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Evidence for subduction in the ice shell of Europa

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Jupiter's icy moon Europa has one of the youngest planetary surfaces in the Solar System, implying rapid recycling by some mechanism. Despite ubiquitous extension and creation of new surface area at dilational bands that resemble terrestrial mid-ocean spreading zones, there is little evidence of large-scale contraction to balance the observed extension or to recycle ageing terrains. We address this enigma by presenting several lines of evidence that subduction may be recycling surface material into the interior of Europa's ice shell. Using Galileo spacecraft images, we produce a tectonic reconstruction of geologic features across a 134,000 km^2 region of Europa and find, in addition to dilational band spreading, evidence for transform motions along prominent strike-slip faults, as well as the removal of approximately 20,000 km^2 of the surface along a discrete tabular zone. We interpret this zone as a subduction-like convergent boundary that abruptly truncates older geological features and is flanked by potential cryolavas on the overriding ice. We propose that Europa's ice shell has a brittle, mobile, plate-like system above convecting warmer ice. Hence, Europa may be the only Solar System body other than Earth to exhibit a system of plate tectonics.

A fundamental unanswered question about Europa is the apparent contradiction between the prevalence of new surface area created along dilational bands in the ice shell (>40% of total surface area in places)[1,2] and the seeming lack of large-scale contraction to provide an area balance[3]. Europa's crater-based age[4] of 40–90 Myr implies that the entire surface (3.09×10^7 km^2) has been overprinted or recycled in this time frame such that its surface records <2% of its total history. There is no evidence that surface cryovolcanic flows are responsible for the resurfacing, implying other endogenic mechanisms.

Dilational bands have internal features that strongly resemble the morphology of mid-ocean spreading ridges[5], implying divergent rigid plates. Thermal, and possibly compositional, buoyancy of warm ice in the convecting portion of the ice shell forces material upwards into progressively dilating cracks, creating new surface area. As such, dilational bands may provide a 'ridge-push' mechanism for lateral plate motions, with similar spreading rates to Earth (up to 40 mm yr^{-1}) and inferred active lifetimes[6,7] of <10–30 Myr.

Sparse, documented contractional features on Europa are insufficient to account for the large amount of dilational band spreading. Rare so-called convergence bands[2,8] imply high contractional strains but lack topography that would be expected from thrust fault uplift, raising questions about how the contraction is physically accommodated. Short-wavelength (∼ a few km) folds within dilational bands[9] do not seem to represent a globally-significant process. Some contraction may occur in long-wavelength (tens of km) folds or by ice shell thickening[10], as well as along shear-heated ridges[11,12]. None of these models can account for the overprinting or removal of large amounts of cratered surface area required to reset the surface age. Given the implausibility[13] that Europa has expanded significantly in the past 40–90 Myr, some additional process is needed to accommodate the creation of new surface area and recycle large portions of the surface in <90 Myr. On Earth, this area-balance process is subduction. We address the enigma of surface age resetting and area balance on Europa by presenting evidence for subduction, and hence plate tectonics.

Study area

A reconstruction of geologic features in a 134,000 km^2 region in Europa's northern trailing hemisphere (imaged by the Galileo spacecraft at 170–228 m pix^{-1}; Supplementary Fig. 1) shows that the current surface configuration evolved from numerous translations and rotations of rigid plates. We present evidence that pink, tabular zones in false-colour images (Fig. 1a) represent regions of substantial surface area removal. The tabular zones are up to ∼30 km wide and can be traced >1,700 km across the surface (Fig. 1b), suggesting they represent the effects of a globally significant process. Tabular zones were mapped, along with relatively older features such as dilational bands and ridges, to provide geologic markers for tectonic reconstruction (Fig. 2). In comparison to the total number of geologic features in the study region (at least several hundred), there are ∼30 relatively younger geological features that crosscut the tabular zones (Supplementary Fig. 1), implying they are relatively young (perhaps <5 Myr).

A case for subduction

We identify eight lines of evidence in support of the hypothesis that the tabular zones represent sites of significant surface removal whereby the outermost portion of the ice shell is recycled into its interior along the europan equivalent of a subduction zone. A detailed tectonic reconstruction sequence of events is described in the Supplementary Information.

