LETTER

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Active formation of 'chaos terrain' over shallow subsurface water on Europa

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Europa, the innermost icy satellite of Jupiter, has a tortured young surface[1–4] and sustains a liquid water ocean[1–6] below an ice shell of highly debated thickness[1–5,7–10]. Quasi-circular areas of ice disruption called chaos terrains are unique to Europa, and both their formation and the ice-shell thickness depend on Europa's thermal state[1–5,7–17]. No model so far has been able to explain why features such as Conamara Chaos stand above surrounding terrain and contain matrix domes[10,18]. Melt-through of a thin (few-kilometre) shell[3,7,8] is thermodynamically improbable and cannot raise the ice[10,18]. The buoyancy of material rising as either plumes of warm, pure ice called diapirs[1,9–15] or convective cells[16,17] in a thick (>10 kilometres) shell is insufficient to produce the observed chaos heights, and no single plume can create matrix domes[10,18]. Here we report an analysis of archival data from Europa, guided by processes observed within Earth's subglacial volcanoes and ice shelves. The data suggest that chaos terrains form above liquid water lenses perched within the ice shell as shallow as 3 kilometres. Our results suggest that ice–water interactions and freeze-out give rise to the diverse morphologies and topography of chaos terrains. The sunken topography of Thera Macula indicates that Europa is actively resurfacing over a lens comparable in volume to the Great Lakes in North America.

Although the settings are different, terrestrial environments can provide critical context for Europa, particularly where water and ice interact under pressure. Melting of ice occurs at subglacial volcanic craters on Earth, such as Iceland's Grimsvotn[19] (Supplementary Fig. 4). Ice covers the volcano, and as it becomes active, the ice cap melts from below, causing surface down draw[19]. Water in glacial systems flows perpendicular to the gradient of the fluid potential (Supplementary Information section 2). In pure ice, the surface slope above a water body is roughly 11 times as important as the basal slope in determining flow direction[19,20], and water collects where the hydraulic gradient approaches zero, at the centre of the depression. Above the activating volcano, the surface slope is steepest at the flanks of the crater, creating a hydraulic seal that prevents the escape of water and drives the formation of a lens-shaped subglacial lake[19,20]. Because Iceland's ice caps are finite in width, breakout flow along the bed or floatation of the ice cap eventually allows water to escape[19,20].

Water also influences Antarctic ice shelves. Brines enter terrestrial ice shelves through basal fractures or the front of the shelf (via a porous layer called firn) and percolate through the ice for tens of kilometres over many years[21]. Beyond enhancing its water and impurity content, introduction of brine can weaken the ice by reducing its shear strength[21–23]. Hydrofracture occurs when tidal cracks fill with water, causing force at the crack tip, which can initiate ice shelf collapse[22,23] (Supplementary Information section 2), producing tabular icebergs surrounded by a matrix of brine-rich ('brash') ice.

Coupled analysis of the geomorphology of Conamara Chaos and Thera Macula, (Figs 1 and 2, respectively) demonstrates that the two features share a quasi-circular shape and floating blocks, whereas their topography differs. Conamara Chaos is raised and contains raised matrix 'domes'. Thera Macula, however, is sunken below the surrounding surface. These observations, informed by the environments on Earth described above, suggest a four-phase 'lens-collapse model' for chaos terrain formation (Fig. 3). (1) Ascending thermal plumes of relatively pure ice[13] cross the eutectic point of overlying impure ice, producing surface deflection in response to volume change associated with pressure melting of the ice (Fig. 3a). (2) Resulting hydraulic gradients and driving forces produce a sealed, pressurized melt lens (Fig. 3b). (3) Extension of the sinking brittle ice 'lid' over the lens ultimately generates deep fractures from below, allowing brine to both be injected into and percolate through overlying ice, forming a fluidized granular ice matrix and calving ice blocks (Fig. 3c). (4) Refreezing of the melt lens and now brine-rich matrix results in topographic heterogeneity (Fig. 3d).

