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Consequences of large impacts on Enceladus' core shape

J. Monteux [a,b,*], G.S. Collins [c], G. Tobie [b], G. Choblet [b]

[a] Laboratoire Magmas et Volcans, Université Blaise Pascal, CNRS, IRD, Clermont-Ferrand, France
[b] Laboratoire de Planétologie et de Géodynamique, LPG Nantes, CNRS UMR6112, Université de Nantes, France
[c] Impacts and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College London, United Kingdom

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ABSTRACT

The intense activity on Enceladus suggests a differentiated interior consisting of a rocky core, an internal ocean and an icy mantle. However, topography and gravity data suggests large heterogeneity in the interior, possibly including significant core topography. In the present study, we investigated the consequences of collisions with large impactors on the core shape. We performed impact simulations using the code iSALE2D considering large differentiated impactors with radius ranging between 25 and 100 km and impact velocities ranging between 0.24 and 2.4 km/s. Our simulations showed that the main controlling parameters for the post-impact shape of Enceladus' rock core are the impactor radius and velocity and to a lesser extent the presence of an internal water ocean and the porosity and strength of the rock core. For low energy impacts, the impactors do not pass completely through the icy mantle. Subsequent sinking and spreading of the impactor rock core lead to a positive core topographic anomaly. For moderately energetic impacts, the impactors completely penetrate through the icy mantle, inducing a negative core topography surrounded by a positive anomaly of smaller amplitude. The depth and lateral extent of the excavated area is mostly determined by the impactor radius and velocity. For highly energetic impacts, the rocky core is strongly deformed, and the full body is likely to be disrupted. Explaining the long-wavelength irregular shape of Enceladus' core by impacts would imply multiple low velocity (<2.4 km/s) collisions with deca-kilometric differentiated impactors, which is possible only after the LHB period.

1. Introduction

Despite its small size ($R = 252$ km), Saturn's moon Enceladus is one of the most geologically active body of the Solar System. Its surprising endogenic activity is characterized by a very active province at the South Pole, from which eruptions of water vapor and ice grains emanating from warm tectonic ridges have been observed by the Cassini spacecraft (Porco et al., 2006; Hansen et al., 2006; Waite et al., 2006; Spencer et al., 2006). This activity is associated with a huge heat power estimated between 5 and 15 GW from thermal emission (Spencer and Nimmo, 2013), which implies a warm interior, consistent with a liquid water layer underneath the ice shell and a differentiated interior (Nimmo et al., 2007; Schubert et al., 2007). Models of tidal dissipation may explain why the activity is concentrated at the poles, where dissipation is predicted to be maximal (Tobie et al., 2008; Běhounková et al., 2010). However, there is still no satisfactory explanation for why this activity is located only in the south, and not in the north.

Based on the global shape data which show a depression at the south pole (Thomas et al., 2007), it has been proposed that the ocean may be located only in the southern hemisphere (Collins and Goodman, 2007), thus explaining why the activity would be concentrated at the south (Tobie et al., 2008). Gravity and shape data indicate that such an ocean would be at depths of about 30–40 km and extend up to south latitudes of about 50° (Iess et al., 2014). It has been proposed that the dichotomy between the north and south hemispheres may be the result of asymmetry in core shape (McKinnon, 2013). Due to the low pressure and moderate temperature expected in Enceladus' core, large topography anomalies may indeed be retained on very long periods of time (McKinnon, 2013) and may explain why convection-driven activities in the ice shell is confined only to the south polar terrain (Showman et al., 2013). Besides the south polar depression, core topography anomalies could explain, at least partly, the existence of other big depressions observed at moderate latitudes (between 15°S and 50°N) and uncorrelated with any geological boundaries (Schenk and McKinnon, 2009).

* Corresponding author at: Laboratoire Magmas et Volcans, Université Blaise Pascal, CNRS, IRD, Clermont-Ferrand, France.

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McKinnon (2013) proposed three hypotheses to explain the possible irregularity of Enceladus' rocky core: accretional melting of the outer region of the icy moon associated with a degree-one instability; accretion of icy protomoons around irregular rock chunks; and collisional merger of two previously differentiated protomoons. Here we test the latter hypothesis by investigating the consequences of the collision of a large differentiated impactor on the shape of Enceladus' core. Collisions with large differentiated bodies were likely at the end of satellite accretion, during the final assemblage phase (e.g. Asphaug and Reufer, 2013). Large impact basins on other saturnian moons (e.g. Iapetus (Giese et al., 2008), Mimas (Schenk, 2011), Titan (Neish and Lorenz, 2012)) and other Solar System bodies (e.g. Vesta (Schenk et al., 2012)) could represent remnant evidences of such collisions. Large impacts occurring at the end of the accretion and after, during the rest of the satellite's evolution, likely influenced the internal structure and especially the shape of its rocky core. It is also important to determine the conditions under which Enceladus would have survived disruption by collisions with deca-kilometric objects, which would place constraints on its accretion and the subsequent impact history.

To constrain the consequences of large-scale impacts on Enceladus, we simulated head-on collisions of differentiated impactors with diameter ranging between 50 and 200 km using the iSALE2D shock physics code (Wünnemann et al., 2006; Collins et al., 2004; Davison et al., 2010). From these simulations, we tracked the evolution of rock fragments coming from the impactor and the impact-induced modification of Enceladus's core shape. In particular, we quantified the sensitivity in these outcomes to key model parameters, such as impactor velocity and radius, as well as structure and mechanical properties of Enceladus' interior (porosity, strength, temperature profile, core size, presence of an internal ocean). In Section 2, we describe our numerical modelling approach; in Section 3 we present our results. We discuss our results in the context of the presence of a water ocean in Section 3.3. Conclusions are highlighted in Section 4.