Mismatch of geological features across tectonic boundaries. Older geological features such as ridges and dilational bands are abruptly truncated at tabular zones (Fig. 2a), which can be achieved by convergence[11]. In the mapped region (Fig. 2a), truncated features show no matching equivalents across the northern tabular zone within the ∼300 km field of view, implying ∼80 km of convergence across the zone (Supplementary Fig. 3). Mismatches of features across other boundaries, such as lateral offsets across transforms (thick black lines, Fig. 2a) and dilational offsets across bands (blue and red, Fig. 2a), imply complementary plate tectonic processes involving lateral and divergent motions of rigid plates, respectively.

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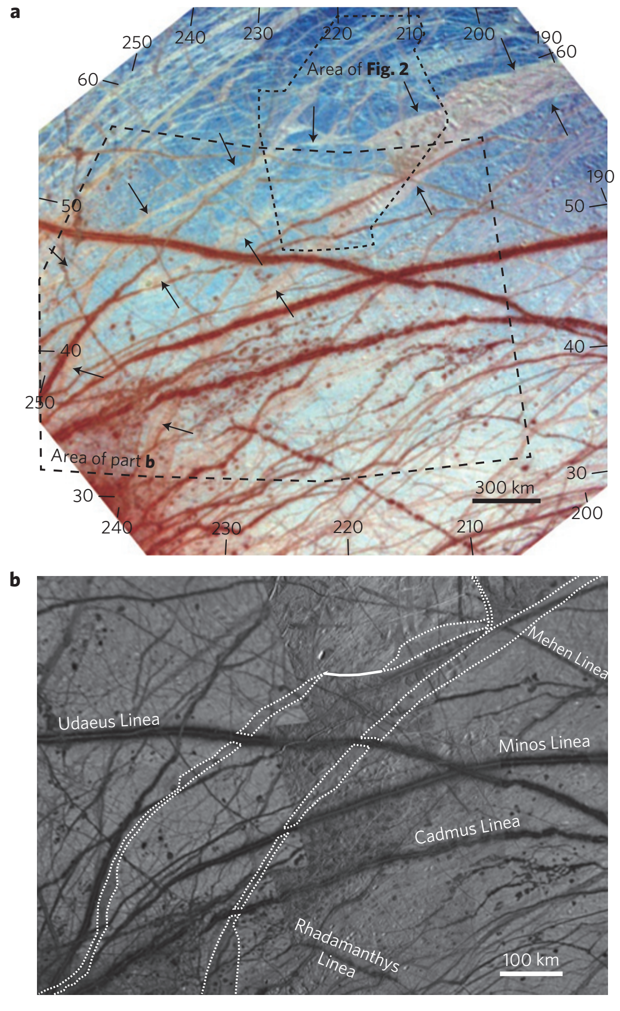

Figure 1 | Study region. a, False-colour image of Europa's northern trailing hemisphere. Pink-hued, tabular zones (arrowed) are convergent bands and potential sites of subduction. Area of (**b**) outlined by wide dashed lines. Area of Fig. 2 outlined by smaller dashed lines. **b**, Regional extent of tabular zones (white dashed areas) in visible light images. Named lineae also shown. E15RegMap01 images (228 m pix^{-1}) superposed on a global Mercator basemap (1 km pix^{-1}). Images from NASA/JPL/University of Arizona.

Missing surface area in tectonic reconstruction. Geological markers were used to make a tectonic reconstruction of the study area, progressively removing offsets and dilations to reconstruct the original geologic architecture down to the finest detail (Fig. 2b and Supplementary Fig. 4). The restored geology shows a ~99-km-wide zone (~20,000 km^2) of unaccounted surface geology (that is, blank space) immediately to the NW of the southernmost tabular zone (Fig. 2b). Such gaps appear in terrestrial reconstructions where the original surface area was physically removed by subduction, raising the possibility that an analogous process may have occurred on Europa.

We use the term subduction to imply that a portion of the surface moved downwards below an adjacent plate, analogous to terrestrial subduction. However, the geodynamical considerations may be quite different and we use the accompanying term subsumption to infer that the descending plate is probably incorporated into the underlying warmer ice through thermal diffusion, in contrast to a dense descending plate in terrestrial systems. We also introduce the term subsumption band to refer to the tabular zones of surface deformation that result from this process (yellow in Fig. 2). This term distinguishes the internal morphology of this band-like feature from dilational bands and convergence bands that currently exist in the Europa surface-feature lexicon. The subsumption band may represent a zone of deformed overriding (that is, non-subducting) plate alongside the subduction margin, although the exact location of the proposed subduction boundary at the subsumption band is unknown. The missing surface area (~15% of the total study area) could have played a significant role in accommodating the ~10–40% new surface area created at dilational bands[2].