The upper crust of Europa is rich in impurities owing to either exogenic implantation or endogenic injection (see, for example, refs 24, 25). Models suggest that melt will be formed as warm, compositionally buoyant plumes cause the cold impurity-rich ice above them to reach its eutectic pressure-melt point, driving partial melting and ice disruption[1,2,9–15,17]. Interconnected pockets of thermally stable melt water will form above a plume and be over-pressurized by an amount equal to the buoyant force of the plume, 10^4–10^5 Pa (ref. 13). It is significant that previous models did not take into account the volume change associated with melting ice[15] and its ramifications [19,20]. Ice melting results in surface draw down, which hydraulically seals the melt in place [19,20] (Fig. 3b; Supplementary Information section 2), rather than melt draining downward as previously speculated[10,13–15,17,26]. That is, water formed from melting above plumes must move perpendicular to local hydraulic gradients, both up the plume head and towards the centre of the depression[24], and will form a lens similar to subglacial volcanic lakes. Ultimately, the volume of melt and hydrostatic equilibrium with the overlying depression determine the shape of the lens; this shape will be slightly modified by any lithostatic stresses at the edge of the lens. On Europa, the lateral continuity of the ice shell prohibits horizontal escape of the water.

Pressure and fracture will contribute to the response of Europa's ice shell to subsurface melting. Prevalent pre-existing faults and discontinuities in ice strength should be regions of localized weakness, akin to ice shelf fractures, accumulating much of the extensional strain from the subsidence of the lid. As cracks propagate upward from the melt lens, hydrofracture will break up the ice (Fig. 3c) wherever high-pressure water inflow contributes force at the crack tip[22,23]. Fracture will calve steep-sided blocks and allow water to enter overlying brittle ice.

The morphology of Conamara Chaos requires the transformation of mostly background plains material[3,11,14] into an impurity-rich matrix (Supplementary Figs 1, 6). Background plains material is characterized by high fracture density, and thus may be more susceptible to brine inflow and disruption as observed[11,14]; the shallow subsurface may also

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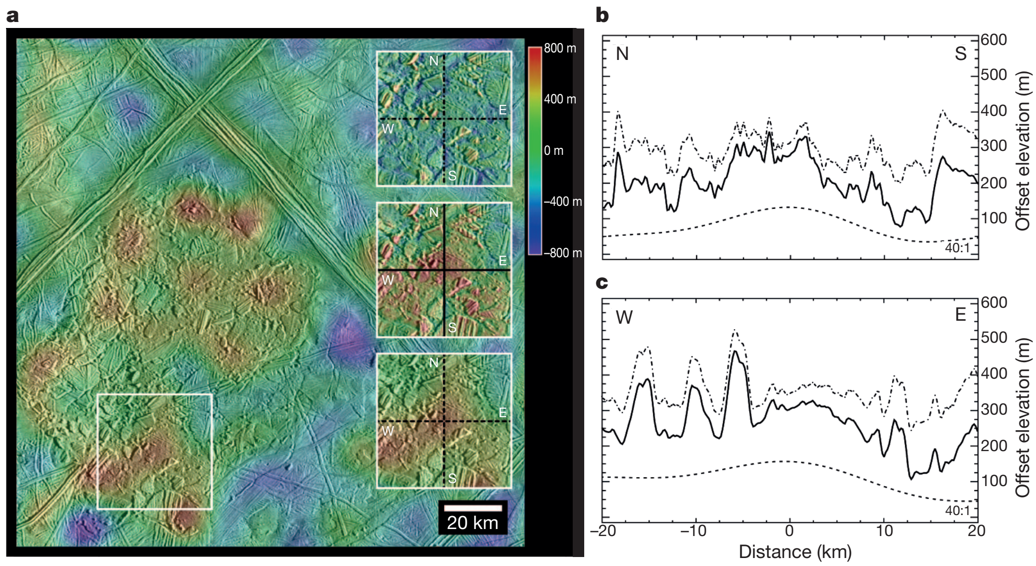
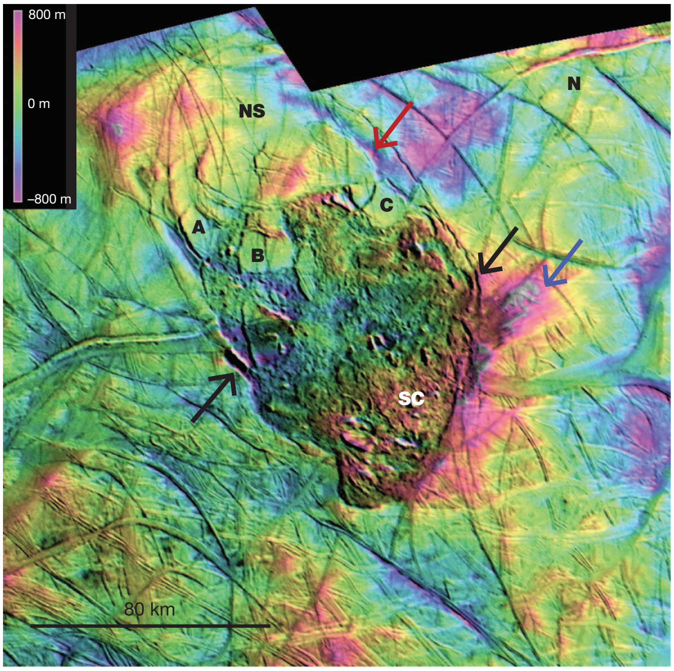


