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Key Points:

- The melting of Europa's mantle is investigated by three-dimensional modeling of heat production and transfer
- Magmatic activity can persist up to the present at high latitudes where tidal heating is maximal
- Measurements by upcoming missions are identified that might confirm ongoing volcanic activity

Supporting Information:

- Supporting Information S1

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Tidally Induced Magmatic Pulses on the Oceanic Floor of Jupiter's Moon Europa

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Abstract The habitability of Europa's subsurface ocean is conditioned by heat released from the deep interior and by intensity of magmatic activity. Here, we investigate the melting of the silicate mantle through time and its consequences for seafloor magmatism by modeling Europa's internal heat production and transfer using a three-dimensional numerical model. We show that melt can be produced during most of Europa's history due to the limited efficiency of internal cooling by thermal convection and the presence of radiogenic heating. The melting rate is amplified by tidal friction, possibly leading to magmatic pulses during enhanced eccentricity periods and focusing melting to high latitudes. The volume of generated melts during magmatic episodes is comparable to those involved in Large Igneous Provinces, commonly observed on Earth, and may impact ocean chemistry. We predict that gravity measurements, detection of anomalous H₂/CH₄, and astrometric data by future missions could confirm ongoing large-scale seafloor activity.

Plain Language Summary Jupiter's icy moon Europa harbors underneath a tectonically modified ice shell a salty ocean in direct contact with a rocky interior. Such an oceanic environment makes Europa a primary target for the search of a habitable world outside the Earth. The occurrence of magmatic activity on the seafloor is essential to determine if it constitutes an environment hospitable to life. Using a three-dimensional numerical model, we demonstrate that the magmatic activity can continue during most of Europa's history even though it progressively decays as the interior cools down. We predict that magmatic activity should be modulated in time due to change in the moon's orbit, and should focus in polar regions where the heat produced by tidal friction is the largest. The predicted magmatic pulses should be accompanied by the release of volatiles that may impact the oceanic chemistry and may be detected by upcoming spacecraft missions.

1. Introduction

Jupiter's icy moon Europa harbors underneath tectonically modified ice shell (Figueredo & Greeley, 2004; Kattenhorn & Prockter, 2014) a salty ocean (Kivelson et al., 2000) in direct contact with a rocky interior that may still be active (Moore & Hussmann, 2009). Such an oceanic environment makes Europa a primary target in the search for a habitable world beyond Earth (Hand et al., 2009). The chemical evolution of Europa's ocean and its habitability is conditioned by the interaction with the rocky seafloor (Vance et al., 2016). It depends on the heat released from the deep interior to the seafloor (Altair et al., 2018), and hence by the intensity of magmatic activity.

Gravity measurements performed by the Galileo spacecraft indicate that Europa's deep interior is likely differentiated into an iron core and a silicate mantle and is overlaid by a hydrosphere estimated to be between 80- and 170-km thick (Anderson et al., 1998; Gomez Casajus et al., 2020). The thickness of the ice may be from a few kilometers to several tens of kilometer thick, depending on the efficiency of heat transfer through the ice shell and the total energy released by the silicate interior (Hussmann & Spohn, 2004; Tobie et al., 2003; Travis et al., 2012; Turtle & Pierazzo, 2001). The heat output from the silicate interior depends on the heat sources available in the interior, but also on how heat is transferred from the silicate mantle and metallic core to the oceanic floor (Hussmann et al., 2010). Heat released by radioactive elements in the silicate layer and by the metallic core cooling is conditioned by Europa's accretion and differentiation, and

progressively decays as a function of time. By contrast to other energy sources, tidal dissipation, which is intimately linked to the orbital configuration, may strongly fluctuate as a function of time (Hussmann & Spohn, 2004). However, the extent to which tidal heating causes magmatic activity has not been well understood (Moore & Hussmann, 2009; Sotin et al., 2009).