Congruent plate motion vectors. The tectonic reconstruction involves five periods of discrete plate motions (Supplementary Fig. 4), implying that changes in plate configurations through time responded to variable forcing factors. This behaviour mimics terrestrial plate motions, which respond to the constantly evolving dynamics of mid-ocean ridge and subduction systems, resulting in temporal changes in plate motion direction vectors. In the study region, there is general congruency in plate motion vector evidence during each step of the reconstruction. These vectors were deduced by reconstructing dilational band offsets using piercing points along band margins and by the translation of matching features across transforms.

Topographic conundrum. Surface area removal is implied by the lack of significant topography across the subsumption bands. In support of this assumption, we explore a scenario in which the missing 99 km of surface was simply contracted into a 23-km-wide tabular band. A concomitant increase in topography would be needed to accommodate the ~81% contractional strain. On Earth, this contraction would be manifested by mountains along a system of thrust faults. No mountains exist on Europa and there is no appreciable surface erosion. There is also no evidence that any portion of the missing geology is preserved within the tabular zones, even in a highly contracted form. Moreover, volume conservation would require a local thickening by a factor of four within the tabular zone. If this thickening occurred within an outer brittle plate overlying warmer ice with Airy isostatic compensation, the resultant mountains would be at least 330–400 m high (for an ~5–6 km thick brittle ice layer[14]). In the imaged area, the sun inclination is 8.8° from horizontal, almost exactly from the east, allowing elevation changes as small as 26 m to be resolvable in a 170 m pix^{-1} image. Shadow lengths for a 330 m high mountain would be >2.1 km; however, no shadows are present (Supplementary Fig. 5). The subsumption bands are thus unlikely to represent zones of highly contracted terrain, suggesting the 99 km of missing material instead moved downwards into the interior of the ice shell.

Morphology and geometry of tectonic boundaries. Subsumption bands and transform boundaries show internal morphologies (Fig. 3 and Supplementary Fig. 5) not previously described on Europa or other icy satellites, and thus represent unique, new types of diastrophic terrain and previously unrecognized processes. Despite their tabular nature, subsumption bands do not resemble documented convergence bands[1,8]. They also differ from dilational bands in having no central trough or bilateral symmetry of morphologic features[5]. Instead, the subsumption bands have an internal morphology of elongate hummocks oriented subparallel to the margins, smooth regions with pits, and margin-parallel internal lineaments (Fig. 3a) that juxtapose disparate morphological zones.

Transform boundaries (Fig. 3b–d) are wider, with less distinct margins, than other linear features imaged on Europa at this resolution. Transpressional boundaries (a combination of lateral motion and convergence, as interpreted from the tectonic reconstruction) are flanked by rough, hummocky material extending up to 5 km away from the transform (Fig. 3b,c). Transtensional (lateral motion plus dilation) transforms seem