Figure 1 | Conamara Chaos is dominated by long-wavelength topography. The region's (8° N, 274° W) topography was analysed by filtering a DEM (Digital Elevation Map) produced through a combined stereo photogrammetric and photoclinometric method (Supplementary Information section 1). The DEM has a spatial resolution of 180 m per pixel, and height accuracy of 20 m. Colour indicates topographic heights relative to the background terrain. **a**, Conamara Chaos. The area boxed in white (bottom left) indicates the locations of the top, middle and bottom insets shown right. Insets show, top to bottom, the short-wavelength (<20 km), absolute, and long-wavelength (>20 km) topographic signals produced by the DEM filtering. **b**, **c**, North–south (**b**) and east–west (**c**) topographic profiles of a typical dome-like matrix swell. Solid lines, the DEM; dashed and dashed-dot lines, the long- and short-wavelength topography, respectively. The profiles are offset in elevation for clarity and vertical exaggeration is 40:1. Overall, the topography is characterized by highs within the disaggregated ice matrix and lows at large polygonal block-like icebergs. Conamara Chaos appears to have completely disrupted the ice fringed by its boundary scarp, and to have thickened relative to the background terrain. Matrix 'domes' reach heights typically of 200 m. These domes can entrain or tilt some smaller blocks. Large blocks represent the lowest points within the region, with heights equivalent to or up to 100 m below the background elevation. On average, the entire region is raised by ~100 m. Comparing insets in **a**, the short-wavelength topography has little spatial variation, while the spatial patterns of the DEM and long-wavelength topography are similar, demonstrating that the long-wavelength signal contributes strongly to Conamara Chaos's heterogeneous topography. That the highest topography is (1) rounded in shape and (2) located within or 'controlled' by matrix swells, indicates that water injection within the matrix and subsequent freezing is responsible for topographic heterogeneities within mature chaos terrain.

be porous. This weak ice can then be disrupted by transient pressure from below, by diurnal tides, by wedging in freezing cracks or by interactions with translating blocks, eventually breaking down into the observed impurity-rich matrix[1,3,7,18]. This mechanism will convert plains material into matrix without requiring thermodynamically unlikely surface melt (see, for example, refs 10, 18).



