Ménec Fossae on Europa: A Strike-Slip Tectonics Origin above a possible Shallow Water Reservoir

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Abstract

Faults and fractures may emplace fresh material onto Europa's surface, originating from shallow reservoirs within the ice shell or directly from the subsurface ocean. Ménec Fossae is a region of particular interest, as it displays, within a relatively small area, the interaction of several geological features such as bands, double ridges, chaotic terrains, and fossae. These features might affect the emplacement of buried material and subsequent exposure of fresh volatiles, prime targets for the upcoming JUICE and Europa Clipper missions in order to assess Europa's astrobiological potential. Previous studies already revealed that a deep central trough is present at Ménec Fossae, flanked by several subparallel minor troughs and by few asymmetrical scarps with lobate planforms. The presence of such features has motivated this study, given its potential to provide clear indications on the tectonic regime involved. Through detailed geomorphological-structural mapping on Galileo Solid State Imager data and terrain analysis on Digital Terrain Models, we could develop a novel hypothesis on the formation mechanisms that might have been involved in the study area. We propose that Ménec Fossae has been shaped by transtensional (strike-slip with a major extensional component) tectonic activity, as indicated by the orientation and relationship of the tectonic features present. The shear heating related to such a tectonic setting possibly led to the formation of a shallow water reservoir, that in turn could have generated the observed chaotic terrains, double ridges, and fossae. These results strengthen the case for widely distributed shallow water reservoirs within Europa's ice shell.

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Key Points:

- Detailed geomorphological-structural analysis of Ménec Fossae has been conducted, using imaging and newly processed topographic data
- Ménec Fossae has been shaped by transtensional tectonic activity, potentially related to the emplacement of a shallow water reservoir
- The hypothesis that shallow water reservoirs are widely distributed within Europa's ice shell is strengthened

Abstract

Faults and fractures may emplace fresh material onto Europa's surface, originating from shallow reservoirs within the ice shell or directly from the subsurface ocean. Ménec Fossae is a region of particular interest, as it displays, within a relatively small area, the interaction of several geological features such as bands, double ridges, chaotic terrains, and fossae. These features might affect the emplacement of buried material and subsequent exposure of fresh volatiles, prime targets for the upcoming *JUICE* and *Europa Clipper* missions in order to assess Europa's astrobiological potential. Previous studies already revealed that a deep central trough is present at Ménec Fossae, flanked by several subparallel minor troughs and by few asymmetrical scarps with lobate planforms. The presence of such features has motivated this study, given its potential to provide clear indications on the tectonic regime involved. Through detailed geomorphological-structural mapping on *Galileo* Solid State Imager data and terrain analysis on Digital Terrain Models, we could develop a novel hypothesis on the formation mechanisms that might have been involved in the study area. We propose that Ménec Fossae has been shaped by transtensional (strike-slip with a major extensional component) tectonic activity, as indicated by the orientation and relationship of the tectonic features present. The shear heating related to such a tectonic setting possibly led to the formation of a shallow water reservoir, that in turn could have generated the observed chaotic terrains, double ridges, and fossae. These results strengthen the case for widely distributed shallow water reservoirs within Europa's ice shell.

Plain Language Summary

Tectonic cracks may emplace fresh material onto Europa's surface, that can originate from shallow water bodies within the icy crust or directly from the subsurface ocean. This kind of material is a prime target for upcoming space missions in order to assess Europa's habitability. We investigated the area of Ménec Fossae, which is characterized by many different geological features and structures within a relatively small area and can therefore provide clues on the mechanisms that shaped it. Our analysis were based on imaging and new topographic data, we developed a new hypothesis involving a combination of different tectonic styles as the driving processes for the formation of this area. This kind of tectonic activity could be related to heating through shear friction, which might have generated a liquid water pocket at shallow depths within Europa's icy crust, explaining the concurrent presence of some particular geological features. These findings strengthen the case for shallow water pockets to be widely distributed within the icy crust, which could allow future space missions to more easily assess Europa's habitability.

1 Introduction

Amongst the three possible Jovian ocean worlds, Europa, Ganymede and Callisto, the most detailed and convincing evidence for an internal ocean has been obtained for Europa (e.g., Nimmo & Pappalardo, 2016). Not only does the magnetic induction response to Jupiter's time-varying magnetic field indicate the existence of a subsurface salty ocean (Khurana et al., 1998; Kivelson et al., 2000), but the moon's surface also shows indications of interaction with a liquid layer beneath the ice crust. Images from Voyager 2 and Galileo show a fractured icy surface, with regions where ice crust blocks seem to have moved in a slushy or liquid medium (Carr et al., 1998; Pappalardo et al., 1999). The orientation of some large-scale linear features also seems to have changed over time, implying rotation of the ice shell and a very low viscosity layer between the interior and the surface (Pappalardo et al., 1998). The thickness and thermo-physical structure of the ice shell are poorly constrained, but models suggest it may be 20–30 km thick (e.g., Howell, 2021; Hussmann, 2002; Quick & Marsh, 2015), with a layer of warm, convecting ice underlying a cold, rigid crust (Barr & Pappalardo, 2005; Pappalardo et al., 1998).

Pressures at the base of the internal global ocean are too low for the formation of high-pressure ice phases, and the ocean is thus believed to be in contact with the rocky interior (Anderson et al., 1998). This raises the possibility of rich chemical exchange between the silicate interior and the subsurface ocean, perhaps via hydrothermal vents, and potentially chemical heating through serpentinization (Vance et al., 2007; Vance et al., 2016). Since long-lived radioactive elements are expected to be present in the silicates, as they are within the Earth, a further source of energy that heats the rocky interior is radioactive decay (Běhounková et al., 2021; Hussmann et al., 2010). However, the major heating source is provided by tidal dissipation due to Europa's eccentric orbit, maintained over long time periods by orbital resonances with Io and Ganymede (Schubert et al., 2009; Sotin et al., 2009). These considerations make Europa one of the main candidates in the Solar System for supporting the development of life (Greenberg et al., 2000; Greenberg & Geissler, 2002). If biosignatures are produced within Europa's ocean, they will need to reach the surface to be detected by the upcoming Jupiter Icy Moons Explorer (*JUICE)* and *Europa Clipper* missions. There are indications of salts at some surface locations (e.g., Dalton et al., 2005; Trumbo et al., 2019), consistent with recent extrusions or ejections of salt-rich liquid water from the moon's interior. Some investigators have recently suggested that the salt minerals present on Europa's surface may be dominated by endogenic chlorinated species (e.g., sodium and/or magnesium chlorides), rather than by sulfates (Hand & Carlson, 2015; Ligier et al., 2016; Trumbo et al., 2017, 2019a, 2019b, 2022), which were the main previously hypothesized compounds (e.g., Dalton et al., 2012; Hansen & McCord, 2008; McCord et al., 1999; Orlando et al., 2005), with radiolysis producing the observed reddish-brown coloration of *lineae* and *chaos* regions. A chloride-rich, sulfate-poor ocean would likely be indicative of ongoing water/rock interaction at the seafloor, whereas a sulfate-rich, chloride-poor ocean could indicate either a primordial, leached composition or significant cycling with the ice shell and delivery into the ocean of radiolytically-produced sulfates (Hand et al., 2022).

At global scales, landform evolution on atmosphereless bodies is primarily driven by impact gardening, tectonics, and (cryo-)volcanism. Crater density and frequency analysis indicate that Europa's geologically active surface (Greenberg et al., 1998; Greenberg & Geissler, 2002) is relatively young (~40-90 My, Bierhaus et al., 2009), with a wide variety of landforms including ridges, troughs, bands, lenticulae, and chaotic terrains (Greeley et al., 2004; Greeley et al., 2000). To understand which resurfacing processes are responsible for Europa's anomalously young surface age, several compressional mechanisms have been invoked, such as subduction (cold, brittle, and dense outer portions of the ice shell sink into the underlying convecting warmer ice, in analogy to Earth's convergent plate boundaries; Kattenhorn & Prockter, 2014) and regional scale folding (e.g., Prockter & Pappalardo, 2000). Nevertheless, the tectonic regime that dominates within the ice shell is extensional, a hypothesis supported by numerous lines of evidence, such as the widespread presence of dilational bands that represent >40% of the total surface area (Kattenhorn & Hurford, 2009). Several types of geological features generated within such a tectonic regime, including bands, double ridges, cycloids, chaotic terrains, and fossae, might affect the emplacement of buried material and subsequent exposure of fresh volatiles on Europa's surface.

Bands (Figure 1a), on Europa, are tabular zones of dilation in the icy shell where new crustal material intruded between the walls of a crack (Kattenhorn & Hurford, 2009); they have lengths of hundreds of km and widths of a few km up to ~30 km. Bands are thought to represent a phenomenon analogous to Earth's mid-ocean ridge spreading centers, potentially making them the only other known feature in the Solar System where complete lithospheric separation has occurred (Kattenhorn & Prockter, 2014; F. Nimmo et al., 2003).

Double ridges (Figure 1b) are the most common tectonically related type of feature on Europa, comprising a central crack or trough flanked by two quasi-symmetric raised edifices, up to a few hundred meters high and less than 5 km wide (Kattenhorn & Hurford, 2009). These ridges may extend for hundreds of kilometers and include some of the oldest features visible on the surface, with frequent cross-cutting implying numerous formation cycles over Europa's history. Numerous double ridges follow cycloidal paths (i.e., chains of arcs) across the surface: as the tidal stress field changes through time, propagation of tensile cracks occurs (Greenberg & Sak, 2014). Double ridges may indicate intrusions of near-surface liquid water (Dombard et al., 2013; Johnston & Montési, 2014), shear heating (Han & Showman, 2008; Kalousová et al., 2016; Nimmo & Gaidos, 2002), eruptions (Fagents, 2003), or direct extrusion of recently frozen ocean water by fractures opening and closing under tidal stresses (Greenberg et al., 2003). More recent studies suggest how double ridges might be formed through a combination of shear heating and refreezing, pressurization and fracturing of shallow water reservoirs (e.g., Culberg et al., 2022).

