rock. We assume that the outer two hundred kilometers of the mantle are permeable and use an average value of 10 millidarcys, typical of the Earth at equivalent overburden depths.

Enceladus: The results of the numerical simulations for Enceladus' thermal evolution support the idea that Enceladus is a differentiated body with a large rock-metal core surrounded by a liquid-ice water shell. The state of Enceladus at the end of our simulations (10 to 20 Myr after formation) is that of a moon with a warm to very hot rock-metal core of 165 km radius and a cold liquid ocean roughly 70 km deep, covered by a 15 km ice shell. An additional simulation of long-term thermal evolution indicates that the rocky interior can remain above freezing through the action of long-lived radioactivity and tidal dissipative heating for the roughly 4.5 Gyr interval between the formation of Enceladus and the present day. This final state is only possible with an early warming and melting period in Enceladus' history. The early warming by ^{26}Al also could help explain Enceladus and Mimas' different thermal evolutions. Mimas' density of 1148 kg m^{-3} corresponds to a rock mass fraction of about 20% at most. This is less than 1/2, and perhaps only 1/3, of that for Enceladus. Consequently, stronger radiogenic heating could easily contribute to the differences observed between Mimas and Enceladus.

Differentiation and the existence of liquid water have important implications for explaining Enceladus' interior and current activity. A layer of liquid water could provide a source for the water-vapor plume detected by Cassini at Enceladus' south polar region [18,19]. Beyond differentiation, the thermal evolution model presented above suggests the possibility that the interior of Enceladus has been further altered through hydrothermal activity and water–rock reactions. Conditions at the rock–liquid water interface are suitable for geochemical processes.

Europa: The simulations for Europa indicate that hydrothermal convection in the satellite can sustain an ocean layer with or without tidal dissipative heating. Prior to the onset of tidal dissipative heating, hydrothermal convection in the silicate mantle induces plumes in the ocean layer. A feedback between ice melting and freezing and fluid motion creates a quasi-steady non-uniform ice shell thickness ranging from 20-80 km thick, depending on latitude. Once tidal dissipative heating is activated, the thick irregular ice shell melts in about 20 Myr. At this point the variation in ice shell thickness is much less. However, some variation remains with ice shell thicknesses ranging from 22 km at the poles to 26 km at ~ 11^{o} latitude and 15 km at the equator. The thickest ice occurs near the latitude of Conamara suggesting that convection in the ice shell could contribute to chaotic terrain [12].

This work also indicates that considerable transport of salt from the silicate mantle to the ice shell occurs. Thus, the presence of salt could have a significant impact on ice shell dynamics. Simulations with salts included (assuming an Earth-like ocean with 35 ppt initial concentration) show that salt builds up along and in the bottom of the ice shell due to long residence time at the ice-water interface and the exclusion of water when brines freeze. Viscosity of sub-0^{o}C brine becomes very high [20], such that brine near the base of the ice shell moves very sluggishly. These results suggest that hydrothermal convection can transport salt from the mantle to the ice shell, possibly affecting convection in the ice shell [21].

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