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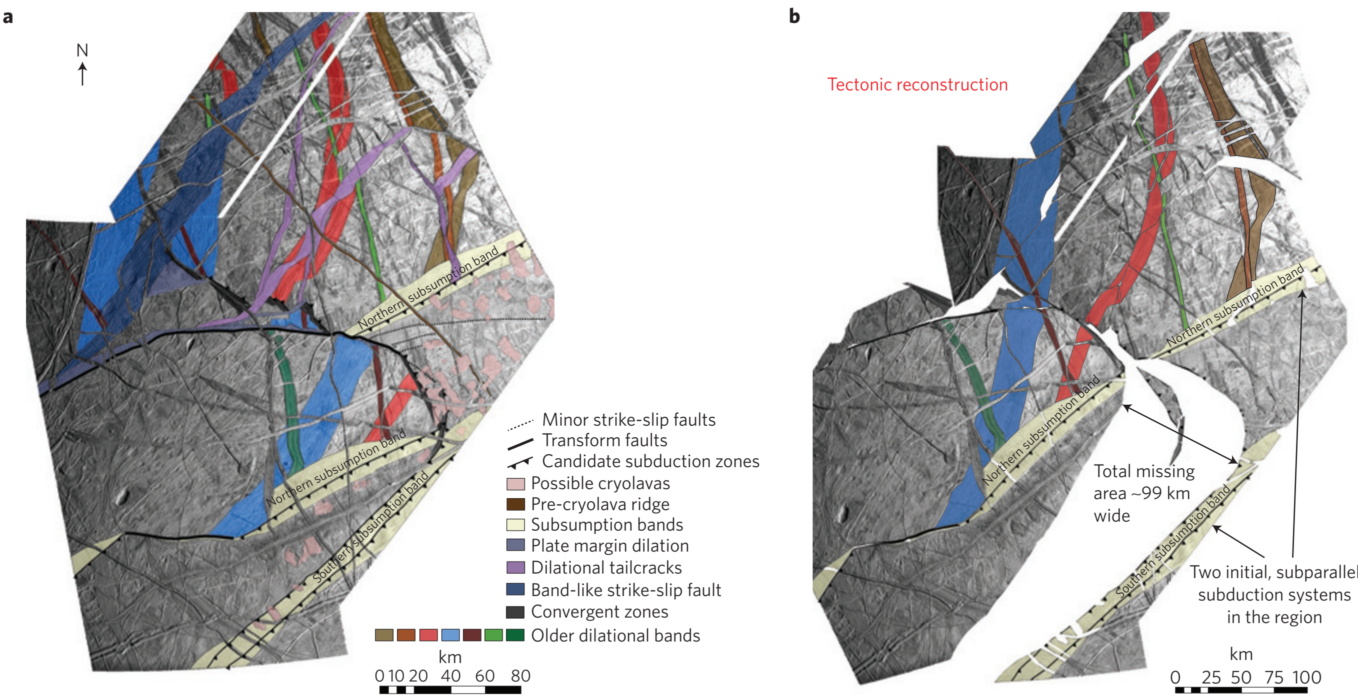

Figure 2 | Interpretation of prominent geologic units and tectonic reconstruction. a, Tabular zones (yellow) represent contractional deformation where subduction may have occurred and are referred to as subsumption bands. All other mapped features predate these bands (mapping in ArcGIS). Original, uninterpreted image shown in Supplementary Fig. 2. **b**, Original configuration of geologic features after tectonic reconstruction via the removal of transform and dilational offsets (see Supplementary Fig. 4 for the entire reconstruction sequence). A zone of missing surface area (white space) ~99 km wide occurs on the NW side of the southern subsumption band and is interpreted to have subducted. Images from NASA/JPL.

smoother along their interiors and preserve en echelon fractured margins that reveal the sense of shear (for example, left-stepping, en echelon geometry along a right-lateral transform, Fig. 3d), analogous to terrestrial transtensional plate boundary transforms and strike-slip systems[15,16].

Potential cryolavas. The terrain adjacent to the southeastern margin of the northern subsumption band is pervasively disrupted by rough-textured patches of material that stand higher than their surroundings by up to ~100 m based on shadow lengths (Fig. 2a and Supplementary Fig. 6). These patches cursorily resemble features called lenticulae or chaos: disruption of the ice shell by diapiric upwelling of thermally or compositionally buoyant material[17,18]. However, on close inspection, these hummocky features seem to drape the surface; some emanate from vent-like point sources, with lobate flow geometries (Supplementary Fig. 6) that suggest eruptive deposits (that is, cryolavas). Particularly compelling, these features occur exclusively on the overriding plate (that is, directly above the portion of the ice shell into which the subducting plate is being subsumed; Fig. 4 and Supplementary Fig. 7), in a zone extending at least 115 km away from the proposed subduction zone boundary. This spatial pattern is unlikely to be a coincidence and implies either a strong thermal signature in the underlying ice shell or a process that preferentially moves existing liquids upwards through the overriding plate. These features may thus represent europan analogs of volcanic constructs on the overriding plates of terrestrial subduction zones, although the melt creation process is unknown in this case.

Distinct surface colour. The pink hue that typifies subsumption bands in false-colour images (Fig. 1a) highlights their disparity with the surrounding terrain and implies chemical or compositional differences in surface materials. Although not necessarily diagnostic of subsumption bands (dilational bands show similar colour properties), the colour characteristic may relate to the exposure of deeper, unweathered icy materials by faulting within the band (as occurs in dilational bands). Furthermore, the proposed cryovolcanism in the region between the northern and southern subsumption bands seems to affect the surface colour (Fig. 1a).