Cycloids (Figure 1c) are linked, arcuate fractures that form hundreds to thousands of kilometres long chains of multiple, concatenated segments (Kattenhorn & Hurford, 2009). As the daily principal tidal stresses on Europa change, cycloids are believed to form in response to that (e.g., Greenberg et al., 1998). A crack forms as the tidal stress in a given region increases and eventually exceeds the failure strength of the ice (i.e., becomes more tensile). A cycloidal path can track the changes in stress orientation with time as it propagates across Europa's surface, if the crack propagates slowly (a few km/h). When the tidal stress decreases, propagation ceases, completing an arc (Rhoden et al., 2021).

Chaotic terrains are (Figure 1d), on Europa, geologically very young and extensively disrupted surface features, interpreted as reflecting recent interaction with shallow subsurface material (Chivers et al., 2021; Collins & Nimmo, 2009; B. E. Schmidt et al., 2011). Leading-hemisphere chaos regions have recently been shown to be compositionally distinct from their surroundings, probably indicating contributions from endogenous sodium chloride sourced from the subsurface ocean (Trumbo et al., 2019a, 2019b, 2022).

Fossae (Figure 1e) are long, narrow depressions. The term is used for topographic features that occur on extraterrestrial planetary surfaces, whose exact origin is uncertain, although they are thought to be the result of predominantly extensional tectonic processes (Schenk et al., 2020).

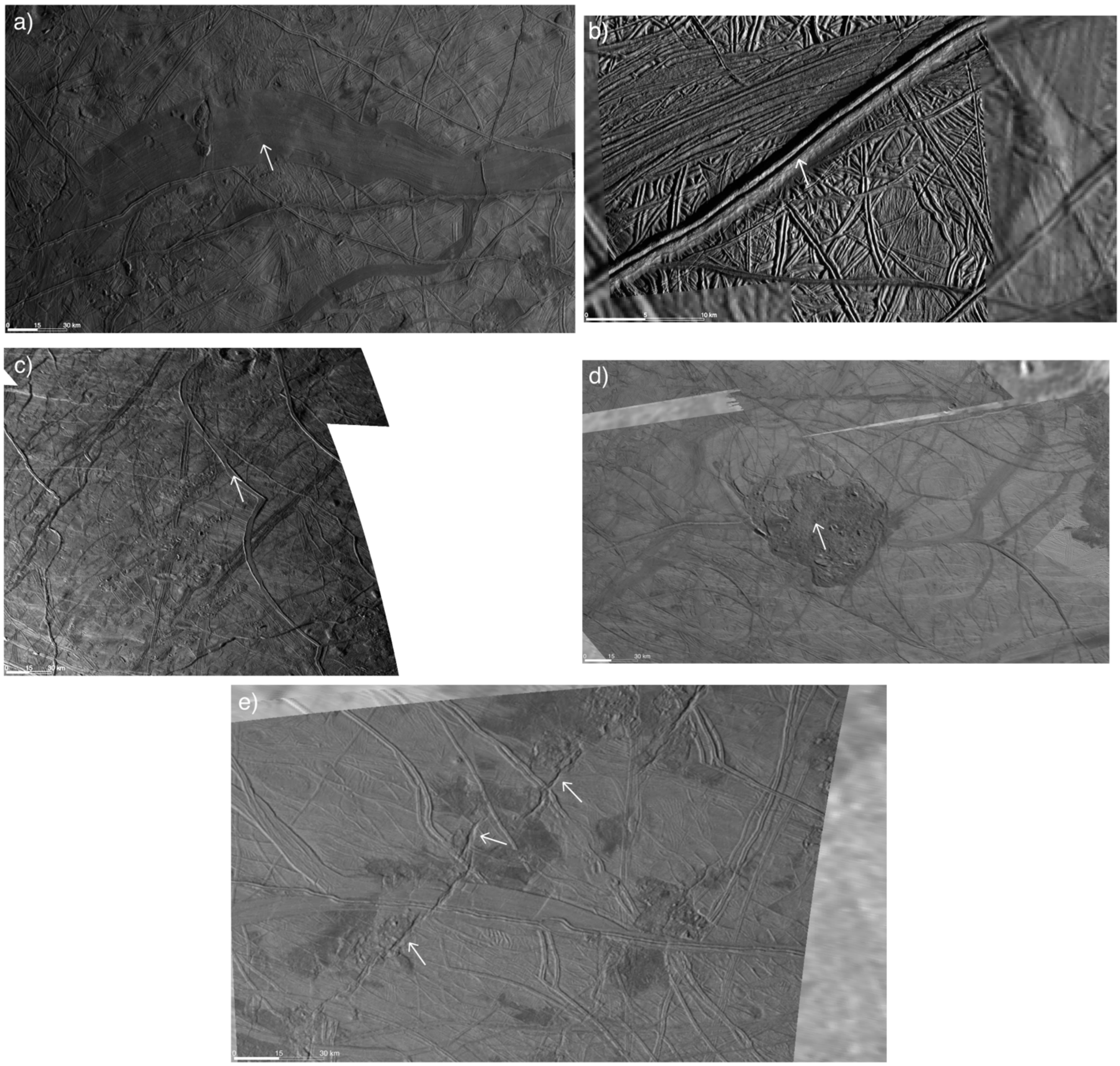


Figure 1. Examples of several geological features on Europa. White arrows point at each terrain type described in the text: a) Band (panel centered at 6°S, 122°E); b) Double ridge (panel centered at 14°N, 86°E); c) Cycloid (panel centered at 53°N, 73°W); d) Chaos (panel centered at 46°S, 178°E); e) Fossa (panel centered at 43°N; 5°E). North is up in all panels.

Here we investigate the region around Ménec Fossae on Europa (centered at 51°S, 177°W; on Europa's trailing hemisphere) for which we produced high-resolution photoclinometrically-derived (Lesage et al., 2021; Schenk & Pappalardo, 2004) digital terrain models (DTMs) and a geomorphological-structural map (scale 1:80,000). This area is of particular interest, as it displays the interaction between bands, double ridges, chaotic terrains and fossae, which might share common formation processes, potentially related to shear heating and refreezing, pressurization and fracturing of shallow water reservoirs (Culberg et al., 2022).

Our results suggest that this area of Europa has undergone transtensional (strike-slip with a major extensional component) tectonic activity, as indicated by the orientation and relationship of the tectonic features present. Such tectonic setting has possibly created a pathway facilitating the ascent of subsurface material, especially volatiles (Aydin, 2006). These results, together with ongoing work on other areas of Europa's surface, will help ascertain the most likely regions on Europa in which to find fresh material, representative of the subsurface ocean, and be used as input data for dust ejecta trajectory models that will ultimately assist the time-of-flight mass spectrometer Surface Dust Analyzer (SUDA), onboard the upcoming *Europa Clipper* mission, in compositionally mapping Europa's surface (Goode et al., 2021; Kempf et al., 2014; Postberg et al., 2011).

2 Materials and Methods

DTMs of the selected areas have been produced using the photoclinometry (PC) technique (e.g., Schenk & Pappalardo, 2004), through the Ames Stereo Pipeline (ASP) Shape-from-Shading (SfS) tool (Beyer et al., 2018). DTMs were derived from *Galileo*'s Solid-State Imager (SSI) images (Belton et al., 1992), which were processed through the Integrated Software for Imagers and Spectrometers (ISIS[1] 4.4.0). In the final map, photogrammetrically controlled image mosaics were used as background (Bland et al., 2021a). For the processing of *Galileo* SSI raw image data, we used the updated SPICE smithed kernels, and projected the processed data on a spheroid with radius of 1560.800 km (i.e., the IAU-defined mean radius for Europa) which is therefore also the DTMs' reference height (Bland et al., 2021a). The PC/SfS technique overcomes the lack, on Europa, of having the same surface area covered by two or more images for traditional stereophotogrammetry DTMs' production. The smoothness parameter μ of the SfS tool, which weighs the smoothness of the resulting DTM and depends on surface properties, plays an important role and can vary the results significantly: optimal μ values with a good S/N ratio of the resulting DTM need to be found by trial and error, where different values need to be applied for each image (a detailed description of how μ affects the DTMs results can be found in Lesage et al., 2021). Manual quality checks have been conducted through features' height H estimation based on shadow length L and solar elevation angle α: $H = L\tan(\alpha)$. The SfS tool assumes uniformity in albedo and photometric parameters across the whole image, based on the reflectance model used. Even though such properties can change at regional or local scales, the overall uncertainties on the SfS DTMs vertical resolution are likely not more than 10-15%, as previously discussed in the literature (Bierhaus & Schenk, 2010; Bland et al., 2021b; Lesage et al., 2021; Schenk et al., 2020; Schenk & Pappalardo, 2004). We further conducted geomorphological-structural mapping of the selected areas on SSI images 9926r and 9939r in stereographic projection using QGIS3[2] and the Mappy plugin[3] (image frames resolution of ~40 m/pixel, which corresponds to a map scale of 1:80,000), units were distinguished based on

[1] https://isis.astrogeology.usgs.gov/7.0.0/index.html
[2] QGIS.org, 2022. QGIS Geographic Information System. QGIS Association. http://www.qgis.org
[3] https://zenodo.org/record/5524389

morphology and albedo differences. Tectonic linear features such as faults were identified based on distinctive morphologies such as scarps, paired with topographical analysis of the DTMs.

3 Results

Ménec Fossa is located in the southern trailing hemisphere of Europa, nearby Thera and Thrace Maculae (Figure 2). We produced high-resolution DTMs of the study area (Figure 3), through the SfS technique described in Section 2.

