Hydrocode modeling of ice-penetrating impacts on Jupiter's moon, Europa

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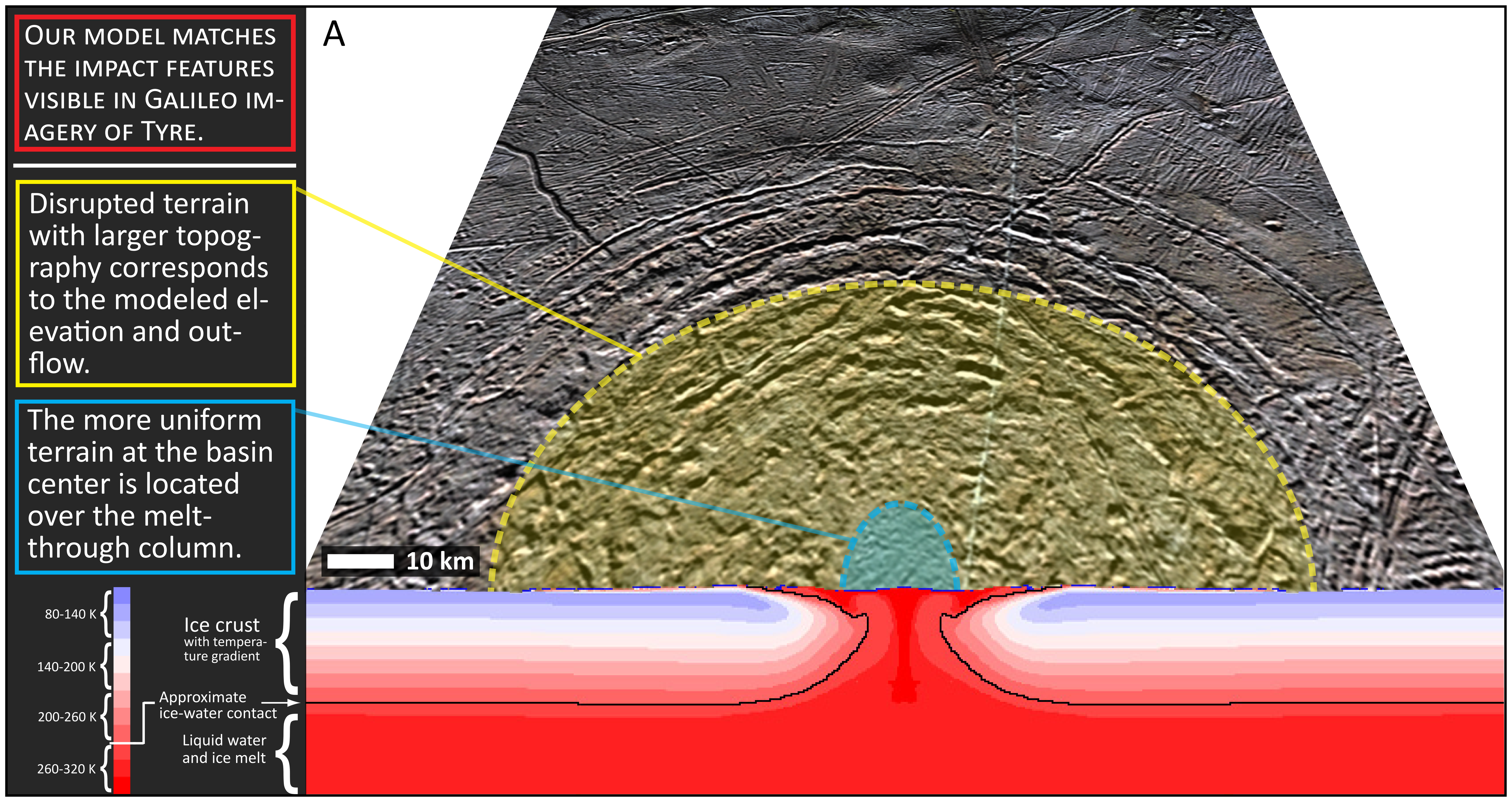
Introduction