Strain partitioning along oblique margins. Adjacent to one sinistral-oblique transpressional boundary, the overriding plate is dissected by small, left-lateral strike-slip faults (Fig. 2a and Supplementary Fig. 7). This pattern resembles terrestrial upper plate deformation[19], where oblique convergence is partitioned between the subduction zone and overriding plate internal deformation.

Implications for surface age and plate tectonics

Europa's young surface age necessitates that a recently active process recycled the entire surface on a timescale of <90 million years. The surface features and plate-like motions evident in our study region point to a process of large-scale surface removal along subduction-like systems, creating localized, tabular zones of deformation (perhaps analogous to terrestrial accretionary prisms or fold-and-thrust belts) that we term subsumption bands (Fig. 4). Buoyancy constraints prevent any subducting plate from moving directly into the underlying europan ocean; however, a subduction system occurring exclusively within the ice shell interior (similar to terrestrial lithospheric plates moving into the asthenosphere) is plausible. We interpret a thin (~ several km), cold, brittle lid overlying a thicker, convecting ice layer, with plate motions and subduction restricted to the rigid lid. We use the term subsumption to imply the subducted plate is thermally subsumed into the warmer interior of the ice shell, ultimately recycling the removed surface area. Subduction is promoted by the cold, brittle outer layer of the ice shell (surface temperature of 100 K) probably

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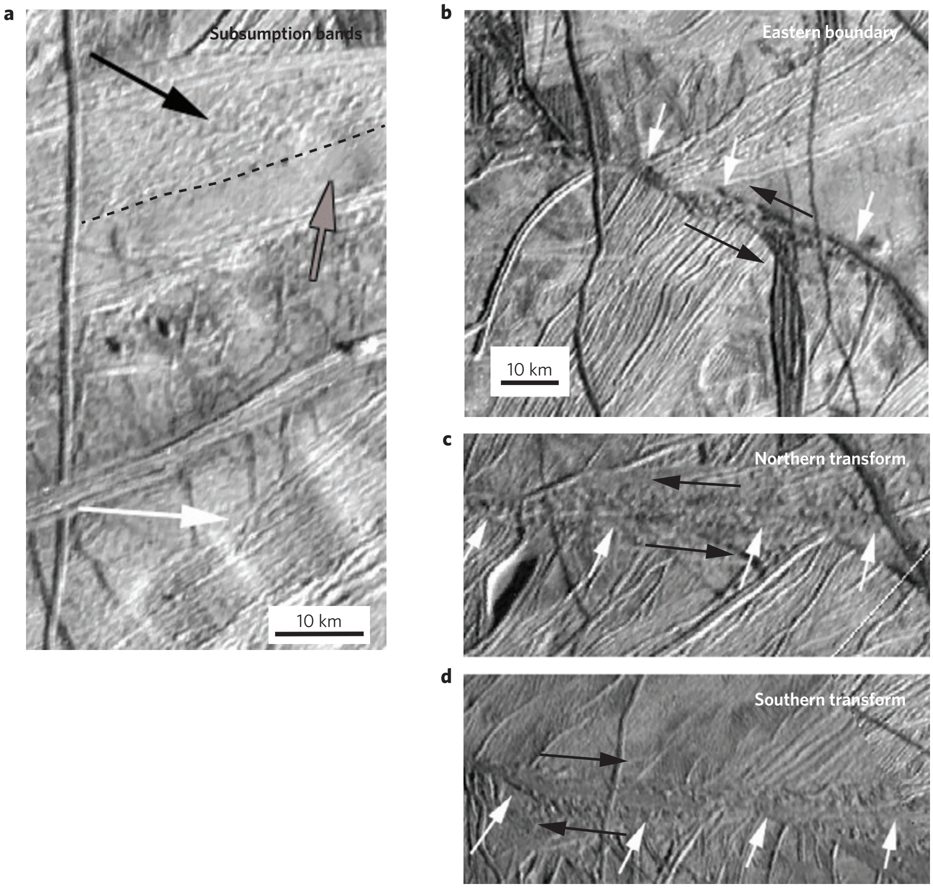

Figure 3 | Plate boundary morphologies. a, Subsumption band interiors show hummocky material (black arrow) and smoother material (grey arrow) juxtaposed along sharp boundaries (dashed line). Older features terminate abruptly at the band edges (white arrow). **b**,**c**, Highly convergent transpressional boundaries (**b**) and predominantly transform transpressional boundaries (**c**) have a complex internal structure and a margin of mottled material several kilometres wide. **d**, The transtensional southern transform has a smooth interior. Ragged edges mark an array of left-stepping, en echelon fractures, consistent with right-lateral motion. Fault motion sense shown by black arrows in **b**–**d**, which have identical scales. Locations shown in Supplementary Fig. 2. Images from NASA/JPL.

being denser[20] (up to 943 kg m^{-3}) than the warmer, underlying ice (~920 kg m^{-3}).