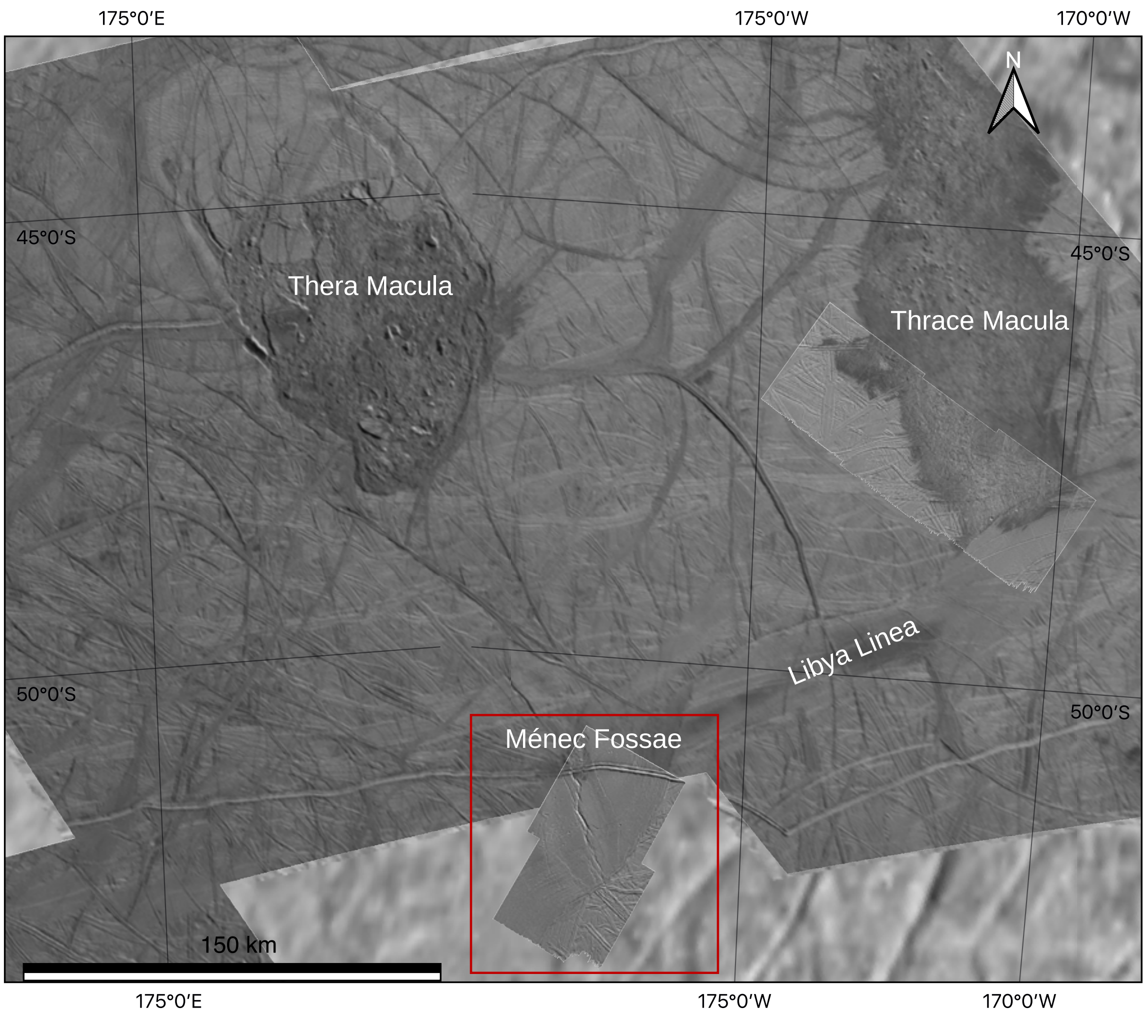


Figure 2. Regional map on photogrammetrically controlled *Galileo* SSI image mosaics, the red box depicts the study area. To the NW, Thera Macula is recognizable, while Thrace Macula is located to the NE. Libya Linea, a large-scale smooth band, continues along a NE-SW into Ménec Fossae.

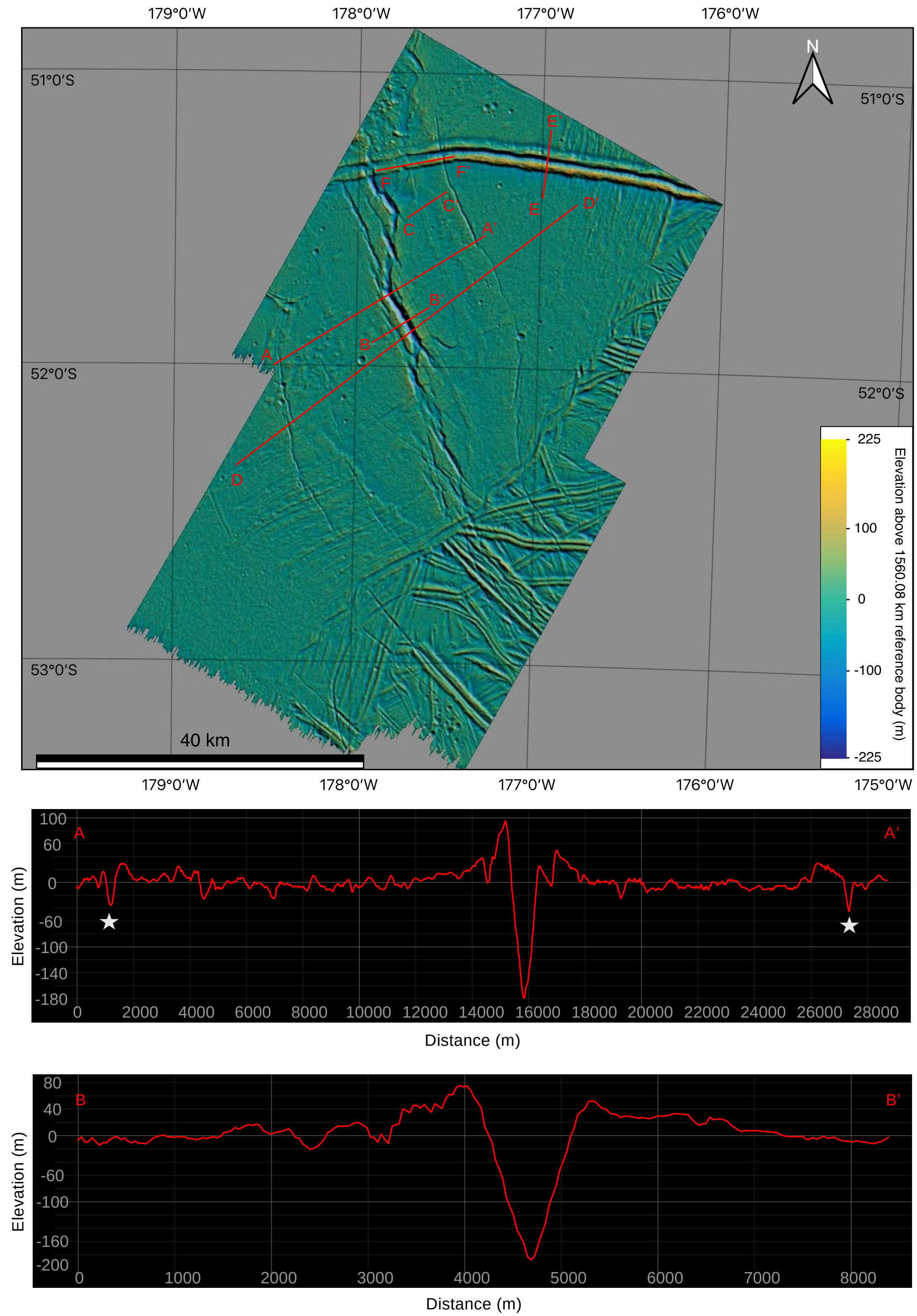
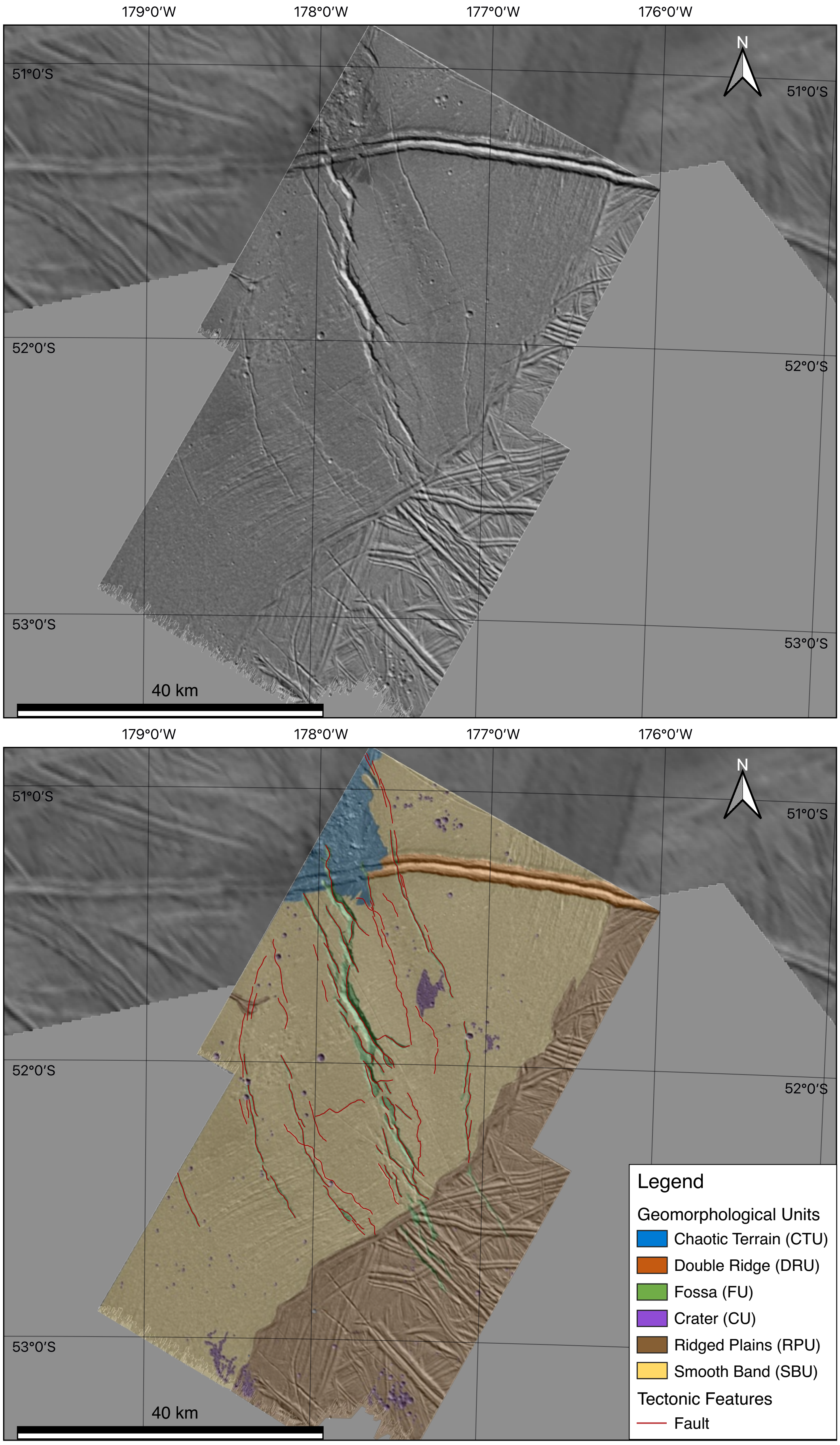