Tidal forces result from the difference between the gravitational forces created by Jupiter and varying across Europa and the centrifugal forces due to its motion around the planet. As the orbit of Europa is elliptical, the tidal forces change during one orbital period (equal to 3.55 days). The amplitude of tidal forces is proportional to the orbital eccentricity (equal to 0.0094 at present), which may have significantly varied in the past due to the interactions with Io and Ganymede through the Laplace resonance (Hussmann & Spohn, 2004). The tidal energy not only depends on the orbital characteristics but also on the mechanical response of Europa's interior to this periodic forcing and it is therefore sensitive to rheological properties including viscosity and shear modulus, and to its internal structure. The amplitude of the response depends mainly on the interior structure (Tobie et al., 2005), and the amount of mechanical energy lost by internal friction is most sensitive to the thermal state controlled by the rheological properties (Běhouňková et al., 2010). For rock containing small to moderate fraction of melts solicited at tidal periods of the order of days, the warmer the interior, the more dissipative it is, which further increases its internal temperature and hence the potential extent of rock melting. In some circumstances, tidal dissipation is so strong that it can lead to thermal and melting runaways, similar to what is observed on the volcanic moon Io (Fischer & Spohn, 1990). Modeling the feedback between tidal dissipation and thermal evolution is, therefore, crucial for assessing the extent of tidal melting of rock and associated seafloor volcanism.

Several models have been developed to describe the role of tidal heating on the evolution of Europa and neighboring moons, Io and Ganymede. However, all of these models are based on a simplified description of heat transfer and assume uniform tidal heating in the mantle (Hussmann & Spohn, 2004; Moore & Hussmann, 2009). A few models tried to address the coupling between heat transfer and heat production by tides, particularly in the case of Enceladus (Běhouňková et al., 2012; Roberts & Nimmo, 2008) but no model so far has been developed for Europa's silicate mantle. Here 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 (Běhouňková et al., 2010, 2011).

2. Methods

2.1. Three-dimensional Thermal Evolution Model Including Melt Production

The thermal evolution and melt production in the silicate mantle of Europa are investigated using a three-dimensional (3D) numerical model that simultaneously solves for thermal convection, radiogenic heating, and tidal dissipation (Běhouňková et al., 2010, 2011). The equations of subsolidus thermal convection in the extended Boussinesq approximation are computed in a spherical shell using the numerical tool Oedipus developed by Choblet (2005) and Choblet et al. (2007). An instantaneous melt extraction further supplements the model once the solidus temperature is reached (Běhouňková et al., 2012), that is, we introduce an energy sink, which ensures that the temperature does not exceed the solidus temperature. The latent heat is used to evaluate the amount of melt produced but no melt remains present in the solid matrix. The amount of extracted melt is radially integrated at Europa's surface. The solidus temperature is computed considering anhydrous peridotites (Katz et al., 2003). This assumption is consistent with the fact that the mantle likely lost most of its volatiles during the early stages of evolution (see Section 2.2). Hydrous melting can be, therefore, neglected throughout the evolution. Detailed effects such as mineralogical influence (e.g., clinopyroxene) on melt productivity are also not considered.

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 (CM-based) and a high content corresponding to LL chondrites (Hussmann et al., 2010). Two spatial configurations are also tested: with the radiogenic heating uniformly distributed or with a simple partitioning model of the radiogenic heating between the crust and the mantle. The tidal dissipation is solved numerically in a

shell following the 3D approach developed in Běhounková et al. (2010, 2012). We also take into account the additional potential due to ice shell deformation, which is not directly solved by the 3D model but is parameterized using a radial function approach (Tobie et al., 2005).

Both thermal convection and tidal dissipation are controlled by the rheology of the rocky mantle. The viscosity is assumed to depend on the temperature:

$$\eta = \eta_{\text{melt}} \exp\left(\frac{E^*}{RT_{\text{sol}}} \left(\frac{T_{\text{sol}}}{T} - 1\right)\right), \quad (1)$$

where η_{melt} is the viscosity at the solidus temperature T_{sol} , E^* is the activation energy, and R is the gas constant. Viscosity at the melting point of silicates η_{melt} ranges between 10^{18} and 10^{20} Pa s, both the viscosity at the melting point and the activation energy are consistent with existing experimental constraints on dry olivine (Karato, 2012). The pressure dependence of viscosity is embedded in the pressure effect on the solidus temperature. The plasticity is not included in our model. We checked *a posteriori* that the maximum convective stresses in our models never exceed 1 MPa, that is, below the anticipated yield stress for silicates (Karato, 2012). The low stress range also guarantees that the viscous creep is dominated by diffusion creep, with no stress dependence (Karato, 2012). Consistent with the available constraints on the link between tidal dissipation function and mantle viscosity on the Earth (Tobie et al., 2019) and Mars (Samuel et al., 2019), we assume an Andrade-like rheological behavior to compute the tidal dissipation rate (Běhounková et al., 2013). Besides the viscosity, the Andrade rheology is characterized by three additional parameters: shear modulus μ and Andrade parameters α_A and ζ_A . The shear modulus is principally sensitive to the presence of melt. The melt in our model is, however, instantly extracted to the surface. The shear modulus is, therefore, considered to be constant ($\mu = 70$ GPa) in our model (cf. Fischer & Spohn, 1990). The Andrade parameters α_A is expected to vary between 0.1 and 0.4 for the silicates (Gribb & Cooper, 1998; Jackson et al., 2002). Besides the reference value $\alpha_A = 0.3$, we have assessed the sensitivity to this parameter ($\alpha_A = 0.25$ and 0.2). The decrease of α_A leads to higher tidal dissipation and favors the prolongation of the melting, but the change remains moderate. Empirical parameter ζ_A is supposed to be the order of unity for the diffusion creep (Castillo-Rogez et al., 2011; Webb & Jackson, 2003). In our simulations, we set $\zeta_A = 1$.