The lack of localized topography within the subsumption bands indicates that missing swaths of surface area in the tectonic reconstruction are not simply contracted into the bands, but rather subducted beneath them. If the subsumption of the subducted plate is relatively rapid (which depends on plate thickness, subduction rate and thermal diffusion constraints), it may preclude the development of a topographic high related to cumulative thickening of the ice shell or underplating. Conversely, a localized area of negative topography is plausible in the event that the colder, denser, subducting plate creates a surface downwelling (Pratt isostacy)[21], perhaps accounting for the lack of topography across the subsumption bands. Ultimately, unless the subsumed material is effectively redistributed by interior convection at the rate at which subduction occurs, subduction could theoretically create a net thickening of the entire ice shell, resulting in a transitory long-wavelength uplift (~300–450 m) across the subduction system that cannot be observed with existing datasets. Similarly, if a narrow trench or trough developed along the line of subduction (as in terrestrial subduction zones), its presence cannot be ascertained in the absence of high-resolution topographic data and knowledge of the angle of subduction or the amount of flexing of the subducting plate.

The potential existence of plate tectonics on Europa raises questions as to likely driving mechanisms for a mobile lid system. A range of forcing factors exist in terrestrial systems, including ridge-push, slab-pull and basal shear stresses. Which of these mechanisms is applicable on Europa is unclear, as are the general geodynamics of a convecting ice shell with a mobile lid, creating important avenues for future research. A cursory evaluation points towards a ridge-push equivalent mechanism to drive plate motions on Europa, related to the opening of dilational bands. Nonetheless, the process of band formation is inherently linked to the dynamics of an underlying convecting shell[22], which could also contribute a basal shear stress to drive plate motions. Slab-pull may be ineffective given the small density differential between the subducting plate and deeper convecting ice, and the fact that the plate could be rapidly subsumed into the ice shell. Also important is the existence of sufficiently high stresses to create the main thrust fault along which subduction occurs. Such stresses would need to overcome the compressive strength of the ice down to depths of at least several kilometres, requiring stresses in the ~10 MPa range[23]. Although global stress-producing mechanisms such as non-synchronous rotation or true polar wander could produce at least several MPa of stress, the creation of such large thrusts may require the contributions of mechanisms such as ridge-push to physically initiate the subduction process. All of these mechanisms probably contributed stresses to Europa's ice shell in the recent geologic past[1].

The creation of cryolavas is enigmatic, but strongly supported by observational evidence. The spatial restriction of cryolavas to the overriding plate in the study region implies that the subduction process facilitates melting and/or the forcing of pressurized fluids

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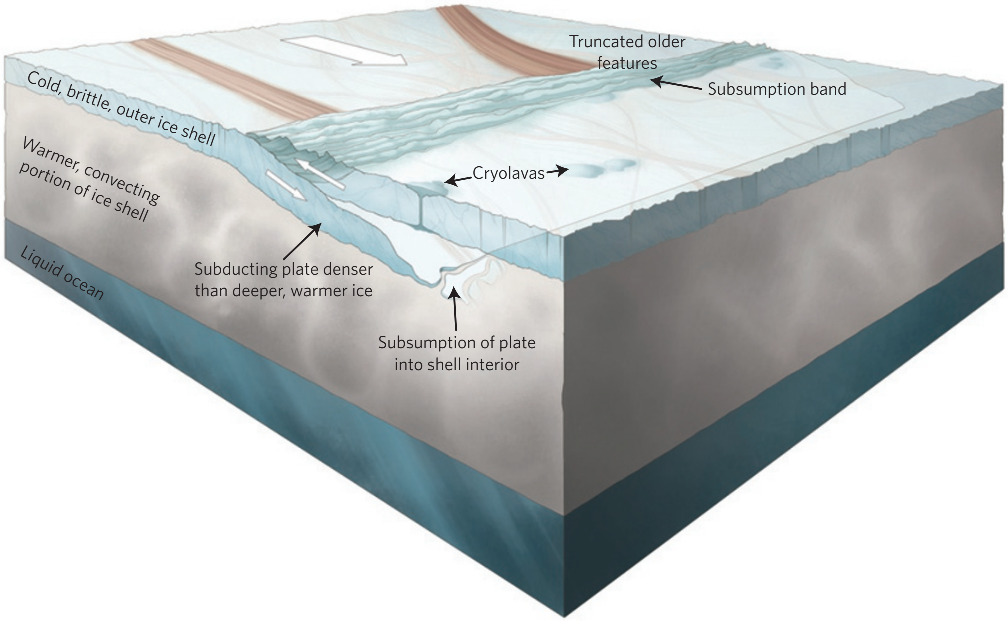