Figure 3. (Top) Regional DTM of Ménec Fossae, individual DTMs are of 9926r and 9939r *Galileo* SSI image frames, later mosaicked together. The DTM has smoothness parameter (μ)

values of 0.004 for the southern 9926r image frame and of 0.1 for the northern 9939r image frame. Image centered at 52°S, 177°W. Several elevation profile paths are shown, A-A’ and B-B’ profiles are displayed in the bottom panel (vertical exaggeration factor 1), the others are in Figure 5. (Bottom) Elevation profiles. The main central depression reaches depths of ~200 m and is ~1 km wide along the elevation profile (detail in B-B’), with slope angles values of ~20-25° on the gentler southern side and of ~30-35° on the steeper northern side. Several minor depressions, flanking the main one, reach depths of 40-50 m (examples as star symbols in profile A-A’).

We further conducted geomorphological analysis paired with fault mapping, resulting in a geomorphological-structural map of the Ménec Fossae area at a scale of 1:80,000 (Figure 4). We could distinguish among six different geomorphological units (Chaotic Terrain, Double Ridge, Fossa, Crater, Ridged Plains and Smooth Band), which are hereafter described and interpreted.


179°0′W
178°0′W
177°0′W
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51°0′S
52°0′S
53°0′S
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40 km
Legend
Geomorphological Units
Chaotic Terrain (CTU)
Double Ridge (DRU)
Fossa (FU)
Crater (CU)
Ridged Plains (RPU)
Smooth Band (SBU)
Tectonic Features
Fault

Figure 4. (Top) Image mosaic of *Galileo* SSI 9926r and 9939r frames centered at 52°S, 177°W, displaying the area of Ménec Fossae. Photogrammetrically controlled SSI image mosaics as background. (Bottom) Geomorphological-structural map of Ménec Fossae. A detailed interpretation of the tectonic features is given in the text and in Figure 6.

3.1 Description and interpretation of geomorphological units

3.1.1 Chaotic Terrain Unit

The Chaotic Terrain Unit (CTU) is formed by high albedo blocks or polygons of pre-existing crustal material, tens of meters to 1-2 km in size, within a low albedo hummocky matrix (Greeley et al., 2000; Leonard et al., 2018) that, in the studied area lie generally at the same or lower level than the surrounding units, with locally higher crustal blocks (Figure 3).

3.1.2 Double Ridge Unit

The Double Ridge Unit (DRU) consists of two subparallel quasi-linear and symmetric topographically high landforms of relatively high albedo. The landforms are rounded to triangular in cross-section and separated by a trough that contains lower albedo material. In the northwestern part of the map (Figure 4), the DRU has been incorporated into the CTU, with a resulting topographic drop in the corresponding area, and therefore predates such unit (Figures 3 and 5f). It is important to note that the mapped double ridge exhibits flexural bulges and flanking troughs along both its sides (Figure 5e), characteristics previously described by Dombard et al. (2013) who suggested that those double ridges displaying them originate from shallow water bodies. On the regional map (Figure 2), it appears clear how the DRU patch is part of a much bigger cycloid structure (i.e., it is a cycloidal double ridge, Hoppa et al., 1999). Nevertheless, it must be taken into account that at the map scale and within the Ménec Fossae setting, this DRU patch has all geomorphological characteristic of a Europan double ridge. Therefore we consider it as such, although this could be deemed as a cycloidal ridge on a wider context. Furthermore, in the literature there is a shared consensus to consider cycloidal ridges (such as the one part of DRU in the mapped area) as most likely having the same formation process as double ridges (Culberg et al., 2022; Figueredo & Greeley, 2004; Greenberg & Sak, 2014; Hoppa et al., 1999; Johnston & Montési, 2014).

3.1.3 Fossa Unit

The Fossa Unit (FU) is formed by topographically low quasi-linear landforms that have a low albedo appearance. In the mapped area these depressions have steep sides, v-shaped cross sections and many exhibit terraces; the major of such features reach depths up to ~200 m. Since it crosscuts all other mapped units, and therefore postdates them, the FU is interpreted as the youngest unit in this area.

3.1.4 Crater Unit

The Crater Unit (CU) consists of moderately high albedo material comprising a crater's floor, wall, and raised rim. It is interpreted as material excavated and/or deposited during impact events. Given their clustered appearance and the lack of significant ejecta blanket deposits, craters in this area of Europa have previously been interpreted as being secondary, i.e., craters formed by material ejected from large primary impact craters (Bierhaus & Schenk, 2010; Bierhaus et al., 2005; Singer et al., 2013).

3.1.5 Ridged Plains Unit

The Ridged Plains Unit (RPU) is characterized by a series of small-scale (~200-500 m in width) high-albedo ridges which can be anywhere from sub-parallel to overlapping, and in several cases in multiple orientations. In general, on Europa's surface, ridged plains are one of the oldest terrain types (Figueredo & Greeley, 2004; Greeley et al., 2000; Leonard et al., 2020; Pappalardo et al., 1999; Prockter et al., 1999). This is the case in the mapped area as well, as they are crosscut by all the units they are in contact with.

3.1.6 Smooth Band Unit

The Smooth Band Unit (SBU) consists of either very subdued ridges and troughs or material with little or no structure. In the mapped area, the SBU is a portion of the very large structure Libya Linea, which extends over thousands of km (Figure 2). Smooth bands are interpreted as regions of crustal extension in which the low relief and lack of internal structure can be due to small-scale fracturing or the emplacement of infilling material (e.g., Prockter et al., 2002)

3.2 Stratigraphic sequence

Based on the crosscutting relationships among the different geomorphological units, we could determine the following sequence of events (numbered, in brackets):

- RPU is the oldest terrain (1), as it occurs in most regions of Europa (Leonard et al., 2020).
- SBU (2), i.e., a portion of Libya Linea, superimpose the RPU.
- Subsequently, the DRU (3) has formed; in the north-western edge of the mapped area, this unit has been incorporated in the CTU (4) which therefore postdates it.
- Ultimately, the FU (5) crosscuts all the other units it is in contact with. The CU (6) is located on top of all other units, while there is no patch of such unit in contact with the FU, thus the cratering events were older or at least concurrent to the FU formation.

Such stratigraphic sequence follows the typical three-stage development on Europa: the initial formation of ridged plains, followed by band-like features and ultimately the imposition of chaotic terrains (Leonard et al., 2020).

3.3 Tectonic features

Different types of faults have been identified and mapped. Note that many other faults are located in the south-eastern part of the mapped area, within the RPU (Figure 4). Considering that this is the oldest of the mapped units, these faults belong to a much older and likely different tectonic regime. We therefore did not distinguish them in the map and consider them as being part of the RPU's general rugged appearance.

Most of the mapped faults display both extensional and strike-slip characteristics, such as clear distinctive elevation drops yet with very steep sides and no clear hanging wall - foot wall distinction (uncommon in purely extensional faults), along with *en échelon* disposition (Figures 3 and 4); we therefore consider them as transtensional faults (i.e., strike-slip features with an extensional component). The most prominent ones in terms of topographic drop have been mapped as part of the FU (Figure 4). These faults follow a roughly NW-SE trend and are distributed within three zones: around the center of the mapped area, where Ménec Fossa *s.s.* takes part most of the extensional component, spread along several quasi-parallel *en échelon* troughs, which become anastomosing towards their SE tips, while reaching depths up to ~200 m (Figure 3). These features are located along the anticline crest of a long-wavelength fold system, as previously observed on SSI image data by (Prockter & Pappalardo, 2000) and further confirmed in this study through the newly available topographic information contained in the DTM (Figure 5d). On both sides of these central features, at distances up to 10-15 km, there are two other sets of subsidiary *en échelon* transtensional faults also aligned along NW-SE trends, subparallel to the main central features. These subsidiary faults have elevation drops of ~40-50 m in their deepest portions (Figure 3). Along with such structures, few other features have been identified. These are flanking the main central feature as well, along similar orientations. They display a clear increase in elevation, along a roughly SW-NE axis, followed by abrupt asymmetrical scarps, with lobate planform geometries (Figures 3 and 5c and 6), all characteristics typical of compressive faults (Prockter & Pappalardo, 2000) on Earth and other planetary bodies (e.g., Mars, Titan). We therefore consider them as compressive tectonic features (i.e., thrust faults).

