HYDROCODE MODELING OF IMPACTS AT EUROPA

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Introduction: Previous hydrocode simulations (e.g. [*1*]) have shown that impacts of sufficient energy could break through Europa's ice crust to the water layer that probably underlies it [*2*], and this provides limiting criteria for formation of first-order (non-penetrating) craters [*3*]. But as the first-order crater population on Europa is small (24 known ≥ 10 km [*4*]), and as estimates of ice thickness (< 1 km to a few 10s of km [*5, 6*]) intersect with the penetration capabilities of likely impactors [*3*], it's necessary to think broadly about a range of possible impact outcomes, and especially about the potential effects of large impacts or impacts into areas of thinner crust.

First-order impacts are contained within the solid crust, and make craters of various kinds; these are well-studied although still not fully understood [*3, 7*]. *Second-order impacts* create an ocean-to-surface connection via melt-through and/or crust-penetrating fractures, and are implicated in generation of multi-ring basins such as Tyre and Callanish [*8-10*]. *Third-order impacts* are those that punch completely through the ice, producing some sort of large hole that exposes the underlying ocean [*8*]. These are both hypothetical and controversial [*11*], but worth thinking about.

We report here results of hydrocode simulations that provide constraints on ice penetration—both second and third order—for crust thicknesses and impact energies within the range of those expected at Europa.

Methods: We used the iSALE hydrocode [*15-17*] to model impacts at Europa. Following Bray's [*18*] approach, we based our simulations on an ice impactor with density 910 kg/m^3 impacting at velocity 15 km/sec, using the Tillotson equation of state, and with initial model resolution of 10 cells per projectile radius (re-running some models subsequently at higher resolution to check details). We modeled a thermal profile across the ice and implemented acoustic fluidisation (AF). Physical parameters are outlined in Table 1. We validated our model by reproducing depths and diameters of mapped Europan craters [*19*], and ran experiments in which we tested crust response under different sets of impact conditions (Table 2).

Table 1: Hydrocode input parameters

Variable	Description	Value
ν	Poisson ratio	0.33
Y0	Intact ice strength, zero P [12]	10 MPa
Yc	Damaged ice strength, zero P [12]	0.0 MPa
Ym	Intact ice strength, infinite P [12]	115 MPa
μi	Intl. friction coeff., intact ice [12]	2.0
μd	Intl. friction coeff., damaged ice [12]	0.55
ξ	Thermal softening parameter	1.2
k	Thermal conductivity [13]	3.3 W m^{-1} k^{-1}
γη	AF viscosity scaling [14]	0.1
γT	AF decay constant scaling [14]	150
Cvib	Max. vibration particle velocity [12]	0.25
Toff	End AF P vibrations [12]	60 s

To model the multi-ringed basin Tyre we used impact energy 1.33 x 10^{21}J, equivalent to a comet of 2 km diameter striking 20 km thick ice over water at the 26.5 km/s nominal average impact velocity at Europa. We chose the 2 km comet size based on Tyre's crater diameter, using data and equations in [*20*]; and the ice thickness of 20 km from analysis in [*19*].

Reproducing Tyre: Previous studies have concluded that Tyre records interaction between the impact process and a liquid or at least mobile layer at depth [*7, 9, 10*], but the nature of that connection has been speculative. Our hydrocode simulations suggest that Tyre's features—including crater depth and diameter, and the suite of concentric fractures out to several crater radii—could be produced by a 2 km comet impacting 20 km thick ice at 26.5 km/sec.

The results of the simulation map well onto the imaged geomorphology of Tyre (Fig. 1). Discrete fractures generated in the upper levels of the ice by the hydrocode correspond—both in terms of location and spacing—to the ring fractures that surround Tyre. The water-filled centre of the structure is the result of post-impact melt-through. The transient cavity extends to a maximum depth of ≈18 km at 70 seconds after impact. Ice (although fully damaged and warmed almost to melting) persists beneath the impact site until ≈600 seconds into the simulation. At that point, central – peak collapse intersects with the rebounding ice-water contact, resulting in a melt-through column extending from the surface to the underlying water.

A series of tsunami-like gravity waves generated during multiple episodes of peak formation and collapse wash in a thin layer across the ice surface. The washover consists of impact melt in the first event, with water from the underlying ocean turbulently admixed in subsequent waves. The thickness of the wave-transported water layer is not well resolved in our model because of resolution limits (and is not shown at the scale of Fig. 1), but is of order 10s of m at maximum thickness, grading to zero ≈30 km beyond the crater rim. What proportion remains on the ice surface to freeze, and what proportion drains back into the impact hole, is not resolved in our model. Finally, the impact site evolves to a very low-relief final profile.