Conamara Chaos is not only elevated above the background terrain, but also contains matrix domes that are in some places higher than blocks[9,18] (Fig. 1). This observation was initially interpreted as resulting from the coalescence of multiple warm ice diapirs[9]. However, Conamara Chaos's continuity and nearly unbroken margin is more consistent with a single source of disruption. The lens-collapse model implies that brines are injected into former plains material as the ice fractures (Supplementary Fig. 6), while increased water pressure from the lens freezing raises the saturation level within the permeable matrix

Figure 2 | Thera Macula is a region of likely active chaos production above a large liquid water lens. The image of There Macula was produced using photoclinometry (Supplementary Information section 1) of Galileo images with illumination from the north (N) and 220 m per pixel resolution. Colour indicates topographic heights relative to background terrain. The region (50° S, 180° W) exhibits Conamara-like icebergs and dark matrix. The centre of Thera Macula is sunken below the background terrain (denoted here by pale green) by up to ~800 m just outside a large semi-circular northern subsiding province (NS), and shows evidence for thickening of matrix in its southern chaotic terrain (SC), which is elevated above the background terrain by up to ~800 m. Despite the distinct difference between the morphologies of the NS and the SC, they share a nearly continuous circular scarp boundary (red and black arrows), suggesting that they formed from a common subsurface disruption. Blocks A, B and C are calving at reactivated pre-existing fractures. Within the NS, the platy-blocks appear bent, presumably by basal thinning and subsidence, and the edge of the NS appears ready to break or is being thinned (red arrow). Tall scarps (black arrows) either cast shadows (southern facing) within the region's interior or have bright faces (northern facing), demonstrating the relatively low-lying nature of the centre of Thera Macula. To the lower right, an older band or ridge complex interrupted by the disruption of Thera Macula appears to be swelling along its ridge-like lineations, consistent with brine infiltration and refreeze (blue arrow). The still sunken topography of Thera Macula is indicative of subsurface water.

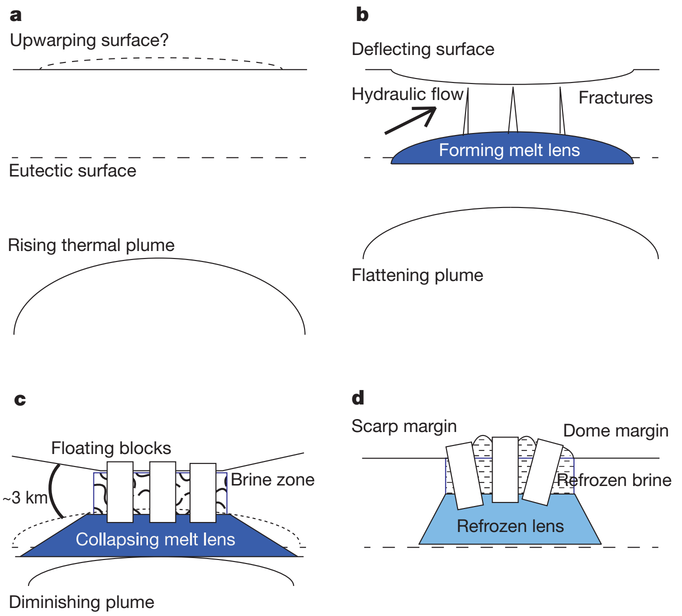


Figure 3 | A new hypothesis for chaos formation. **a**, An ascending thermal plume in the subsurface approaches the pressure-melting eutectic point of the overlying impure brittle ice. **b**, Melting causes surface subsidence that hydraulically confines water, and produces tensile cracks. This behaviour is governed by the relationship[19,20]

$$\nabla\phi_b = (\rho_w - \rho_i)g\nabla z_p + g\rho_i\nabla z_s \qquad (1)$$

where ϕ_b is the fluid potential at the lens base (initially the plume head), ρ_i and ρ_w are the densities of ice and water, and z_p and z_s are the elevations of the base and the surface relative to the geoid, respectively. The slope factor, $\rho_i/(\rho_w - \rho_i)$, which is dependent on the impurity content of the ice and water, determines the relative importance of the surface and basal slopes in controlling the direction of water flow. Equation (1) requires that the melt form a lens-shaped pocket with finite effective pressure due to the plume below and overburden from the ice above, unless the slope over the lens is $\rho_i/(\rho_w - \rho_i)$ times steeper (and in the opposite sense) than the surface slope within the depression. Ultimately the lens top must reach hydraulic equilibrium between the melt volume and the melt-induced depression overlying it. **c**, Hydrofracture from the melt lens calves ice blocks, while fracture and brine infiltration form a granular matrix. **d**, Refreezing of the melt lens and freezing of now brine-rich matrix raises the chaos feature above surrounding terrain, and can cause domes to form between blocks and at margins. Note also that the topography at chaos margins can depend both on the ice type at the margin as well as the direction of the ice collapse. Where deep fractures of blocks define the margin, steep scarps are expected, whereas boundaries defined by matrix (or shallow fractures) will warp into a dome.