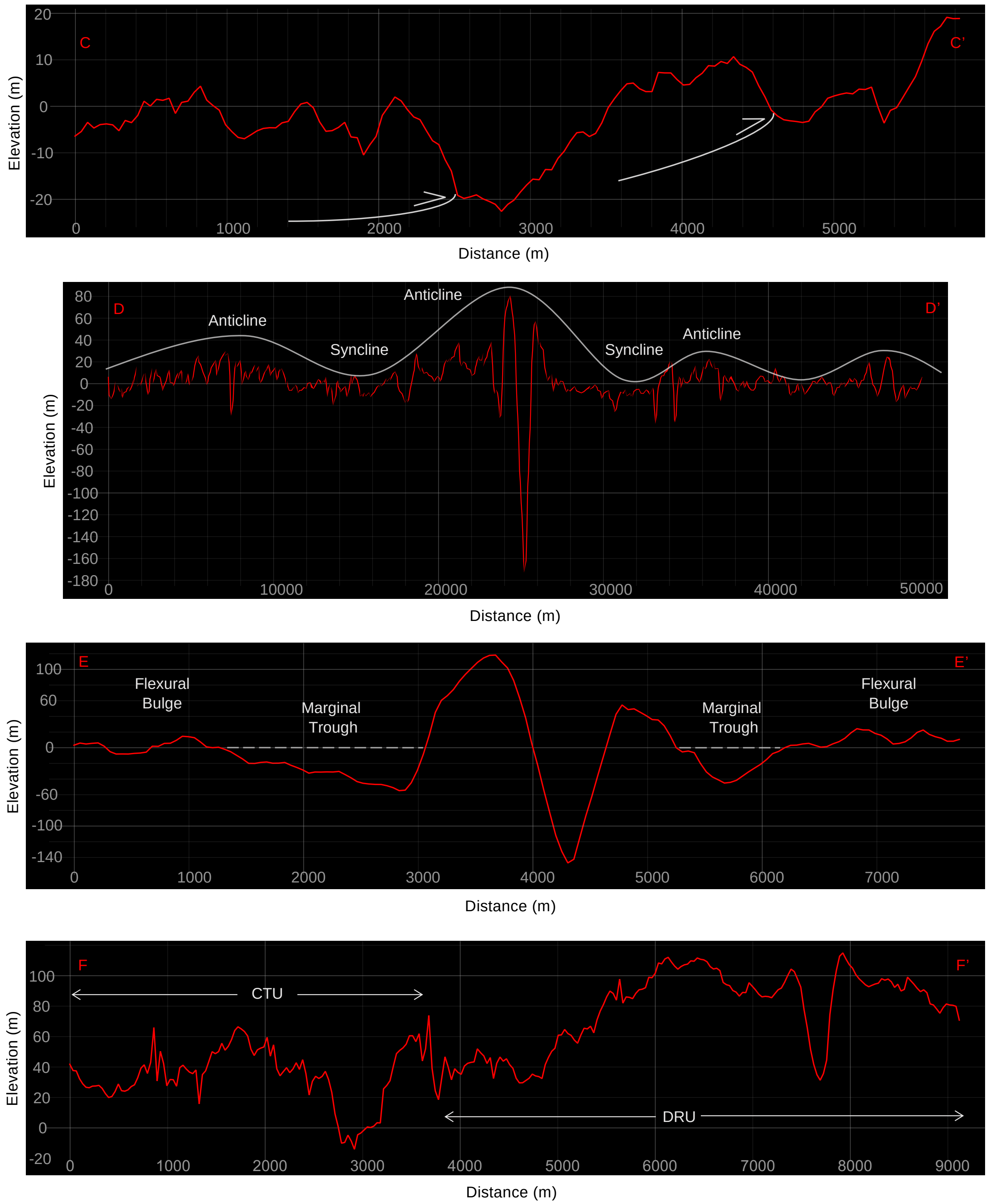

Figure 5. Elevation profiles along the DTM at various locations, profiles' paths are displayed in Figure 3. Vertical exaggeration factor is 1 in all panels. (C-C') Examples of mapped thrust faults, with hypothetical fault traces sketched in white. The two thrusts seem to follow a typical imbricate fan geometry. (D-D') Long distance profile displaying the long-wavelength fold system discussed in Section 3.3. (E-E') Detail of the double ridge (DRU), depicting the observed

marginal troughs and flexural bulges that support the shallow water reservoir's hypothesis as its origin (Section 3.1.2). (F-F') Detail of the CTU-DRU transition, showing the elevation drop corresponding to the incorporation of the DRU in the CTU, proving the DRU relative older formation timing (Section 3.1.2).

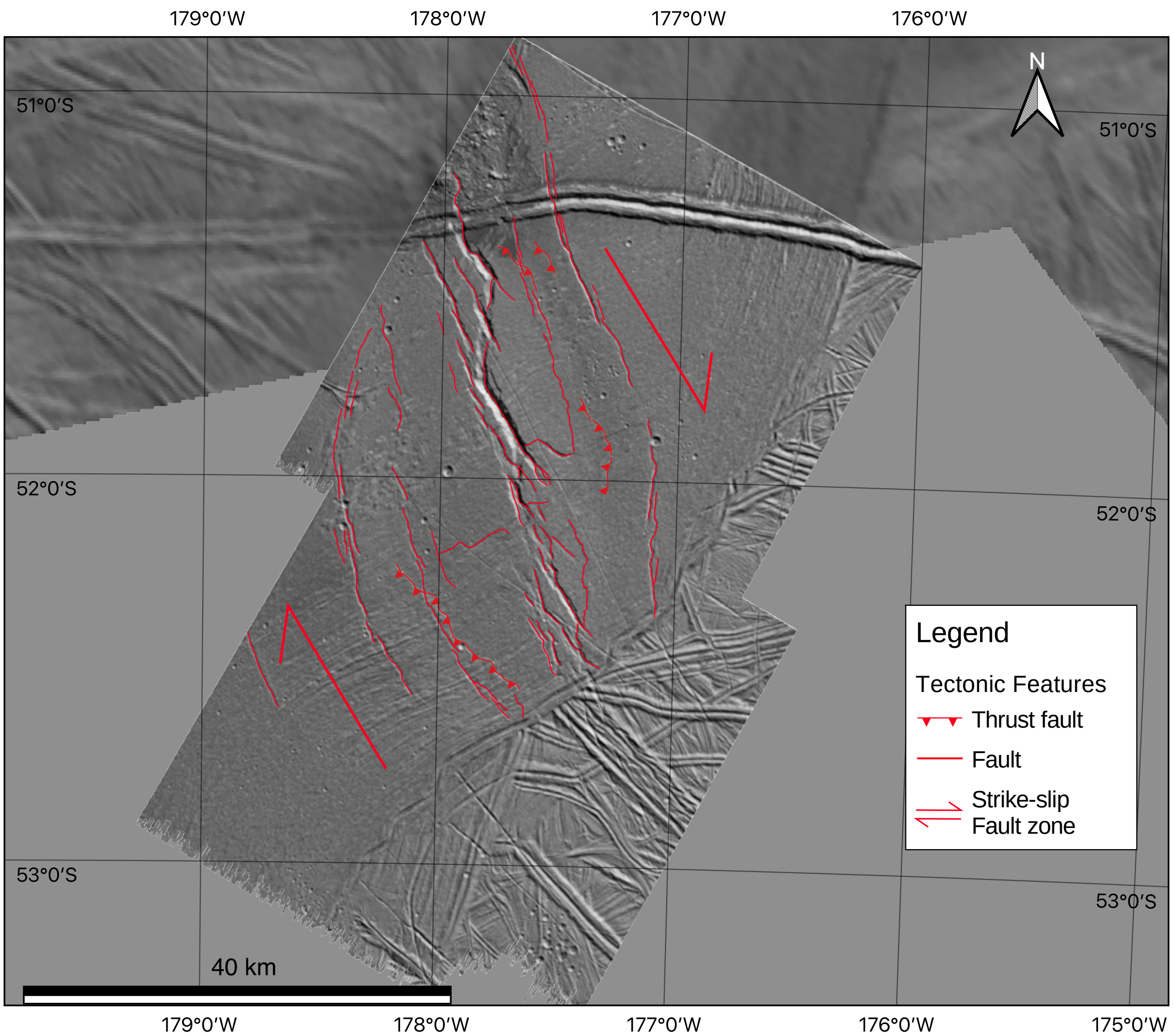

Figure 6. Proposed structural setting in the area of Ménec Fossae, image centered at 52°S, 177°W. The right-lateral strike-slip faulting controls the deformation along a wide shear zone, generating several extensional and transtensional features (marked together in the legend for ease of use of the structural map) and few compressive structures, in an predominantly transtensional

tectonic setting. Local portions have a larger compressional component, resulting in folding (see Figure 5) and thrust faulting.

3 Discussion and conclusions

Several formation hypotheses have been previously proposed for the area of Ménec Fossae. Prockter & Pappalardo (2000) consider it as a regional scale anticline (upward convex) fold's crest flanked by small reverse faults, which are inferred to mark syncline (upward concave) folds' hinges. In this case, the folding and associated small scale thrust faulting would imply that compression was, or is, ongoing in this area of Europa, which would locally compensate for the ubiquitous extension observed on this Jupiter's icy moon. More recently, it has been suggested (Schenk et al., 2020) that Ménec Fossa is part of a set of *en échelon* fissures associated with True Polar Wander (TPW) of the ice shell (Schenk et al., 2008), involving a 70° global rotation of surface features. The authors consider these features as sets of multiple parallel faults in which most of the extension is confined within a single narrow central feature. The fissures are also thought to be closely associated with buckling or tilting of the surface by a few tens of meters within the deformation zone. Other features on Europa associated with TPW (Schenk et al., 2020) include the same terrain type, displaying similar geomorphological and structural characteristic as Ménec Fossae (Kermario Fossae - 43°N, 5°E; Kerlescan Fossae - 3°N, 238°W).