Europa's ice crust appears to overlie a water ocean (Schubert et al. 2009). If ice thickness is ≤20 km (indicated by crater depth-diameter ratios and lithostatic stress constraints: Schenk 2002), impacts of sufficient energy could break through to the underlying water; but little is known about the impact conditions under which this could occur, or what the morphology of resulting impact sites would be. We have modeled combinations of bollide sizes and crust thicknesses to create a matrix of impact outcomes (Table 1). We have also investigated the nature of Europa's multi-ringed basins, focusing on Tyre, and our results suggest that the impact event caused complete melt-through of the underlying crust.

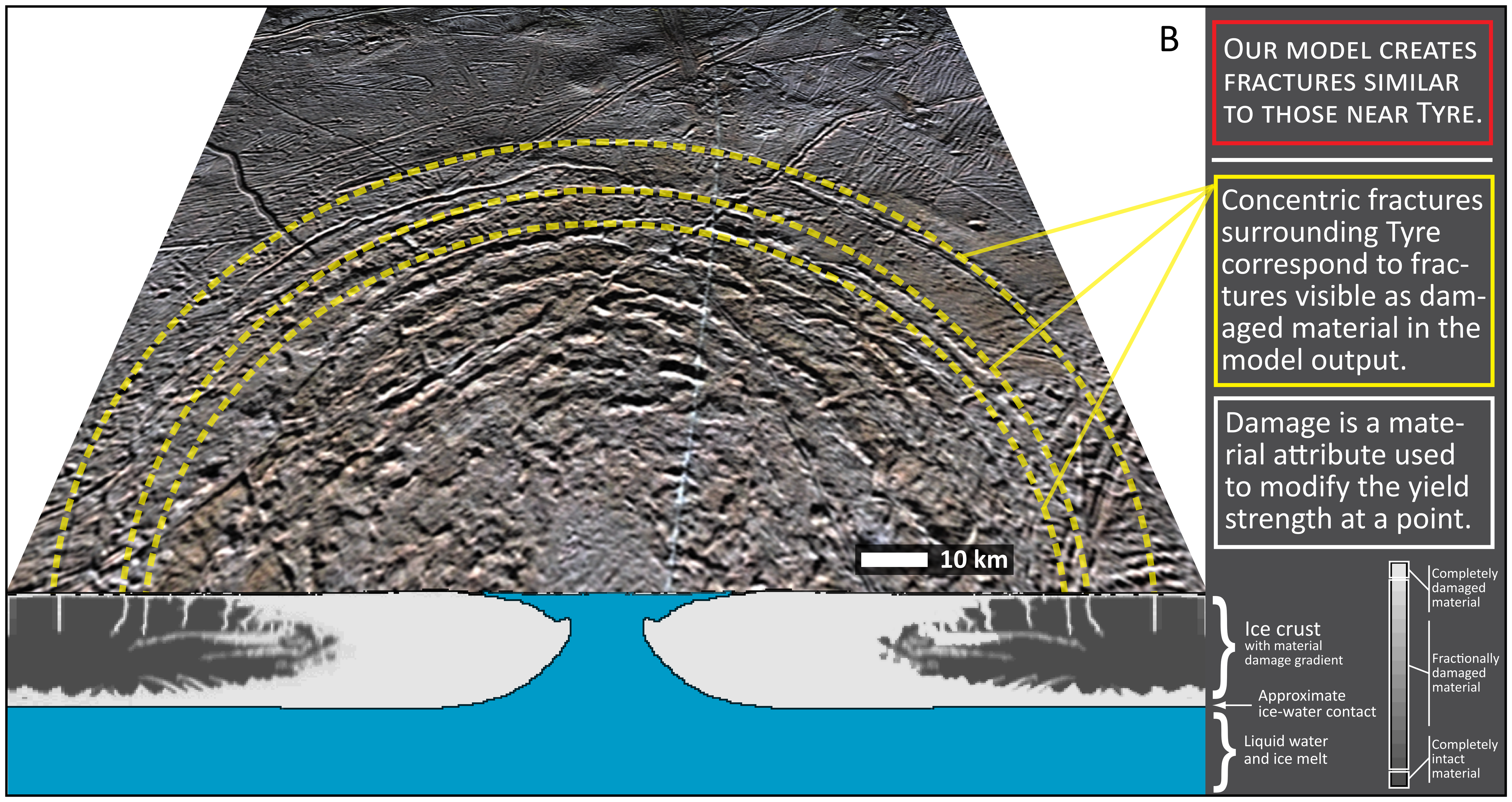
Methods

We used the iSALE hydrocode (Amsden et al. 1980, Ivanov et al. 1997, Wunnemann et al. 2006) to produce full-scale models of impacts at Europa. We used a cometary impactor with density 910 kg/m^3, and phsyical parameters as outlined in Tabel 2. We validated our model by reproducing the depth-diameter ratios of mapped craters on Europa (Schenk 2002), and then ran experiments in which we tested for ice response and impact site morphology under different sets of impact conditions (Table 1). To reproduce the multi-ringed basin Tyre, we used a bollide size of 2 km (calculated based on Tyre's crater diameter, using equations in Zahnle et al. 2003), and a crust thickness of 20 km (based on Shenk's (2002) analysis of crust thicknesses beneath Europan craters). We used the nominal average impact velocity at Europa, 26.5 km/s (Zahnle et al. 2003).

Modeling accurately reproduces Europa's Tyre



The block diagrams A and B show our model output 1500 seconds after impact along with Gallileo images of Tyre at the same scale. A is color-coded for temperature and B is shaded to show the degree of crustal damage. The model (a 2 km diameter comet impacting 20 km ice over water, with impact velocity 26.5 km/s) indicates that impact melting extends through the full thickness of the crust, that meltwater outflows beyond the crater rim, and that concentric fractures are created 70-90 km from the crater's center. The locations of crater rim and ring fractures in our models correspond well with those in the Galileo imagery.