(Fig. 3d). This now brash ice eventually swells in response to thermal expansion of freezing brines that fill its once empty pores and cracks. The thickening of brine-infiltrated ice will raise chaos terrains above undisrupted blocks of background terrain and form matrix domes, as confirmed by our analysis of the detailed topography of Conamara Chaos (Fig. 1; Supplementary Information section 1).

Whereas block morphology and motion[3,11] chronicle chaos kinematics, matrix preserves a record of its thermodynamics and Europa's ice rheology. The addition of a minimum of 940 km^3 of liquid water into the matrix is required to produce the average height of Conamara Chaos (Supplementary Information section 3); this is probably only a small fraction of the lens required to produce such a large feature. Also, the stability of any floating ice block to toppling within the matrix depends strongly on its shape[27,28]; rectangular blocks are stable against toppling for aspect ratios (thickness to width) below ~1.4 (ref. 28). The smallest tilting blocks at Conamara Chaos thus give us an estimate of the depth to liquid water when they formed. The smallest upright but tilting (conditionally stable) blocks are ~2 km wide[11], and thus ~2.8 km thick, providing an estimate of the brittle layer's thickness and the minimum depth of water lenses. Ice block and matrix dome heights within Conamara Chaos (Fig. 1) are consistent with 10–35% ice porosity for reasonable brine densities (Supplementary Information section 3).

Most importantly, the lens-collapse model developed here makes testable predictions: whereas swelling matrix indicates lens freeze-out, liquid water may be found where the surface subsides and blocks 'float' above the matrix. At Thera Macula, we are probably witnessing active chaos formation (Fig. 2). The large concentric fracture system encircling Thera Macula resembles those of collapsing ice cauldrons[19,20] (Supplementary Fig. 4), and, given the absence of a continuous moat, suggests that subsurface melt and ice disaggregation is forming Thera Macula, rather than the collapse of a dome[29]. Topographic contrast indicates that the rapid freeze of matrix is occurring at the region's south, but surface slopes, ice blocks and incomplete break-up to the north indicates that the lens below Thera Macula was liquid at the time of the Galileo encounter. Today, a melt lens of 20,000–60,000 km^3 of liquid water probably lies below Thera Macula; this equates to at least the estimated combined volume of the Great Lakes (Supplementary Information section 3). Although it is unclear how rapidly the break-up of Thera Macula took place, such a volume would take ~10^5–10^6 years to freeze. Surface modification should be extensive just after the collapse and persist as long as the lens is mostly liquid, such that Thera Macula may have noticeable changes between the Galileo encounter and the present day. Such features can be well understood by coupled topographic and subsurface imaging[30].

The existence of globally distributed chaos terrain[1,2] argues that pervasive shallow subsurface water has existed and continues to exist within Europa's icy shell; surface draw down at Thera Macula suggests that it exists within 3 km of the surface. The lens-collapse model presented here explains previously discrepant observations of chaos (refs 10, 18; Supplementary Information section 4). Our work predicts that it is the scale of ascending plumes and local surface geology that produces diverse chaos morphologies, and thus our model may be extended to other features, such as Murias Chaos, as well as pits and domes. Our analyses suggest that ice–water dynamics are active today on Europa, sustaining large liquid lakes perched in the shallow subsurface.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions B.E.S. and D.D.B. conceived of and actively discussed this project. B.E.S. analysed Galileo imaging data, found and studied terrestrial analogue information, analysed results, formulated the model, calculated values, and wrote the paper. D.D.B. provided discussion and direction, and edited the paper. G.W.P. performed the FFT analysis of Conamara Chaos topography data. P.M.S. produced the original DEM of Conamara and the photoclinometry of Thera Macula.

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