Based on observations on geomorphology and topography of the Ménec Fossae area, our novel hypothesis for its formation mechanisms involves transtensional tectonics (Figure 6) above a shallow water reservoir. Such hypothesis considers the two main previous models on this area, described above (Prockter & Pappalardo, 2000; Schenk et al., 2020), and combines them with proposed mechanisms for the formation of different surface features on Europa, including chaotic terrains and double ridges (e.g., Chivers et al., 2021; Craft et al., 2016; Culberg et al., 2022; Dombard et al., 2013; Kalousová et al., 2016; B. E. Schmidt et al., 2011). These last contributions all invoke the emplacement of shallow water bodies within the ice shell to generate the various surface expressions they focus on. In particular, through a comparison with an analysis of an Earth's double ridge in Greenland, Culberg et al. (2022) show how double ridges might form via refreezing, pressurization and fracturing of shallow water reservoirs, potentially induced by shear heating (Han & Showman, 2008; Kalousová et al., 2016; Nimmo & Gaidos, 2002). Moreover, our observations (Section 3.1.2) on the flexural bulges and flanking troughs along the sides of the mapped double ridge (DRU), further strengthen the case for it originating from a shallow water body. In fact, Dombard et al. (2013) suggest how shallow water reservoirs must be involved in double ridges' formation in order to explain the aforementioned flanking features, where those are present. These processes could also operate in conjunction with other proposed double ridges' formation mechanisms, such as shear heating (Johnston & Montési, 2014).

In this study, our analyses on the geomorphological units and tectonic features of the Ménec Fossae area are consistent with such models. We observe a deep central feature (Ménec Fossa s.s.) that takes up most of the extension, flanked by numerous quasi-parallel subsidiary extensional and strike-slip faults and few thrust faults, all in a deformation zone of 20-30 km (see Section 3.3). We propose that such a tectonic setting is generated within a right-lateral strike-slip fault zone, with a major contribution from an extensional component, i.e., a transtensional tectonic setting (Figure 6). The shear heating related to such a tectonic setting possibly led to the formation of a shallow water reservoir within the ice shell, that in turn could have generated the DRU first and the CTU later (timing based on their crosscutting relationships). Such a scenario is consistent with the 70° global rotation of surface features through TPW proposed by Schenk et al. (2020), to explain the abrupt different orientation of the DRU (E-W) and the CTU and FU (NW-SE), which fits to a 70° rotation. The shallow water reservoir likely responsible for the DRU and CTU formation would have then been involved in such a rotation; its ultimate expression would be the FU and the associated faulting, which are a display on the surface of shearing through transtensional tectonics. Most formation models have calculated depths of 1-5 km for the emplacement of shallow water reservoirs beneath various geological features (lenticulae, chaos, double ridges, Chivers et al., 2021; Craft et al., 2016; Dombard et al., 2013; Johnston & Montési, 2014; Kalousová et al., 2016; Manga & Michaut, 2017; B. E. Schmidt et al., 2011), with estimates varying depending on the adopted thickness value of Europa's ice shell. We therefore assume a water reservoir's emplacement depth within such range in the study area, in agreement with the observed lowest elevations at Ménec Fossae of ~ -200 m (see Section 3.3). Compositional information is not available for the study area, as there are no *Galileo* Near Infrared Mapping Spectrometer (NIMS) data at this location. Having such kind of information would have been essential for detailed characterization of fresh subsurface material potentially emplaced by the Ménec Fossae fault system.

Transtensional tectonic features are widely common on Earth, mainly within large-scale strike-slip settings (Donzé et al., 2021). They have also been observed on terrestrial planets (e.g., Mars, Andrews-Hanna et al., 2008; G. Schmidt et al., 2022) and on other ocean worlds, Ganymede (e.g., Rossi et al., 2018), Enceladus (e.g., Rossi et al., 2020), and Titan (e.g., Burkhard et al., 2022; Matteoni et al., 2020). Several other examples exist on Europa as well, such as along Agenor Linea in the southern trailing hemisphere and Astypalaea Linea in the south polar region (Hoyer et al., 2014; Kattenhorn & Prockter, 2014; Tufts et al., 1999). In transtensional tectonic regimes, minor compressional features are common and expected (Fossen et al., 1994; Petit, 1987). In this context, the small thrust faults observed are consistent as being formed within a predominantly transtensional setting. This hypothesis does not rule out that of Prockter & Pappalardo (2000), which consider such thrust faults as marking synclinal folds' hinges and Ménec Fossa s.s. as a regional scale anticline's crest within the same fold system. In fact, in transtensional settings folding (on an oblique axis with respect to the major strike-slip fault zone, as we observe in the sudy area) is also common (Fossen et al., 1994).

We conclude that Ménec Fossa and its surroundings have been shaped by transtensional tectonic activity, most likely above a shallow water reservoir, whose emplacement has been potentially induced by shear heating. This model explains how an intriguing area of Europa, displaying several major terrain types, might have formed through one single major mechanism, while further strengthening the case for widely distributed shallow water reservoirs within Europa's ice shell.

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Open Research

Data Availability Statement

Galileo's SSI data used in this manuscript can be accessed from the PDS Cartography and Imaging Science Node via https://pds-imaging.jpl.nasa.gov/volumes/galileo, while the SSI photogrammetrically-corrected basemap mosaics can be accessed from the USGS Astrogeology website via https://doi.org/10.5066/P9VKKK7C. The Digital Terrain Model (Figure 3) and data of the geomorphological-structural map (Figure 4) produced are available on TRR 170-DB (Matteoni, 2022).

References

Anderson, J. D., Schubert, G., Jacobson, R. A., Lau, E. L., Moore, W. B., & Sjogren, W. L. (1998). Europa's Differentiated Internal Structure: Inferences from Four Galileo Encounters. *Science*, *281*(5385), 2019–2022. https://doi.org/10.1126/science.281.5385.2019

Andrews-Hanna, J. C., Zuber, M. T., & Hauck, S. A. (2008). Strike-slip faults on Mars: Observations and implications for global tectonics and geodynamics. *Journal of Geophysical Research*, *113*(E8), E08002. https://doi.org/10.1029/2007JE002980

Aydin, A. (2006). Failure modes of the lineaments on Jupiter's moon, Europa: Implications for the evolution of its icy crust. *Journal of Structural Geology*, *28*(12), 2222–2236. https://doi.org/10.1016/j.jsg.2006.08.003

Barr, A. C., & Pappalardo, R. T. (2005). Onset of convection in the icy Galilean satellites: Influence of rheology. *Journal of Geophysical Research*, *110*(E12), E12005. https://doi.org/10.1029/2004JE002371

Běhounková, M., Tobie, G., Choblet, G., Kervazo, M., Melwani Daswani, M., Dumoulin, C., & Vance, S. D. (2021). Tidally Induced Magmatic Pulses on the Oceanic Floor of Jupiter's Moon Europa. *Geophysical Research Letters*, *48*(3), 1–11. https://doi.org/10.1029/2020GL090077

Belton, M. J. S., Klaasen, K. P., Clary, M. C., Anderson, J. L., Anger, C. D., Carr, M. H., et al. (1992). The Galileo Solid-State Imaging experiment. *Space Science Reviews*, *60*(1–4), 413–455. https://doi.org/10.1007/BF00216864

Beyer, R. A., Alexandrov, O., & McMichael, S. (2018). The Ames Stereo Pipeline: NASA's Open Source Software for Deriving and Processing Terrain Data. *Earth and Space Science*, *5*(9), 537–548. https://doi.org/10.1029/2018EA000409

Bierhaus, E. B., & Schenk, P. M. (2010). Constraints on Europa's surface properties from primary and secondary crater morphology. *Journal of Geophysical Research E: Planets*, *115*(12), 1–17. https://doi.org/10.1029/2009JE003451

Bierhaus, Edward B., Chapman, C. R., & Merline, W. J. (2005). Secondary craters on Europa and implications for cratered surfaces. *Nature*, *437*(7062), 1125–1127. https://doi.org/10.1038/nature04069

Bierhaus, Edward B., Zahnle, K., & Chapman, C. R. (2009). Europa's Crater Distributions and Surface Ages. In *Europa* (pp. 161–180). University of Arizona Press. https://doi.org/10.2307/j.ctt1xp3wdw.13

Bland, M. T., Kirk, R. L., Galuszka, D. M., Mayer, D. P., Beyer, R. A., & Fergason, R. L. (2021). How Well Do We Know Europa's Topography? An Evaluation of the Variability in Digital Terrain Models of Europa. *Remote Sensing*, *13*(24), 5097. https://doi.org/10.3390/rs13245097

Bland, M. T., Weller, L. A., Archinal, B. A., Smith, E., & Wheeler, B. H. (2021). Improving the Usability of Galileo and Voyager Images of Jupiter's Moon Europa. *Earth and Space Science*, *8*(12). https://doi.org/10.1029/2021EA001935

Burkhard, L. M. L., Smith-Konter, B. R., Fagents, S. A., Cameron, M. E., Collins, G. C., & Pappalardo, R. T. (2022). Strike-slip faulting on Titan: Modeling tidal stresses and shear failure conditions due to pore fluid interactions. *Icarus*, *371*(March 2021), 114700. https://doi.org/10.1016/j.icarus.2021.114700

Carr, M. H., Belton, M. J. S., Chapman, C. R., Davies, M. E., Geissler, P., Greenberg, R., et al. (1998). Evidence for a subsurface ocean on Europa. *Nature*, *391*(6665), 363–365. https://doi.org/10.1038/34857