The orbital eccentricity, another element controlling the tidal dissipation, is considered as a parameter between 0 and $2e_0$, e_0 being the present day value equal to 0.0094. The eccentricity is assumed to be constant through time or to vary periodically, assuming a sinusoidal function. The former allows us to study the impact of a relatively simple tidal heating model on the evolution of Europa's mantle. The latter is inspired by the eccentricity evolution modeled by (Husmann & Spohn, 2004).

Most of the performed simulations start at 4.5 Gyr before the present. A fully differentiated structure is assumed, with a temperature profile following the solidus temperature 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 the massive release of volatiles from the interior (see Melwani Daswani and Vance (2020)). 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. For more details on the modeling approach, list of parameters, detailed results description and sensitivity of our results especially to rheological parameters, see Text S1–S3 and Tables S1–S4.

2.2. Volatile Release From the Silicate Interior

The thermal evolution of the mantle is expected to have a direct impact on ocean chemistry through volatile release from the deep interior. Note that, on the other hand, the ocean chemistry has only negligible effect on the mantle evolution, allowing to neglect the feedback between the mantle and hydrosphere evolution. We can, therefore, *a posteriori* consider the volatile release associated with the thermal evolution of Europa's silicate mantle and quantify the possible effect of the mantle's thermal state on the ocean's chemistry. The composition and abundance of volatile elements released and extracted from the silicate interior during Europa's thermal evolution were calculated using the Perple_X Gibbs free energy minimization code (Connol-

Figure 1. Time evolution of global energy budget of Europa's silicate mantle for models with (a) low CM-based and (b) high LL-based homogeneously distributed radionuclide content and $\eta_{\text{melt}} = 10^{19}$ Pa s, $e = e_0$. Arrows mark the onset of convection. The power corresponding to the temperature changes is defined as volume integral of scaled temperature change: $-\int_V \rho c_p \frac{\partial T}{\partial t} dV$.

ly, 2009) together with a speciation algorithm (Connolly & Galvez, 2018) and the Deep Earth Water Model (Pan et al., 2013; Sverjensky et al., 2014) to quantify electrolytic fluids produced. Solution thermodynamic data for mineral phases and silicate melt phases were selected from the “igneous set” implemented in *PepX*, adapted from (Holland et al., 2018). The bulk compositions used were that of bulk CM chondrites and LL chondrites (Lodders & Fegley, 1998), minus Fe and S, to form a model core composed of Fe and S consistent with sulfur partitioning behavior into at the Fe-FeS eutectic at pressures relevant to Europa's core (Saxena & Eriksson, 2015). The *Rcrust* program (Mayne et al., 2016) was used to calculate an isobaric prograde heating path up to the 0 Gyr temperature profile, and then an isobaric retrograde cooling path up to Europa's present temperature profile. A retention-to-extraction ratio of 1:1 at each heating step was assumed for fluids. Masses of extracted fluids were integrated between the temperature profiles. Further details are provided in Text S4 and Tables S5–S6.