Impact site morphologies

Crust Thickness (km) \ Impactor Diameter (meters)	50	500	800	1000	1500	2000	3000	5000
1		P		P				
2		P						
3		P						
4		P						
5	C	M	P	P		P		
10	C	C	M	M	P	P		
15	C		C	C	M	P		
20	C		C	C	C	M	P	P
30						C		

Table 1. A summary of the outcomes of our simulations classified as either crater-forming (C), melt-through (M), or penetrating (P).

Variable	Description	Value
ν	Poisson ratio	0.33
Y_0	Strength of intact ice at zero pressure (Senft 2009)	10 MPa
Y_c	Strength of damaged ice at zero pressure (Senft 2009)	0.0 MPa
Y_m	Strength of intact ice at infinite pressure (Senft 2009)	115 MPa
μ_i	Internal friction coefficient for intact ice (Senft 2009)	2.0
μ_d	Internal friction coefficient for damaged ice (Senft 2009)	0.55
T_m	Melting temperature	273 K
ξ	Thermal softening parameter	1.2
k	Thermal conductivity (Barr and Showman 2009)	3.3 W/m/k
γ_η	Scaling parameter for A.F. viscosity (Wünnemann and Ivanov 2003)	0.1
γ_T	Scaling parameter for A.F decay constant (Wünnemann and Ivanov 2003)	150
C_{vib}	Maximum vibration particle velocity (Senft 2009)	0.25
T_{off}	Time after which no new A.F. pressure vibrations are generated (Senft 2009)	60 s

Table 2. The material parameters our models used to simulate the ice crust and bollide. These include strength, temperature and acoustic fluidization (A.F.) parameters.

Take home message:

Our numerical models accurately reproduce the geometry of Tyre, and therefore suggest that full-crustal melt-through occurred during formation of the structure. The 2-km bollide represented by our Tyre model has a return interval of <10 m.y., so larger impacts have definitely occurred on Europa. Our models of a range of impacts indicate that these could produce impact breaches of the crust, which would result in open holes in the ice, possibly represented by chaos terrain.

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