Impact penetration of Europa's ice layer: Numerical simulations indicate that the full range of likely ice thicknesses [*5, 6*] is susceptible to penetration by impactors (Table 2). As impact energy increases at constant ice thickness, the impact outcome changes from first order crater through second order melt-through event, to impact punch-through.

Ice 10 km thick is punctured by a 1 km impactor (at 26.5 km/sec). A 2 km impactor will punch through ice 15 km or less, and will melt through ice up to 20 km thick (Fig. 1). We have not yet run simulations for the larger impactors, but we hypothesise that a 2.5 or 3 km object will melt through 30 or 35 km thick ice (we hope to have these results by time of the meeting).

Impacts of this size are not rare: Tyre-type events have probable recurrence interval < 10 m.y., and impactors capable of producing 100 km craters (≈5 km comets) have recurrence ≈30 m.y. [*20*]. Extrapolation from our data suggests a 5 km object would penetrate through even the 35 km upper limit on ice thickness given by [*6*]. That Europa's ice layer has been penetrated by impact therefore seems highly likely.

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Table 2: Simulation results for impactors 0.5-2 km diameter, and crust thicknesses 5-30 km. Empty cells represent no data; only bolide size-ice thickness pairs that have been modeled are shown.

	Impactor diameter (m)				
	50	**500**	**1000**	**1500**	**2000**
Ice (km)					
5	Crater	Melt-through	Punch through		Punch through
10	Crater	Crater	Melt-through	Punch through	Punch through
15	Crater		Crater	Melt-through	Punch through
20	Crater			Crater	Melt-through
30					Crater

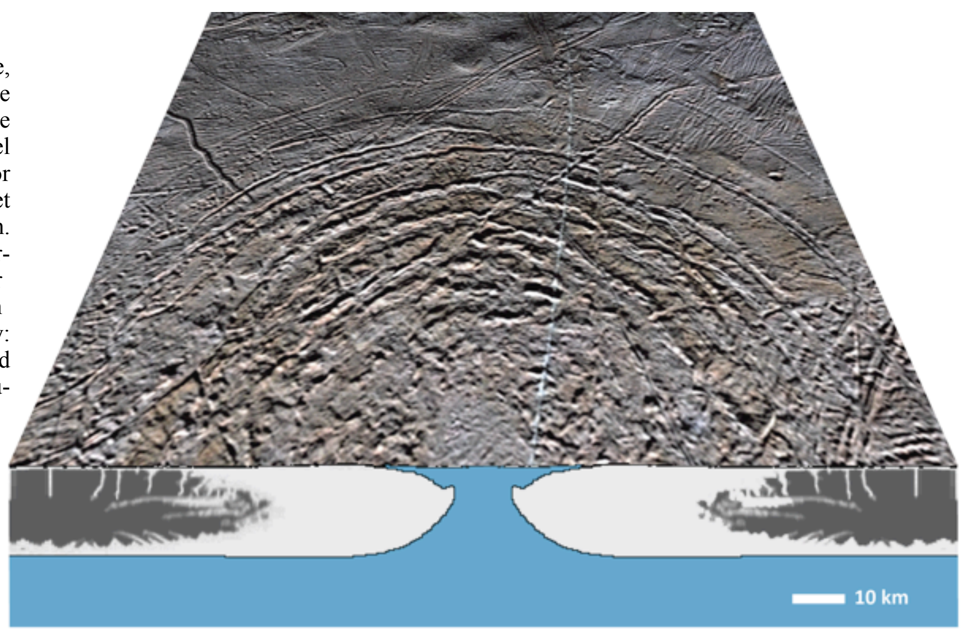

Fig. 1. Schematic cross-section of Tyre, produced by superimposing hydrocode results on Galileo imagery at the same scale. Hydrocode data in front panel represent 1500 seconds post-impact, for energy input equivalent to a 2 km comet at 26.5 km/sec. Ice thickness is 20 km. Colours on front panel represent different material properties. Blue: water (impact melt not differentiated from water sourced from beneath ice). Grey: undamaged ice. White: fully damaged ice (damage is a material attribute calculated by iSALE).