2. Impact modeling

To model the thermo-mechanical evolution of material during an impact between two differentiated icy bodies, we use iSALE2D (Wünnemann et al., 2006; Collins et al., 2004). This numerical model is a multi-rheology, multi-material shock physics code based on the SALE hydrocode (Amsden et al., 1980) that has been extended and modified specifically to model planetary-scale impact crater formation (e.g., Amsden et al., 1980; Melosh et al., 1992; Ivanov et al., 1997; Collins et al., 2004; Wünnemann et al., 2006; Davison et al., 2010). In our simulations, the target structure and the impactor were simplified to two- or three-layer spherical bodies consisting of a rocky core, an icy mantle and for the three-layer case an internal ocean. Interpretation of gravity data collected by the Cassini spacecraft indicates that the core density could be as low as 2400 kg m^{-3}, corresponding to a core radius of about 200 km (Iess et al., 2014). However, as Enceladus appears to be relatively far from hydrostatic equilibrium (Iess et al., 2014), there are still significant uncertainties on the core radius and density. The low core density inferred from gravity data suggests that the rocky core might be significantly porous, with pores filled by water ice and/or liquid water, and that a significant fraction of the core may consist of hydrated silicate minerals. Currently, iSALE2D does not have provision to describe the behavior of an ice–rock or water–rock mixture. In our simulations, for simplicity, we assume complete segregation of the rock and ice-water phase into discrete layers and we consider dunite as representative of the rock phase (with density $\rho_s = 3330$ kg m^{-3}). We reduce the density of the core by including some initial porosity ϕ (defined as the ratio of pore volume to total volume) within it, varying from 0% to 50%, corresponding to radius varying between typically 160 km and 200 km. Assuming a core made of pure dunite, a radius as large as 200 km is consistent with a core porosity of about 50%, which is at the upper end of the estimated porosity in large asteroids (Lindsay et al., 2015). A significant fraction of the core may also consist of hydrated minerals such as serpentine. In this case a 200 km core radius would imply a lower porosity. For simplicity, we consider only dunite as core materials and vary the porosity up to values of 50%. We also test the possible effect of porosity in the ice shell by considering values up to 20% as suggested by Besserer et al. (2013).

In our models, we consider the extreme case where the pores of both ice and rocks consist of voids, and are not filled with secondary materials (i.e. water or ice in rock pores). The difference between saturated porosity (with ice or liquid water) and voids may lead to differences in terms of mechanical and thermal properties. This aspect will be discussed in the last section. The effect of both rock and ice porosity is treated using the ϵ–α porosity compaction model (Wünnemann et al., 2006; Collins et al., 2013), which accounts for the collapse of pore space by assuming that the compaction function depends upon volumetric strain. For sake of simplicity, we assume that the impactor material has an identical composition and porosity to those of the target.

The impact velocity v_{imp} can be decomposed into two contributions:

$$v_{imp} = \sqrt{v_{esc}^2 + v_{\infty}^2} \quad (1)$$

where v_{esc} is the escape velocity of the impacted planet and v_{∞} is the velocity of the impactor at a distance much greater than that over which the gravitational attraction of the impacted planet is important. The escape velocity of Enceladus is $v_{esc} = 240$ m/s. As we consider collisions with relatively large objects (R_{imp} = 25–100 km), we limit our analysis to moderate relative velocities, varying between v_{esc} and $10 \times v_{esc}$, in order to limit the impact-induced deformation of the satellite and avoid full disruption (Benz and Asphaug, 1999; Asphaug, 2010). Moreover, this low-velocity impact regime is representative of the collisional environment at the end of the accretion. Indeed, N-body simulations from Dwyer et al. (2013) show that random impact velocity of proto-satellites mostly ranges between v_{esc} and $5\,v_{esc}$.

We approximated the thermodynamic response of the icy material using the Tillotson EoS for Ice as in Bray et al. (2008) and of the rocky material using the ANEOS EoS for dunite material as in Benz et al. (1989) and Davison et al. (2010) (see Table 1 for parameter values). Standard strength parameters for dunite were used to form the static strength model for the rocky core (Collins et al., 2004; Davison et al., 2010). The static strength model for ice used in iSALE was derived from low temperature, high pressure laboratory data and accounts for the material strength dependence on pressure, damage and thermal softening (Bray et al., 2008). We also explored the effect on our results of the cohesion of the damaged material (referred to here as Y_i for ice and Y_s rocks), which represents the minimum zero-pressure shear strength of cold material (strength is reduced to zero at the melt temperature). The minimum strength values considered in our models range between 10–500 kPa for ice and 100–10^4 kPa for silicate material. The Tillotson EoS for ice is severely limited in its applicability for hypervelocity impact; it includes no solid state or liquid phase changes. However, as we limit here our analysis to low velocity encounters ($240 < v_{imp} < 2400$ m s^{-1}), thought to be dominant at the end of the accretion, as shown in our simulations, no significant ice melting occurs and the use of Tillotson EoS is a reasonable approximation. We also used the Tillotson EoS for the liquid water.