3. 3D Simulation Results

For two simulations with high (LL-based) and low (CM-based) homogeneously distributed radionuclide contents, and a viscosity at the melting point equal to 10^{19} Pa s, Figure 1 displays the total heat budget of the silicate mantle in terms of heat sources due to radioactive decay and tidal dissipation, heat sinks due to melt production, temperature change, surface and basal heat fluxes. During the early stage of evolution, heat loss is controlled by melt production and extraction and rapid thickening of the upper thermal boundary layer until the onset of convection in the mantle indicated by the arrow in Figure 1. The first convective motion occurs as cold downwellings through the destabilization of the cold boundary layer. Due to lower radiogenic content in the CM-based model, the initial temperature is lower and the upper conductive lid is thicker, that is, the top conductive outflux, inversely proportional to the cold boundary layer thickness, is smaller than for the LM-based model (Figure 1). Lower volumetric heating also allows for larger temperature differences to develop in the mantle. Consequently, the onset of convection occurs earlier for the low radionuclide content model (at 0.3 Gyr, Figure 1a) than for the high radionuclide content model (at 0.9 Gyr, Figure 1b). In both cases, the onset of convection results in a pulse of melt production. The melting decays progressively afterward as a consequence of decreasing radioactive power and mantle cooling.

For the low radionuclide content model, no melting is observed after ~ 2.5 Gyr, while, for high radionuclide content, melting persists until ~ 4 Gyr. For these two simulations with constant eccentricity, tidal dissipation

Figure 2. Temperature distribution and associated melt production in Europa's mantle at 2.1 and 4.2 Gyr. The simulation corresponds to the one displayed in Figure 1b (high radionuclide content, $\eta_{\text{melt}} = 10^{19}$ Pa·s, $e = e_0$); (a–b) the temperature profiles (blue: minimum, red: maximum, black: average, green: solidus temperature); (c–d) lateral heating variations; (e–f) melting rate melting patterns; (g–h) co-latitude averaged melting rate.

Figure 3. Time-varying tidal heating and melt production due to a periodically varying eccentricity: (a) global power produced by tidal dissipation and LL-based radioactive decay, (b) corresponding melting rate for models with eccentricity constant in time or varying sinusoidally on a period ranging between 0.125 and 1 Gyr, (c) melting rate for models with radiogenic heating scenarios. Insets in (b)–(c) focus on the last 1 Gyr, the corresponding integrated melt during last 1 Gyr is provided in Table S3. Black arrows in the inset of panel (c) indicate the currently observed value of eccentricity.

remains moderate and only slightly decreases as a function of time due to progressive interior cooling, ranging typically from 155–170 GW at the beginning of the simulation to 60–90 GW at the end of the simulation, respectively for low and high radionuclide contents. Tidal dissipation is negligible compared to radiogenic power at the beginning of the evolution, assuming the present day eccentricity value, corresponding to 10%–15% of the radiogenic power depending on the radionuclide concentration. In the present era, it becomes comparable to radiogenic power, reaching about 40%.

The surface heat flux associated with conduction through the cold upper boundary layer is predominant throughout the evolution, but heat loss by melt production and extraction is also a major contributor during the early stages of the evolution (Figure 1). Solid-state convection occurs after an initial stage of conductive thickening of the cold boundary layer (proportional to the reciprocal value of the top outflux, see Figure 1). Once thermal convection is well established, silicate melting occurs in a region beneath the conductive stagnant lid (Figure 2, first row), focused in hot upwellings. The melt is almost uniformly distributed as it is controlled by homogeneously distributed radiogenic sources (Figure 2c, 2e and 2g for $t = 2.1$ Gyr). The melt zone is only modulated by randomly distributed cold downwellings. However, as the interior cools, tidal dissipation, which is enhanced at high latitudes (Figure 2d), keeps the mantle warmer in the polar regions, favoring the occurrence of melting there (Figure 2f and 2h for $t = 4.2$ Gyr). The cold downwellings are preferentially located in the equatorial regions.

The first set of simulations presented above considers a constant eccentricity, resulting in almost constant tidal dissipation throughout the whole evolution. In reality, the eccentricity of Europa is expected to vary due to the Laplace resonance (Husmann & Spohn, 2004). Thermal-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 (Husmann & Spohn, 2004). 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 thermal-orbital models (Husmann & Spohn, 2004).

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. As shown in Figure 3a, tidal dissipation can exceed radiogenic power in the present during periods of enhanced eccentricity. These periods of enhanced

heating result in a transient increase in internal temperature, enhancing melt production (Figure 3b). 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 3b). However, the melting rate is strongly modulated by eccentricity changes and becomes the primary driver of the melt evolution during the last two billion years (Figure 3b and 3c). The amplitude of the melting rate naturally depends on the assumed periodicity of eccentricity change, but the integrated volume over one billion years remains comparable (Figure 3b – inset). Interestingly, the melting rate in the present era depends on the way the eccentricity is currently evolving. If the eccentricity is increasing (Figure 3c – inset; left arrow), our simulations indicate that Europa should be in a minimum melt production period. By contrast, if the eccentricity is currently decreasing (Figure 3c – inset; middle arrow), a significant heating rate and melt production are predicted in the recent past, and Europa may still be in a period of enhanced melt production.