Figure 4 | Conceptual model for subduction. Recycling of surface area through the subduction of a cold, brittle, outer portion of the ice shell into its warmer interior, where it is ultimately subsumed. Potential cryolavas are forced to the surface through the overriding plate. The higher density of the subducting outer ice layer obviates buoyancy-induced topographic relief at the site of subduction. Plate collision results in contractional deformation in the overriding plate along the collisional margin, creating the tabular subsumption bands.

within the ice shell[18] to the surface in response to plate collision. Fluid production is unlikely to resemble melt-generation processes in terrestrial subduction systems, but may be influenced by the incorporation of chemical compounds moved downwards from the surface. Frictional melting along the subduction zone interface cannot be ruled out, especially if motions occur periodically in the form of europan quakes, analogous to terrestrial subduction zone megathrust events. Whatever the process at work, buoyancy constraints require that pressurized fluids be rapidly forced to the surface along conduits such as hydrofractures. This process is not unreasonable on Europa given documented evidence of cryolavas elsewhere[24] and recent evidence for eruptive jets[25].

The prospect of plate tectonics on Europa is remarkable and congruent with a previous study that inferred rigid motions of portions of the surface[26]; however, the question remains whether subduction can address the fundamental problem of Europa's young surface age. There is no observational evidence for subduction rates; however, given that modelled dilational band spreading rates[6,7] (up to 40 mm yr^{-1}) resemble terrestrial spreading rates, subduction rates on Europa may resemble terrestrial rates. On Earth, oceanic lithosphere removal along a cumulative 55,000 km length of subduction zones occurred in <200 Myr at 20–80 mm yr^{-1}. Similar subduction rates on Europa, if valid, could recycle its surface area (~6% of Earth's) in its 40–90 Myr surface age time frame (at a cumulative rate of 0.34–0.77 $km^2\ yr^{-1}$) given a total length of subduction zones in the range 4,300 to 39,000 km (based on the range of potential subduction rates and the range of inferred surface ages). These values seem credible, considering that we have identified a single band >1,700 km in length in low-resolution images and potentially other examples nearby (Fig. 1a). Nonetheless, more subduction zones than those we identify are needed on Europa to accomplish complete resurfacing in <90 Myr.

This study focused on a single area where subduction is evident; however, we note other locations have documented convergence[1,27], providing target sites to test if subduction is potentially widespread on Europa. Despite the apparent morphological differences between previously documented convergence bands and subsumption bands described here, there may be overlap in the underlying processes responsible for these features. Future missions to Europa that return higher resolution images, gravity measurements, or laser altimetry to measure local or regional topographic signatures, could aid in testing the viability of subduction for removing portions of the surface.

Our work suggests Europa is the only other Solar System body beyond Earth to exhibit all of the fundamental components of plate tectonics: subduction (surface area removal), mid-ocean-ridge-like spreading (surface area creation at dilational bands) and transform motions[28]. The notion of a cold, brittle mobile layer provides a framework for understanding other deformation processes on Europa, such as ridge and band formation, chaos development, large-magnitude strike-slip displacements, and flexure alongside ridges. Our work thus potentially provides a new paradigm for interpreting Europa's surface features, age and interactions between the surface and interior.

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Author contributions

S.A.K. was responsible for the tectonic reconstructions of the study area. L.M.P. was responsible for the morphological analyses of the boundaries. Both authors contributed to the interpretation and analysis and to the preparation and finalization of the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to S.A.K.

Competing financial interests

The authors declare no competing financial interests.

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