Chivers, C. J., Buffo, J. J., & Schmidt, B. E. (2021). Thermal and Chemical Evolution of Small, Shallow Water Bodies in Europa's Ice Shell. *Journal of Geophysical Research: Planets*, *126*(5), 1–26. https://doi.org/10.1029/2020JE006692

Collins, G., & Nimmo, F. (2009). Chaotic Terrain on Europa. In *Europa* (pp. 259–282). University of Arizona Press. https://doi.org/10.2307/j.ctt1xp3wdw.17

Craft, K. L., Patterson, G. W., Lowell, R. P., & Germanovich, L. (2016). Fracturing and flow: Investigations on the formation of shallow water sills on Europa. *Icarus*, *274*. https://doi.org/10.1016/j.icarus.2016.01.023

Culberg, R., Schroeder, D. M., & Steinbrügge, G. (2022). Double ridge formation over shallow water sills on Jupiter's moon Europa. *Nature Communications*, *13*(1), 1–10. https://doi.org/10.1038/s41467-022-29458-3

Dalton, J. B., Prieto-Ballesteros, O., Kargel, J. S., Jamieson, C. S., Jolivet, J., & Quinn, R. (2005). Spectral comparison of heavily hydrated salts with disrupted terrains on Europa. *Icarus*, *177*(2), 472–490. https://doi.org/10.1016/j.icarus.2005.02.023

Dalton, J. B., Shirley, J. H., & Kamp, L. W. (2012). Europa's icy bright plains and dark linea: Exogenic and endogenic contributions to composition and surface properties. *Journal of Geophysical Research: Planets*, *117*(E3), n/a-n/a. https://doi.org/10.1029/2011JE003909

Dombard, A. J., Patterson, G. W., Lederer, A. P., & Prockter, L. M. (2013). Flanking fractures and the formation of double ridges on Europa. *Icarus*, *223*(1), 74–81. https://doi.org/10.1016/j.icarus.2012.11.021

Donzé, F.-V., Klinger, Y., Bonilla-Sierra, V., Duriez, J., Jiao, L., & Scholtès, L. (2021). Assessing the brittle crust thickness from strike-slip fault segments on Earth, Mars and Icy moons. *Tectonophysics*, *805*(May 2020), 228779. https://doi.org/10.1016/j.tecto.2021.228779

Fagents, S. A. (2003). Considerations for effusive cryovolcanism on Europa: The post-Galileo perspective. *Journal of Geophysical Research: Planets*, *108*(E12), 13–1. https://doi.org/10.1029/2003JE002128

Figueredo, P. H., & Greeley, R. (2004). Resurfacing history of Europa from pole-to-pole geological mapping. *Icarus*, *167*(2), 287–312. https://doi.org/10.1016/j.icarus.2003.09.016

Fossen, H., Tikoff, B., & Teyssier, C. (1994). Strain modeling of transpressional and transtensional deformation. *Norsk Geologisk Tidsskrift*, *74*(3), 134–145.

Goode, W., Kempf, S., & Schmidt, J. (2021). Detecting the surface composition of geological features on Europa and Ganymede using a surface dust analyzer. *Planetary and Space Science*, *208*(September), 105343. https://doi.org/10.1016/j.pss.2021.105343

Greeley, R, Chyba, C. ~F., Head, I. I. I. J. ~W., McCord, T. ~B., McKinnon, W. ~B., Pappalardo, R. ~T., & Figueredo, P. ~H. (2004). *Geology of Europa*. *Jupiter. The planet, satellites and magnetosphere*.

Greeley, Ronald, Figueredo, P. H., Williams, D. A., Chuang, F. C., Klemaszewski, J. E., Kadel, S. D., et al. (2000). Geologic mapping of Europa. *Journal of Geophysical Research: Planets*, *105*(E9), 22559–22578. https://doi.org/10.1029/1999JE001173

Greenberg, R., & Geissler, P. (2002). Europa's dynamic icy crust. *Meteoritics & Planetary Science*, *37*(12), 1685–1710. https://doi.org/10.1111/j.1945-5100.2002.tb01158.x

Greenberg, R., & Sak, P. B. (2014). The ridges of Europa: Extensions of adjacent topography onto their flanks. *Earth and Planetary Science Letters*, *389*, 43–51. https://doi.org/10.1016/j.epsl.2013.12.009

Greenberg, R., Geissler, P., Hoppa, G., Tufts, B. R., Durda, D. D., Pappalardo, R., et al. (1998). Tectonic Processes on Europa: Tidal Stresses, Mechanical Response, and Visible Features. *Icarus*, *135*(1), 64–78. https://doi.org/10.1006/icar.1998.5986

Greenberg, R., Geissler, P., Tufts, B. R., & Hoppa, G. V. (2000). Habitability of Europa's crust: The role of tidal-tectonic processes. *Journal of Geophysical Research: Planets*, *105*(E7), 17551–17562. https://doi.org/10.1029/1999JE001147

Greenberg, R., Hoppa, G. V., Bart, G., & Hurford, T. (2003). Tidal stress patterns on Europa's crust. *Celestial Mechanics and Dynamical Astronomy*, *87*(1–2), 171–188. https://doi.org/10.1023/A:1026169424511

Han, L., & Showman, A. P. (2008). Implications of shear heating and fracture zones for ridge formation on Europa. *Geophysical Research Letters*, *35*(3), L03202. https://doi.org/10.1029/2007GL031957

Hand, K. P., & Carlson, R. W. (2015). Europa's surface color suggests an ocean rich with sodium chloride. *Geophysical Research Letters*, *42*(9), 3174–3178. https://doi.org/10.1002/2015GL063559

Hand, K. P., Phillips, C. B., Murray, A., Garvin, J. B., Maize, E. H., Gibbs, R. G., et al. (2022). Science Goals and Mission Architecture of the Europa Lander Mission Concept. *The Planetary Science Journal*, *3*(1), 22. https://doi.org/10.3847/PSJ/ac4493

Hansen, G. B., & McCord, T. B. (2008). Widespread CO2 and other non-ice compounds on the anti-Jovian and trailing sides of Europa from Galileo/NIMS observations. *Geophysical Research Letters*, *35*(1), 2–6. https://doi.org/10.1029/2007GL031748

Hoppa, G. V., Tufts, B. R., Greenberg, R., & Geissler, P. E. (1999). Formation of Cycloidal Features on Europa. *Science*, *285*(5435), 1899–1902. https://doi.org/10.1126/science.285.5435.1899

Howell, S. M. (2021). The Likely Thickness of Europa's Icy Shell. *The Planetary Science Journal*, *2*(4), 129. https://doi.org/10.3847/PSJ/abfe10

Hoyer, L., Kattenhorn, S. A., & Watkeys, M. K. (2014). Multistage evolution and variable motion history of Agenor Linea, Europa. *Icarus*, *232*, 60–80. https://doi.org/10.1016/j.icarus.2013.12.010

Hussmann, H. (2002). Thermal Equilibrium States of Europa's Ice Shell: Implications for Internal Ocean Thickness and Surface Heat Flow. *Icarus*, *156*(1), 143–151. https://doi.org/10.1006/icar.2001.6776

Hussmann, H., Choblet, G., Lainey, V., Matson, D. L., Sotin, C., Tobie, G., & Van Hoolst, T. (2010). Implications of Rotation, Orbital States, Energy Sources, and Heat Transport for Internal Processes in Icy Satellites. *Space Science Reviews*, *153*(1–4), 317–348. https://doi.org/10.1007/s11214-010-9636-0

Johnston, S. A., & Montési, L. G. J. (2014). Formation of ridges on Europa above crystallizing water bodies inside the ice shell. *Icarus*, *237*, 190–201. https://doi.org/10.1016/j.icarus.2014.04.026

Kalousová, K., Souček, O., Tobie, G., Choblet, G., & Čadek, O. (2016). Water generation and transport below Europa's strike-slip faults. *Journal of Geophysical Research: Planets*, *121*(12). https://doi.org/10.1002/2016JE005188

Kattenhorn, S. A., & Hurford, T. (2009). Tectonics of Europa. In *Europa* (pp. 199–236). University of Arizona Press.

Kattenhorn, S. A., & Prockter, L. M. (2014). Evidence for subduction in the ice shell of Europa. *Nature Geoscience*, *7*(10), 762–767. https://doi.org/10.1038/ngeo2245

Kempf, S., Altobelli, N., Briois, C., Grün, E., Horanyi, M., Postberg, F., et al. (2014). SUDA: A Dust Mass Spectrometer for Compositional Surface Mapping for a Mission to Europa. *European Planetary Science Congress 2014*, *9*(EPSC2014-229). Retrieved from http://adsabs.harvard.edu/abs/2014EPSC....9..229K

Khurana, K. K., Kivelson, M. G., Stevenson, D. J., Schubert, G., Russell, C. T., Walker, R. J., & Polanskey, C. (1998). Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto. *Nature*, *395*(6704), 777–780. https://doi.org/10.1038/27394

Kivelson, M. G., Khurana, K. K., Russell, C. T., Volwerk, M., Walker, R. J., & Zimmer, C. (2000). Galileo Magnetometer Measurements: A Stronger Case for a Subsurface Ocean at Europa. *Science*, *289*(5483), 1340–1343. https://doi.org/10.1126/science.289.5483.1340

Leonard, E. J., Pappalardo, R. T., & Yin, A. (2018). Analysis of very-high-resolution Galileo images and implications for resurfacing mechanisms on Europa. *Icarus*, *312*, 100–120. https://doi.org/10.1016/j.icarus.2018.04.016

Leonard, E. J., Yin, A., & Pappalardo, R. T. (2020). Ridged plains on Europa reveal a compressive past. *Icarus*, *343*, 113709. https://doi.org/10.1016/j.icarus.2020.113709