Our simulations show that a significant fraction of the mantle melts, especially during the first few billion years. As the concentration of radiogenic elements increases in silicate melts, melt production and extraction to the surface are expected to lead to a transfer of radioactive heat sources from the mantle to the crust (Breuer & Spohn, 2006). The radiogenic power partitioning between the crust and mantle is relatively well constrained on the Earth (Jaupart et al., 2007), but on other planetary bodies may vary with different model assumptions. To test the effect of radionuclide partitioning into the crust, we performed additional simulations for an end-member case for which 50% of the total radiogenic power is assumed to be in the mantle, and the remaining 50% is in a 100-km-thick uppermost crust-like shell. This simple end-member neglects possible lateral variations such as radionuclide enrichment in the polar regions due to enhanced melting. The depletion in radionuclide elements naturally leads to colder mantle states, but even in these less favorable conditions, peaks of melt production still occur during periods of enhanced eccentricity (Figure 3c – inset). Melt production only ceased in the last 500 Myr for the low radionuclide content case with 50% partitioning. In this low radionuclide (CM-based) content scenario, melt production is much weaker during most of the evolution. 50% partitioning can, therefore, be considered as an extreme case providing a conservative low estimate of the possible melt production. The sensitivity tests also show that the melt can even persist for models with very low viscosity $\eta_{\text{melt}} = 10^{18}$ Pa s and LL-based model with no partitioning.

As already shown in Figure 2, tidal heating tends to concentrate melt production at high latitudes. Figure 4 displays the distribution of melt volume predicted during the last heat pulse (i.e., the last eccentricity variation period equal to 0.25 Gyr), assuming either a homogeneous radiogenic heat source or partitioning between the crust and the mantle (i.e., considering mantle depletion). In both cases, we observe the focusing of melt production near the poles, in regions corresponding to hot upwelling mantle plumes. The generated melt volumes in the selected areas (Figure 4, black circles) are comparable to the volume generated in Large Igneous Provinces on Earth, which typically range between 0.5 and $10 \cdot 10^6$ km³ (Ernst et al., 2005; Ross et al., 2005; Sobolev et al., 2011), and may influence the ocean's chemistry (Vance et al., 2016).

4. Implication for Volatile Release and Potential Detection

Silicate melts exposed at the seafloor during magmatic pulses could induce volatile release from a combination of magma degassing, destabilization of a volatile-rich outer crustal layer, or associated hydrothermal activity. We have estimated the amount of volatiles that might be released during the mantle evolution (see Section 2.2 and Text S4). The release of volatiles is controlled by the initial volatile content in the silicate mantle and the subsequent outgassing history. Most of the volatiles initially contained in the primordial block that formed Europa would have been released during the very early stage of evolution when strong radiogenic heating led to the very warm initial profile considered as the starting point in our simulations. This early radiogenic heating would have left behind a relatively devolatilized mantle. We have used the approach of Melwani Daswani and Vance (2020) to evaluate *a posteriori* the release of volatiles as a function of time by considering radial temperature profiles from our 3D models. We estimate that, during the subsequent evolution, $5.5 \cdot 10^{18}$ kg CO₂ and $1.7 \cdot 10^{18}$ kg CH₄ could have been released for a CM-based mantle composition, while an LL-based mantle composition would have led to $2.4 \cdot 10^{18}$ kg CO₂ and a negligible amount of CH₄.

Figure 4. Spatial distribution of integrated melt produced during the last heat pulse. Global (panels a and c) and polar (panels b and d) coverage of melt production integrated during the last heat pulse, assuming an eccentricity period of 0.25 Gyr, $\eta_{\text{melt}} = 10^{19}$ Pa s, LL-based radionuclide content (a–b) without or (c–d) with partitioning (i.e., with enhanced concentration of radiogenic elements in the 100-km-thick crust and depleted concentration in the mantle). The black circles indicate the area for which the locally integrated volume is 7.2 (I), 5.3 (II), 4.7 (III), 5.5 (IV), 2.4 (V), 2. (VI), and 0.8 (VII) 10^6 km³. Further details are in Table S4.

