THROUGH THE ICE, EXPOSING THE OCEAN: IMPACT BREAKTHROUGH PARAMETERS FOR EUROPA

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Introduction: The idea that impacts could deposit organic and other compounds on Europa's surface is well established, but whether and how these materials might be transported to a subsurface ocean remains in question [*1*]. Previous studies have shown that Europa's ice shell is vulnerable to impact breaching [*2, 3*], and this analysis quantifies the conditions under which impacts might penetrate to water. Impact exposure of the ocean would provide a conduit for surface-subsurface exchange of biogenic materials.

Methods: We used the iSALE hydrocode [*4-6*] to model ice overlying water. We simulated ice thicknesses (T) from 1-40 km to cover the range of likely values for Europa [*7*]. Impactors were ice spheres of density 910 kg/m^3. Median impact velocity at Europa is about 26 km s^{-1} [*8*], but since high impact velocities require smaller time steps, we ran simulations at lower velocity (15 km s^{-1}) and scaled projectile size to produce the energies of interest [*9*]. Impactor diameters (26 km s^{-1} equivalent) ranged from 200-5000 m .

Impact outcomes and breakthrough criterion: Craters form when the ratio between impact energy and ice thickness is small (in thick ice or for small impactors). But as energy increases, transient crater depths (d_t) approach the ice-water contact [*3, 9*]. Surface-to-ocean communication occurs when the full ice thickness is melted or vapourised [*3, 9*]. The transition from non-penetrating craters to ocean-exposing melt-through events comes at $d_t \approx 0.8T$, where post-impact melting and rebound of the sub-crater ice combine to produce a surface-to-ocean water column; so we take $d_t = 0.8T$ AS the breakthrough criterion.

Largest possible non-penetrating craters: The upper limit on crater size at Europa depends on ice thickness. For ice 40 km thick, the largest possible non-penetrating crater has transient diameter (D_t) ≈80 km, which would produce a final diameter ≈160 km: there are no craters of this size on Europa. For 20 km ice, the upper limit for a crater-producing event is D_t ≈40 km, which is close to the estimated D_t for Europa's largest mapped craters [*10*]. This may be telling us that the likely ice thickness on Europa is in the 15-20 km range, which lines up with results from other lines of evidence [*7*].

Likelihood of breakthrough: All ice thicknesses tested are subject to full penetration by impactors with geologically short return times at Europa. The return time for a 5-km diameter cometary impact (100-km crater) is about 50 m.y. [*8*]. Such an object impacting 40 km-thick ice at 26.5 km s^{-1} produces d_t 38 km deep, with subsequent melt-through to ocean. For ice 10-20 km thick, the breakthrough criterion is met by impactors 0.8-2 km diameter (return times 3-15 million years [*8*]). Most estimates for Europa's ice thickness are in the 10-20 km range [*7*], so we expect that Europa's ice can be breached on timescales of 10^6- 10^7 m.y.

Evidence for breakthrough at Europa? Impact penetration to liquid has been proposed to explain features of Callanish and Tyre, Europa's largest craters [*10, 11*]; and also as a mechanism for forming chaos terrane [*2, 12-14*]. Our numerical models support these interpretations and suggest a need to consider impact breakthrough as a geomorphic process on Europa.

Implications of impact breakthrough: Exposure of the ocean via impact represents a protracted opportunity for transfer of materials into the subsurface realm because refreezing is estimated to take 10^5-10^6 years [*14*]. Although mass delivered by the hole-forming impactor is unlikely to end up in the ocean [*1*], ejecta from subsequent impacts might well land on its receptive, still molten surface. Cometary organic matter can survive and be retained by Europa's gravity field [*15*]; such material, released and impelled by subsequent impacts elsewhere on the moon, might fall onto older but incompletely frozen impact sites, and thence into the subsurface ocean.

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