THERMAL MODELS OF MARGINAL DIFFERENTIATION ON GANYMEDE AND CALLISTO; S.K. Croft, Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721

The surfaces of Ganymede and Callisto - two icy satellites of nearly identical size and composition - are astonishingly different: the former being heavily modified by endogenic melting and tectonism while the latter has remained in a primitive cratered state. Several solutions have been proposed to account for this anomalous situation, most of which invoke complete or nearly complete differentiation of one or both of the satellites (e.g., 1,2,3,4). A new hypothesis was recently suggested (5), prompted primarily by geologic considerations, which proposes that Ganymede underwent only marginal differentiation, while Callisto, being slightly smaller and containing slightly less rock (and hence radioactive heating) per unit mass than Ganymede, retained a somewhat cooler interior and thus presumably never melted. This paper presents the preliminary results of thermal modeling designed to test the plausibility and implications of the marginal differentiation hypothesis.

The Thermal Model: A parameterized convection scheme for the case of an internally-heated, spherically symmetric satellite was assumed (6). A single internal convection zone was coupled to a conductive lid of variable thickness. The adopted ice creep relation was derived from measurements in the antarctic ice cap (7) and corresponds well to recent laboratory determinations (8) except at very low temperatures. A stiffening of the ice due to silicate inclusions (9) was included. The viscosity was averaged over the volume of the convecting interior to crudely account for the difference in slope between the water solidus and the convective adiabat at pressures above 0.2 MPa. Chondritic heating and cold initial interior temperatures were assumed. Following the assumption of the marginal differentiation hypothesis, the model for Ganymede was arbitrarily varied by changing the critical Rayleigh number, Rc, for the onset of convection until melting was obtained. Callisto models were computed by changing only the satellite mass, radius, and rock content to appropriate values. Melt water was assumed to escape directly to the surface, carrying part of the heat flux in the form of latent heat. The rate of resurfacing by water was calculated from the amount of heat transported by the liquid.

Results: For each model, the interior heated until the heat allowed to escape the coupled conductive/convective system equaled the radioactive heating. Thereafter, surface heat flux and internal temperatures declined monotonically in virtual equilibrium with the declining radioactive heat production. For silicate ("Iorock") mass fractions of 0.57 for Ganymede and 0.52 for Callisto (1), and an initial temperature of 100°K, the temperature maximum was reached in about 4×10^8 years. Shorter heating times are obtained by assuming higher initial temperatures. Initial melting at the temperature maximum in the Ganymede model was achieved for Rc ≈ 6000. Increasing Rc above 6000, equivalent to raising the effective viscosity of the interior and forcing higher temperatures to carry the same heat flux, generated increasingly long periods of partial melting. The Callisto models, with about 20% less heat flux, ran 6° to 7°K cooler than the Ganymede models at similar values of Rc and did not reach initial melting until Rc was about 14000. For Rc ≈ 14000, the duration of the melt era on Ganymede was about 7×10^8 years, representing the maximum duration of melting. The most likely duration is somewhat shorter. The range of Rc from 6000 to 14000, which represents the range over which a marginally melted Ganymede and an unmelted Callisto can be simultaneously achieved, falls in the (rather broad) range of Rc calculated by (13) for internally heated convecting spheres, implying that the marginal melting hypothesis is plausible within a physically reasonable range of parameters.

Other results of thermal modeling include: 1) heat transport via melt is so efficient that total melting does not occur, implying that conditions for a thermal runaway as suggested by (3) are never achieved. 2) The rapid time of heating and relatively short duration of the melt episodes implies that light terrain emplacement (the last melting event by hypothesis) ended at least before about 3.5 to 3.7 billion years ago, somewhat earlier than the 3.1 suggested by (11). 3) Maximum globally averaged resurfacing rates of about 10^{-6} km/yr are achieved for all Ganymede models reaching partial melting except for Rc very near 6000. This resurfacing rate is near the minimum rate inferred for Io and is thus more than sufficient to continuously bury all crater-derived topography and produce the "clean" surface upon which the furrows later formed (12). 4) Convection circulation times in both Callisto and Ganymede are on the order of 10^6 years, implying geologically rapid convective turnover. The interiors of both satellites should be fairly uniform below the lithosphere. 5) Convective stresses are very similar (and quite low) in both Ganymede and Callisto, implying that while convection will generate oriented stress patterns in both lithospheres, an additional stress source is needed to generate the observed fractures on Ganymede. Lastly, 6) effective lithospheric thicknesses estimated using a Maxwell time criterion and the viscosities and thermal profiles of these thermal models compare well with the values estimated from surface tectonic features on both satellites, thus lending support to the plausibility of the assumed heat flow.

It is emphasized that these results are preliminary and are meant to establish plausibility and not the definitive case for the marginal differentiation hypothesis. Uncertainties in the model and in our understanding of these two satellites are large, and much work remains on this challenging problem.

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