Averaged over the course of 4.5 Gyr, the volatile release corresponds to an outgassed flux of $\sim 2.9 \cdot 10^{10}$ mol/yr of CO₂ and $2.5 \cdot 10^{10}$ mol/yr of CH₄ for the CM-based composition, and $\sim 1.2 \cdot 10^{10}$ mol/yr of CO₂ for the LL-based composition. Because we predict that the magmatic activity was higher in the past due to the combined radiogenic and tidal power, CO₂ and CH₄ outgassed fluxes were probably much higher than this average value during the three first billion years and may have been the dominant carbon source in the ocean, especially during tidally induced magmatic pulses. At present, due to declining activity, the volcanic release rate of CO₂ at the seafloor would barely exceed the rate of CO₂ provided by surface radiolytic processes (Bouquet et al., 2019; Hand et al., 2007), even during the most recent magmatic pulse. Such a trace CO₂ signature would be difficult to distinguish from background CO₂. Detection of CH₄, either directly from surface gas emissions or from ice grains in the form of clathrate hydrate (Bouquet et al., 2019), might be more discriminating as it would suggest a CM-based mantle composition.

In addition to mantle outgassing, magmatic activity may be accompanied by the release of H₂ and CH₄ due to associated seafloor hydrothermal activity, which might leave chemical signatures in the oceanic composition. By analogy with the Earth where the hydrogen production by hot basaltic vents is estimated to $6 \cdot 10^{10}$ mol/yr for a crustal production of ~ 20 km³/yr (Sleep & Bird, 2007), basaltic crust production of 1–3 km³/yr during recent a magmatic pulse may generate $0.3\text{--}0.9 \cdot 10^{10}$ mol/yr on Europa. According to Cassidy et al. (2013), sputtering processes may produce H₂ at a rate of 10^{10} mol/yr, which is slightly higher but still comparable to our H₂ predicted estimate. If internally generated H₂ is released in a few places, local enhancement in H₂ may reveal an endogenic source. Detection of anomalous CH₄ may be more diagnostic. According to Teolis et al. (2017), a CH₄ to O₂ ratio exceeding $3.5 \cdot 10^{-3}$ would also indicate an endogenic source.

5. Discussions and Conclusions

Detection of local enhancements in H_2 , CH_4 and potentially other gas species by mass spectrometers on-board the future missions to Europa, NASA's Europa Clipper and E.S.A.'s JUICE, will be essential to confirm the existence of recent seafloor activity on Europa, as predicted here. Identification of local enhancement in gas abundances alone would probably not be sufficient to ensure an endogenic origin. However, correlation with surface features indicating recent deposits of fresh oceanic materials may provide a strong evidence for ongoing subsurface activities.

Gravity measurements performed by Europa Clipper (Verma & Margot, 2018) may also reveal long-wave-length variations in the gravity field indicative of the concentration of the magmatic activities that we predict at high latitude. While the expected precision of gravity measurements would not allow the acquisition of detailed spatial information about the seafloor topographic or thermal anomalies (Dombard & Sessa, 2019), the analysis of the main gravity field coefficients together with a detailed determination of the surface shape will permit the separation of the ice shell and rocky mantle contributions and may point to mass anomalies at the poles (Pauer et al., 2010). According to (Pauer et al., 2010), an isolated feature (e.g., volcano) with a size of 75–200 km could be detectable but would require a measurement accuracy of 1 mGal, which seems beyond the capabilities of the Europa Clipper mission (Verma & Margot, 2018). However, an excess in crustal thickness at high latitudes may be retrieved from the analysis of the low-degree gravity field, witnessing enhanced melt production in these latitudes.

Geological mapping of Europa's surface (Figueredo & Greeley, 2004; Leonard et al., 2018) 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. Moreover, precise determination of the Galilean moons' ephemerides using radio-tracking and astrometric data obtained by the JUICE and Europa Clipper missions (Dirkx et al., 2017) would yield crucial information about the orbital dynamics of Europa and its interaction with Io and Ganymede through the Laplace resonance. Precise determination of the mean motion rate changes for the three satellites (Lainey et al., 2009) could provide constraints on the present day dissipation rate in the Jovian system. This would test whether Europa recently experienced a period with enhanced eccentricity.

Identifying regions at Europa's surface where oceanic materials have been recently exposed, and detecting hydrothermally derived volatile species, gravity anomalies at high latitudes, and changes in Europa's orbital motion by Europa Clipper and JUICE would confirm ongoing large-scale seafloor activities predicted by our models.

Data Availability Statement

Data used for producing figures in this paper can be found online (<https://doi.org/10.5281/zenodo.3950431>).

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