TIDALLY-INDUCED MAGMATIC PULSES ON THE OCEANIC FLOOR OF JUPITER'S MOON EUROPA.

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Introduction: Jupiter's icy moon Europa harbors underneath a tectonically active ice shell [1], a salty ocean interacting with a rocky interior that may still be active [2]. Such an oceanic environment makes Europa a primary target in the search for a habitable world beyond the Earth [3]. The habitability of Europa's ocean is conditioned by the heat released from the deep interior to the seafloor, and hence by the intensity of magmatic activity. Similarly to the volcanic moon, Io, tidal energy dissipated in Europa's interior is expected to influence its thermal state [4]. However, the impact of tidal heating on magmatic activity is still poorly constrained. Here we investigate the melting of the silicate mantle through time and the consequences for seafloor magmatism by modelling Europa's heat production and transfer using a three-dimensional numerical model [5].

Numerical Model: We employ a three-dimensional model enabling us to solve in a self-consistent manner heat transfer by mantle convection and heat production by tidal friction [5, 6]. Both thermal convection and tidal dissipation are controlled by the rheology of the mantle. Consistent with the available constraints on the link between tidal dissipation function and mantle viscosity on the Earth [7] and Mars [8], we assume an Andrade-like rheological behaviour to compute the tidal dissipation rate. The viscosity is assumed to depend on the temperature, with a viscosity at the melting point of silicates ranging between 10^{18} and 10^{20} Pa·s, consistent with existing experimental constraints on dry olivine [9]. No direct constraints exist on the internal heat sources inside Europa. However, we can estimate the radiogenic power using the typical radionuclide abundances in chondrites as a guideline. We consider two end-member radionuclide contents: a low content corresponding to carbonaceous chondrites and a high content corresponding to LL-chondrites [10].

Most of the simulations start at 4.5 Gyr before the present, assuming a fully differentiated structure and a temperature profile following the melting temperature of anhydrous peridotites [11], except in the upper part of the mantle where an equilibrium conductive profile including volumetric radiogenic heating is considered. These simulations assume rapid internal warming shortly after accretion, leading to full differentiation and to the massive release of volatiles from the interior. The temperature at the ocean floor is constant with time and fixed to 273 K, while the core-mantle temperature has evolved due to secular cooling.

The eccentricity of Europa and hence tidal heating is expected to vary due to the Laplace resonance [4]. Thermo-orbital models indicate that Europa's eccentricity may vary by a factor of two, and even higher, on timescales of the order of several hundred million years [4]. To test the influence of variable eccentricity, we performed a series of simulations assuming sinusoidal changes in eccentricity on periods varying between 0.125 and 1 Gyr, as predicted by thermo-orbital models[4].

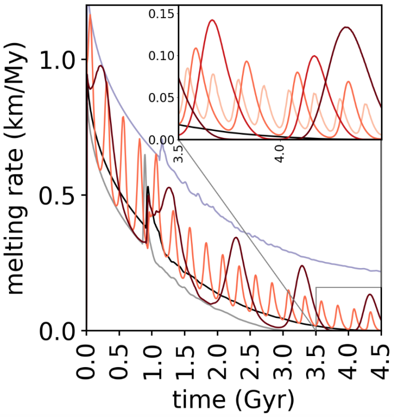

Figure 1: Time-varying melt production due to a radiogenic decay and various scenarios of eccentricity evolution (either constant with time or varying sinusoidally between 0.5 and 2 times the present-day value on a period ranging between 0.125 and 1 Gyr).

Results: Because the tidally dissipated power varies as the square of the eccentricity, even moderate modulations of the eccentricity can lead to strong variations in heat production. These periods of enhanced heating result in a transient increase in internal temperature, enhancing melt production (Figure 1). The long-term evolution of the melting rate is still controlled by radiogenic power, which remains the dominant heat source during the first few billion years (Figure 1). Tidal dissipation can exceed radiogenic power in the present during periods of enhanced eccentricity. The melting rate is strongly modulated by eccentricity changes and becomes the primary driver of the melt evolution during the last two billion years. The amplitude of the melting rate naturally depends on the assumed periodicity of eccentricity change, but the integrated volume over a period of one billion years remains comparable. Interestingly, the melting rate in the present era depends on the way the eccentricity is currently evolving. If the eccentricity is increasing, our simulations indicate that Europa should be in a minimum melt production period. On the contrary, if the eccentricity is currently decreasing, a large heating rate and melt production are predicted in the recent past, and Europa may still be in a period of enhanced melt production. Geological mapping of Europa's surface [1] suggests that the ice shell was thinner in the recent past, requiring more tidal energy, and thickened on the timescale of < 100 Myr. This inference from stratigraphic mapping of Galileo data awaits confirmation from global geologic mapping by the Europa Clipper. Nevertheless, it would be consistent with an eccentricity decrease and hence the possibility for ongoing active melt production.

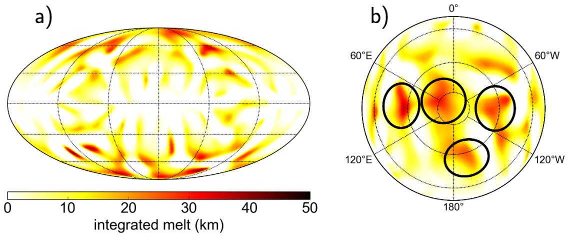

Figure 2: Spatial distribution of integrated melt (global (a) and polar (b) coverage) produced during the last heat pulse assuming an eccentricity period of 0.25 Gyr.

As shown in Figure 2, tidal heating tends to concentrate melt production at high latitudes. The distribution of melt volume predicted during the last heat pulse (i.e. the last eccentricity variation period equal to 0.25 Gyr) shows a clear focusing of melt production near the poles, in regions corresponding to hot upwelling mantle plumes. The generated melt volumes in the selected areas indicated with a black circle in Figure 2 are comparable to the volume generated in Large Igneous Provinces on Earth, which typically range between 0.5 and $10 \cdot 10^6$ km^3 [12].

Conclusion: Even though silicate volcanism is strongly reduced compared to Io, we show that significant amounts of silicate melt can be produced during most of Europa's history due to the limited efficiency of internal cooling by thermal convection. The melting rate is amplified by tidal friction, possibly leading to magmatic pulses during periods of enhanced eccentricity. The volumes of melt generated during magmatic episodes are comparable to those involved in Large Igneous Provinces (LIPs), commonly observed on Earth[12], and may influence the oceanic chemistry [13].

The existence of seafloor magmatic activities and their focusing at high latitudes may be confirmed by futures observations by the NASA Europa Clipper mission and the ESA JUICE mission. Gravity measurements may reveal mass anomalies at high latitudes [14, 15] while detection of local enhancements in H_2, CH_4 and potentially gas species by mass spectrometers [16] may confirm ongoing seafloor hydrothermal activity powered by these magmatic systems. Precise determination of the Galilean moons' ephemerides using radio-tracking and astrometric data obtained by the JUICE and Europa Clipper missions [17] would also yield crucial information about the orbital dynamics of Europa and its interaction with Io and Ganymede through the Laplace resonance and thus provide pertinent test whether Europa recently experienced a period with enhanced eccentricity. For more details see [5].

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