Lesage, E., Schmidt, F., Andrieu, F., & Massol, H. (2021). Constraints on effusive cryovolcanic eruptions on Europa using topography obtained from Galileo images. *Icarus*, *361*, 114373. https://doi.org/10.1016/j.icarus.2021.114373

Ligier, N., Poulet, F., Carter, J., Brunetto, R., & Gourgeot, F. (2016). Vlt/Sinfoni Observations of Europa: New Insights Into the Surface Composition. *The Astronomical Journal*, *151*(6), 163. https://doi.org/10.3847/0004-6256/151/6/163

Manga, M., & Michaut, C. (2017). Formation of lenticulae on Europa by saucer-shaped sills. *Icarus*, *286*, 261–269. https://doi.org/10.1016/j.icarus.2016.10.009

Matteoni, P. (2022). Replication Data for: Ménec Fossae on Europa: a Strike-Slip Tectonics Origin above a possible Shallow Water Reservoir. TRR170-DB. https://doi.org/10.35003/8CU23S

Matteoni, P., Mitri, G., Poggiali, V., & Mastrogiuseppe, M. (2020). Geomorphological Analysis of the Southwestern Margin of Xanadu, Titan: Insights on Tectonics. *Journal of Geophysical Research: Planets*, *125*(12), 1–22. https://doi.org/10.1029/2020JE006407

McCord, T. B., Hansen, G. B., Matson, D. L., Johnson, T. V., Crowley, J. K., Fanale, F. P., et al. (1999). Hydrated salt minerals on Europa's surface from the Galileo near-infrared mapping spectrometer (NIMS) investigation. *Journal of Geophysical Research: Planets*, *104*(E5), 11827–11851. https://doi.org/10.1029/1999JE900005

Nimmo, F., & Pappalardo, R. T. (2016). Ocean worlds in the outer solar system. *Journal of Geophysical Research: Planets*, *121*(8), 1378–1399. https://doi.org/10.1002/2016JE005081

Nimmo, F., Pappalardo, R. ., & Giese, B. (2003). On the origins of band topography, Europa. *Icarus*, *166*(1), 21–32. https://doi.org/10.1016/j.icarus.2003.08.002

Nimmo, Francis, & Gaidos, E. (2002). Strike-slip motion and double ridge formation on Europa. *Journal of Geophysical Research*, *107*(E4), 5021. https://doi.org/10.1029/2000JE001476

Orlando, T. M., McCord, T. B., & Grieves, G. A. (2005). The chemical nature of Europa surface material and the relation to a subsurface ocean. *Icarus*, *177*(2), 528–533. https://doi.org/10.1016/j.icarus.2005.05.009

Pappalardo, R. T., Head, J. W., Greeley, R., Sullivan, R. J., Pilcher, C., Schubert, G., et al. (1998). Geological evidence for solid-state convection in Europa's ice shell. *Nature*, *391*(6665), 365–368. https://doi.org/10.1038/34862

Pappalardo, R. T., Belton, M. J. S., Breneman, H. H., Carr, M. H., Chapman, C. R., Collins, G. C., et al. (1999). Does Europa have a subsurface ocean? Evaluation of the geological evidence. *Journal of Geophysical Research: Planets*, *104*(E10), 24015–24055. https://doi.org/10.1029/1998JE000628

Petit, J. P. (1987). Criteria for the sense of movement on fault surfaces in brittle rocks. *Journal of*

Structural Geology, *9*(5–6), 597–608. https://doi.org/10.1016/0191-8141(87)90145-3

Postberg, F., Grün, E., Horanyi, M., Kempf, S., Krüger, H., Schmidt, J., et al. (2011). Compositional mapping of planetary moons by mass spectrometry of dust ejecta. *Planetary and Space Science*, *59*(14), 1815–1825. https://doi.org/10.1016/j.pss.2011.05.001

Prockter, L. M., & Pappalardo, R. T. (2000). Folds on Europa: Implications for Crustal Cycling and Accommodation of Extension. *Science*, *289*(5481), 941–943. https://doi.org/10.1126/science.289.5481.941

Prockter, L. M., Antman, A. M., Pappalardo, R. T., Head, J. W., & Collins, G. C. (1999). Europa: Stratigraphy and geological history of the anti-Jovian region from Galileo E14 solid-state imaging data. *Journal of Geophysical Research: Planets*, *104*(E7), 16531–16540. https://doi.org/10.1029/1998JE001015

Prockter, L. M., Head, J. W., Pappalardo, R. T., Sullivan, R. J., Clifton, A. E., Giese, B., et al. (2002). Morphology of Europan bands at high resolution: A mid-ocean ridge-type rift mechanism. *Journal of Geophysical Research*, *107*(E5), 5028. https://doi.org/10.1029/2000JE001458

Quick, L. C., & Marsh, B. D. (2015). Constraining the thickness of Europa's water–ice shell: Insights from tidal dissipation and conductive cooling. *Icarus*, *253*, 16–24. https://doi.org/10.1016/j.icarus.2015.02.016

Rhoden, A. R., Mohr, K. J., Hurford, T. A., Henning, W., Sajous, S., Patthoff, D. A., & Dubois, D. (2021). Obliquity, Precession, and Fracture Mechanics: Implications of Europa's Global Cycloid Population. *Journal of Geophysical Research: Planets*, *126*(3). https://doi.org/10.1029/2020JE006710

Rossi, C., Cianfarra, P., Salvini, F., Mitri, G., & Massé, M. (2018). Evidence of transpressional tectonics on the Uruk Sulcus region, Ganymede. *Tectonophysics*, *749*(March), 72–87. https://doi.org/10.1016/j.tecto.2018.10.026

Rossi, C., Cianfarra, P., Salvini, F., Bourgeois, O., & Tobie, G. (2020). Tectonics of Enceladus' South Pole: Block Rotation of the Tiger Stripes. *Journal of Geophysical Research: Planets*, *125*(12), 1–21. https://doi.org/10.1029/2020JE006471

Schenk, P., Matsuyama, I., & Nimmo, F. (2008). True polar wander on Europa from global-scale small-circle depressions. *Nature*, *453*(7193), 368–371. https://doi.org/10.1038/nature06911

Schenk, P., Matsuyama, I., & Nimmo, F. (2020). A Very Young Age for True Polar Wander on Europa From Related Fracturing. *Geophysical Research Letters*, *47*(17), 1–9. https://doi.org/10.1029/2020GL088364

Schenk, P. M., & Pappalardo, R. T. (2004). Topographic variations in chaos on Europa: Implications for diapiric formation. *Geophysical Research Letters*, *31*(16), 1–5. https://doi.org/10.1029/2004GL019978

Schmidt, B. E., Blankenship, D. D., Patterson, G. W., & Schenk, P. M. (2011). Active formation of "chaos terrain" over shallow subsurface water on Europa. *Nature*, *479*(7374), 502–505. https://doi.org/10.1038/nature10608

Schmidt, G., Luzzi, E., Rossi, A. P., Pondrelli, M., Apuzzo, A., & Salvini, F. (2022). Protracted Hydrogeological Activity in Arabia Terra, Mars: Evidence from the Structure and

Mineralogy of the Layered Deposits of Becquerel Crater. *Journal of Geophysical Research: Planets*. https://doi.org/10.1029/2022JE007320

Schubert, G., Sohl, F., & Hussmann, H. (2009). Interior of europa. *Europa*, 353–367.

Singer, K. N., McKinnon, W. B., & Nowicki, L. T. (2013). Secondary craters from large impacts on Europa and Ganymede: Ejecta size–velocity distributions on icy worlds, and the scaling of ejected blocks. *Icarus*, *226*(1), 865–884. https://doi.org/10.1016/j.icarus.2013.06.034

Sotin, C., Tobie, G., Wahr, J., McKinnon, W. B., McKinnon, W. B., & Khurana, K. K. (2009). Tides and tidal heating on Europa. *Europa*, *11*.

Trumbo, S. K., Brown, M. E., Fischer, P. D., & Hand, K. P. (2017). A New Spectral Feature on the Trailing Hemisphere of Europa at 3.78 μ m. *The Astronomical Journal*, *153*(6), 250. https://doi.org/10.3847/1538-3881/aa6d80

Trumbo, S. K., Brown, M. E., & Hand, K. P. (2019a). H 2 O 2 within Chaos Terrain on Europa's Leading Hemisphere. *The Astronomical Journal*, *158*(3), 127. https://doi.org/10.3847/1538-3881/ab380c

Trumbo, S. K., Brown, M. E., & Hand, K. P. (2019b). Sodium chloride on the surface of Europa. *Science Advances*, *5*(6), 2–6. https://doi.org/10.1126/sciadv.aaw7123

Trumbo, S. K., Becker, T. M., Brown, M. E., Denman, W. T. P., Molyneux, P., Hendrix, A., et al. (2022). A New UV Spectral Feature on Europa: Confirmation of NaCl in Leading-hemisphere Chaos Terrain. *The Planetary Science Journal*, *3*(2), 27. https://doi.org/10.3847/PSJ/ac4580

Tufts, B. R., Greenberg, R., Hoppa, G., & Geissler, P. (1999). Astypalaea Linea: A Large-Scale Strike-Slip Fault on Europa. *Icarus*, *141*(1), 53–64. https://doi.org/10.1006/icar.1999.6168

Vance, S., Harnmeijer, J., Kimura, J., Hussmann, H., DeMartin, B., & Brown, J. M. (2007). Hydrothermal Systems in Small Ocean Planets. *Astrobiology*, *7*(6), 987–1005. https://doi.org/10.1089/ast.2007.0075

Vance, S. D., Hand, K. P., & Pappalardo, R. T. (2016). Geophysical controls of chemical disequilibria in Europa. *Geophysical Research Letters*, *43*(10), 4871–4879. https://doi.org/10.1002/2016GL068547